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OIL SPILL MODELING FOR IMPROVED RESPONSE TO ARCTIC MARITIME SPILLS: THE PATH FORWARD

Megan Patricia Verfaillie
University of New Hampshire, Durham

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Megan Verfaillie
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This thesis/dissertation was examined and approved in partial fulfillment of the requirements for the degree of Master of Science in Civil and Environmental Engineering by:

Thesis/Dissertation Director, Dr. Nancy Kinner
Professor of Civil and Environmental Engineering

Dr. Katharine Duderstadt
Research Scientist in the Earth Systems Research Center

Dr. Diane Foster
Professor of Mechanical and Ocean Engineering

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Approval signatures are on file with the University of New Hampshire Graduate School.

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LIST OF ACRONYMS / DEFINITIONS†

- **ADAC:** Arctic Domain Awareness Center
- **ADEC:** Alaska Department of Environmental Conservation
- **ARD:** NOAA OR&R Assessment and Restoration Division
- **ASIP:** Alaska Sea Ice Program
- **COA:** Certificates of Waiver or Authorization
- **CSE:** Center for Spills and Environmental Hazards
- **CRRC:** Coastal Response Research Center
- **DHI:** Danish Hydraulic Institute
- **DHS:** Department of Homeland Security
- **DOE:** Department of Energy
- **DWH:** Deepwater Horizon
- **ECCC:** Environment and Climate Change Canada
- **ERD:** NOAA OR&R Emergency Response Division
- **ERMA:** Environmental Response Management Application
- **Federal On-Scene Coordinator (FOSC):** Official who coordinates the federal government's response to an oil spill. In the coastal/marine zone, the FOSC is typically an officer in the USCG.
- **First Year Sea Ice:** Thicker than young ice, but has no more than one year of growth (thickness from ~ 1 to 6.6 feet) [1].
- **General NOAA Operational Modeling Environment (GNOME):** Modeling tool for predicting fate and transport of pollutants spilled into water. Available publicly via Web interface. Developed and used by NOAA OR&R's Emergency Response Division.
- **GFDL:** NOAA Geophysical Fluid Dynamics Laboratory
- **GOIN:** N.N. Zubov's State Oceanographic Institute, Moscow, Russia
- **Incident Command System:** ICS
- **Landfast Ice:** Anchored to the shore or bottom of the ocean. Also referred to as fast ice [1].
- **Marginal Ice Zone:** Part of the seasonal ice zone which varies in width from 100 to 200 kilometers. Extends from the ice edge into the ice pack and is defined as the transitional zone between open sea and dense drift ice. It spans the gap between ~15% and 80% ice cover. Often characterized by highly variable ice conditions [1, 2].
- **Multi-Year Ice:** Ice that has survived at least one melt season (thickness from ~ 6.6 to 13.1 feet) [1].
- **NETL:** Department of Energy National Energy Technology Laboratory
- **NOAA:** National Oceanic and Atmospheric Administration
- **NRC Canada:** National Research Council Canada
- **NWS:** NOAA National Weather Service
- **OR&R:** NOAA Office of Response and Restoration

† English units are used because this product is focused on the USCG FOSC.

- **Pack Ice:** Ice that drifts with wind and currents and is not attached to the shoreline. Also referred to as drift ice [1].
- **RPS ASA:** RPS Applied Science Associates
- **RRT:** Regional Response Team
- **Scientific Support Coordinator (SSC):** Assists the FOSC in gathering and analyzing environmental and safety information to during a spill response to aid in decision-making. In the coastal/marine zone, the SSC is typically a NOAA scientist.
- **UAA:** University of Alaska Anchorage
- **UAF:** University of Alaska Fairbanks
- **UC:** Unified Command
- **USCG:** United States Coast Guard
- **USCG D17:** USCG District 17 (Alaska)
- **USCG FOSC:** USCG Federal On-Scene Coordinator
- **USCG MER:** USCG Marine Environmental Response
- **USNIC:** U.S. National Ice Center
- **UW:** University of Washington
- **80-20 or 80-30 % Rule:** Typically uses the following assumptions (N.B., Conditions between specified coverage amount are interpolated).
    - For 0 - 20/30% ice coverage: oil behaves as if there is no ice present, weathering as in open water
    - For 20/30-80% ice coverage: oil moves at the average of ice and current velocities, weathering occurs at a reduced rate over that in open water
    - For 80-100% ice coverage: oil behaves as if there is full ice coverage, evaporation/dispersion do not occur

ABSTRACT

Maritime shipping and natural resource development in the Arctic are projected to increase as sea ice coverage decreases, resulting in a greater probability of more and larger oil spills. The increasing risk of Arctic spills emphasizes the need to identify the state-of-the-art oil trajectory and sea ice models and the potential for their integration. The Oil Spill Modeling for Improved Response to Arctic Maritime Spills: The Path Forward (AMSM) project, funded by the Arctic Domain Awareness Center (ADAC), provides a structured approach to gather expert advice to address U.S. Coast Guard (USCG) Federal On-Scene Coordinator (FOSC) core needs for decision-making. The National Oceanic & Atmospheric Administration (NOAA) Office of Response & Restoration (OR&R) provides scientific support to the USCG FOSC during oil spill response. As part of this scientific support, NOAA OR&R supplies decision support models that predict the fate (including chemical and physical weathering) and transport of spilled oil. Oil spill modeling in the Arctic faces many unique challenges including limited availability of environmental data (e.g., currents, wind, ice characteristics) at fine spatial and temporal resolution to feed models. Despite these challenges, OR&R's modeling products must provide adequate spill trajectory predictions, so that response efforts minimize economic, cultural and environmental impacts, including those to species, habitats and food supplies. The AMSM project addressed the unique needs and challenges associated with Arctic spill response by: (1) identifying state-of-the-art oil spill and sea ice models, (2) recommending new components and algorithms for oil and ice interactions, (3) proposing methods for improving communication of model output uncertainty, and (4) developing methods for coordinating oil and ice modeling efforts.

1. INTRODUCTION/BACKGROUND

1.1 Oil Spills and Modeling in the Arctic Environment

Polar amplification is causing the Arctic to experience climate change at rates more than three times higher than lower latitudes, resulting in decreasing sea ice extent and thickness and longer periods of open water in the Northwest Passage and Northern Sea Route [3, 4, 5, 6]. A report from the Intergovernmental Panel on Climate Change predicts that by 2080 Arctic sea ice duration is expected to be 20-30 days shorter, extending the length of the summer shipping season [7]. In ice free conditions, the Northern Sea Route provides a shorter travel distance between Pacific and Atlantic ports compared to the Suez and Panama Canal [8, 9]. As the Arctic becomes more accessible, shipping and resource extraction are likely to increase. Between 2013 and 2019, the Arctic Council reported a 25% increase in the number of ships entering the region [10]. Oil in the Arctic maritime environment may originate from vessel spills (e.g., cargo ships, tankers, cruise ships), as well as natural resource development (e.g., pipelines, drilling), and may include a range of types including crude, distillates (e.g., marine gas oil, marine diesel oil), and liquified natural gas [11].

Accidental releases or illegal discharges of oil into the Arctic environment pose a significant threat to the region [12]. Oil has the potential to negatively impact sensitive species and coastal and marine habitats, as well as local communities which rely on culturally significant, subsistence-based food sources [11], many of which are already threatened by the impacts of climate change [13]. Organisms exposed to oil through ingestion, inhalation or dermal contact may experience lethal or sublethal impacts, such as the disruption of insulation and water repellency of fur and feathers, reproductive impairment and reduced growth [14]. Sensitivity and exposure of Arctic species depends on the type of spilled oil and population density near the spill location [15]. Unlike oil released in lower latitudes, oil in the Arctic environment may weather more slowly (e.g., slower evaporation, biodegradation) due to the extremely cold temperatures, making it more persistent [15]. Its behavior, and the effectiveness of response and recovery techniques, are primarily determined by ice concentration and the season in which oil is spilled (i.e., summer open-water season, freeze-up, mid-winter, thaw/breakup) [16].

In the United States (U.S.), emergencies are managed via the federal government's Incident Command System (ICS). The Unified Command (UC) (i.e., local, state and federal officials, responsible party representatives) is responsible for developing response objectives and strategies, improving the flow of information and optimizing the combined efforts of multiple agencies and stakeholders [17]. The U.S. Coast Guard (USCG) is responsible for responding to incidents in the U.S. marine environment and receives scientific support from the National Oceanic and Atmospheric Administration (NOAA) Office of Response and Restoration (OR&R). As part of this scientific effort, the NOAA OR&R Emergency Response Division (ERD) supplies decision support models that predict the fate and trajectory of spilled oil (including chemical and physical weathering), characterizes habitats and species at risk and analyzes the potential performance of cleanup alternatives. A NOAA Scientific Support Coordinator (SSC) helps facilitate communication and understanding between responders and modelers.

In the Arctic, oil spill response and modeling face unique challenges, including limited response infrastructure (e.g., vessels, equipment, accommodations, oil storage capacity) and personnel, extreme weather conditions, extended periods of darkness, and sparse observational data. The Arctic Ocean is approximately 14 million km^2 and has > 45,000 km of coastline in six of the Arctic nations (Canada, Denmark, Iceland, Norway, Russian, and the U.S.). It is mostly covered in ice for 8-9 months per year and receives little to no sunlight for nearly three months. The remoteness of the Arctic region means that response resources and personnel may have to travel 1,000 + miles to respond to a spill [11]. In addition, atmospheric conditions in the Arctic can disrupt high frequency radio signals, making communication during response operations challenging [18]. As a result, oil spill models play a crucial role in minimizing spill impacts through informed decision-making and more efficient allocation of resources. They must also: operate with extended timescales to track oil frozen into sea ice, adjust existing algorithms to address the impact of freezing temperatures on oil behavior and weathering and address the complex movement and interactions of oil and sea ice. The limited availability of data also means that models often rely on a series of "best guesses" in order to predict oil movement based on expert advice and historical experience.

1.2 AMSM Project

The increasing risk of oil spills emphasizes the need to identify, enhance and develop tools and techniques to address the unique needs and challenges in the Arctic and improve preparedness of response agencies. The Oil Spill Modeling for Improved Response to Arctic Maritime Spills: The Path Forward (i.e., Arctic Maritime Spill Modeling (AMSM)) project was funded by the Arctic Domain Awareness Center (ADAC) and executed by the Coastal Response Research Center/Center for Spills and Environmental Hazards (CRRC/CSE) at the University of New Hampshire (UNH).

ADAC was established in 2014 by the U.S. Department of Homeland Security (DHS) Science and Technology Directorate Office of University Programs and is part of the DHS Center of Excellence Network. It is located at the University of Alaska Anchorage (UAA) and conducts research to provide a scientific basis to address challenges faced by the USCG and other DHS maritime missions in the Arctic. ADAC completes its mission by leading Arctic-focused science and technology research, convening experts at workshops and conducting educational programs [19].

The AMSM project provided a structured approach to gather expert advice to evaluate models that could address USCG FOSC core needs during Arctic oil spill response. The overall project objectives were to: (1) identify current state-of-the-art Arctic maritime oil spill response and sea ice models, (2) evaluate potential integration of oil spill models, sea ice models and components from recent research efforts and (3) determine gaps in current models that need to be addressed by future research. The AMSM project considered the fundamental needs of the FOSC and response community during spill events, such as communication of the sources and meaning of uncertainty and the understanding of model output visualizations. It also recommended investments to improve response by identifying specific needs to make models more functional in appropriate time scales. Improvement of model outputs will allow FOSCs to make informed decisions on deployment of assets and minimize impacts to economic, cultural and ecological resources [11].

The AMSM project considered oil spill models from the private sector (e.g., RPS's (South Kingstown, RI) OILMAP/SIMAP), U.S. and Canadian governments (e.g., NOAA's General NOAA Operational Modeling Environment (GNOME), Canadian Oil Spill Modeling Suite (COSMoS)) and those from other international entities (e.g., SINTEF's Marine Environmental Workbench (MEMW)). In addition to oil spill models, the influence and integration of major sea ice models (e.g., neXtSIM, CICE) were also investigated to identify their ability to provide relevant information to existing oil spill models.

The AMSM project was divided into six phases over two years. During the project, two workshops and four working groups were hosted by CRRC. The project deliverables included:

1. A list of the needs/questions related to oil spill modeling that must be addressed to support the USCG FOSC in decision-making during an Arctic response.
2. A review of the current state-of-the-art response modeling for Arctic maritime oil spills and sea ice modeling/data services.
3. Delineation of uncertainty in model predictions and how to express it in a format that can be easily interpreted by an FOSC.
4. Outline of new and existing technologies that are available to locate and determine the characteristics of spilled oil in the Arctic, including their usefulness in anticipated spill scenarios.
5. Suggestions for incorporating local and indigenous knowledge into oil spill trajectory forecasts [N.B., Not covered in thesis].
6. Detailed recommendations/scopes of work on modeling research needed to fill gaps identified during the project.

Collaboration between the Project Core Team, key stakeholders from USCG and NOAA and industry and international experts throughout these phases identified: (1) USCG FOSC core needs during Arctic spill response (e.g., visualization, uncertainty); (2) the current state-of-the-art Arctic maritime oil spill response models, sea ice models and ice observing systems; (3) challenges for integration of oil spill models, sea ice models and ice observations (i.e., scale of available data, existing algorithms, data assimilation); (4) new and existing technologies for observing oil and sea ice; and (5) gaps in current models to be addressed by future research. The author of this thesis was responsible for: (1) organization of Core Team, working group and supplementary meetings; (2) assisting with workshop planning, logistics and execution; (3) drafting and finalizing reference documents, reports and working group conclusions; and (4) compiling project findings in support of the final Knowledge Product.

This thesis includes a summary of AMSM project deliverables 1, 2, 3, 4, and 6 and will serve as the basis for creation of the final Knowledge Product. Deliverable 5 will be included in a UNH undergraduate honor's thesis completed by former ADAC Fellow Jessica Manning. The final Knowledge product will be completed following approval of this thesis and will integrate stakeholder and Core Team feedback before it is submitted to ADAC. In addition to the deliverables discussed in this thesis, the Knowledge Product will include suggestions for incorporating local and indigenous knowledge into spill trajectory forecasts, clearly delineate the characteristics of oil spill response that make some models inappropriate for the time scales required to inform daily planning and decision-making and recommend what specific new components/submodels should be developed and validated to better inform FOSC decision-making.

This thesis contains an introduction, methods, results/discussion, conclusions, and suggestions for future research. The remainder of the introduction includes a background on previous, project-related research used to develop the AMSM project and a summary on the model algorithms and operation using NOAA's GNOME oil spill model and the CICE sea ice model as examples. Following the introduction is a detailed description of the project methodology organized into six phases. The results and discussion section summarizes the project findings on state-of-the-art oil spill models, sea ice models and ice observing systems, challenges for model integration (e.g., scale of available data, algorithms, data assimilation), a summary of responder needs and how models address uncertainty, new and existing technologies for collecting data on spilled oil and sea ice conditions, and the path forward. The conclusions section organizes the results into the five project deliverables addressed by this thesis. A detailed appendix includes relevant AMSM documentation and products. The methods, results and conclusion will be directly integrated into the final Knowledge Product. Additional materials will also be included in the Knowledge Product appendix based on feedback provided by ADAC and the Core Team.

1.3 Background

Spill response modeling has been a focus of CRRC since 2006 when it facilitated a workshop for OR&R on "Innovative Coastal Modeling for Decision Support: Integrating Physical, Biological and Toxicological Models." This workshop brought together OR&R scientists and other experts from diverse fields to discuss how to improve and integrate trajectory fate and effects forecasting capabilities across the physical, biological and toxicological fields of spill response and modeling. In addition, CRRC and OR&R facilitated a Spill Modeling Summit in June 2007. This summit resulted in the formation of an Oil Spill Modeling Working Group that met between 2008 and 2011. The group focused on development of new 3D algorithms to improve modeling. Modelers, responders and scientists discussed oil spill-related topics such as spreading, water-in-oil emulsification and time-length scales. They created a matrix detailing models' inputs, outputs and limitations related to fate, transport and biology.

In the wake of the 2010 Deepwater Horizon (DWH) spill, the Gulf of Mexico Research Initiative (GoMRI) was established to improve understanding, response and mitigation of the impacts of petroleum pollution and related stressors to marine and coastal ecosystems. Ten years of GoMRI research have resulted in eight Core Areas, which include major research themes and their applications to operational and user communities. Three of these Core Areas included modeling topics: Plume & Circulation Observations and Modeling (Area 1), Fate of Oil & Weathering: Biological & Physical-Chemical Degradation (Area 2) and Integrated/Linked Modeling Systems (Area 7). Area 1 focused on research and modeling relevant to oil transport and fate in: (1) the Gulf of Mexico river, wetland, estuary, coastal, and open ocean regions, (2) the near-field, mid-field and far-field plume, and (3) small scale, near-surface and sub-mesoscale observations. Area 2 reviewed research related to oil spill chemical and biological analysis (e.g., genomics, molecular biology tools, oil exposure studies), marine oil snow, degradation, and dispersants. Area 7 included a workshop on operational oil spill modeling and discussed tools for decision-making (e.g., development of a system dynamics model) [20].

Of these Core Areas, Area 7 on Integrated/Linked Modeling Systems is the most relevant to the AMSM project. The research produced by Barker et al. (2020) as part of Area 7 determined the state-of-the-art of operational modeling as a result of GoMRI research and identified future developments, knowledge gaps and technology requirements. Operational oil spill models focus on the time period immediately following a spill (hours to days) and use predictive numerical models to describe real-world environmental conditions (e.g., oceanic circulation, wind, waves) to forecast oil fate and transport. The forecasts produced by operational models provide information to inform response activities and operations. Barker et al. also discussed that in computer modeling, the term “operational” does not have a standard meaning. In some cases, Operational (usually with a capital “O”) refers to a system with defined standards for accuracy, reliability and availability. Other times, operational refers to systems that provide results continuously on a regular basis, often referred to as “real-time” systems. These systems do not require 24/7 support and reliability and do not meet the criteria defined for Operational models [21].

Barker et al. also proposed improvements to oil models including collection of more data from controlled release experiments, especially at the field-scale. Release experiments completed at the bench scale (laboratory) or mesoscale (intermediate) are limited in their ability to reproduce real-world environmental conditions, and field data are not usually collected during an active spill event as it may conflict with response operations. Field release experiments require extensive permitting and usually have a lengthy approval process. Currently, controlled release experiments for model development and testing of cleanup methods have only been done in Canada, Norway, the UK, and the Netherlands. Improvement of integrated models, or those that combine physical, chemical and biological research/data to predict oil spill trajectory and fate, is essential to oil spill preparedness, planning and response decision-making. This requires creation of better parameterizations of: oil transport (especially wind drift, oil and dissolved constituents, breaking waves); oil fate (i.e., entrainment and its parameterizations, processes influencing droplets at the surface and subsurface); tarball formation and photooxidation; and marine oil snow sedimentation and flocculent accumulation [22]. Barker et al. identified new methodologies for further development for Lagrangian approaches, such as the use of Lagrangian Coherent Structures (LCS) which are mathematically-classified objects used to differentiate parts of fluid flows and represent the areas with the most influence on the fluids around them [23]. LCS indicate boundaries that oil would not cross and areas where the greatest change in an oil spill may occur [22].

In addition to GoMRI, U.S. and Canadian federal agencies such as BOEM (Bureau of Ocean Energy Management), BSEE (Bureau of Safety and Environmental Enforcement), Environment and Climate Change Canada (ECCC), Fisheries and Oceans Canada (DFO), and U.S. Environmental Protection Agency's research have resulted in model advancements.

Concurrently, modeling work has been funded through the American Petroleum Institute (API) and the International Association of Oil and Gas Producers (IOGP).

Oil spill modeling for the Arctic has been addressed by some research efforts. IOGP provided support for the Arctic Oil Spill Response Technology – Joint Industry Programme (JIP) to improve Arctic trajectory and fate models [24]. Olason et al. (2016) contributed to Phase 1 of the JIP by improving oil spill trajectory forecasting in models through introduction of sea ice rheology and validation techniques. They introduced two models: (1) ice floe interactions in the Marginal Ice Zone (MIZ), and (2) a new rheology and Lagrangian approach for the ice pack. These models were compared to buoy observations from the International Arctic Buoy Program (IABP) and the TOPAZ ice-ocean model. The comparison determined that the ice floe interaction model provides better understanding of MIZ properties (i.e., diffusion, dispersion) and the rheology/Lagrangian model simulated sea ice drift better than the TOPAZ model [25]. The JIP also concluded that time-averaging of long periods (> 5 days) in ice-ocean models introduces errors by mitigating impacts of storms and sudden weather changes. Ice-ocean inputs provided at smaller timesteps (e.g., daily, 6 hourly) improve the performance of the oil spill models that use them.

Afenyo et al. (2016) performed an in-depth review of fate and transport models in open water and ice-covered conditions which expanded upon previous work by Spaulding (1988), Reed et al. (1999) and Fingas and Hollebone (2003). They described: (1) factors that influence the movement of oil-in-ice conditions, (2) the order of importance of weathering and transport processes for response and contingency planning in ice-covered waters, and (3) algorithms for transportation and weathering of oil-in-ice. They also identified research needs for improving oil spill trajectory and fate models in ice-covered waters including development of ice-specific algorithms for transport and weathering (e.g., photo-oxidation, sedimentation, dissolution) and creation of a database for spilled oil in ice-covered waters. Afenyo et al. suggested that despite the existence of modes for individual oil-in-ice processes, none consider the comprehensive effects of the linkages between processes [26].

The 2019 ADAC Arctic Oil Spill Modeling (AOSM) project focused on estimation of the spread of spilled oil under ice following a well blowout, pipeline rupture or ship grounding within NOAA's GNOME model. The project consisted of two components: the Texas A&M Oil Spill Calculator (TAMOC) for underwater transport and the Arctic Oil Spill Calculator (AOSC) for surface transport of oil (including ice interactions). TAMOC has been fully integrated into the GNOME model whereas AOSC is a standalone MATLAB model driven by ADAC's High-Resolution Ice-Ocean Modeling and Assimilation System (HIOMAS). At the conclusion of the AOSM project, it was determined that further development of the AOSC oil-under-ice spreading algorithms was needed before they can be integrated into GNOME.

Wilkinson et al. (2017) explained the challenges related to modeling of oil spills in ice-covered waters and discussed technology for oil detection and monitoring. They concluded that field exercises that address different sea ice types, ocean and meteorological conditions are necessary to evaluate oil spill response capabilities and technologies. Findings suggested that while models allow for understanding of complex systems, they are only as good as the parametrizations and input data (e.g., wind, currents, oil properties) that drive them. A clear understanding of model limitations is essential, especially those related to the uncertainty associated with model output [16].

The conclusions of this prior research related to Arctic and operational oil spill modeling served as the basis for AMSM. The project continued discussion of the ice-specific algorithms used in state-of-the-art oil spill models, identified issues with the spatial and temporal scales of ice-ocean model outputs (e.g., time averaging), explored Arctic-specific oil spill model limitations related output uncertainty (e.g., estimation of quantitative uncertainty) and discussed applicability of oil detection and monitoring technologies for specific Arctic spill scenarios.

Oil Spill Model Algorithms and Operation

In order to be response-relevant, oil spill models must: initialize quickly (i.e., prepare model and inputs to provide answers within hours), calibrate easily when new data becomes available, model at a wide range of scales, and run with minimal data inputs [27]. In many cases, initial data available on spill volume and location; release duration; oil properties; and wind/wave, ocean and sea ice forecasts may be unavailable or unreliable. All environmental drivers (inputs) originate from other sources (e.g., other models, environmental data) [27]. Virtually all oil spill models use a Lagrangian element (particle tracking) approach. This approach has no grid size dependence, preserves sharp gradients, couples to 3D transport equations, and has no numerical diffusion. Particles can move independently of one another with their own unique behavior and drivers (e.g., wind, currents) and can be superimposed on different grids and time scales to influence particle movement [27]. The Lagrangian particle approach cannot directly provide oil concentrations (i.e., must be derived from algorithms, grid size and number of elements used). The approach also encounters complications when oil partitions (e.g., dissolved compounds move differently than droplets) [27]. As a result, models may also use Lagrangian to Eulerian transformations to estimate oil concentration (mass per unit area or volume) [22].

While many oil spill models from the U.S. and international were considered as part of the AMSM project, ADAC is primarily concerned with improvements to NOAA's oil spill model due to its role in scientific support for the USCG during a spill event. As a result, NOAA's WebGNOME will be used as an example to describe model structure and typical algorithms as it is the primary source for trajectory and fate predictions during a U.S.-based, USCG led oil spill response. A complete summary of WebGNOME's algorithms and operation is included in the GNOME Technical Documentation [28, 28]. [N.B., The desktop version of GNOME and the ADIOS2 weathering model are operational but are no longer actively maintained. They will be replaced by WebGNOME, run by PyGNOME, once validation is complete. Information on GNOME reported in this Thesis reflects the latest available information for the WebGNOME/ PyGNOME model.] GNOME is a publicly available, open source oil spill response model developed and operated by OR&R. Other public and private models have different use restrictions (e.g., available publicly, upon request, by licensing, by subscription). Both types may be open source (source code is available for use and modification) or closed source (code is proprietary and cannot be modified by the public) [29]. GNOME is a 2D/3D Eulerian/Lagrangian model that is applicable anywhere in the world where shoreline maps are available or can be created/substituted (e.g., all water boundaries). It provides two user modes: standard (for novice users) and diagnostic (for more sophisticated users) [30].

The basic data components of GNOME are maps, movers (e.g., wind, currents, diffusion) and spills. Maps are used to define shorelines in a particular area and are available at varying resolutions via GNOME's Online Oceanographic Data Server (GOODS) or may be manually generated by the user. "Movers" describe physics that moves oil in the water (e.g., currents, winds, diffusion). Movers, such as wind and diffusion, may be universal and apply everywhere. Other movers, such as currents, may only apply to the map from which they are sourced. Spills describe the type of release (e.g., continuous, point source) and include mass balance over time to describe the portion of oil in the water, beached and evaporated. Once the map, movers and spills are determined, the model is run to produce oil trajectory, usually a best estimate, which assumes all input data to be correct. A minimum regret version is also produced which includes uncertainties to estimate possible outcomes that may be less likely to occur, but have higher risks (e.g., marine protected areas) [30]. Trajectory analysis and visualizations provide relevant information to decision-makers quickly and effectively. Model outputs from GNOME are usually communicated to responders using OR&R's Environmental Response Management Application (ERMA), a geographic information system-based platform [11].

Algorithms for oil transport and weathering in open water are well tested and validated during many spills. Open water oil transport equations include advection, spreading, sedimentation, and dispersion. Factors such as beaching and refloating may also be considered. Weathering processes include evaporation, emulsification, dissolution, biodegradation, and photo-oxidation [26]. Oil and sea ice interactions are not well understood (e.g., behavior of oil in cold or ice-infested water), so best available predictions often estimate the fate of spilled oil in the Arctic. Oil trajectory outputs are only as accurate as their inputs and oil and ice algorithms are an approximation of true conditions. Few include considerations for different ice types (e.g., fresh, multi-year ice, frazil ice) and existing models do not account for several important ice-related environmental factors (e.g., currents under ice, ridges, keels, water density as a function of melting). In addition to the impact of low temperatures and long periods of sunlight (summer) and darkness (winter), sea ice concentration is a primary concern for oil fate and trajectory in the Arctic.

Sea ice concentration is incorporated into models by the 80/20 rule. The 80/20 rule uses sea ice concentration in the form of percent cover to explain how the fate and transport of oil will change in the presence of sea ice. Sea ice floats on the sea surface, which reduces the amount of open water and impacts the fate and trajectory of spilled oil. Percent sea ice cover may be derived from ice model outputs, observational charts/maps, or a combination thereof. If sea ice concentration < 20% cover oil spill models assume open water conditions (i.e., the oil behaves as if no ice is present). Ice concentrations > 80% cover are considered full sea ice coverage (i.e., surface oil behaves as if there is no open water and is moved with ice). Between 20 and 80% cover is a transition zone (i.e., the MIZ) and models do not agree on how oil moves in these conditions. [N.B., Some models use 20% instead of 30% or 75% instead of 80%.] Within GNOME, processes (e.g., advection) are linearly interpolated between 20% and 80% ice cover. For example, it is assumed that no spreading occurs at > 80% ice cover and that spreading is the same as in open water at < 20% ice cover. In between, the percent coverage is used to modify the increase in area computed at each time step [31].

<u>Transport</u>

Advection

Advection describes the movement of oil due to winds and currents. GNOME determines resulting oil movement as a vector sum of wind drift, surface current and spreading/diffusion [32]. Surface currents are calculated using a forward Euler scheme (i.e., 1st order Runge-Kutta):

Equation 1: Calculation of zonal, meridional and vertical displacement by currents (1st order Runge-Kutta).

$$\Delta x = \frac{\frac{u(x,y,z,t)}{111{,}120.00024} * \Delta t}{\cos(y)},\ \Delta y = \frac{v(x,y,z,t)}{111{,}120.00024} * \Delta t, \text{ and } \Delta z = w(x,y,z,t) * \Delta t \quad (1)$$

where u is the overall movement in the east/west direction, v is the overall movement in the north/south direction, Δt, or t_{i+1}-t_i, is the time elapsed between time steps i+1 and I, Δx, Δy and Δz are the 2D longitude, latitude, and vertical displacement, respectively, for the specified time step, w is the vertical component of velocity, y is the latitude in radians, and 111,120.00024 is the number of meters per degree of latitude. In most cases, w is equal to zero, but if the hydrodynamic model input into GNOME has 3D currents it can be included [28]. Decreasing the model time step can increase model accuracy [30].

For oil spilled in the presence of sea ice, GNOME and most other oil spill models use the 80/20 rule to determine how it will move. At < 20% ice cover, oil and ice move separately and at > 80% ice cover, oil moves with the ice. Between these two concentrations, advection is linearly interpolated. The effects of currents and wind on surface oil movement are both scaled down according to ice coverage and the 80/20 rule (e.g., at 50% ice coverage, oil moves at an average of sea ice and current velocity) [31].

Spreading/Diffusion

Spreading in GNOME uses a simple random walk with square unit probability based on a horizontal diffusion value (default is 100,000 cm^2/s) set in the model and calibrated based on overflight data obtained during the spill [30]. Spreading occurs quickly for most spills (i.e., within the first hour) depending on currents, winds, turbulence, water temperature, and oil viscosity. Surface slicks do not spread evenly and often have areas of thicker and thinner oil [32].

Windage describes the movement of oil by wind and is typically ~3% of the wind speed, but may range from 1-4% (based on overflight reports). GNOME defaults to the 1-4% range using a uniform distribution to describe how an oil droplet may move differently based on how close it is to the surface (i.e., weathered oil below the surface experiences lower windage). GNOME pairs the windage range with a persistence time step which describes how long until the random value is reset (default is 15 minutes). Persistence is important for helping the model to behave the same when the time step is changed and to model particles with windage that increases or decreases over time (e.g., oil particles that are pushed below the surface and refloat). GNOME selects a random number within the user-selected range for each Lagrangian Element (LE) and moves it for each time step based on windage. Spreading of LE's due to wind is described by an equation:

Equation 2: Spreading of Lagrangian Elements (LE) in GNOME due to wind.

$$\frac{d\sigma^2}{dt} = S(t) \tag{2}$$

where σ^2 is the variance of LE locations and S(t) is a spreading parameter as a function of time [28]. The classical horizontal diffusion equation used by GNOME is:

Equation 3: GNOME classical diffusion equation.

$$\frac{\partial C}{\partial t} = D\nabla^2 C \tag{3}$$

where C is the concentration of a material (e.g., oil) and D represents the horizontal eddy diffusivity in the water. The effects of gravitational and surface tension are ignored as these are only important at the very beginning of the spill. The equation can also be written in Cartesian coordinates:

Equation 4: GNOME classical diffusion equation in Cartesian coordinates.

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} \tag{4}$$

where D_x and D_y are scalar diffusion coefficients in the x and y direction [30]. Spreading in ice-covered waters is impacted by ice type and coverage where high ice cover results in increasing oil thickness as ice constrains the spreading of the spilled oil [26]. Diffusion in high ice concentrations is expected to be very small or zero. GNOME does not adjust the diffusion coefficient in the presence of ice and instead implements the 80/20 rule by scaling the net movement at each random walk step based on the percent ice cover [31].

Sedimentation

Sedimentation describes the adhesion of oil to suspended sediments. Sedimentation causes oiled particles to settle to the seafloor [26]. Sedimentation is not usually an important oil removal process in the response time frame, but in areas where there is a high concentration of suspended sediments it may play a role in mass-balance equations [28]. GNOME uses modified equations proposed by Payne et al. (1987) to calculate total sedimentation rate by slick area and the mass lost per unit water volume by time:

Equation 5: Total sedimentation rate per unit area of slick from Payne et al. (1987).

$$Q_{sed} = \int_0^{1.5H} q_{sed} dz \tag{5}$$

Equation 6: Mass lost to sedimentation per unit water volume per unit time from Payne et al. (1987).

$$q_{sed} = K_s \sqrt{\frac{\varepsilon}{V_w}} C_{oil} C_{sed} \tag{6}$$

where H is the water depth, ε is the rate of energy dissipation, and K_s depends on material type and size (e.g., clay). There are few studies to describe sedimentation in ice-covered waters and GNOME does not modify the equation for Arctic use [26]. However, modifications to surface dispersion processes that drive dissolution and sedimentation will indirectly affect results in the presence of ice [31].

Dispersion

Dispersion describes the process by which breaking waves drive oil droplets into the water column. Small droplets (diameters < 50-70 µm) are prevented from resurfacing due to natural turbulence in the water. The droplets that remain in the water column are considered dispersed oil. The amount of oil dispersed depends on oil properties (i.e., viscosity, surface tension) and water conditions. Chemical dispersants may also be used to lower surface tension of the oil and encourage higher rates of oil dispersion in the water column [32]. Dispersed oil is removed from the water surface and high surface area to volume ratio increases rates of biodegradation [33]. GNOME uses a modified form of the equation proposed by Delvigne and Sweeney (1988) to predict entrainment of dispersed oil:

Equation 7: GNOME dispersion equation modified from Delvigne and Sweeney (1988).

$$Q_{disp} = C_{Roy} * C_{disp} * V_{entrain} * (1.0 - Y) * A/\rho \tag{7}$$

Where Q_{disp} is the rate of dispersion and $V_{entrain} = 3.9e^{-8}\,m^3$ and represents the volume of oil entrained per unit volume of water. C_{Roy} is a constant used to describe the effects of oil viscosity and was derived from experiments:

Equation 8: Experimentally derived parameter used to calculate oil entrainment.

$$C_{Roy} = 2400.0 * \exp(-73.682 * \sqrt{v}) \tag{8}$$

and v is the kinematic viscosity of the oil. C_{disp} describes the increased dispersion as a function of wave height and fraction of breaking waves. It can be calculated using the fraction of breaking waves per wave period (f_{bw}) and the dissipative wave energy (D_e):

Equation 9: C_{disp} based on fraction of breaking waves and dissipative wave energy.

$$C_{disp} = D_e^{0.57} * f_{bw} \tag{9}$$

D_e per unit surface area is given by:

Equation 10: Equation for dissipative wave energy.

$$D_e = 0.0034 * \rho_w g H_{rms}^2 \tag{10}$$

where g is the gravitational acceleration and ρ_w is the water density. H_{rms} is the root-mean wave height which is related to the spectrally-based significant wave height H_o:

Equation 11: Equation for root-mean wave height.

$$H_{rms} = 0.707H_0 \tag{11}$$

$V_{entrain}$ is proportional to the integral of the product of droplet volume and frequency distribution of droplets over the volume of oil; traditionally between the minimum and maximum droplet sizes (d_{max} and d_{min}) determined from experimental data:

Equation 12: Equation for $V_{entrain}$.

$$V_{entrain} \propto \int_{d_{min}}^{d_{max}} N(\delta)\delta^3 d\delta \tag{12}$$

where d_{max} is equal to 70 microns, d_{min} is zero microns and δ is the droplet diameter. $N(\delta)$ is the number of oil droplets per unit volume of water per unit droplet diameter determined by:

Equation 13: Equation for number of oil droplets per unit volume of water per unit droplet diameter.

$$N(\delta) = N_0 \left(\frac{\delta_0}{\delta}\right)^{\frac{2}{3}} \tag{13}$$

where N_0 and δ_0 are experimental reference values [28].

The presence of ice significantly reduces or prevents dispersion due to the dampening of wave action, especially when ice concentration is high [26]. Depending on ice concentration, dispersion may be reduced or not included at all. GNOME does not modify the dispersion algorithm, and instead relies on modified wave fields (e.g., from field measurements, ice-ocean models, estimation using ice-modulated wind fields) [31]. There is no consideration for how the presence of ice and the dampening of wind and waves will influence droplet size distribution or the dissipating breaking wave energy per unit surface area. The constant C_{Roy} will change due to the influence of temperature on viscosity. Oil entrainment and droplet size distribution are independent of oil thickness and for thicker oil slicks, large droplets resurface more quickly [34].

Weathering

Evaporation

Evaporation describes the conversion of liquid oil to gas and is a major mechanism for removing oil from the water. The amount of oil evaporated is dependent on the type of oil, wind speed and water temperature [32]. The desktop version of GNOME uses a simplistic three-phase evaporation algorithm that simulates oil as a three-component substance with independent half-lives:

Equation 14: GNOME simplistic three-phase evaporation equation.

$$X_{prob} = \frac{P_1 * \left(2^{\frac{-t_i}{H_1}} - 2^{\frac{t_{i-1} - 2 * t_i}{H_1}}\right) + P_2 * \left(2^{\frac{-t_i}{H_2}} - 2^{\frac{t_{i-1} - 2 * t_i}{H_2}}\right) + P_3 * \left(2^{\frac{-t_i}{H_3}} - 2^{\frac{t_{i-1} - 2 * t_i}{H_3}}\right)}{P_1 * 2^{\frac{-t_i}{H_1}} + P_2 * 2^{\frac{-t_i}{H_2}} + P_3 * 2^{\frac{-t_i}{H_3}}} \quad (14)$$

where t and t_1 are the time elapsed/age at time steps *i* and *i-1* since the release, H_1, H_2 and H_3 are the half-lives in hours of each constituent (e.g., gasoline, diesel, kerosene) for each pollutant and P_1, P_2 and P_3 are the percentages of each constituent (as decimals) for each pollutant. A random number, $R_{(0, 1)}$, between 0 and 1 is generated at each time step *i* to determine the mass of the LE ($R_{(0, 1)} \leq X$, LE mass is set to zero). An LE with a mass of 0 is considered evaporated [30]. NOAA's ADIOS2 model calculates detailed information on oil fate using more sophisticated evaporation and oil fate algorithms than those found in the desktop version of GNOME. The evaporation equation used in ADIOS2 was formulated for use in WebGNOME:

Equation 15: Evaporation equation from WebGNOME based on equation used in NOAA's ADIOS2 model.

$$\frac{dm_i}{dt} = -(1 - f_w)\left(\frac{AK_iMW_iP_i}{RT_w}\right)\left[\frac{m_i/MW_i}{\sum m_i/mW_i}\right] \tag{15}$$

where m_i is the mass (in kg) of the pseudocomponent *i* in the LE, f_w is the fractional water content in the emulsion, A is the surface area associated with the element, MW_i is the molecular weight of the pseudocomponent *i*, P_i is the vapor pressure at the water temperature of the pseudocomponent *i*, R is the universal gas constant (8.3144 J/K, mole), T_w is the water temperature, and K_i is the mass transfer coefficient. K is determined through relationship with the wind speed. When $U \leq 10\,\frac{m}{s}$,

$K = c * U_{10}^{0.78}$ and when $U > 10\,\frac{m}{s}$, $K = 0.06 * c * U_{10}^{2}$ where U_{10} is the wind speed 10 meters above the water surface and c = 0.0025 [28].

In the Arctic, evaporation rates change between the winter and summer due to the long periods of darkness and sunlight, respectively. The presence of ice also reduces evaporation rates due to the decreased temperature and increased slick thickness [26]. GNOME does not directly change the evaporation algorithm in the presence of ice, but weathering results are altered due to changes in other algorithms resulting from reduced wind, waves and temperature and increased oil thickness. Evaporation should be zero in high ice concentrations and the same as open water in low concentrations. An ice-modified exposed area, based on sea ice concentration, is used to calculate evaporation in between these conditions [31].

Emulsification

Emulsification occurs when water droplets are mixed into weathered liquid oil, usually as a result of wave action. Emulsified oil, sometimes called "mousse." can have a water content of 50-80%, increasing the area and amount of the contaminant to be recovered. Formation of emulsions depends on water conditions and oil properties (e.g., wax, asphaltene content). In stable emulsions, water droplets can remain mixed with oil for weeks to months [32]. GNOME uses an equation from Eley et al. (1988) to calculate interfacial area:

Equation 16: GNOME emulsification equation from Eley et al. (1988).

$$\frac{dY}{dt} = k_{emul}\left(1 - \frac{S}{S_{max}}\right) \tag{16}$$

where k_{emul} is the water uptake coefficient and S and S_{max} are the oil-water interfacial area and maximum interfacial area respectively. The water fraction Y is related to interfacial area by the following equation:

Equation 17: Equation for water fraction based on interfacial area.

$$Y = \frac{Sd_{max}}{6+Sd_{max}} \tag{17}$$

where d_{max} is the maximum emulsion droplet diameter [28]. The presence of ice slows emulsification, especially in high ice concentrations, due to the dampening of wind and waves by a broken ice field [26, 31]. No specific changes are made to GNOME's emulsification algorithms in the presence of ice, but results are altered by reduced wind and wave inputs.

Dissolution

Dissolution describes the mixing of water soluble components of oil into water and usually occurs in the first few days of a spill, continuing throughout the weathering process. While this does not account for a major loss of oil from the slick (usually less than 0.1-2% depending on oil type), the most water soluble components of oil are also usually the most toxic and pose risk to marine organisms that live and feed near the spill area [32]. GNOME does not include dissolution, but a simple method based on droplet size and soluble vs. insoluble components is in development. It is likely that dissolution will still occur in ice-covered waters, but will be diminished along with dispersion [26, 31].

Biodegradation

Biodegradation occurs when naturally-occurring microbes degrade oil into smaller compounds (eventually water and carbon dioxide). Oil that has biodegraded is considered removed from the environment and is often considered the "ultimate fate of weathered oil in the marine environment" [26, 32]. The rate at which biodegradation occurs is dependent on oil and water properties, quantity of oil, type and amount of microbial activity, and the available nutrients and oxygen to stimulate microbial degradation. It can take anywhere from weeks to years for oil to biodegrade [32]. GNOME does not currently consider biodegradation, but is working towards experimental implementation based on droplet size, composition and temperature using an equation for change in mass for pseudocomponent *j*:

Equation 18: GNOME equation for change in biodegradation mass.

$$\frac{d}{dt}m_j = -k_j \cdot 4\pi r_{droplet}^2(t) \cdot \left(\frac{m_j(t)}{\sum_i m_i(t_{m+1})}\right) \tag{18}$$

where $r_{droplet}$ is the radius of a single droplet of the pseudocomponent, *t* is the time step, m_j is the change in biodegradation mass, k_j is the biodegradation rate constant, $4\pi r_{droplet}^2(t)$ is the surface area of the droplet at time t, $\frac{m_j(t)}{\sum_i m_i(t_{m+1})}$ is the mass fraction of pseudocomponent *j* at time *t* and *i* = 1, …, n where n is the number of pseudocomponents [28].

Much like sedimentation and dissolution, biodegradation will be scaled down with dispersion in the presence of ice. Dispersed oil in the water column biodegrades more quickly so reduced concentration of oil droplets will result in less biodegradation of oil [31].

Photo-oxidation

Photo-oxidation occurs when sunlight exposure changes the chemical and physical properties of the surface of oil, resulting in a thin, crusty layer on top of slicks and, ultimately, the formation of tarballs. Photo-oxidation may take weeks to months and, in some cases, may increase oil emulsification, dissolution and dispersion. It is also thought to impact evaporation by reducing diffusion of lighter oil components [32, 26]. Photo-oxidation is the least studied of all the weathering and transport processes [26]. GNOME, like most other response models, does not consider photo-oxidation. In the Arctic, photo-oxidation will be limited seasonally as day and night cycles change and is probably more significant during the first 24 hours of daylight during a spill than in temperate climates. The effect of oil albedo (reflectivity) also accelerates melting of snow and ice [26].

Sea Ice Model Algorithms and Operation

Sea ice models are used to predict future ice conditions (e.g., growth, melt, movement) and their outputs are essential for estimation of spreading and transportation of oil via sea ice drift, as well as prediction of oil and ice interactions. Satellite, airborne and historical observations of sea ice are useful for understanding past sea ice characteristics and movement, but cannot predict future conditions [35].

Sea ice models may operate at global/climate scales or at subgrid scales. Subgrid refers to processes that are smaller (< 1 km) than the standard grid size of a model (> 1-2 km) meaning they are not well described in large scale models. Depending on the intended use, they can provide long term forecasts for climate studies, upcoming seasonal forecasts and short term operational forecasts (e.g., for the next ten days). The influences of the ocean (e.g., temperature, currents) and the atmosphere on ice are included in models as boundary conditions (forcings) which maintain or change sea ice conditions. Sea ice models operate independently of oil spill models and are often coupled with ocean/hydrodynamic and atmosphere models. The benefit of these coupled models is that they do not require modelers to specify forcings and instead allow the sea ice, ocean and atmosphere to interact with each other [35].

In general, sea ice models work by representing sea ice in grid cells which are created by the model. Each grid cell provides an average of sea ice properties (e.g., thickness) over the modeled grid region. Each cell has a predetermined area and a group of cells makes up a domain. Spatial resolution describes the number of grid cells inside of a domain (large number of grid cells = higher resolution). Modeling at smaller scales requires a higher number of grid cells, which uses more computing resources and data storage [35].

One of the major sea ice models discussed in the AMSM project was the Community Ice CodE (CICE). CICE 4 and 5.12 were developed by DOE’s Los Alamos National Laboratory and are now replaced by CICE6, developed by the CICE Consortium. CICE simulates growth, melting and movement of polar sea ice and is designed to serve as the sea ice component of coupled atmosphere-ocean-land-ice global climate models. It is coded in FORTRAN, publicly available and open source and requires a supercomputer to operate. CICE is suitable for use in research, short term operational forecasting and climate modeling [36]. CICE has several components (Figure 1): an ice dynamics model which predicts the velocity field for the ice pack as a function of modeled material strength of ice and includes three methods for measurement of internal stress (i.e., viscous plastic, elastic viscous plastic, elastic anisotropic plastic); a transport model for advection of concentration, ice volumes and other variables; and the ICEPACK submodule.

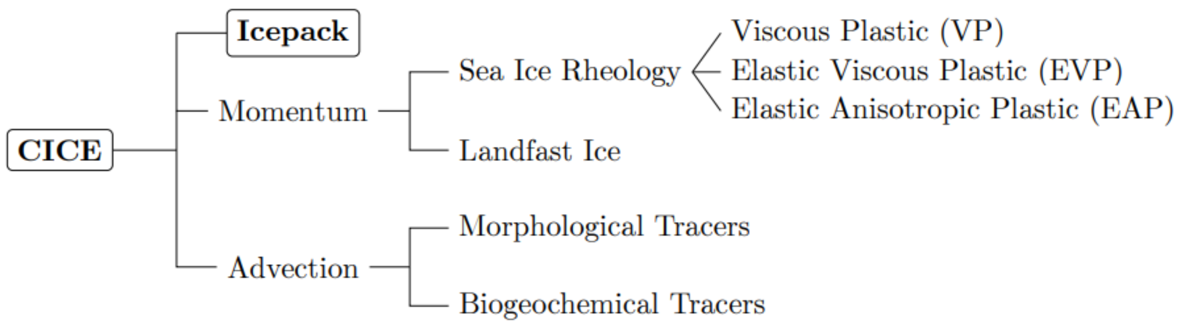

Figure 1: CICE dynamical core that models sub-grid scale physics and biogeochemistry with Icepack as a submodule. CICE also includes infrastructure for running the model and providing outputs (not shown in this diagram). Source: Sea Ice Model Provenance (Appendix L).

ICEPACK (Figure 2) is a vertical physics package including mechanical (morphology), thermodynamic and biological models to calculate changes in thickness and the hydrological ice-brine ecosystem in ice [37]. It is a column physics model developed by Los Alamos National Laboratory that serves as a separate library for use in CICE. It is coded in FORTRAN, is publicly available and open source and can be run on multiple operating systems including UNIX and LINUX. ICEPACK provides ice morphology, physics and biogeochemistry in netCDF format at a 15-30-minute temporal resolution and a sub-grid scale spatial resolution.

The ice fraction per grid cell is described in the CICE model by the variable a_i. When $a_i = 0$, there is no ice, when $a_i = 1$, there is no open water, and when $0 < a_i < 1$, there is ice and open water [38]. New sea ice is formed when the ocean temperature drops below a specified freezing temperature (dependent on salinity). If the freezing/melting potential is positive, its resulting value indicates a certain amount of frazil ice that has formed in the ocean and floated to the surface, contributing to the thinnest ice category. If the potential is negative, it heats, and potentially melts, existing ice from below using an oceanic heat flux applied to the bottom of the ice [38].

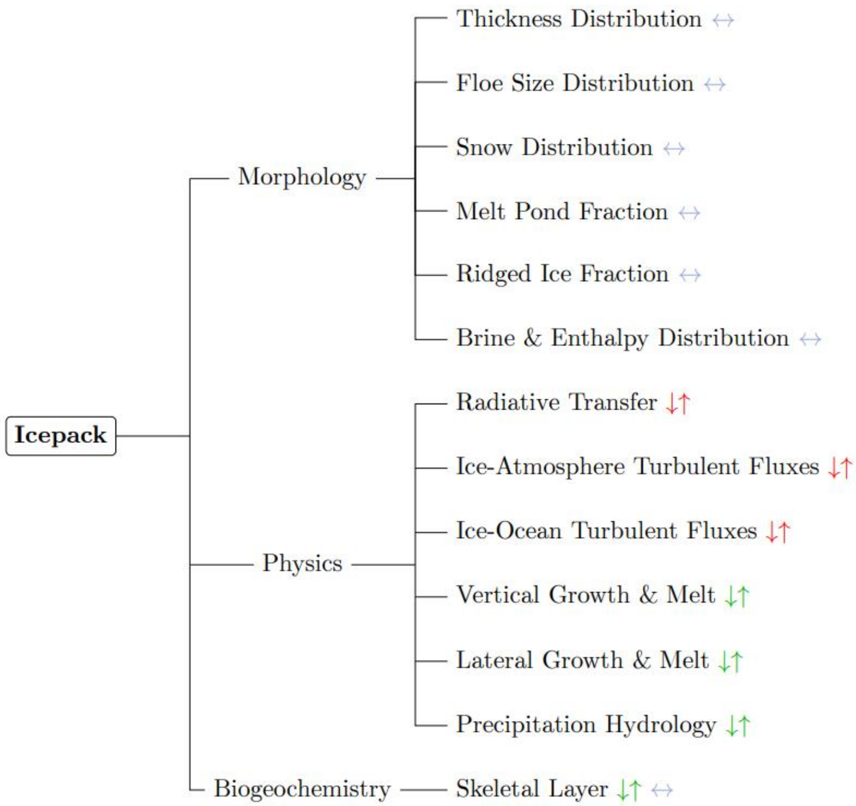

Figure 2: Components of ICEPACK. Blue arrows indicate horizontal advection using a dynamical core (e.g., CICE). Red arrows indicate energy flux and green indicate mass flux exchange with ocean and atmosphere. Source: Sea Ice Model Provenance (Appendix L).

The fundamental equation solved by CICE is:

Equation 19: Fundamental equation solved by CICE.

$$\frac{\partial g}{\partial t} = -\nabla \cdot (gu) - \frac{\partial}{\partial h}(fg) + \psi \qquad (19)$$

where u is the horizontal ice velocity, $\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}\right)$, f is the rate of thermodynamic ice growth, ψ is a ridging redistribution function, and g is the ice thickness distribution function. $g(x, h, t)dh$ is defined as the fractional area covered by ice across the thickness range $(h, h + dh)$ for a given time and location. It is solved by partitioning the ice pack in each grid cell into user-specified thickness categories, n (default n = 5). Each category is also assigned a lower (H_{n-1}) and upper

(H_n) thickness bound. $g(h)$ is replaced by a_{in} which is the fractional area covered by ice over the thickness range. In addition to a_{in}, variables for ice volume (v_{in}), snow volume (v_{sn}), internal ice energy in layer k (e_{ink}), negative of the energy need to melt a unit volume of ice and raise its temperature to 0 ºC (q_{ink}), the internal snow energy in layer k (e_{snk}), surface temperature (T_{sfn}), and the volume-weighted mean ice age (T_{age}) are defined for each category. The three terms on the right side of the question describe three kinds of sea ice transport: (1) horizontal transport (x, y); (2) transport in thickness space h due to thermodynamic growth and melting; and (3) transport in thickness space h due to ridging [38].

Horizontal transport is determined for the fractional ice area in each thickness category n:

Equation 20: CICE horizontal transport by fractional ice area in each thickness category.

$$\frac{\partial a_{in}}{\partial t} + \nabla \cdot (a_{in} u) = 0 \tag{20}$$

which describes the conservation of ice area. Similar conservation equations exist for ice volume and energy, as well as snow volume and energy [38].

Ice dynamics are modeled using the force balance per unit area in the ice pack and are described by a 2D momentum equation:

Equation 21: CICE ice dynamics/2D momentum equation.

$$m\frac{\partial u}{\partial t} = \nabla \cdot \sigma + \overrightarrow{\tau_a} + \overrightarrow{\tau_w} - \hat{k} \times mfu - mg\nabla H_o \tag{21}$$

where m is the combined mass of ice and snow per unit area and $\overrightarrow{\tau_a}$ and $\overrightarrow{\tau_w}$ are wind and ocean stresses, respectively. σ_{ij} represents the internal stress tensor which determines the strength of the ice. The other two terms on the right side of the equation are stresses due to Coriolis effects and sea surface slope [38].

Thermodynamics are modeled by computing changes in ice and snow thickness and a vertical temperature profile from radiative, turbulent and conductive heat fluxes. The net energy flux from the atmosphere to the ice is defined by:

Equation 22: CICE thermodynamics equation for net energy flux from the atmosphere.

$$F_0 = F_s + F_l + F_{L\downarrow} + F_{L\uparrow} + (1 - \alpha)(1 - i_0)F_{sw} \tag{22}$$

where F_s is the sensible heat flux, F_l is the latent heat flux, $F_{L\downarrow}$ is the incoming longwave flux, $F_{L\uparrow}$ is the outgoing longwave flux, F_{sw} is the incoming shortwave flux, α is the shortwave albedo, and i_0 is the fraction of absorbed shortwave flux that penetrates into ice [38].

2. METHODS

2.1 Project Phases

The project objectives were to identify: current state-of-the-art Arctic maritime oil spill and sea ice models, potential integration of these models and specific needs to be addressed for improvements that will be functional and effective in response time scales to advance the FOSC's decision-making. The project consisted of six phases (Figure 3) which occurred during ADAC Program Years 5-7 (March 14, 2019 – June 30, 2021):

- Phase 1: Formation of the Project Core Advisory Team (ADAC Program Year 5)
- Phase 2: Meeting of the Core Team and Key Agency Stakeholders to Determine the Needs of/Questions Addressed by Models to Facilitate FOSC Decision-Making During Arctic Oil Spill Response (ADAC Program Year 5)
- Phase 3: Three-Day Workshop on Arctic Maritime Spill Response Modeling (ADAC Program Year 6)
- Phase 4: Working Groups on Specific Response Model Components/Criteria (ADAC Program Year 6)
- Phase 5: Workshop and Stakeholder Working Sessions to Review Working Group Findings and Integrate Feedback into Knowledge Product (ADAC Program Year 7)
- Phase 6: Completion of Knowledge Product (ADAC Program Year 7)

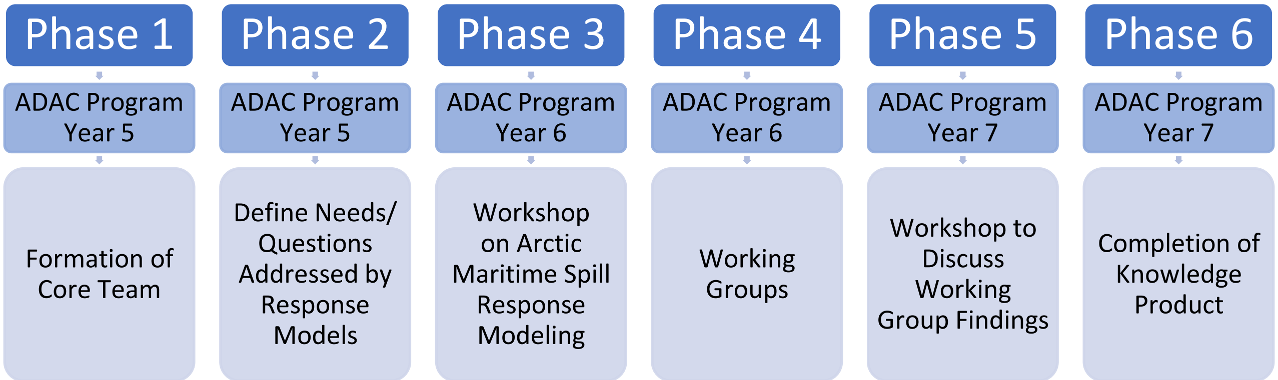

Figure 3: AMSM Project Phases.

2.2 Phase 1 – Formation of the Project Core Advisory Team

The Project PI, Dr. Nancy Kinner (UNH CRRC/CSE), organized a kickoff meeting with the Project Champion and Chair of the Core Team, Captain Kirsten Trego (USCG 5RI, Deputy Director of Emergency Management for USCG), and the Core Team. The Core Team included representatives from NOAA OR&R, USCG PACAREA, USCG D17, and ADAC Center leadership (Appendix A). The PI and ADAC Fellows (students funded by ADAC to participate in the project: Megan Verfaillie and Jessica Manning) met with the Core Team once per month via Zoom conference call throughout the project. The first conference call occurred on April 15, 2019 to review the project workplan and milestones and to set the date for the Phase 2 meeting.

2.3 Phase 2 – Meeting of the Core Team and Key Agency Stakeholders to Determine the Needs of/Questions Addressed by Response Models

The Phase 2 meeting occurred on May 23, 2019 at UAA. This full day meeting included the Core Team and the Project Champion's representative, Karin Messenger (Environment & Waterways Domain Lead at the USCG Office of Research, Development, Test, and Evaluation). The meeting coincided with ADAC's 2019 Arctic IoNS Workshop. The product of the Phase 2 meeting was a list of the needs and questions that must be addressed by models during an Arctic oil spill emergency response. These needs and questions served as guideposts for the project and subsequent workshops and were related to responder/FOSC needs, concerns of existing spill response models, desired capabilities for new models, confidence levels and communication with the public, validation, and suggestions for the December 2019 workshop.

The use of these needs and questions throughout the project kept the focus on USCG and OR&R and reduced the tendency for a diverse group of stakeholders to deviate into related, but not mission-relevant topics. Following the Phase 2 meeting, a third Core Team meeting was held on June 4, 2019 to review the results of the draft needs and questions. A fourth meeting was held on July 10, 2019 to complete the list (Appendix B).

2.4 Phase 3 – Three-Day Workshop on Arctic Maritime Spill Response Modeling

A Workshop Organizing Committee (OC) (Appendix C) was selected by the Project PI, with guidance from the Core Team, and formed in September 2019. The OC was tasked with planning the December 2019 Workshop and assisting the Project PI with establishing the agenda (Appendix D) and selection of participants, plenary speakers and breakout group (Appendix E). The OC met online every 2-3 weeks for one hour (i.e., five times). Many of the Core Team members also participated on the OC. The workshop had six specific objectives:

1. Review list of Specific FOSC Needs & Questions Developed by Core Team (Phase 2),
2. Establish current state-of-the-art Arctic maritime oil spill models and their utility for response (including the role of sea ice models as inputs),
3. Determine components from recent non-Arctic maritime oil spill models that may be useful for incorporation into Arctic models,
4. Discuss ways to incorporate natural resource and food security protection and Traditional Ecological Knowledge [N.B., not covered in this thesis],
5. Identify gaps in Arctic maritime oil spill modeling, and

6. Determine the topics to be resolved by three to four working groups following the completion of the workshop.

The Phase 3 AMSM Workshop was hosted by CRRC and ADAC on December 3-5, 2019 at UAA. There were 49 participants (Appendix F) from the U.S., Canada, Norway, Denmark, and Russia representing a range of oil spill and sea ice modelers, responders and Arctic experts.

The full list of needs and questions was organized into six key areas of concern (Appendix G) for use during the workshop: (1) the influence of cold/ice on oil fate (weathering) and transport processes, (2) needs for subsea blowout modeling in Arctic waters, (3) current and future coupling of sea ice and/or regional ocean models with spill trajectory and fate models, (4) model operational considerations (e.g., run time, resolution, uncertainty, visualization), (5) model outputs needed for resource risk analysis in the Arctic, and (6) data availability.

Initial presentations covered the models available for oil spill response in the Arctic. Presentations also included the response perspectives from the USCG and Alaska Department of Conservation (ADEC). Breakout sessions focused on potential spill scenarios where modeling could be applied (well blowout under ice, pipeline spill under landfast ice, large vessel spill involving combinations of oil in the shoulder season). Critical elements included oil fate and transport, subsea blowout modeling and operational conditions. Breakout group sessions answered questions related to: responder needs that can be addressed by modeling, major limitations of sea ice and response models, potential updates needed for existing algorithms, and anticipated observational gaps for each scenario. Following each of the three sessions, the groups presented a summary of their findings to the plenary. The entire group identified potential overlaps and key findings between spill scenarios.

A final plenary session identified gaps in Arctic maritime response modeling, delineated topics for working groups to address and determined how best to engage oil and sea ice modelers going forward.

All workshop notes, presentations and breakout group discussions were included in a final Workshop Report summarizing all workshop findings (available at: https://crrc.unh.edu/AMSM_Arctic_Modeling).

2.5 Phase 4 – Working Groups on Specific Response Model Components/Criteria

The Project PI, with help from the Core Team and Workshop OC, formed four Working Groups. An OR&R lead was designated for each group (Appendix H). The leads, collaborated with the Project PI, to ensure that the working groups made good progress and were on task. Meetings for each working group took place virtually every three weeks for one hour from March to November 2020. The Project PI and ADAC Fellows provided administrative coordination for all working groups, including taking meeting notes, maintaining records and files, and collecting and organizing relevant materials. All materials were accessible to the groups via Google Drive. Working Group topics selected during the workshop and approved by the Core Team and Workshop OC were:

- Oil and Ice Interactions at the Meter/Subgrid Scale
- Oil and Ice Interactions at the Kilometer +/Grid Scale
- New and Existing Technologies for Observing Sea Ice and Informing Models
- Visualization & Uncertainty

Each Working Group devised its own set of objectives based on the findings from the final workshop plenary and the original needs and questions document. These objectives were detailed topics or questions that the group planned to address during their meetings. Where there was overlap between group objectives, cross-team meetings were planned with members of the working groups or specific individuals. In addition to regular working group discussions, additional meetings were held to talk with related experts and organizations (e.g., the U.S. National Ice Center, NOAA social and behavioral scientists). The findings from these supplementary meetings were presented to the relevant working groups. Additionally, several outside experts were invited to present to the working groups (e.g., Alaska Ocean Observing System (AOOS), NOAA National Environmental Satellite, Data and Information Service (NESDIS)).

2.6 Phase 5 – Virtual Workshop and Stakeholder Working Sessions to Review Working Group Findings and Integrate Feedback into Knowledge Product

The second workshop was initially planned as a two day in-person event scheduled for October 2020 at UAA. Due to COVID-19-related travel and occupancy restrictions, the in-person workshop was replaced with a virtual one, held on November 16, 2020, and two Stakeholder Working Sessions, held on November 23 and 30, 2020. The virtual workshop was planned by the Core Team and members of the December 2019 Workshop OC. A pre-workshop video was created that detailed the overall project, working group goals, available resources, and project-related oil spill and sea ice models. Approximately 75 individuals attended the workshop session on November 16.

The purpose of the second November 2020 Virtual Workshop was to initiate, broaden and maintain an open channel of communication among responders, scientists and modelers. Each working group prepared and presented PowerPoint slides which detailed their goals, findings and proposed research needs (Appendix I). Each presentation was followed by a question and answer session. The November 16 workshop concluded with a discussion of these findings and needs to solidify recommendations and ensure cross-topic collaborations and initiatives. These presentations and the associated stakeholder feedback (e.g., from OR&R, USCG, Core Team, Project Champion) served as each working group's outline for their Final Knowledge Product (Phase 6) sections.

The Stakeholder Working Sessions, attended by invitation only, determined a path forward for Arctic spill response and sea ice modeling, prioritized recommendations and developed potential research ideas. Invitees were selected by the Core Team and Workshop OC and included members of the response community and oil spill and sea ice modeling specialists from the international, government and private sectors. The Stakeholder Working Sessions focused discussion on specific findings and needs from the working groups, which were determined by the Project PI and Core Team following the November 2020 Virtual Workshop. The sessions also allowed cross-fertilization with other groups and the delineation of a path forward for additional activities (i.e., a future working group, tabletop exercises, research needs). Discussions focused on near term goals (1-5 years) to improve the operation of oil spill models in the Arctic and topics to be revisited in the future based on new developments. Two scenarios from the December 2019 Workshop were chosen as most relevant: a large vessel spill of combinations of oil in the shoulder season (during fall as ice is developing) and a pipeline spill under landfast ice. November 23 Stakeholder Working Session topics included: sea ice modeling and observational needs/scale of outputs and under ice roughness/storage capacity/oil migration. November 30 Stakeholder Working Session topics included: data assimilation for oil spill and sea ice models and visualization and uncertainty improvements.

Findings from the November 2020 Virtual Workshop and subsequent Stakeholder Working Sessions were captured by the ADAC Fellows. Core Team feedback on the workshop and working session results was received during meetings on November 19 and December 17, 2020. Once all feedback had been collected, the Project PI and graduate ADAC Fellow Megan Verfaillie began outlining, writing and editing the Final Knowledge Product.

2.7 Phase 6 -- Completion of Knowledge Product

The final Knowledge product will be completed following approval of this thesis and will integrate stakeholder and Core Team feedback before it is submitted to ADAC. The Final Knowledge Product will be a comprehensive report containing:

1. A list of the needs/questions related to oil spill modeling that must be addressed to support the USCG FOSC in decision-making during Arctic response.
2. A review of the current state-of-the-art on oil spill response modeling for Arctic maritime oil spills and sea ice modeling/data services.
3. Delineation of model output uncertainty and how to express it in a format that can be easily interpreted by an FOSC.
4. Outline of new and existing technologies that are available to locate and determine the characteristics of oil in the Arctic and notation of their usefulness in anticipated Arctic scenarios.
5. Suggestions for incorporating local and indigenous knowledge into oil spill trajectory forecasts [N.B., Not included in this thesis].
6. Detailed recommendations/scopes of work on modeling research needed to fill gaps identified during the project.

The Project PI and graduate ADAC Fellow developed the content and outline of the Final Knowledge product with reviews and coordination by the Core Team and Project Champion, Captain Trego. Following approval of the overall outline, the graduate ADAC Fellow drafted this thesis and incorporated feedback from the Project PI. Following approval of the thesis, the Project PI will incorporate additional findings (i.e., on local and indigenous knowledge) and forward it to the Project Champion, Core Team, Workshop OC, and Working Group Co-Leads for their edits. The project PI will then send it to ADAC for final editing. Following the integration of ADAC feedback, the Final Knowledge Product will be submitted to ADAC, the Core Team and the Project Champion. Once the report is submitted, the Project PI and ADAC will coordinate a corresponding peer-reviewed journal article.

2.8 Student Involvement: ADAC Fellows

Throughout the project, the PI focused on workforce development with one undergraduate and one graduate student from the UNH's Civil and Environmental Engineering Department funded by ADAC. These students were awarded ADAC fellowships and assisted with taking notes during conference calls and at the workshops, organized resources for the Core Team and working groups, drafted documents, progress reports, and presentations, and conducted a literature review. Jessica Manning, the undergraduate student, had her ADAC Fellowship between January 2019 and January 2021. Her UNH senior honor's thesis (May 2021) describes the role of local and indigenous knowledge in response and includes an in-depth review of the sea ice models and services available for the Arctic, as explored by the AMSM working groups. This document will be included in the Final Knowledge Product. Megan Verfaillie, the master's student, had her ADAC fellowship between January 2019 and May 2021. [N.B., This thesis will serve as the basis for the Final Knowledge Product.]

Through conference call and workshop participation and attendance, notetaking, database maintenance, and report writing, these Fellows have met key individuals in the field of oil spill response, assessment, restoration, and research as well as modelers and USCG experts and operators. They participated in the ADAC Arctic Summer Intern Program in 2019, a ten week program which included a one week orientation in Anchorage, AK followed by two weeks of field work in Utqiagvik (formerly known as Barrow). Field work on the North Slope allowed the Fellows to experience work, research and life in the Arctic. The remaining seven weeks were spent participating in Arctic workshops (ADAC Arctic Incidents of National Significance Workshop (IoNS)), visiting with former UNH master's student Jesse Ross at the NOAA Kasitsna Bay Laboratory (located near Seldovia, AK) to learn about interactions between marine snow and spilled oil, and supporting AMSM project activities. Jessica Manning participated in the virtual ADAC Arctic Summer Intern Program experience in 2020 which featured independent research projects and guest presentations on ongoing ADAC research and Arctic science, security and geopolitics. This experience taught the Fellows foundational principles in the field of Arctic science and oil spill modeling, the state of current science and new and emerging topics.

3. RESULTS/DISCUSSION

3.1 State-of-the-Art Oil Spill Models

The Project Core Team and OC completed a review of the current state-of-the-art response modeling for Arctic maritime oil spills. The AMSM project uses state-of-the-art to refer to the latest, most well developed models available. A spill in the Arctic maritime environment has the potential to affect more than one Arctic nation and the Emergency Prevention Preparedness and Response (EPPR) Working Group of the Arctic Council wrote its Agreement on Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic. The Agreement emphasizes the need for coordination, cooperation and exchange of information between the Arctic nations so international models were also included in AMSM discussions [39]. Publicly-available models developed by governmental agencies, as well as proprietary models developed by private industry, were considered. The models discussed as part of the AMSM project did not include all available oil spill models, but focused on those that include Arctic-specific considerations (e.g., sea ice) or have Arctic-specific capabilities under development. The review of Arctic oil spill models was not designed as a competition among models, but to assess their current capabilities and planned improvements.

In order to maintain a clear understanding of the inputs, outputs and operational abilities of each oil spill model, a list of commonly asked questions for oil spill models (specific and nonspecific to the Arctic environment) was created. These questions were based on the outcome of the December 2019 AMSM workshop, as well as feedback from OR&R ERD modelers. Representatives of each model provided answers to the questions, which were collected in a comprehensive spreadsheet (Appendix J). This resource provides a list of available oil spill models and their capabilities accessible to responders operating in the Arctic, and their usefulness during response planning and training. In addition, determining the capacity of each model for certain situations delineates how they may be interoperable and adaptable for use in areas like the Arctic and highlights potential areas for research and development.

The Core Team and OC developed a list of well known models available for use during oil spills in the Arctic (Table 1):

Table 1: List of Well-Known Models Available for Oil Spill Modeling in the Arctic.

Major U.S. Oil Spill Models	NOAA General NOAA Operational Modeling Environment (GNOME)
	RPS OILMAP/SIMAP
International Oil Spill Models (i.e., Canada, Norway, Russia, Denmark)	SINTEF Marine Environmental Workbench (MEMW)
	ECCC COSMoS
	MET Norway OpenDrift
	NRC Canada's Model
	N.N. Zubov State Oceanographic Institute SPILLMOD
	DHI MIKE Oil Spill Module
Other U.S. Oil Spill Models	DOE NETL Office of Research and Development BLOSOM
	TetraTech SPILLCALC

Modelers from each of these groups were invited to participate in the December 2019 workshop and subsequent working groups to present on the unique capabilities of their models and to encourage discussions among the developers.

Oil Spill Model Summaries

<u>NOAA GNOME</u>

NOAA's GNOME was developed by OR&R ERD (Seattle, WA). It is primarily used in support of spill response decision-making for predicting the transport of surface spills, but also includes oil weathering algorithms for evaporation and emulsification. Algorithms for dissolution and biodegradation are under development. GNOME is open source (public domain) and has been used extensively for oil spill response since the late 1990's through the DWH oil spill and into the present. GNOME is coded in Python and C++ and uses a Lagrangian particle tracking approach with customizable "behavior" of individual elements. It has no grid size dependence because oil is represented by particles that are not averaged over a modeled grid cell/area. Each element represents a specific mass of oil, with initial physical properties based on oil type, that change if oil weathering algorithms are applied. Optional separate "uncertainty particles" can be added to trajectories to develop uncertainty bounds during post-processing. These particles experience different forcings (i.e., diffusion, wind, currents) which results in spreading of the elements [28]. GNOME produces particle data in netCDF, KMZ and shapefiles which may be visualized within the web-based GNOME application (i.e., WebGNOME), NOAA's Environmental Response Management Application (ERMA) or using post-processing tools (e.g., Google Earth, GIS tools systems). GNOME modifies transport algorithms in the presence of ice. Weathering algorithms are not directly modified but results are altered due to the reduced effect of wind and waves in the presence of ice. GNOME developers suggested that modeling of more oil-in-ice interactions (e.g., under ice storage capacity) is key to improving the model's applicability to the Arctic.

RPS OILMAP/SIMAP

OILMAP and SIMAP were originally developed by ASA (South Kingstown, RI) for response planning, risk assessment and impact analysis to inform emergency response. [N.B., ASA was purchased by RPS in 2011.] These products have been used to model thousands of spills and exercises. Validation studies have been completed for OILMAP and SIMAP for over

20 spills including Exxon Valdez and DWH. The models are coded in Fortran and are available globally by licensing. The source code is proprietary, hence, customization must be done through RPS.

OILMAP primarily focuses on transport and fate of surface slicks, but also tracks movement of subsurface oil. SIMAP is a more complex model that requires more inputs and longer run times, but includes processes such as dissolution and fate of dissolved components. OILMAP and SIMAP are Lagrangian. Like GNOME, uncertainty in OILMAP is demonstrated through the use of "uncertainty particles." OILMAP also uses ensemble deterministic modeling which predicts potential outcomes by varying environmental inputs (e.g., different data sources) and running the model several times for the same spill scenario. SIMAP performs stochastic modeling with multiple model runs using varying input ranges. OILMAP does not require gridded geographical data inputs and instead relies on point data with polygons and polylines. SIMAP uses a grid to depict water depth, shoreline location and habitat type and is constrained by the grid size and resolution. Resolution in SIMAP is defined during post-processing of the model output. Both models produce graphical animations, pictures, shapefiles, text, and netCDF outputs which can be visualized by a graphical user interface. OILMAP and SIMAP modify transport and weathering algorithms in the presence of ice. Developers at RPS determined the model could be improved for the Arctic with more high-resolution input data and real-time ice data.

SINTEF MEMW

MEMW combines three SINTEF (Trondheim, Norway) models including DREAM (Dose-related Risk and Effect Model), OWM (Oil Weathering Model) and OSCAR (Oil Spill Contingency and Response). It is intended for use in oil spill response, planning, drills, and scenario testing and has been validated using several oil release experiments in ice-covered waters. MEMW is coded in Fortran and is available via commercial or research subscription. Oil spill modeling is addressed by OSCAR which is primarily used for planning, preparedness and response. Much like GNOME, SIMAP and OILMAP, MEMW is Lagrangian and includes weathering and surface advection. It also includes subsurface advection and dispersion like OILMAP and SIMAP.

Unique features of OSCAR include real-time, integrated response optimization using actual water temperature and wind data collected from individual vessels. Unlike GNOME, OILMAP and SIMAP, OSCAR does not consider uncertainty. MEMW outputs are used to inform responders on the most applicable response techniques (e.g., in-situ burning, dispersants). Biodegradation by oil component is currently under development and will consider different types of oil, biological communities and modification of oxygen levels from oil biodegradation. MEMW outputs an oil mass balance and its geographical distribution, chemical transformations and biological conditions in netCDF, binary files and images. A full graphical user interface is provided for visualization. MEMW modifies transport equations in the presence of ice and weathering is addressed within OWM. Developers at SINTEF suggested that the model could be improved for Arctic use by using Lagrangian coherent structures and further oil in ice field data.

ECCC Canadian Oil Spill Modeling Suite (COSMoS)

COSMoS is being developed by ECCC's Meteorological Service of Canada (Québec, Canada) for guiding response resource development and environmental protection for small to large spills. It will undergo validation studies once it becomes operational. COSMoS is coded in TCL/Tk and C and uses geo-referenced maps for Lagrangian elements which estimate oil density, viscosity, surface concentration, and environmental fields (e.g., temperature, winds, waves). COSMoS will include uncertainty. ECCC plans to share COSMoS publicly. The version under development is available upon request. COSMoS produces particle-based outputs (e.g., coordinates, density, mass) and gridded outputs (e.g., oil concentration, number of particles per cell, deposited mass to shorelines). Outputs are produced as ESRI shapefiles, PNG, JPEG, mp4, gif, csv, GeoJSON, GeoPackage, and binary files and can be visualized in any GIS software or browser. COSMoS modifies transport equations the same way as GNOME in the presence of ice and weathering algorithms are not directly modified but are influenced by decreased wind and waves as well as lower water temperatures. COSMoS developers suggested that the model could be improved for Arctic use through the addition of algorithms for more oil-in-ice specific interactions (e.g., encapsulation, under ice movement) and cold water processes (e.g., tar ball formation, pour point).

TetraTech SPILLCALC

Tetra Tech (Pasadena, CA) designed SPILLCALC to support spill response planning and environmental impact assessments through estimation of trajectory and oil weathering. It is coded in Fortran and Python and uses a Lagrangian approach. Uncertainty is shown by overlaying a number of simulations created based on deviations from the wind forecast. SPILLCALC focuses on surface spills and mechanical recovery options and does not include dispersant application.

The model has not been used operationally, but has been tested operationally during a spill and used multiple times in hindcast mode to support planning and impact assessments. The SPILLCALC source code is proprietary, but transport and weathering algorithms have been published and are included in the Oil Spill Model Summary Table (Appendix J). Outputs of SPILLCALC are provided in GIS map and Tecplot formats, with a netCDF under development.

They include oil mass balance, time to first contact with shoreline and specific location, length of shoreline affected, oil thickness, and probability of oil presence. Maps can be output in GIS software or MATLAB for visualization. SPILLCALC sources sea ice data from observed ice charts instead of ice models, so each modeled grid cell contains a value for ice cover which is updated at every timestep. These values are used to modify transport and weathering equations. SPILLCALC developers suggested that the model could be improved for Arctic use via better understanding of stripping velocity, updates to ice drift values and consideration of additional processes related to oil-in-ice interactions.

Norwegian Meteorological Institute (MET Norway) OpenDrift

OpenDrift is a generic framework for trajectory modeling developed by MET Norway (Oslo, Norway) to aid with oil fate and trajectory predictions for directing recovery and cleanup and in scientific studies. It has been used operationally at MET Norway since 2013 and is available 24/7 for oil, search and rescue and vessel accidents. It runs off a "core" which contains everything common to ocean drift. It is coded in Python and has four classes: a reader (retrieves data from a given source), writer (writes output to a specific file format), LagrangianArray® (describes a particular particle type and its properties), and an OpenDrift Simulation (the trajectory model). Uncertainty is shown based on the spread of elements/particles simulated. OpenDrift produces CF compliant netCDF files which contain all model information (e.g., configuration settings, environmental variables, oil location and properties). Functions are available to produce MP4/GIF, PNG, 2D structure, and particle density plots (GeoTiff/KML). GeoTiff and netCDF files can be displayed using GIS systems and other outputs (i.e., MP4, PNG) can use appropriate image/video viewers. OpenDrift modifies transport equations in the presence of ice but does not make any modifications to weathering algorithms. OpenDrift developers suggested that the model could be improved for Arctic use by adding more detailed interactions with oil and ice.

National Research Council Canada (NRC) Surface Trajectory Modeling of Oil in Ice-Covered Waters

The NRC Canada model is designed to estimate surface trajectories of oil-in-ice through two modules which address specific scenarios: (1) high ice concentration, rough under ice topography where oil and ice move together; and (2) partially or fully ice-covered conditions and short range oil tracking. Uncertainty is not built into the model, but is estimated by running ensemble forecasts and using analysis and visualization codes. It is coded in C++ and is currently only used internally at NRC Canada. NRC Canada may give special permission to interested parties to test, run, share, and modify the model. Outputs include oil trajectories, state, thickness and coverage area in formats compatible with NRC’s software platforms, as well as netCDF. The outputs may be viewed using NRC’s freely available BlueKenue software. The NRC Canada model does not include any weathering algorithms but adjusts transport algorithms in the presence of ice. NRC Canada modelers determined that the model could be improved for Arctic use through the addition of weathering algorithms, implementation of open water advection of oil (i.e., waves, wind) and by increasing computational speed of the second module (currently ~ 2 hours to simulate a week long spill).

N.N. Zubov (Russian) State Oceanographic Institute, Roshydromet (GOIN) SPILLMOD

SPILLMOD was designed by GOIN (Moscow, Russia) to forecast oil spill behavior in support of response in emergency situations, response strategy testing and impact assessment. It includes modeling of oil spill recovery techniques (e.g., skimmers, chemical dispersants), trajectory estimates and weathering. It is primarily focused on oil spreading on the sea surface, but also calculates parameters for subsurface spills. SPILLMOD is proprietary, but program code may be made available for scientific research if adapted into a new input data configuration. It is coded in C++, Delphi and MapInfo/MapBasic. Uncertainty estimation in SPILLMOD is under development. Currently, the model outputs trajectory information and characteristics of the slick, as well as the amount of oil evaporated and dispersed. Data are presented in text form, JPEG and GIS shapefiles, which can be displayed in most common viewers. SPILLMOD modifies transport algorithms in the presence of ice but only considers the impact of reduced wind, waves and oil spreading on evaporation and other weathering algorithms. SPILLMOD developers suggested that the model could be improved for Arctic use through the addition of an ice grid to model movement of oil with ice.

DHI MIKE 21/3 Oil Spill Module

The MIKE 21/3 Oil Spill Module was designed by DHI (Hørsholm, Denmark) to model spreading and fate of dispersed and dissolved oils from surface or subsurface spills and the effectiveness of recovery techniques (e.g., skimmers, dispersants, in-situ burning). It has been used in support of contingency planning and impact assessments. The model is proprietary and coded in Fortran and C++ and is commercially-available for professional use or through research agreements for noncommercial work. It uses a Lagrangian particle method for dispersed oil and a Eulerian model for dissolved oil. The model produces 2D or 3D maps with statistical values for all oil parameters (i.e., min, mean, max); traditional oil trajectory and fate outputs (e.g., oil mass, slick thickness); a mass budget as a time series; and particle tracks and properties. All 2D maps can be exported as GIS shapefiles. MIKE offers a “MIKE Data Viewer” and “MIKE Animator+” that allow for visualization of additional data. MIKE modifies transport algorithms in the presence of ice but makes no specific changes to weathering algorithms. Modelers at DHI suggested that the model could be improved for Arctic use by adding more complexity to the existing oil and ice interactions for use in longer term simulations (> 2-3 weeks after a spill).

DOE National Energy Technology Laboratory (NETL) Office of Research and Development Blowout and Spill Occurrence Model (BLOSOM)

BLOSOM is part of the NETL-GAIA Offshore Risk Modeling Tools Group designed by DOE NEL (Albany, OR) for spill prevention and response planning, but is primarily used for research and prediction. It is coded in C++ and includes a 4D modeling suite for offshore blowout and spill events. BLOSOM is composed of a series of interconnected modules that each represent a model or service supporting the model (e.g., jet/plume model, 4D Lagrangian transport model for the far field, weathering component). Uncertainty is not shown as part of model output. BLOSOM is public and open source and the source code is available upon request. The model is also linked to the Climatological Isolation and Attraction Model (CIAM) which predicts likely pathways for oil, based on predicted changes in oceanographic currents and locations of particulates. BLOSOM produces 3D/4D visual products and tabular data in GeoJSON, CSV, text, PNG, GIS shapefiles, and MATLAB files which can be displayed in their respective visualization software. BLOSOM does not include sea ice at this time and is focused on research instead of response, making it less suitable for Arctic response applications.

3.2 State-of-the-Art Sea Ice Models

Sea ice models simulate future data about ice conditions including growth, melt and movement. The outputs are essential for estimation of spreading and transportation of oil via sea ice drift, as well as prediction of oil and ice interactions. Sea ice models operate independently of oil spill models and are often coupled with ocean/hydrodynamic models. While most operate at scales larger than 1-2 km, several of the models discussed during this project are developing new capabilities to operate at smaller/subgrid scales. Prior to the December 2019 AMSM Workshop, there was limited communication and collaboration between the oil spill and sea ice modeling communities regarding compatibility and interoperability. In addition, there was a lack of understanding of the types of data oil spill models needed and the types of data and formats sea ice models produce. Currently, oil spill models use few sea ice model outputs (e.g., ice thickness, velocity, age) and the data that is ingested must be manually input (i.e., direct data assimilation is not possible).

In order to improve the linkages between the two types of models, the project identified well known sea ice models that may be used to provide forecast data during an Arctic maritime spill response. U.S. and international sea ice models were considered, as well as those publicly available and operated by private industry. A table of commonly asked questions for sea ice models was created based on the outcome of the December 2019 workshop and feedback from the Oil and Ice Interactions at the Meter/Subgrid Scale Working Group. Responses to these questions were written by representatives from each sea ice modeling group and collected into a spreadsheet similar to that used for the oil spill models (Appendix K). The goal is to make the list of sea ice models and their capabilities available to oil spill modelers to improve communication between these groups. The primary sea ice models discussed throughout the project are shown in Table 2.

Table 2: List of Major Sea Ice Models Discussed during the AMSM Project.

Major U.S. Sea Ice Models	Los Alamos National Laboratory ICEPACK
	CICE Consortium CICE6
	ADAC/Axiom Data Sciences HIOMAS
	NOAA Unified Forecasting System
International Sea Ice Models (i.e., Canada, Norway)	NERSC TOPAZ4
	NERSC neXtSIM-F
	SINTEF SINMOD

Some sea ice models use a community-driven approach to development (e.g., CICE), which allows improvements to be made by a wide variety of stakeholders, not just the original developers. There is currently no existing framework for community-driven collaboration between sea ice and oil spill modelers.

Ice Model Summaries

Community Ice CodE (CICE) Consortium CICE6

CICE 4 and 5.12 were developed by Los Alamos National Laboratory and are now replaced by CICE6, developed by the CICE Consortium (community-driven approach). CICE is two-way coupled with the Global Ocean Forecast System (GOFS 3.1), which is based on the Hybrid Coordinate Ocean Model (HYCOM). The U.S. Navy Coupled Ocean Data Assimilation (NCODA) program provides data assimilation for GOFS 3.1 using 24-hour model forecasts and satellite observations, in-situ sea surface temperature and in-situ vertical temperature and salinity profiles [40, 41]. CICE6 provides: (1) information to support navigation, facilitate upgrades to the Earth System Modeling Framework (ESMF) and provide sea ice drift fields; and (2) serves as the sea ice component for use in fully coupled, atmospheric-ice-ocean-land global circulation models. It is coded in FORTRAN, publicly available and open source and requires a supercomputer to operate.

CICE6 outputs a wide range of data including ice thickness, grid cell mean snow thickness, snow/ice surface temperature, ice velocity, ice area, ocean currents, ice melt, and salt and heat fluxes. It also offers three methods for measurement of internal ice stress (i.e., viscous plastic, elastic viscous plastic, elastic anisotropic plastic). CICE6's temporal resolution is determined by the GOFS 3.1 model (soon to be replaced by GOFS 3.5). GOFS 3.1 produces 7-day forecasts at a global/kilometer + scale resolution that are run daily at the U.S. Naval

Oceanographic Office and include: (1) location of features such as oceanic eddies and fronts; (2) 3D ocean temperature, salinity and current structure; (3) boundary conditions for regional coastal models; (4) indirect measurements (proxies) for acoustics (e.g., mixed layer depth); and (5) ice concentration, thickness and drift from CICE [40]. Outputs are available at the U.S. Navy 7320 (Ocean Dynamics and Prediction Branch) Naval Research Laboratory website [42].

High-resolution Ice-ocean Modeling and Assimilation System (HIOMAS)

HIOMAS was developed as part of an ADAC-funded project at the University of Washington (UW) Applied Physics Laboratory. It supports USCG Arctic operators and planners by predicting conditions such as sea ice thickness, internal stress and deformation and melting/freezing, in addition to aiding the USCG in oil spill response and search and rescue missions, HIOMAS also supports other Arctic stakeholders in planning and managing economic activities and in modeling efforts that require high resolution outputs. HIOMAS code is closed source and outputs for the Arctic Ocean are provided by Axiom Data Sciences, a NOAA affiliate (Anchorage, AK). HIOMAS produces 2D sea ice thickness, concentration and velocity; 2D sea ice internal stress, deformation, fraction of ice thickness, and major leads; 2D sea ice melt and freezing; 2D snow depth; and 3D ocean velocity, temperature and salinity. HIOMAS operates at a 2 km horizontal spatial resolution and has a forecast range of 1-3 months. One week of hindcast data and one month of forecast data are provided by Axiom biweekly. Outputs are available via the Alaska Ocean Observing System (AOOS) and NOAA's Arctic ERMA.

NOAA Unified Forecasting System (UFS)

The NOAA UFS is a comprehensive, community-developed Earth modeling system designed as a research tool and is the basis for NOAA's operational numerical weather prediction applications [43]. It is open source and the Arctic prototype is ready for developmental use. The UFS is being released incrementally. The current version uses the CICE5 model coupled with ocean, wave, storm surge, ice, aerosol, and land models using the NOAA Environmental Modeling System (NEMS) Infrastructure. Processing requires LINUX and Mac for Intel and GNU compilers which output coupled ensembles. Currently, the spatial and temporal scale of data outputs are limited by the models used in the coupling. UFS applications span predictive timescales of less than an hour to more than a year.

Nansen Environmental and Remote Sensing Center (NERSC) TOPAZ4

NERSC (Bergen, Norway) developed TOPAZ4 to provide forecasts and reanalysis of ocean and sea ice drift. It is open source, coded in FORTRAN 90 and is mostly operational. It outputs a range of data including ice age; first year ice fraction; sea ice area fraction, thickness and velocity; and sea water salinity and velocity. TOPAZ4 produces 10-day forecasts that are updated daily. The model operates at a scale of ~10 km for the Arctic. Products are available through the E.U. Copernicus Marine Environment Monitoring Service (CMEMS) on a 24/7 basis 365 days per year and supported by a service desk open 5 days per week.

NERSC neXtSIM-F

neXtSIM-F was created by NERSC to produce sea ice simulations of processes such as ice drift, deformation, thickness, and concentration. It is coded in C++ and is still undergoing development, but is mostly operational, publicly available and closed source. neXtSIM-F outputs ice concentrations, thickness, drift velocity, and snow depths as part of its 7-day forecasts which are updated daily. neXtSIM-F is produced at spatial scales between 1-10 km and time scales from several hours to decades. Products are available through the CMEMS on a 24/7 basis 365 days per year and supported by a service desk open 5 days per week.

SINTEF SINMOD

SINMOD is a 3D fully coupled ice-ocean-ecosystem model developed by SINTEF starting in 1981. It is used for research on physical and biological processes in the ocean (e.g., to predict effects of climate change on primary and secondary production). In addition, it is used for estimation of: water contact between aquaculture sites, dispersal and sedimentation of dissolved and particulate waste from aquaculture sites and conditions for maritime installations, aquaculture sites, bridge building and dredging activities. SINMOD includes ecological and hydrodynamic models, as well as a biological model incorporated through online coupling. SINMOD is a fully coupled hydrodynamic-ice-chemical-biological model system. The model simulates changes in ice mass and the fraction of open water due to advection, deformation and thermodynamic effects. The model is coded in Fortran 90 and the code is not publicly available, but can be shared. SINMOD is a complex and advanced system that requires specific training and the model system is computationally demanding. It is run on local and national high performance computing resources. The system is established in different regions around the world with spatial resolution varying from 32 m to 20 km. The region covered and time step depends on spatial resolution. The ice model provides output on ice velocities, ice thickness and compactness and ice salinity. The hydrodynamic module provides ocean currents, hydrography and heat fluxes. Other variables available from the model can also be provided in netCDF format.

3.3 State-of-the-Art Sea Ice Observing Systems

While the project initially focused on contributions from sea ice models, it became apparent that sea ice observing systems could provide data that current sea ice models cannot. Sea ice observing systems are a common source of data on existing sea ice concentration, velocity and thickness that is collected by reviewing satellite data and imagery for a particular area/region.

The orbit of a remote sensing satellite dictates the areas from which its instruments can collect data. There are two common types of orbits for remote sensing satellites: geostationary (also known as geosynchronous) and polar orbiting. Geostationary satellites orbit at ~ 36,000 km above the equator at the same speed as the Earth rotates which allows them to constantly collect data for the same geographical area [44]. Due to their position over the equator, they provide imagery for sub-Arctic areas and areas near the Antarctic Peninsula [45]. Polar orbiting satellites travel from north to south, covering the Arctic and Antarctic. They fly at altitudes ranging from 700 to 800 km with orbital periods of 98 to 102 minutes [46]. Polar orbiting satellites may also be sun synchronous, meaning they maintain the same angle with respect to the sun [47].

Satellite instruments come in two primary types: active sensors and passive sensors. Active sensors provide the energy source (i.e., radiation) used to illuminate the object they observe. The active sensor then detects and measures the energy backscattered or reflected from the object. The majority of active sensors operate in the microwave portion of the electromagnetic spectrum (~ 1 centimeter to 1 m in wavelength), which allows them to penetrate most atmospheric conditions (i.e., cloud cover) [48, 49, 50]. Examples of active sensor instruments include lidar (light detection and ranging sensor that uses a laser), radar (active radio detection and ranging sensor that emits microwave radiation) and scatterometers (high-frequency microwave radar).

Passive sensors detect the natural energy emitted or reflected by the object. These sensors commonly use sunlight as the energy source and include different kinds of radiometers and spectrometers. Radiometers measure the intensity of electromagnetic radiation in specific bands within a spectrum (e.g., 380-700 nanometers/visible, 780 nanometers-1 millimeter/infrared, 1 cm-1 m/microwave), while spectrometers measure the intensity of radiation in multiple wavelength bands (i.e., multispectral) [50].

Sea ice observation experts may also use outputs from sea ice or hydrodynamic models to predict future conditions. Using this imagery and modeled data, they can provide a variety of products on different time intervals (i.e., daily to yearly) on sea ice concentration, thickness and development, as well as forecasts of sea ice location, concentration and ice edge. The two sea ice observing systems reviewed by AMSM were: the US National Ice Center (US NIC) and the NOAA NWS Alaska Sea Ice Program (ASIP). Outputs from the US NIC and ASIP are shared on their websites and through AOOS.

Ice Observing System Summaries

U.S. National Ice Center (NIC)

The NIC is a multi-agency organization including the U.S. Navy, NOAA and USCG. It provides ice and snow products, sea ice forecasts and environmental intelligence services at the global and tactical scale for use by the government. The NIC provides various data for the Arctic, Antarctic, Great Lakes and Mid-Atlantic region, and across the Northern Hemisphere [51]. It is not research-focused, but can provide data and information for research purposes. In the Arctic, the NIC provides daily analysis of the ice edge and MIZ (the transition zone between open sea and dense drift ice), as well as weekly analyses for the Arctic, Antarctic, Great Lakes, and Mid-Atlantic that include sea ice concentrations (including partial concentrations) and ice types.

Information availability is based on orbits, satellites radar calibration times and environmental conditions that may obscure sensors and prevent data collection (e.g., clouds).

The NIC collects data from polar orbiting and geostationary satellites [52, 45] which may carry visible/infrared sensors, passive microwave sensors, scatterometers, and/or Synthetic Aperture Radar (SAR) [53]. Their primary source of data is RADARSAT (100 m resolution, launched in 2019), but in areas where it is not available other visual satellite sources (e.g., VIIRS and MODIS) can be substituted. In general, a couple of images are available every two hours at a spatial scale of approximately 100 m for a particular location. Higher spatial resolution imagery can be produced at 10 m, but requires justification to order and may take longer to collect depending on the radar (up to 24 hours for first image).

The NIC compares satellite data to the GOFS model (coupled with CICE). GOFS is run every 12 hours for the NIC to predict sea ice movement and approximate location of leads. Satellite data for the Arctic can provide percent cover, estimated thickness and direction of sea ice drift. Based on the imagery, sea ice leads and ridge locations can also be identified. NIC forecasters use the most current imagery, environmental parameters from models and knowledge of the Arctic region to produce forecasts. The NIC is an on call center available 24/7 and offers tailored support to certain projects or groups upon request.

NOAA NWS Alaska Sea Ice Program (ASIP)

The NOAA NWS ASIP works closely with the NIC, but primarily focuses on nearshore monitoring of Alaskan waters (~ 80º N to as far south as sea ice forms including the Bering Strait and Cook Inlet). ASIP produces analyses on a daily basis including shapefiles and maps of sea ice concentration, stage, thickness and temperature which are made available on their website. Under normal operations, ASIP produces a 5-day sea ice forecast three times each week and a three month sea ice outlook at the end of each month [54]. Much like the NIC, the spatial resolution of the data depends on the weather conditions and available satellite imagery and ranges from 100 m to 12 km. On a clear day, data from infrared or visible sensors is available on a 12-hour basis. ASIP routinely uses data from satellite missions carrying visible and infrared sensors (i.e., SNPP, MODIS, NOAA20), microwave sensors (i.e., AMSR2) and SAR (i.e., RADARSAT-2, Sentinel 1A and 1B).

Daily imagery is usually available at the 1 to 2 km spatial resolution with varying confidence based on analysis by ice experts. Confidence is based on how much of the ice pack is visible during observations and environmental conditions. Low confidence indicates that only small portions of the ice pack were visible, whereas high confidence indicates most or all of the ice pack was visible for analysis. Poor visibility combined with recent storms/changes to the ice pack will reduce confidence further. Sea ice velocity is not produced as part of normal operations, but these data, as well as others (e.g., gridded, pointwise), could be included in analyses during an oil spill event. As an operational center, ASIP does not do modeling, but uses them for forecasting future conditions (e.g., GOFS). Satellite imagery is not directly integrated as part of the forecast process [55].

3.4 Integration of Models (Scale, Algorithms, Data Requirements)

Currently, there are few well established linkages between sea ice and oil spill models. Oil trajectory outputs are only as accurate as their inputs and existing models do not account for several important ice-related environmental factors (e.g., currents under ice, ridges, keels, water density as a function of melting). In the Arctic, there is an increased need for short term, localized forecasts for sea ice, hydrodynamic and climatological data to inform models and improve understanding of these factors. Following the December 2019 Workshop, working groups were established to investigate oil and ice interactions at the meter/subgrid scale and kilometer + grid scale.

The Meter/Subgrid Scale group identified response-relevant small scale oil-in-ice processes, summarized what existing sea ice submodels do and how they can be used to inform response and discussed what information is needed from sea ice models (Table 3). The Kilometer + Grid Scale group was focused on identifying the current state-of-the-art oil spill models, their Arctic-specific and other fate and transport algorithms and potential improvements. This group primarily focused on algorithms and models operating at the kilometer and greater scale, but also worked closely with the Meter/Subgrid Scale group to ensure findings were consistent (Table 4).

Table 3: Oil and Ice Interactions at the Meter/Subgrid Scale - Objectives/Questions.

1. Determine and identify outputs from sub ice models to determine how they could be used to improve understanding of submodels and their uses in an oil model, and to define when oil is going to show up (e.g., on surface, encapsulation, enter water under ice).	a. Discuss how subgrid sea ice models may mesh with oil spill models (e.g., inform high resolution coupled simulations that can feed into larger scale models).
	b. List possible dynamic feedbacks from oil to sub ice models: how does oil affect what sea ice is doing?
	c. How do different types/characteristics of sea ice affect oil behavior?
	d. How do we recognize/incorporate the value in including local and indigenous knowledge (with specialty in small ice interactions)?
	e. Define key timescales for the information and processes (near term vs. long term).

The working groups determined that the primary concerns related to oil and sea ice model integration are: (1) incompatibility of the formats/scales of available sea ice data, (2) lack of appropriate algorithms to ingest sea ice data into oil spill models, and (3) lack of clear communication of the oil spill modeler’s sea ice data-related needs (e.g., type, format/scale) to sea ice data producers (i.e., models, observing systems).

Table 4: Oil and Ice Interactions at the Kilometer + Scale - Objectives/Questions

1. What is the current state of the art of oil-in-ice modeling? Revisit oil and sea ice transport and fate algorithms to determine potential improvements.	a. What is the scale of information useful for USCG decision-making?
	b. How well tested are the algorithms and how well do they inform what is happening?
	c. How much information is available in a timely enough manner to be useful?
	d. What processes need to be included?
	e. What are the values of the needed input parameters?
	f. How well do the algorithms inform the response options (real-time vs. predictive)?
2. Review widely adopted algorithms for oil spill models.	a. How is the spreading algorithm modified in the presence of sea ice?
	b. How does entrainment differ in the presence of sea ice?
	c. Are there any special considerations for dispersant use in the presence of sea ice?
3. Propose algorithms for under ice storage capacity.	a. As a function of the type of sea ice (characterized by age, thickness, roughness) and under ice current velocity, what would be the static storage capacity (i.e., m^3 of oil per km^2 of sea ice)? Set low, medium and high ranges for storage capacity estimates.
	b. How to quantify mobilization and stripping velocity?

Scale of Available Data

While sea ice models and observation systems can provide data on sea ice concentration, thickness, roughness, and velocity, the spatial and temporal resolution (scale) needed by oil spill models is much smaller than that for which the average sea ice characteristics are considered (e.g., sea ice thickness). This poses a major obstacle to improving the interoperability of the two types of models. Movement of sea ice is a major driver of spilled oil behavior. Without compatible data resolution, oil spill model predictions cannot accurately estimate trajectory and fate of oil in the presence of ice, especially on scales ≤1 km. Multiple regional scale sea ice models (e.g., CICE, HIOMAS, neXtSIM-F) exist for the Arctic to estimate sea ice conditions (e.g., concentration, thickness, snow depth on ice surface) and simulate movement and growth/melting of sea ice. However, most of the sea ice models require boundary conditions from larger global models to understand how external factors influence the region. Boundary conditions are used in regional or small scale models to describe conditions outside of the modeled area (e.g., currents, sea level) [56].

Ideally, oil spill modelers want data from sea ice models hourly at approximately a 1-kilometer spatial resolution or less. While this spatial and temporal resolution is available in many parts of the world, it is challenging to produce for the Arctic due to the complex environment and technology limitations and availability that reduce the amount of data collected. This is especially true in transition regions such as the MIZ [2] and near shore where higher resolution data is essential for differentiating landfast ice, pack ice and open water [57]. Averaging of data across grid cells and time steps reduces the accuracy of the resulting trajectory outputs, especially in the MIZ and near shore, as it does not adequately represent processes that occur at the regional scale within the response time frame. The 1-kilometer scale is challenging as most existing sea ice models are either at the climate/global or meter scale, with few that can produce high quality outputs at intermediate levels. Global scale sea ice models make certain assumptions about ice physics in order to operate and as the scale is refined, some of these assumptions (e.g., those related to ice rheology) begin to break down. As a result, regional models also require different sea ice physics than global models. Models that consider intermediate scales are not likely to be available in the near term (next 1-5 years) due to limitations in understanding of intermediate scale ice physics and availability of data to describe them [58].

NIC and ASIP are capable of producing outputs on the 1-2-kilometer scale upon request, but due to limitations in swath width (width of area covered), spatial resolution and satellite revisit periods (number of days between each pass over of the same ground location), they are unable to produce data for large areas on an hourly basis [59]. They are also limited by weather conditions which may obscure sensors and satellite return times to a particular area. Changes to normal satellite operations also take time to plan and execute, so data may not be available until later in the response (up to 24 hours).

Small scale sea ice data may be available through the integration of local and indigenous knowledge. Members of local and indigenous Arctic communities may have knowledge of the sea ice in a specific region that exceeds what is available from sea ice models or observations. This expertise may be crucial in the event of a near shore or coastal oil spill when satellite and modeled data is limited. [N.B., Local and indigenous knowledge is not covered in this thesis, but will be in the AMSM Knowledge Product.]

Creation of outputs at the 1-kilometer spatial and hourly temporal resolution are also limited by available data storage capacity for outputs/imagery and the computing power necessary to run models. Large scale sea ice models cannot easily be scaled down to 1-kilometer resolution due to the assumptions required to reproduce sea ice behavior (e.g., cracking) across the whole Arctic. Conversely, scaling up small scale models to a larger region requires a significant amount of computing power and storage.

Oil spill modelers noted that there is a need to streamline communication with sea ice modelers and observing system operators to allow finer scale sea ice outputs to be requested for a specific region during an active spill event or exercise. In order for the data produced to be useful for response, a communication and data sharing framework must be organized in advance. Oil spill models must be able to ingest the sea ice data directly, but that will likely require improvement of existing oil and ice algorithms and development of new ones. Once the framework and the necessary algorithms have been well established, the working group proposed making them the focus of a drill or exercise to test creation of trajectory estimates and their associated uncertainty.

Oil Spill Algorithms

Physics of oil and sea ice interactions are not well understood (e.g., behavior of oil in cold or ice-infested water). As a result, best available trajectory predictions often inadequately estimate the fate of spilled oil in the Arctic. Existing algorithms are an approximation of true conditions and few include considerations for different ice types (e.g., fresh, multi-year ice) and even fewer the influence of under ice roughness (i.e., the topography of the underside of the ice). Many algorithms require updates to improve trajectory models, but data to improve them is limited as there are few technologies capable of monitoring conditions (e.g., underside of ice). Hence, some processes require methods for statistical estimation of conditions (e.g., under ice topography) based on existing or observed data (e.g., sea ice age, type). Development of publicly available algorithms appropriate for oil spill models that use sea ice model outputs or derived data are a necessary step to improve oil spill trajectory predictions.

Under Ice Oil Storage Capacity

Many oil-in-ice processes require finer scale simulations (spatially and temporally) than what is currently available. The Meter/Subgrid Scale Working Group identified research needs (Appendix M) that must be addressed in order to improve oil spill modeling.

The primary need is related to estimation of storage capacity based on under ice roughness and oil stripping velocity. Storage capacity is the amount of oil that can be trapped or held in the void spaces under the ice (Figure 4). In open water, oil may spread until it is a fraction of a millimeter thick. Under ice, depending on the topography, it may spread to 4-9 cm thick. The extent of the spill may also be significantly lower than that of spills in open water

[60]. Currently, there are few data available to describe under ice roughness, and the relationship between under ice conditions and surface conditions (e.g., ice age, type, topography) is not well understood. Under ice roughness and topography are also an important property for estimation of oil movement under ice (e.g., oil pooling under ice to fill up void spaces, gravity-driven flow moving oil along streamlines) along with stripping velocity. Stripping velocity refers to the velocity necessary to move oil under ice and is influenced by under ice topography and under ice current velocity. Storage capacity and stripping velocity influence the amount of oil that will be retained under the ice following a spill, but few studies exist to describe their interactions.

Wilkinson et al., (2007) determined that existing models for the spread of oil under ice are unable to replicate the complexity of different ice types. They demonstrated that combining 3D under ice imagery from multibeam sonar fitted to an autonomous underwater vehicle (AUV) with oil trajectory modeling can improve estimates. This combination also allows for estimation of the potential holding capacity of sea ice and the spread of oil at a specific location. Wilkinson et al. determined that the spread of oil under sea ice is most likely under-estimated by an order of magnitude. Variability of the potential holding capacity of sea ice is high, and accurate knowledge on under ice topography is needed to predict the flow of oil [61].

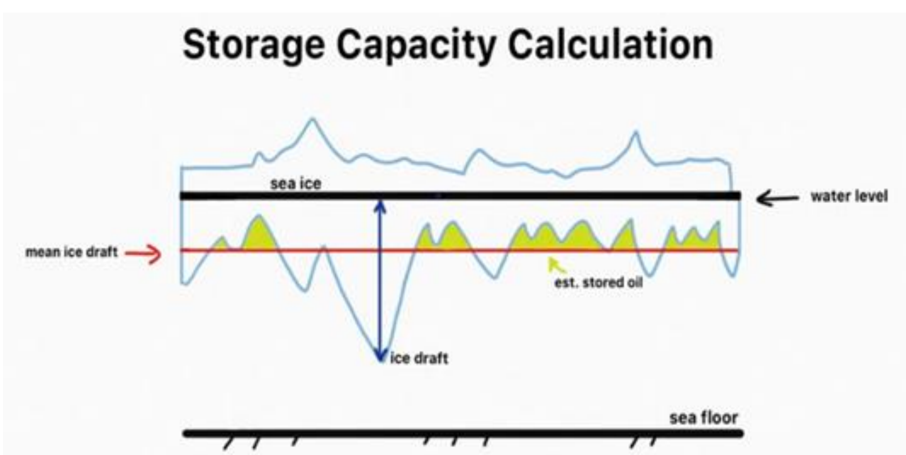

Figure 4: Storage capacity calculation courtesy of Kelsey Frazier, UAA [62].

Frazier (2019) introduced the development of a 3D model for calculating subsurface storage capacity in Arctic sea ice. She expanded upon previous work which identified that the depth of under ice topography is related to ice age and estimated storage capacity based on ice stage (e.g., first year, thin ice). This research used data from the Shell Exploration and Production Company (Houston, TX) which was collected by upward looking sonar at sites in the Beaufort and Chukchi Seas each winter from 2005-2013. The upward looking sonar directly measured ice draft, which was correlated with weekly ice stage for each location (supplied by AOOS). Frazier's work concluded that storage capacity is tied with subsurface roughness, which requires better understanding of the relative distribution of sea ice drafts [63]. In addition to that used by Wilkinson et al. and Frazier, data on under ice topography and thickness has been collected by the Woods Hole Oceanographic Institution (WHOI). WHOI scientists are currently developing an AUV for the Arctic which will measure ice thickness from below the surface for thousands of miles at a time [64].

Current algorithm development for retention of oil under ice is occurring for GNOME in partnership with ADAC and Texas A&M University. This development is based on the foundation laid by the ADAC AOSM project which used the AOSC MATLAB model. The new algorithm, being developed by Dr. Scott Socolofsky, calculates the volume of oil for each Lagrangian element using the mass of oil provided by GNOME and the oil density. The volume is then used to determine the area of ice that will be filled by the oil (i.e., the oil "disk" area). If the ice storage capacity is exceeded (i.e., disks overlap), oil disks will move under ice via diffusion and advection with currents until they encounter an open void space where they will stick to the sea ice.

The Subgrid Scale working group proposed development of an approximation to be used until more information is available to produce an estimate of storage capacity (i.e., low, medium, high oil storage capacity) based on known sea ice conditions (e.g., type, age). This rule would estimate a quantitative volume or range for holding capacity of sea ice based on under ice roughness. The roughness would be based on ice type, age and surface conditions and the oil would be assumed to fill any available void space under the ice. This estimate could be created quickly using existing data and spilled oil volume and would serve as a starting point for spill modelers while more complex solutions are being developed. For example, the approximation could be replaced by a statistical distribution based on sea ice type and age for Lagrangian elements that employs empirically-based algorithms for estimating under ice storage capacity. In order to create this distribution, the factors that influence storage capacity (e.g., macroporosity of sea ice, vertical water column stratification) require further research. More data (e.g., from a mesoscale study/field test) may be required depending on the degree of refinement necessary. This is especially true in areas near large sea ice features such as keels that may collect large amounts of oil. Time dependency of storage capacity based on freezing, thawing and breakup should also be investigated to improve the statistical distribution.

Under ice roughness and storage capacity are only two of the ways that sea ice can store spilled oil. Identification and characterization of the processes by which oil can become trapped in sea ice is important for estimating the quantity of oil stored (i.e., encapsulated) in sea ice. Oil trapped under sea ice behaves differently than that in open water and may experience decreased rates of weathering and degradation. Modelers need a better understanding of processes and the interactions between oil and ice to improve estimation of oil trajectory and fate, including those that occur on the small/subgrid scale. They identified small scale processes of interested including: interactions between oil droplets and brine channels, microscale simulations of oil penetrating pores in sea ice and becoming locked in a matrix in brine channels, encapsulation (i.e., freezing of oil in sea ice), re-entrainment of oil droplets stored in sea ice, dissolution, and degradation. The cumulative influence of these processes on oil storage and movement is not well understood and better estimation of these processes will determine their importance in future modeling efforts.

Large Scale Simulations

The Kilometer + Scale Working Group completed a review of available oil spill models and determined that, of those that consider sea ice, they all use very similar oil-in-ice algorithms (Appendix N). Among the models discussed, all that include sea ice use some form of the 80/20 rule, making their own adjustments to the percentages (e.g., 75/20 rule, 80/30 rule) used to define conditions related to oil transport and weathering (e.g., normal evaporation at < 30%, no evaporation at > 80%, linearly interpolated in between). The influence of these changes is small due to the interpolation between the maximum and minimum thresholds. In addition, there are many other uncertainties (e.g., wind, currents) that may cause predictions to differ from real-world conditions. Ice concentration is often reported as a fraction (tenths) or in 10% increments, and in many cases, there is little to no difference between 20 and 30% ice concentration. For example, ASIP reports sea ice concentration as a range from 1-3 tenths, meaning that 20 and 30% are equivalent [65].

In GNOME, an 80/20 rule is used to modify advection (e.g., at 50% ice coverage, oil moves at the average of the ice and current velocity), wind drift, diffusion, spreading, and the amount of oil that may be encapsulated (Table 5). Evaporation algorithms are not directly changed, but results are impacted. OILMAP and SIMAP use the 80/30 rule to modify advection, wind drift, diffusion, spreading, evaporation, and encapsulation, as well as the entrainment of oil in the presence of sea ice. OILMAP and SIMAP use an 80/30 rule to estimate sea ice conditions. The rules for percent sea ice cover can be adjusted within SIMAP as a choice for input. SINTEF's MEMW uses the 80/20 rule to modify advection, wind drift, entrainment, and stranding, but does not include encapsulation. COSMoS uses a 75/20 rule to modify sea ice cover, windage, spreading, and fate and behavior algorithms. In the future, the COSMoS model will also be able to address free sea ice drift, oil-sea ice interaction, evaporation, thickness measurements within the sea ice, and cold water processes (e.g., tar ball formation). TetraTech's SPILLCALC uses an 80/20 rule to adjust algorithms for advection, wind drift, waves, stranding, entrainment, and evaporation. MET Norway OpenDrift uses sea ice fraction and velocity to characterize encapsulation and advection of oil within sea ice, but the weathering algorithms are only modified by temperature and do not use percent ice cover. The NRC Canada model does not include weathering, but uses an 80/30 rule to modify advection algorithms. SPILLMOD uses an 80/30 rule to modify advection, wind drift, adhesion of oil to sea ice, and spreading. The DHI MIKE 21/3 Oil Spill Module contains transport algorithms specific for sea ice conditions that treat sea ice cover as a barrier to which oil may adhere, move away from, submerge under, be trapped by, and drift with and uses an 80/30 rule to modify advection, wind drift, stranding, spreading, and weathering algorithms.

Sea ice modelers from DOE Los Alamos National Laboratory recommended that future research should develop a list of key oil- and ice-related algorithms to be added into ICEPACK (shared community physics for ice models) or a similar product. This will allow oil spill and sea ice modelers to define and address specific oil spill scenarios and share resources. In order for

Table 5: Percent Sea Ice Cover Rules for Arctic Oil Spill Models‡.

	GNOME	OILMAP	SIMAP	MEMW	COSMoS	SPILLCALC	OpenDrift	NRC Canada	SPILLMOD	MIKE
Rule Used	80/20	80/30	User Specified	80/20	75/20	80/20	80/20	80/30	80/30	80/30
Transport										
Advection	X	X	X	X	X	X	X	X	X	X
Wind Drift	X	X	X	X	X	X	X	Indirectly	X	X
Diffusion	X	X	X	Nordam et al.	No mod.	No mod.	X	Not modeled.	Not modeled.	No mod.
Stranding	No mod.	No mod.	No mod.	Indirectly	No mod.	X	No mod.	Not modeled.	Indirectly	X
Vertical Movement	No mod.	No mod.	No mod.	No mod.	Indirectly		No mod.	Not modeled.	No mod.	
Weathering										
Evaporation	Indirectly	X	X	Separate Oil Weathering Model	No mod.	X	No mod.	Not modeled.	X	No mod.
Emulsification		X	X		Indirectly	X	No mod.	Not modeled.	No mod.	No mod.
Dissolution		Not modeled.	No mod.		No mod.	Indirectly	No mod.	Not modeled.	Not modeled.	No mod.
Biodegradation		No mod.	No mod.		Not modeled.		No mod.	Not modeled.	Not modeled.	No mod.
Sedimentation		No mod.	No mod.		No mod.	No mod.	No mod.	Not modeled.	Not modeled.	No mod.
Photo-Oxidation		Not modeled.	No mod.		Not modeled.	Not modeled.	No mod.	Not modeled.	Not modeled.	No mod.
Spreading	X	X	X	X	X	X	No mod.	Not modeled.	X	X
Ice Processes										
Sticking to Ice		No	No	Not modeled.		X	No	X	X	X
Entrainment or Waves				X		X		Not modeled.	Indirectly	Indirectly
Encapsulation	X	X	X				X	Not modeled.	Not modeled.	Not modeled.

‡ No mod. refers to "no modification" of the algorithm in the presence of ice.

this solution to be effective, a workshop, tutorial session and/or an online discussion forum would be required for oil spill modelers and researchers who are unfamiliar with ICEPACK to teach them how to access and upload information.

Data Needs and Assimilation

Future research should define sea ice data and processes of interest (e.g., encapsulation) and the type of coupling desired between oil spill and sea ice models. Coupling refers to the models' abilities to influence each other using feedbacks and fluxes (data) passed between models. Fully coupled models evolve together to produce more realistic results [66]. Oil spill and sea ice models are not fully coupled because sea ice models do not ingest data from oil spill models (i.e., impact of spilled oil on ice properties). Sea ice model and observational system outputs are also not developed specifically for use in oil spill response and, due to the unique needs of oil spill models, existing outputs may not provide all of the data required for fate and trajectory estimates or be supplied in compatible data input formats. As a result, while many sea ice models and observing systems may produce additional data that could support response, it may not be supplied in routine outputs/visualizations or be in a format that oil spill models can ingest. Currently, oil spill modelers are primarily concerned with data related to sea ice concentration (as percent cover), sea ice thickness, under ice roughness (if available) and sea ice velocity. Sea ice modelers requested that a complete summary of sea ice data types/formats and the minimum resolution needed during Arctic spill response be made available to them to guide data production efforts.

Data assimilation refers to the science of combining (assimilating) different sources of information to estimate the state of a system over time [67]. In oil spill and sea ice modeling, this refers to automatically ingesting observational data from monitoring stations/technologies, satellite data, or other environmental data sources (with suitable formats/scales) to inform modeling. Data assimilation is challenging because model outputs and observations do not always agree and certain regions may experience this disconnect more than others. Near shore and the MIZ are particularly difficult to model and therefore, observations are needed to refine predictions. Data assimilation is used to determine a best possible estimate of conditions by comparing forecasts and observations at each time step and updating the model prior to the next time step [68].

Within GNOME, data assimilation consists of gathering reports of oil on water from remote sensing or aerial overflights and comparing them with model forecasts. The model parameters (i.e., wind, diffusion, currents) are then adjusted so that the output better matches the observations. The next forecast is derived using the new parameters. Oil location will also be re-initialized at the beginning of the forecast based on observations. Automation of this process is challenging as oil observations are sparse and data availability and formats are inconsistent. For example, oil may be present in an area, but not included in observations due to lack of overflights or the inability of a sensor to detect it. False positives (i.e., oil reported in an area where there is none) are also a concern for assimilation as they may skew forecasts. OILMAP/SIMAP use a different method for data assimilation that relies on a time series of GIS polygons of oil location and thickness that are input into the model. The model then moves the floating oil into the polygons at the time step instructed and continues calculations. These polygons can be made in real-time by modelers based on coordinates or photographs of oil, georeferenced from GIS maps, or imported from shapefiles (e.g., for sea ice concentration).

The accuracy of each of these approaches is dependent on the quality of observational data available. GNOME's approach involves using observations to adjust input parameters, improving the environmental conditions modeled. Adjustments are made to hindcasts (i.e., predictions for past conditions) and then used to influence forecasts. Alternatively, the approach used by OILMAP/SIMAP focuses on real-time observational data inputs to adjust the model at each time step instead of relying on previous forecasts.

The Kilometer + Scale Working Group discussed how to improve data assimilation by oil spill and sea ice models and identified key questions to be addressed by future research including: (1) what space and time scales can sea ice models be considered deterministic (accurate) in their predictions for different aspects of sea ice (e.g., leads, sea ice edge, percent cover), (2) how can oil spill models improve assimilation of observational data on oil location, (3) how are field observations used to create better predictions of oil movement, (4) how are uncertainties propagated, and (5) what algorithms can be adjusted or created to better align predictions with observations (e.g., changing initial conditions, updating trajectories, adjusting model input parameters).

3.5 Responder Needs and Uncertainty

The Core Team identified a need for improved understanding of what confidence means for model outputs, how models are verified and how results may be communicated to responders, media and the public. Improving communication and understanding of confidence levels was of special interest to the Core Team as terminology, such as confidence level, can be easily misinterpreted (e.g., statistical confidence vs. responder's qualitative trust in the reliability of the output). The Core Team developed a list of needs and questions related to responder needs concerning confidence level and communication (Tables 6 and 7) that were reviewed by the NOAA Alaska SSC and FOSCs. Much like the Core Team, the response community and FOSCs

Table 6: Core Team Meeting Questions and Needs from the Responder/FOSC perspective[1].

Where did the oil spill occur, where is it going, what assets are available, and where should people be assigned? • How does modeling inform pre-staging of gear and personnel?
What is the confidence level vs. uncertainty, how do we know what the probability associated with the model estimates are?
How acceptable is this model going to be to corporate partners/responsible parties (corporate equity)? • Inherent responsibility to protect company, reduce liability and decrease costs. • May result in conflicts of interest.
What are the implications of the model on response tactics? • Normally oil is portrayed by the model as a monolith but responders may want to know where density/thickness of the oil is greatest. • Current models show contours (heavy, medium, light).
What is an acceptable run time for a model and what is the level of resolution/detail needed?
Who is going to use/report out the results of the model?

1 *Referenced from "Responder Needs Addressed by Arctic Maritime Oil Spill Modeling"* [11].

Table 7: Core Team Meeting Questions and Needs on Confidence Level and Communication[2].

Is it possible to get a qualitative confidence level for a model (i.e., % confidence)? • The % confidence is based on number of model runs that are repeatable (e.g., ensemble models). • Confidence and uncertainty are not well defined with respect to trajectory models. • How well will concepts of confidence and uncertainty be accepted by a corporate party/responsible party?
What kinds of inputs (e.g., weather, reliable wind speed) are needed to obtain a certain confidence?
Models and inputs should be widely distributed to all parties to improve “confidence”.
How to improve communication of results (intended audience and communication medium)? • Who is the end user (e.g., public affairs, scientists)? • To what extent can the end user manipulate visualization of the output? • Public affairs component is critical, special concern for international affairs (e.g., Russia and U.S.).
How to translate outputs to a “layperson’s level” so that they are realistic and accurate, but easy to understand? • For press, public and politicians. • How much/what type of information can be shared?
Terms can mean different things to different people. • Trajectory may define what shorelines the oil will contact or how much time it will take for the oil to reach the shoreline. • Confidence referring to statistics vs. confidence of the user.

2 *Referenced from "Responder Needs Addressed by Arctic Maritime Oil Spill Modeling"* [11].

are primarily concerned with responder-specific topics such as implications of model results for cleanup tactics, confidence and communication [11].

The needs and questions of responders, confidence level and communication were discussed in detail during the December 2019 Workshop. As a result of these discussions, a working group entitled Visualization and Uncertainty was developed. The objectives of this group (Table 8) included determination of how uncertainty is demonstrated in existing oil spill and sea ice forecasts, identification of responder needs and desires for model outputs and discussions on the efficacy of standard trajectory products for public communication.

Table 8: Visualization and Uncertainty Working Group: Objectives/Questions[3].

1. How is uncertainty shown and to what extent is it demonstrated in existing oil and sea ice forecasts?	a. What do responders mean by uncertainty?
	b. What is the state of the art with respect to uncertainty?
	c. How should this evolve to suit modern needs in the Arctic?
2. What do responders want with respect to uncertainty?	a. How are model outputs currently presented in visualization systems utilized by NOAA (e.g., ERMA) or USCG (e.g., CG1 View, HSIN, AIS)?
	b. How should this evolve to suit modern needs in the Arctic?
3. What would responders like to see/know that they aren't getting now? Especially specific to oil in sea ice/Arctic?	a. Circular error of probability, thickness estimates?
	b. How should this evolve to suit modern needs in the Arctic?
4. Are standard trajectory products an effective communication strategy? If not, what needs to be done (i.e., response community, public)?	a. What are current trajectory products?
	b. How should this evolve to suit modern needs in the Arctic?

3 Referenced from "Responder Needs Addressed by Arctic Maritime Oil Spill Modeling" [11].

Operating in the Arctic increases the importance of including uncertainty in outputs, as personnel and equipment resources, as well as available data, are limited. USCG FOSCs want to know which fate and trajectory modeling prediction will most likely occur, what the worst case scenario is and what the implications are on response operations. As a result, a qualitative confidence level in model outputs at a predefined low, medium or high level is sufficient for most decision-making during oil spill response. The UC is responsible for making all response decisions, including setting command priorities and objectives. Accurate fate and trajectory modeling are crucial for deployment of response personnel and equipment, creation of aerial overflight search patterns, actual spill response operations and data collection efforts. The amount of acceptable uncertainty for each of these activities is different.

The current state of oil spill model input data (Figures 5 and 6) makes it difficult to estimate quantitative confidence levels, but modelers usually have a qualitative sense of the uncertainty associated with outputs. The modelers involved in the AMSM project determined that a high/medium/low confidence estimation was achievable for most spill scenarios. This is because a quantitative range (e.g., low = 0-30% confidence associated with a particular model input) would be difficult to assign due to the lack of numerical confidence estimates for many input parameters (e.g., hydrodynamic model outputs) [11]. In some cases, especially at the beginning of a spill when there are limited data available, inputs may be a "best guess" based on modeler experience. In addition, trajectory forecasts are multi-dimensional, making uncertainty relevant only to a specific scale or quantity. For example, a 30% uncertainty in wind data may not be equivalent to a 30% uncertainty in currents.

Qualitative estimates are also spill-specific because the input with the greatest impact on model results often changes based on data values (e.g., strong winds may have greater influence on trajectory than weak currents). Uncertainty is often caused by data gaps (e.g., the model needs 5 inputs and 3 are unavailable) and varies by data source (e.g., observational data are more reliable than modeled data, different forecasts each have their own confidence levels, sometimes no data are available). Age of data may also contribute to uncertainty as same day data are more reliable than several day old data. Data quality and accuracy, such as that associated with oil type and composition, also influence the uncertainty of outputs. In order to use qualitative confidence estimates, however, the terminology (i.e., low, medium and high confidence) must be clearly defined to reduce individual interpretations of the probability/level of concern associated with an estimate. This requires testing the proposed terminology with different end users to ensure that their perceptions match the intended meaning.

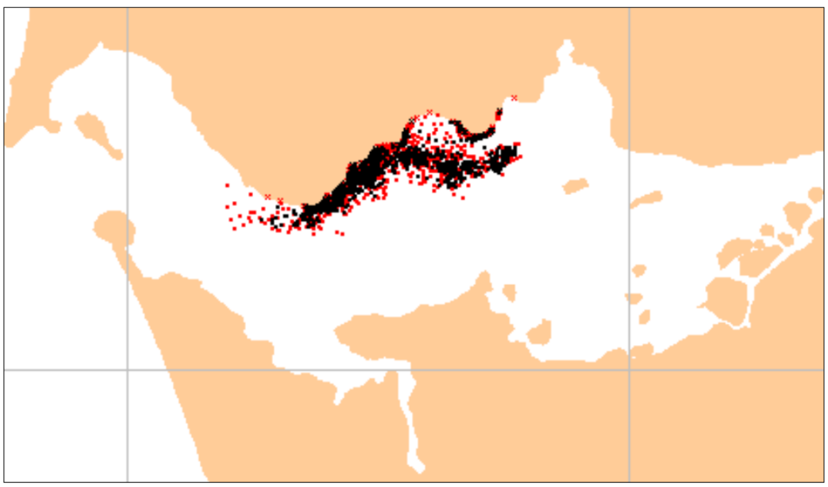

Figure 5: Showing trajectory of Lagrangian elements (black) and uncertainty particles (red) for a modeled spill. Source: GNOME User's Manual [69].

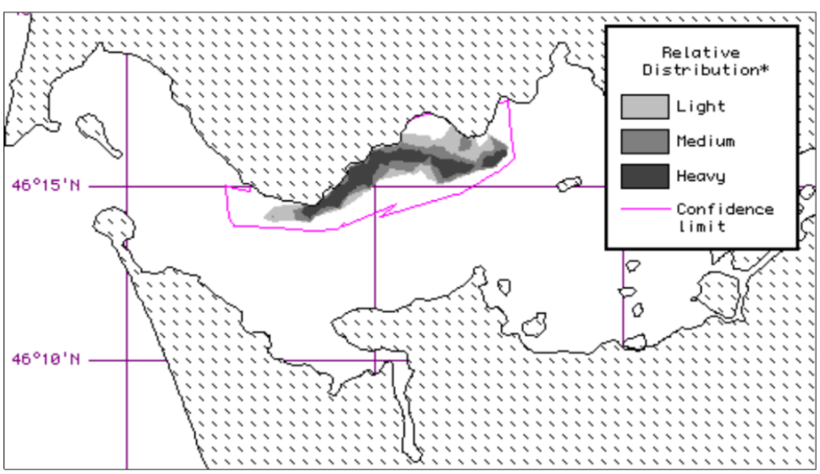

Figure 6: Showing relative distribution of oil (black/gray) and confidence limit (pink). Source: GNOME User's Manual [69].

The OR&R modelers and USCG responders in the working group created recommendations for visualization and output trajectory analysis maps. Figure 7 shows a sample trajectory analysis map from the DWH spill. Visualizations should include: (1) color coded, general, qualitative confidence levels, (2) clear confidence bounds (upper and lower range of likely values) and (3) a summary of missing/unavailable data. One challenge with this is the appearance of multiple trajectory paths on one output that make interpretation difficult. In addition, communication of high resolution information may be necessary for spills that occur near critical habitats and resources, further complicating trajectory output visualization. Modeling is a multi-dimensional space (e.g., horizontal movement on water surface, concentration, probability), so graphics are never a complete description of results. For example, predicted slick thickness is averaged over a modeled grid cell and, in reality, oil in that location may be patchy. As a result, the group concluded that verbal descriptions are necessary during emergency response to ensure the FOSC has a complete understanding of the model estimates. The working group proposed that output trajectory analysis maps should include: (1) verbal narratives to accompany the data/graphics, (2) areas of high and low oil concentration, (3) colored contours for higher and lower thickness estimates, and (4) indications of where the actionable oil is. Modelers and responders also agreed that in cases where there is not sufficient quality data to feed the model, no graphics should be produced.

Confidence Estimation of Oil Spill Model Inputs and Outputs (CEOMIO) Table

In order to address challenges related to visualization and uncertainty, it was necessary to determine how to put recommendations for visualization into practice (e.g., during a USCG-led drill or exercise) to integrate uncertainty into model outputs and a common operating picture (e.g., ERMA). Model output visualizations (e.g., for oil spill or sea ice models) must be

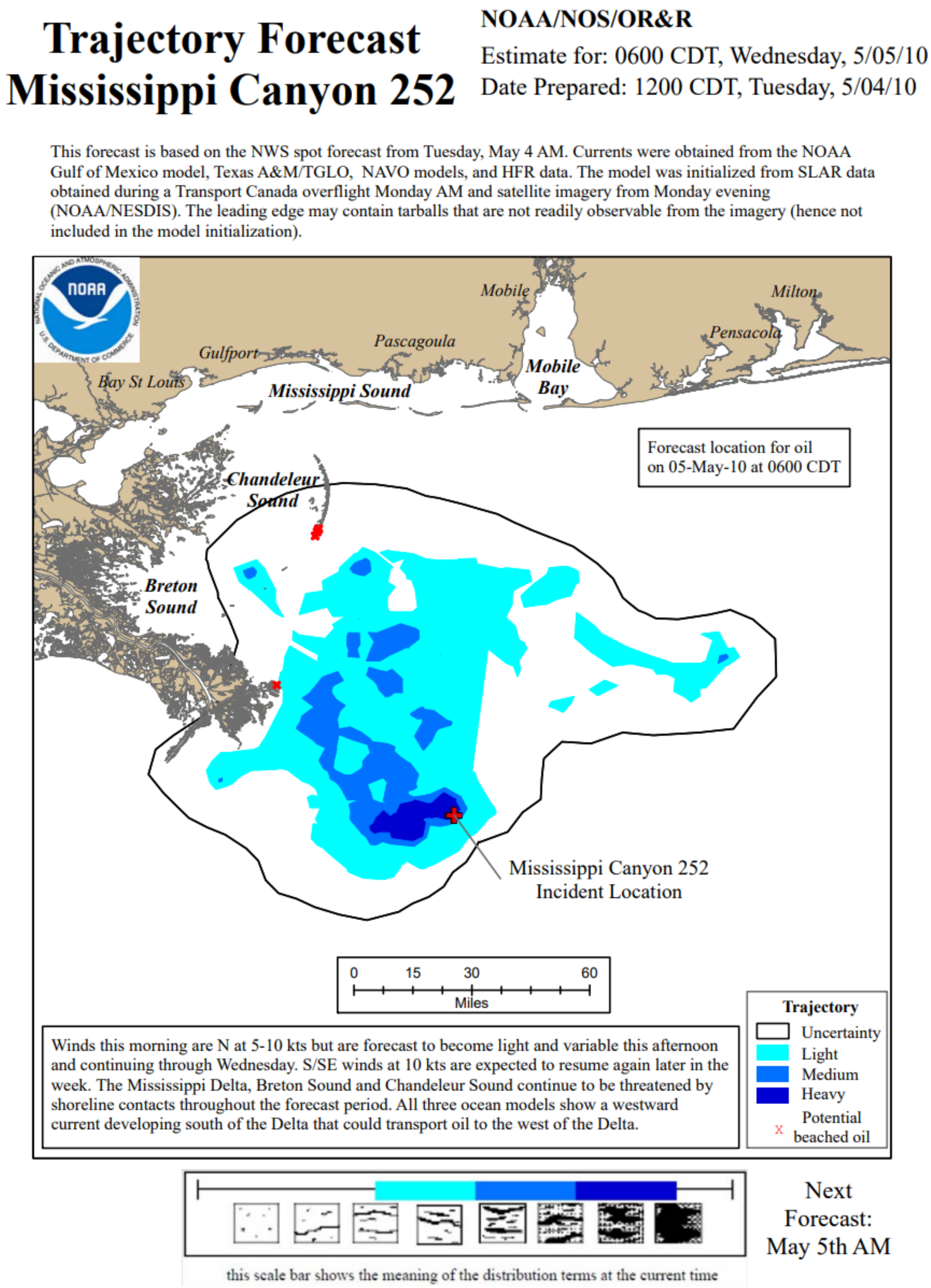

Figure 7: NOAA model trajectory analysis map from the Deepwater Horizon Oil spill. Published by NOAA, 2010 [70].

understood at the SSC/FOSC level and by the layperson (e.g., news media, public). This includes the overall results, as well as high resolution/small scale information (e.g., tables). In addition, a major challenge to improving confidence and reducing uncertainty is related to input data quality. Model output uncertainty may be caused by the lack of data or the quality of the inputs. Confidence estimation must include an explanation of data sources that contribute to uncertainty, whether due to data type, quality or availability. Modeler experience is key to improving uncertainty estimation, as they can adjust the input parameters to reflect actual conditions, provide a narrative to accompany the forecast and conduct a quality check of data. Modeler produced, qualitative confidence estimates must be well defined, clearly explained and presented to end users in order to ensure consistent interpretation.

The working group created the Confidence Estimation of Oil Model Inputs and Outputs (CEOMIO) table to address these challenges (Table 9). The CEOMIO table is a communication tool intended to help modelers and NOAA SSCs communicate the confidence associated with an oil spill model's output to the FOSC and UC. The table includes a list of model inputs and outputs and their data sources. Each input and output is assigned a relative importance (#1-5) based on the type of data source, modeler's knowledge of a specific input/output and its relevance to a particular spill scenario. These inputs and outputs are then assigned a spill-specific confidence level (i.e., high, medium, low, none, not applicable). A set of notes and instructions accompanies the CEOMIO table to provide details on how it should be completed (Table 10). While the CEOMIO table was designed for Arctic spills, it can be used in other regions [11].

The CEOMIO table was reviewed by NOAA NWS social and behavioral scientists with expertise in visualization optimization and communicating uncertainty in atmospheric/hurricane forecasts. The NWS team proposed solutions to improve readability and comprehension by end users. These suggestions included using gradient color schemes to make the table colorblind- and photocopier-friendly and referencing other types of uncertainty visualization used in modeling (e.g., NWS hurricane forecasts) to ensure color schemes are used in similar ways. They also

Table 9: Confidence Estimates of Oil Model Inputs and Outputs (CEOMIO) Example Table[4§].

Confidence Estimates of Oil Model Inputs and Outputs (Example)

	Variable	Data Source	Relative Importance	Forecast Time/Date Intervals			
				9/21/20 6:00	9/21/20 12:00	9/21/20 18:00	9/22/20 0:00
				9/21/20 12:00	9/21/20 18:00	9/22/20 0:00	9/22/20 6:00
Model Inputs	Wind	IS	5	High	High	Medium	Medium
	Oil Properties	EST	4	High	High	Medium	Medium
	Waves	MOD	4	High	Medium	Medium	Low
	Surface Currents	MOD	4	High	Medium	Low	Low
	Bathymetry	RS	4	High	High	High	High
	Water Temperature	IS	3	High	High	High	High
	Ice (kilometer-scale)	RS	2	Medium	Medium	Medium	Low
	Under Ice Roughness	EST	1	Medium	Medium	Medium	Low
	Ice (meter-scale)	ND	1	None	None	None	None
	Under Ice Currents	NA	0	Not Applicable (NA)	Not Applicable (NA)	Not Applicable (NA)	Not Applicable (NA)
Model Output	Fate			High	High	High	Medium
	Trajectory			High	Medium	Low	Low

Legend

Data Source (Model Input)		Relative Importance (Model Input)		Confidence Estimate (Model Input & Output)
IS	In Situ Observation	5	Very High	High
RS	Remote Sensing Observation	4	High	Medium
MOD	Modeled	3	Moderate	Low
EST	Estimated (no data)	2	Low	None
ND	No Data (and no estimate)	1	Very Low	Not Applicable (NA)
NA	Not Applicable	0	Not Applicable	

4 Referenced from "Responder Needs Addressed by Arctic Maritime Oil Spill Modeling" [11].

§ Example table shown was developed for potential spill of floating oil. The role of submerged oil was not considered.

Table 10: Notes and Instructions for CEOMIO Table[5].

Notes and Instructions:	
1	The purpose of this table is to provide Unified Command staff with an easy-to-digest summary of subjective modeler confidence in oil spill trajectory model data from time zero forwards, and to highlight the data needs for improving model results in future runs.
2	Model input variables included in this example table are for illustration only; final variables to be included are TBD.
3	Data source types are shown in order to provide information about where the data came from, which in turn provides clues about data accuracy, spatial extent and spatial resolution. In general, in situ data observations are the most accurate (assuming the instruments used to measure the variable are accurate) and have the highest spatial resolution, but are limited in spatial extent to the local area. Remotely sensed data are also accurate, in general, and have large spatial extents, but spatial resolution is often low (e.g., 5 km grid cells for wind data), which may result in limited utility for a spill in a coastal environment with a complex coastline. Data accuracy, spatial scale and spatial resolution are all important components of a model input variable, but to meet the goal of simplicity, these components were not individually included in this table.
4	The relative importance values for model input variables shown here are for example only. The actual relative importance of a model input variable is incident-specific (e.g., ice data not needed during ice-free season), and would be assigned by the modelers running the model. In the example table shown here, the model input variables were sorted in descending order of relative importance, so the most important input variables are shown first.
5	Forecast intervals could be delineated either arbitrarily (e.g., by logistical response operational periods, weather forecast update times) or by natural breaks (e.g., tidal ebb/flow cycles in areas with strong tidal influence), depending upon incident-specific conditions and needs. This determination should be made jointly between Unified Command and modelers.
6	A confidence estimate for a model input variable can be provided even if no data are available, if a reasonable estimate can be made (e.g., via proxy data or correlation). For example, in this table, there are no data available for three model input variables (i.e., oil properties, under ice roughness, ice at the meter scale), but reasonable estimates could be made for the oil properties (e.g., by assumptions based on a vessel type and size) and under ice roughness (e.g., via correlation with ice-age from kilometer-scale ice cover data); no data were available for ice at the meter scale, and no reasonable estimate could be made, so no confidence estimate was provided. Data on subsurface currents were considered not applicable in this example.
7	The confidence estimates for the Model Output are the modeler's best subjective opinion on the quality of the model output, which is based upon the quality of the model itself and the quality of the input data. The model output was separated into Fate and Trajectory because these different outputs often have different levels of confidence associated with them.

5 *Referenced from "Responder Needs Addressed by Arctic Maritime Oil Spill Modeling"* [11].

emphasized that the reader's eye will likely be drawn to the darkest and most vivid color (which should be associated with the highest confidence parameters) [11].

The left side of the table lists model input (e.g., oil properties, surface currents) and output (i.e., fate and trajectory) variables. The uncertainty contributed by the data source of each input variable is defined. A relative importance is assigned by the modelers on an incident-specific basis (e.g., sea ice data not needed during ice-free conditions) based on the data value, source and influence on the oil's trajectory and fate. Acronyms for each data source and a verbal description of relative importance are defined in the key. The next four columns show the forecast time/date intervals and explain the time period for which the confidence estimate is applicable (e.g., first 6 hours of modeled spill). Finally, each variable and time interval is assigned a confidence level based on the type, quality and associated confidence of the input data source, estimated quality of the resulting model output data and modeler's expertise.

The color coded confidence levels provide the FOSC and UC with an organized, easy to read summary of the modeler's confidence in the spill trajectory and fate output over a certain time period. They also highlight unavailable data and quality issues that need to be addressed to improve model results. Communicating the confidence in this way identifies sources of uncertainty and obstacles to improving confidence (i.e., no data available for input variable).

The CEOMIO table was discussed during the November 2020 AMSM Virtual Workshop and Stakeholder Working Sessions. Much like the Visualization and Uncertainty Working Group, the workshop participants concluded that a qualitative confidence level is sufficient for most Arctic oil spill response decision-making. During the session, USCG and NOAA representatives also provided perspectives on how to identify the qualitative confidence level for each input, as well as how to introduce the table to the response community (e.g., Alaska

Regional Response Team (RRT) presentation, part of a planned exercise). Further discussions are required to determine methods for improving consistency of estimations over a spill time frame (e.g., using example tables with associated data, clearly describing each confidence level).

Verbal descriptions should accompany CEOMIO tables because they may not capture all of the information FOSCs need for response decision-making and, currently, lack a formal, repeatable structure to be used between spills. The implications of uncertainty for a particular spill should be well defined to improve understanding of associated risks. Supplementing existing outputs with the CEOMIO table may increase end user comprehension and retention of the factors and data influencing model output confidence. In addition, the CEOMIO table highlights data gaps that could be addressed during spill response operations, by reconnaissance technologies or with future model developments [11].

Working groups and workshop participants suggested that more refinement from potential end users is needed before the CEOMIO can be put into practice. Following the conclusion of AMSM, CRRC and OR&R plan to further develop the CEOMIO table using a similar partnership to that used to refine ERMA [11]. They will convene a working group of oil spill modelers and SSCs to produce draft CEOMIO tables based on existing model output data from prior incidents. This process will determine how easily the tables can be created and inputs/outputs can be ranked. The working group will also identify areas of concern or aspects of the table that require further development (e.g., methods for improving consistency between modeling groups and end user comprehension, considerations for submerged oil).

Once the working group has approved the table, it will be vetted by other responders and FOSCs. Full review is essential to vet the CEOMIO table for use during an oil spill exercise or active spill event. Successful integration into response requires collaboration between oil spill modelers (government and industry) and sea ice models/observation systems. This collaboration must be completed in advance to identify data types, formats and data communication methods. As part of this final review, CEOMIO would be presented to the Alaska RRT and other relevant groups (e.g., Alaska Oil Spill Response Organizations (OSROs), Arctic and Western Alaska Area Committees) [11]. The cumulative feedback should result in a CEOMIO table that can be produced without adding excess strain and workload to modelers and responders during response. In this way, the CEOMIO table will improve the quality of communication between modelers, SSCs and responders/FOSCs. Once the table has been fully vetted, the AMSM team will conduct a webinar including modelers and responders to socialize the new tool prior to integration into an Arctic oil an Arctic oil spill tabletop exercise.

3.6 Collection of Environmental Data

Validation is necessary to ensure that improvements to oil spill models (e.g., adjustments to algorithms) are accurate. In many spills, trajectory estimates are validated using aerial observations from overflights above the spill. The observations can be compared to the model's results and parameters can be adjusted to match field conditions (i.e., re initializing the model). In the Arctic, overflight data may be challenging or impossible to collect due to limited resources, darkness or storms. As a result, other methods (e.g., unmanned aerial vehicles) may be used to support validation of outputs from data collected prior to a spill. There are very few real-world datasets from actual spills or other sources (e.g., SINTEF MIZ release experiments) that are suitable for this purpose. Datasets are also useful to ensure oil and sea ice model algorithms are accurate and operational through validation with standardized, generic scenarios and associated real-world data. They also allow for model intercomparison studies which highlight unique features and Arctic capabilities of each model. Scenario-specific datasets used for algorithm development and validation should be publicly available to improve collaboration between modelers.

In addition to validation, quality data collection in the Arctic can improve existing models by providing inputs that more accurately describe environmental conditions during an emergency. The AMSM Oil and Ice Interactions working groups identified sea ice-related data gaps and the Visualization and Uncertainty working group emphasized the need for data with high confidence (e.g., from direct observations). Data-related model improvements are hindered by the difficulty of data collection in remote Arctic locations, but fully leveraging new and existing technologies will allow these needs and gaps to be addressed. The New and Existing Technologies for Observing Ice and Informing Models working group was developed to identify available, Arctic-capable technologies, as well as new technologies and features that are needed to advance Arctic oil spill modeling and response (Table 11).

Table 11: New and Existing Technologies for Observing Ice and Informing Models - Objectives/Questions

1. Operationalizing technologies: what capabilities exist/should be used to make recommendations?	a. Include Alaska Ocean Observing System (AOOS) to determine what data is already being collected (e.g., HF Radar data) that might be useful.
	b. What new technologies might be available (e.g., induced polarization, satellite remote sensing, LRAUV – US and Canadian)?
	c. How long does it take to deploy certain sensors (e.g., buoys)?
	d. Summarize information on what technologies/sensors are available, how accessible are they, network between resources within sea ice modeling and oil spill modeling (e.g., suitable formats to ensure compatibility).
	e. How would the group take what was learned and incorporate it into the other working groups? When/how should this be done?

Components of the New and Existing Technologies Spreadsheet

The working group compiled a spreadsheet of new and existing technologies available for monitoring oil and ice in the Arctic (Appendix O). The spreadsheet includes answers to key questions (Table 12) and is organized into five sections by type: (1) satellite, (2) airborne, (3) on ice surface and subsurface, (4) under ice and open water surface, and (5) seafloor mounted.

Table 12: Questions for New and Existing Technologies Spreadsheet.

- Contact/manufacturer/developer
- Overview of technology
- Sensor type/description
- Operating conditions
- Spatial and temporal resolution
- Time required for taking measurements
- Applications (e.g., emergency response, damage assessment)
- Oil type and condition
- Availability and needs for deployment
- Time for mobilization
- Permit requirements
- Raw and final data formats
- Time required for data processing
- Strengths and weaknesses
- Validation studies

<u>Satellites</u>

Satellite remote sensing data for Arctic sea ice is reported by the NIC and ASIP. Satellites are employed for monitoring oil spills and supporting response efforts in the Continental U.S. Despite satellite applications for oil spills and sea ice, few studies have focused on remote sensing of oil spilled in sea ice. Preliminary studies have explored applications of optical and active microwave sensors. Optical sensors are limited by clouds and extended periods of darkness in the Arctic region. Active microwave sensors (i.e., SAR) are preferred because of their ability to collect data regardless of clouds or darkness. SAR can map objects down to a few meters and can target specific areas (e.g., individual floes, oil slicks) [16]. The SAR sensors, discussed in the working group, provide footprints from 2 to 500 km with resolutions ranging from ~0.5 to 50 m (compared to the optical sensors which had footprints from 10's to 1000's of km and resolution from ~0.5 to 375 m). Depending on the number of SAR satellites in orbit, it may be possible to collect multiple images during a single 24-hour period. Longer spills will allow for the collection of more images for a specific area due to a higher number of satellite revisit periods. SAR imagery detects oil on water when there is enough wave action to identify areas where activity as dampened by the slick compared to open water [71]. Detection of oil in sea ice is challenged by factors which dampen waves (i.e., formation of new ice, low speed winds) and produce the same SAR signature as floating oil [16]. SAR is most applicable for detection of large slicks when there is < 30% ice cover [71].

Airborne

Airborne remote sensing platforms (e.g., unmanned aerial systems (UAS), fixed wing aircraft) are capable of collecting data on oil and sea ice during overflights of the spill area. Airborne platforms are capable of carrying many of the same sensor packages as satellites (e.g., SAR, infra-red cameras), but can collect data at a much higher resolution (centimeters to meters) by flying closer to the Earth's surface. They achieve this higher resolution at the cost of lower coverage area for a single overflight, making them less applicable for locating surface oil that is spread over a wide area [72]. Airborne systems are available in many sizes and have limited payload capacity which restricts the types and number of sensors and batteries/fuel they can carry and how long they can carry them [73].

Sensors are only as valuable as the expertise of the pilot/operator in control of the platform. Operation of UAS requires special training and permitting from the Federal Aviation Administration (FAA), especially for operating at night or beyond visual line of sight [74]. Certified operators are limited, especially in the Arctic, and time to deploy aircraft may be 24 hours or more depending on requirements (e.g., personnel, runway availability), range and flight time [16]. First responders and government agencies may be eligible for expedited permit approvals in emergency situations (~24 hours), but applications must be submitted by certified pilots or those with an existing Certificates of Waiver or Authorization (COA) [75, 76]. ADAC has recently funded a project ("Remote Unmanned Aircraft System (UAS) Inspection and Response Team Development in the Bearing Strait Region") which will train eight UAS pilots in the Native Village of Unalakleet, AK to assist with emergency response data collection needs [49]. These operators will be trained under the FAA Part 107 Rule (line of sight operation, < 55 pounds, < 100 MPH, < 400 feet elevation) [49]. Having trained pilots and UAS staged in the Bering Strait region will support community and USCG maintenance inspection and emergency response [48]. Preplacement of personnel and equipment in these remote areas is essential to improving information flow during USCG-led emergency response.

The applicability of airborne systems operating in the Arctic is dependent on their flight time, payload capacity, modifications for freezing temperatures, and environmental conditions. For example, small UAVs with limited range must be deployed near the spill from vessels, landfast ice or the shoreline, reducing their applicability for offshore spills in locations inaccessible by vessels. Large AUVs with longer flight times are more applicable, but may also be more expensive and less available. Temperature controlled/heated hulls are necessary for many Arctic operations to reduce icing of equipment and sensors. Strong winds and reduced visibility (e.g., fog, snow) may prevent data collection entirely. Applicability of sensors is also a concern as many are optimized for detection of oil on water. Snow events and encapsulation can obscure oil, preventing detection by sensors which rely on reflected energy that does not penetrate the ice/snow surface (e.g., optical). Some technologies have sensors that can remotely "penetrate" ice, such as the laser fluorosensor which uses UV light to measure spectral emissions up to 6 cm within ice. Airborne ground penetrating radar (deployed via helicopter using a sling) is still in development, but may be applicable for detection of oil under snow and ice at a depth of > 9m in ideal conditions [77].

<u>On Ice Surface and Subsurface</u>

On ice surface and subsurface technologies are deployed by vessels or by operators on ice (e.g., snow machine, on foot). Surface vessels can carry a range of sensors (e.g., radar) to detect features and identify oil on the water or ice surface. Many shipboard radar systems (e.g., Norwegian Clean Seas Association for Operating Companies (NOFO) ship-based radar system) have been used for detection of oil on open water, but their applicability for oil spills in ice-covered waters is poorly studied [16]. Vessel mounted 3D laser scanners can be used to measure the rate of sea ice ridging over time. Ridges are formed when wind and currents push sea ice into piles above the sea surface and the part of the ridge below the surface (i.e., keel) [1]. Oil on the underside of ice is likely to be trapped by large keels. In addition to vessel mounted technologies, specially trained oil detecting dogs have been used to detect small spills and determine dimensions of larger spills up to 5 km upwind [16]. Vessel-based systems are challenging to operate during freeze up and are not applicable where ice is too packed to allow navigation.

Technologies deployed by operators on ice are limited in their area coverage, making data collection over a large area challenging and time consuming. In addition, they can only be deployed when conditions are safe (e.g., temperature, ice thickness) for personnel on the ice [16]. Oil detecting dogs are also applicable on ice and were included in the Oil-in-Ice JIP project in 2009. The dogs and their trainers were able to detect and identify weathered crude and bunker fuels up to 5 km away in low temperatures and strong winds, even after several days of transport by scooter sledges to the testing area [78]. In cases where the spill has been located or its approximate location is known, operators may also use ice augers to determine ice thickness, water depth below the ice and oil presence/absence and properties (e.g., weathering) [79]. Acoustic profilers can be used if placed in holes in ice to measure small scale information on under ice currents and oceanographic data (e.g., temperature, dissolved organic matter). Ground penetrating radar has also been tested on ice and has detected oil under the ice surface and snow. Its performance and depth of penetration into the ice depends on electrical conductivity of the medium which is influenced by ice thickness, temperature and distribution of brine. Ground penetrating radar is less applicable for warm, young year ice with a higher amount of brine pockets and increased electrical conductivity [16].

Under Ice and Open Water Surface

Underwater vehicles (e.g., remotely operated vehicles (ROV), autonomous underwater vehicles (AUV)) carry a variety of sensors capable of collecting data on under ice topography, oil under ice and oceanographic conditions (e.g., temperature). Despite their use in polar regions, underwater vehicles have not been extensively used for oil spill detection as the focus been on locating oil in open water [16]. Methods for detecting the extent and volume of oil spilled under ice are crucial components of Arctic maritime response [60]. ROVs are tethered to an operator by a series of cables that transmit command and control signals [80]. Small ROVs can be operated from ice or nearshore, but larger ROVs require infrastructure from a vessel to deploy and retrieve them [16]. ROVs have been widely used in the oil and gas industry. Remote operation allows operators to maneuver the vehicle in confined spaces, such as under fast ice in shallow water. The cost of this precise operation is reduced range (especially in complex environments) and more complex logistics with personnel and deployment near/in the spill area [60].

Unlike ROVs, AUVs operate independently of a vessel and do not require tethers or connecting cables [80]. The lack of tether means they are capable of covering large areas (several to hundreds of km) if they have the power supply. Deployment and recovery are also easier. AUV operation under sea ice requires long range acoustic communication to determine vehicle location and status and for data real-time data collection [60].

ROVs and AUVs often carry a range of sensors capable of detecting oil under ice and in the water column. Three common ones include sonar, laser fluorometers and cameras. Sonars transmit acoustic pulses and detect the echoes from the intended target (e.g., the underside of ice, encapsulated oil). The oil/ice interface has a different reflection than the water/ice interface [81]. Fluorometers used under ice are similar to those on airborne platforms and operate using an ultraviolet light source to detect oil which exhibits broad-spectrum fluorescence. Laser fluorometers for AUVs and ROVs can be more compact because they usually operate closer to the ice than airborne platforms [60]. Cameras are widely used on ROVs and AUVs and are relatively easy to use. Images are also easier to interpret. However, cameras are less applicable when conditions are dark or turbidity is high and cannot readily measure encapsulated oil [60].

ROVs/AUVs may also carry samplers, mass spectrometers and CTD instrument packages (i.e., measure conductivity, temperature, water depth).

Currently, an ADAC funded project is focused on development of a Long Range Autonomous Underwater Vehicle (LRAUV) for under ice mapping of oil spills and environmental hazards. LRAUV is helicopter portable and designed for rapid response, while providing situational awareness for USCG responders. It has a 15-day battery life with 6 kWh rechargeable batteries. This can be extended more than twice with non-rechargeable batteries. LRAUV carries a range of sensors measuring CTD, dissolved oxygen, fluorescence/backscatter and hydrocarbons. It can also support an Acoustic Doppler Current Profiler (ADCP), and camera. LRAUV is the only propeller-driven AUV in the world capable of drifting, hovering and accurately navigating to determine the exact location of an anomaly. It has been tested at the Santa Barbara Oil Seeps in 2019 and under ice in New England's Buzzard's Bay and Bog Lake in 2020. Testing under ice in the Great Lakes and Barrow, AK have been postponed due to the Coronavirus Pandemic [82].

Another ongoing ADAC project is evaluating Marine Induced Polarization (IP) in the Arctic environment, especially within and under broken ice fields. The marine IP system is towed behind a vessel and uses transmit electrodes to produce an electrical currents and a receiver electrode to measure changes in a return signal based on substances (e.g., oil) encountered. Tests performed at the Cold Regions Research and Engineering Laboratory (CRREL) (Hanover, NH) in 2020 determined the system should be more compact, resistant to cold temperatures and more robust for transport (e.g., vibration, jarring) [83].

While underwater vehicles became the focus of discussions on under ice and open water surface technologies, the working group also considered applications of open water surface technologies such as sorbent pads/dip plates, tube samplers and capacitance thickness sensors (under development) which are used at the water surface to detect oil and/or measure thickness. These technologies face many of the same limitations as on ice and vessel based sensors as they must be deployed by personnel at or near the location of the spill.

Seafloor Mounted

Oil may sink due to its initial density, weathering or environmental conditions (e.g., adhesion to marine snow). Sunken oil (i.e., oil that is on the bottom) sampling is difficult and time consuming, especially in deeper waters. Species that live and feed in the benthic zone of the Arctic Ocean (e.g., fish, shellfish, marine mammals) are at risk of negative impacts from sunken oil [84]. As a result, the working group also considered seafloor sampling technologies that may be applicable to the Arctic.

Three technologies were included in discussions: seafloor mounted acoustic systems, solid collection traps and cameras for observing particle settling. All focus on collection, measurement and observation of oil as droplets or associated with particles (e.g., marine snow) and in-situ burning residuals. These are most useful in areas away from the shoreline, where there is appropriate space under ice and beneath the water surface to allow for their deployment. Their deployment is based on several factors: suspected presence of sunken oil/in-situ burn residuals, accessibility to desired deployment area (e.g., vessel, on ice) and water depth.

It is important to note that oil pipelines in the Arctic Ocean may use seafloor and pipeline mounted technologies to monitor oceanographic conditions (e.g., current density, temperature), and detect leaks or assess structural health [85, 86]. Pipeline leak detection methods can be external or internal and include software-based (e.g., monitoring of pressure, temperature and flow rate of oil in pipelines) and hardware-based (e.g., sensors to detect leak occurrence) methods. External leak detection systems for subsea pipelines may include hydrocarbon vapor sensing systems and fiber optic cable systems (i.e., for temperature, acoustic, or strain sensing). Internal systems determine the mass balance of material and pressure trends [87]. While pipeline based technologies do not measure oil in the water column or on the seafloor, they are important for estimation of the source and quantity of spilled oil during a leak or blowout.

Potential Arctic Spill Scenarios

The technologies spreadsheet was used by the working group to determine the applicability of specific technologies for two USCG-relevant Arctic spill scenarios. These scenarios, identified by the working group and Project Core Team, were selected due to the range of challenges they include and the likelihood of their occurrence. A summary of the technologies applicable to each scenario provides guidance and recommendations for an active spill, tabletop exercise or drill and identifies current gaps in technology availability and capability to direct future research needs and developments. Sensors are only valuable if their platform is satisfactory (i.e., capable of carrying them to the sampling location) and the operator and analyst are skilled at collecting and interpreting their data in response time frames.

<u>Scenario A: Large Vessel Spill of Combinations of Oil in the Shoulder Season (During Fall as Sea Ice is Developing)</u>

This scenario was chosen because it was identified as the most likely to occur in the U.S. Arctic, with a special focus on the Bering Strait within the U.S. and Russia transboundary region. The hypothetical spill was described as occurring during the fall shoulder season where freeze up usually takes 20-30 days and results in a range of sea ice types and conditions. The vessel spilled a combination of heavy fuel oil (HFO) (~175,000 gallons) and diesel (~50,000 gallons). Modeling and response in these dynamic conditions will be more challenging than in open water, and technologies to observe ice and oil will be essential to improving model performance, validating estimates of oil trajectory and providing the information needed for FOSC decision-making (e.g., deployment of personnel, allocation of resources).

Ice formation occurs when ocean water begins to freeze into small crystals (frazil ice). These crystals float to the surface and begin to accumulate into sheets of sea ice. In calm conditions, frazil will form into thin layers (grease ice) which then develop into a thin sheet (nilas). These sheets are pushed together by a process called rafting which results in thicker, more stable sheets (congelation ice) with a smooth bottom surface. The congelation ice continues to develop and thicken vertically at a rate slower than frazil ice. In rough conditions, frazil ice forms circular disks (pancakes) of ice with raised edges. Wave motion causes rafting and ridging as ice fractures and joins, forming ridges on the surface and keels underneath and creating a sheet of ice with a rough bottom surface [35]. Conditions during the spill will determine ice roughness as development occurs.

Satellites are useful for detection of spills when there is < 30% ice cover. They can provide information on ice conditions and changes when ice cover is > 30%. During the fall shoulder season, ice will be changing significantly. Therefore, satellite monitoring is useful for identification of the transition from ice to open water, location of large ridges and movement of large masses. The Beaufort Sea, off the northern coast of Alaska, gets no sunlight from November to January, so spill response in the fall will likely occur in darkness. Satellites with optical sensors that collect wavelengths of visible light will be less useful than SAR which is able to collect imagery despite darkness and clouds. The same applies to airborne optical sensors. Depending on the distance from shore and accessibility by vessels, small, short range airborne remote sensing platforms may be unable to deploy close enough to collect data on spill conditions. Longer range airborne platforms may be more applicable, but are limited by availability in remote areas, restricted FAA permitting (e.g., beyond visual line of sight, nighttime operation) and availability of certified operators. Airborne systems can provide higher resolution data than satellites over a smaller coverage area using many of the same sensor types (e.g., SAR, optical). They are useful for providing detailed data on oil and ice surface conditions and features.

During freeze up, the likelihood of oil encapsulation is high. Sea ice extent usually reaches its minimum in September and sea ice grows throughout the Arctic cold season until it reaches its maximum extent in March [88]. Oil encapsulation is a relatively slow process that will likely not be a priority in the first 24-48 hours after a spill. Sensors capable of penetrating into ice and snow will be useful for locating and tracking encapsulated oil to determine where it may be released during the melt season. It is unlikely that on ice surface technologies will be deployed for identifying encapsulated oil due to the changing conditions. Ground penetrating radar, deployed by helicopter, is a potential solution based on flight time/range. AUVs and ROVs equipped with sonar or fluorometers may also be able to locate encapsulated oil. These platforms can also provide information on under ice roughness and oil pooling under ice, but are limited by deployment needs and travel distances (i.e., battery capacity for AUVs, tether length for ROVs, operator safety). Seafloor mounted sampling devices may be useful for detection of in-situ burn residuals and sunken oil. In-situ burning has the potential to remove oil in pack ice where oil spreading is limited, but will also produce burn residuals and deposit soot onto ice [89, 90]. Seafloor mounted technologies will likely not be the first deployed as the initial focus will be on spill detection and recovery and they are less applicable in deeper waters where recovery of devices may be difficult. Vessel based systems (e.g., 3D laser scanners) can provide information on ice ridging and keels where oil may become trapped under ice, but many of the systems are challenging to operate during freeze up and are not applicable where ice is too packed to allow for navigation.

Scenario B: Pipeline Spill Under Landfast Sea Ice

Pipeline spills may originate from ruptures or slow pinhole leaks, both resulting in the release of crude oil. The type, location and amount of oil spilled from a pipeline are important for coordinating data collection, modeling and response efforts. There are several offshore pipelines in the U.S. Arctic that could be used as an example for this release scenario. Four artificial (manmade) islands are located off the northern coast of Alaska for offshore oil and gas development, with a fifth in development. Three of these islands, Oooguruk, Nikaitchuq and Endicott Islands are located in relatively shallow waters (~ 4 – 8 feet). Northstar and Liberty Islands (completion date to be determined) are located in deeper waters (~40 feet and 19 feet, respectively). Northstar, Nikaitchuq, Oooguruk, and Liberty Islands use subsea pipelines to transport oil produced 3.8 miles to 6 miles to onshore processing facilities. The Endicott pipeline is not subsea and instead is elevated along the Endicott Causeway [91, 92]. The Northstar Island transports oil and gas to the Sea Island processing facility using two 10-inch trenched (buried) pipelines designed to withstand gouging by sea ice along the seafloor and permafrost thaw conditions [93].

Landfast ice usually grows in the fall and melts away in the summer. It forms off the coast in shallow water. The extent of landfast ice varies based on bathymetry and topography (~50 meters off coast of Beaufort Sea) and the thickness is usually 1 to 2 meters [57]. The presence of landfast sea ice in this scenario means that sea ice cover will likely be > 80%. The lack of open water makes many airborne and satellite technologies less applicable, but they can provide information on ice conditions (e.g., ice edge) and surface oil location and validate model predictions.

The Arctic Ocean is the shallowest of the five major oceans with an average depth of ~ 3,953 feet but the pipelines are usually close to shore where depths are much shallower (i.e., ≤ 6 miles long). The presence of landfast sea ice in shallow water makes the use of under ice and seafloor monitoring technologies very difficult due to the limited space under the ice for navigation and deployment. For example, small, tethered ROVs are more useful than large, untethered AUVs under landfast ice due to their more precise operation, lack of major deployment infrastructure (e.g., crane) and ability to fit into smaller spaces. Due to the lack of open water in this scenario, oil will likely be trapped in void spaces under ice. Data on how oil moves under ice (e.g., stripping velocity, storage capacity) is limited, so deployment of under ice technologies will be essential to informing models.

In-situ burning is less applicable in the presence of landfast ice unless oil is already on the surface of the ice (e.g., oil pools, mixed with snow) [89]. As a result, the use of seafloor mounted sampling technologies is unlikely. Vessels are not applicable in the presence of landfast ice, but on ice technologies (e.g., ground penetrating radar, oil detecting dogs, acoustic profilers) could be useful in areas where ice is thick enough to support personnel, vehicles and equipment. These technologies could provide high resolution data on ice characteristics (e.g., thickness), identify encapsulated oil and locate nearby oil that has migrated to the surface.

Technology Needs and Integration

In order to advance Arctic maritime oil spill response, improve model validation and develop algorithms and submodels (e.g., for surface spreading, encapsulation, stripping velocity), more robust environmental data and monitoring of spill conditions are needed. Current technologies can address many of the potential data needs during a spill, but many are limited by the distance from shore (i.e., under ice, airborne) or high sea ice concentrations (i.e., satellites).

Virtual Workshop and Stakeholder Working Session attendees proposed investigation of available, “off-the-shelf” GPS drift buoys deployed to track oil and/or sea ice movement. The International Arctic Buoy Program (IABP), managed by the US NIC and Polar Science Center at UW, has a network of drifting buoys which provide meteorological and oceanographic data. Approximately 25 buoys are in service at any time and data products are provided every 12 hours to describe pressure, temperature, position, and ice velocity grids. Data is available from the National Snow and Ice Data Center (NSIDC) (https://nsidc.org/data/g00791) or on the IABP website (https://iabp.apl.uw.edu/data.html) from 1979 through the present [94]. Itkin et al. (2017) and Lei et al. (2020), monitored sea ice motion and deformation using drifting buoys deployed in an array on first- and second-year ice [95, 96]. Open water oil spill response operations often involve drift buoys to track assets or floating oil, which may be deployed from aircraft or in arrays to provide data on currents over a large area via satellite communications [97]. Attendees also suggested that in the event of an Arctic spill, buoys may be placed onto sea ice near the spill to track movement of encapsulated oil. This is especially important for first year sea ice suspected to contain encapsulated oil to track potential locations where oil may be released during melting. Participants suggested developing a process (including contacts and a list of available resources) to organize the deployment of sampling buoys in the event of an emergency spill to maximize data collection and the ease of deployment.

3.7 Path Forward

AMSM Year 8

This report details the findings from the AMSM project in Program Years 5-7 (2018-2021). Recently, the AMSM project was granted supplementary funding to continue into Year 8 (2021-2022). The Year 8 work will: (1) determine the exact sea ice model/observational data feeds that are needed by the U.S. Arctic oil spill models; (2) create, implement and test the computer code necessary to ensure that those data can be ingested directly by the oil models during a spill in a timely and accurate manner and (3) conduct a small tabletop exercise to validate that the linkages will lead to improved Arctic spill model trajectories that will enhance FOSC decision-making.

In Year 8, the Project PI will work with the Project Champion and the Core Team to establish a working group comprised of U.S. and Canadian Arctic oil spill modelers (e.g.., NOAA OR&R GNOME modelers, RPS OILMAP/SIMAP modelers, ECCC COSMoS modelers) and sea ice forecaster/modelers (e.g., ASIP, USNIC, HIOMAS, U.S. Naval Research Laboratory (CICE), neXtSIM). The specific goals of the working group will be:

1. Determine the exact sea ice data/parameters needed for the oil spill models (e.g., % ice coverage/concentration, sea ice velocity and direction), and the types of temporal and spatial scales that can be accommodated (Figure 8).
2. Determine the data feeds and sources that can provide the necessary inputs to the oil spill models.
3. Ensure the sea ice model/observational system parameters, outputs and data are all accessible and available on short notice (i.e., first 24 hours) when a spill occurs.

4. Create and validate the computer code necessary to get the sea ice data feed inputs into GNOME in the correct format efficiently.
5. Test and debug the code, as needed.
6. Conduct a small tabletop exercise with an Arctic oil spill scenario that includes: sea ice data providers, NOAA SSCs, USCG FOSCs and GNOME modelers and practices the notification of the sea ice data providers, transfer of information into GNOME and presentation of the oil trajectory.
    a. The scenario and planning for the tabletop will be coordinated with the Alaska RRT, USCG D17 and NOAA OR&R, along with the AMSM Core Team.
7. Write a Lessons Learned/Path Forward report as a follow-up to the tabletop exercise.
8. Include the Year 8 activities in an addendum to the AMSM Knowledge Product published in Year 7. Publish a peer-reviewed journal article on the Year 8 activities.

Project Year 8 will include discussion of oil spill model inputs and outputs to determine the exact sea ice data and parameterizations needed to inform oil and ice algorithms and the spatial and temporal scales at which data is needed. While other major U.S. and Canadian models will be considered, the focus will be on improvements to GNOME. Preliminary discussions have identified the basic input/output structure of GNOME (Figure 8). Inputs include ice data (from models or observations), hydrodynamics (from models) and oil information (from the ADIOS oil library). Ice data and hydrodynamics may originate from independent models or coupled ice-ocean-atmosphere models. GNOME uses these inputs to simulate particle data (e.g., location, mass, composition) in the form of netCDF and shapefiles.

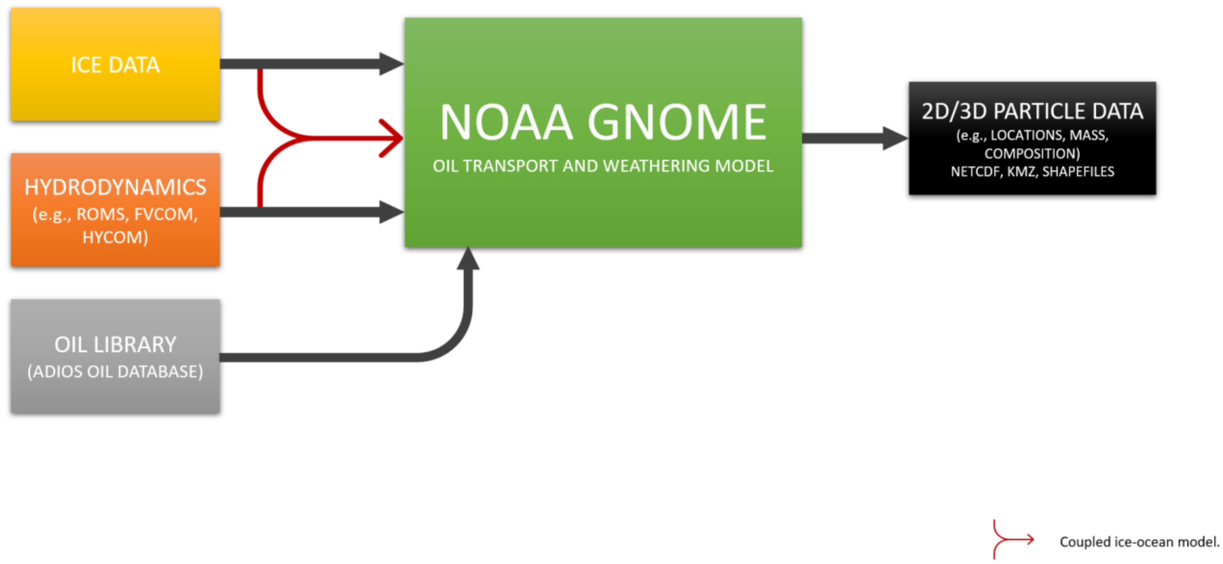

Figure 8: GNOME model inputs and outputs in relation to hydrodynamic models and ice data.

Year 8 will primarily focus on inputs from ice models/observations and hydrodynamic models (Figure 9).

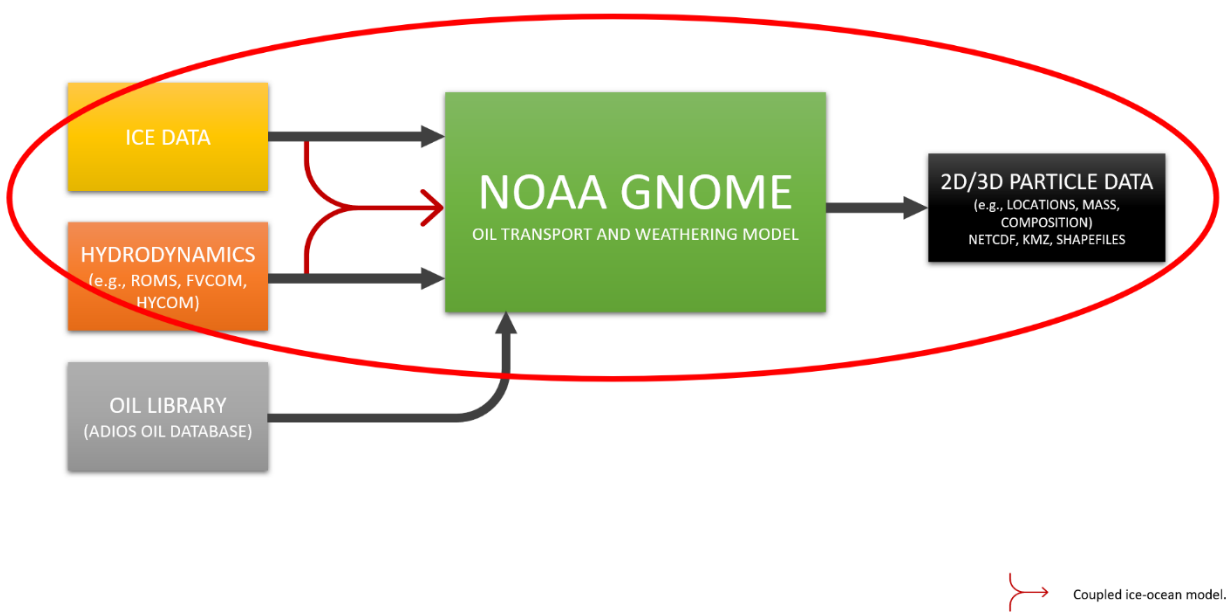

Figure 9: GNOME inputs and outputs that will be the focus of Year 8 AMSM efforts.

GNOME ice inputs are sourced from coupled ice-ocean numerical models (e.g., HYCOM+CICE, HIOMAS). Figure 10 highlights the interactions between environmental observations, NWS operational products and numerical models. Environmental observations of ice and hydrodynamics are used for numerical modeling and to produce NWS operational products (e.g., maps). Numerical model outputs (e.g., from GOFS) are also incorporated into NWS operational forecast products as observations cannot predict future conditions. While GNOME can directly ingest numerical model outputs (e.g., from HIOMAS, HYCOM), it cannot directly ingest outputs from operational products to initialize models. Further discussions between ice observing system, scientists and oil spill modelers are needed to determine what input types can be provided (e.g., ice movement vectors) to improve modeling of oil-in-ice in GNOME and other major U.S. and Canadian models (e.g., RPS OILMAP, ECCC COSMoS).

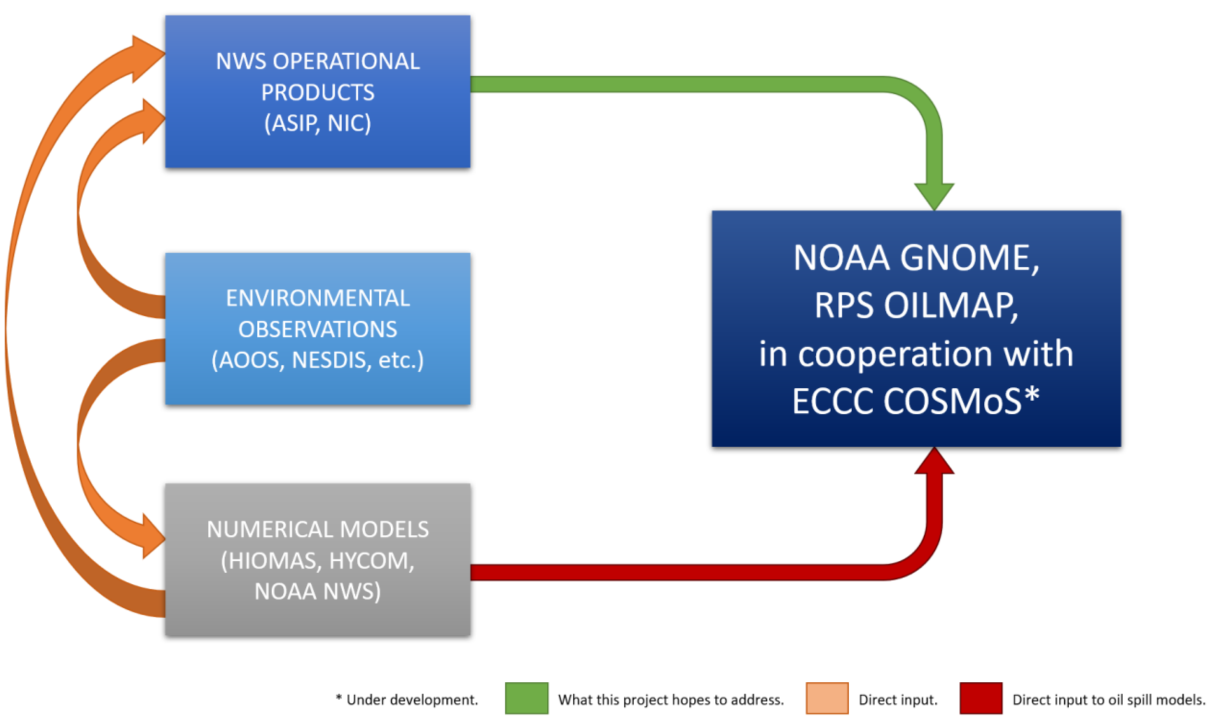

Figure 10: Oil spill model inputs and outputs and their relationship to hydrodynamic and sea ice numerical models and operational products and observations.

4. CONCLUSIONS AND FUTURE RESEARCH

The AMSM Project provided a structured approach to gather expert advice to develop models that address USCG FOSC core needs during Arctic spill response. The unique approach used by CRRC for the AMSM project allowed for involvement from a wide audience of responders, modelers and agencies who supplied a range of expert perspectives on modeling, response, technologies, and uncertainty. The resulting dialog produced findings that are relevant and useful to oil spill response in the Arctic. Collaboration between the Project Core Team, key stakeholders from USCG and NOAA and industry and international experts identified: USCG FOSC core needs during Arctic spill response (e.g., visualization, uncertainty); the current state-of-the-art Arctic maritime oil spill response and sea ice models; new and existing technologies for observing oil and sea ice; potential integration of oil and sea ice models; and gaps in current models to be addressed by future research.

Despite the success of the AMSM project, the involvement of a diverse group of stakeholders across a variety of disciplines posed several challenges. The first challenge encountered was related to communication, especially when discussing terms that may have multiple meanings depending on the end user (e.g., confidence level). This was resolved by relating terms to the needs of the USCG FOSC and what the modelers can produce to determine project-relevant definitions (e.g., qualitative confidence level of high/medium/low). Inclusion of experts from the U.S., Canada, Norway, Denmark, and Russia also resulted in scheduling challenges. Meeting conflicts and absences were mitigated through careful planning and collection of detailed minutes (or meeting recordings) which were shared with group members. Despite these challenges, the AMSM project was successful in engaging experts from public and private industry by demonstrating the value of collaboration and the potential for new, publicly available developments, resources and communication techniques to improve the capability of existing models.

Deliverable 1: List of the needs/questions related to oil spill modeling that must be addressed to support the USCG FOSC in decision-making during an Arctic response.

The list of needs and questions to be addressed by models during Arctic oil spill emergency response was created in Phase 2 (Appendix B). These needs and questions served as guideposts for the project and were related to responder/FOSC needs and concerns regarding existing spill response models, desired capabilities for new models, confidence levels and communication with the public, validation, and suggestions for the December 2019 Workshop. Prior to the December workshop, they were organized into six key areas of concern (Appendix G): (1) the influence of cold/ice on oil fate (weathering) and transport processes, (2) needs for subsea blowout modeling in Arctic waters, (3) current and future coupling of sea ice and/or regional ocean models with spill trajectory and fate models, (4) model operational considerations (e.g., run time, resolution, uncertainty, visualization), (5) model outputs needed for resource risk analysis in the Arctic, and (6) data availability. The discussions on the needs and questions and the final workshop plenary were used to develop the objectives for the working groups and became part of the final results/outputs of each group (Appendix I).

Deliverable 2: A review of the current state-of-the-art response modeling for Arctic maritime oil spills and sea ice modeling/data services.

The state-of-the-art oil spill and sea ice models identified were included in the Oil Spill Model Summary and the Ice Model Summary spreadsheets (Appendices J & K). Discussions between the oil spill and sea ice modeling/observation communities compared the spatial and temporal scales of sea ice data produced vs. desired oil spill model inputs. Ideally, oil spill models need data from sea ice models and observation systems hourly at approximately $\leq$ 1 km spatial resolution. Most ice models are either at the climate/global scale or the meter scale, with few that can produce outputs at the intermediate scales needed by oil spill modelers. Sea ice observing systems are capable of producing outputs at the 1-2 kilometer scale, but are limited by weather conditions (with the exception of SAR) and satellite revisit periods which may delay data availability by hours or days. Future research should address how to improve availability and communication of ice data with ≤ 1 km spatial and hourly temporal resolution and methods to improve intermediate scale sea ice models in the near term (next 1-5 years) by improving understanding of sea ice physics and the data that describe them.

The oil spill modeling community identified similarities in oil and sea ice algorithms used in major oil spill models (e.g., the 80/20 rule) and new algorithms necessary to improve modeling of oil and sea ice interactions. New algorithms should be publicly available and primarily address storage capacity, under ice roughness, stripping velocity, oil movement under ice, encapsulation, and other small scale oil-in-ice processes (e.g., interactions between oil droplets and brine channels, re-entrainment of oil stored in ice) using data available from ice models and observing systems. Algorithm development is most effective when modeled data can be validated with real-world observations. However, few real-world data sets exist for oil spills in the presence of sea ice. Working groups proposed development of standardized, generic scenarios (e.g., vessel spill during the shoulder season, pipeline spill under landfast ice) with associated data that can improve accuracy and operation of oil and sea ice algorithms in oil spill models and determine how close modeling results are to reality. Scenarios and their associated data should be made publicly available to improve collaboration between stakeholders on development of model algorithms and advancements and to allow for model intercomparison studies that highlight unique features and Arctic capabilities.

Deliverable 3: Delineation of uncertainty in model predictions and how to express it in a format that can be easily interpreted by an FOSC.

Uncertainty is inherent to oil spill model outputs. Output uncertainty can be the result of data gaps or data quality issues. Understanding the source of uncertainty is the first step to improving end user confidence in model outputs. The AMSM project discussed how to improve visualization of model outputs (e.g., qualitative confidence levels, summary of missing data), incorporate modeler experience into outputs and convey fine grain/small scale uncertainty information. The CEOMIO table was developed to address these challenges and communicate causes of model uncertainty as well as the associated level of confidence of each input and output over the duration of the spill.

The CEOMIO table requires more refinement from the oil spill response community before it can be put into practice. Involvement of NOAA NWS social and behavioral scientists was integral to the creation of the table and should be continued. While modelers usually have a general idea of the qualitative uncertainty of inputs and outputs, it may be difficult to ensure consistency of these estimates between spills. Qualitative confidence levels may also be subject to different interpretation depending on the end user. The verbal descriptions that accompany model outputs are a potential method for communicating how modeler expertise influenced responses in the CEOMIO table (e.g., determination of relative importance) and the implications of uncertainties on response. Collaboration between modelers and social and behavioral scientists may resolve some of these inconsistencies and improve end user comprehension.

CRRC has partnered with OR&R to further develop the CEOMIO table using a similar method to that used to refine ERMA [11]. CRRC and OR&R will convene a working group of oil spill modelers and SSCs to create draft CEOMIO tables using existing model output data from previous incidents. The modelers and SSCs will determine how easily the tables can be created and inputs/outputs ranked and identify aspects requiring further development. Once the table has been improved by the working group, it will be vetted by responders, FOSCs, Alaska RRT and other relevant groups (e.g., Alaska OSROs, Arctic and Western Alaska Area Committees) [11]. For integration into an exercise to be successful, collaboration between oil spill modelers (government and industry) and sea ice observation system operators must be completed in advance regarding data types, formats and communication. The culmination of all feedback should result in a CEOMIO table that improves the quality of communication between modelers, SSCs and responders/FOSCs during oil spills in the Arctic and beyond.

Deliverable 4: An outline of new and existing technologies that are available to locate and determine the characteristics of spilled oil in the Arctic, including their usefulness in anticipated spill scenarios.

The New and Existing Technologies working group developed a spreadsheet of technologies for observing sea ice and oil (Appendix O). The spreadsheet includes details specific to each technology (e.g., time for mobilization, permit requirements) and is organized by application (i.e., satellite, airborne, on ice surface and subsurface, under ice and open water surface, seafloor mounted). The group determined the applicability of each technology to two Arctic-specific scenarios of interest to the USCG: (A) a large vessel spill of combinations of oil in the shoulder season (during fall as sea ice is developing), and (B) a pipeline spill under landfast sea ice. These technologies have the potential to supply data for planning/algorithm development purposes as well as support active response during a spill. Future research should expand the technologies spreadsheet as new information and sensors become available.

Deliverable 5: Detailed recommendations/scopes of work on modeling research needed to fill gaps identified during the project.

The AMSM project established the current state of oil spill modeling for the Arctic maritime environment. More research and development are needed to address the gaps identified by oil spill modelers, ice modelers and ice observing system operators and overcome the challenges associated with oil spill response modeling in the Arctic. Many of the research recommendations proposed by the working groups are related to data availability, format and communication, as well as development of algorithms (e.g., storage capacity) and data assimilation to improve the ability of models to use available data.

<u>Data Formats and Communication</u>

Modes of communication among ice and oil spill modelers and observational system operators must be organized in advance of an Arctic maritime spill to ensure data is provided in compatible formats, at useful spatial and temporal scales and can be produced in a response time frame. This may mean increased data collection or model outputs within the first 24-48 hours following a spill, resulting in a greater need for computing capacity and data storage. Establishing these needs in advance will allow for development of the appropriate algorithms to ingest available data into oil spill models and identifies methods for rapid data sharing and communication between agencies. This communication framework will be the focus of Year 8 AMSM research project which will: (1) determine the exact sea ice model/ observational data feeds that are needed by the Arctic oil spill models; (2) create, implement and test the code necessary to ensure that those data can be ingested directly by the oil models during a spill in a timely and accurate manner; and (3) conduct a small tabletop exercise to validate that the linkages will lead to improved Arctic spill model trajectories that will enhance FOSC decision-making.

In addition to communication of input data, the AMSM project identified the importance of communicating the uncertainty of input and output data. The CEOMIO table was proposed to address this challenge, but requires further review (i.e., by FOSCs, responders, OSROs) before it is ready for use during a drill or exercise.

Data Collection, Availability and Processing via Algorithms

The greatest need for data collection is related to development of an approximation to estimate storage capacity of ice. Creation of an approximation (i.e., low, medium, high) based on ice type, age and surface conditions could be completed in the near term based on work by Frazier (2019). While the data available may be sufficient to give a general estimate based on ice conditions, more information is required to identify the factors which influence storage capacity. The approximation can be improved by coupling under ice observations from ROVs/AUVs with ice surface conditions to improve correlation of under ice roughness and surface conditions (process used by Frazier). A partnership between OR&R modelers, ADAC and Texas A&M University is ongoing to develop algorithms that determine the area of ice filled by spilled oil and potential spreading of oil under ice resulting when storage capacity is exceeded.

In addition to data on under ice storage capacity, more robust environmental and spill data are needed to inform oil spill model algorithm development and for use in exercises/drills. This includes creation of real-world data sets from mesoscale studies/field tests that describe oil in the presence of ice. Data could be collected to describe potential Arctic spill scenarios such as those used in the AMSM project (i.e., vessel spill during the shoulder season, pipeline spill under landfast ice). Participants at the stakeholder working session also proposed development of an emergency buoy deployment framework to incorporate data from spill response and Arctic monitoring buoys into modeling and decision making.

Observational data is useful for scenario and algorithm development, but is difficult to directly ingest into models. Working groups proposed further exploration of data assimilation to understand: (1) at what space and time scales sea ice models can be considered deterministic (accurate) in their predictions and for different aspects of sea ice (e.g., leads, sea ice edge, percent cover), (2) how oil spill models can improve assimilation of observational data on oil location, (3) how field observations can create better predictions of oil movement, (4) how uncertainties are propagated, and (5) what algorithms can be adjusted or created to better align predictions with observations (e.g., changing initial conditions, updating trajectories, adjusting model input parameters).

Summary

The AMSM project provided a structured approach to gather expert advice to evaluate models that address USCG FOSC core needs during Arctic oil spill response. This thesis summarized project findings related to: (1) USCG FOSC core needs during Arctic spill response (e.g., visualization, uncertainty); (2) current state-of-the-art Arctic maritime oil spill response models, sea ice models and ice observing system; (3) challenges for integration of oil spill models, sea ice models and ice observations (i.e., scale of available data, existing algorithms, data assimilation); (4) new and existing technologies for observing oil and sea ice; and gaps in current models (e.g., uncertainty, data availability, technology availability) that need to be addressed by future research. The AMSM project considered the fundamental needs of the USCG FOSC and response community during Arctic spill events and proposed recommendations for future research to support decision-making during Arctic response including: improving compatibility of data formats between models, further development of the

CEOMIO table, algorithm development related to under ice storage capacity, and collection and ingestion of more robust observational data into models.

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APPENDICIES

APPENDIX A: List of Core Team Members

The following were members of the Project Core Team:

- Sarah Allan (NOAA OR&R)
- Chris Barker (NOAA OR&R)
- Gary Barnum (USCG, Pacific Area)
- CJ Beegle-Krause (SINTEF Ocean)
- Catherine Berg (NOAA OR&R)
- Omar Borges (USCG, Office of Marine Environmental Response Policy Research and Development Center)
- Rick Bernhardt (AK DEC)**
- Lisa DiPinto (NOAA OR&R)*
- Michael Donnellan (AK DEC)*
- Mark Everett (USCG, 17th District)
- Clifton Graham (USCG Headquarters (HQ))*
- Kate Hedstrom (UAF)*
- Randy Kee (ADAC)
- Amy MacFadyen (NOAA OR&R)
- Guillaume Marcotte (Environment and Climate Change Canada (ECCC))*
- Phillip McGillivary (USCG, Pacific Area)
- Karin Messenger (USCG HQ)***
- Kirsten Trego (USCG HQ)

* January 2020 – January 2021

** May 2019 – January 2020

*** May 2019 – April 2020

APPENDIX B: List of Needs and Questions from May 2019 Core Team Meeting

Table 13: List of Needs and Questions from May 2019 Core Team Meeting.

From the Responder/FOSC Point of View:
Where did it spill, where is it going, what resources are at risk, what assets are available, and where should personnel be allocated? How does modeling inform prestaging of gear and personnel? What spilled/what is the product? How much was spilled? What response assets are available? How long will it remain/persist? How long do responders have to react? What are the implications of the model on response tactics?
How much qualitative confidence do we have in the output/results? How uncertain are the results and what are the factors contributing to that uncertainty? Understand what equipment, etc. are needed and were to send them to encounter the oil?
How acceptable is this model going to be to the corporate partner/responsible party (corporate equity)? Inherent responsibility to protect company, reduce liability, and decrease costs. May result in a conflict of interest.
What is the best way to visualize/display the output? What should the product look like? Some models portray oil as monolithic, but it is important to know where density/thickness of the oil is greatest. Particle output can be processed to show contours (quantitative (e.g., g/m^2) or qualitative (e.g., heavy, medium, light).
How long is an acceptable run time for the model and what is the level of resolution/detail needed? What is the optimal tradeoff between model runtime and resolution of accuracy?
What is going to use/report out the results of the model?
Concerns with Existing Models and Desired Capabilities
Existing NOAA Response Models/Tools:
GNOME Suite for Oil Spill Modeling: a set of modeling tools for predicting the fate and transport of pollutants (such as oil) spilled in water. These modeling tools are used for NOAA's spill response support and are also publicly available for use by the broader academic, response, and oil spill planning communities. Components include: WebGNOME –web-based user interface PyGNOME -computational core and scripting environment. Coupled weathering and transport algorithms ADIOS II (stand-alone oil weathering/persistence model) Outdated oil characteristics, some types are unavailable (e.g. condensate, hydraulic fluids, blends of oil/products, non-U.S. oil types) Lacking funding to update the data Potential for collaboration with organizations like Environment Canada to update database based on their analysis Impact of new MPRI Canada Oil Database Project Treats dissolved/dispersed oil as if it no longer exists

NOAA GNOME (desktop trajectory model – does not consider weathering) ADIOS Oil Database: Work in Progress, and not really a model, but is an important source of information about oils that may spill (note: ADIOS included a database and weathering model in one – now the weathering model is integrated with GNOME, and the oil database will be a stand alone product). Arctic ERMA (GIS display for Common Operational Picture ALOFT (models gasses) Cannot model multiple gasses from the same release ALOFT was developed by NIST and is no longer maintained. ERD is making some effort to assess options for burning oil plume modeling, but have no resources to pursue this currently.
Desired Capabilities
Modifications to Existing Models/Tools Update oil characteristics (New ADIOS oil database) Enhance functionality to model multiple release types from the same spill (e.g. lube oil, hydraulic oil, and diesel fuel: GNOME weathering components) Enhance functionality to model multiple gas types from same release (ALOHA) Bathymetry map lined to output (e.g. shore zone) available in ERMA ShoreZone may be a good resource on shoreline types
Mesh Area Contingency Plan (ACP) with modeling program (shoreline information, ESI maps) Model a worst-case scenario for use in the ACP (e.g. Trajectory Analysis Planning (TAP) for drilling operations in oil fields).
New Models/Components Computationally driven, amount of time to run a model should be considered Modeling of plumes generated by wellhead ignition (particulate matter, pyrogenic compounds, etc.). Improved 3D models (includes oil above and below the water surface, non-floating oils, burn residues), think about whole hydrodynamic profile of water column. Low cost/free models are preferred. Model predictions driven by quality of hydrodynamic (location) files and ice models. Better small-scale forecast models for localized predictions. Subsurface release models for blowouts and pipeline ruptures – consider turbidity’s effect on surface expression.

Specific Model Concerns for the Arctic:
Impacts of storm surge on modeling/potential oil on a beach.
Improve understanding of what a spill looks like beneath the water surface and beneath the ice.
Improve understanding of how oil interacts with the ice itself: brine channels, encasement, etc.
Presence/absence of ice has major influence on modeling Weakest part of transport and hydrodynamic models is ice, need mechanism to measure ice conditions and changes in mobility of oil due to ice. Inputs related to ice types/states/etc. currently come from coupled hydrodynamic ice model (includes % coverage, thickness, velocity) – but very limited info about the nature of the ice. Most accidents occur in between seasons when ice formation and mobility are unpredictable. Currents under the ice are not the same as the currents in the open ocean (no ice cover). Seasonal variation of ice coverage should be considered (e.g., melt/thaw cycle, frazil ice, shore fast ice on beaches). Ice ridges/keels change and constrain oil dispersion and change the movement of the ice itself.
River outflows may impact oil transport. Existing Alaska regional models may not resolve the dynamics of freshwater inputs in the coastal zone at the relevant scales. Many rivers do not have gauging stations, difficult to achieve this level of sophistication, many rivers have large sediment outputs.
Subsurface release models for blowouts from wells and pipelines. Lots of work going on in this area, but existing models may be readily useable for response. Gas pressure and water pressure at depth are both important factors to consider. Area of interest would be Cook Inlet with active oil production (high turbidity, suspended sediments, swift currents, and extreme tides) as well as Beaufort Sea with shallow drilling operations, extreme cold affecting microbial action, persistence, and altered photolysis rates.
Lack of sensors/monitoring equipment and lack of information/infrastructure. Information needed from sensors includes local winds and waves, currents, temperature, salinity, sediment, river discharge, ice presence/thickness/dams, etc.

Confidence Level & Communication
Is it possible to get a qualitative confidence level for a model's output (e.g., % confidence or categorized assessment)? % confidence is based on number of model runs that are repeatable (e.g. ensemble models) and availability/reliability of measured environmental conditions (e.g. from local vs. distant buoys). Definitions of confidence and uncertainty are not well defined. How well will this hold up with a corporate party/responsible party?
What kind of inputs (e.g., metocean data, weather, reliable wind speed, wave height, precise flow rates) are needed to get a certain confidence level?
Models and inputs should be widely distributed to all parties to improve acceptance and "confidence."
How to improve the communicability of the results (intended audience and communication medium)? Challenge of keeping metadata (caveats, etc.) with the product. Public affairs component is critical, special concern for international affairs (e.g. Russia and U.S.). Who is the end user (e.g., public affairs, scientists)? Ability to tailor output to a certain audience.
How to translate outputs to a "layman's level" so that they are realistic and accurate, but relatively simple? For press, public, politicians. How much/what type of information can be shared?
Terms can mean different things to different people. Trajectory may define what shorelines, how much time? Confidence referring to statistics vs. confidence for the user.

Validation
Validation may help with funding and aftermath of a spill (Natural Resource Damage Assessment)?
Ideal model will have “ground truthing.” Ability to verify the model to some degree, more than just consistent outputs. Compare results to a floating buoy in a representative location (high cost), spill tracking cards (limited area coverage), and/or oil simulant dyes (limited area coverage). Challenge: there is no surrogate that moves like oil… Seasonal and climatic variation are confounders to any model or validation. Using Shoreline Cleanup & Assessment Techniques (SCAT) to verify shoreline oiling.
Consider linking app inputs, AOOS, into the model or something like ERMA? This would be better information for validation, not included in the model itself. May be applicable to ERMA or used by the scientific support team. More interested in spatial extent, type of environment, and summary.
Models are limited by their inputs (e.g., environmental data forecasts, regional variation) and inherent simplicity/complexity.
Hydrodynamic models have been validated, but still face challenges.
Workshop
The most probable big spills that might happen in the Arctic, should be used to frame the workshop. Get towards a tangible result, what’s state-of-the-art and what are the gaps now?
Whatever changes are proposed, public relations component should also be updated.

APPENDIX C: List of December 2019 Workshop OC Members

The following were members of the December 2019 Workshop Organizing Committee:

- Sarah Allan (NOAA OR&R)
- Chris Barker (NOAA OR&R)
- Gary Barnum (USCG, Pacific Area)
- CJ Beegle-Krause (SINTEF Ocean)
- Catherine Berg (NOAA OR&R)
- Rick Bernhardt (AK DEC)
- Omar Borges (USCG, Office of Marine Environmental Response Policy Research and Development Center)
- Lisa DiPinto (NOAA OR&R)
- Mark Everett (USCG, 17th District)
- Randy Kee (ADAC)
- Amy MacFadyen (NOAA OR&R)
- Philip McGillivary (USCG, Pacific Area)
- Karin Messenger (USCG HQ)
- Guillaume Marcotte (Environment and Climate Change Canada (ECCC))
- Scott Socolofsky (Texas A&M University)
- Kirsten Trego (USCG HQ)

APPENDIX D: Agenda for December 2019 Workshop

ARCTIC MARITIME SPILL RESPONSE MODELING (AMSM) WORKSHOP

AGENDA

Tuesday, December 3, 2019

08:00 Registration / Light Continental Breakfast

08:15 Welcome & Logistics

- Larry Hinzman, Research Director, Arctic Domain Awareness Center (ADAC)
- Dr. Cathy Sandeen, Chancellor, University of Alaska, Anchorage
- Captain Kirsten Trego, Deputy Director, Emergency Management, U.S. Coast Guard (USCG)
- Nancy Kinner, Center for Spills and Environmental Hazards (CSE), University of New Hampshire

08:30 Background & Workshop Objectives - Nancy Kinner, CSE, University of New Hampshire

- Specific objectives of the workshop include:
  1) Review list of Specific Needs and Questions Developed by the Core Team.
  2) Establish current state-of-the-art Arctic maritime oil spill models and their utility for response modeling.
  3) Determine components from recent non-Arctic maritime oil spill models that may be useful for incorporation in Arctic models.
  4) Discuss ways to incorporate natural resource and food security protection, Traditional Ecological Knowledge, and models with each other.
  5) Identify gaps in Arctic maritime oil spill modeling.
  6) Determine the topics to be resolved by the three to four working groups.

08:45 Participant Introductions

09:00 Plenary Panel I: The Role of Oil Spill Models in Response

- Captain MacKenzie, U.S. Coast Guard Federal On-Scene Coordinator
- Crystal Smith, State of Alaska On-Scene Coordinator

09:20 Plenary Presentation II: Overview of Arctic Spill Modeling Needs, Questions, and Goals

- Chris Barker, NOAA OR&R Emergency Response Division

09:35 Plenary Presentation III: Oil and Ice Interactions

- Environment and Climate Change Canada

09:50 Plenary Presentation IV: Review of Existing Oil Spill Models

- 09:55 NOAA GNOME, Amy MacFadyen, NOAA OR&R

10:15 *Break*

10:30 Plenary Presentation IV: Review of Existing Oil Spill Models (continued)

- 10:30 OILMAP, Debbie French McCay, RPS
- 10:50 SINTEF Marine Environmental Modeling Workbench (MEMW), CJ Beegle-Krause
- 11:10 OpenDrift/OpenOil, (presented by CJ Beegle-Krause), MET Norway
- 11:30 COSMoS, Guillaume Marcotte, MET Canada

11:50 *Lunch*

- 12:50 National Research Council Canada, Hossein Babaei (Remote)
- 13:10 TetraTech Oil Spill Model, Aurelien Hospital, TetraTech
- 13:30 COSIM, Venkat Kolluru, Environmental Resources Management
- 13:50 SPILLMOD, Sergei Zatsepa, GOIN – State Oceanographic Institute
- 14:10 MOHID, Haibo Niu, Dalhousie University
- 14:30 BLOSOM, Kelly Rose, DOE NETL Office of Research & Development

14:50 *Break*

- 15:10 TAMOC Oil Spill Calculator, Scott Socolofsky, Texas A&M University

15:30 Plenary Presentation IV: Review of Existing Ice Models

Remote Sensing Integration

- 15:30 HIOMASS, Jinlun Zhang, University of Washington (Remote)
- 15:50 Graigory Sutherland, Environment Canada
- 16:10 NERSC (presented by CJ Beegle-Krause, SINTEF)

16:30 Recap of the Day

17:00 Adjourn

06:00 Reception at Glacier Brewhouse

737 West 5th Ave, #110

Anchorage, AK 99501

Wednesday, December 4, 2019

08:00 Light Continental Breakfast

08:15 Recap & Recalibrate

Plenary Presentation IV: Review of Existing Oil Spill Models (continued)

- 08:20 Oil Spill Module, Mads Madsen, DHI (Remote)

Non-Remote Sensing Integration

- 08:40 Naval Postgraduate School, Wieslaw Maslowski
- *09:00* DOE Model Los Alamos, Adrian Turner
- 09:20 SINMOD Coupled Ice Ocean Model, CJ Beegle-Krause
- 09:40 University of Alaska, Fairbanks, Kate Hedstrom
- 10:00 NOAA-GFDL, Robert Hallberg (Remote)

10:20 *Break*

10:30 Overview of Scenario-Based Discussion

- Breakout Group A: Well Blowout Under Ice
- Breakout Group B: Pipeline Spill Under Landfast Ice
- Breakout Group C: Large Vessel Spill of Combinations of Oil in the Shoulder Season (during fall as ice is developing)

10:45 Breakout Session I (3 parallel groups)

Session I Questions:

- Which of the responder's priorities need to be addressed by modeling for this scenario?
- Which oil-in-ice processes are most important to capture?
- What can we do now (state of the art) for response modeling and ice modeling?

12:30 *Lunch*

13:30 Plenary Group Reports

14:15 Breakout Session II: Overview and Charge

Session II Questions:

- What are the biggest limitations for ice modeling and response modeling?
- Which algorithms could be improved to give a more useful answer? How could they be improved?

Break as needed

15:45 Plenary Group Reports

16:30 Recap of the Day and Plenary Discussion

17:00 *Adjourn*

Thursday, December 5, 2019

08:00 Light Continental Breakfast

08:15 Recap and Recalibrate

08:30 Breakout Session III: Overview and Charge

Session III Questions:

- What observational gaps (e.g., oil location, ice conditions, oceanographic conditions, observational platforms) might we anticipate and can we make recommendations to address them?
    - Near real time, local data used in model run on response vessels versus models run remotely using synoptic data
- How can we best interface oil and ice modelers going forward?

10:00 *Break*

10:15 Plenary Group Reports

11:00 Plenary: The Path Forward

12:00 *Adjourn*

APPENDIX E: December 2019 Workshop Breakout Group Leads and Participants

Table 14: December 2019 Workshop Breakout Group Leads and Participants.

AMSM Breakout Groups		
Group A	Group B	Group C
Group Lead: Jessica Garron	Group Lead: Lisa DiPinto	Group Lead: Sarah Allan
Recorder: ADAC Fellow	Recorder: Jess Manning	Recorder: Megan Verfaillie
Chris Hall	Venkat Kolluru	Wolfgang Konkel
Brandon Booker	Sergei Zatsepa	Faisal Khan
Haibo Niu	Wieslaw Maslowski	Michel Boufadel
Graigory Sutherland	Debbie French McCay	Aurelien Hospital
Vyacheslav Solbakov	Kirsten Trego	Kate Hedstrom
Eric Adams	Chris Barker	Amy MacFadyen
Dylan Righi	Catherine Berg	Phil McGillivary
Gary Barnum	Rick Bernhardt	Omar Borges
CJ Beegle-Krause	Guillaume Marcotte	Scott Socolofsky
Kelly Rose	Jeremy Wilkinson	Tom DeRuyter
Adrian Turner	Hossein Babaei	Kelsey Frazier
	Caryn Smith	

APPENDIX F: December 2019 Workshop Participants

ARCTIC MARITIME SPILL RESPONSE MODELING (AMSM) WORKSHOP

PARTICIPANTS

DECEMBER 3-5, 2019

Eric Adams
Massachusetts Institute of Technology (MIT)
eeadams@mit.edu

Sarah Allan*
NOAA OR&R,
Assessment and Restoration Dviision (ARD)
sarah.allan@noaa.gov

Hossein Babaei (Remote)
National Research Council (NRC), Canada
hossein.babaei@nrc-cnrc.gc.ca

Chris Barker*
NOAA OR&R Emergency Response Division (ERD)
chris.barker@noaa.gov

MST1 Gary Barnum*
U.S. Coast Guard (USCG), Pac Area
gary.d.barnum@uscg.mil

CJ Beegle-Krause*
Sintef Ocean AS (Norway)
cj.beegle-krause@sintef.no

Catherine Berg*
NOAA OR&R Emergency Response Division (ERD),
Scientific Support Coordinator
catherine.berg@noaa.gov

Rick Bernhardt*
Alaska Department of Environmental Conservation (DEC), Prevention, Preparedness, and Response Program
rick.bernhardt@alaska.gov

Laurent Bertino (Remote)
National Energy Research Scientific Computing Center (NERSC), Copernicus Marine Service
laurent.bertino@nersc.no

Brandon Booker
U.S. Army Corps of Engineers (USACE),Engineer Research and Development Center (ERDC)
brandon.k.booker@usace.army.mil

LT Omar Borges*
U. S. Coast Guard Headquarters, Office of Marine Environmental Response Policy (CG-MER)
omar.borges@uscg.mil

Michel Boufadel
New Jersey Institute of Technology (NJIT)
michel.boufadel@njit.edu

Seth Campbell
Arctic Domain Awareness Center (ADAC)
sethcampbell88@gmail.com

Douglas Causey
Arctic Domain Awareness Center (ADAC)
dcausey@alaska.edu

Tom DeRuyter
Alaska Department of Environmental Conservation (ADEC), State On Scene Coordinator, Northern Alaska Region
tom.deruyter@alaska.gov

Lisa DiPinto*
NOAA OR&R
lisa.dipinto@noaa.gov

Mark Everett* (unable to attend)
U.S. Coast Guard (USCG), D17
mark.everett@uscg.mil

Kelsey Frazier

BP, ADAC Fellow
kafrazier@alaska.edu

Debbie French McCay
RPS
debbie.mccay@rpsgroup.com

Jessica Garron
University of Alaska, Fairbanks
jigarron@alaska.edu

Chris Hall
Alaska Clean Seas
planning@alaskacleanseas.org

Robert Hallberg (Remote)
NOAA Geophysical Fluid Dynamics Laboratory (GFDL)
robert.hallberg@noaa.gov

Katherine "Kate" Hedstrom*
University of Alaska Fairbanks
kshedstrom@alaska.edu

Larry Hinzman
Arctic Domain Awareness Center (ADAC)
ldhinzman@alaska.edu

Bruce Hollebone (Remote)
Environment and Climate Change Canada
bruce.hollebone@canada.ca

Amy Holman
NOAA
amy.holman@noaa.gov

Aurelien Hospital
TetraTech
aurelien.hospital@tetratech.com

Randy "Church" Kee* (unable to attend)
Arctic Domain Awareness Center (ADAC)
rakee@alaska.edu

Faisal Khan
Memorial University, Canada Research Chair (Tier I) in Offshore Safety & Risk Engineering
fikhan@mun.ca

Venkat Kolluru
Environmental Resources Management, Water Resources, Climate Change & Modeling
venkat.kolluru@erm.com

Wolfgang Konkel
ExxonMobil Biomedical Sciences, Inc.
wolfgang.j.konkel@exxonmobil.com

Amy MacFadyen*
NOAA OR&R Emergency Response Division (ERD)
amy.macfadyen@noaa.gov

Kathy Mandsager
Center for Spills and Environmental Hazards (CSE), University of New Hampshire
kathy.mandsager@unh.edu

Jessica Manning*
Center for Spills and Environmental Hazards (CSE), University of New Hampshire, ADAC Fellow
jm1416@wildcats.unh.edu

Guillaume Marcotte*
Environment and Climate Change Canada, Meteorological Service of Canada Branch (MET)
guillaume.marcotte@canada.ca

Wieslaw Maslowski
Naval Postgraduate School (NPS), Department of Oceanography
maslowsk@nps.edu

Elizabeth Matthews
Arctic Domain Awareness Center (ADAC)
ematthews@alaska.edu

Molly McCammon
Alaska Ocean Observing System (AOOS)
mccammon@aoos.org

Dr. Phillip McGillivary*
U.S. Coast Guard (USCG), Pac Area
philip.a.mcgillivary@uscg.mil

Karin Messenger* (unable to attend)
U.S. Coast Guard (USCG)
karin.e.messenger2@uscg.mil

Haibo Niu
Dalhousie University (Canada)
haibo.niu@dal.ca

Heather Paulsen
Arctic Domain Awareness Center (ADAC)
hpaulsen@alaska.edu

Dylan Righi

NOAA OR&R Emergency Response Division (ERD)
dylan.righi@noaa.gov

Kelly Rose
DOE National Energy Technology Laboratory (NETL), Office of Research & Development
kelly.rose@netl.doe.gov

Crystal Smith
Alaska Department of Environmental Conservation (DEC), Prevention, Preparedness and Response Program
crystal.smith2@alaska.gov

Caryn Smith
U.S. Department of the Interior, Bureau of Ocean Energy Management (BOEM)
caryn.smith@boem.gov

Scott Socolofsky
Texas A&M University
ssocolofsky@civil.tamu.edu

Vyacheslav Solbakov
GOIN-State Oceanographic Institute (Russia)
my.qwerty@mail.ru

Graigory Sutherland
Environment and Climate Change Canada
graigory.sutherland@canada.ca

CAPT Kirsten Trego*
U.S. Coast Guard (USCG), Emergency Management Directorate
kirsten.r.trego@uscg.mil

Adrian Turner
Los Alamos National Lab
akt@lanl.gov

Juan Velasco (Remote)
NOAA National Environmental Satellite, Data and Information Service (NESDIS)
juan.velasco@noaa.gov

Megan Verfaillie*
Center for Spills and Environmental Hazards (CSE), University of New Hampshire, ADAC Fellow
mpv1000@wildcats.unh.edu

Jeremy Wilkinson
British Antarctic Survey (United Kingdom)
jpw28@bas.ac.uk

Graham Wood* (unable to attend)
Alaska Department of Environmental Conservation (DEC)
graham.wood@alaska.gov

Sergei Zatsepa
GOIN-State Oceanographic Institute (Russia)
zatsepa@gmail.com

Jinlun Zhang (Remote)
ADAC, University of Washington's Applied Physics Laboratory, HIOMASS developer
zhang@apl.washington.edu

*Designates Workshop Organizing Committee Member

APPENDIX G: List of Needs and Questions from December 2019 Workshop

Table 15: Needs, Questions and Goals from December 2019 Workshop.

Needs, Questions and Goals
Oil fate (weathering) and transport: how are the key factors influenced by cold/ice?
Evaporation Dispersion/entrainment Spreading/oil thickness in ice, including broken ice, brash ice, leads, etc. Modifications to weathering/transport algorithms in broken ice, brash ice, leads, etc. Spreading under ice Transport under ice Diffusion under ice Movement/weathering within ice (e.g., brine channels) Emulsion formation
Subsea blowout modeling in Arctic waters
Relatively shallow water (dynamics as plume reaches the surface -- initial transport and spread) Plume trapping under ice cover (impact on initial spreading) Ice melting by plumes Gas component trapping or becoming concentrated under ice
Coupling of ice and/or regional ocean models with spill trajectory and fate models
What is the state of the art for modeling sea ice extent, characteristics, thickness, and movement? Where is ice modeling going in the next few years? What will ice models forecast that can be used to drive oil models? E.g. leads, under ice roughness, etc. Ice state for brine channels, other within-the-ice processes Flow/diffusion under ice: can this feed the oil models? Consideration of seasonal variation for ice [shoulder seasons] Marginal Ice Zone
Model Operational Considerations
How long is the acceptable run-time? What is the level of resolution needed? Uncertainty analysis and incorporation in decision-making (is it possible to get a qualitative confidence level?) Visualization and analysis tools including polar projections (e.g. model linkages to ERMA): Do the models need to operate on a polar projection?
Model Outputs Needed for Resource Risk Analysis in the Arctic
Shoreline vs. water column vs. ocean floor vs. ice interface Incorporation of ecotoxicological conditions
Other Topics
Data availability Need a clear understanding of available circulation and ice data in Arctic waters

APPENDIX H: Active Working Group Participants and Co-Leads

<u>Oil and Ice Interactions (Meter / Subgrid scale)</u>

NOAA Representative/Co Lead:

- Chris Barker (NOAA OR&R ERD)

Members:

- Rick Allard (Navy NRL)
- Hossein Babaei (NRCC)
- CJ Beegle-Krause (SINTEF)
- Ben Fieldhouse (ECCC)
- Kelsey Frazier (ADAC)
- Kate Hedstrom (UAF)
- Bruce Hollebone (ECCC)
- Aurelien Hospital (Tetra Tech)
- Zhen Li (BOEM)
- Guillaume Marcotte (ECCC)
- Andrew Roberts (LANL)
- Scott Socolofsky (Texas A&M University)
- Peter Wadhams (University of Cambridge)
- Jeremy Wilkinson (British Antarctic Survey)
- Yongsheng Wu (Bedford Institute of Oceanography)
- James Yao (ECCC)

Oil and Ice Interactions (Kilometer+ Scale)

NOAA Representative/Co Lead:

- Amy MacFadyen (NOAA OR&R ERD)

Members:

- Eric Adams (MIT)
- Rick Allard (Navy NRL)
- Eric Anderson (NOAA/GLERL)
- Hossein Babaei (NRCC)
- Chris Barker (NOAA OR&R ERD)
- CJ Beegle-Krause (SINTEF)
- Rodrigo Duran (US DOE NETL)
- Debbie French-McCay (RPS)
- Kate Hedstrom (UAF)
- Aurelien Hospital (Tetra Tech)
- Zhen Li (BOEM)
- Dylan Righi (NOAA OR&R ERD)
- Scott Socolofsky (Texas A&M University)
- Patrick Wingo (NETL)
- James Yao (ECCC)

New and Existing Technologies for Observing Ice and Informing Models

NOAA Representative/Co Lead:

- Dylan Righi (NOAA OR&R ERD)

Members:

- Rick Allard (Navy NRL)
- Julke Brandt (ITOPF)
- Lisa DiPinto (NOAA OR&R)
- Susannah Domaille (ITOPF)
- Rodrigo Duran (US DOE NETL)
- Ben Fieldhouse (Environment Canada)
- Jessica Garron (University of Alaska Fairbanks)
- Carol Janzen (AOOS)
- Zhen Li (BOEM)
- Molly McCammon (AOOS)
- Phillip McGillivary (USCG)
- Ellen Ramirez (NOAA Satellite Analysis Branch)
- Alexandria Rodriguez (NOAA Satellite Analysis Branch)
- Kelly Rose (US DOE NETL)
- Hanu Singh (Northeastern University)
- Tayebeh TajalliBakhsh (RPS Group)
- Jeremy Wilkinson (British Antarctic Survey)
- James Yao (Environment Canada)
- Chris Zappa (Lamont Doherty Earth Observatory of Columbia University)
- Brian Zelenke (IOOS)

Visualization and Uncertainty

NOAA Representative/Co Lead:

- Catherine Berg (NOAA Alaska Scientific Support Coordinator)

Members:

- Chris Barker (NOAA OR&R ERD)
- Gary Barnum (USCG MST1)
- CJ Beegle-Krause (SINTEF)
- Laurent Bertino (Nansen Center, Norway)
- Mike Donnellan (Alaska DEC)
- Mark Everett (USCG)
- Rodrigo Fernandes (Bently Systems)
- Ben Fieldhouse (Environment and Climate Change Canada)
- Jessica Garron (University of Alaska Fairbanks)
- Bruce Hollebone (Environment and Climate Change Canada)
- Bryan Klostermeyer (USCG)
- Patrick Lambert (Environment and Climate Change Canada)
- Zhen Li (BOEM)
- Amy MacFadyen(NOAA OR&R ERD)
- Mads Nistrup Madsen (DHI)
- Gabrielle McGrath (RPS)
- Dylan Righi(NOAA OR&R ERD)
- Jason Roe (ADAC)
- Kelly Rose (US DOE NETL)
- James Yao (Environment Canada)

APPENDIX I: Working Group November 2020 Virtual Workshop Presentations

Oil and Ice Interactions (Meter / Subgrid scale)

Report on Activities, Findings, and Research Needs

Rapporteur:
Aurelien Hospital (TetraTech)

AMSM Workshop November 16, 2020

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1

Oil and Ice Interactions (Subgrid Scale): Members

NOAA Representative:

- Chris Barker (NOAA ORR ERD)

Members:

- Rick Allard (Navy NRL)
- Hossein Babaei (NRCC)
- CJ Beegle-Krause (SINTEF)
- Ben Fieldhouse (ECCC)
- Kelsey Frazier (ADAC)
- Kate Hedstrom
- Bruce Hollebone (ECCC)
- Aurelien Hospital (Tetra Tech)
- Zhen Li (BOEM)
- Guillaume Marcotte (ECCC)
- Andrew Roberts (LANL)

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2

Oil and Ice Interactions (Subgrid Scale): Members

Members (continued):

- Scott Socolofsky (Texas A&M University)
- Peter Wadhams (University of Cambridge)
- Jeremy Wilkinson (British Antarctic Survey)
- Yongsheng Wu (Bedford Institute of Oceanography)
- James Yao (ECCC)

Oil and Ice Interactions (Subgrid Scale): Goals

1. Determine and identify outputs from sub ice models to determine: how they could be used to improve understanding of sub models and their uses in an oil model, and to define when oil is going to show up (e.g., on surface, encapsulation, enter water under ice).
   a. Discuss how models may mesh with oil spill modelers (e.g., inform high resolution coupled simulations that can feed into larger scale models).
   b. List dynamic feedbacks from oil to sub ice models: how does oil affect what ice is doing?
   c. How do different types/characteristics of ice affect oil behavior?
   d. How do we recognize/incorporate the value in including local and indigenous knowledge (with specialty in small scale ice interactions)?
   e. Define key timescales for the information and processes (nearterm vs longterm).

Oil and Ice Interactions (Subgrid Scale): Activities/Accomplishments

1. Identified ice processes relevant to oil fate and transport.
2. Presentations from ice modelers (*list on next slide*).
3. Spreadsheet on what ice models tell responders/modelers about the ice, and what the working group would like to know from the ice models but is not yet available.
4. Discussed where the information from the ice models would interface with the oil models.
5. Presentation from Hajo Eicken on how local and indigenous knowledge (e.g., ice strength) can be incorporated into oil spill response in the Arctic.

Oil and Ice Interactions (Subgrid Scale): Activities/Accomplishments

6. Presentations from ice modelers
   a. SINMOD (CJ Beegle-Krause, SINTEF)
   b. Icepack (Andrew Roberts & Elizabeth Hunke, LANL)
   c. CICE (Rick Allard, Navy NRL)
   d. HIOMAS (Jinlun Zhang, University of Washington)
   e. Unified Forecasting System (Hendrik Tolman, NOAA NWS)
   f. TOPAZ4 (Laurent Bertino & Einar Olason, Nansen Center)
   g. neXtSIM-F (Laurent Bertino & Einar Olason, Nansen Center)

Oil and Ice Interactions (Subgrid Scale): Findings

1. A lot of information is available from ice models.
2. Ice models are not well suited to provide for oil spill model needs.
3. Challenge to have resolution of ice models at small enough scale for time and place of spill.
   a. Ice modelers need boundary conditions from larger (global) models and maybe different physics suitable for small scale - at some point the ice rheology breaks down when you go to smaller scale.
4. Working group's discussions on under ice roughness formed basis for future research needs.
   a. Some models are not sufficient for capturing stratification in the Arctic - requires high vertical resolution.
   b. Ice ocean coupling is very rudimentary in models.

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Oil and Ice Interactions (Subgrid Scale): Research Needs

1. Under ice roughness / storage capacity:
   a. Need to define under ice roughness further.
   b. Use observed sea ice data at a scale that makes sense.
   c. Calculate under ice drag for different types of sea ice.
   d. Quantify storage capacity beneath different types/ages of sea ice with a statistical distribution.
   e. Use ice velocity and current data to potentially estimate stripping velocity.
   f. Explore extent to which under ice velocity impacts storage capacity.
   g. How many factors impact storage capacity?
   h. Determine impact of macroporosity in ice (blocks of ice that form when ridges form: 1cm to several meters in size).
   i. Ocean mixing schemes are ongoing area of research.
   j. Improve ice ocean coupling in models.
   k. Determine how to obtain proper resolution of vertical stratification in models.

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Oil and Ice Interactions (Subgrid Scale): Research Needs

2. Incorporate mixed density fluid interactions in models:
   a. Interaction between oil droplets and brine channels.
   b. Important micro scale simulations to model how oil penetrates pores in ice (and then encapsulation) and how it gets locks in matrix in brines.

3. Model validation:
   a. How close are the modeling results to reality?

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Oil and Ice Interactions (Subgrid Scale): Research Needs

4. Develop publicly available algorithms appropriate for oil spill models that use outputs readily available in ice models (macro and sub grid scale ice models) or outputs that can be derived from them or other parameters that may be included in ice models in the near term. Including:
   a. Under ice storage capacity for Lagrangian elements
   b. Synthesis of 80/20 rule with stripping model
   c. Oil penetration into porous ice (e.g., Darcy laws)
   d. Encapsulation
   e. Effect of oil on ice albedo so that the ice model can melt the ice properly
      a. Coupling between oil and ice
   f. CICE has landfast ice from ECCC and is in several models
   g. Estimate of oil thickness in leads because has application in response

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Thank you for listening!

Questions?/ Comments?

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Oil and Ice Interactions (Kilometer+ Scale)

Report on Activities, Findings, and Research Needs

Rapporteur:
Debbie French-McCay (RPS ASA)

AMSM Workshop November 16, 2020

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Oil and Ice Interactions (km scale): Members

NOAA Representative:

- Amy MacFadyen (NOAA ORR ERD)

Members:

- Eric Adams (MIT)
- Rick Allard (Navy NRL)
- Eric Anderson (NOAA/GLERL)
- Hossein Babaei (NRCC)
- Chris Barker (NOAA ORR ERD)
- CJ Beegle-Krause (SINTEF)
- Rodrigo Duran (US DOE NETL)
- Debbie French-McCay (RPS)
- Kate Hedstrom (UAF)
- Aurelien Hospital (Tetra Tech)
- Zhen Li (BOEM)
- Dylan Righi (NOAA ORR ERD)
- Scott Socolofsky (Texas A&M University)
- Patrick Wingo (NETL)
- James Yao (ECCC)

Oil and Ice Interactions (km scale): Goals

1. **What is the current state of the art of oil-in-ice modeling?** Revisit oil and ice transport and fate algorithms to determine potential improvements.
   a. What is the scale of information useful for USCG decision making?
   b. How well tested are the algorithms and how well do they inform what's happening?
   c. How much information is available in a timely enough manner to be useful?
   d. What processes need to be included?
   e. What are the values of the needed input parameters?
   f. How well do the algorithms inform the response options (real -time versus predictive)?

Oil and Ice Interactions (km scale): Goals

2. Review widely adopted algorithms for oil spill models.
   a. How is the spreading algorithm modified in presence of ice?
   b. Does entrainment differ in the presence of ice?
   c. Are there any special considerations for dispersant use in the presence of ice?
3. Propose algorithms for under ice storage capacity.
   a. As a function of the type of ice (characterized by age, thickness, roughness) and under ice current velocity, what would be the static storage capacity (i.e., m^3 of oil per km^2 of ice)?
      1) Low, medium, and high ranges for storage capacity estimates.
   b. How to quantify mobilization - stripping velocity

Oil and Ice Interactions (km scale): Activities/Accomplishments

1. Compiled summary document of present state of the art modeling of oil in ice.
   a. Presentation by Dalina Viveros (NOAA) on GNOME's degradation algorithm.
2. Discussion of under ice roughness and storage capacity.
   a. Kelsey Frazier (ADAC)
   b. Jeremy Wilkinson (British Antarctic Survey)
   c. Ted Maksym (WHOI)
3. Discussion of needed ice data for oil spill modeling at the kilometer+ scale.
   a. Spatial and temporal resolution needs.
   b. How will modelers use this data?

Oil and Ice Interactions (km scale): Findings

1. Oil in ice algorithms used in oil models are all similar.
2. Many different parameters are needed for oil spill modeling.
   a. e.g., ice concentration, thickness, roughness, velocity
   b. Ice models generally can provide this information
3. Scale of information needed
   a. Hourly, ~1 km scale ice data is needed, particularly in the Marginal Ice Zone and near shore. Averaging degrades the accuracy of the trajectory.
   b. Discussed difficulty of acquiring and storing fine resolution outputs at hourly timesteps - scales of ice model products are determined by computing power and data storage capacity, so is somewhat limited.
   c. Ice modelers should be made aware of the output desired by the oil modeling community.

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Oil and Ice Interactions (km scale): Findings

4. Under ice storage capacity and mobilization
   a. Agreed this could use model development
   b. Empirically-based algorithms for under ice storage capacity may be developed based on existing knowledge.
   c. Roughness and stripping velocity may be linked.
      a. Stripping velocity may be influenced by under ice topography as well as under ice current velocity.
      b. Need quantitative information on how roughness changes if under-ice storage capacity is exceeded and how this will affect stripping velocity.
   d. Discussed importance of storage capacity and mobilization at a 1 km+ resolution and whether this is a priority for smaller spills, given the scale resolution of the ice models.

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Oil and Ice Interactions (km scale): Findings

5. Reviewed current ice models, the different parameters required to run them, and the kind of outputs produced.
   a. Multiple regional scale models exist that simulate ice in the Arctic.
   b. Ice models are good at the regional scale at:
      a. Including physics and thermodynamic processes.
      b. Simulating growth and melting of the ice.
      c. Simulating ice age.
      d. Including and interpolating thickness from age.
      e. Simulating ice drift.
      f. Producing graphical outputs of fracturing on large scales.

Oil and Ice Interactions (km scale): Findings

8. Communication
   a) Ice modelers should be made aware of the outputs and spatial and temporal scales desired by the oil modeling community.
   b) Ice models should be prepared to create needed outputs and oil spill modelers should be prepared to ingest ice data inputs at any time, but not all the time.
   c) This should be the focus of a drill/exercise to make sure products can be successfully produced and ingested.
   d) Important to understand and communicate uncertainties in model predictions.

Oil and Ice Interactions (km scale): Research Needs

1. Oil spill modelers **need finer scale ice data** than climate scale and larger than the meter scale.
   a. Transport questions answered on ~1 km scale.
   b. Hourly data is needed. Time -averaging reduces accuracy.
   c. Disconnect between scale of oil and ice models.
   d. Trajectory estimates for oil depend on accuracy of data for water and ice velocities. Many ice models can't provide this on the 1 km scale.
   e. How can the accuracy of water and ice velocities be improved on the 1 km scale?

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Oil and Ice Interactions (km scale): Research Needs

2. **Data assimilation by ice models**
   a. What data is/can be assimilated and how it is/can be used in ice models?
   b. At what space and time scale can we consider the models to be deterministic (accurate) in their predictions?
   c. Does present data assimilation in the Arctic capture mesoscale circulation?
   d. What scales of ice/current model predictions are accurate for different aspects (e.g., leads, ice edge, % ice cover)?

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Oil and Ice Interactions (km scale): Research Needs

3. **Data assimilation by Arctic oil spill models**
   a. What field data can be assimilated and how it can be used, e.g.:
      a. Location of oil, given ice & snow obscuring or interfering with sensors?
      b. Location of oil with respect to ice such as underneath or on top?
   b. How do or could models use field observations to develop better predictions of oil movement?
   c. What algorithms could be used to "nudge" oil predictions to better align with observations (e.g., changing initial conditions, updating trajectories, adjusting model input parameters)?
   d. How do the uncertainties propagate in the oil spill model?

Oil and Ice Interactions (km scale): Research Needs

4. Investigate **under-ice topography and how oil migrates**
   a. Provide description of ice properties from regional scale ice model outputs that could be used by oil spill models (e.g., to inform roughness, stripping velocity, spreading of oil under ice).
   b. These processes are in the sub grid scale.
   c. What parameterizations can be used?
      a. Pooling capacity - do all the voids in ice area "fill up" with oil?
      b. Gravity-driven flow - does oil flow along streamlines?
   d. How are the uncertainties propagated in the oil spill model?

Thank you for listening!

Questions?/ Comments?

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New and Existing Technologies for Observing Ice and Informing Models

Report on Activities, Findings, and Research Needs

Rapporteur:
Jessica Garron (University of Alaska, Fairbanks)

AMSM Workshop November 16, 2020

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1

New and Existing Technologies: Members

NOAA Representative:

- Dylan Righi (NOAA ORR ERD)

Members:

- Rick Allard (Navy NRL)
- Julke Brandt (ITOPF)
- Lisa DiPinto (NOAA ORR)
- Susannah Domaille (ITOPF)
- Rodrigo Duran (US DOE NETL)
- Ben Fieldhouse (Environment Canada)
- Jessica Garron (University of Alaska Fairbanks)
- Carol Janzen (AOOS)
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- Molly McCammon (AOOS)
- Phillip McGillivary (USCG)

New and Existing Technologies: Members

Members (continued):

- Ellen Ramirez (NOAA Satellite Analysis Branch)
- Alexandria Rodriguez (NOAA Satellite Analysis Branch)
- Kelly Rose (US DOE NETL)
- Hanu Singh (Northeastern University)
- Tayebeh TajalliBakhsh (RPS Group)
- Jeremy Wilkinson (British Antarctic Survey)
- James Yao (Environment Canada)
- Chris Zappa (Lamont Doherty Earth Observatory of Columbia University)
- Brian Zelenke (IOOS)

New and Existing Technologies: Goals

1. Operationalizing technologies: what capabilities exist/should be used make recommendations?
   a. Include Alaska Ocean Observing System (AOOS) to determine what data is already being collected (e.g., HF Radar data) that might be useful.
   b. What new technologies might be available (e.g., induced polarization, satellite remote sensing, LRAUV- US and Canadian)?
   c. How long does it take to deploy certain sensors (e.g., buoys)

New and Existing Technologies: Goals

2. Operationalizing technologies: what capabilities exist/should be used make recommendations?
   d. Summarize information on what technologies/sensors are available, how accessible are they, network between resources within ice modeling and oil spill modeling (e.g., suitable formats to ensure compatibility)
   e. How would we take what we learn and incorporate it into the other working groups? When/how should this be done?

New and Existing Technologies: Activities/Accomplishments

1. Discussed existing technologies of relevance to oil and ice detection in the Artic/ice filled environment.
   a. Including names of technologies and primary contacts.
2. Designed list of questions on technologies (e.g., time to deploy, cost, output data format, strengths and weaknesses, applications).
3. Alaska Ocean Observing System representatives discussed current monitoring and data collection in the Arctic.
4. Experts/vendors completed spreadsheet of technologies including answers to key questions.
5. Determined which of the technologies from the spreadsheet are applicable to two potential Arctic spill scenarios:
   a. Pipeline spill under landfast ice.
   b. Vessel spill of combinations of oil in the shoulder season as ice is developing.

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New and Existing Technologies: Activities/Accomplishments

6. Spreadsheet of technologies includes answers to key questions:
   - Contact/manufacturer/developer
   - Overview of technology
   - Sensor type/description
   - What conditions is it designed to operate in
   - Spatial and temporal resolution
   - Time required for taking measurements
   - Applications (e.g., emergency response, damage assessment)
   - Oil type and condition
   - Availability and needs for deployment
   - Time for mobilization
   - Permit requirements
   - Raw and final data formats
   - Time required for data processing
   - Strengths and weaknesses
   - Validation studies

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New and Existing Technologies: Findings

1. Scenario A: Large Vessel Spill of Combinations of Oil in the Shoulder Season (During Fall as Ice is Developing)
   - Assumptions:
     a. Highest likelihood
     b. Heavy fuel oil and light fuel oil products were being transported
     c. 175,000 gallons of HFO and 50,000 gallons of diesel were spilled
     d. Spill occurs during shoulder season where freeze up takes 2030 days
     e. Takes place over a range of ice conditions
     f. Occurs in the Bering Strait (area of common interest between U.S. and Russia)

New and Existing Technologies: Findings

- Applicability of Satellites:
  - Hyperspectral, visible or other combinations of wavelengths (e.g., Sentinel 2A, LandSat) over an area at a useful time if conditions are daylight, unobscured, and have no significant cloud cover.
  - Radar (e.g., SAR) could provide information about ice location and condition as well as oil condition.
  - IceSatII can provide information on ice conditions.
  - Longer spill events can utilize more satellite resources.

New and Existing Technologies: Findings

- Applicability of Airborne Technologies:
  - Valuable if they can get on site and perform overflights. Time to deploy may be 24 hours or more.
  - Temperature control/heated hull is necessary for Arctic operations.
  - Small UAVs only valuable if they can be deployed from ship near the spill.
  - Longer range fixed wing UAVs are more useful but require additional waivers.
  - Sensors are only as valuable as the UAV they are deployed on.
  - Freeze up and snow events obscure oil so it can no longer be detected by most sensors.
    - Airborne ground penetrating radar may be applicable in this scenario but is still prototypical.

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New and Existing Technologies: Findings

- Applicability of On Ice Surface and Subsurface Technologies:
  - Dangerous to do during freeze up, putting things on ice may be risky. Have to define ice thickness to determine applicability.
  - Ground penetrating radar, ice auger.
  - 3D laser scanner can be mounted on vessel but won't pick up ridges where new ice is forming.
  - Dogs would be valuable (depends on environmental conditions, safety, accessibility via shallow boat).
  - On ice profilers can give quality baseline information.
  - Underwater vehicles (e.g., LRAUV, REMUS 100 & 600) depending on tethers and communication requirements.
  - Photo acoustic detector effective on the underside of ice but may be less reliable during formation of new ice.
  - Upward looking LIDAR, upward looking fluorescence, high -definition camera.

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New and Existing Technologies: Findings

- Applicability of Seafloor Mounted Technologies:
  - None applicable to this scenario.

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New and Existing Technologies: Findings

2. Scenario B: Pipeline Spill Under Landfast Ice
   - Assumptions:
     a. Two types of pipeline spills including ruptures and slow pinhole leaks
     b. Large and small spills/leaks will be discussed
     c. Crude oil is released
     d. The location where the incident occurs is important
     e. Necessary to try and determine the amount of oil that is released, but often only pressure change information is available

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New and Existing Technologies: Findings

Applicability of Satellites:

- Helpful for determining where the land fast ice is and where the drifting pack ice starts. Useful for safety of responders (e.g., Synthetic Aperture Radar).
- SAR is useful for seeing in darkness and through cloud cover.
- All have the potential to provide baseline environmental and ice data information in clear weather and daylight conditions.
- Caveats:
  - Repeat interval and location above the Arctic.
  - Don’t get the exact same image every time, may be at a slightly different angle.

Applicability of Airborne Technologies:

- Airborne ground penetrating radar is possible via helicopter. Never been tested with airplane. Non-operational at present time.

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New and Existing Technologies: Findings

Applicability of On Ice Surface & Subsurface Technologies:

- Ground penetrating radar, ice auger.
- On ice profiler is not applicablewith the exception ofmeasuring under ice current velocity.
- Acoustic/Towed Ultrasound System using a sonar mounted on ROV or AUV.
- Oil detecting dogs if given a safe location.

Applicability of Seafloor Mounted Technologies:

- Would have to have these all along the pipeline, not sure any of these are applicable.
- Need a certain amount of headroom to operate.
- More focused on impact assessment than response.

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New and Existing Technologies: Findings

Applicability of Under Ice & Open Water Surface Technologies:

- Acoustic Thickness Sensors are applicable to oil detection.
- ROV and AUV if given enough headroom based on pipeline bathymetry.
- LRAUV is cold tested and meant to go under the ice with acoustic sensors and holographic cameras. Same for REMUS 100 and REMUS 600 AUVs.
- Sonar can measure ice thickness. Multibeam can give surface roughness as well.
- LIDAR can give very accurate mapping of the bottom of sea ice, but not the best returns.
- Fluorescence (both upward looking fluorescence and laser flourosensor) gives good return from oil on ice bottom even in small amounts.
- Camera with strobe and mass spectrometer.
- Photo acoustic detector when deployed on AUV under ice, still prototype.
- Marine Induced Polarization is a possibility but is still in development.

Thank you for listening!

Questions?/ Comments?

http://crrc.unh.edu/

Visualization and Uncertainty

Report on Activities, Findings, and Research Needs

Rapporteur:
Catherine Berg (NOAA ORR ERD SSC)

AMSM Workshop November 16, 2020

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1

Visualization and Uncertainty: Members

NOAA Representative:

- Catherine Berg (NOAA Alaska Scientific Support Coordinator)

Members:

- Chris Barker (NOAA ORR ERD)
- Gary Barnum (USCG MST1)
- CJ Beegle-Krause (SINTEF)
- Laurent Bertino (Nansen Center, Norway)
- Mike Donnellan (Alaska DEC)
- Mark Everett (USCG)
- Rodrigo Fernandes (Bently Systems)
- Ben Fieldhouse (Environment and Climate Change Canada)

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Visualization and Uncertainty: Members

Members (continued):

- Jessica Garron (University of Alaska Fairbanks)
- Bruce Hollebone (Environment and Climate Change Canada)
- Bryan Klostermeyer (USCG)
- Patrick Lambert (Environment and Climate Change Canada)
- Zhen Li (BOEM)
- Amy MacFadyen (NOAA ORR ERD)
- Mads Nistrup Madsen (DHI)
- Gabrielle McGrath (RPS)
- Dylan Righi (NOAA ORR ERD)
- Jason Roe (ADAC)
- Kelly Rose (US DOE NETL)
- James Yao (Environment Canada)

Visualization and Uncertainty: Goals

1. How is uncertainty shown and to what extent is it demonstrated in existing oil and ice forecasts?
   a. What do responders mean by uncertainty?
   b. What is the state of the art with respect to uncertainty?
   c. How should this evolve to suit modern needs in the Arctic?
2. What do responders want with respect to uncertainty?
   a. How are model outputs currently presented in visualization systems utilized by NOAA (e.g., ERMA) or USCG (e.g., CG1View, HSIN, AIS)?
   b. How should this evolve to suit modern needs in the Arctic?

Visualization and Uncertainty: Goals

3. **What would responders like to see/know** that they aren't getting now? Especially specific to oil in ice/Arctic?
    a. Circular error of probability, thickness estimates?
    b. How should this evolve to suit modern needs in the Arctic?
4. **Are standard trajectory products an effective communication strategy?** If not, what needs to be done (i.e., response community, public)?
    a. What are current trajectory products?
    b. How should this evolve to suit modern needs in the Arctic?

Visualization and Uncertainty: Goals

5. **How can model outputs and field data be compared** (e.g., not just visually)?
    a. Do the models accurately predict what actually happens? How can models be adjusted (in forecast cycles) to make predictions better?

Visualization and Uncertainty: Activities/Accomplishments

1. Discussed Variable Grid Method for Visualizing Uncertainty from DOE NETL.
2. Met with key responders and U.S. modelers (NOAA ORR ERD, RPS, USCG, NOAA SSC) to define what responder needs are and to define uncertainty.
3. Overview of visualization systems (e.g., ERMA, CG1View, HSIN).
4. Creation of table delineating uncertainty based on model inputs, response time frame, and data source and how they influence uncertainty of outputs.
5. Determined how models are currently using input data to inform uncertainty.
6. Discussed with NOAA NWS Social and Behavioral Sciences group about preferred visualization schemes.

Visualization and Uncertainty: Activities/Accomplishments

7. Presentations from modelers on uncertainty and visualization:
   a. NOAA GNOME (Barker)
   b. RPS OILMAP/SIMAP (McGrath)
   c. DHI MIKE (Madsen)
   d. Bently Systems MOHID (Fernandes)
   e. Texas A&M University TAMOC (Socolofsky)
   f. TetraTech SpillCalc (Hospital)
   g. MET Canada COSMoS (Marcotte)
   h. NRC Canada (Babaei)

Visualization and Uncertainty: Findings

- **Defined uncertainty and what responder needs are:**
  - Federal On-Scene Coordinators (FOSCs) are concerned with most likely prediction, worst-case scenario, and resulting implications on response operations.
  - A qualitative confidence level at a predefined low, medium, high level is sufficient for most decision making.
    - Modelers usually have a good idea of uncertainty of outputs from a qualitative perspective, but quantifying uncertainty of inputs is challenging.
    - NOAA NWS social scientists suggest that "low, medium, and high" must be defined to reduce converging interpretations of the associated probability/level of concern (e.g., percentage range or clear definition).

Visualization and Uncertainty: Findings

- **Defined uncertainty and what responder needs are:**
  - NOAA OR&R modelers recommend visualizations that include:
    - Color coded, general, qualitative confidence level
    - Clear confidence bounds
    - Summary of missing data
  - Output trajectory analysis maps should have:
    - Areas of high and low concentrations
    - Colored contours for higher and lower thickness estimates
    - Indications of where the actionable oil is
    - Verbal narrative to accompany data/graphics
    - No data to feed model = no graphic

Visualization and Uncertainty: Findings

Spill Trajectory Model Confidence Summary (example)

	Variable	Data Source	Relative Importance	Forecast Periods			
				9/21/20 6:00 9/21/20 12:00	9/21/20 12:00 9/21/20 18:00	9/21/20 18:00 9/22/20 0:00	9/22/20 0:00 9/22/20 6:00
Model Inputs	Wind	IS	5				
	Oil Properties	EST	4				
	Waves	MOD	4				
	Surface Currents	MOD	4				
	Bathymetry	RS	4				
	Water Temperature	IS	3				
	Ice (kilometer-scale)	RS	2				
	Under-Ice Roughness	EST	1				
	Ice (meter-scale)	ND	1	ND	ND	ND	ND
	Subsurface Currents	NA	0				
Model Output	Fate						
	Trajectory						

Issue Date & Time: 9/21/20 5:43

Legend

Data Source (model input)	
IS	*In Situ* Observation
RS	Remote Sensing Observation
MOD	Modeled
EST	Estimated (no data)
ND	No Data (and no estimate)
NA	Not Applicable
Relative Importance (model input)	
5	Very High
4	High
3	Moderate
2	Low
1	Very Low
0	Not Applicable
Confidence Estimate (model input & output)	
	High (% Upper - % Lower)
	Medium (% Upper - % Lower)
	Low (% Upper - % Lower)
ND	None
	Not Applicable (NA)

Visualization and Uncertainty: Findings

Notes and Instructions:	
1	The purpose of this table is to provide Unified Command staff with an easy-to-digest summary of subjective modeler confidence in oil spill trajectory model data from time zero forwards, and to highlight the data needs for improving model results in future runs.
2	Model input variables included in this example table are for illustration only; final variables to be included are TBD.
3	Data source types are shown in order to provide information about where the data came from, which in turn provides clues about data accuracy, spatial extent, and spatial resolution. In general, *in situ* data observations are the most accurate (assuming the instruments used to measure the variable are accurate) and have the best spatial resolution, but are limited in spatial extent to the local area. Remotely sensed data are also accurate, in general, and have large spatial extents, but spatial resolution is often low (e.g., 5 km grid cells for wind data), which may result in limited utility for a spill in a coastal environment with a complex coastline. Data accuracy, spatial scale, and spatial resolution are all important components of a model input variable, but to meet the goal of simplicity, these components were not individually included in this table.
4	The relative importance values for model input variables shown here are for example only. The actual relative importance of a model input variable is incident-specific (e.g., ice data not needed during ice-free season), and would be assigned by the modelers running the model. In the example table shown here, the model input variables were sorted in descending order of relative importance, so the most important input variables are shown first.
5	Forecast periods could be delineated either arbitrarily (e.g, by logistical response operational periods, weather forecast update times) or by natural breaks (e.g., tidal ebb/flow cycles in areas with strong tidal influence), depending upon incident-specific conditions and needs. This determination should be made jointly between Unified Command and modelers.
6	A confidence estimate for a model input variable can be provided even if no data are available, if a reasonable estimate can be made (e.g., via proxy data or correlation). For example, in this table, there are no data available for three model input variables (i.e., oil properties, under-ice roughness, ice at the meter scale, or subsurface currents), but reasonable estimates could be made for the oil properties (e.g., by assumptions based on a vessel type and size) and under-ice roughness (e.g., via correlation with ice age from kilometer-scale ice cover data); no data were available for ice at the meter scale, and no reasonable estimate could be made, so no confidence estimate was provided. In the Confidence Estimate section of the legend, the numbers in parentheses are provided for modelers to enter in each appropriate data cell in the table; these numbers would then be converted to a color by the EU and then provided to the Unified Command.
7	The confidence estimates for the Model Output are the modeler's best subjective opinion on the quality of the model output, which is based upon the quality of the model itself and the quality of the input data. The model output was separated into Fate and Trajectory because these different outputs often have different levels of confidence associated with them.

Visualization and Uncertainty: Research Needs

1. Determine how to put recommendations for visualization into practice (e.g., in ERMA) to create a more integrated model including uncertainty in a common operating picture.
2. Determine the best way to visualize model applications (e.g., for oil spill or ice models) to the layperson.
3. Determine how to mitigate shortfalls in uncertainty with additional input data?
   a. Determine if the uncertainty comes from inputs themselves or lack of inputs and how inputs can be improved to minimize uncertainty?

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Visualization and Uncertainty: Research Needs

4. Determine how to convey the overall picture and fine grain/small scale information to the USCG FOSC using images, tables, etc.
5. Determine how to incorporate modeler experience into outputs?
   a. Model tuning and adjusting, narrative to accompany forecast, quality check based on experience.
6. Determine how numbers can be put on confidence levels.
   a. Present qualitative and quantitative confidence bounds to different end users and see how they interpret it.
   b. Could different definitions of what characteristicsare associated with a given confidence level help?

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Thank you for listening!
Questions?/ Comments?
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APPENDIX J: Oil Spill Model Summary Table*†

* Adapted from combined Excel spreadsheet for readability.

† Some cells were intentionally left blank by the modeler completing the table (no response provided).

Table 16: Oil Spill Model Summary Table.

Model Name	GNOME
Developer	**NOAA OR&R ERD**
Model Purpose (e.g., response, injury assessment), please list all that apply	Spill response modeling (primarily predicting transport of surface spills). Can also be used for modeling transport of other pollutants or drifting objects. Oil Weathering has recently been included, so it will be used for fate analysis in the future. Also used for planning and research.
Who is the typical/intended end user for the model?	
Webpage/URL	https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/response-tools/gnome-suite-oil-spill-modeling.html
Coding Language(s)	Python/C++
Development Status (e.g., beta version, available for use in spills)	Both the older operational desktop version (GNOME) and beta updated version (WebGNOME/PyGNOME) are used routinely for spill response modeling.
Most Recent Update (version # and release date)	Desktop version static since 2017; WebGNOME/PyGNOME are under active development
Source Code (open source license/location, closed source license/location)	Open source (public domain) code available on GitHub.
Use Restrictions (e.g., publicly available)	Model is publicly available to use.
Scale of Operation (local (<10km), regional (>100 km) or global)	Can be used on any scale with appropriate inputs.
Can this model be used for a subsurface release (e.g., well blowout)? If yes, does the model have its own near-field model, or is it coupled to another modeling system (e.g., TAMOC)? What is the name of the near-field model?	Includes support for well-blowout via coupling with TAMOC model. Can also introduce a subsurface spill at any depth and release rate with specified droplet size distribution (rise velocity) or neutrally buoyant particles.
What products (e.g., types of oil) can the model address?	Numerous oils (refined, crude) can be selected from the ADIOS oil database.
Where does the model get information on the properties of spilled oil/products? Can it handle refined and crude products? Does it consider natural gas?	ADIOS oil database includes refined and crude products.
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	Can be used anywhere.

Processing needs	GNOME1 is a single processor desktop application. PyGNOME can be run on a desktop/laptop or in the cloud. WebGNOME uses a browser for user interface, and can be run on a remote server or in the cloud. PyGNOME includes a system to multiprocess multiple runs for uncertainty analysis.
Model Name	**GNOME**
Developer	**NOAA OR&R ERD**
Transport	
Algorithms Not Specific to the Arctic	
Advection (interpolated or uniform)	Particle advection due to currents via 1st, 2nd or 4th order Runge-Kutta (2nd order is default).
Wind Drift	Surface wind effects from user input range of "windage" coefficients with persistence time: tunable spread in the downwind direction (no drift angle).
Diffusion (random walk or random displacement)	Spatially constant horizontal diffusion by random walk. Vertical diffusion by random walk, with ability to set a separate mixed layer diffusion.
Stranding	Beaching and refloating based on refloat "half-life". No shoreline type differentiation within the model, but global half life can be specified.
Vertical Movement: Rise velocity of bubbles/droplets	Particles can have specified rise (or settling) velocities (based on a range) or calculated from droplet sizes and oil density.
Other	
Algorithms Specific to the Arctic	
Advection	Modified by 80/20 rule (>80% ice coverage oil moves with ice velocity, <20% ice coverage oil moves as with no ice, linear interpolation between the extremes.
Wind Drift	Modified by 80/20 rule. (No wind drift > 80%, normal wind drift <20%, reduced linearly in between).
Diffusion	Modified by 80/20 again. No diffusion > 80%, normal <20%, linear in between.
Stranding	No modification. Potential stranding on ice edge not included.
Vertical Movement	No modification.
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for advection	80/20
Sticking to ice	No
Reentrainment under ice	As there is no sticking, there is no reentrainment
Encapsulation	Yes at >80%
Inputs and Source of Data (i.e., what model(s) is used for wind, hydrodynamics, ice velocity, ice concentration, etc.)	Can use output from commonly used hydrodynamic and meteorological models in native format (e.g., ROMS, FVCOM, HYCOM). Have used ice data from HIOMAS and ACNFS but any CF compliant model output should work.

Model Name	GNOME
Developer	**NOAA OR&R ERD**
Weathering	
Algorithms Not Specific to the Arctic	
Evaporation	Evaporation: Pseudo-component model based on distillation data
Emulsification	Emulsification: Modified MacKay et al. (1980)
Dissolution	Under development: simple(ish) method based on droplet size and soluble vs insoluble components.
Biodegradation	Under development: experimental implementation based on droplet size, composition, and temperature (warm or cold). Thrift-Viveros (2015) AMOP Paper.
Sedimentation	Sedimentation: Payne et el. (1987)
Photo-Oxidation	No.
Surface Spreading	
Vertical Movement: Entrainment	Modified Delvigne and Sweeny -- under review.
Other	Dispersion: Modified Delvigne and Sweeney (1988)
Algorithms Specific to the Arctic	
Evaporation	No specific changes to any weathering algorithms -- but the *results* are modified due to reduction in waves/wind effect in presence of ice. Basically 80/20 rule in effect here also.
Emulsification	
Dissolution	
Biodegradation	
Sedimentation	
Photo-Oxidation	
Spreading	Spreading rate modified according to 80-20 rule
Vertical Movement: Entrainment	
Other	
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for weathering	>= 80 -- <= 20
Sticking to ice	
Reentrainment under ice	
Encapsulation	80/20 rule here: >=80 is encapsulated.
Other	
Inputs and Source of Data (i.e., what model(s) is used for weathering inputs)	Oil type, wind speed, water temperature, salinity, sediment load. Use ice concentration and ice velocity from ice forecast models.

Model Name	GNOME
Developer	**NOAA OR&R ERD**
Outputs/Results	
List outputs produced?	all particle properties: e.g. locations, mass, composition, etc. 2D surface density for surface oil (mass / area). particle status: breached, off maps, etc.
Output File Formats	Particle data in netCDF, KMZ, Shapefiles.
Output Visualization (e.g., GIS, PDF Maps)	Within WebGNOME particle can be visualized based on densities (concentration) or oil properties (viscosity etc.). No 3D visualization at present.
Output Visualization Platform (e.g., ERMA, CG1 View)	Visualization supplied in a browser via WebGNOME or ERMA, or with post-processing tools: Google Earth, GIS tools systems, in-house mapping applications (MapRoom)
How is uncertainty shown?	Optional Separate "Uncertain" particles -- uncertainty bound added in post processing.
Limitations (with an emphasis on Arctic specific limitations)	3D applications only supported through scripting. Need to do post-processing for computing visual concentrations.
Suggestions for Improved Arctic Use	Better oil-ice interactions: "holding capacity" and "stripping velocity"
Applications	
What (major) spills has the model been applied to?	DWH, Cosco Busan, many others in US Coastal waters post 1996
Has the model been applied to the Arctic? For what purpose?	For real spills, only in no (low) ice conditions. For planning, used for Arctic TAP: https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/response-tools/trajectory-analysis-planner.html
Has the model been validated to data for oil transport within ice? What datasets?	A little bit by an ADAC project.

Model Name	OILMAP
Developer	**RPS ASA**
Model Purpose (e.g., response, injury assessment), please list all that apply	Emergency oil spill response decision support; Oil spill drills and exercises; Oil spill response training; Pre-positioning of response capabilities; Positioning of loading facilities; Contingency planning; Management of spill-related data; Evaluation of multiple spill scenarios; Hindcasting (mystery spills). Response questions: trajectories; oil weathering; effects of booming, mechanical removal, burning and dispersants on trajectories; Resources at risk; Possible spill sources; Testing Geographic Response Strategies (GRSs). Stochastic modeling - probabilities of oil pathways and timing
Who is the typical/intended end user for the model?	OILMAP is licensed to many users internationally, including industry (e.g., oil companies, response organizations), government agencies (e.g., Canadian = ECCC, CEDRE in France, EMSA), and academic/research organizations. Not sure if any NGOs. The users are response planners. In some places internationally, it is used for risk assessments (based off trajectories and mass balance/oil fate). RPS also performs response-related studies using OILMAP. Australian office uses OILMAP to help the Australian government respond to spills.
Webpage/URL	https://www.rpsgroup.com/search/?q=oilmap
Coding Language(s)	FORTRAN
Development Status (e.g., beta version, available for use in spills)	Used over 3 decades modeling thousands of spills. Simulation can be prepared and run in minutes. Computing resources required is a standard Windows PC
Most Recent Update (version # and release date)	
Source Code (open source license/location, closed source license/location)	Closed source/license
Use Restrictions (e.g., publicly available)	Globally by licensing proprietary source code
Scale of Operation (local (<10km), regional (>100 km) or global)	Can be used on any scale with appropriate inputs.
Can this model be used for a subsurface release (e.g., well blowout)? If yes, does the model have its own near-field model, or is it coupled to another modeling system (e.g., TAMOC)? What is the name of the near-field model?	Coupled to OILMAPDeep nearfield model. Can also introduce a subsurface spill at any depth and release rate with specified droplet size distribution.
What products (e.g., types of oil) can the model address?	Numerous oils (refined, crude) can be selected from OILMAP/SIMAP and the ADIOS oil databases.
Where does the model get information on the properties of spilled oil/products? Can it handle refined and crude products? Does it consider natural gas?	Oil property data have been compiled from the Environment Canada, ADIOS and other public data sets. Crude oils and refined products are included. Natural gas is considered as it influences oil density.

Model Name	OILMAP
Developer	**RPS ASA**
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	Can be used in any marine or freshwater environment.
Processing needs	Can be run on desktop or on a remote server in the cloud. There is a web version of OILMAP
Transport	
Algorithms Not Specific to the Arctic	
Advection (interpolated or uniform)	Oil particles (spillets) moved with 1-3-d time-varying currents, interpolated spatially and temporally. Floating oil moves with surface currents or with ice (see Arctic-specific algorithms).
Wind Drift	Wind drift (user-entered or modeled Stokes drift and Ekman transport)
Diffusion (random walk or random displacement)	Spatially constant horizontal and vertical diffusion by random walk.
Stranding	Stranding subject to shore type-based holding capacity, which varies with oil viscosity
Vertical Movement: Rise velocity of bubbles/droplets	Subsurface oil rises by buoyancy, calculated by oil density relative to water and droplet size
Other	
Algorithms Specific to the Arctic	
Advection	Floating oil moves with surface currents or with ice (see Arctic-specific algorithms). Drift ice (0 - 30%): surface oil moves and spreads as in open water. Marginal Ice Zone (30-80% ice cover): surface oil moves with the ice - dispersion reduced proportionate to ice cover and spreading is constrained by open water area.
Wind Drift	No wind drift > 80%, normal wind drift <30%, moves with ice drift in between.
Diffusion	No diffusion > 80%, normal <30%, linear in between.
Stranding	No modification. Potential stranding on ice edge not included.
Vertical Movement	No modification.
Other	
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for advection	Drift ice 0 - 30% ; Pack ice >80%; Marginal Ice Zone in between
Sticking to ice	No
Reentrainment under ice	As there is no sticking, there is no reentrainment
Encapsulation	> 80% assumed encapsulated
Other	

Model Name	OILMAP
Developer	**RPS ASA**
Transport	
Inputs and Source of Data (i.e., what model(s) is used for wind, hydrodynamics, ice velocity, ice concentration, etc.)	Environmental Data Server software for downloading currents, ice and wind model data products from web and formatting for model input. Currents (2D or 3D; e.g., HYCOM, ROMS, ADCIRC, FVCOM), winds (e.g., NOAA, NOGAPS, ECMWF), ice cover (modeled or observational data), geographic data (bathymetry , shore type), oil properties, scenario specifics. File formats: netCDF and others. Grid types: 2D or 3D, structured or unstructured. Projections: any covered by ESRI software Protocols: time step - daily is insufficient, hourly is best, 3 hourly is acceptable. Need ice and current vectors. RPS can read any model that provides data in a geo-referenced S/Z coordinate-system NetCDF (NC) file format, where ice and currents have been reported on the same grid points, in the same file. If the data is not in this format, RPS needs to prepare NC files in this format, or adapt our code to read the native format. In the past, RPs has used TOPAZ (NERSC) and HYCOM data. RPS has also used geographic information system data, such as from the National Snow and Ice Data Center (https://nsidc.org/) and the BOEM data or Alaska. (Yearly averaged data and minimum, mean, or maximum of monthly data for the 12-year period (1996-2007) were available in 2015 at the website (http://boemre-new.gina.alaska.edu/ Beaufort-sea/landfast-summary). RPS sometimes prepares temporally varying ice cover data in GIS raster type files to use as model input.
Weathering	
Algorithms Not Specific to the Arctic	
Evaporation	Evaporation by pseudocomponents
Emulsification	Based on Mackay et al (1980) model. Emulsification related to maximum water content and wind speed
Dissolution	No tracking of dissolution
Biodegradation	Biodegradation of floating oil, subsurface oil and shoreline oil included at rates typical of these environmental compartments.
Sedimentation	Sedimentation: Payne et el. (1987)
Photo-Oxidation	Not modeled
Surface Spreading	Based on Fay/Holt; also via entrainment and resurfacing
Vertical Movement: Entrainment	Surface wave entrainment moves oil subsurface, facilitated by dispersants. Entrainment of floating oil into water related to wind speed, oil viscosity, interfacial tension.
Other	Density and viscosity increase with weathering.
Algorithms Specific to the Arctic	
Evaporation	No evaporation under ice > 80% , normal if ice <30% , wind speed linear in between, slows process.

Model Name	**OILMAP**
Developer	**RPS ASA**
Weathering	
Emulsification	No evaporation under ice > 80% , normal if ice <30% , wind speed linear in between, slows process.
Dissolution	Not modeled
Biodegradation	Biodegradation of floating oil, subsurface oil and shoreline oil included at rates typical of these environmental compartments. Not changed by presence of ice
Sedimentation	Not changed by presence of ice
Photo-Oxidation	Not modeled
Spreading	Pack Ice (80 - 100%): no spreading; spreading constrained by ice cover in marginal ice zone
Vertical Movement: Entrainment	No entrainment in ice > 80% , normal if ice <30% , wind speed linear in between, slows process.
Other	
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for weathering	Drift ice 0 - 30% ; Pack ice >80%; Marginal Ice Zone in between
Sticking to ice	No
Reentrainment under ice	As there is no sticking, there is no reentrainment
Encapsulation	> 80% assumed encapsulated
Other	
Inputs and Source of Data (i.e., what model(s) is used for weathering inputs)	Oil properties (density, viscosity) as spilled; boiling curve; maximum water content of emulsions
Outputs/Results	
List outputs produced?	3D results over time. Trajectory, concentrations, shoreline oiling locations and amounts, mass balance
Output File Formats	Graphical and animations, pictures and shapefiles, text, netCDF
Output Visualization (e.g., GIS, PDF Maps)	Graphical User Interface developed over 30 years. Windows system or on web
Output Visualization Platform (e.g., ERMA, CG1 View)	
How is uncertainty shown?	Uncertain particles to indicate uncertainty bounds
Limitations (with an emphasis on Arctic specific limitations)	Resolution and accuracy of input data; Does not track gas or dissolved component concentrations.
Suggestions for Improved Arctic Use	Higher resolution input data Real-time ice data
Applications	
What (major) spills has the model been applied to?	EVOS, North Cape, many others in US and international waters post 1984
Has the model been applied to the Arctic? For what purpose?	Yes, for planning and risk assessments
Has the model been validated to data for oil transport within ice? What datasets?	Yes, compared to ice buoy data [French-McCay, D.P., T. Tajalli-Bakhsh, K. Jayko, M. L. Spaulding, and Z. Li, 2018a. Validation of oil spill transport and fate modeling in Arctic ice. Arctic Science 4: 71–97. dx.doi.org/10.1139/as-2017-0027]

Model Name	SIMAP
Developer	**RPS ASA (Debbie French-McCay, director)**
Model Purpose (e.g., response, injury assessment), please list all that apply	Risk assessment and spill response decision support; Dispersant use decision-making; Oil spill drills and exercises; Contingency planning; Evaluation of multiple spill scenarios; Exposure and impact assessments. Response questions: trajectories; oil weathering; effects of booming, mechanical removal, burning and dispersants on trajectories; Tradeoffs of dispersant use; Stochastic modeling - probabilities of oil pathways and timing, including implications of dispersant use.
Who is the typical/intended end user for the model?	SIMAP is used only for "service work", i.e., analyses RPS performs and provides in reports and as data. It has been licensed only to a few groups: MMS/BOEM and ExxonMobil being the only current ones. Even they ask RPS to do analyses for them, and mostly just use the model for quick internal assessments. RPS decided some time back when we had more clients using SIMAP, that it was too complex to support at the cost of licensing and maintenance fees, and more cost effective (and better) for the client to hire RPS to do the work. Otherwise, we recommend they license OILMAP, as mostly that satisfies their need (i.e., for response planning, trajectory analysis).Done a lot of studies using SIMAP for government and industry, also NGOS, and with academics for research studies. Many NRDAs, risk assessments, oil fate analyses, NEBA/SIMA, potential effects, impact assessments.
Webpage/URL	https://www.rpsgroup.com/services/oceans-and-coastal/modelling/products/simap/
Coding Language(s)	FORTRAN
Development Status (e.g., beta version, available for use in spills)	Used over 3 decades modeling thousands of spills. Simulation can be prepared and run in hours. Computing resources required is a standard Windows PC
Most Recent Update (version # and release date)	
Source Code (open source license/location, closed source license/location)	Services
Use Restrictions (e.g., publicly available)	Globally by commissioning studies proprietary source code
Scale of Operation (local (<10km), regional (>100 km) or global)	Can be used on any scale with appropriate inputs.
Can this model be used for a subsurface release (e.g., well blowout)? If yes, does the model have its own near-field model, or is it coupled to another modeling system (e.g., TAMOC)? What is the name of the near-field model?	Coupled to OILMAPDeep nearfield model. Can also introduce a subsurface spill at any depth and release rate with specified droplet size distribution.
What products (e.g., types of oil) can the model address?	Numerous oils (refined, crude) can be used, including those from the OILMAP/SIMAP and the ADIOS oil databases.

Model Name	SIMAP
Developer	**RPS ASA**
Where does the model get information on the properties of spilled oil/products? Can it handle refined and crude products? Does it consider natural gas?	Oil property data have been compiled from the Environment Canada, ADIOS and other public data sets. Crude oils and refined products are included. Natural gas is considered as it influences oil density.
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	Can be used in any marine or freshwater environment.
Processing needs	Can be run on desktop or on a remote server in the cloud. Parallel processing is used for multiple runs and concentration calculations.
Transport	
Algorithms Not Specific to the Arctic	
Advection (interpolated or uniform)	Oil particles (spillets) and dissolved components moved with 1-3-d time-varying currents, interpolated spatially and temporally. Floating oil moves with surface currents or with ice (see Arctic-specific algorithms).
Wind Drift	Wind drift (user-entered or modeled Stokes drift and Ekman transport)
Diffusion (random walk or random displacement)	Spatially constant or 3-D gridded horizontal and vertical diffusion by random walk; also ability to set separate mixed layer diffusion.
Stranding	Stranding subject to shore type-based holding capacity, which varies with oil viscosity
Vertical Movement: Rise velocity of bubbles/droplets	Subsurface oil rises by buoyancy, calculated by oil density relative to water and droplet size
Other	
Algorithms Specific to the Arctic	
Advection	Floating oil moves with surface currents or with ice (see Arctic-specific algorithms). Drift ice (0 - about 30%): surface oil moves and spreads as in open water. Marginal Ice Zone (~30 to ~80% cover; these percentage ice cover thresholds set by model input): surface oil moves with the ice - dispersion reduced proportionate to ice cover and spreading is constrained by open water area.
Wind Drift	No wind drift > 80% or user input, normal wind drift <30% or user input, moves with ice drift in between.
Diffusion	No diffusion > 80% or user input, normal <30% or user input, proportionate to ice cover in between.
Stranding	No modification. Potential stranding on landfast ice edge included if mapped.
Vertical Movement	No modification.
Other	
Ice Processes	Spreading is constrained by open water area
Maximum/minimum thresholds for ice (e.g., 80/20) for advection	Drift ice 0 - 30% by default, model input; Pack ice >80% by default, model input; Marginal Ice Zone in between
Sticking to ice	No
Reentrainment under ice	As there is no sticking, there is no reentrainment
Encapsulation	> 80% or model input percent, assumed encapsulated
Other	

Model Name	SIMAP
Developer	**RPS ASA**
Transport	
Inputs and Source of Data (i.e., what model(s) is used for wind, hydrodynamics, ice velocity, ice concentration, etc.)	Environmental Data Server software for downloading currents, ice and wind model data products from web and formatting for model input. Currents (2D or 3D; e.g., HYCOM, ROMS, ADCIRC, FVCOM), winds (e.g., NOAA, NOGAPS, ECMWF), ice cover (modeled or observational data), geographic data (bathymetry , shore type), oil properties, scenario specifics. File formats: netCDF and others. Grid types: 2D or 3D, structured or unstructured. Projections: any covered by ESRI software Protocols: time step - daily is insufficient, hourly is best, 3 hourly is acceptable. Need ice and current vectors. RPS can read any model that provides data in a geo-referenced S/Z coordinate-system NetCDF (NC) file format, where ice and currents have been reported on the same grid points, in the same file. If the data is not in this format, RPS needs to prepare NC files in this format, or adapt our code to read the native format. In the past, RPs has used TOPAZ (NERSC) and HYCOM data. RPS has also used geographic information system data, such as from the National Snow and Ice Data Center (https://nsidc.org/) and the BOEM data or Alaska. (Yearly averaged data and minimum, mean, or maximum of monthly data for the 12-year period (1996-2007) were available in 2015 at the website (http://boemre-new.gina.alaska.edu/ Beaufort-sea/landfast-summary). RPS sometimes prepares temporally varying ice cover data in GIS raster type files to use as model input.
Weathering	
Algorithms Not Specific to the Arctic	
Evaporation	Evaporation by pseudocomponents
Emulsification	Based on Mackay et al (1980) model. Emulsification related to maximum water content and wind speed
Dissolution	Dissolution by pseudocomponents
Biodegradation	Biodegradation of floating oil, subsurface oil, dissolved oil components and shoreline oil included at rates typical of these environmental compartments.
Sedimentation	Sedimentation: Payne et el. (1987)
Photo-Oxidation	Modeled based on incident light
Surface Spreading	Based on Fay/Holt; also via entrainment and resurfacing
Vertical Movement: Entrainment	Surface wave entrainment moves oil subsurface, facilitated by dispersants. Entrainment of floating oil into water related to wind speed, oil viscosity, interfacial tension.
Other	Density and viscosity increase with weathering.
Algorithms Specific to the Arctic	
Evaporation	No evaporation under ice > 80% or user input, normal if ice <30% or user input, wind speed linear in between, slows process.

Model Name	**SIMAP**
Developer	**RPS ASA**
Weathering	
Emulsification	No evaporation under ice > 80% or user input, normal if ice <30% or user input, wind speed linear in between, slows process.
Dissolution	Not changed from non-ice rates
Biodegradation	Biodegradation of floating oil, subsurface oil, dissolved oil components and shoreline oil included at rates typical of these environmental compartments. Not changed by presence of ice
Sedimentation	Not changed by presence of ice
Photo-Oxidation	Not changed from non-ice rates
Spreading	Pack Ice (80 - 100%): no spreading; spreading constrained by ice cover in marginal ice zone
Vertical Movement: Entrainment	No entrainment in ice > 80% or user input, normal if ice <30% or user input, wind speed linear in between, slows process.
Other	
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for weathering	Drift ice 0 - 30% by default, model input; Pack ice >80% by default, model input; Marginal Ice Zone in between
Sticking to ice	No
Reentrainment under ice	As there is no sticking, there is no reentrainment
Encapsulation	> 80% or model input %, assumed encapsulated
Other	
Inputs and Source of Data (i.e., what model(s) is used for weathering inputs)	Oil properties (density, viscosity) as spilled; boiling curve; composition of volatiles, monoaromatics, PAHs; maximum water content of emulsions
Outputs/Results	
List outputs produced?	3D results over time. Trajectory, concentrations, shoreline oiling locations and amounts, mass balance
Output File Formats	Graphical and animations, pictures and shapefiles, text, netCDF
Output Visualization (e.g., GIS, PDF Maps)	Easily by knowledgeable practitioner. Graphical User Interface developed over 30 years. Windows system or on web
Output Visualization Platform (e.g., ERMA, CG1 View)	
How is uncertainty shown?	Normally perform stochastic modeling with multiple model runs, varying in potential range of inputs
Limitations (with an emphasis on Arctic specific limitations)	Resolution and accuracy of input data; Does not track gas concentrations.
Suggestions for Improved Arctic Use	Higher resolution input data Real-time ice data

Model Name	SIMAP
Developer	**RPS ASA**
Applications	
What (major) spills has the model been applied to?	DWH, EVOS, North Cape, many others in US and international waters post 1984
Has the model been applied to the Arctic? For what purpose?	Yes, for planning and risk assessments
Has the model been validated to data for oil transport within ice? What datasets?	Yes, compared to ice buoy data [French-McCay, D.P., T. Tajalli-Bakhsh, K. Jayko, M. L. Spaulding, and Z. Li, 2018a. Validation of oil spill transport and fate modeling in Arctic ice. Arctic Science 4: 71–97. dx.doi.org/10.1139/as-2017-0027]

Model Name	MEMW
Developer	SINTEF Ocean
Model Purpose (e.g., response, injury assessment), please list all that apply	Transport, fate and effects of oil spill in open and ice covered waters. The Marine Environmental Modeling Workbench (MEMW) includes the Oil Spill Contingency And Response (OSCAR) model and the Dose-related Risk and Effect Model (DREAM). The model includes response options, such a boom, skimmers, dispersant application, Subsurface Dispersant Injection. The commercial model has a GUI, while there is also a version of the model without the GUI that can be scripted for large statistical calculations. The model includes the DeepBlow well blowout model. The model is based on theoretical developments with laboratory, mesoscale and field scale experimental work. The SINTEF Oil Weathering Model is based on extensive analysis of oils in the SINTEF Oil Library.
Who is the typical/intended end user for the model?	The commercial model is used by major oil companies and consulting companies. The model has been tested with field experiments, used operationally (e.g. DWH) and in Damage Assessments (e.g. DWH). The model can be use in (1) oil spill operational response including the oil spill response options, (2) oil spill planning e.g. statistical calculations, (3) oil spill drills, (4) oil spill scenario testing.
Webpage/URL	https://www.sintef.no/en/software/oscar/ and https://www.sintef.no/en/software/dream/ https://www.sintef.no/globalassets/sintef-industri/faktaark/miljoteknologi/oil-weathering-studies.pdf/
Coding Language(s)	Fortran
Development Status (e.g., beta version, available for use in spills)	Commercial model is available for oil spills, and has been used in the past successfully, e.g. DWH. The model is most commonly used with the GUI interface, but other options are possible.
Most Recent Update (version # and release date)	10.0.0 June 6, 2019.
Source Code (open source license/location, closed source license/location)	Commercially licensed software. Research licenses are available. The source code is proprietary, but key algorithms are published in the peer reviewed literature.
Use Restrictions (e.g., publicly available)	Commercial subscription or research subscription.
Scale of Operation (local (<10km), regional (>100 km) or global)	Scale of Operation: local (<10km), regional (>100 km).
Can this model be used for a subsurface release (e.g., well blowout)? If yes, does the model have its own near-field model, or is it coupled to another modeling system (e.g., TAMOC)? What is the name of the near-field model?	The model can be use for surface and subsurface releases. The model contains the DeepBlow well blowout model.
What products (e.g., types of oil) can the model address?	The SINTEF Oil Weathering Model (OWM) is based on the extensive SINTEF oil library.
Where does the model get information on the properties of spilled oil/products? Can it handle refined and crude products? Does it consider natural gas?	The SINTEF Oil Weathering Model (OWM), SINTEF oil library, oil weathering, fate and effects studies and oil/gas field release studies.

Model Name	MEMW
Developer	**SINTEF Ocean**
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	The model can be used anywhere with local data sets for key features, e.g. bathymetry, oil circulation, winds, etc.
Processing needs	The model can be run on a desktop version of a scripted computation core or cloud system.
Transport	
Algorithms Not Specific to the Arctic	
Advection (interpolated or uniform)	The model uses a spillet formulation.
Wind Drift	The user can adjust the windage, with the default at 0.3%, and expected values between 0%-6%. (Beegle-Krause, 2018, Simecek-Beatty, 2011) with wind at U10.
Diffusion (random walk or random displacement)	The random walk scheme is consistent with the diffusivity profile, e.g. Nordam et al (2019), Visser (1997).
Stranding	Oil contacting the shore and remaining is related to the type of shoreline.
Vertical Movement: Rise velocity of bubbles/droplets	Velocities are calculated from oil density and droplet / bubble sizes.
Other	SINTEF Ocean has research departments and one laboratory department that work on oil chemistry, weathering, fate and effects.
Algorithms Specific to the Arctic	
Advection	Surface oil movement is modified at transition ice concentrations.
Wind Drift	Wind drift is not used at high ice concentrations.
Diffusion	See Nordam et al., (2019) "On the use of random walk schemes in oil spill modeling".
Stranding	Oil can strand on the beach. Ice may block oil stranding.
Vertical Movement	Velocities are calculated based on the droplet sizes, vertical diffusivity and vertical water velocities.
Other	Experimental field work on oil-in-ice chemistry and movement. There are many references from laboratory, mesoscale and field scale work.
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for advection	The range of windage values is between 0%-6% (ASCE, 1996, Beegle-Krause, 2018). At 80% ice coverage, the oil is assumed to move with the ice. At 0-30% ice coverage, the oil moves independently of the ice. Nordam et al., (2018) AMOP. Windage is linear between these two values. If ice coverage is available, but not ice velocity, the ice velocity is estimate by v_ice = v_water-surface + 0.015 v_wind_10m.
Sticking to ice	The small scale process of oil sticking to ice is not modeled.
Reentrainment under ice	The oil can reentrain and move under the ice.
Encapsulation	N/A
Other	

Model Name	MEMW
Developer	**SINTEF Ocean**
Transport	
Inputs and Source of Data (i.e., what model(s) is used for wind, hydrodynamics, ice velocity, ice concentration, etc.)	Coastline, bathymetry, currents, waves, wind speed, sea temperature, sea ice coverage, biological resources, oil type, spill rate, location, special conditions, response. SINMOD is SINTEF's own model coupled ice-ocean-plankton model. SINMOD is used for climate, fisheries to oil spill scale simulations. SINTEF has set up detailed output from SINMOD related to oil spills that has more information than the standard output from coupled ice-ocean models. These addition fields are used to improve simulations of oil spills in MEMW (OSCAR and DREAM).
Weathering	
Algorithms Not Specific to the Arctic	
Evaporation	Laboratory and field experiments and the SINTEF OWM.
Emulsification	Laboratory and field experiments and the SINTEF OWM.
Dissolution	Laboratory and field experiments and the SINTEF OWM.
Biodegradation	Biodegradation of oil droplets by components. Next upgrade will include dissolved oxygen consumption by oil component.
Sedimentation	Once the oil becomes heavier than water, the oil will sink.
Photo-Oxidation	Simple process.
Surface Spreading	Based on literature and field experiments.
Vertical Movement: Entrainment	Entrainment by waves.
Other	Two departments that work on oil chemistry and modeling from bench scale to mesoscale. Ice drift, oil-in-ice weathering, field experiments with oil released in temperate waters and with or in ice. Evaporative Loss, Flash Point, Water Content, Viscosity, Surface oil
Algorithms Specific to the Arctic	
Evaporation	Oil Weathering Model.
Emulsification	Oil Weathering Model.
Dissolution	Oil Weathering Model.
Biodegradation	Simple model.
Sedimentation	
Photo-Oxidation	
Spreading	Oil spreading included.
Vertical Movement: Entrainment	Wave entrainment included.
Other	Weathering processes based on field and laboratory studies.
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for weathering	80/20 rule.
Sticking to ice	Not included.
Reentrainment under ice	Not included.
Encapsulation	
Other	

Model Name	MEMW
Developer	**SINTEF Ocean**
Weathering	
Inputs and Source of Data (i.e., what model(s) is used for weathering inputs)	Coastline, bathymetry, currents, waves, wind speed, sea temperature, sea ice coverage, biological resources, oil type, spill rate, location, special conditions, response. SINMOD is SINTEF's own model coupled ice-ocean-plankton model. SINMOD is used for climate, fisheries to oil spill scale simulations. SINTEF has set up detailed output from SINMOD related to oil spills that has more information than the standard output from coupled ice-ocean models. These addition fields are used to improve simulations of oil spills in MEMW (OSCAR and DREAM).
Outputs/Results	
List outputs produced?	Oil mass balance, geographical distribution, chemical transformation, biological implications.
Output File Formats	netCDF CF, binary, images.
Output Visualization (e.g., GIS, PDF Maps)	Full GUI interface.
Output Visualization Platform (e.g., ERMA, CG1 View)	
How is uncertainty shown?	Not calculated.
Limitations (with an emphasis on Arctic specific limitations)	Access to field observations and high quality ice forecasts.
Suggestions for Improved Arctic Use	Lagrangian Coherent Structures. Further oil-in-ice field data.
Applications	
What (major) spills has the model been applied to?	The most recent major application was the DWH oil spill. Since a number of consulting companies and oil companies around the world use the model, we do not have a full list.
Has the model been applied to the Arctic? For what purpose?	The model is used for contingency and planning purposes in the Arctic.
Has the model been validated to data for oil transport within ice? What datasets?	SINTEF has been involved in several oil release experiments in ice covered waters.
Notes	
	Details in differences in output among the different available coupled ice-ocean models is an important consideration for oil spill planning and response. There are also differences among the individual implementations of any MetOcean model between different Users. So the same base model (HYCOM, FVCOM, ROMS, SINMOD, etc.) could be implemented well for use in oil spills by one group, and not implemented will for oil spills by another group. Selection of the resolution, time step, grid and temporal resolution all make differences in the run times and the resolution. The quality of the observations that are assimilated, e.g. satellite maps of ice, ocean surface temperature fields, resolution of wind model output, also make differences in the quality output of the same model by different groups.

Model Name	SPILLCALC
Developer	**Aurelien Hospital, TetraTech**
Model Purpose (e.g., response, injury assessment), please list all that apply	Used for several energy development projects in both east/west coasts of Canada in support of EIA, and HHRA; Used for response planning on the west coast of Canada. Information in support of spill response planning and EIA: - Trajectory and weathering (amount dispersed, evaporated, dissolved, forming OMAs, emulsified...) - Mass Balance - Time to first contact (location on water or shoreline) - Length of shoreline affected - Probability of oil presence, oil thickness (maximum and average)
Who is the typical/intended end user for the model?	Largest clients for SPILLCALC are related to environmental impact assessment, spill response planning and stakeholder engagement. SPILLCALC was initially developed to be an internal (i.e. within the company) tool as an extension to the 3-D hydrotechnical modelling capabilities. Therefore, most clients have requested a study (EIS…) but the use of SPILLCALC itself stayed within the company for years, while the client and other groups/consultants used SPILLCALC's results to build on the next stage of the work (spill response planning, impact…). Over the more recent years, we have enhanced SPILLCALC visuals and practicality in order to present SPILLCALC as a tool that the client can use. Most recent end users are government-related, Transport Canada, for risk assessment and stakeholder engagement purpose. List of clients for large scale projects: Trans Mountain (used to be Kinder Morgan, now bought by Government of Canada) – EIA/HHRA and spill response planning Energy East/Trans Canada Pipelines – EIA/HHRA Transport Canada (Government of Canada) – risk assessment and stakeholder engagement Vancouver Airport – EIA/HHRA Enbridge/Northern Gateway – EIA At a smaller scale: Municipalities (City of Kelowna for example) to understand the risk of having a spill (dissolved hydrocarbons) reaching their source water intake. Stakeholders (Houston, Galveston Bay) to understand the quantity of MTBE that washed ashore and potentially infiltrated groundwater during the March 2015 spill in Galveston Bay. Port of Quebec to provide an understanding of spill fate and behavior if a spill were to occur at the proposed extended port facility (Beauport Extension) Universities (University of Santander, Columbia / University of Estadual Paulista, Brazil) to quantify the fate and behavior of a spill in a large Columbian river during dry/wet season
Webpage/URL	No technical webpage available, except the brochure at https://www.tetratech.com/en/projects/spillcalc-oil-and-contaminant-spill-model
Coding Language(s)	Fortan (model) with some Python for Visualization

Model Name	SPILLCALC
Developer	**Aurelien Hospital, TetraTech**
Development Status (e.g., beta version, available for use in spills)	- Has not been formally used in operational mode. - Tested in operational mode during the Marathassa spill in Vancouver harbor (2015), where positive feedback was received regarding areas where oil was the most concentrated. - Used in multiple projects in hindcast mode to support EIA, HHRA and response planning. - The setup in operational mode is underway for the Salish Sea. - If key data such as oil properties (pseudo-components) and current/ wave/ wind inputs are in proper format, a 2D 'simulation will take 5-10min (dependent on grid size and # of particles), a stochastic model from an hour to a day and a 3D deterministic simulation several hours - Platform: Windows – not tested on Linux - Computing resources: the model runs on a single core. It is not CPU intensive but requires a RAM allocation of 2 GB. Multiple scenarios can be launched at once, assuming the machine is multi-core.
Most Recent Update (version # and release date)	
Source Code (open source license/location, closed source license/location)	Proprietary code with algorithms described in papers and client reports
Use Restrictions (e.g., publicly available)	- Proprietary of Tetra Tech - Algorithms related to transport / weathering are available in past reports and paper publications - Supporting environmental data (wind/ wave/ current) are provided by other public models (SWAN, Delft3D, HYCOM…) - Model can be leased with all data, except the source code
Scale of Operation (local (<10km), regional (>100 km) or global)	Used in local areas (<10 km) and regional area (>100km). Not used on a global scale.
Can this model be used for a subsurface release (e.g., well blowout)? If yes, does the model have its own near-field model, or is it coupled to another modeling system (e.g., TAMOC)? What is the name of the near-field model?	Only for surface spills, no subsurface (well blowout) module currently part of SPILLCALC
What products (e.g., types of oil) can the model address?	Most oil types from heavy oil (diluted bitumen, Bunker C) to crude oils to light crudes and diesel/Jet A
Where does the model get information on the properties of spilled oil/products? Can it handle refined and crude products? Does it consider natural gas?	Detailed chemical breakdown provided by client through lab analysis. SPILLCALC can handle refined and crude products. Natural gas wasn't used so far, but could.
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	It can be used anywhere, as long as a grid can be created and supporting environmental data are available. To-date, SPILLCALC was used in coastal and ocean environments (St Lawrence Estuary, Bay of Fundy, the entire western coast of Canada, northern Columbia) and in riverine environments (Fraser River and St Lawrence River)
Processing needs	SPILLCALC is single-core and can be used on any machine. It requires a limited amount of RAM, about 2GB depending on the domain size and number of particles.

Model Name	SPILLCALC
Developer	**Aurelien Hospital, TetraTech**
Transport	
Algorithms Not Specific to the Arctic	
Advection (interpolated or uniform)	Lagrangian approach
Wind Drift	Wind drift (user can update/modify the wind drift coefficient)
Diffusion (random walk or random displacement)	Horizontal diffusion through random walk
Stranding	Stranding on shore is part of the model. Each shoreline segment has its own characteristic (shore type, length, width and potential maximum oil retention)
Vertical Movement: Rise velocity of bubbles/droplets	Subsurface oil (driven underwater by wave action) mixes throughout the surface layer when strong wave activity, rises by buoyancy when conditions calm down and moves with currents
Other	Inclusion of molecular diffusion as part of the evaporation process: important in the first few hours of the spill when looking at heavy products (diluted bitumen for example)
Algorithms Specific to the Arctic	
Advection	Vertical dispersion parameter: '- 0-30% ice coverage: oil behaves as if ice was not present and no modification of wave condition - 30-80% ice coverage: wave height reduced based on a reduction factor. Reduction by 0% when ice coverage is 30%, reduction by 50% when ice coverage is 55% and reduction by 100% when ice coverage is 80%. - 80-100% ice coverage: vertical entrainment does not occur, i.e. waves do not develop. - The vertical dispersion transport item also impacts the weathering
Wind Drift	80-100% ice coverage: - Oil under ice adheres to ice surface; oil mainly drifts with ice (assumed to be 2% of the wind speed - this is an input parameter); - When under-ice currents become greater than the stripping velocity, oil detaches from ice and travels at reduced speed with under-ice currents. - Stripping velocity based on Buist et el. (2009). The stripping velocity is based on fresh oil, not weathered. When the oil viscosity is greater than a set value, then it is assumed that the oil is attached to the ice and cannot detach, regardless of the under-ice current speed. - Oil travel speed under-ice when under-ice currents above stripping velocity based on Cox and Schultz (1980)
Diffusion	Not modified
Stranding	If the ice coverage is >80% then no stranding of the oil on shore takes place.
Vertical Movement	
Other	No wave when ice coverage more than 80%. Linear reduction in wave height when ice between 30 and 80%.

Model Name	SPILLCALC
Developer	**Aurelien Hospital, TetraTech**
Transport	
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for advection	Trajectory parameter: 0-30% and 30-80% ice coverage: - Surface currents are slightly to significantly affected by the presence of ice. Effect of ice on the current component of the oil trajectory is incorporated through the ice stress calculation in the 3D hydro model.
Sticking to ice	When ice coverage is greater than 80%
Reentrainment under ice	When under-ice current speed greater than stripping velocity, then the oil detaches from the ice, is reentrained in the water and travels at reduced speed underneath the ice with current.
Encapsulation	
Other	
Inputs and Source of Data (i.e., what model(s) is used for wind, hydrodynamics, ice velocity, ice concentration, etc.)	Shoreline data provided by provincial/national database, indicating shoreline length, width and type (rocky, sand...). Wind/current/waves provided by other models on a gridded basis (ex: SWAN, Delft3D, HYCOM, FVCOM…). Format: binary format or ASCII format. NetCDF format in SPILLCALC underway. - Source for wind: GFS / WRF / CALPUFF / Interpolation based on observed station data - Source for current: Delft3D / HYCOM / FVCOM / H3D… - Source for wave: SWAN / WAVEWATCHIII - Source for ice conditions: observed ice charts (from Canadian Ice Center). - Format of data: matrix (dimensions m x n) indicating the interpolated ice coverage and computed wave/current/wind for each model grid cell. This ice coverage interpolation step can be done quite readily in GIS by superposing the model grid with ice maps. Similarly the same matrix can be produced for (u,v) wind/current as well as Hs/Tp.
Weathering	
Algorithms Not Specific to the Arctic	
Evaporation	Evaporation based on the pseudo-component approach
Emulsification	Water uptake and emulsion stability based on Mackay et al (1980) and Mackay and Zagorsky (1982). Impact of emulsion on evaporation based on Ross and Buit (1995)
Dissolution	Mass transfer coefficient for dissolution provided by Mackay and Leinonen (1977)
Biodegradation	SPILLCALC uses a time- and mass-dependent decay process since bacterial population is usually unknown.
Sedimentation	Payne et al (1987) OMA forming based on i) oil concentration within a cell, ii) suspended sediment concentration and iii) mixing energy
Photo-Oxidation	Not included

Model Name	SPILLCALC
Developer	**Aurelien Hospital, TetraTech**
Weathering	
Surface Spreading	
Vertical Movement: Entrainment	Delvigne and Sweeney (1988) for the entrainment / Tkalich and Chan for the resurfacing of the oil Wave conditions provided by a full wave model (SWAN/WaveWatchIII). No dispersant part of the model yet
Other	Classic suite of weathering processes (evaporation, vertical dispersion and resurfacing, emulsification, dissolution, shoreline retention, oil-mineral interaction, sinking). - Pseudo-component approach based on oil within a grid cell and updated every timestep (~10min) - Shoreline retention based on shore type/oil viscosity - Molecular diffusion for evaporation (application for thick slick and viscous oil) - Spill response: hourly potential recovery, skimming, deflection boom can be used as inputs - Resurfacing of the oil modelled when the mixing energy reduces.
Algorithms Specific to the Arctic	
Evaporation	Evaporation: - 0-30% ice coverage: evaporation occurs normally - 30-80% ice coverage: the area available for evaporation is reduced, based on a reduction factor (same as transport algorithm) - 80-100% ice coverage: no evaporation occurs
Emulsification	Emulsification: less mixing energy, due to reduction in wave height
Dissolution	Dissolution: indirectly affected by the presence of ice. Lighter hydrocarbon fractions might not evaporate due to ice cover, hence are available for dissolution.
Biodegradation	SPILLCALC uses a time- and mass-dependent decay process since bacterial population is usually unknown.
Sedimentation	Sedimentation is part of the model, but nothing specific to the Arctic
Photo-Oxidation	No photo-oxidation in the model
Spreading	No specific spreading impact aside from the 80/20 rule
Vertical Movement: Entrainment	Entrainment can be reduced due to the reduction in wave energy. For example: 80%+ ice coverage results in no wave developing in the model, therefore no vertical entrainment (except having the oil underneath the ice)
Other	Shoreline contact: no longer possible if ice cover is total
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for weathering	< 20% ice coverage: no ice impact >80% ice coverage: full ice impact on weathering (for example: no wind stress on oil…)
Sticking to ice	When ice coverage is greater than 80%

Model Name	SPILLCALC
Developer	**Aurelien Hospital, TetraTech**
Weathering	
Reentrainment under ice	When under-ice current speed greater than stripping velocity, then the oil detaches from the ice, is reentrained in the water and travels at reduced speed underneath the ice with current.
Encapsulation	
Other	
Outputs/Results	
List outputs produced?	GIS maps and Tecplot format: - Probability of Oil Presence on Surface after 6hrs / 12hrs / 24hrs / 48hrs / end of simulation (stochastic mode) - Probability of Oil Contacting each shoreline segment at the end of the simulation (stochastic mode) - Trajectory of oil particles (deterministic mode) - Amount of oil retained by each shoreline segment - Maximum concentration of dissolved oil in surface layer (2-D plan view in stochastic mode) GIS / ASCII (text) / JPEG results Graphical mass balance Time series (ASCII text format): - Mass balance, density and viscosity - Length of shoreline oiled - Statistics (text format) on current speed, wind speed and wave height over the period of record at any given point of the model domain. This output is independent of the spill modelling but provides useful metocean information to spill responders.
Output File Formats	Maps are in GIS format and Tecplot format. Maps can also be output for a MATLAB graphical plot. NetCDF format under development (expected to be operational by early 2021). Time series are in a plain text format.
Output Visualization (e.g., GIS, PDF Maps)	ArcGIS/ QGIS (Free) will display the results on a map. Text file can be opened with Notepad and imported in Excel for analysis. MATLAB/Tecplot can also analyze the results, both time series and maps.
Output Visualization Platform (e.g., ERMA, CG1 View)	Visualization platform: GIS, MATLAB and Tecplot.
How is uncertainty shown?	Uncertainty in forecast is shown through a number of simulations based on deviations from the wind forecast (in terms of direction and speed). The trajectories from these simulations is overlaid on the main forecast trajectory (directly based on wind forecast) and presents the potential deviation due to forecast uncertainty. No specific uncertainty characterization for the arctic.

Model Name	SPILLCALC
Developer	**Aurelien Hospital, TetraTech**
Outputs/Results	
Limitations (with an emphasis on Arctic specific limitations)	Main limitations: - When ice cover exceeds 80%, the oil drifts with ice and assumes 2% of the wind speed (or any value given by the modeler in the input file). The drift value should be based on a stress balance between wind drag and current drag; or perhaps should correspond to the ice drift value computed in the ice model. - Independent of SPILLCALC: the SWAN wave model does not take into account the ice, hence the wave field might appear as fully developed, when in fact it couldn't due to the presence of ice. SPILLCALC is partially addressing this wave model limitation by reducing the wave height based on ice coverage. - The use of dispersant is not part of the model yet. - SPILLCALC is not set up for deep sea blowout, instead only focuses on surface spills. - No remobilization is accounted after the oil hits the shore.
Suggestions for Improved Arctic Use	1. Better understand stripping velocity 2. Update the ice drift value 3. Consideration of additional processes related to oil-ice interaction such as encapsulation of oil in the ice sheet and its migration towards the surface of the ice not yet developed
Applications	
What (major) spills has the model been applied to?	The model has primarily been used for planning and Environmental Impact Assessments. Documents on SPILLCALC available in the National Energy Board of Canada and in various conference proceedings (main one being AMOP). For real spills, SPILLCALC has been used during the Marathassa incident in Vancouver (2015) and the Houston MTBE spill (2015).
Has the model been applied to the Arctic? For what purpose?	The model has been used in the Gulf of the St Lawrence during winter conditions, but not in the Arctic
Has the model been validated to data for oil transport within ice? What datasets?	Not validated for oil transport within ice

Model Name	OpenDrift/OpenOil
Developer	**MET Norway**
Model Purpose (e.g., response, injury assessment), please list all that apply	OpenDrift/OpenOil
Who is the typical/intended end user for the model?	MET Norway
Webpage/URL	Predict where oil will drift and how its properties will change to assist cleanup Designed for operational use and scientific studies. Where will (or may) the oil be in 24 hours? Which part of the coastline might be affected? Is the oil submerged or at the surface?
Coding Language(s)	In Norway there are two main end-users for oil drift simulations: The national (governmental) coastal administration (www.kystverket.no), and NOFO (The Norwegian Clean Seas Association for Operating Companies, www.nofo.no). They run OpenOil through a web interface, but MET Norway forecasters can also do it for them on demand (24/7 service, with 30 min response time).
Development Status (e.g., beta version, available for use in spills)	https://opendrift.github.io/
Most Recent Update (version # and release date)	Python
Source Code (open source license/location, closed source license/location)	Used operationally at Norwegian Meteorological Institute for oil, search&rescuse and ship-drift. Pure Python, install with anaconda. Platform independent (Linux, Mac, Windows). Bottleneck is normally Input-Output (reading 3D ocean model data from file or remote Threddsserver)
Use Restrictions (e.g., publicly available)	Version #1.3.1 released 2020-07-03, but nearly daily updates of code on GitHub
Scale of Operation (local (<10km), regional (>100 km) or global)	Open source (public domain) code available on GitHub.
Can this model be used for a subsurface release (e.g., well blowout)? If yes, does the model have its own near-field model, or is it coupled to another modeling system (e.g., TAMOC)? What is the name of the near-field model?	Openly available from GitHub GPL2 License
What products (e.g., types of oil) can the model address?	Can be used on any scale with appropriate inputs.
Where does the model get information on the properties of spilled oil/products? Can it handle refined and crude products? Does it consider natural gas?	Basic well blowout functionality included. 3rd party user has integrated OpenDrift with TAMOC, and this coupling will be available in the main repository in the near future.

Model Name	**OpenDrift/OpenOil**
Developer	**MET Norway**
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	OpenOil is coupled to the NOAA ADIOS database, and can thus use all oils there.
Processing needs	Supports any machine size, and both Linux, OS X and Windows. Output is flushed to disk during simulation, so that there is no upper limit to the size of the simulation request (duration/number of timestep, number of oil elements).
Transport	
Algorithms Not Specific to the Arctic	
Advection (interpolated or uniform)	Particle advection due to currents via 1st, 2nd or 4th order Runge-Kutta (1st order is default).
Wind Drift	Default is 2% windage, plus Stokes Drift. Stokes Drift is optional, and windage should be increased to 3.5 percent if omitted.
Diffusion (random walk or random displacement)	Spatially constant horizontal diffusion by random walk. Vertical diffusion by random walk, with ability to set a separate mixed layer diffusion.
Stranding	Default is that oil elements stick to shore, independent of the type of shoreline.
Vertical Movement: Rise velocity of bubbles/droplets	Particles can have specified rise (or settling) velocities (based on a range) or calculated from droplet sizes and oil density.
Other	
Algorithms Specific to the Arctic	
Advection	Two schemes are implemented for drift of oil-in-ice: Nordam (2019) and Arneborg (2018), each modifying the percentage of advection/windage.
Wind Drift	As described under advection.
Diffusion	As described under advection.
Stranding	No modification. Model can be configured so that oil will strand on ice, as alternative to drifting with ice.
Vertical Movement	No modification.
Other	
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for advection	80/20
Sticking to ice	No
Reentrainment under ice	As there is no sticking, there is no reentrainment
Encapsulation	Yes at >80%
Other	

Model Name	OpenDrift/OpenOil
Developer	**MET Norway**
Transport	
Inputs and Source of Data (i.e., what model(s) is used for wind, hydrodynamics, ice velocity, ice concentration, etc.)	"The most common is to read forcing data (currents, wind, temperatures, ice...) from netCDF files, often directly from remote OPeNDAP/Thredds-servers. The map projection is detected automatically from CF-compatible sources, and reprojection and vector rotation is performed automatically. Sources of global currents include ths.hycom.org and www.cmems.eu, and global NCEP wind fields are available e.g. through a Thredds server at www.pacioos.hawaii.edu. Local or regional high-resolution models are however preferred for the short term simulations, and the Norwegian Meteorological Institute would normally use in house ocean, atmospheric and wave models from thredds.met.no. Sources of ice information would normally be the same models as provide currents. Also using the TOPAZ ocean model: https://resources.marine.copernicus.eu/?option=com_ csw&view=details&product_id=ARCTIC_ANALYSIS_FORECAST_PHYS_002_001_a Shoreline from ocean model may be used for the stranding, but default is to use the global GSHHG shoreline at full resolution, which is included within OpenDrift. Forcing data may also be ingested from other formats (modular reader mechanism), and plain text or csv files is used e.g. for in situ measurements as alternative to numerical models."
Weathering	
Algorithms Not Specific to the Arctic	
Evaporation	Essentially the same as in GNOME
Emulsification	Essentially the same as in GNOME
Dissolution	Not implemented.
Biodegradation	Simple relationship based on temperature and age only (Adcroft et al. (2010), Simulations of underwater plumes of dissolved oil in the Gulf of Mexico.)
Sedimentation	No, but can be configured so that oil hitting seafloor is deactivated.
Photo-Oxidation	No
Surface Spreading	No
Vertical Movement: Entrainment	Based on Li (2017)
Other	
Algorithms Specific to the Arctic	
Evaporation	No specific changes to the Arctic
Emulsification	No specific changes to the Arctic
Dissolution	No specific changes to the Arctic
Biodegradation	No specific changes to the Arctic

Model Name	**OpenDrift/OpenOil**
Developer	**MET Norway**
Weathering	
Sedimentation	No specific changes to the Arctic
Photo-Oxidation	No specific changes to the Arctic
Spreading	No specific changes to the Arctic
Vertical Movement: Entrainment	No specific changes to the Arctic
Other	None, but temperature is included in parameterizations
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for weathering	80/20
Sticking to ice	No
Reentrainment under ice	As there is no sticking, there is no reentrainment
Encapsulation	Yes at >80%
Other	
Inputs and Source of Data (i.e., what model(s) is used for weathering inputs)	Oil type and properties are obtained from the NOAA ADIOS database. Wind speed, water temperature and possibly ice concentration/velocity is normally obtained from ice/ocean forecast models (as uses for the drift), but reasonable default values are provided, and may be adjusted by the user. Wave height and period is used for water entrainment, but this is parameterized from wind if not available.
Outputs/Results	
List outputs produced?	CF-compliant netCDF files are produced, containing all available information: configuration settings, and the position and properties of each element at each time step, as well as the environmental variables (wind, current...) for each element and time step. These netCDF may be re-imported later, for further analysis or plotting. Functions are available to produce MP4/GIF-animations (individual particles or density) and plots with trajectories. Any forcing field (e.g. current) can be used as background to the plots and animations, and the lines and particles can be colored with any property, e.g. the depth or the viscosity of the oil particle. A graphical representation of the oil budget can be made, and can also be obtained numerically. Examples of the output provided are found on https://opendrift.github.io
Output File Formats	netCDF following CF-convention for trajectory data. Using simple 2D structure (particle, timestep). netCDF (native), PNG (trajectory plots, oil budget plot, etc.), MP4/GIF (trajectory animation), GeoTiff/KML (particle density plot)
Output Visualization (e.g., GIS, PDF Maps)	GeoTiff can be visualized by GIS systems, which can also be used to produce WMS layers
Output Visualization Platform (e.g., ERMA, CG1 View)	
How is uncertainty shown?	Only through the spread of elements/particles.
Limitations (with an emphasis on Arctic specific limitations)	Rather basic algorithms, and output has not been validated against independent observations.
Suggestions for Improved Arctic Use	More detailed interaction with ice

Model Name	**OpenDrift/OpenOil**
Developer	**MET Norway**
Applications	
What (major) spills has the model been applied to?	DWH (scientific studies afterwards), several controlled oil spill releases in the North Atlantic/North Sea.
Has the model been applied to the Arctic? For what purpose?	OpenOil has not been applied to real spills in the Arctic, but several other OpenDrift modules (fish eggs, search&rescue, plastics...) have been used in the Arctic.
Has the model been validated to data for oil transport within ice? What datasets?	No

Model Name	COSMoS
Developer	Canadian Centre for Meteorological and Environmental Prediction, National Operations Division, Environmental Emergency Response Section (Lead: Guillaume Marcotte)
Model Purpose (e.g., response, injury assessment), please list all that apply	Operational uses (guidance for response resource deployment, small (few 100s L) to large spills (thousands tons), environmental protections response in Canadian waters). Use extended to drifting objects and Search and Rescue applications (in development).
Who is the typical/intended end user for the model?	Client is internal. It is another branch of Environment and Climate Change called the National Environmental Emergency Centre (NEEC). This is the group that will use, diffuse and communicate model results to relevant actors on the field, typically Canadian Coast Guard and the polluter. They are also responsible for international communication with US during spill events near the Canada-US border (mainly in the Great Lakes and Saint Lawrence river areas). Our models rarely make it to the public. Having a single client allows the product to be tailored to their needs.
Webpage/URL	None
Coding Language(s)	TCL/Tk and C
Development Status (e.g., beta version, available for use in spills)	Under development, beta version used in parallel response 36 - 48 h, 500k Les; 8 MPI processes, 10 OMP threads each; About 10 min to preprocess input
Most Recent Update (version # and release date)	No stable version released yet. Current beta (development version on 2020-07-30): model version 3.4.0, libraries version 3.4.1, interface version 8.1.0
Source Code (open source license/location, closed source license/location)	Open Government of Canada license (https://open.canada.ca/en/open-government-licence-canada) and LGPL 2.1
Use Restrictions (e.g., publicly available)	To be broadly opened, currently available on demand
Scale of Operation (local (<10km), regional (>100 km) or global)	5 m to planetary, depending on the availability of input fields
Can this model be used for a subsurface release (e.g., well blowout)? If yes, does the model have its own near-field model, or is it coupled to another modeling system (e.g., TAMOC)? What is the name of the near-field model?	Coupling with TAMOC model under development. TAMOC+COSMoS should be available before March 2021.
What products (e.g., types of oil) can the model address?	NOAA library completed with ECCC oil library. Requires complete entries, i.e. density, viscosity, distillation, SARA and interfacial tension
Where does the model get information on the properties of spilled oil/products? Can it handle refined and crude products? Does it consider natural gas?	Oil information from NOAA oil library + ECCC oil physicochemical database. Include refined and crude oils.
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	Can be used where data is available (no currents estimation included)

Model Name	COSMoS
Developer	**Canadian Centre for Meteorological and Environmental Prediction, National Operations Division, Environmental Emergency Response Section (Lead: Guillaume Marcotte)**
Processing needs	Parallelized in MPI and OMP standards. Runs with 1 or several processors. Current beta is developed for Ubuntu 18.04 LTS (Linux) and uses 80 processors (8 MPI tasks with 10 OMP threads each). 36 h forecast runs in less than 20 min (7-12 min required for input field preprocessing).
Transport	
Algorithms Not Specific to the Arctic	
Advection (interpolated or uniform)	Direct Euler or Runge-Kutta 4th order. Default is RK4.
Wind Drift	Surface wind fraction specified by user. Default 2% with explicit Stokes drift.
Diffusion (random walk or random displacement)	Constant horizontal diffusion with added diffusivity in strong horizontal shear. Independent vertical diffusion. Both implemented as random walk with a truncated probability distribution to avoid large unphysical perturbations.
Stranding	Beaching and refloating based on a statistical implementation of 1st order kinetics. Half-life constant, oil capacity and deposition velocity classified in 5 different shoreline types based on a survey of Canadian coastlines.
Vertical Movement: Rise velocity of bubbles/droplets	Rise velocity calculated from density difference (buoyancy). Droplet size is derived from oil viscosity, interfacial tension and energy from waves.
Other	
Algorithms Specific to the Arctic	
Advection	Same as GNOME (translated from the available version on Github). Upper limit defined at 75% for consistency with wave forecasting systems.
Wind Drift	Same as GNOME (translated from the available version on Github). Upper limit defined at 75% for consistency with wave forecasting systems.
Diffusion	No modification with ice
Stranding	No modification with ice. Ice is not defined as a surface for available for stranding.
Vertical Movement	Waves are heavily dampened with ice, thus preventing droplet formation. Otherwise, no modification.
Other	
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for advection	75/20
Sticking to ice	No
Reentrainment under ice	No
Encapsulation	Not really. Oil is considered at the air-water interface at coverage > 75%, but there is no explicit encapsulation in ice if it means incorporation of oil in the bulk of ice.
Other	

Model Name	COSMoS
Developer	**Canadian Centre for Meteorological and Environmental Prediction, National Operations Division, Environmental Emergency Response Section (Lead: Guillaume Marcotte)**
Transport	
Inputs and Source of Data (i.e., what model(s) is used for wind, hydrodynamics, ice velocity, ice concentration, etc.)	Canadian forecast data from operational systems used in COSMoS found at: https://dd.meteo.gc.ca/ From ice-ocean models (NEMO, FVCOM, ROM, CICE, etc.) : 2D or 3D currents, ice fraction, ice velocity, water temperature, salinity, oil properties, water column height. From wave models (WWIII): Stokes transport, significant wave height. From atmospheric models: surface winds, wave fields (when no wave model available at specified location, wave information is derived from fetch with OpenStreetMap coastlines), surface temperature (when not available from an ocean model, surface analysis is used). Coastline classification: https://open.canada.ca/data/en/dataset/27515ccc-0cad-4f7d-b8ab-2a909090f128 https://open.canada.ca/data/en/dataset/30449352-2556-42df-9ffe-47ea8e696f91 https://open.canada.ca/data/en/dataset/1c61d457-4d03-4f3a-9005-9aabb5a201bb https://open.canada.ca/data/en/dataset/09051eee-c28a-4746-8033-8e85815f4c73 https://open.canada.ca/data/en/dataset/ba580518-59e8-4d1c-b3ef-41d2658e6965
Weathering	
Algorithms Not Specific to the Arctic	
Evaporation	Evaporation flux calculated for each fraction of the distillation curve
Emulsification	Emulsification based on Fingas and Fieldhouse composition model
Dissolution	None
Biodegradation	None
Sedimentation	None
Photo-Oxidation	None
Surface Spreading	Based on the first and second flow regimes of Fay. Implemented as a pseudo-diffusion (from NOAA technical documentation).
Vertical Movement: Entrainment	Entrainment, inhibited mass deposition to shorelines, beaching
Other	Dispersion: Mixed Johansen et al. 2015 Mar. Poll. Bull. 93, 20-26 with Li et al. 2017 Mar. Poll. Bull. 119, 145-152.
Algorithms Specific to the Arctic	
Evaporation	No modification, but evaporation would be slowed by the reduction of oil area exposed to the atmosphere.
Emulsification	The decrease in wave energy associated with ice coverage prevents further emulsification. Emulsions weather normally.
Dissolution	No change expected.
Biodegradation	N/A

Model Name	COSMoS
Developer	**Canadian Centre for Meteorological and Environmental Prediction, National Operations Division, Environmental Emergency Response Section (Lead: Guillaume Marcotte)**
Weathering	
Sedimentation	No change expected.
Photo-Oxidation	N/A
Spreading	Spreading limited by ice coverage and pour point.
Vertical Movement: Entrainment	Entrainment limited in absence of waves
Other	
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for weathering	75/20
Sticking to ice	None
Reentrainment under ice	No
Encapsulation	None
Other	
Inputs and Source of Data (i.e., what model(s) is used for weathering inputs)	Oil information typically taken from: https://open.canada.ca/data/en/dataset/e7dd9382-21b2-46dc-98fb-7d71fcf14130 Mandatory: surface winds, surface currents, sea surface temperature, location, oil type (density, viscosity, distillation). Nice to have: 3D currents, water salinity, water depth (model), marine ice fraction, ice velocity, Stokes drift and transport, sign. wave height, full oil database entry. Optimized for internal binary format, possible to use netCDF with converter
Outputs/Results	
List outputs produced?	Particle based: coordinates (lat, lon, depth), viscosity, emulsion type, state (active, dead, out of grid), density, mass repartition (surface, evaporated, entrained, beached). Gridded: concentration (surface or 3D), particle number per grid cell, evaporative flux (instantaneous and integrated), deposited mass to shorelines (instantaneous and integrated), viscosity.
Output File Formats	ESRI shapefiles, png, jpeg, MP4, geojson, geopackage, csv, gif, and native (binary)
Output Visualization (e.g., GIS, PDF Maps)	In any GIS (georeferenced format) or browser (snapshots or animations)
Output Visualization Platform (e.g., ERMA, CG1 View)	Browser-based java loop, any GIS or MP4 player, internal scientific GIS.
How is uncertainty shown?	Under development, probably color coded.
Limitations (with an emphasis on Arctic specific limitations)	Missing some fate processes, issues with code availability, requires Linux machine, runs only with internal binary format
Suggestions for Improved Arctic Use	Free ice drift when ice concentration reported but out of ice model, oil-ice specific interaction (e.g. stickiness, encapsulation and under ice movement with ice blocks or frazil), evaporation and thickness of oil-in-ice, cold water processes (tar balls, pour point, windows of opportunity)

Model Name	**COSMoS**
Developer	**Canadian Centre for Meteorological and Environmental Prediction, National Operations Division, Environmental Emergency Response Section (Lead: Guillaume Marcotte)**
Applications	
What (major) spills has the model been applied to?	None operationally, verified with Bella Bella and Hibernia events in Canada. Verification with Norwegian field experiment planned.
Has the model been applied to the Arctic? For what purpose?	2 cases in Canadian Arctic to date. Both out of the ice-ocean model coverage.
Has the model been validated to data for oil transport within ice? What datasets?	No. The model is used to validate ice drift against ice buoys, but nothing for oil in ice.

Model Name	National Research Council Canada Model
Developer	**Hossein Babaei**
Model Purpose (e.g., response, injury assessment), please list all that apply	Estimate surface trajectory of oil-in-ice covered waters.
Who is the typical/intended end user for the model?	Research model so far and hasn't yet been used by anyone outside of NRC.
Webpage/URL	NA
Coding Language(s)	C++
Development Status (e.g., beta version, available for use in spills)	The model has been under development from 2015 to 2019. It hasn't been operationally used. However, three separate studies have been conducted to validate the model for a few spill and ice trajectory studies. The model currently runs on Windows and is designed for surface trajectories only.
Most Recent Update (version # and release date)	The model has been used for contingency planning and EIA in the Barents Sea.F74:M79
Source Code (open source license/location, closed source license/location)	Can be freely distributed under an agreement such as GNU GPL after discussions with interested parties.
Use Restrictions (e.g., publicly available)	Willing to discuss ways to make this model available for interested parties to test, run, share, and modify
Scale of Operation (local (<10km), regional (>100 km) or global)	Local and regional
Can this model be used for a subsurface release (e.g., well blowout)? If yes, does the model have its own near-field model, or is it coupled to another modeling system (e.g., TAMOC)? What is the name of the near-field model?	No
What products (e.g., types of oil) can the model address?	The latest version of the model only requires oil density and viscosity, among oil properties.
Where does the model get information on the properties of spilled oil/products? Can it handle refined and crude products? Does it consider natural gas?	The latest version of the model only requires oil density and viscosity. The two properties can be manually input.
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	It is a regional and smaller scale model. The model can be adopted for any location.
Processing needs	Currently only runs in scalar mode (not parallel). It is embedded in an in-house data linking, processing and visualization software.

Model Name	National Research Council Canada Model
Developer	**Hossein Babaei**
Transport	
Algorithms Not Specific to the Arctic	
Advection (interpolated or uniform)	Simple advection by the current in open waters.
Wind Drift	NA
Diffusion (random walk or random displacement)	NA
Stranding	NA
Vertical Movement: Rise velocity of bubbles/droplets	NA
Other	It computes the terminal spreading of the oil in open water
Algorithms Specific to the Arctic	
Advection	By current if ice coverage is < 30%, solely by ice if it is > 80% and based on a weighted averaged velocity field for coverages in-between. If the current is fast, under-ice oil will be mobilized with respect to the ice and moves with the current.
Wind Drift	Wind impacts the ice motion that is an input to the model.
Diffusion	NA
Stranding	NA
Vertical Movement	NA
Other	Use first module when oil and ice move together (high ice concentration and rough underside of ice) Second module: Takes into account the possibility of the mobilization of oil in contact with ice underside with respect to the ice Advects oil by the ice, or the current, or a combination of both depending on the ice coverage Computes oil thickness in leads, under- and over-ice Computes the pumping of oil from leads to under, or onto ice with closing leads
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for advection	Advection by current if ice coverage is < 30%, solely by ice if it is > 80% and based on a weighted averaged velocity field for coverages in-between.
Sticking to ice	Yes, if the oil in under-ice, it moves with it unless current is very fast.
Reentrainment under ice	NA
Encapsulation	NA (but the oil will/could move with ice)
Other	
Inputs and Source of Data (i.e., what model(s) is used for wind, hydrodynamics, ice velocity, ice concentration, etc.)	First module inputs: structured-grid ice velocity, and landfast ice extent. Second module inputs: spatially and temporally variable structured-grid ice thickness, concentration, velocity, and surface current, and average floe diameter and under-ice surface roughness along with other ice and oil properties. The info on ice is currently provided by an in-house ice drift and dynamics model. Environmental input data sources for wind are CMC and NOAA and for water current, CMC, NOAA and BIO.

Model Name	**National Research Council Canada Model**
Developer	**Hossein Babaei**
Weathering	
Algorithms Not Specific to the Arctic	NA
Evaporation	
Emulsification	
Dissolution	
Biodegradation	
Sedimentation	
Photo-Oxidation	
Surface Spreading	
Vertical Movement: Entrainment	
Other	
Algorithms Specific to the Arctic	NA
Evaporation	
Emulsification	
Dissolution	
Biodegradation	
Sedimentation	
Photo-Oxidation	
Spreading	
Vertical Movement: Entrainment	
Other	
Ice Processes	NA
Maximum/minimum thresholds for ice (e.g., 80/20) for weathering	
Sticking to ice	
Reentrainment under ice	
Encapsulation	
Other	
Inputs and Source of Data (i.e., what model(s) is used for weathering inputs)	

Model Name	National Research Council Canada Model
Developer	**Hossein Babaei**
Outputs/Results	
List outputs produced?	First module is capable of both deterministic and probabilistic modelling of trajectories when the uncertainty in ice velocity field is known. Applicable to long-range trajectory estimations (weeks to months) Second module is suitable for short-range tracking of oil (days to a couple weeks) Oil state (in leads, over or under ice), oil thickness and coverage area, trajectory, ...
Output File Formats	Compatible with NRC's EnSim software platform. Can be modified to accept/produce other data formats such as GRIB and NetCDF.
Output Visualization (e.g., GIS, PDF Maps)	Results can be visualized by NRC's freely available BlueKenue software.
Output Visualization Platform (e.g., ERMA, CG1 View)	BlueKenue software developed by NRC and publicly available.
How is uncertainty shown?	Not automatic at the moment. Needs to be run several times and results analyzed and visualized. The analysis and visualization codes are already developed.
Limitations (with an emphasis on Arctic specific limitations)	Cannot address any 3D process. Does not simulate weathering of the oil. Needs improvement on the open water aspects of oil spill transport.
Suggestions for Improved Arctic Use	1- Weathering of oil can be relatively readily included. 2- The open water advection of oil subject to waves and wind can be also relatively easily implemented. 3- The first module is extremely fast (a couple minutes). For the second module, although the computational time is not a significant issue (~ 2 wall-clock hours for simulating a week-long spill including the time required for ice dynamics simulation), the module computational speed could be improved by the application of Graphical Processing Unit (GPU) of computing machines.
Applications	
What (major) spills has the model been applied to?	Used to hindcast oil-in-ice for two real events: One in Barents Sea and the other in Gulf of Finland.
Has the model been applied to the Arctic? For what purpose?	Yes, the above two cases are for the Arctic and sub-arctic waters.
Has the model been validated to data for oil transport within ice? What datasets?	Yes, the model has been validated by available data of the above two spills. Model info and the validation results are under publication.

Model Name	SPILLMOD
Developer	N.N. Zubov's State Oceanographic Institute, Moscow, Russia
Model Purpose (e.g., response, injury assessment), please list all that apply	Oil spill trajectory and fate forecast (and operative forecast); Oil spill response (including oil recovery, chemical dispersion and in situ burning); Training exercises; Oil spill response decision support; Calculate oil spill area, thickness distribution taking into account the arbitrary contact boundaries (booms, port facilities), mass balance, amount of evaporated, dispersed and beached oil.
Who is the typical/intended end user for the model?	The end users of SPILLMOD simulation results are: Subdivisions of Roshydromet for marine oil spill operational forecasts and monitoring. Offshore oil/gas and transport companies for OSR planning, EIA and NEBA provisions. Marine Rescue Service to provide exercises and forecasts of actual oil spills. Interested non-profit organizations of environment protection profile.
Webpage/URL	
Coding Language(s)	C++/Delphi/MapInfo MapBasic
Development Status (e.g., beta version, available for use in spills)	a. Desktop operational versions of SPILLMOD are installed in subdivisions of the Hydrometeorological Service of Russia in Barents and Caspian Seas. Forecasts of wind velocity fields, sea currents and sea ice characteristics are calculated separately on a high-performance computing cluster b.Multi-user server software is tested for several marine areas (Barents, Baltic, Okhotsk, Caspian, Black Sea). c. Single-user application is implemented on a modern personal computer (with OSP planning).
Most Recent Update (version # and release date)	Desktop version static since 2011; Multi-user application and OSR single-user application under active development
Source Code (open source license/location, closed source license/location)	Proprietary software.
Use Restrictions (e.g., publicly available)	For scientific research, the prepared program code can be transmitted “as is.” When distributing, the model needs to be adopted to appropriate input data configuration, including information about the coastline and file formats with the results of the hydro-meteorological forecasts of wind fields and currents. The desktop version of the model implies GIS MapInfo is to be preinstalled.
Scale of Operation (local (<10km), regional (>100 km) or global)	Local and regional scale
Can this model be used for a subsurface release (e.g., well blowout)? If yes, does the model have its own near-field model, or is it coupled to another modeling system (e.g., TAMOC)? What is the name of the near-field model?	SPILLMOD is designed for calculating the oil spreading on the sea surface. In the case of subsurface spill several parameters are calculated: 1) droplets size distribution at the blowout point 2) the fate of buoyant jet with gas bubbles, 3) dispersion and advection of multi dispersed oil drops with positive buoyancy, 4) time, radius and place of droplets surfacing area. Programs to simulate subsurface spill are developed in State Oceanography Institute and are not integrated to the SPILLMOD code yet. Programming languages/software environments are Fortran, C/C++, Maple.

Model Name	SPILLMOD
Developer	**N.N. Zubov's State Oceanographic Institute, Moscow, Russia**
What products (e.g., types of oil) can the model address?	Any type with known distillation curve, density, viscosity, IFT
Where does the model get information on the properties of spilled oil/products? Can it handle refined and crude products? Does it consider natural gas?	Own database generated in the preparation EIA projects and OSR plans
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	The model can be used for any region. Adaptation to regional hydrometeorological forecasts is required
Processing needs	Adaptation to "external" hydrometeorological data is required. a. Operational models are integrated with GIS. Information about the oil spill source is set via the program interface, the results are transmitted in exchange GIS formats, as text, and so on. b. The Server application receives the task as a package. Results are transmitted in GIS exchange formats, as text, and so on. c. The workstation application operates in the MapInfo environment. The interface is implemented in Delphi/MapInfo MapBasic. Results are transmitted in GIS exchange formats, as text, and so on.
Transport	
Algorithms Not Specific to the Arctic	
Advection (interpolated or uniform)	Time-dependent spatially in homogeneous fields of wind speeds and currents are interpolated to the oil spill area
Wind Drift	The wind coefficient and parametric angle of rotation are used.
Diffusion (random walk or random displacement)	Not used.
Stranding	The amount of oil on the shore depends on the time and length of contact of the oil slick with the shore and the accumulating capacity of the coastline
Vertical Movement: Rise velocity of bubbles/droplets	Vertical movements of oil droplets of different sizes are taken into account parametrically when calculating the dispersion of the oil film on the sea surface
Other	A CFD solution of oil spill spreading. The model describes the spreading process taking into account the contact boundaries represented by sets of polylines. In OSR applications the model calculates the configuration of the oil slick taking into account the booms deployment, including in the tidal seas.
Algorithms Specific to the Arctic	
Advection	Oil transport in ice conditions is the combination of the open water surface drift velocity and sea ice velocities with weights, depending on ice concentration.
Wind Drift	Oil transport in ice conditions is the combination of the open water surface drift velocity and sea ice velocities with weights, depending on ice concentration.
Diffusion	Not use.
Stranding	Fast ice prevents oil stranding on the shore
Vertical Movement	None
Other	

Model Name	SPILLMOD
Developer	**N.N. Zubov's State Oceanographic Institute, Moscow, Russia**
Transport	
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for advection	the 80/30 rule is used
Sticking to ice	Yes, under 80%
Reentrainment under ice	None
Encapsulation	None
Other	
Inputs and Source of Data (i.e., what model(s) is used for wind, hydrodynamics, ice velocity, ice concentration, etc.)	Metocean data: fields of wind velocity, current velocity, temperature and water salinity in the ocean upper layer, ice concentration, floe size distribution, thickness and velocity of ice drift. Source of data: INMOM+CICE (Institute of Numerical Mathematics Russian Academy of Science Ocean Model or others. Oil spill source: position (geographic coordinates), date/time of the accident, the amount of oil spilled, the duration of discharge. Oil properties: density, viscosity, distillation curve, concentration of resins, asphaltenes, paraffins, interfacial tension at the oil-water interface.
Weathering	
Algorithms Not Specific to the Arctic	The pseudo-component model of evaporation taking into account ambient temperature, the film thickness of the oil and the chemical composition is used.
Evaporation	Model based on Mackay (1980) work.
Emulsification	
Dissolution	None
Biodegradation	None
Sedimentation	None
Photo-Oxidation	None
Surface Spreading	A CFD solution of oil spill spreading is used. An arbitrary shape of contact boundaries is taken into account.
Vertical Movement: Entrainment	The new model of natural dispersion an oil layer by waves consists of the calculation of several successive steps - penetration of oil under the surface of the sea due to breaking waves, crushing into droplets of various sizes in the wave mixing layer, resurfacing of drops due to positive buoyancy and penetration into the water column due to vertical diffusion S. Zatsepa et.al. The Role of Wind Waves in Oil Spill Natural Dispersion in the Sea, Oceanology, (2018), Vol. 58, No. 4, pp. 517–524, 2018, DOI: 10.1134/S0001437018040136 S. Zatsepa et.al. Phenomenological Model of Natural Dispersion of the Oil Spill in the Sea and Some Associated Processes Parameterizations, Oceanology, (2018), Vol. 58, No. 6, pp. 769-777. DOI: 10.1134/S0001437018060152
Other	

Model Name	SPILLMOD
Developer	**N.N. Zubov's State Oceanographic Institute, Moscow, Russia**
Weathering	
Algorithms Specific to the Arctic	
Evaporation	It is reduced by reducing the area of the spill.
Emulsification	Just like in open water (under consideration)
Dissolution	None
Biodegradation	None
Sedimentation	None
Photo-Oxidation	
Spreading	In broken ice conditions, oil dynamics model consider resistance of ice floes to spreading, depending on ice compactness. Under solid ice, oil is spreading to minimal thickness depending on IFT.
Vertical Movement: Entrainment	Decreases with the reduction of wind impact on waves, due to an increase in the thickness of the oil layer in the spaces between ice floes (under consideration)
Other	The characteristics of waves developing in or near ice fields differ from the same characteristics of open water waves. If there are models of wind waves taking into account the presence of ice of various concentration, then these models must be used. The oil natural dispersion is reduced in presence of ice proportional to the ice concentration
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for weathering	None
Sticking to ice	None
Reentrainment under ice	None
Encapsulation	None
Other	
Inputs and Source of Data (i.e., what model(s) is used for weathering inputs)	Metocean data: Fields of wind velocity, current velocity, temperature and water salinity in the ocean upper layer, ice concentration, floe size distribution, thickness and velocity of ice drift. Source of data: INMOM+CICE (Institute of Numerical Mathematics Russian Academy of Science Ocean Model or others. Oil spill source: position (geographic coordinates), date/time of the accident, the amount of oil spilled, the duration of discharge. Oil properties: density, viscosity, distillation curve, concentration of resins, asphaltenes, paraffins, interfacial tension at the oil-water interface.

Model Name	**SPILLMOD**
Developer	**N.N. Zubov's State Oceanographic Institute, Moscow, Russia**
Outputs/Results	
List outputs produced?	Surface oil thickness distribution, the amount of oil on the surface, evaporated and dispersed, estimates of the area and geometric dimensions of the slick, density, viscosity, water content Time series (ASCII text format): mass balance, density and viscosity, length of shoreline oiled Amount of oil retained by each shoreline segment Graphical mass balance
Output File Formats	GIS (mif/mid or ArcGIS shape files)/ ASCII (text) / JPEG
Output Visualization (e.g., GIS, PDF Maps)	MapInfo GIS will display the results on a map. Text file can be opened with Text editor and imported in Excel for analysis.
Output Visualization Platform (e.g., ERMA, CG1 View)	MapInfo GIS
How is uncertainty shown?	Estimation and construction of area where the probability to detect an oil spill exceeds the specified thresholds. Under development
Limitations (with an emphasis on Arctic specific limitations)	Simplified understanding of the mechanisms of interaction between an oil spill on the sea surface and sea ice. Insufficient observational data to create and verify a model of oil behavior in various ice conditions (ice forms, types, and development). There is a problem of different spatial scales for oil spills and the characteristics of sea ice fields provided by hydrodynamic models.
Suggestions for Improved Arctic Use	Implementation of revised models of weathering and transport into the model.
Applications	
What (major) spills has the model been applied to?	Norilsk diesel fuel spill (Nornickel), 2020; West Cork oil spill (2009); Kerch Strait oil spill (2000); Gulf War oil spill (1991): others
Has the model been applied to the Arctic? For what purpose?	Several projects completed on Greenpeace order in Arctic, for example, on assessment of the risk of high levels of marine pollution as a result of uncontrolled discharge in the Franz Josef Land area.
Has the model been validated to data for oil transport within ice? What datasets?	The model was developed in view of the data of both field observations and laboratory experiments, among others: Uzuner, Weiskopf, Cox, Schultz. Transport of oil under smooth ice, (1978), Konno Akihisa, Izumiyama, On the relationship of the oil/water interfacial tension and the spread of oil slick under ice cover. S. Løset et al. OLJEVERN I NORDLIGE OG ARKTISKE FARVANN (Report for SINTEF NHL) (1994-12-06); Matsuzaki, Ogasawara, Sakai, Izumiyama , Kanada. NUMERICAL SIMULATION OF CURRENT-INDUCED DEFORMATION AND MOVEMENT OF THE OIL SLICK UNDER THE ICE COVER. (2006).

Model Name	BLOSOM
Developer	**DOE NETL**
Model Purpose (e.g., response, injury assessment), please list all that apply	Spill prevention and response planning; Targets 4D fate & transport for deep water blowouts as well as surface spills. "What-if" scenarios to determine: Spill extent Spill duration Amount of oil Location of oil
Who is the typical/intended end user for the model?	BLOSOM is primarily targeting research, mostly in academia. Some government buy-in with BSEE, and potentially BOEM (as part of the online Common Operating Platform, or COP), but BLOSOM's main target has typically been prediction and research over response.
Webpage/URL	https://edx.netl.doe.gov/dataset/blosom-release
Coding Language(s)	C++ (previously Java)
Development Status (e.g., beta version, available for use in spills)	Focused on research but accessible for response. Development ongoing. Desktop (Windows, Linux) and web platform through Common Operating Platform
Most Recent Update (version # and release date)	Desktop original version: 2014 Latest releases via EDX first deployed: Jun 10, 2019 COP: May 2020 (limited access)
Source Code (open source license/location, closed source license/location)	Individual: Open Source. Commercial: Copyrighted and licensed through NETL
Use Restrictions (e.g., publicly available)	Open-Source available on request
Scale of Operation (local (<10km), regional (>100 km) or global)	Local and / or regional, depending of scale of data and parameters
Can this model be used for a subsurface release (e.g., well blowout)? If yes, does the model have its own near-field model, or is it coupled to another modeling system (e.g., TAMOC)? What is the name of the near-field model?	Yes; Custom Jet/plume module
What products (e.g., types of oil) can the model address?	Mostly tested with crude oil profiles (e.g. Adios library etc.)
Where does the model get information on the properties of spilled oil/products? Can it handle refined and crude products? Does it consider natural gas?	Built in profiles taken from a previous BP publication (I think…). Subset of Adios oils, mostly untested. Users can define their own oil profile if not present in BLOSOM.
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	Can be used anywhere metocean data is provided for in a structured grid form.
Processing needs	Desktop/single processor or cluster computing environment options (Cloud or local) Can be run with or without UI. Transport processing is multithread, and can take advantage of multiple processors. Docker container exists for convenience of working with COP framework.

Model Name	BLOSOM
Developer	**DOE NETL**
Transport	
Algorithms Not Specific to the Arctic	
Advection (interpolated or uniform)	Interconnected modules: gas/hydrates module, crude oil module, jet/plume module, conversion module, hydrodynamic handler. Utilizes Lagrangian transport acting on representative spill parcels. Euler's method used for time-step integration. Buoyancy, water advection, random diffusion, and wind advection (if surfaced)
Wind Drift	Wind deflection can be calculated or use a fixed angle provided by modeler
Diffusion (random walk or random displacement)	Option of constant diffusivity Random walk for vertical or horizontal. Option of Smagorinsky diffusivity Random walk for horizontal.
Stranding	Parcels considered "dead" when beached, sunk, or otherwise marked out of bounds. Such parcels traits are no longer updated at this point.
Vertical Movement: Rise velocity of bubbles/droplets	Calculated from droplet size, density.
Other	
Algorithms Specific to the Arctic	
Advection	N/A
Wind Drift	N/A
Diffusion	N/A
Stranding	N/A
Vertical Movement	N/A
Other	
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for advection	N/A
Sticking to ice	N/A
Reentrainment under ice	N/A
Encapsulation	N/A
Other	
Inputs and Source of Data (i.e., what model(s) is used for wind, hydrodynamics, ice velocity, ice concentration, etc.)	Oil and hydrodynamic properties Hydrodynamic handler: dynamic ocean characteristics (NetCDF, CSV), bathymetry & shoreline (GeoTiff, IMG), detailed shoreline boundary (ESRI Shapefile). Crude oil module: pre-defined oil profiles, can import from NOAA'S ADIOS OilLib, or custom oil profile. gas hydrate module: relative proportions of the gasses. Jet/Plume: Maximum droplet size (if control volume hits terminal velocity), initial droplet size distribution (custom or predefined; can emulate application of dispersants) Sources can include: - HYCOM (current velocity, salinity, temperature) - NCOM (current velocity, salinity, temperature, surface wind stress) - ETOPO1 Global Relief Model (Bathymetry) - Wavewatch III (wind)

Model Name	BLOSOM
Developer	**DOE NETL**
Weathering	
Algorithms Not Specific to the Arctic	
Evaporation	Choice of equation from 5 literature based implementations.
Emulsification	Either Rasmussen (1985) or Mackay (1980).
Dissolution	(Release pending) Implementation based on Zheng, L., and Yapa, P. D. (2002). "Modeling gas dissolution in deep water oil/gas spills."
Biodegradation	Biodegradation forthcoming
Sedimentation	No
Photo-Oxidation	No
Surface Spreading	Fay, J.A. (1971). Or Lehr, W.J., Caking, H.M., Fraga, R.J., Belen, M.S. (1984).
Vertical Movement: Entrainment	Shear and forced entrainment based on Yapa and Zheng (1997).
Other	Surface / wave dispersion (release pending).
Algorithms Specific to the Arctic	
Evaporation	N/A
Emulsification	N/A
Dissolution	N/A
Biodegradation	N/A
Sedimentation	N/A
Photo-Oxidation	N/A
Spreading	N/A
Vertical Movement: Entrainment	N/A
Other	
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for weathering	N/A
Sticking to ice	N/A
Reentrainment under ice	N/A
Encapsulation	N/A
Other	N/A
Inputs and Source of Data (i.e., what model(s) is used for weathering inputs)	Selection from list of models integrated into BLOSOM for evaporation, emulsification, mass transport, spreading.

Model Name	**BLOSOM**
Developer	**DOE NETL**
Outputs/Results	
List outputs produced?	3D/4D data and visual products: Tabular data of jet/plume, transport/spill parcels; geographic distributions of spill parcels captured incrementally through simulation; image captures of user-selected regions of map/visualizer.
Output File Formats	GeoJSON, CSV, Shp (ESRI), Mat (MATLAB), Text (Tabular), png (screenshots)
Output Visualization (e.g., GIS, PDF Maps)	Tabular data can be displayed in any spreadsheet-capable program (Excel). Geospatial data can be displayed in GIS software (ArcGIS, QGIS). Screenshots can be viewed in any image program (Windows, Paint)
Output Visualization Platform (e.g., ERMA, CG1 View)	Built-in visualization for desktop; web-based /open box visualization on COP.
How is uncertainty shown?	No directly shown.
Limitations (with an emphasis on Arctic specific limitations)	While the smallest possible simulation step is 1 second, the smallest record recording interval is 1 hour.
Suggestions for Improved Arctic Use	Improved resolution of transport physics; inclusion of basic ice-oil interactions; increase range of data accepted by the Hydrodynamic Handler.
Applications	
What (major) spills has the model been applied to?	DWH, Pt Wells (Puget Sound), Taylor Well, Santa Barbara
Has the model been applied to the Arctic? For what purpose?	Only for some testing/development purposes.
Has the model been validated to data for oil transport within ice? What datasets?	No

Model Name	MIKE 21/3 Oil Spill
Developer	**DHI A/S**
Model Purpose (e.g., response, injury assessment), please list all that apply	Oil spill modeling worldwide in support for spill forecast, contingency planning and EIA's from potential spills (Stochastic approach) A new innovative method for risk screening in the Barents sea by combining agent based modeling of marine mammals and oil spill Spreading and fate of dispersed (free floating or in the water column) and dissolved oil from surface or sub-surface oil (and gas) spills Effect of mitigating measures such as use of skimmers, dispersants and in-situ burning (and fate of residuals)
Who is the typical/intended end user for the model?	Main users are "Engineering Consultancies" and "Government Agencies". However , universities worldwide are also typical users and are provided special University agreements for non-commercial use of the MIKE software.
Webpage/URL	https://www.mikepoweredbydhi.com/products/mike-21/sediments/oil-spill https://www.mikepoweredbydhi.com/areas-of-application/coast-and-sea/globalsea-oil-spill
Coding Language(s)	Fortran (HD) and C++ (MIKE ECO Lab)
Development Status (e.g., beta version, available for use in spills)	For Planning/Risk assessment use-case types, the Desktop version of MIKE Oil Spill needs to be installed either on a local PC or a remote server for running simulations. A cloud based solution is in pipeline (also with respect to stochastic model result assessment during planning). The minimum system requirements is a x64 2.2 GHz processer, running windows 2019 system with 2GB of memory and 40 GB
Most Recent Update (version # and release date)	MIKE Zero Release 2020 Update 1, from 20, May 2020
Source Code (open source license/location, closed source license/location)	Commercial licensed software. Oil spill model process equations readable via Text Editors, but cannot be executed without a software license
Use Restrictions (e.g., publicly available)	All MIKE software is proprietary, and commercially available for professional use. Access to MIKE software for non-commercial work (e.g. research) can be obtained via a research agreement with DHI. The oil spill model is contained within a template which is open through our Template Editor (license controlled). The user can review and edit any aspect of the Oil Spill module formulation relative to latest research in the field.
Scale of Operation (local (<10km), regional (>100 km) or global)	Can be used on any scale with appropriate inputs.
Can this model be used for a subsurface release (e.g., well blowout)? If yes, does the model have its own near-field model, or is it coupled to another modeling system (e.g., TAMOC)? What is the name of the near-field model?	An integrated jet model to handle subsurface blow out.
What products (e.g., types of oil) can the model address?	

Model Name	MIKE 21/3 Oil Spill
Developer	**DHI A/S**
Where does the model get information on the properties of spilled oil/products? Can it handle refined and crude products? Does it consider natural gas?	
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	Can be used anywhere.
Processing needs	MIKE OS can be run on desktop or on Azure (emulating desktop). The OS model requires to input detailed information of the flow field in the domain. This can be obtained from e.g. a MIKE HD running coupled with MIKE OS.
Transport	
Algorithms Not Specific to the Arctic	
Advection (interpolated or uniform)	A coupled Lagrangian (particle/ agent for dispersed oil) and Eulerian model (for dissolved oil). Advection by currents and dispersion (for dissolved oil).
Wind Drift	The user specify the fraction of wind (e.g. 3 %) that will be applied as wind drift. The wind drift angle due to Coriolis is included as proposed by Al-Rabeh (1994).
Diffusion (random walk or random displacement)	Spatially constant horizontal diffusion by random walk. For dissolved oil both horizontal and vertical diffusion is applied.
Stranding	A spatial variation of beaching probability can be applied to account for variation in shoreline types.
Vertical Movement: Rise velocity of bubbles/droplets	Particles can have specified rise (or settling) velocities calculated from droplet sizes and oil density. Vertical dispersion by breaking waves are likewise included.
Other	
Algorithms Specific to the Arctic	
Advection	Submerged oil is free to move under the ice or it may be trapped. The oil will drift with the ice for concentrations larger than 30%.
Wind Drift	Particle wind drift is excluded at higher ice concentrations.
Diffusion	Spatially constant horizontal diffusion by random walk. For dissolved oil both horizontal and vertical diffusion is applied.
Stranding	The ice cover act as barrier and the oil may either: adhere to ice or be free to move.
Vertical Movement	
Other	
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for advection	
Sticking to ice	Optional
Reentrainment under ice	The oil is free to move under the ice
Encapsulation	None
Other	

Model Name	**MIKE 21/3 Oil Spill**
Developer	**DHI A/S**
Transport	
Inputs and Source of Data (i.e., what model(s) is used for wind, hydrodynamics, ice velocity, ice concentration, etc.)	Spatial and temporal data in relation to currents (HYCOM, Copernicus, MIKE HD models), waves, wind, ice (e.g. hourly ice fraction from Climate Forecast System Reanalysis (CFSR) 1979-2019) Oil /gas properties (e.g., distillation curve, content of asphaltene and wax, gas type and oil water interfacial tension (under sub sea blow out), and density and viscosity (preferably at various degrees of evaporation) All MIKE inputs/outputs need to be defined in a native MIKE binary .dfsfile.. MIKE software supports conversion from e.g. ASCII formats to native MIKE formats. Possible to convert MIKE output results to other data formats (.NetCDF, .mat, etc., .kmz, .shp) in postprocessing Built-in support for more than 3000 predefined projections, with the option to modify/ create new ones within user interface, and is able to handle both metric or imperial units For spatial data, data can be stored either in structured 2D or 3D equidistant rectangular structured grid, or as an unstructured grid consisting of triangular and quadrangular elements
Weathering	
Algorithms Not Specific to the Arctic	
Evaporation	Evaporation calculated according to Reed (1989).
Emulsification	Emulsification according to Xie et al (2007).
Dissolution	Dissolution according to model of Donald MacKay et al.
Biodegradation	Included as a simple first order process.
Sedimentation	If the density of the oil exceeds the density of the ambient water, the settling of the oil is included. However, sedimentation due to the uptake of heavier particles is only considered relevant for oil close to the coastlines, where adsorption to sediment followed by sedimentation may be of relevance.
Photo-Oxidation	Included as a simple first order process.
Surface Spreading	Gravitational viscous spreading included according to Fay (Lehr, W.J , 2001).
Vertical Movement: Entrainment	Entrainment by breaking waves.
Other	Weathering processes and dispersion into the water column by wave action Spreading, Evaporation, Emulsification, Dissolution, Sedimentation, Biodegradation, Dispersion, Oxidation All processes/features may be inspected (and updated) using the Ecolab editor (requires Ecolab license)
Algorithms Specific to the Arctic	
Evaporation	No specific changes
Emulsification	No specific changes
Dissolution	No specific changes
Biodegradation	No specific changes

Model Name	**MIKE 21/3 Oil Spill**
Developer	**DHI A/S**
Weathering	
Sedimentation	No specific changes
Photo-Oxidation	No specific changes
Spreading	Controlled by ice concentrations
Vertical Movement: Entrainment	No specific changes
Other	Weathering processes are modified in case of ice cover (e.g., there is no entrainment due to wave activity).
Ice Processes	
Maximum/minimum thresholds for ice (e.g., 80/20) for weathering	
Sticking to ice	
Reentrainment under ice	
Encapsulation	
Other	
Inputs and Source of Data (i.e., what model(s) is used for weathering inputs)	(See input under Transport Algorithms).
Outputs/Results	
List outputs produced?	2D-maps or 3D maps containing instantaneous value / statistical value (min, mean, max, time average or cell average) of all oil parameters. Typical output parameters include: total oil mass or emulsion mass (as mass or area /volume concentrations), slick thickness, amount stranded, time of first arrival. Mass budget as a time series. Particle tracks and particle properties. All sub processes and parameters can be provided as output if requested.
Output File Formats	All 2-D maps produced by MIKE can be exported to GIS (shapefiles).
Output Visualization (e.g., GIS, PDF Maps)	MIKE offers visualization tools, “MIKE Data Viewer”, “MIKE Results Viewer” and “MIKE Animator+” which allows for both 2D and 3D visualization of particle tracks overlayed with area/volume parameters and shapefiles. For outputs of particle tracks, MIKE software currently supports 3 file format types. .XML (compressed/uncompressed), .TRACK (binary file) and .KML (for direct import to Google Earth). Integrated in global forecast systems.
Output Visualization Platform (e.g., ERMA, CG1 View)	
How is uncertainty shown?	
Limitations (with an emphasis on Arctic specific limitations)	Trade-off between computational efficiency vs. the number of oil particles that can be made to represent the actual oil spill. High quality/accurate MetOcean data (forecast or hindcast) is a prerequisite.
Suggestions for Improved Arctic Use	The present oil /ice interaction is rather simple which can be justified for short term simulations (about 2-3 weeks after a spill). Long term simulation would require an improved and more comprehensive description of these processes.

Model Name	**MIKE 21/3 Oil Spill**
Developer	**DHI A/S**
Applications	
What (major) spills has the model been applied to?	
Has the model been applied to the Arctic? For what purpose?	The model has been used for contingency planning and EIA in the Barents Sea.
Has the model been validated to data for oil transport within ice? What datasets?	None

APPENDIX K: Sea Ice Model Summary Table[*][†][‡]

[*] Adapted from combined Excel spreadsheet for readability.
[†] SINTEF was unavailable to complete the table for SINMOD at the time of publication.
[‡] Some cells were intentionally left blank by the modeler completing the table (no response provided).

Table 17: Sea Ice Model Summary Table.

Model Name	Icepack
Developer	**Los Alamos National Laboratory**
Model Purpose(s)	Provide column physics model as a separate library for use in other host models (e.g., CICE)
Webpage/URL	https://github.com/CICE-Consortium
Coding Language(s)	FORTRAN
Development Status (e.g., beta version, available for use)	Available for use
Most Recent Update (version # and release date)	Icepack 1.2.3 (August 27, 2020) https://github.com/CICE-Consortium/Icepack/wiki/Icepack-Release-Table
Use Restrictions (e.g., publicly available)	Publicly available (GitHub)
Source Code License (open vs closed source)	Open-source
Scale of Operation (local (<10km), regional (>100 km) or global)	subgrid scale
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	
Processing needs	Runs on platforms using UNIX, LINUX, and other operating systems
Processes relevant to:	
Oil migration through ice	YES
Cracks/leads in icepack	NO
Brine channels	YES
	https://cice-consortium-icepack.readthedocs.io/en/icepack1.2.2/science_guide/sg_thermo.html
Porosity	YES
	microporosity
Ice thickness	YES
	Distribution from continuity equation
Ice type	YES
	Age tracer
Ice floe size	YES
	Under-ice
Melting	YES
	energy of melting https://cice-consortium-icepack.readthedocs.io/en/icepack1.2.2/science_guide/sg_thermo.html

Model Name	**Icepack**
Developer	**Los Alamos National Laboratory**
Oil pooling and retention under ice	NO
Under-ice roughness	NO
Under-ice storage capacity	NO
Stripping velocity	NO
Stickiness	NO
Freezing/melting as it affects under-ice roughness	NO
Pumping oil under ice and oil encapsulation	YES
Ice movement	YES
	velocity
Ice geolocation	
Freezing	YES
	growth rate https://cice-consortium-icepack.readthedocs.io/en/icepack1.2.2/science_guide/sg_thermo.html#thermo-growth
Ice controlling oil movement (small scale)	
Different ice types (frazil vs new ice vs multi-year ice)	
Ice keels	
Oil on surface of ice	YES
Snow	YES
	Snow thickness https://cice-consortium-icepack.readthedocs.io/en/icepack1.2.2/science_guide/sg_thermo.html Blowing snow Redistribution of snow with thickness distribution
Albedo / enhancing melting	YES
	changes albedo according to thickness and type of ice
Melt ponds	YES
	Flocco et al (2010): Topographic Melt Ponds & Hunke et al. (2013): Level Ice Melt Ponds https://cice-consortium-icepack.readthedocs.io/en/icepack1.2.2/science_guide/sg_thermo.html

Model Name	Icepack
Developer	**Los Alamos National Laboratory**
Other	NO
Landfast ice	NO
Inputs	
	Atmosphere (downwelling longwave and shortwave radiative fluxes, latent and sensible heat fluxes, precipitation rate, and near surface potential temperature and specific humidity), Ocean, and Hydrology https://github.com/CICE-Consortium/Icepack/wiki/Icepack-Input-Data
Outputs/Results	
List Outputs Produced	Ice thickness distribution, Thermodynamics, microporosity, Ridging, floe size, melt ponds, Biogeochemistry
Output File Formats	NetCDF
Output Visualization (e.g., GIS, PDF Maps, Shapefiles)	
Output Visualization Platform (e.g., ERMA, CG1 View)	
How is uncertainty shown?	
Limitations	
Suggestions for Improved Arctic Use	
Temporal resolution	15-30 minutes
Who uses the model?	

Model Name	CICE
Developer	**CICE Consortium (for CICE6); Los Alamos developed CICE 4, 5.12**
Model Purpose(s)	·Provide first look information "anywhere, anytime" ·Support navigation ·Earth System Modeling Framework (ESMF) used to facilitate upgrades ·Provides sea ice drift fields from NAVY ESPC and GOFS 3.1 to data portal for Sea Ice Drift Forecast Experiment (SIDFEx): https://sidfex.polarprediction.net/ ·Sea ice component for use in fully coupled, atmosphere-ice-ocean-land global circulation models
Webpage/URL	https://github.com/CICE-Consortium/About-Us
Coding Language(s)	FORTRAN
Development Status (e.g., beta version, available for use)	Global Ocean Forecast System (GOFS) 3.1: operational 11/7/18 Initial Operational Capability (IOC) scheduled to be operational May 2020
Most Recent Update (version # and release date)	GOFS 3.5 is scheduled for transition later this year (uses CICE 5.1.2)
Use Restrictions (e.g., publicly available)	Publicly available
Source Code License (open vs closed source)	Open-source
Scale of Operation (local (<10km), regional (>100 km) or global)	km+ scale
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	Global
Processing needs	Super computer
Processes relevant to:	
Oil migration through ice	YES
Cracks/leads in icepack	NO
Brine channels	YES
Porosity	YES
Ice thickness	YES
	Icepack Last 30 days & last 12 months & previous years to 2014 https://www7320.nrlssc.navy.mil/GLBhycomcice1-12/arctic.html
Ice type	YES
Ice floe size	Not until CICE6 is used (~FY22)
	Floe size distribution Roach, L.A. (2018)
Melting	YES

Model Name	CICE
Developer	**CICE Consortium (for CICE6); Los Alamos developed CICE 4, 5.12**
Oil pooling and retention under ice	NO
Under-ice roughness	NO
Under-ice storage capacity	NO
Stripping velocity	NO
Stickiness	NO
Freezing/melting as it affects under-ice roughness	NO
Pumping oil under ice and oil encapsulation	YES
Ice movement	YES
	Speed and drift (forecast & last 30 days & last 12 months & previous years to 2014) https://www7320.nrlssc.navy.mil/GLBhycomcice1-12/arctic.html
Ice geolocation	
Freezing	YES
Ice controlling oil movement (small scale)	
Different ice types (frazil vs new ice vs multi-year ice)	
Ice keels	
Oil on surface of ice	YES
Snow	YES
	(Icepack)
Albedo / enhancing melting	YES
	(Icepack)
Melt ponds	YES
	(Icepack)
Other	YES
Landfast ice	Soon
	CICE6 (ESPC Version 2: FY22)
Inputs	
	GOFS 3.1 uses the Navy Coupled Ocean Data Assimilation (NCODA) to assimilate available real-time observations: satellite altimeter, SST and sea ice concentration data, in- situ SST, profile data (Argo profiles, XBTs, CTDs, gliders, marine mammals)

Model Name	CICE
Developer	CICE Consortium (for CICE6); Los Alamos developed CICE 4, 5.12
Outputs/Results	
List Outputs Produced	boundary conditions grid cell mean ice thickness (m) grid cell mean snow thickness (m) snow/ice surface temperature (°C) ice area (aggregate) % ice velocity (x) (m/s) ice velocity (y) (m/s) down solar flux (W/m**2) down longwave flux (W/m^2) snowfall rate (cm/day) rainfall rate (cm/day) sea surface temperature (°C) sea surface salinity (PSU) ocean current (x) (m/s) ocean current (y) (m/s) freeze/melt potential (W/m^2) snow/ice/ocn absorbed solar flux (W/m^2) snw/ice broad band albedo (%) latent heat flux (W/m*2) sensible heat flux (W/m*2) upward longwave flux (W/m^2) evaporative water flux (cm/day) congelation ice growth (cm/day) frazil ice growth (cm/day) snow-ice formation (cm/day) top ice melt (cm/day) basal ice melt (cm/day) lateral ice melt (cm/day) freshwtr flx ice to ocn (cm/day) salt flux ice to ocean (kg/m^2/s) heat flux ice to ocean (W/m^2) SW flux thru ice to ocean (W/m^2) atm/ice stress (x) (N/m^2) atm/ice stress (y) (N/m^2) coriolis stress (x) (N/m^2) coriolis stress (y) (N/m^2) ocean/ice stress (x) (N/m*2) ocean/ice stress (y) (N/m^2) compressive ice strength (N/m) strain rate (divergence) (%/day) lead area opening rate (%/day) visible direct albedo (%) near IR direct albedo (%) air temperature (°K) shortwave scaling factor
Output File Formats	
Output Visualization (e.g., GIS, PDF Maps, Shapefiles)	

Model Name	**CICE**
Developer	**CICE Consortium (for CICE6); Los Alamos developed CICE 4, 5.12**
Outputs/Results	
Output Visualization Platform (e.g., ERMA, CG1 View)	
How is uncertainty shown?	
Limitations	
Suggestions for Improved Arctic Use	New techniques and additional satellite-derived ice freeboard data present opportunities for improving predictive skill with coupled modeling.
Temporal resolution	GOFS 3.1 Runs daily at Navy DSRC under FNMOC control: 7-day forecasts
Who uses the model?	

Model Name	HIOMAS
Developer	**ADAC**
Model Purpose(s)	·Support USCG Arctic operators and planners by developing a High-resolution Ice-Ocean Modeling and Assimilation System (HIOMAS) to predict Arctic sea ice thickness, motion, and edge location, ocean currents, and other useful parameters. ·Help USCG conduct search and rescue missions more safely and reliably; enhance USCG's ability to prepare for and respond to disasters such oil spills. ·Support other Arctic stakeholders in planning and management of economic activities. ·Support other modeling efforts such as oil spill and storm surge modeling that may use high-resolution output as forcing.
Webpage/URL	·http://thredds.aoos.org/thredds/catalog.html?dataset=HIOMAS_2KM_HINDCAST ·http://thredds.aoos.org/thredds/catalog.html?dataset=HIOMAS_2KM_FORECAST
Coding Language(s)	
Development Status (e.g., beta version, available for use)	Transitioned to Axiom Data Sciences
Most Recent Update (version # and release date)	
Use Restrictions (e.g., publicly available)	Output is provided through Axiom
Source Code License (open vs closed source)	Closed source - contact Dr. Jinlun Zhang
Scale of Operation (local (<10km), regional (>100 km) or global)	Uniform 2 km horizontal resolution
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	Arctic Ocean
Processing needs	
Processes relevant to:	
Oil migration through ice	YES
Cracks/leads in icepack	YES
Brine channels	NO
Porosity	
Ice thickness	YES
	8-category subgrid-scale thickness & enthalpy distribution (TED) sea ice model covering ice thickness up to 28 m; 8-category subgrid-scale snow depth distribution (Zhang/Rothrock 2003).
Ice type	
Ice floe size	
Melting	YES
	2D

Model Name	**HIOMAS**
Developer	**ADAC**
Oil pooling and retention under ice	NO
Under-ice roughness	NO
Under-ice storage capacity	NO
Stripping velocity	NO
Stickiness	NO
Freezing/melting as it affects under-ice roughness	NO
Pumping oil under ice and oil encapsulation	YES
Ice movement	YES
	Zhang/Hibler 1997
Ice geolocation	
Freezing	YES
Ice controlling oil movement (small scale)	
Different ice types (frazil vs new ice vs multi-year ice)	
Ice keels	
Oil on surface of ice	YES
Snow	YES
	2D snow depth
Albedo / enhancing melting	
Melt ponds	
Other	YES
Landfast ice	YES
	Teardrop is useful to calculate landfast ice
Inputs	
	Forecasts are driven by atmospheric forecast forcing from the NCEP Climate Forecast System (CFS).

Model Name	**HIOMAS**
Developer	**ADAC**
Outputs/Results	
List Outputs Produced	·2D sea ice thickness, concentration, and velocity ·2D sea ice internal stress, deformation, fraction of thin ice, fraction of ridged/thick ice, and major leads ·2D sea ice melt and freezing ·2D snow depth ·3D ocean velocity, temperature, and salinity
Output File Formats	
Output Visualization (e.g., GIS, PDF Maps, Shapefiles)	
Output Visualization Platform (e.g., ERMA, CG1 View)	
How is uncertainty shown?	
Limitations	
Suggestions for Improved Arctic Use	
Temporal resolution	Forecast range is up to 3 months - focus on 1 month (provided by Axiom biweekly)
Who uses the model?	

Model Name	Unified Forecasting System (Coupled atmosphere-ocean-ice)
Developer	NOAA Contributors: NCEP, ESRL, NESII, GFDL, UCAR/NCAR
Model Purpose(s)	Comprehensive, community-developed Earth modeling system, designed as both a research tool and as the basis for NOAA's operational forecasts
Webpage/URL	https://ufscommunity.org/ Online forum support: forums.ufscommunity.org Graduate Student Test: https://github.com/ESCOMP/UFSCOMP/wiki/Milestone:-CMEPS-0.5-Appendix-Graduate-Student-Test-Evaluation-SST-Experiment EPIC: https://owaq.noaa.gov/Programs/EPIC
Coding Language(s)	
Development Status (e.g., beta version, available for use)	Incremental releases Arctic prototypes ready for developmental use
Most Recent Update (version # and release date)	Medium Range Weather Application V1.0 March 11, 2020
Use Restrictions (e.g., publicly available)	
Source Code License (open vs closed source)	Open
Scale of Operation (local (<10km), regional (>100 km) or global)	Local to global
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	Relocatable
Processing needs	Linux & Mac for Intel & GNU compilers (NOAA Hera, NCAR Cheyenne, NSF Stampede and Mac laptops)
Processes relevant to:	Currently uses CICE5 ice model
Oil migration through ice	
Cracks/leads in icepack	
Brine channels	
Porosity	
Ice thickness	
Ice type	
Ice floe size	
Melting	

Model Name	Unified Forecasting System (Coupled atmosphere-ocean-ice)
Developer	**NOAA** **Contributors: NCEP, ESRL, NESII, GFDL, UCAR/NCAR**
Oil pooling and retention under ice	
Under-ice roughness	
Under-ice storage capacity	
Stripping velocity	
Stickiness	
Freezing/melting as it affects under-ice roughness	
Pumping oil under ice and oil encapsulation	
Ice movement	
Ice geolocation	
Freezing	
Ice controlling oil movement (small scale)	
Different ice types (frazil vs new ice vs multi-year ice)	
Ice keels	
Oil on surface of ice	
Snow	
Albedo / enhancing melting	
Melt ponds	
Other	
Landfast ice	

Model Name	Unified Forecasting System (Coupled atmosphere-ocean-ice)
Developer	NOAA Contributors: NCEP, ESRL, NESII, GFDL, UCAR/NCAR
Inputs	
	·FV3 dycore-atmosphere: 4 resolutions [C96 (~100km), C192 (~50km), C384 (~25km) and C768 (~13km)] & 64 vertical levels ·Physics (using CCPP): GFS v15 (operational) or GFS v16 (developmental) ·NEMS for infrastructure ·MOM6 and HYCOM ocean models (ROMS, FVCOM) ·ADCIRC storm surge model ·WW3 wave model ·CICE5 ice model ·GOCART aerosol model ·Noah MP land model
Outputs/Results	
List Outputs Produced	Coupled ensemble & reanalysis & reforecast
Output File Formats	
Output Visualization (e.g., GIS, PDF Maps, Shapefiles)	
Output Visualization Platform (e.g., ERMA, CG1 View)	
How is uncertainty shown?	
Limitations	
Suggestions for Improved Arctic Use	
Temporal resolution	Predictive time scales from less than an hour to more than a year
Who uses the model?	

Model Name	TOPAZ4 (HYCOM-CICE-EnKF)
Developer	**NERSC**
Model Purpose(s)	Operational forecasts and reanalysis of ocean and sea ice drift for all purposes (ecosystem, general public)
Webpage/URL	https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=ARCTIC_ANALYSIS_FORECAST_PHYS_002_001_a Part of Phase 1 of JIP Project: http://www.arcticresponsetechnology.org/wp-content/uploads/2017/09/synthesis-report-final-report-to-the-iogp-arctic-oil-spill-response-technology-joint-industry-programme-1.pdf Part of Copernicus Marine Service (CMEMS): A core service / data portal: https://marine.copernicus.eu/
Coding Language(s)	Fortran 90
Development Status (e.g., beta version, available for use)	Mostly operational
Most Recent Update (version # and release date)	CICE3, EnKF v2, 2011
Use Restrictions (e.g., publicly available)	Open website
Source Code License (open vs closed source)	open
Scale of Operation (local (<10km), regional (>100 km) or global)	Local (about 10km)
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	Arctic, relocatable
Processing needs	N/A
Processes relevant to:	
Oil migration through ice	YES
Cracks/leads in icepack	NO
Brine channels	NO
Porosity	NO
Ice thickness	YES
	Underestimated: https://doi.org/10.5194/tc-12-3671-2018
Ice type	YES
	Ice age
Ice floe size	NO
Melting	YES

Model Name	TOPAZ4 (HYCOM-CICE-EnKF)
Developer	**NERSC**
Oil pooling and retention under ice	NO
Under-ice roughness	NO
Under-ice storage capacity	NO
Stripping velocity	NO
Stickiness	NO
Freezing/melting as it affects under-ice roughness	NO
Pumping oil under ice and oil encapsulation	YES
Ice movement	YES
	Ice drift predicts oil diffusion, which is overestimated, https://doi.org/10.5194/os-13-123-2017
Ice geolocation	YES
Freezing	YES
Ice controlling oil movement (small scale)	YES
Different ice types (frazil vs new ice vs multi-year ice)	YES
	FYI/MYI + /- 200 km
Ice keels	NO
Oil on surface of ice	YES
Snow	YES
	Snow depths
Albedo / enhancing melting	YES
	Sea ice and snow albedo
Melt ponds	NO
Other	NO
Landfast ice	NO
Inputs	
	EnKF: Weekly assimilation of Sea Surface Temperature, Sea Level, In situ temperature and salinity profiles, sea ice concentrations, sea ice thickness. Surface winds from ECMWF, climatological river fluxes

Model Name	TOPAZ4 (HYCOM-CICE-EnKF)
Developer	NERSC
Outputs/Results	
List Outputs Produced	age_of_first_year_ice; fraction_of_first_year_ice; ocean_barotropic_streamfunction; ocean_mixed_layer_thickness; sea_floor_depth_below_sea_level; sea_ice_albedo; sea_ice_area_fraction; sea_ice_thickness; sea_ice_x_velocity; sea_ice_y_velocity; sea_surface_elevation; sea_water_potential_temperature; sea_water_potential_temperature_at_sea_floor; sea_water_salinity; surface_snow_thickness; x_sea_water_velocity; y_sea_water_velocity;
Output File Formats	NetCDF-3
Output Visualization (e.g., GIS, PDF Maps, Shapefiles)	WMS, polar stereographic projection, https://resources.marine.copernicus.eu/?option=com_csw&view=details &product_id=ARCTIC_ANALYSIS_FORECAST_PHYS_002_001_a
Output Visualization Platform (e.g., ERMA, CG1 View)	Compatible with most
How is uncertainty shown?	Overall numbers in QuID report
Limitations	Coastline imprecise, smoothness
Suggestions for Improved Arctic Use	Addition of tides (not sure we understood the question: improvements we can do or users can perform?)
Temporal resolution	Daily updated 10-day forecasts
	Hourly output frequency (surface), daily output (3D fields)
Who uses the model?	RPS-ASA, MET Norway, NIPR

Model Name	**neXtSIM-F**
Developer	**NERSC**
Model Purpose(s)	Sea ice simulations of drift, deformation, thickness, concentration, etc. at spatial scales between 1 km and 10 km and time scale from several hours to decades. For both operational and research use.
Webpage/URL	https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=ARCTIC_ANALYSISFORECAST_PHY_ICE_002_011 Part of Phase 1 of JIP Project: http://www.arcticresponsetechnology.org/wp-content/uploads/2017/09/synthesis-report-final-report-to-the-iogp-arctic-oil-spill-response-technology-joint-industry-programme-1.pdf Part of Copernicus Marine Service (CMEMS): A core service / data portal: https://marine.copernicus.eu/
Coding Language(s)	C++
Development Status (e.g., beta version, available for use)	Mostly operational - still under relatively heavy development.
Most Recent Update (version # and release date)	7/7/20 [CMEMS: 11789]
Use Restrictions (e.g., publicly available)	Publicly available
Source Code License (open vs closed source)	close source
Scale of Operation (local (<10km), regional (>100 km) or global)	Local (about 5km)
Is this a global or regional model? If so, what is its intended use area? Is it "relocatable" (can be used anywhere)?	Central Arctic, relocatable
Processing needs	N/A
Processes relevant to:	
Oil migration through ice	YES
Cracks/leads in icepack	YES (as locally reduced concentration)
Brine channels	NO
Porosity	NO
Ice thickness	YES
Ice type	YES
	Ice age
Ice floe size	NO
Melting	YES

Model Name	neXtSIM-F
Developer	**NERSC**
Oil pooling and retention under ice	NO
Under-ice roughness	NO
Under-ice storage capacity	NO
Stripping velocity	NO
Stickiness	NO
Freezing/melting as it affects under-ice roughness	NO
Pumping oil under ice and oil encapsulation	YES
Ice movement	YES
	Ice drift velocity predicts oil diffusion, which was validated by IABP buoys, along with the spatial distribution of the diffusivity. https://doi.org/10.5194/tc-10-1513-2016
Ice geolocation	YES
Freezing	YES
Ice controlling oil movement (small scale)	
Different ice types (frazil vs new ice vs multi-year ice)	YES
	Newly formed (frazil, grease, pancake) and thick ice
Ice keels	NO
Oil on surface of ice	YES
Snow	YES
	Snow depths
Albedo / enhancing melting	YES
	Surface temperature dependent ice and snow albedos
Melt ponds	NO
Other	YES
Landfast ice	YES
	Represented by including a basal stress
Inputs	
	Daily sea ice concentration fields from satellites , winds from ECMWF, ocean currents from TOPAZ

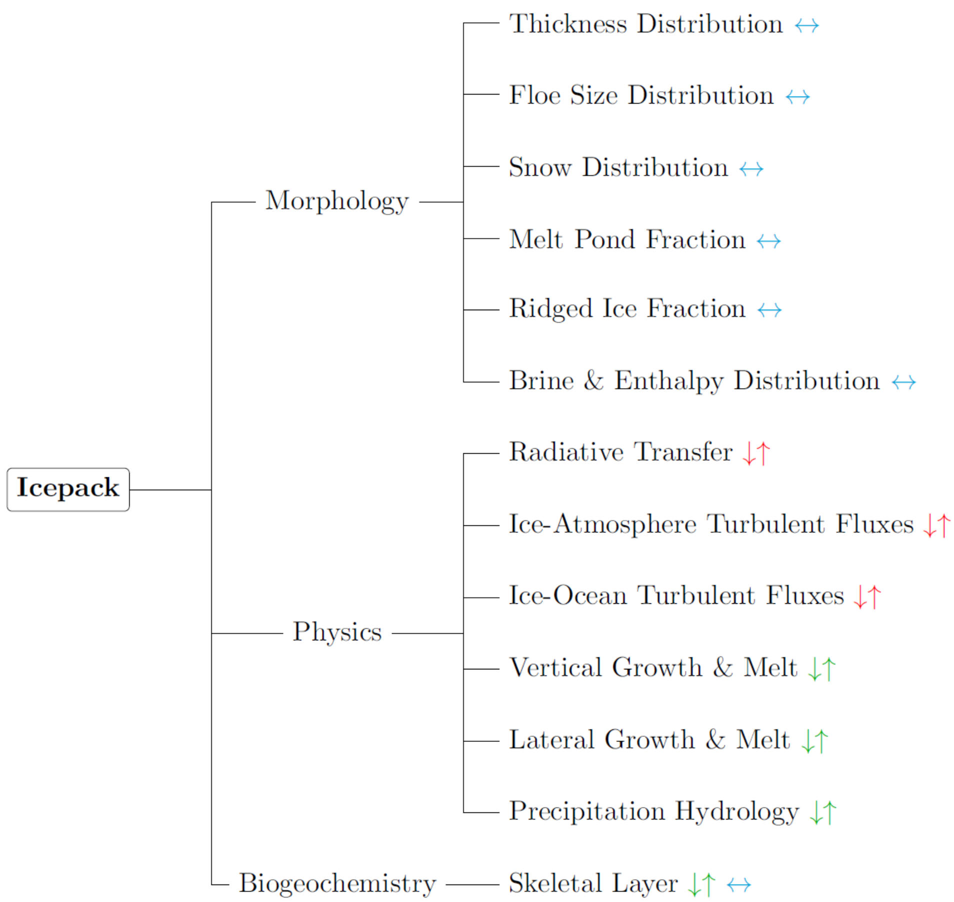
Model Name	neXtSIM-F
Developer	**NERSC**
Outputs/Results	
List Outputs Produced	ice concentrations, ice thickness, ice drift velocity and snow depths
Output File Formats	NetCDF-4
Output Visualization (e.g., GIS, PDF Maps, Shapefiles)	Identical to other ARC MFC products
Output Visualization Platform (e.g., ERMA, CG1 View)	Compatible with most
How is uncertainty shown?	Overall numbers in QuID report
Limitations	Canadian Archipelago is not included in the model domain yet
Suggestions for Improved Arctic Use	Include Canadian archipelago
Temporal resolution	Daily updated 7-day forecasts
Who uses the model?	Hourly output frequency
	OILMAP & OSCAR

APPENDIX L: Sea Ice Model Provenance Diagram

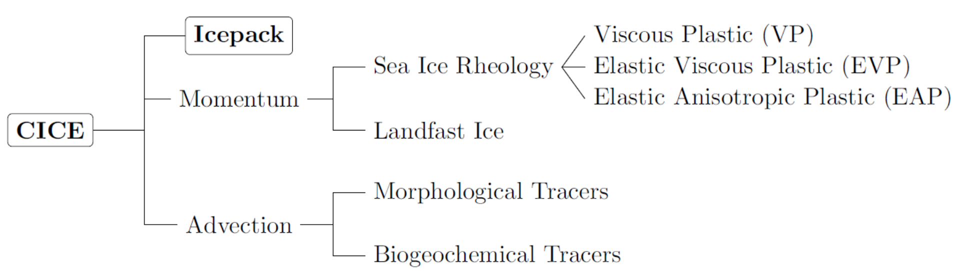
DRAFT: AMSM Sea Ice Model Provenance

Andrew Roberts, Elizabeth Hunke, Bonnie Brown, Nicole Jeffery

October 25, 2020



Icepack as an example of a state-of-the-art sea ice physics and biogeochemistry column package. Arrows indicate energy (↓↑) and mass (↓↑) flux exchange with the ocean and atmosphere, as well as horizontal advection (↔) using a dynamical core with Icepack, such as CICE. Addition of oil to Icepack would require a constituent hydrocarbon tracer, in turn affecting each of the morphology, physics and biogeochemistry of the model. Diagnostic tracers useful for oil spill tracking, such as sea ice age, are available but not listed here.



CICE as an example of a dynamical core that uses a column package to represent sub-grid scale physics and biogeochemistry with Icepack as a submodule. As with other dynamical cores, CICE also includes infrastructure for running the model and providing output (not shown), and offers a choice of three methods for modeling internal ice stress: VP, EVP and EAP.

Model[†]	Sea Ice Lead[‡]	Domain	DyCore[§]		Column[ξ]	Max. Timescale
a) Prominent sea ice component models applicable to coupled configurations						
CICE	LANL	global	native	ESQ	Icepack	centennial
MPAS-SI	LANL	global	MPAS	EU	Icepack	centennial
neXtSIM	NERSC	northern	native	LC	native	seasonal
DEMSI	LANL	northern	LAMMPS	LD	Icepack	centennial
TOPAZ	NERSC	northern	native	LD	native	synoptic
b) Coupled forecast systems expected to be applicable to Arctic oil spill tracking						
ESPC	NRL	global	CICE	ESQ	Icepack	synoptic
CCMEP	ECCC	global	CICE	ESQ	Icepack	synoptic
HYCOM-CICE	DMI	northern	CICE	ESQ	Icepack	synoptic
TOPAZ4	NERSC	northern	native	ESQ	native	synoptic
RTOFS	NWS	global	CICE	ESQ	Icepack	synoptic
c) Examples of U.S. earth system models adaptable for studying Arctic oil spill impacts						
E3SM	LANL	global	MPAS-SI	EU	Icepack	centennial
CESM	NCAR	global	CICE	ESQ	Icepack	centennial
RASM	NPS	northern	CICE	ESQ	Icepack	decadal

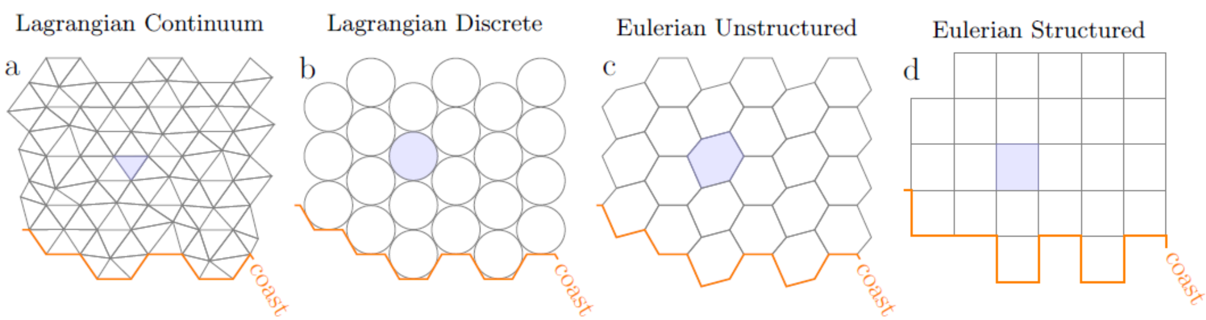
Sea Ice Model Provenance: U.S., Canadian, Danish and Norwegian Models surveyed by the meter-scale working group for potential oil spill response and planning from 2021 onwards. Models have been divided into stand-alone (a) sea ice models, (b) coupled atmosphere-sea ice-ocean-land hydrology synoptic analysis and forecast models, and (c) fully coupled earth system models used for decadal to multi-centennial climate studies. In 2020, not all models listed as using CICE use the latest version that includes the meter- to sub-grid scale physics and biogeochemistry of Icepack, but a switch to Icepack is anticipated starting in 2021. Acronyms are as follows:

† Codes - CICE Consortium sea ice model; MPAS-SI - Model for Prediction Across Scales, Sea Ice component; neXtSIM: neXt generation Sea Ice Model; DEMSI: Discrete Element Model of Sea Ice; TOPAZ: Ocean analysis and forecast system of the Nansen Environmental and Remote Sensing Center; ESPC: Earth System Prediction Capability of the U.S. Navy; CCMEP: Canadian Centre for Meteorological and Environmental Prediction forecast model; HYCOM-CICE: Configuration of the Hybrid-Coordinate Ocean Model coupled to CICE; TOPAZ4: Fourth operational version of TOPAZ; RTOFS: Global Real-Time Ocean Forecast System; E3SM: Department of Energy Exascale Earth System Model; CESM: Community Earth System Model; RASM: Regional Arctic System Model.

‡ Institutions leading sea ice development within the stated codes - LANL: Los Alamos National Laboratory; NERSC: Nansen Environmental and Remote Sensing Center. NRL: Naval Research Laboratory; ECCC: Environment and Climate Change Canada; DMI: Danish Meteorological Institute; NWS: U.S. National Weather Service; NCAR: National Center for Atmospheric Research; NPS: U.S. Naval Postgraduate School;

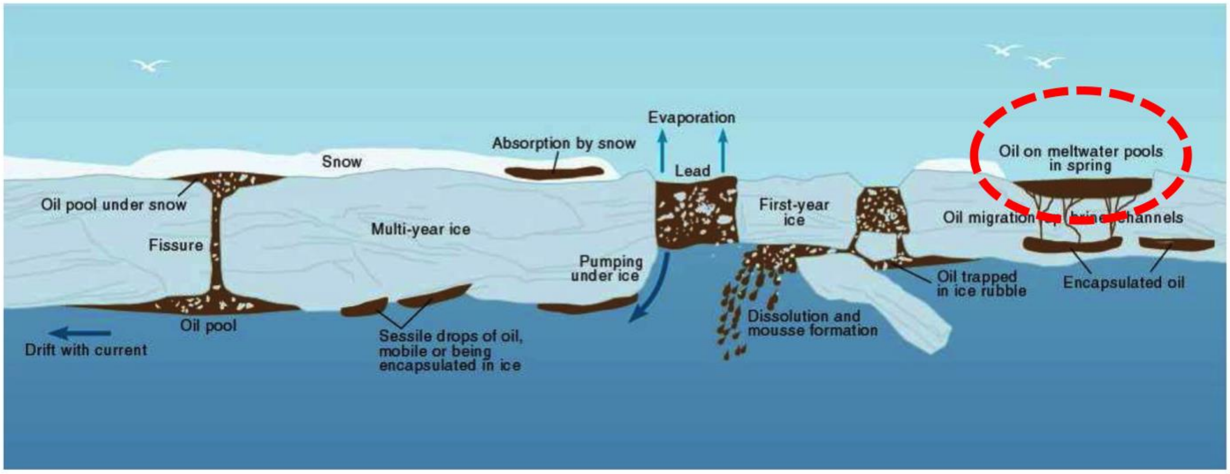
§ Dynamical Cores - MPAS: Model for the Prediction Across Scales; CICE: Native consortium Dynamical Core; LAMMPS: Large-scale Atomic/Molecular Massively Parallel Simulator; Tnative refers to a dynamical core that does not access external software. Key: E - Eulerian DyCore on either a structured quadrilateral (SQ) or unstructured (U) mesh; L - Lagrangian DyCore, either using continuum mechanics (C) or the discrete element method (D).

ξ Sub-grid scale column physics and biogeochemistry - Icepack: CICE Consortium saline ice package; native refers to a sub-grid scale representation that does not access external software.



Meshes for dynamical cores within which sub-grid and meter scale sea ice physics and biogeochemistry are represented statistically (blue shading) to simulate oil spills . Examples from the table include (a) neXtSIM, (b) DEMSI, (c) MPAS-SI, and (d) CICE. The location of the vertices in (a) and discrete elements in (b) move with the pack, whereas the mesh is fixed in space for (c) and (d). The mesh illustrated in (d) is both structured and quadrilateral.

APPENDIX M: Meter/Subgrid Scale Questions for Ice Modelers



Oil-in-ice processes diagram – courtesy of Kelsey Frazier (ADAC).

List of ice processes relevant to oil fate and transport – **meter + scale, subgrid scale**

1. Oil migration through ice
    - Cracks in icepack
    - Brine channels
    - Porosity
    - Ice thickness and type
    - Melting
2. Oil pooling and retention under ice
    - Under ice roughness
    - Under ice capacity
    - Stripping velocity
    - Stickiness
    - Freezing/melting as it affects under ice roughness
3. Pumping oil under ice and oil encapsulation
    - Ice movement
    - Freezing
4. Ice controlling oil movement (small scale)
    - Stickiness/retention of oil in different ice types
        - Frazil vs. new ice vs. multi-year ice
    - Ice keels
5. Oil on surface of ice
    - Absorption by / burying under snow
    - Oil altering albedo / enhancing melting

Introduction: Because Arctic oil spill modelers have to address oil migration through the ice, oil pooling and retention under ice, pumping oil under ice and oil encapsulation, ice controlling oil movement (small scale), and oil on the surface of ice, they are interested in how sub ice models address the following:

Questions related to 1. Oil migration through ice

- Crack formation: ice melting? Stress on icepack?
- Crack representation in ice models: deterministic, statistical?
- Brine channel representation in ice models
- Ice thickness interpretation for sub-grid physics (e.g. averaging? Standard deviation?)
- Icepack melting induced by sunlight absorption by oil: ice thickness and sunlight transmission in ice
- Ridge formation – oil migration in ridges
- Leads formation – are they sub-km leads captured in large scale model

Questions related to 2. Oil pooling and retention under ice

- Representation of under ice roughness in ice models
    - Sub-scale or resolved (i.e. information per grid cell based on ice model primitives or parameterized)?
    - Translate this information to oil storage volume
- Ridge formation – increased oil retention capacity under ice?
- **Current under ice and representation of the boundary layer under ice – usable for stripping velocity?**
    - Currents under ice verification?
- Ice fine structure – capillaries and pores to promote oil stickiness?
- Ice freezing and melting
    - At ice edges and under pack ice (more or less oil storage capacity, roughness of ice at edges vs. under pack ice)

Questions related to 3. Pumping oil under ice and oil encapsulation

- Ice floes movement: pushing oil under pack ice?
- Ice freezing and melting
    - Kinetics of freezing and melting
    - Typical thickness increment (what is the thickest oil layer possible to encapsulate?)
    - Supercooled water from melted ice – flash freeze with oil trapping at edges?
    - Super saline environment – oil mixing in water enhanced?
- Wind-induced currents under ice – possible to push a buoyant substance under ice?

Questions related to 4. Ice controlling oil movement (small scale)

- Oil mixed in frazil ice
    - Windage on frazil ice?
- Frazil ice transport vs. pack ice transport vs. ice floes transport
- Ridge formation
- Ice distribution and patchiness
- Size of ice floes
- Spatial and time resolution

Questions related to 5. Oil on surface of ice

- How is ice melting at the surface represented?
- How is the top of the ice surface represented (including snow)?

APPENDIX N: Oil Spill Model Algorithm Considerations in the Presence of Ice*

* SINTEF was unavailable to provide response for the OSCAR model at the time of publication.

Table 18: Oil Spill Model Algorithm Considerations in the Presence of Ice.

Model	**GNOME**
Response from:	**Chris Barker (NOAA)**
How is the spreading algorithm modified in the presence of ice?	Spreading is slowed by partial ice coverage, and the "exposed area" is modified by the fraction of ice coverage -- 50% ice coverage, 50% of the area is exposed.
Do you do something different about entrainment in the presence of ice?	Not directly -- but the wave field is modified, usually by modification of the wind field. And entrainment is driven by dispersion.
Does your model have any special considerations in the presence of ice if chemical dispersants are used?	No, GNOME does not currently model chemical dispersants at all.

Model	**SIMAP/OILMAP**
Response from:	**Debbie French McCay (RPS)**
How is the spreading algorithm modified in the presence of ice?	Oil spilled on top of pack ice is allowed to evaporate, but does not spread from the initial condition of the release. Oil collected under or in pack ice does not spread (i.e., it is assumed to pool). Spreading is constrained to the area of open water under partial ice conditions. If oil is below pour point then it won't spread (controlled by temperature).
Do you do something different about entrainment in the presence of ice?	In ice coverage between 30% and 80%, a linear reduction in wind speed from the open-water value (used in <30% ice) to zero in pack ice (>80% ice coverage) is applied to simulate shielding from wind effects. (The thresholds for open water (default 30%) and pack ice (default 80%) are model inputs. The defaults are typically assumed.) This reduces the evaporation, volatilization, emulsification, and entrainment rates due to reduced wind and wave energy. Entrained oil droplets are larger under these low energy conditions, and so dissolution from the droplets is reduced by lower surface area and reduced residence time in the water column.
Does your model have any special considerations in the presence of ice if chemical dispersants are used?	Use of chemical dispersants reduces interfacial tension, which changes (increases) entrainment rate. The algorithm is not changed for ice conditions.

Model	COSMoS
Response from:	**Guillaume Marcotte (ECCC)**
How is the spreading algorithm modified in the presence of ice?	Spreading is stopped at 75% ice coverage. 75% is used as the upper limit for behavior instead of the usual 80% to be consistent with the wave model (it uses 75% as its upper limit also). We use the pseudo-diffusion coefficients as defined in ADIOS2. They are based on Fay's 3 regimes of spreading. The empirical equations are used to derive a pseudo-diffusions coefficient and to calculate the slick area growth with respect to spreading. In presence of ice, there is no modification to either the growth rate of the slick or to the magnitude of the diffusion parameters. When ice fraction in a grid cell reaches 75%, spreading is stopped. The slick area is kept constant and the pseudo-diffusion to approximate spreading is set to 0. There is no slick contraction, thickness increase or other effects included in the model. We have plans to implement those contraction effects based on the number of elements in a grid cell and cell volume available to oil. This would have the following effect on the elements: ·If the total free area (1 - ice fraction times grid cell area) exceeds the total oil area in the grid cell (sum of the element areas in the grid cell), spreading continues normally ·If the total free area is equal to the total oil area, spreading is stopped (kind of steady state of spreading) ·If the total free area is less than the total oil area, spreading is stopped, area should be lowered (by a proportional fraction of area occupied by each element, as they might not have an equal one) to match free area and thickness adjusted consequently. Several reasons could lead to total oil area being higher than free area in a grid cell: ·More elements can move into an already occupied grid cell ·Ice cover can change over time As for the 75% coverage, this is the limit for wave propagation in ice covers in our implementation of the WaveWatch III model in Canada. From 75% and higher, it is approximated that waves cannot propagate in ice. Thus, to be consistent with wave models, we use 75% instead of the usual 80% (which probably comes from the fractional 1/10 of ice cover that are delivered by Coast Guard observation or by the Ice Services). I do not think this makes a huge difference in the behavior, but consistency between models used in the same context is always nice to have.
Do you do something different about entrainment in the presence of ice?	Entrainment is wave driven. Waves stop with ice >= 75%, thus entrainment will also stop and elements are allowed to buoyantly raise to the surface/bottom of ice.
Does your model have any special considerations in the presence of ice if chemical dispersants are used?	Dispersant use is not yet included in the model.

Model	BLOSOM
Response from:	**Rodrigo Duran (NETL)**
How is the spreading algorithm modified in the presence of ice?	BLOSOM does not currently handle ice.
Do you do something different about entrainment in the presence of ice?	BLOSOM does not currently handle ice.
Does your model have any special considerations in the presence of ice if chemical dispersants are used?	BLOSOM does not currently handle ice.

Model	TAMOC Oil Spill Calculator
Response from:	**Scott Socolofsky (Texas A&M University)**
How is the spreading algorithm modified in the presence of ice?	TAMOC itself does not account for ice in the spreading algorithm. When coupling to a far-field model (e.g., GNOME), one would use a different initial condition accounting for under-ice storage. But, this is done on the far-field side (e.g., GNOME), and not the TAMOC side. (TAMOC is a near-field jet/plume model, so it does not track the far-field transport of oil.)
Do you do something different about entrainment in the presence of ice?	TAMOC does not predict entrainment in the sense you mean below. I believe you are talking about entrainment of oil off the surface of the ocean and back into the water column. TAMOC does not model this process. That is done by the far-field model.
Does your model have any special considerations in the presence of ice if chemical dispersants are used?	Chemical dispersants affect the underwater behavior of TAMOC, but would not affect the way TAMOC interacts with ice. It could affect the initial conditions to the far-field model, but again, this effect would be modeled by the far-field model (e.g., GNOME).

Model	SPILLCALC
Response from:	**Aurelien Hospital (TetraTech)**
How is the spreading algorithm modified in the presence of ice?	a. Follows this basic 80/20 rule b. A factor, F, is used in this ice-environment oil transport: 1 - ((c-0.3) / 0.5), with *c* the ice concentration. Same as any other models, except that SPILLCALC smooths the impact of ice at c=30% and when the cover is deemed total at c=80%. c. Wind shear on the slick is reduced by F. d. The underlying hydrodynamics should include ice effect, resulting in different surface currents for the transport of the slick. Note that the component is independent of the 80/20 since the 3D hydro model will consider the impact of ice, regardless of the concentration. As a result, SPILLCALC considers the effect of ice for the current component of transport regardless of the concentration. e. When c>80%: i. oil assumed to adhere under ice, and drift with the ice, except if the under-ice current is above a threshold called “stripping velocity” and empirically quantified by Cox, Shultz and Buist. ii. Limitation with stripping velocity: currently based on fresh un-weathered oil iii. When the under-ice current is greater than the stripping velocity, then SPILLCALC considers the oil to detach from the ice and travel at reduced speed (given by Cox and Shultz) with under-ice currents. iv. Whenever the oil travels to an area with ice concentration less than 80%, the regular algorithms start being reactivated.
Do you do something different about entrainment in the presence of ice?	a. The wave parameters leading to entrainment of oil in the water column, is reduced by the factor F (described above), resulting in no entrainment when ice concentration is greater than 80%. b. If ice concentration is more than 80%, then some weathering processes can be un-directly affected: for example enhanced dissolution can occur since no more evaporation taking place, allowing the light hydrocarbon fractions to be dissolved.
Does your model have any special considerations in the presence of ice if chemical dispersants are used?	SPILLCALC does not have a dispersant module. So no dispersant modelling in SPILLCALC.

Model	NRC
Response from:	Hossein Babaei (NRC)
How is the spreading algorithm modified in the presence of ice?	The spilled oil can end up under, between or above ice. Imagine a spill from a sunken ship in ice-covered waters. The oils comes to the surface and depending on the ice concentration, some of the oil will be “stored” under ice. There are papers in literature about the capacity of ice of different roughness in storing oil and the thickness of the oil in contact with ice under side. The oil that is not under ice in this sunken ship case, will end up between the ice floes. There are paper in literature on approximate thickness of oil between ice floes. Assuming that the spilled oil is denser than ice and after some mathematical calculations and assumptions one can estimate the initial spreading area over which oil is either under, or between ice. Note that in reality, the ice condition could be highly variable and the oil spill is continuous over a period of time which need to be taken into account for a more realistic modelling. The model presently estimates terminal (non-transient) spreading of oil suddenly released at the close vicinity of water (or ice underside) surface. Depending on ice concentration and its density, the oil can be found between, over or under ice. Some oil is always stored under ice for concentrations more than 0.3 due to the probable existence of ice above the location of the release. This oil volume depends on the ice concentration, horizontal area of a typical ice floe and the ice thickness [1]. The remaining oil is available to be stored between ice floes, over ice or more under ice. The thickness of oil between ice floes in stagnant waters (for ice concentrations between 0.8 to 0.95) can be approximated as a function of ice, water and oil densities and the ice thickness [1]. The volume of oil stored between ice floes depends on this thickness and ice concentration and the area of the horizontal region in which oil exists, Aoi. For concentrations between 0.8 to 0.95, if the oil is lighter than ice, it is expected that some oil overtops ice and if it is denser than ice, some more oil (additional to the initial volume of oil under ice explained early in this paragraph) to stay under ice. The thickness of oil over ice can be approximated by an equation given in [2] and depends on the available oil volume over ice and oil viscosity. When ice concentration is less than 0.3, all oil is assumed to be freely floating with a thickness given in [1]. When ice concentration is in the 0.3-0.8 range, some oil will be under ice and the rest of it will spread to a freely floating thickness and over an area depending on the oil thickness and ice concentration (the higher the concentration, the larger the area). When ice concentration is in the 0.8-0.95 range it is assumed that the horizontal extent associated with floating oil and over-, or additional under-ice oil are the same and the Aoi is numerically calculated by knowing the oil thickness between ice floes and other thickness and volumes explained in the first paragraph. [1] Venkatesh, S., El-Tahan, H., Comfort, G., Abdelnour, R., 1990. Modelling the behavior of oil spills in ice-infested waters. Atmosphere-Ocean, 28(3), pp.303-329. [2] Kawamura, P., Mackay, D., Goral, M., 1986. Spreading of chemicals on ice and snow. Technical report No. EE-79, Environment Canada, 106p.

Model	NRC
Response from:	**Hossein Babaei (NRC)**
Do you do something different about entrainment in the presence of ice?	The model currently doesn't have any non-surface process
Does your model have any special considerations in the presence of ice if chemical dispersants are used?	No. The model at its current stage only deals with initial spreading, advection and pumping of oil.

Model	AOSM
Response from:	**Scott Socolofsky (Texas A&M University)**
How is the spreading algorithm modified in the presence of ice?	Spreading is limited by the under-ice storage capacity: oil cannot spread out until the storage capacity of the ice where the oil is has been fully filled. Only then can oil continue to spread.
Do you do something different about entrainment in the presence of ice?	The model does not consider entrainment differently in the presence of ice.
Does your model have any special considerations in the presence of ice if chemical dispersants are used?	Chemical dispersants do not change the ice algorithms.

Model	MOHID
Response from:	**Rodrigo Fernandez (Bentley Systems)**
How is the spreading algorithm modified in the presence of ice?	At this right moment the ice is not taken in consideration for modifying oil spreading, movement or weathering (MOHID is a living software, because is public domain and opensource, and there's people working on MOHID in the scope of oil-in-ice)
Do you do something different about entrainment in the presence of ice?	
Does your model have any special considerations in the presence of ice if chemical dispersants are used?	

APPENDIX O: New and Existing Technologies Spreadsheet[*][†]

[*] Adapted from combined Excel spreadsheet for readability.
[†] Blank cells from original spreadsheet were omitted.

Satellites

Table 19: Satellite Tab from New and Existing Technologies Spreadsheet.

	Multispectral: Mid day pass, Cloud free Conditions
Sensor	MODIS Terra/Aqua
Agency/Vendor	NASA
Working Group Contact	Ellen Ramirez (ER)
Cost $	Freely available
Routinely Collected?	yes
Taskable?	no
New or Existing (number in constellation)	Existing (2)
Overview of Technology (how it works). Include sensor type.	Visible band wavelength combinations
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Passive, 36 band, 1.3 - 2155nm
Min & Max Scene Footprint size/swath width, if applicable	2330km swath width
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	250m
Temporal Resolution/ Revisit	1 day per sensor
Time required for taking measurements	N/A
Latency: Image acquisition to image receipt	4hr
Accuracy	N/A
Precision	N/A
Sensitivity	N/A
Operational Procedure Available	^ POC
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	open water
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Cloud free, relatively calm sea
Oil type and condition	Crude
Space requirements (size, weight)	N/A
Power Requirements	N/A
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	N/A
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Internet
Lab Requirements	N/A
Data size and Volume	200MB
How/where has technology been used to date	Operational, NOAA Satellite Analysis Branch

Sensor	VIIRS
Agency/Vendor	NOAA/NASA
Working Group Contact	ER
Cost $	Freely available
Routinely Collected?	yes
Taskable?	no
New or Existing (number in constellation)	Existing (2)
Overview of Technology (how it works). Include sensor type.	Visible band wavelength combinations
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Passive, 22 band, 412 - 12000nm
Min & Max Scene Footprint size/swath width, if applicable	3060km swath width
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	375m
Temporal Resolution/ Revisit	1 day
Time required for taking measurements	N/A
Latency: Image acquisition to image receipt	4hr
Accuracy	N/A
Precision	N/A
Sensitivity	N/A
Operational Procedure Available	^ POC
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	open water
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Cloud free, relatively calm sea
Oil type and condition	Crude
Space requirements (size, weight)	N/A
Power Requirements	N/A
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	N/A
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Internet
Lab Requirements	N/A
Data size and Volume	200MB
How/where has technology been used to date	Operational, NOAA Satellite Analysis Branch

Sensor	Landsat 7
Agency/Vendor	USGS
Working Group Contact	ER
Cost $	Freely available
Routinely Collected?	yes
Taskable?	no
New or Existing (number in constellation)	Existing (1)
Overview of Technology (how it works). Include sensor type.	Visible band wavelength combinations
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Passive, 7 band 450 - 2350nm
Min & Max Scene Footprint size/swath width, if applicable	185 km swath width
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	30m
Temporal Resolution/ Revisit	16 days per sensor
Time required for taking measurements	N/A
Latency: Image acquisition to image receipt	4-6hr
Accuracy	N/A
Precision	N/A
Sensitivity	N/A
Operational Procedure Available	^ POC
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	open water
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Cloud free, relatively calm sea
Oil type and condition	Crude, possible diesel
Space requirements (size, weight)	N/A
Power Requirements	N/A
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	N/A
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Internet
Lab Requirements	N/A
Data size and Volume	600MB
How/where has technology been used to date	Operational, NOAA Satellite Analysis Branch

Sensor	Landsat 8
Agency/Vendor	USGS
Working Group Contact	ER
Cost $	Freely available
Routinely Collected?	yes
Taskable?	no
New or Existing (number in constellation)	Existing (1)
Overview of Technology (how it works). Include sensor type.	Visible band wavelength combinations
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Passive, 11 band 430 - 12510nm
Min & Max Scene Footprint size/swath width, if applicable	185 km swath width
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	15m panchromatic 30m multispectral 100m TIR
Temporal Resolution/ Revisit	16 days per sensor
Time required for taking measurements	N/A
Latency: Image acquisition to image receipt	4-6hr
Accuracy	N/A
Precision	N/A
Sensitivity	N/A
Operational Procedure Available	^ POC
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	open water
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Cloud free, relatively calm sea
Oil type and condition	Crude, possible diesel
Space requirements (size, weight)	N/A
Power Requirements	N/A
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	N/A
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Internet
Lab Requirements	N/A
Data size and Volume	600MB
How/where has technology been used to date	Operational, NOAA Satellite Analysis Branch

Sensor	Sentinel 2A/B
Agency/Vendor	European Space Agency/ Copernicus
Working Group Contact	ER
Cost $	Freely available
Routinely Collected?	yes
Taskable?	no
New or Existing (number in constellation)	Existing (2)
Overview of Technology (how it works). Include sensor type.	Visible band wavelength combinations
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Passive, 13 band, 443 - 2190nm
Min & Max Scene Footprint size/swath width, if applicable	290km swath width
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	10m
Temporal Resolution/ Revisit	10 days per sensor
Time required for taking measurements	N/A
Latency: Image acquisition to image receipt	6-8hr
Accuracy	N/A
Precision	N/A
Sensitivity	N/A
Operational Procedure Available	^ POC
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA, MD
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	open water, potentially shoreline
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Cloud free, relatively calm sea
Oil type and condition	Crude, possible diesel
Space requirements (size, weight)	N/A
Power Requirements	N/A
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	N/A
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Internet
Lab Requirements	N/A
Data size and Volume	100-300MB per tile
How/where has technology been used to date	Operational, NOAA Satellite Analysis Branch

Sensor	Aster
Agency/Vendor	NASA
Working Group Contact	ER
Cost $	Free, by request
Routinely Collected?	no
Taskable?	yes
New or Existing (number in constellation)	Existing (1)
Overview of Technology (how it works). Include sensor type.	VNIR bands only
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Passive, 3 band
Min & Max Scene Footprint size/swath width, if applicable	60km swath width
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	15m
Temporal Resolution/ Revisit	3-5 days
Time required for taking measurements	1-2 business days
Latency: Image acquisition to image receipt	6hr
Accuracy	N/A
Precision	N/A
Sensitivity	N/A
Sensor	Aster
Agency/Vendor	NASA
Operational Procedure Available	^ POC
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	open water
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Cloud free, relatively calm sea
Oil type and condition	Crude, possible diesel
Space requirements (size, weight)	N/A
Power Requirements	N/A
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	N/A
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Internet
Lab Requirements	N/A
Data size and Volume	300MB
How/where has technology been used to date	Operational, NOAA Satellite Analysis Branch

Sensor	Worldview 1
Agency/Vendor	Maxar/ DigitalGlobe
Working Group Contact	ER
Cost $	Commercial but free, by request and via USG agreement
Routinely Collected?	no
Taskable?	yes
New or Existing (number in constellation)	Existing (1)
Overview of Technology (how it works). Include sensor type.	Visible band wavelength combinations
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Passive, 1 band, panchromatic
Min & Max Scene Footprint size/swath width, if applicable	18km swath width
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	1m
Temporal Resolution/ Revisit	1-3 days
Time required for taking measurements	1 business day
Latency: Image acquisition to image receipt	6-8hr
Accuracy	N/A
Precision	N/A
Sensitivity	N/A
Operational Procedure Available	^ POC
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	open water, shoreline, potentially marsh
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Cloud free, relatively calm sea
Oil type and condition	Crude, possible diesel
Space requirements (size, weight)	N/A
Power Requirements	N/A
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	N/A
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Internet
Lab Requirements	N/A
Data size and Volume	800MB
Format of Final Data File and Access Point	Derived map product in jpeg
Format of Data delivery	GeoTiff
How/where has technology been used to date	Operational, NOAA Satellite Analysis Branch

Sensor	Worldview 2
Agency/Vendor	Maxar/ DigitalGlobe
Working Group Contact	ER
Cost $	Commercial but free, by request and via USG agreement
Routinely Collected?	no
Taskable?	yes
New or Existing (number in constellation)	Existing (1)
Overview of Technology (how it works). Include sensor type.	Visible band wavelength combinations
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Passive, 8 band, panchromatic, visible
Min & Max Scene Footprint size/swath width, if applicable	16km swath width
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	0.5m
Temporal Resolution/ Revisit	1-3 days
Time required for taking measurements	1 business day
Latency: Image acquisition to image receipt	6-8hr
Accuracy	N/A
Precision	N/A
Sensitivity	N/A
Operational Procedure Available	^ POC
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA, MD
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	open water, shoreline, potentially marsh
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Cloud free, relatively calm sea
Oil type and condition	Crude, possible diesel
Space requirements (size, weight)	N/A
Power Requirements	N/A
Sensor	Worldview 2
Agency/Vendor	Maxar/ DigitalGlobe
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	N/A
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Internet
Lab Requirements	N/A
Data size and Volume	800MB
Format of Final Data File and Access Point	Derived map product in jpeg
Format of Data delivery	GeoTiff
How/where has technology been used to date	Operational, NOAA Satellite Analysis Branch

Sensor	Worldview 3
Agency/Vendor	Maxar/ DigitalGlobe
Working Group Contact	ER
Cost $	Commercial but free, by request and via USG agreement
Routinely Collected?	no
Taskable?	yes
New or Existing (number in constellation)	Existing (1)
Overview of Technology (how it works). Include sensor type.	Visible band wavelength combinations
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Passive, 16 band, panchromatic, visible, SWIR
Min & Max Scene Footprint size/swath width, if applicable	13km swath width
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	0.35m
Temporal Resolution/ Revisit	1-3 days
Time required for taking measurements	1 business day
Latency: Image acquisition to image receipt	6-8hr
Accuracy	N/A
Precision	N/A
Sensitivity	N/A
Operational Procedure Available	^ POC
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER NRDA, MD
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	open water, shoreline, potentially marsh
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Cloud free, relatively calm sea
Oil type and condition	Crude, possible diesel
Space requirements (size, weight)	N/A
Power Requirements	N/A
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	N/A
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Internet
Lab Requirements	N/A
Data size and Volume	800MB
Format of Final Data File and Access Point	Derived map product in jpeg
Format of Data delivery	GeoTiff
How/where has technology been used to date	Operational, NOAA Satellite Analysis Branch

Sensor	Worldview 4
Agency/Vendor	Maxar/ DigitalGlobe
Working Group Contact	ER + NASA contact?
Cost $	Commercial but free, by request and via **NASA** agreement
Routinely Collected?	no
Taskable?	yes
New or Existing (number in constellation)	Existing (1)
Overview of Technology (how it works). Include sensor type.	Visible band wavelength combinations
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Passive, 8 band, panchromatic, visible
Min & Max Scene Footprint size/swath width, if applicable	13km swath width
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	0.5m
Temporal Resolution/ Revisit	1-3 days
Time required for taking measurements	1 business day
Latency: Image acquisition to image receipt	6-8hr
Accuracy	N/A
Precision	N/A
Sensitivity	N/A
Operational Procedure Available	^ POC
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER NRDA, MD
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	open water, shoreline, potentially marsh
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Cloud free, relatively calm sea
Oil type and condition	Crude, possible diesel
Space requirements (size, weight)	N/A
Power Requirements	N/A
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	N/A
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Internet
Lab Requirements	N/A
Data size and Volume	800MB
Format of Final Data File and Access Point	Derived map product in jpeg
Format of Data delivery	GeoTiff

Sensor	Skysat
Agency/Vendor	Planet Labs
Working Group Contact	ER + NASA contact?
Cost $	Commercial but free, by request and via **NASA** agreement
Routinely Collected?	no
Taskable?	yes
New or Existing (number in constellation)	Existing (15)
Overview of Technology (how it works). Include sensor type.	Visible band wavelength combinations
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Passive, 4 band, RBG, NIR
Min & Max Scene Footprint size/swath width, if applicable	8km swath width
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	0.5m
Temporal Resolution/ Revisit	2 days
Time required for taking measurements	1 business day
Latency: Image acquisition to image receipt	6-8hr
Accuracy	N/A
Precision	N/A
Sensitivity	N/A
Operational Procedure Available	^ POC
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA, MD
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	open water, shoreline, potentially marsh
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Cloud free, relatively calm sea
Oil type and condition	Crude, possible diesel
Space requirements (size, weight)	N/A
Power Requirements	N/A
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	N/A
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Internet
Lab Requirements	N/A
Data size and Volume	1GB
Format of Final Data File and Access Point	Derived map product in jpeg
Format of Data delivery	GeoTiff
How/where has technology been used to date	Operational, NOAA Satellite Analysis Branch

Sensor	Formosat-5
Agency/Vendor	National Space Organization - Taiwan
Working Group Contact	ER
Cost $	Commercial but free, via **NOAA/NESDIS** agreement
Routinely Collected?	no
Taskable?	yes
New or Existing (number in constellation)	Existing (1)
Overview of Technology (how it works). Include sensor type.	Visible band wavelength combinations
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Passive, 5 band
Min & Max Scene Footprint size/swath width, if applicable	24km swath width
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	2m panchromatic 4m multispectral
Temporal Resolution/ Revisit	2 days
Time required for taking measurements	1 business day, with time zone difference consideration
Latency: Image acquisition to image receipt	6-8hr
Accuracy	N/A
Precision	N/A
Sensitivity	N/A
Operational Procedure Available	^ POC
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER NRDA, MD
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	open water, shoreline, potentially marsh
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Cloud free, relatively calm sea
Oil type and condition	Crude, possible diesel
Space requirements (size, weight)	N/A
Power Requirements	N/A
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	N/A
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Internet
Lab Requirements	N/A
Data size and Volume	750MB
Format of Final Data File and Access Point	Derived map product in jpeg
Format of Data delivery	GeoTiff
How/where has technology been used to date	Operational, NOAA Satellite Analysis Branch

Sensor	SPOT 6/7
Agency/Vendor	French Space Agency (CNES)
Working Group Contact	ER
Cost $	Commercial, for purchase
Routinely Collected?	no
Taskable?	yes
New or Existing (number in constellation)	Existing (2)
Overview of Technology (how it works). Include sensor type.	Visible band wavelength combinations
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Passive, 5 band, 450 - 890nm
Min & Max Scene Footprint size/swath width, if applicable	60km swath width
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	1.5m panchromatic 6m multispectral
Temporal Resolution/ Revisit	2 days
Time required for taking measurements	TBD
Latency: Image acquisition to image receipt	TBD
Accuracy	N/A
Precision	N/A
Sensitivity	N/A
Operational Procedure Available	^ POC
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA, MD
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	open water, shoreline, potentially marsh
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Cloud free, relatively calm sea
Oil type and condition	Crude, possible diesel
Space requirements (size, weight)	N/A
Power Requirements	N/A
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	N/A
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Internet
Lab Requirements	N/A
Data size and Volume	500MB
Format of Final Data File and Access Point	Derived map product in jpeg
Format of Data delivery	GeoTiff
How/where has technology been used to date	Operational, NOAA Satellite Analysis Branch

Sensor	Pleiades
Agency/Vendor	French Space Agency (CNES)
Working Group Contact	ER
Cost $	Commercial, for purchase
Routinely Collected?	no
Taskable?	yes
New or Existing (number in constellation)	Existing (2)
Overview of Technology (how it works). Include sensor type.	Visible band wavelength combinations
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Passive, 5 band, 470 - 940nm
Min & Max Scene Footprint size/swath width, if applicable	20km swath width
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	0.7 panchromatic 2.8m multispectral
Temporal Resolution/ Revisit	2 days
Time required for taking measurements	TBD
Latency: Image acquisition to image receipt	TBD
Accuracy	N/A
Precision	N/A
Sensitivity	N/A
Operational Procedure Available	^ POC
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER NRDA, MD
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	open water, shoreline, potentially marsh
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Cloud free, relatively calm sea
Oil type and condition	Crude, possible diesel
Space requirements (size, weight)	N/A
Power Requirements	N/A
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	N/A
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Internet
Lab Requirements	N/A
Data size and Volume	1BG
Format of Final Data File and Access Point	Derived map product in jpeg
Format of Data delivery	GeoTiff
How/where has technology been used to date	Operational, NOAA Satellite Analysis Branch

Sensor	Kompsat-2/3
Agency/Vendor	Korea Aerospace Research Institution (KARI)
Working Group Contact	ER
Cost $	Commercial, for purchase
Routinely Collected?	no
Taskable?	yes
New or Existing (number in constellation)	Existing (2)
Overview of Technology (how it works). Include sensor type.	Visible band wavelength combinations
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Passive, 5 band, 450 - 900nm
Min & Max Scene Footprint size/swath width, if applicable	15km swath width
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	0.7 panchromatic 2.8m multispectral
Temporal Resolution/ Revisit	2-4 days
Time required for taking measurements	TBD
Latency: Image acquisition to image receipt	TBD
Accuracy	N/A
Precision	N/A
Sensitivity	N/A
Operational Procedure Available	^ POC
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA, MD
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	open water, shoreline, potentially marsh
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Cloud free, relatively calm sea
Oil type and condition	Crude, possible diesel
Space requirements (size, weight)	N/A
Power Requirements	N/A
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	N/A
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Internet
Lab Requirements	N/A
Data size and Volume	500MB
Format of Final Data File and Access Point	Derived map product in jpeg
Format of Data delivery	GeoTiff
How/where has technology been used to date	Operational, NOAA Satellite Analysis Branch

Hyperspectral: Mid day pass, Cloud free	
Sensor	DESIS
Agency/Vendor	Teledyne Brown Engineering
Working Group Contact	ER
Cost $	Commercial but free, via USG agreement
Routinely Collected?	no
Taskable?	yes… working on learning the procedure
New or Existing (number in constellation)	Existing (1)
Overview of Technology (how it works). Include sensor type.	hyperspectral
How is it operated?	International Space Station
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Passive, 235 bands, 400-1000nm
Min & Max Scene Footprint size/swath width, if applicable	30km x 30km footprint
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	30m
Temporal Resolution/ Revisit	Variable
Time required for taking measurements	2 business days
Latency: Image acquisition to image receipt	Up to 2 days
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA, MD
Sensor	Planet Watcher
Agency/Vendor	
Working Group Contact	Phil McGillivary
New or Existing (number in constellation)	Existing
Overview of Technology (how it works). Include sensor type.	hyperspectral & SAR
How is it operated?	unmanned

Radar: Dawn and Dusk Orbit, Winds 5-15 knots	
Sensor	RADARSAT Constellation Mission (RCM)
Agency/Vendor	MacDonald Detwiler and Associates
Working Group Contact	Gordon Staples
Cost $	Not sure…
Routinely Collected?	yes
Taskable?	yes
New or Existing (number in constellation)	Existing (3)
Overview of Technology (how it works). Include sensor type.	C-band SAR
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Active Sensor
Min & Max Scene Footprint size/swath width, if applicable	350km (up to 1000km for maritime)
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	50m
Temporal Resolution/ Revisit	2-4 days
Time required for taking measurements	1 business day
Latency: Image acquisition to image receipt	TBD
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA, MD
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	Open ocean - yes. Coastal–Yes, but can be challenging due to inherent near-shore dynamics, e.g. upwelling, coastal run off, wind lee affects. Shoreline/marsh–Very challenging discrimination due to breaking waves, influence of vegetation. Lakes/Rivers–Unknown, but likely limited by wind fetch/duration to achieve suitable water-surface roughness. Bottom–No - virtually no water penetration with SAR. Ice–Leads - possible, but same constraint as lakes, rivers–Under ice – Unknown, but unlikely
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Wind speeds ~ 2m/s to ~ 12 m/s
Oil type and condition	Variable oil types and weathering state
Describe raw data format	Data formats: Radar imagery --> GeoTiff. Plus many other format: PDF, JPG, SHP, KML, NetCDF, … Data volume – SAR image–GeoTiff processing image ~ 250 MB/per data channel–SAR data can be compressed significantly, but still retain meaningful information–Full resolution image of oil area (assumed < scene size) reduces data volume. Data volume – Information product–100 kB - 10s MB (typical product)

Sensor	RADARSAT Constellation Mission (RCM)
Agency/Vendor	MacDonald Detwiler and Associates
Time required for Data Processing to data delivery (emergency vs nonemergency)	Programing–The satellite can be programmed in as little as twelve hours, with four-hour programming possible for emergencies as defined by RADARSAT-2 Mission Management. Data Downlink–Within a ground station mask: data acquisition/downlink are simultaneous–Record and downlink: depends on ground station location with-respect-to acquisition AOI, but typically no more than ~ 4-6 hours. Data Processing, Information Extraction, and Delivery–Processing: < 10 minutes–Information extraction: depends on scene complexity, but usually < 2 hours–Electronic delivery: depends on communication bandwidth and information-product volume
SOP available data processing	
Data size and Volume	
Format of Final Data File and Access Point	RCM acquires data using Standard Acquisition Plan --> regular, routine coverage using the same imaging mode. Data are free and open, but relatively limited opportunities for end users to request data acquisition. Users must obtain account from the GC–Anonymous: very restricted data access–Vetted. Access to all data. Must be a company. Some countries will be restricted
Format of Data delivery	
Uncertainty bounds expression	
TRL #	Currently at TRL 5/6. Steps to move to next level:–Further analysis of data acquired off the coast of Louisiana (Taylor slick)–Analysis of data acquired off Santa Barbara (Coal Oil Pt.)–Piggy-back on CAMPRI field studies, if planned
Reports, articles available	Reference:–Oscar Garcia-Pineda, Gordon Staples, Cathleen E. Jones, Chuanmin Hu, Benjamin Holt, Villy Kourafalou, George Graettinger, Lisa DiPinto, Ellen Ramirez, Davida Streett, Jay Cho, Gregg Swayze, Shaojie Sun, Diana Garcia, Francisco Haces-Garcia, Classification of Oil Thickness using Multiple Remote Sensors (2019), Accepted for Publication in Remote Sensing of Environment
Strengths and weaknesses	Strengths–SAR has been used or decades for oil slick detection–Very good understanding of oil detection as a function of radar, environmental, and oil characteristics–SAR continuity, e.g. RADARSAT Constellation Mission, Sentinel, and discussion of “flocks” of small-sat SARs–Progress on estimating relative oil thickness. Weaknesses–NESZ (noise floor). U-shaped for a single image. Increases with increasing incidence angle. To obtain suitable S/N, choice of incidence angles will be constrained–Standard acquisition plans may be restrictive for oil spill response–SAR is sensitive to environmental and radar parameters, so may require interpretation–SAR is sometimes not fully understood, so perceived to be the domain of “wizards in long robes”
Testing QA/QC	RCM will be calibrated using similar procedure to RADARSAT-2

Sensor	Radarsat-2
Agency/Vendor	MacDonald Detwiler and Associates
Working Group Contact	Gordon Staples
Cost $	Commercial but free, by USG agreement
Routinely Collected?	yes
Taskable?	yes
New or Existing (number in constellation)	Existing (1)
Overview of Technology (how it works). Include sensor type.	C-band SAR
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Active Sensor
Min & Max Scene Footprint size/swath width, if applicable	500km
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	Highest is 1m
Temporal Resolution/ Revisit	2-4 days
Time required for taking measurements	1-2 business days
Latency: Image acquisition to image receipt	1-2 hours
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA, MD
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	Open ocean - yes. Coastal–Yes, but can be challenging due to inherent near-shore dynamics, e.g. upwelling, coastal run off, wind lee affects. Shoreline/marsh–Very challenging discrimination due to breaking waves, influence of vegetation. Lakes/Rivers–Unknown, but likely limited by wind fetch/duration to achieve suitable water-surface roughness. Bottom–No - virtually no water penetration with SAR. Ice–Leads - possible, but same constraint as lakes, rivers–Under ice – Unknown, but unlikely
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Wind speeds ~ 2m/s to ~ 12 m/s
Oil type and condition	Variable oil types and weathering state
Describe raw data format	Data formats: Radar imagery --> GeoTiff. Plus many other format: PDF, JPG, SHP, KML, NetCDF, … Data volume – SAR image–GeoTiff processing image ~ 250 MB/per data channel–SAR data can be compressed significantly, but still retain meaningful information–Full resolution image of oil area (assumed < scene size) reduces data volume. Data volume – Information product–100 kB - 10s MB (typical product)

Sensor	Radarsat-2
Agency/Vendor	MacDonald Detwiler and Associates
Describe data process workflow and requirements	Near-real time data delivery example: As part of an oil-spill response study off the coast of Louisiana, RADARSAT-2 Fine quad-polarized data was acquired on April 25 at 07:00 Central Time and downlinked to the Gatineau, Quebec ground station for processing. A digitized oil-extent map and compressed RADARSAT-2 image (~ 2 MB) of the oil slick were delivered via satellite link to the vessels 42 minutes after acquisition.
Time required for Data Processing to data delivery (emergency vs nonemergency)	Programing–The satellite can be programmed in as little as twelve hours, with four-hour programming possible for emergencies as defined by RADARSAT-2 Mission Management. Data Downlink–Within a ground station mask: data acquisition/downlink are simultaneous–Record and downlink: depends on ground station location with-respect-to acquisition AOI, but typically no more than ~ 4-6 hours. Data Processing, Information Extraction, and Delivery–Processing: < 10 minutes–Information extraction: depends on scene complexity, but usually < 2 hours–Electronic delivery: depends on communication bandwidth and information-product volume
TRL #	Currently at TRL 5/6. Steps to move to next level:–Further analysis of data acquired off the coast of Louisiana (Taylor slick)–Analysis of data acquired off Santa Barbara (Coal Oil Pt.)–Piggy-back on CAMPRI field studies, if planned
Strengths and weaknesses	Strengths–SAR has been used or decades for oil slick detection–Very good understanding of oil detection as a function of radar, environmental, and oil characteristics–SAR continuity, e.g. RADARSAT Constellation Mission, Sentinel, and discussion of "flocks" of small-sat SARs–Progress on estimating relative oil thickness. Weaknesses–NESZ (noise floor). U-shaped for a single image. Increases with increasing incidence angle. To obtain suitable S/N, choice of incidence angles will be constrained–Standard acquisition plans may be restrictive for oil spill response–SAR is sensitive to environmental and radar parameters, so may require interpretation–SAR is sometimes not fully understood, so perceived to be the domain of "wizards in long robes"
Validation tests conducted to date: lab, field, test tank	Ohmsett–Due to tank size and SAR resolution, it does not make sense to acquire data–Acquisitions were tried with RADARSAT-2 SpotLight and TSX SpotLight a few years ago, but these imaging modes my provide insight into SAR capability, but resolution ~ 1m is far better than typical imaging modes for oil ~ 10 m to 50 m, so results need to be interpreted with care. Previous work (open water):–North Sea (NOFO) controlled spill: 2011 – 2013–MC20 slick: 2014 – 2017. Ongoing–Santa Barbara (Coal Oil Pt.): 2019 – and forward
Testing QA/QC	RADARSAT-2 data calibration–Currently ± 0.75 dB for mission life–Calibration checks ~ monthly via active transponders and Amazon rain forest–Calibration applied during data processing, so if calibration changes, archived data can be re-processed with updated calibration files
Vendor/Owner/Representative and Contact Info	Gordon Staples MDA

Sensor	Sentinel 1A & 1B
Agency/Vendor	ESA/ Copernicus
Working Group Contact	Jessica Garron
Cost $	Freely available
Routinely Collected?	yes
Taskable?	no
New or Existing (number in constellation)	Existing (2)
Overview of Technology (how it works). Include sensor type.	C-band SAR
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Active Sensor
Min & Max Scene Footprint size/swath width, if applicable	Up to 400km
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	Down to 5m
Temporal Resolution/ Revisit	6 days
Time required for taking measurements	N/A
Latency: Image acquisition to image receipt	4-8 hours
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA, MD
How/where has technology been used to date	Globally, many applications
Next steps to get to a higher TRL and to field application	Product delivery through ERMA

Sensor	ICEye
Agency/Vendor	ICEye
Working Group Contact	Phil McGillivary
Cost $	Commercial, for purchase
Routinely Collected?	no?
Taskable?	no
New or Existing (number in constellation)	Existing (18)
Overview of Technology (how it works). Include sensor type.	SAR
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Active Sensor
Min & Max Scene Footprint size/swath width, if applicable	TBD
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	TBD
Temporal Resolution/ Revisit	TBD
Time required for taking measurements	TBD
Latency: Image acquisition to image receipt	TBD
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA, MD

Sensor	Capella
Agency/Vendor	Capella Space
Working Group Contact	Phil McGillivary
Cost $	Commercial, for purchase
Routinely Collected?	Not sure
Taskable?	Not sure
New or Existing (number in constellation)	Existing (18 launched '19-'20, 18 planned for '21)
Overview of Technology (how it works). Include sensor type.	X-band SAR
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Active Sensor
Min & Max Scene Footprint size/swath width, if applicable	Up to 50km
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	Down to 0.5m
Temporal Resolution/ Revisit	6 hours
Time required for taking measurements	TBD
Latency: Image acquisition to image receipt	TBD
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA, MD

Sensor	TerraSAR-X/TanDEM-X
Agency/Vendor	Operated by German Space Agency (DLR); Research access: from ESA (https://tpm-ds.eo.esa.int/oads/access/collection/TerraSAR-X); Commercial Access: AIRBUS (https://www.intelligence-airbusds.com/geostore/)
Working Group Contact	Jessica Garron
Cost $	Research access: proposal to ESA required, Commercial access: Account required with AIRBUS, SpotLight: $2125 (archive), $4250 (acquisition) StripMap: $1844 (archive), $3688 (acquisition) ScanSAR: $1094 (archive), $2188 (acquisition)
Routinely Collected?	yes
Taskable?	yes
New or Existing (number in constellation)	Existing (2)
Overview of Technology (how it works). Include sensor type.	X-band SAR
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Active Sensor
Min & Max Scene Footprint size/swath width, if applicable	SpotLight: 10 km x 5 km StripMap: 30 km x 50 km ScanSAR: 100 km x 150 km
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	SpotLight: 25 cm to 1 m StripMap: 3 m ScanSAR: 16 m
Temporal Resolution/ Revisit	2.5 days
Time required for taking measurements	140 sec over target per orbit
Latency: Image acquisition to image receipt	NRT to 2.5 days
Accuracy	65 arcsec (3σ)
Precision	
Sensitivity	
Operational Procedure Available	L1 products from ESA
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA, MD, baseline
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	Water surface; land surface; ice surface
Range of sea state and other environmental conditions (e.g., day/night, clouds)	All day/night; 3-12 m/s wind ideal
Oil type and condition	Fresh crude, some emulsifications
Space requirements (size, weight)	N/A

Sensor	TerraSAR-X/TanDEM-X
Agency/Vendor	Operated by German Space Agency (DLR); Research access: from ESA (https://tpm-ds.eo.esa.int/oads/access/collection/TerraSAR-X); Commercial Access: AIRBUS (https://www.intelligence-airbusds.com/geostore/)
Power Requirements	N/A
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	24/7 availability for emergencies from AIRBUS
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Satellite uplink/downlink; large data volume networks for transmission
Lab Requirements	N/A
Describe raw data format	COSAR binary to GeoTiff from ESA; jpg or km from AIRBUS
Describe data process workflow and requirements	Order for download jpg or KML from AIRBUS; Download L1 as COSAR binary or GeoTiff from ESA
Time required for Data Processing to data delivery (emergency vs nonemergency)	NRt up to 2.5 days
SOP available data processing	Yes, through ESA
Data size and Volume	SpotLight: 300-800 MB StripMap: 2.5-3.5 GB ScanSAR: 5-6 GB
Format of Final Data File and Access Point	COSAR raw and GeoTiff from ESA https://tpm-ds.eo.esa.int/oads/access/collection/TerraSAR-X; jpg KML from AIRBUS https://www.intelligence-airbusds.com/geostore/
Format of Data delivery	COSAR binary and GeoTiff
Uncertainty bounds expression	
TRL #	8 or 9
How/where has technology been used to date	Globally, many applications
Next steps to get to a higher TRL and to field application	Product delivery through ERMA
Strengths and weaknesses	Non-intuitive to interpret; requires significant processing from raw to GeoTiff; commercially available regularly, freely available under declaration of International Disaster Charter; at end of life
Vendor/Owner/Representative and Contact Info	Non-commercial: https://tpm-ds.eo.esa.int/oads/access/collection/TerraSAR-X, Commercial: AIRBUS https://www.intelligence-airbusds.com/geostore/

Sensor	COSMO-SkyMed
Agency/Vendor	Operated by Italian Space Agency (Agenzia Spaziale Italiana; ASI), Data vendor (primary) Research access: https://earth.esa.int/web/guest/data-access/view-data-product/-/article/cosmo-skymed-esa-archive Commercial access: https://www.telespazio.com/en/home; https://www.e-geos.it/EGEOS_Portal_Login?startURL=%2Fproducts%2Fcosmo.html
Working Group Contact	Jessica Garron
Cost $	Research access: proposal required from non-U.S. researchers, Commercial access from Telespazio : Spotlight: $769.14 (archive), $4,733.20 (acquisition) Stripmap: $354.99 (archive), $2,366.60 (acquisition)
Routinely Collected?	yes
Taskable?	yes
New or Existing (number in constellation)	Existing (4)
Overview of Technology (how it works). Include sensor type.	X-band SAR
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Active Sensor
Min & Max Scene Footprint size/swath width, if applicable	Spotlight: 10 km2 Stripmap: 40 km2; 30 km2; 100 km2
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	Spotlight: 1 m Stripmap: 2.6 m; 10 m; 13.5 m x 23 m
Temporal Resolution/ Revisit	4-16 days
Time required for taking measurements	Spotlight: 10 sec Stripmap: 10 min continuous
Latency: Image acquisition to image receipt	3-18 hours
Accuracy	1 dB
Precision	
Sensitivity	
Operational Procedure Available	L1 products from ESA
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA, MD, baseline
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	Water surface; land surface; ice surface
Range of sea state and other environmental conditions (e.g., day/night, clouds)	All day/night; 3-12 m/s wind ideal
Oil type and condition	Fresh crude, some emulsifications
Space requirements (size, weight)	N/A
Power Requirements	N/A; 14 Kw

Sensor	COSMO-SkyMed
Agency/Vendor	Operated by Italian Space Agency (Agenzia Spaziale Italiana; ASI), Data vendor (primary) Research access: https://earth.esa.int/web/guest/data-access/view-data-product/-/article/cosmo-skymed-esa-archive Commercial access: https://www.telespazio.com/en/home; https://www.e-geos.it/EGEOS_Portal_Login?startURL=%2Fproducts%2Fcosmo.html
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	24/7 availability for emergencies from EGEOS (Telespazio)
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Satellite uplink/downlink; large data volume networks for transmission
Lab Requirements	N/A
Describe raw data format	SCS to HDF5
Describe data process workflow and requirements	Order for download jpg or KML from EGEOS; Download L1 as COSAR binary or GeoTiff from ESA
Time required for Data Processing to data delivery (emergency vs nonemergency)	3-18 hours (emergency), 72 hours (non-emergency)
SOP available data processing	Yes, through ESA
Data size and Volume	Spotlight: 17 MB, Stripmap: 8-30 MB
Format of Final Data File and Access Point	HDF5 from ESA https://earth.esa.int/web/guest/data-access/view-data-product/-/article/cosmo-skymed-esa-archive Commercial access: https://www.telespazio.com/en/home; https://www.e-geos.it/EGEOS_Portal_Login?startURL=%2Fproducts%2Fcosmo.html
Format of Data delivery	HDF5
Uncertainty bounds expression	1 dB
TRL #	7
How/where has technology been used to date	Globally, many applications
Next steps to get to a higher TRL and to field application	Product delivery through ERMA
Strengths and weaknesses	Non-intuitive to interpret; requires significant processing from raw to GeoTiff; commercially available regularly, freely available under declaration of International Disaster Charter; at end of life
Testing QA/QC	Yes
Vendor/Owner/Representative and Contact Info	HDF5 from ESA https://earth.esa.int/web/guest/data-access/view-data-product/-/article/cosmo-skymed-esa-archive Commercial access: https://www.telespazio.com/en/home; https://www.e-geos.it/EGEOS_Portal_Login?startURL=%2Fproducts%2Fcosmo.html

Sensor	PALSAR-2
Agency/Vendor	Operated by Japan Space Agency (JAXA) Data vendor (primary) RESTEC (https://www.restec.or.jp/en/solution/product-alos-2.html)
Working Group Contact	Jessica Garron
Cost $	Spotlight: $3780/scene ScanSAR: $756/scene Strip Map: $2268/scene Quad Pol: $2268/scene *$1417 extra for defined acquisitions
Routinely Collected?	Yes
Taskable?	Yes
New or Existing (number in constellation)	Existing (1)
Overview of Technology (how it works). Include sensor type.	L-band SAR
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
Sensor Description	Active Sensor
Min & Max Scene Footprint size/swath width, if applicable	Spotlight: 25 km x 25 km ScanSAR: 350 km x 355 km Strip Map: 70 km x 70 km Quad Pol: 30 km x 70 km
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	Spotlight: 1-3 m (.625 m/pixel) ScanSAR: 100 m (25 m/pixel) Strip Map: 10 m (6.25 m/pixel) Quad Pol: 10 m (6.25 m/pixel)
Temporal Resolution/ Revisit	14-days (100 minute orbit)
Time required for taking measurements	Spotlight: N/A ScanSAR: 52 sec Strip Map: 10 sec Quad Pol: 10 sec
Latency: Image acquisition to image receipt	2-12 hours under emergency declaration IN ASIA
Accuracy	
Precision	
Sensitivity	
Operational Procedure Available	
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, NRDA, MD, baseline
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	Water surface; land surface; ice surface
Range of sea state and other environmental conditions (e.g., day/night, clouds)	All day/night; 3-12 m/s wind ideal

Sensor	PALSAR-2
Agency/Vendor	Operated by Japan Space Agency (JAXA) Data vendor (primary) RESTEC
Oil type and condition	Fresh crude, some emulsifications
Space requirements (size, weight)	N/A
Power Requirements	N/A
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	2-12 hours under emergency declaration IN ASIA
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Satellite uplink/downlink; large data volume networks for transmission
Lab Requirements	N/A
Describe raw data format	CEOS and GeoTiff available from PASCO
Describe data process workflow and requirements	Download any level of data desired up to geocoded GeoTiff
Time required for Data Processing to data delivery (emergency vs nonemergency)	2-12 hours for data delivery in emergency OVER ASIA, unclear about time for delivery in other parts of world
SOP available data processing	Yes, through ASF Map Ready
Data size and Volume	650 MB - 3 GB for operational products
Format of Final Data File and Access Point	GeoTiff from https://www.restec.or.jp/en/solution/product-alos-2.html
Format of Data delivery	CEOS/GeoTiff
Uncertainty bounds expression	22 - 35 dB
TRL #	8 or 9
How/where has technology been used to date	Globally, many applications https://global.jaxa.jp/projects/sat/alos2/pdf/daichi2_SolutionBook_3rd_En.pdf
Next steps to get to a higher TRL and to field application	Product delivery through ERMA
Reports, articles available	https://global.jaxa.jp/projects/sat/alos2/pdf/daichi2_SolutionBook_3rd_En.pdf
Strengths and weaknesses	Non-intuitive to interpret; requires significant processing from raw to GeoTiff; commercially available regularly, freely available under declaration of International Disaster Charter; at end of life
Testing QA/QC	Yes
Vendor/Owner/Representative and Contact Info	PASCO corporation, email: order@alos-pasco.com, Tel: +81-3-5465-7376
Notes	NASA working on a cooperative agreement for data access, no timeline for implementation

Sensor	RISAT 1
Agency/Vendor	
Working Group Contact	Phil McGillivary
New or Existing (number in constellation)	Existing (1)
Overview of Technology (how it works). Include sensor type.	C-band SAR
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	oil monitoring, open water
New or Existing (number in constellation)	Existing (1)
Overview of Technology (how it works). Include sensor type.	X-band SAR
How is it operated?	unmanned
Sensor	GAOFEN-7
Agency/Vendor	China National Space Agency
Working Group Contact	Phil McGillivary
New or Existing (number in constellation)	Existing
How is it operated?	unmanned
Sensor	Russian Kundor
Agency/Vendor	
Working Group Contact	Phil McGillivary
Sensor	IQPS
Agency/Vendor	
Working Group Contact	Phil McGillivary
Sensor	ICESAT-2
Agency/Vendor	Operated by NASA, Data vendor National Snow and Ice Data Center
Working Group Contact	Jessica Garron
Cost $	No Cost
Routinely Collected?	Yes
Taskable?	No
New or Existing (number in constellation)	Existing (1)
Overview of Technology (how it works). Include sensor type.	Advanced Topographic Laser Altimeter System (ATLAS; times the travel of laser pulses to measure the elevation of Earth's surface); full list of data products available from https://icesat-2.gsfc.nasa.gov/science/data-products; ATL07: Along-track sea ice and sea surface height ATL10: Along-track sea ice freeboard
How is it operated?	unmanned
Ice / Open Water / Oil Monitoring	Ice/open water/ unknown sensitivities to oil on surfaces
Sensor Description	Active Sensor
Min & Max Scene Footprint size/swath width, if applicable	15 m footprint; 3 km swath
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	Dependent on cloud cover and surface reflectivity
Temporal Resolution/ Revisit	91-days
Time required for taking measurements	1-minute between each point

Sensor	ICESAT-2
Agency/Vendor	Operated by NASA, Data vendor National Snow and Ice Data Center
Latency: Image acquisition to image receipt	3 months+
Accuracy	0.5 m
Precision	1/1,000,000,000 of a second
Sensitivity	Dependent on cloud cover and surface reflectivity
Operational Procedure Available	L3A products
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	ER, baseline
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	Water surface; land surface; ice surface
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Daylight, low clouds
Oil type and condition	UNKNOWN
Space requirements (size, weight)	N/A
Power Requirements	N/A; 1374 watts
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	N/A
Needs for Deployment (e.g., boats, cranes)	N/A
Time for Mobilization/ Demobilization	N/A
Permits Required for deployment	N/A
# of people required to deployment	N/A
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Satellite uplink/downlink; large data volume networks for transmission
Lab Requirements	N/A
Describe raw data format	CMOS to NetCDF to HDF5
Describe data process workflow and requirements	Download L3A products as HDF5; need HDF5 viewer or use command line to manipulate
Time required for Data Processing to data delivery (emergency vs nonemergency)	3 months +
SOP available data processing	No, but there is a User Guide
Data size and Volume	30-230 MB

Sensor	ICESAT-2
Agency/Vendor	Operated by NASA, Data vendor National Snow and Ice Data Center
Format of Final Data File and Access Point	HDF5 from NSIDC https://nsidc.org/data/icesat-2/data-sets
Format of Data delivery	HDF5
Uncertainty bounds expression	up to 100 m
TRL #	7
How/where has technology been used to date	Primarily in Arctic regions to measure sea ice; also used for veg heights and general land height
Next steps to get to a higher TRL and to field application	Product delivery through ERMA
Reports, articles available	https://icesat-2.gsfc.nasa.gov/publications
Strengths and weaknesses	scattering errors and photon misidentification;
Validation tests conducted to date: lab, field, test tank	Not for oil
Oil type and condition tested	No
Results of testing	No
Testing QA/QC	Yes for ice, not for oil
Vendor/Owner/Representative and Contact Info	NSIDC https://nsidc.org/data/icesat-2/data-sets
Notes	L3B gridded monthly products not yet available
Sensor	Kondor-FKA 1 & 2
Agency/Vendor	
Working Group Contact	Phil McGillivary
New or Existing (number in constellation)	#1 launching 2020; #2 in 2021
Overview of Technology (how it works). Include sensor type.	S-band SAR satellite for civilian use (N. Sea Route ice guidance, etc.); ScanSAR, swath or spot mode
Min & Max Scene Footprint size/swath width, if applicable	Swath mode width 10km
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	1-2m in spot mode, 1-3m in strip mode, 5-30m in ScanSAR mode
Reports, articles available	https://space.skyrocket.de/doc_sdat/kondor-fka-1.htm
Strengths and weaknesses	
Vendor/Owner/Representative and Contact Info	Russia
Notes	Planned 5 year minimum lifetime
Working Group Contact	Phil McGillivary
New or Existing (number in constellation)	'improved' version of Kondor-FKA, planned for launch in 2025
Overview of Technology (how it works). Include sensor type.	SAR
Min & Max Scene Footprint size/swath width, if applicable	Swath mode width 10km
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	1-2m in spot mode, 1-3m in strip mode, 5-30m in ScanSAR mode
Reports, articles available	https://space.skyrocket.de/doc_sdat/kondor-fka-m-1.htm
Vendor/Owner/Representative and Contact Info	Russia
Notes	No details on what the 'improvements' are

Sensor	Obzor-R-1
Agency/Vendor	
Working Group Contact	Phil McGillivary
New or Existing (number in constellation)	Planned for launch summer 2021
Overview of Technology (how it works). Include sensor type.	X-band SAR; swath or spot mode
Min & Max Scene Footprint size/swath width, if applicable	Swath size 2km x 470km
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	Area of earth in single image: 10 x 20km; Resolution at least 1m, intended resolution 0.3-0.5m
Temporal Resolution/ Revisit	
Time required for taking measurements	Intended to collect images during at least 10 min of orbit
Reports, articles available	http://syntheticapertureradar.com/russia-to-launch-first-obzor-r-radar-satellite-in-2020/; https://space.skyrocket.de/doc_sdat/obzor-r.htm; http://www.russianspaceweb.com/obzor_r.html
Vendor/Owner/Representative and Contact Info	Russia
Sensor	iQPS QPS-SAR 1 IZANAGI
Agency/Vendor	
Working Group Contact	Phil McGillivary
New or Existing (number in constellation)	IZANAGI was the first launched mid-Dec. 2019 of an intended 36 satellite constellation, Second QPS SAR-2 IZANAMI to launch in first half of 2020
Overview of Technology (how it works). Include sensor type.	X-band SAR
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	Area in a single image: spot mode 10km; strip mode 25km Resolution: spot mode 1m (@300km altitude); strip mode 3.6x3m (@618km altitude)
Reports, articles available	http://syntheticapertureradar.com/japans-iqps-launched-on-a-pslv/; https://space.skyrocket.de/doc_sdat/qps-sar-1.htm; https://i-qps.net/; http://www.isas.jaxa.jp/home/saito_hirobumi_lab/_src/sc1242/SAR.pdf
Vendor/Owner/Representative and Contact Info	Japan: Institute for Q-shu Pioneers of Space, Inc.

Sensor	Synspective StriX-alpha
Agency/Vendor	
Working Group Contact	Phil McGillivary
New or Existing (number in constellation)	first launch late 2020 by Rocket Labs, from NZ, of planned 25 satellite constellation ($100M funding); first 6 satellites will be launched by 2022 w Asian region focus
Overview of Technology (how it works). Include sensor type.	X-band SAR
Min & Max Scene Footprint size/swath width, if applicable	spot beam 10km; strip swath 30km
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	spot beam 1.0m; strip beam 3.0m
Reports, articles available	https://synspective.com/satellite; https://space.skyrocket.de/doc_sdat/strix-alpha.htm
Vendor/Owner/Representative and Contact Info	Japan
Sensor	GRUS 1A, 1B, 1C, 1D, 1E & WNISAT AxelSpace / AxelGlobe
Agency/Vendor	
Working Group Contact	Phil McGillivary
New or Existing (number in constellation)	first launch 2018, next 4 launches Q2, 2020, constellation completed 2022. Data availability started May 2019
Overview of Technology (how it works). Include sensor type.	GNSS-Reflectometry & 4optical bands: RGB, Near IR Also includes onboard magnetometer which provides info on space weather/auroral disturbances
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	AxelGlobe is intended to provide 2.5m resolution WNISAT: 500m Imaging area: 500 x 500km (intended specifically to collect images of sea ice across wide areas of the Arctic Ocean in a single image)
Application: Emergency response (ER), damage assessment (NRDA), restoration, marine debris (MD), disaster preparedness, testing verification tool	observations of Arctic sea ice & icebergs, esp. for No. Shipping Route (N. coast Russia) & weather data & space weather/auroral disturbances for use by pilots, etc.
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	WNISAT - specializing in observations of Arctic sea ice & icebergs, esp. for No. Shipping Route (N. coast Russia) & weather data
Reports, articles available	https://www.axelspace.com/en/solution_/wnisat1r/;

Sensor	WNISAT-1R
Agency/Vendor	
Working Group Contact	Phil McGillivary
Overview of Technology (how it works). Include sensor type.	GNSS-R and 4 optical bands (IR, red, green, panchromatic)
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	IR & Red band 400m; Green & Panchromatic band 200m
Reports, articles available	https://www.axelspace.com/en/solution_/wnisat1r/;
Vendor/Owner/Representative and Contact Info	Japan
Notes	will test/demo optical (laser) data comms
Sensor	GRUS
Agency/Vendor	
Working Group Contact	Phil McGillivary
Min & Max Scene Footprint size/swath width, if applicable	Swath width: 57+km
Nadir Resolution (GSD e.g. 10m/pixel), if applicable	Area in image: 50 x 50 km; 2.5m , five bands: Panchromatic, RGB, Red Edge, Near IR
Reports, articles available	https://www.axelspace.com/en/axelglobe_/ https://www.axelspace.com/en/solution_/grus/ https://www.spaceitbridge.com/axelspace-show-first-images-signs-3-satellite-launch-deal.htm
Sensor	Soil Moisture Ocean Salinity (SMOS)
Agency/Vendor	ESA
Working Group Contact	https://earth.esa.int/web/guest/-/smos-level-3c-sea-ice-thickne-1
New or Existing (number in constellation)	Microwave Imaging Radiometer using Aperture Synthesis (MIRAS) radiometer picks up faint microwave emissions from Earth's surface to map levels of soil moisture, sea surface salinity, sea ice thickness and others geophysical variable such as wind speed over ocean and freeze / thaw soil state.
Overview of Technology (how it works). Include sensor type.	This data set contains daily estimations of SMOS retrieved sea-ice thickness and its uncertainty, at the edge of the Arctic Ocean during the period October-April and for Antarctica over the period April-October. The sea-ice thickness is retrieved up to a depth of ~ 0.5-1 m, depending on the ice temperature and salinity, with a spatial grid of 12.5 km. Daily maps (polar stereographic grids) are derived from the SMOS L1C product and are produced by the Integrated Climate Data Center (ICDC) at the University of Hamburg and Alfred Wagner Institute, in NetCDF format and with a latency of about 24 hours. This product is complementary with sea-ice thickness measurements from ESA's CryoSat and Sentinel-3 missions. Detailed information on the SMOS products is available. Spatial coverage: Northern Hemisphere (50 N to 90 N) Spatial coverage: Southern Hemisphere (50 S to 90 S)
How is it operated?	Sun-synchronous, dawn/dusk, circular orbit
Min & Max Scene Footprint size/swath width, if applicable	Swath Width: 900 km

Airborne

Table 20: Airborne Tab from New and Existing Technologies Spreadsheet.

Technology	**AVIRIS**
Working Group Contact	**CAMPRI Spreadsheet**
New or Existing (number in constellation)	Existing
Overview of Technology (how it works). Include sensor type/description.	Hyperspectral Imaging. AVIRIS=Wisk Broom AVIRIS-NG=Push Broom
How is it operated?	
Manufacturer/Developer	HySpex
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	Laboratory but applied to DWH spill in 2010
Min & Max Scene Footprint size/swath width, if applicable	m to km
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	Relative to distance from target (cm to m), sunlight glint can disrupt data, need sunny skies. Spectral resolution varies between 3-15nm for each detector channel. Pixel size is cm to 10's of m.
Time required for taking measurements	minutes to hours
Accuracy	Depends on radiometric accuracy of instrument, not all companies calibrate as well as JPL, best way to test accuracy is in the field, difficult to field sample emulsions in general as well as at the same time as overflights. C-H bands don't necessarily change their shape but scattering level changes, accuracy and aerial fraction can vary. Extract pixels from data and compare spectra for accuracy testing.
Precision	TBD
Sensitivity	Sunlight glint, cloudy skies.
Operational Procedure Available	Eventually published and can be modified by people as they see fit
Range of sea state and other environmental conditions (e.g., day/night, clouds)	ideal sunny days, wave height under 0.5m, no clouds, Macondo oil
Oil type and condition	Used Macondo crude for DWH spill, is there a
Space requirements (size, weight)	30 to 160cm
Power Requirements	50-100s watts
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	uav, satellite, aircraft
Needs for Deployment (e.g., boats, cranes)	Aircraft, drones, satellites
Time for Mobilization/ Demobilization	few days to weeks
Turnaround time for data	Will get faster with adequate resources; close to real time.
Permits Required for deployment	drone ceiling wavers
# of people required to deployment	Few to a dozen of trained support staff

Technology	**AVIRIS**
Working Group Contact	**CAMPRI Spreadsheet**
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Satellite uplinks, hard drives, SD cards, etc. This data takes up a lot of space -- 10's of Gb in size.
Describe raw data format	16 bit unsigned integer, 32-bit real number
Describe data process workflow and requirements	varies
Time required for Data Processing to data delivery (emergency vs nonemergency)	Can be near real time with sufficient resources and programming
SOP available data processing	Not yet
Data size and Volume	very large file (60 Gb)
Format of Final Data File and Access Point	varies may be GeoTiff with ENVI headers
Format of Data delivery	zipped files
Communication and transmission requirements	varies
TRL #	level of 7 (may need modification)
How/where has technology been used to date	Over the DWH spill in 2010
Next steps to get to a higher TRL and to field application	Testing synthetic emulsions at the Ohmsett tank with known emulsion thicknesses and water content
Reports, articles available	Spectral library may be universally applicable to different oil types -- listed slide with strengths and weaknesses
Validation tests conducted to date: lab, field, test tank	Has not yet been tested at OHMSETT
Oil type and condition tested	Sweet light crude (i.e., Macondo); DWH testing, July 9th, 2010
Testing QA/QC	NIST traceable thickness standards used for lab tests
Vendor/Owner/ Representative and Contact Info	Gregg Swayze

Technology	TRACS Multi Sensor System
Working Group Contact	**CAMPRI Spreadsheet**
New or Existing (number in constellation)	Existing
Overview of Technology (how it works). Include sensor type/description.	Flies on in aircraft, can detect oil as far as presence/absence, refined so we can avoid false positives, can differentiate fresh oil from weathered/emulsified, thick sheens versus thin sheens (don't always see thin sheens), treatable oil/actionable oil is on the range of 40-50 microns or greater -- can see in the thermal and pick up in RGB. This definition is not set. Can provide oil characterization, big difference between controlled environment/Lab at OHMSETT and the natural environment. Controlled environment (Ohmsett) from ~ .01 um to 5000 um (5 mm) Real world spill 2-4 classes 1 um to 200 um. 3-CCD, multispectral RGB digital camera with a thermal infrared imaging camera.
How is it operated?	
Manufacturer/Developer	As far as manufacturers, the thermal infrared camera in TRACS is Jenoptik, the RGB camera is made by JAI the IMU is made by Oxford Technologies. All of the hardware and software integration was done by Ocean Imaging. The rest of the system was built, integrated and developed (software) by Ocean Imaging and we'd prefer that certain elements of the integration remain proprietary.
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	TBD
Min & Max Scene Footprint size/swath width, if applicable	200-4,250 m, varies by altitude
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	0.2m to 4m, relative to altitude
Time required for taking measurements	
Accuracy	
Precision	Varies by incident, type of aircraft, location, how much data you want to take. Sometimes tasked to only go to one shoreline/marsh area where we go out and get the data and go back. RP or NOAA sometimes wants as much data as they can/get whole big picture, depends on what the task at hand is. Tactical information can vary by what you're doing. Can be as simple as looking at the screen, getting a Lat/Lon of where we think oil is and relaying it down to a boat over radio. Can also make mosaic imagery as GIOTIFF or KMZ or other methods. Also have quick classify that takes thermal imagery with help of RGB imagery to make 2-3 class color imagery, small file on order of KB, JPEG, KMZ, or GEOTIFF image.
Sensitivity	
Operational Procedure Available	Thickness ranges/classes examples - had a BSEE and NOAA funded study out of RAMSEE (??) 20 and compared thickness measurements to data from the boats and flew from 0 to 2 hours +/- from when they actually took the data, the ocean is very dynamic. When we were +/- 2 hours, 60% of the time was correct within 50 m of the sample spots. When we flew over precisely w/in minutes, were 70+% accurate within 10 m of the spot, 100% match within 50 to 100 m of sampling spot. Difficult to take samples, sample size isn't excellent, wouldn't pass peer reviewed paper because of the thickness ranges being fairly uncertain.

Technology	TRACS Multi Sensor System
Working Group Contact	**CAMPRI Spreadsheet**
Range of sea state and other environmental conditions (e.g., day/night, clouds)	
Oil type and condition	
Space requirements (size, weight)	Immediate tactical oil detection and characterization. COP-ready thickness products
Power Requirements	open water, shoreline mapping, oil entrainment in marshland
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	Have flown in a variety of weather and wave conditions (imaged successfully using full wave height at Ohmsett). Flown cloud cover as low as 800 feet, 500 feet is lowest flown (800 during Lake Washington Spill) and got good data. Really high resolution but 500+ frames to work with, much more data. Exact Beaufort scale wind speed parameters of operation unknown.
Needs for Deployment (e.g., boats, cranes)	Can generate thickness classes for fresh crude or near fresh, not emulsified. Can detect and discriminate emulsified oil as well as estimate general level of emulsification. Can discriminate thickness for many types of fresh-near-fresh crude types: AMS, Monterey, GOM crudes, thicker fuel oils. Refined/processed fuels like jet fuel and diesel are more of a presence/absence for detection
Time for Mobilization/ Demobilization	15.5"x11.5"x13" 27 lb.
Turnaround time for data	5.5 amps, 72 watts
Permits Required for deployment	Can be shipped via fed-ex or as luggage on commercial flights. Mounts for numerous planes or helicopters, mobilized in about 4-12 hours, four systems pre-staged in the U.S. During every spill always have a backup on site in case of any situation with primary. Backup gets shipped immediately overnight to flight base of operations, always on the ready. State of Washington has mandate/statute that we have to mobilize in 12 hours.
# of people required to deployment	No special requirements, designed for aircraft of opportunity. Been on small or large helicopters, float plane in Alaska, one to two pilots (partnership with MSRC safety rule, system doesn't need two pilots)
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	4-12hours
Lab Requirements	1-8 hours, usually in 4-5 now but a bit longer 7-9 hour range for some particularly difficult spills. Based on flight times and mission objectives
Describe raw data format	No special requirements, designed for aircraft of opportunity. Been on small or large helicopters, float plane in Alaska, one to two pilots (partnership with MSRC safety rule, system doesn't need two pilots)
Describe data process workflow and requirements	1-2 pilots, 1 operator

Technology	TRACS Multi Sensor System
Working Group Contact	**CAMPRI Spreadsheet**
Time required for Data Processing to data delivery (emergency vs nonemergency)	Specialized air to vessel system -- can communicate up to 10 miles in just a few minutes, don't want to send a whole lot of raw data down, want to send easy to use end products down that can be used. Antennae are used to get data off the plane as quickly as possible. Always have an MSRC person at the command center to facilitate getting that information. Sending the full load of GB data, need broadband connection for this. Part of our protocol is to make sure this is available to make this available ahead of time.
Format of Final Data File and Access Point	Some end users can't use a GEOTIFF file, now using google earth and PDFs, IMG files, etc. . Capable of delivering in whatever format the end user can use. Can't assume what they know how to use. Now protocol is to better communication with end users about what format they need. Classification type files, vector files, are all important. Tactical information products have on board software data processing, corrects for distortion and georeferenced, coregisters the bands, quick classified product and sends down from aircraft as GeoTiff, JPG or KMZ .
Format of Data delivery	5-60 minutes for digital products sent from aircraft to vessel or ICC, instant for radio, 1-8 hours for full oil characterization thematic maps
Uncertainty bounds expression	Analyst looks at situation/quality of data to decide what tools/algorithms to use. No public SOP available
Communication and transmission requirements	Varies by data product. Small for quick, tactical products. large volume, multiple gigabytes of raw data for full classification data and derived products
TRL #	geotiff,.bil/.bip,.img, JPEG, .kmz, ESRI Shapefile
How/where has technology been used to date	geotiff,.bil/.bip,.img, JPEG, .kmz, ESRI Shapefile
Next steps to get to a higher TRL and to field application	Oil thickness delivered in 50 um to 200 um wide classes. Last test during NOAA project revealed TRACS-derived thickness classes were ~70% to 100% accurate when compared to field samples depending on time and geographical proximity of sample.
Reports, articles available	TRACS incorporates an air-to-ground (or vessel) high speed data transmission system. Transferring the full, unprocessed data requires a broadband Internet connection
Strengths and weaknesses	9
Validation tests conducted to date: lab, field, test tank	"DMSC (precursor to TRACS), Operational 2007 - 2014: Suisun Marsh chemical spill, McKittrick well blowout, Romic spill, California, Cosco Buson, San Francisco Bay, Platform A Santa Barbara, Deep Water Horizon,
Oil type and condition tested	Numerous tests at Ohmsett, Santa Barbara Channel, OSPR drills, DWH data used for NOAA Technical Working Group, BSEE demo in Anchorage Alaska. TRACS, Operational 2014 – Present:
Results of testing	Refugio, Santa Barbara, Lake Washington, LA
Testing QA/QC	Ohmsett tests
Vendor/Owner/ Representative and Contact Info	BSEE/NOAA Oil Thickness and Emulsion project (contract E16G0023)

Technology	ASPECT Plane
Working Group Contact	**CAMPRI Spreadsheet**
New or Existing (number in constellation)	Existing
Overview of Technology (how it works). Include sensor type/description.	The Airborne Spectral Photometric Environmental Collection Technology (ASPECT) sensor suite is mounted in a fixed wing aircraft. The system provides stand-off, remote hazard detection to image, map, identify, and quantify chemical vapors, radioactive/nuclear material, and oil on water. Longwave multi-spectral pattern recognition using IR band.
Min & Max Scene Footprint size/swath width, if applicable	Scene footprint is a 60-degree field of view, ½ mile wide swath on the surface
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	The GSD would depend on the flight height. In general, the pixel resolution is 0.5 meters at 850-meter collection altitude above ground level (AGL).
Precision	Each flight is different based on the situation/size (in general, roughly 1-4 hours)
Sensitivity	In general, all collected data undergoes a scientific review before being released. During an incident or deployment, while the aircraft is airborne, a satellite communications link is utilized to allow the extraction of processed data and information to the ground. The Scientific Reach-back team reviews and certifies the data as scientifically valid in as short a time as possible (approximately 3-5 minutes from time of collection. QA/QC assessments on sensor operation and performance includes validation of automated processing and interpretation of the data. Only ASPECT government personnel communicate findings and data with the end-user or emergency management personnel. Originally, ASPECT was not initially designed to detect oil. However, during the BP Oil Spill response, EPA accidentally discovered that the technology used on ASPECT could be used to detect oil. EPA tested ASPECT's capability during the BP oil spill. The data for this method was collected over a period of 3-month period during the BP Oil spill. Several days of data was assessed by the Coast Guard and reported by the Coast Guard Boat Commanders in the field as to whether skim-able oil was "present" or "absent" at a particular location. The data was reviewed by the ground data analysis team as to whether a spectral emissivity was observed at the location. A classification matrix was developed on this assessment for this data.
Operational Procedure Available	During the BP Oil Response, the precision observed was above 99% classification accuracy. A set of 15,000 active observations were used for the oil containing training set and 75,000 observations were used for those pixels that did not contain oil.
Range of sea state and other environmental conditions (e.g., day/night, clouds)	The range of detectable oil is greater than 10 micrometers up to 50 millimeters
Oil type and condition	Because this was only a scientific research project during the BP Oil Spill, no Standard Operating Procedures were ever developed. Methods were only developed under a research effort and were continually changed during the entirety of the collection of the data exercise. Although the research results were wildly successful, the EPA did not continue this research after the BP Oil Spill and no further development has occurred to include a method development.

Technology	**ASPECT Plane**
Working Group Contact	**CAMPRI Spreadsheet**
Space requirements (size, weight)	The primary role of the ASPECT program is emergency response. In recent years, this role has expanded to include participation in homeland security events, geographical/ radiological characterization of removal/remedial sites, and atmospheric characterization. During emergency response operations, ASPECT could be tasked for various missions including initial/current/post damage assessment, restoration progress, and marine debris assessment (e.g. assessment of shorelines/waterways potentially contaminated with household hazardous waste/oil). Initially, ASPECT was not designed for oil detection. During the BP Oil Spill, ASPECT team accidentally discovered that the technologies onboard could be used to detect oil. The BP Oil Spill was the only time that oil detection capability for ASPECT was tested.
Power Requirements	• Both near-shore and deep-water applications • Surface oil, mixed oil/ water • Sheen to thick • Surface roughness reduces emissivity • Identification in presence of sediment or algae
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	Detection techniques are independent of time of day
Needs for Deployment (e.g., boats, cranes)	• Types of oil (e.g., crude oil type, diesel) • Fresh, weathered, emulsified Designed oil classification algorithm classifies the detections into four categories: (See visual example below) 1. surface oil, 2. mixed oil/sea water, 3. water, and 4. other
Time for Mobilization/ Demobilization	Hangar Space needed: 14ft tail height x 52ft wing span x 42ft length Runway Length: • minimum distance for runway: 3,000ft • minimum distance (only under specific conditions) 1500ft but only 1 pilot and little fuel. NOTE: Safety becomes a factor "Fixed based operation" would be needed—this is the base location for the crew. Ideally, crew would need a conference room, internet speed, open 24/7, hangar space
Turnaround time for data	110volts with average 40 amps (alternator and generator—powered by battery)

Technology	ASPECT Plane
Working Group Contact	**CAMPRI Spreadsheet**
Permits Required for deployment	• Wheels up in 1-hour, available 24/7. • Operates out of Dallas TX but can travel to any location • Multi-use; o Identifies oil on the surface of the water o Monitors vapors from oil burning and oil thickness for skimming operations • Ortho-rectified, filtered, digital imagery (reduce reflection) No, shipping needs required unless traveling to long distances/across ocean (e.g. Hawaii). If traveling long distances/across an ocean, the instruments would need to be shipped separately to account for space on the plane needed for fuel—a bladder would be added to the plane. ASPECT program has 1 plane with one complete instrument suite of detection and sensory instruments. We have other backup, individual instruments but not for a complete suite of instruments. Many of the backup equipment is older, out of date, and/or not calibrated. Typically, we operate with satellite capability. Without satellite capability, we wouldn't be able to provide real-time data. Data would be received at the end of the mission once the plane has landed.
# of people required to deployment	No additional needs for deployment
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Roughly about 1 hour for mobilization. No extra time is needed for demobilization—the plane directly flies back to duty station when mission is complete.
Lab Requirements	Data can be processed live (roughly 2 mins is needed for processing). After the flight, the plane will do a data dump of all the data collected.
Describe raw data format	No permits are needed; however, ASPECT plane must adhere to all FAA requirements. If a temporary flight restriction (TFR) is in place, we must get permission to be able to fly in specific areas during events.
Describe data process workflow and requirements	• 2 pilots and 2 operators on the plane, one lead for the team on ground • 1 remote technical team of roughly 4 personnel including one lead for the team to collect data, troubleshoot, post-process, and initiate deliverables (i.e. report) • 1 Federal employee (Contracting Officer Representative for the contract)
Time required for Data Processing to data delivery (emergency vs nonemergency)	Communication and transmission of data is done by satellite
SOP available data processing	N/A
Data size and Volume	Wide range of raw data formats based upon specific sensor
Format of Final Data File and Access Point	
Format of Data delivery	Approx. 3 to 5 minutes from collection to final processing Approx. 5 minutes to download and QC data products.
Uncertainty bounds expression	The ASPECT program has many procedures for chemical and radiological detection, but not for oil detection. Because this was only a scientific research project during the BP Oil Spill, no Standard Operating Procedures were ever developed.

Technology	**ASPECT Plane**
Working Group Contact	**CAMPRI Spreadsheet**
Communication and transmission requirements	• Final data products consist of either native image files (jpeg) of about 3 Mb full resolution • GIS packages include both kml and ESRI formats of sizes ranging from 500 Kb to several Mb depending on the nature. • Data extracted from the aircraft is in a kml format and processed raw data format (for QC purposes) • Final data is dependent on the end user needs and is primarily in kml or ESRI formats.
TRL #	The ASPECT program can generate data in three formats including a generic format such as JPEG, GeoJPEG and/or TIFF/GeoTiff, a Google Earth kml format and an ESRI ArcGIS collection of image and shape files. The type(s) of formats generated is completely flexible and can be established prior to, during or after data collection. The primary factor that must be considered is the amount of time and available band width that is available for data transmission. For this reason, the program typically generates emergency response data in a Google Earth format due to compactness and efficiency when using the satellite link.
How/where has technology been used to date	Typically, a written report is documented and provided to the customer; as well as an electronic deliverable of files or thumb drive of data depending on the extent of information requested. For BP oil response, a KML file was provided
Next steps to get to a higher TRL and to field application	N/A—only qualitative data has been provided
Reports, articles available	The ASPECT plane has satellite antennas mounted on the plane to communicate with the staff in the plane and the technical team observing the data. No additional communication/transmission hardware is needed in addition to what is already on the plane.
Strengths and weaknesses	Technical Readiness Level (TRL) #9 – Flight proved through mission operations
Validation tests conducted to date: lab, field, test tank	Specific to oil response, ASPECT was deployed to Gulfport, Mississippi April - August 2010 to provide airborne remotely sensed air monitoring and situational awareness data and products in response to Operation Deepwater Horizon oil rig disaster. ASPECT flew over 75 missions that included over 250 hours of flight operation. For non-oil, ASPECT has been a variety of emergency responses, both local and national, and has participated in a many exercises and studies to help improve the technology and collaboration amongst other Agencies with similar technology. Below is a complete list of these events:
Oil type and condition tested	Due to Federal staff turnover/retiring, we have not investigated how to increase our TRL. This will be done in the future when the new staff members coming onboard.

Technology	**ASPECT Plane**
Working Group Contact	**CAMPRI Spreadsheet**
Testing QA/QC	§ Strengths • Proven remote sensing technology – Over 170 deployments • Proven pattern recognition software • Multipurpose cost-effective platform – Visible images, air monitoring (vapor species) and assess oil presence/ thickness • Tread Analysis – Monitor to determine oil presence increasing or decreasing as a function of time. • Optimize resource allocation, increase effectiveness, positioning of skimmers • Enhanced aerial surveillance coverage • Situational awareness to incident command structure § Weakness • Limited real-world usage other than the BP oil spill and other limited usage. • No experience in cold water/ice
Technology	**UAS WaterMapping**
Working Group Contact	**CAMPRI Spreadsheet**
New or Existing (number in constellation)	Existing
Overview of Technology (how it works). Include sensor type/description.	Micasense camera (5 Channels) 475, 560, 669, 717, 840 Flir Vue Pro R (3 Thermal Channels) Mapir (2 NIR Channels) 880, 940
How is it operated?	
Manufacturer/Developer	Water Mapping, LLC and 3rd party drones
Min & Max Scene Footprint size/swath width, if applicable	200m to 4k
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	5cm at max height
Precision	real time
Sensitivity	cross-validation with multiple platforms
Operational Procedure Available	The oil thickness classification requires cross examination of: Aspect of the oil (If the classification is done with Visual sensor). Reflectance of Multispectral sensor (UV, NIR, Thermal bands). Thermal gradient. In-situ thickness measurements
Range of sea state and other environmental conditions (e.g., day/night, clouds)	sun glare can be a major issue
Oil type and condition	Classification Of Oil Spill By Thicknesses Using Multiple Remote Sensors. BSEE report
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	Depends on size of vessel (small = 3ft seas, large = 5ft seas), wind operating conditions up to 15 mph, only operational on daylight, sun at nadir dampers operations due to glare
Needs for Deployment (e.g., boats, cranes)	All types oil, and fresh, weathered, or emulsified
Time for Mobilization/ Demobilization	minimum it requires a safe operating area for takeoff and landing
Turnaround time for data	Bank of batteries allows to fly constantly by replacing batteries. Flight is limited to 15-30 minutes depending on mission and aircraft. Tether UAS can be flown continuously (for monitoring, tactical positioning

Technology	UAS WaterMapping
Working Group Contact	**CAMPRI Spreadsheet**
Permits Required for deployment	During daylight. Airspace restrictions. Synchronization with the vessel's captain. Magnetic interference for compass navigation (large metal structures). Frequency interference (for data transmission)
# of people required to deployment	Pilot, Observer, Assistance for landing and take off
Lab Requirements	real time or near real time
Describe raw data format	FAA requires a UAS licensed commercial pilot. Some Federal Agencies require as a minimum private pilot license in addition to the UAS license. Class G airspace does not require pre-approval from FAA. Restricted airspace requires authorization from FAA (COA or LAANC). Flying for DoD requires the use of non-Chinese UAS brands
Describe data process workflow and requirements	pilot, observer, assistance
Time required for Data Processing to data delivery (emergency vs nonemergency)	UAS equipment includes real time video transmission. Internet required for broadcasting data (live, near-real time). Data collection requires SD cards. Data storage and handling requires large space for HighRes videos and Multispectral imagery
SOP available data processing	laptops and work stations
Data size and Volume	very large data files for multi-spectral
Format of Final Data File and Access Point	
Format of Data delivery	depends if real time, near, or post process
Uncertainty bounds expression	Projection routine (MATLAB), Mosaiques (ArcMAP), etc.....
Communication and transmission requirements	very large data files for multi-spectral
TRL #	shapefiles and rasters
How/where has technology been used to date	data transfer through diver
Next steps to get to a higher TRL and to field application	false positives
Reports, articles available	sd cards, memory cards, or direct with internet
Strengths and weaknesses	not sure
Validation tests conducted to date: lab, field, test tank	Over 400 flown missions for: Federal Agencies: NOAA, EPA, BSEE, DOJ, USCG, Next years (NASA). Public/Private: FSU, FWC, MSRC-Chevron.
Oil type and condition tested	Improve methods for Near Real Time of oil Thickness Classification
Technology	**PIXYS - Polarized Thermal Sensor (not ready for thickness)**
Working Group Contact	**CAMPRI Spreadsheet**
New or Existing (number in constellation)	Existing
Overview of Technology (how it works). Include sensor type/description.	LWIR (Long Wave Infra Red) imager, polarizes images
Manufacturer/Developer	Polaris
Min & Max Scene Footprint size/swath width, if applicable	relative to site conditions and mounting / platform specifics
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	relative to site conditions and mounting / platform specifics
Precision	real-time, low processing requirements
Sensitivity	needs further testing with accurate ground truth
Operational Procedure Available	precision "poorly addressed"

Technology	PIXYS - Polarized Thermal Sensor (not ready for thickness)
Working Group Contact	**CAMPRI Spreadsheet**
Oil type and condition	operators manual
Space requirements (size, weight)	Best suited for detection and tracking, dispersant monitoring
Power Requirements	Floating oil, will not penetrate surface, have not tested ice conditions yet
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	2-3 sea state, day or night, no thermal contrast required, rain buildings and vessels will disturb signal
Needs for Deployment (e.g., boats, cranes)	ANS,HOOPs,MC20, Diesel, Kerosene
Time for Mobilization/ Demobilization	small, handheld 5oz
Turnaround time for data	5 W
Permits Required for deployment	many models and stock
# of people required to deployment	handheld, mast mounted, drone, aircraft
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	minimal
Lab Requirements	real-time, low processing requirements
Describe raw data format	none for operation. permits for drone flight if used
Describe data process workflow and requirements	1 to fly drove
Time required for Data Processing to data delivery (emergency vs nonemergency)	sent real time, data is also stored
SOP available data processing	none
Data size and Volume	binary for PVS software
Format of Final Data File and Access Point	processed data / final data products can be sent real time
Format of Data delivery	Immediate
Uncertainty bounds expression	Detailed Camera manual.
Communication and transmission requirements	
TRL #	PDF. Video. Saved binary data can be used for additional post processing
How/where has technology been used to date	PDF snapshots sent. Video
Next steps to get to a higher TRL and to field application	
Reports, articles available	Standard radio transmission and data links
Strengths and weaknesses	7-8
Validation tests conducted to date: lab, field, test tank	Ohmsett, GOM, Santa Barbara, Refinery facility, Marina fire response
Oil type and condition tested	Believe that we're immune to kelp for polarization, need more experience for fish oil, etc. TRL 8 for sensor is 7 8 or 9, need to combine with other sensors and integrate this. Need to add data comms to command post. None of this is difficult, just requires programming and engineering time. Have published a couple of papers on this.
Results of testing	Yes.

Technology	**PIXYS - Polarized Thermal Sensor (not ready for thickness)**
Working Group Contact	**CAMPRI Spreadsheet**
Testing QA/QC	Strengths, remote sensing approach is mature, export control is good, 7. 5 Hz frame rate is exportable to most countries. Weaknesses -- developing a SWIR polarized camera to help improve. Cannot be used looking Nadir, do require some altitude because its an optical camera, larger format...
Vendor/Owner/ Representative and Contact Info	All
Technology	**Fixed Wing Multi-Spectral System (Fototera)**
Working Group Contact	**CAMPRI Spreadsheet**
New or Existing (number in constellation)	Existing
Overview of Technology (how it works). Include sensor type/description.	multiple sensors for complimentary data. SLAR (Side looking aperture radar, detection of surface films) EO/IR (high-definition and thermal imaging) MWR(absolute thickness hotspots) LFS(Oil Typer Classification) VIS(Oil appearance code) IR/UV(Mapping and relative thickness).
How is it operated?	
Manufacturer/Developer	Optimare GmbH
Min & Max Scene Footprint size/swath width, if applicable	50 nm swath, 7500 square nm per hour
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	resolution changes between sensors
Precision	instantaneous when in flight
Sensitivity	Depends on the sensor
Operational Procedure Available	Depends on the sensor
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Depends on the sensor
Oil type and condition	Yes
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	All-Weather system. SLAR, LFS, MWR, IR, OE/IR working under low light/weather conditions.
Needs for Deployment (e.g., boats, cranes)	Oil type ranges from light Crude to Heavy crude, LFS capabilities includes also biogenic slicks, clorophille etc. Status includes emulsioned oil and submerged oil (in the range of LFS underwater penetration.
Time for Mobilization/ Demobilization	large requirement for plane
Turnaround time for data	The system is permanently mounted in the Aircraft. Single sensors can be mounted on the bridge at Ohmsett. We'll provide the 28V power supply and the needed power is standard 110V - 20A
Permits Required for deployment	The system is permanently mounted on the Aircraft.
# of people required to deployment	Aircraft - Also in Ohmsett the sensors can be mounted over the bridge
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	2h for mobilization from Aircraft home base (Houma/Houston)
Lab Requirements	hours depending on product
Describe raw data format	No permits required

Technology	Fixed Wing Multi-Spectral System (Fototera)
Working Group Contact	**CAMPRI Spreadsheet**
Describe data process workflow and requirements	2 pilots 1 operator
Time required for Data Processing to data delivery (emergency vs nonemergency)	deliver information with satellite link, and MBR
SOP available data processing	No lab required
Data size and Volume	Raw data are proprietary - Data delivered is Shapefiles and GeoTiff
Format of Final Data File and Access Point	large processing requirements for all of the sensors included
Format of Data delivery	hours, depending on the product processed
Uncertainty bounds expression	Operating Procedures available
Communication and transmission requirements	Depends on the mission (order of 100 Mb)
TRL #	Geotiff / Shapefiles / Pdf report
How/where has technology been used to date	GIF web service ; Cloud
Reports, articles available	MBR and satellite link
Strengths and weaknesses	TRL 9 (NASA) - System proven through successful mission operations
Validation tests conducted to date: lab, field, test tank	Technology used since 1997 mainly in Europe. About 16 systems operational to date with about 90,000 cumulative hours of operation.
Oil type and condition tested	N/A
Results of testing	Various see attachment
Testing QA/QC	Is probably the most complete system in the world for airborne oil spill remote sensing.
Vendor/Owner/ Representative and Contact Info	See above
Technology	NASA UAV SAR
Working Group Contact	CAMPRI Spreadsheet
New or Existing (number in constellation)	Existing
Overview of Technology (how it works). Include sensor type/description.	Right now NOAA has operational oil extent product courtesy of Oscar Garcia, like to incorporate all the new sensors coming online and have field tests to calibrate these efforts -- use SAR to do damage assessment after storms to do quick assessments of what platforms may have been lost after a big storm -- give products to analysts. NASA L-band synthetic aperture radar airborne system, UAVSAR, that flies on a GulfStream.
Manufacturer/Developer	JPL
Format of Final Data File and Access Point	Not strongly dependent on time, can use same statistics now and then later
Reports, articles available	Use ARL (Applications readiness level) -- for oil thickness at level 4 where 8 is ready to put into operation. "Research to Operations" slide. Big deal to go from science to operations.
Strengths and weaknesses	Currently only tuned for C-BAND SAR -- storm damage assessment to determine platforms after a storm
Validation tests conducted to date: lab, field, test tank	need data for calibration and algorithm
Vendor/Owner/ Representative and Contact Info	thickness, oil/water fraction

Technology	DASH8 NASP
Working Group Contact	**Jessica Garron**
Overview of Technology (how it works). Include sensor type/description.	4 De Haviland Dash 8s equipped with a large suite of RS tools (SLAR, UV infrared line scanner, electro-optical, infrared); winds are < 30 knots, the cloud base is at least 1000 feet, and the horizontal visibility is at least 3 nautical miles (nm). Assuming these conditions are met, visual observation is conducted from 1000 to 1500 feet and remote-sensing monitoring from 5000 to 10,000 feet.
How is it operated?	Airplane
Manufacturer/Developer	Transport Canada
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	Some dependence on daylight (EO, IR, UV); All sea state (see operational conditions above in Overview)
Min & Max Scene Footprint size/swath width, if applicable	Variable by sensor
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	Variable by sensor
Time required for taking measurements	Variable by mission
Accuracy	Yes
Precision	Seconds once in flight; Variable by distance to target (based in Quebec)
Sensitivity	Variable by sensor
Operational Procedure Available	Variable by sensor
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Variable by sensor
Oil type and condition	Upon request
Space requirements (size, weight)	Pollution surveillance, emergency response, damage assessment, restoration, marine debris, disaster preparedness, testing verification tool
Power Requirements	All
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	winds are < 30 knots, the cloud base is at least 1000 feet, and the horizontal visibility is at least 3 nautical miles (nm). Assuming these conditions are met, visual observation is conducted from 1000 to 1500 feet and remote-sensing monitoring from 5000 to 10,000 feet.
Needs for Deployment (e.g., boats, cranes)	Crude oil on the surface of ice and water; some emulsions in water
Time for Mobilization/ Demobilization	System permanently configured on aircraft
Turnaround time for data	UNK
Permits Required for deployment	System permanently configured on aircraft
# of people required to deployment	Transport Canada Dash 8 fleet
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Variable based on spill location
Lab Requirements	2 hours after landing

Technology	**DASH8 NASP**
Working Group Contact	**Jessica Garron**
Describe raw data format	Airspace access
Describe data process workflow and requirements	2 pilots 1 operator
Time required for Data Processing to data delivery (emergency vs nonemergency)	Satellite uplink and hard drives (post mission)
Data size and Volume	Variable by sensor
Format of Final Data File and Access Point	UNK
Format of Data delivery	approximately 2 hours
Uncertainty bounds expression	UNK
Communication and transmission requirements	Variable by sensor
TRL #	GeoTiff directly delivered to requestor
How/where has technology been used to date	GeoTiff directly delivered to requestor
Next steps to get to a higher TRL and to field application	Variable by sensor
Strengths and weaknesses	9
Validation tests conducted to date: lab, field, test tank	Program developed in 1990s and was relied upon heavily during DWHOS; used daily for surveillance of Canadian waters
Oil type and condition tested	Integration into Arctic ERMA or other COP
Results of testing	Mostly conference proceedings
Testing QA/QC	Extensive, complimentary sensor suite; multiple aircraft available; challenge associated with its heavy use for daily operations in Canada
Vendor/Owner/ Representative and Contact Info	Yes
Technology	**Laser fluorosensor (Raman spectroscopy)**
Working Group Contact	**Jessica Garron**
Overview of Technology (how it works). Include sensor type/description.	Measurement of spectral emission from excited target, usually UV light is used to excite the target
How is it operated?	Airplane or UAS
Manufacturer/Developer	Optamere & EIC Laboratories
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	Not reliant on daylight; Can penetrate 6 cm into ice; can penetrate 1-2 m into water column
Min & Max Scene Footprint size/swath width, if applicable	Variable by sensor and platform
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	Variable by sensor
Time required for taking measurements	Variable by mission
Accuracy	Yes
Precision	Seconds once in place
Sensitivity	high accuracy due to unique signature of petroleum products
Operational Procedure Available	Very precise as based on unique spectral signature of oil vs other materials

Technology	**Laser fluorosensor (Raman spectroscopy)**
Working Group Contact	**Jessica Garron**
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Dependent on depth of oil and encapsulation
Oil type and condition	UNK
Space requirements (size, weight)	Pollution surveillance, emergency response, damage assessment, restoration, marine debris, disaster preparedness, testing verification tool
Power Requirements	Can penetrate 6 cm into ice; can penetrate 1-2 m into water column
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	UNK
Needs for Deployment (e.g., boats, cranes)	Crude oil on the surface of ice and water; some emulsions in water
Time for Mobilization/ Demobilization	Variable based on platform
Turnaround time for data	UNK
Permits Required for deployment	UNK
# of people required to deployment	handheld or aircraft or underwater vehicle
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Available only with expert to operate and interpret, at least 48 hours notice prior to deployment
Lab Requirements	real-time to hours for final product
Describe raw data format	none if airborne, otherwise variable by "landowner"
Describe data process workflow and requirements	1 pilot, 1 operator
Time required for Data Processing to data delivery (emergency vs nonemergency)	UNK
SOP available data processing	
Data size and Volume	Reflected signal returns
Format of Final Data File and Access Point	UNK
Format of Data delivery	real-time to hours for final product
Uncertainty bounds expression	UNK
Communication and transmission requirements	Variable but "small"
TRL #	UNK
How/where has technology been used to date	Graph and output directly delivered via hard drive
Strengths and weaknesses	6
Validation tests conducted to date: lab, field, test tank	Oil spill detection from above and below the water surface and above/below ice surface
Oil type and condition tested	Operational protocol application
Results of testing	Sensors 2018, 18(1), 91; https://doi.org/10.3390/s18010091
Testing QA/QC	Highly accurate but VERY SMALL FOV
Vendor/Owner/ Representative and Contact Info	Yes

Technology	**Airborne ground penetrating radar**
Working Group Contact	**Jessica Garron**
Overview of Technology (how it works). Include sensor type/description.	Ground Penetrating Radar (GPR) reflections are generated at boundaries separating materials with differing electromagnetic properties relative dielectric permittivity and electric conductivity, oil can be detected as one of the different materials exhibiting different conductivity and emissivity as compared to the layers of snow and ice
How is it operated?	Helicopter via sling
Manufacturer/Developer	Numerous; PulseEKKO PRO
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	ON (over) snow and ice
Min & Max Scene Footprint size/swath width, if applicable	When on the ice surface, the footprint is that of the GPR unit; when airborne, varies from 1.52 m to 3.5 m based on height of GPR above snow/ice
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	Variable based on height of GPR
Time required for taking measurements	m/sec
Accuracy	Yes
Precision	Seconds
Sensitivity	within 2 m
Operational Procedure Available	within 2 m
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Depends on water content of snow and ice layers, and height GPR above snow/ice
Oil type and condition	No
Space requirements (size, weight)	Pollution surveillance, emergency response, damage assessment, testing verification tool
Power Requirements	Over land, ice or snow
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	Weather and daylight independent (except for flight vehicle carrying it)
Needs for Deployment (e.g., boats, cranes)	Crude oil on surface, and layered under snow an dice to a depth of 9 m (or deeper) under ideal conditions
Time for Mobilization/ Demobilization	Variable but approximately 6 inch cube
Turnaround time for data	UNK
Permits Required for deployment	Available only with expert to operate and interpret, at least 48 hours notice prior to deployment
# of people required to deployment	Available only with expert to operate and interpret, at least 48 hours notice prior to deployment
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Available only with expert to operate and interpret, at least 48 hours notice prior to deployment
Lab Requirements	hours to days
Describe raw data format	none if airborne, otherwise variable by "landowner"

Technology	**Airborne ground penetrating radar**
Working Group Contact	**Jessica Garron**
Describe data process workflow and requirements	1 pilot, 1 GPR operator
Time required for Data Processing to data delivery (emergency vs nonemergency)	SD cards and hard drives
SOP available data processing	
Data size and Volume	raw radar waveform data
Format of Final Data File and Access Point	Lots of processing required
Format of Data delivery	2-6 hours?
Uncertainty bounds expression	Yes
Communication and transmission requirements	Variable but large
TRL #	No defined access point; format is graph of signal returns from different materials encountered in profile
How/where has technology been used to date	Graph and model output directly delivered via hard drive
Next steps to get to a higher TRL and to field application	Based on conductivity and height
Reports, articles available	None
Strengths and weaknesses	5
Validation tests conducted to date: lab, field, test tank	Oil spill detection from above and on the snow/ice surface in situ and in the laboratory setting at CRREL
Oil type and condition tested	Protocol development and more testing under many different conditions
Results of testing	Bradford, J., Dickins, D., & Brandvik, P. J. (2010). Assessing the potential to detect oil spills in and under snow using airborne ground-penetrating radar. Geophysics, 75(2). https://doi.org/doi.org/10.1190/1.3312184
Testing QA/QC	Highly accurate when coupled with the snow/ice/land surface, but not very reliable when suspended; data complex and requires significant interpretation
Vendor/Owner/ Representative and Contact Info	Tested at CRREL and in the field

Technology	**NRL LiDAR**
Working Group Contact	**CAMPRI Spreadsheet**
Overview of Technology (how it works). Include sensor type/description.	Visible light penetrates well the water body (low absorption, medium scattering) Does not need to be into water (around 98% transmission at the air/water interface vs 0.12% for acoustic) No perturbation of the flow Capability to provide range resolved information (depth profiling) Measurements NRL SSC Oceanography division LiDAR Systems –Ship LiDAR Optical Profiler (SLOP), TURBulenceOcean LiDAR (TURBOL)Complementary measurements: UV Fluorescence –LDI ROW instrument Remote Oil Watcher (ROW) instrument •Operates above-water •Pulsed UV LED light source •Can detect oil on the surface and oil dissolved in the water •Detects slicks as thin as 1 µm •Fluorescence level changes in proportion to oil film thickness •Help to calibrate LiDAR data, acoustic data Complementary measurements: •Visible Reflectance –ASD FieldSpec, hyperspectral –new instrument purchase: Spectral Evolution RS-8800 •Acoustic Backscatter –ASL Acoustic Zooplankton Fish Profiler (AZFP), multi-frequency (cm vertical resolution, 0.3-10 cm particle size). Will be correlated with LiDAR backscatter returns, UV fluorescence.
How is it operated?	Different oil thickness show different spectral signature (Svejkovskyet al. 2012) which will be visible in the lidar signal. Complementary measurements (passive, acoustic) will help to make the most out of the experiment. The new spectroradiometer will extend the measurement range out to 2500 nm for improved oil detection/analysis via reflectance.
Manufacturer/Developer	U.S. Naval Research Laboratory
Min & Max Scene Footprint size/swath width, if applicable	Variable (depends on laser repetition rate and platform speed).
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	LiDAR spot size depends on instrument aperture, beam divergence, and height above water surface (for about 15' separation, yields spot size of about 6" on the water surface for TURBOL, 10" for SLOP).
Precision	Instantaneous once the lidars are in place
Sensitivity	Used a given volume of oil into a target with a fixed area (1m X 1m).
Operational Procedure Available	Used the temporal variability of the oil slick. A higher statistic of data would be useful. Standard Operating Procedure (SOP) are a requirements to deploy the lidar systems.
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Sensitivity and maximum detectable thickness were not determined.

Technology	**NRL LiDAR**
Working Group Contact	**CAMPRI Spreadsheet**
Space requirements (size, weight)	Emergency response, damage assessment, restoration, marine debris, disaster preparedness, testing verification tool The emphasis of the project for which BSEE funded NRL is on oil thickness. The ultimate goal would be to measure oil volume and oil fluxes from an accidental spill in the field.
Power Requirements	Lidar technology is very flexible. It can be either above or under the water and on a multitude of platforms (satellite, plane, boat, UAV, UUV). The systems we tested were designed to be on a boat and above the water surface. We are also developing a new airborne LiDAR system (Bubble LiDAR Scanner).
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	No day/night limitation, sea state 2 or 3. Simpler to operate below clouds (i.e., limited cloud penetration and cloud presence may require dedicated algorithm developments). Not an issue –our current systems are ship-mounted, (although NRL is building an airborne LiDAR).
Needs for Deployment (e.g., boats, cranes)	Types of oil (e.g., crude oil type, diesel) Fresh, weathered, emulsified currently we do not distinguish oil type (could explore methods to do so –fluorescence, reflectance, polarization).
Time for Mobilization/ Demobilization	Approximately 20.7 m x 4.57 m. Combined weight of approximately 2350 lbs.
Turnaround time for data	Varies but typically, SLOP is 110V/20A –TURBOL is 208V/30A and two 110V/20A.
Permits Required for deployment	One lidar(SLOP) is usually available. TURBOL is a basic research system with no operational requirements, it's not always available. NRL is building an airborne lidar.
# of people required to deployment	Crane
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Between a few hours to a day (first deployment on a given platform is slower).
Lab Requirements	Typically 30 min for visualization, more for in-depth data processing (no real time or near real time yet).
Describe raw data format	Outdoor use require approval from the Laser Safety Review board. Test in the field are more involved (environmental impact assessment, etc.). NRL deploys the lidars in the field regularly.
Describe data process workflow and requirements	At least two persons to deploy (including crane operator), one person needed to operate.
Time required for Data Processing to data delivery (emergency vs nonemergency)	Data are saved directly on the LiDAR computers (can be moved with external hard drives, Ethernet connection, etc.).
SOP available data processing	N/A the lidars are field systems
Data size and Volume	Binary for SLOP, HDF5 for TURBOL

Technology	**NRL LiDAR**
Working Group Contact	**CAMPRI Spreadsheet**
Format of Final Data File and Access Point	•Describe specific analysis being conducted (method of data analysis and data pre-processing) •Criteria for eliminating/filtering data •Too long to describe in a presentation. MATLAB code. We have a pending BSEE proposal to create user friendly data (maps) in near real time.
Format of Data delivery	Between 30 min (visualization) to a few days (scientific data). Pending BSEE proposal to speed up significantly data delivery.
Uncertainty bounds expression	Yes, it’s a safety requirement
Communication and transmission requirements	500MB for 30 min data, TURBOL is 400MB for 20 min data.
TRL #	Customized on demand
How/where has technology been used to date	Customized on demand
Strengths and weaknesses	TRL 6
Oil type and condition tested	Go back to Ohmsett to obtain a higher statistic of data and establish the near real time data stream.
Results of testing	R. W. Gould, Jr., D. Josset, S. Anderson, W. Goode, R. N. Conmy, B. Schaeffer, S. Pearce, T. Mudge, J. Bartlett, D. Lemon, D. Billenness, O. Garcia (2019) ; Estimating Oil Slick Thickness with LiDAR Remote Sensing Technology ; Bureau of Safety and Environmental Enforcement (BSEE) Oil Spill Response Research Branch ; https://www.bsee.gov/sites/bsee.gov/files/research-reports//1091aa.pdf
Testing QA/QC	Strength: lidar is the only technology available to get high resolution (cm) underwater range resolved information from above the water surface Weakness: for oil research, only very limited investigations have been conducted.
Vendor/Owner/ Representative and Contact Info	NRL conducted an oil thickness experiment at Ohmsett in July 2018, with project partners U.S. EPA, ASL Environmental Sciences, Inc. (acoustics), and WaterMapping, LLC. NRL has a pending project submitted to BSEE for a follow-on experiment at Ohmsett. If successful, the lidar systems should be much closer to estimating oil thickness in the field.

Technology	**TRACS Multi Sensor System: Ocean Imaging**
Working Group Contact	**Jessica Garron**
New or Existing (number in constellation)	Ocean Imaging, POC: Mark Hess
Overview of Technology (how it works). Include sensor type/description.	Flies on in aircraft, can detect oil as far as presence/absence, refined so we can avoid false positives, can differentiate fresh oil from weathered/emulsified, thick sheens versus thin sheens (don't always see thin sheens), treatable oil/actionable oil is on the range of 40-50 microns or greater -- can see in the thermal and pick up in RGB. This definition is not set. Can provide oil characterization, big difference between controlled environment/Lab at OHMSETT and the natural environment. Controlled environment (Ohmsett) from ~ .01 um to 5000 um (5 mm) Real world spill 2-4 classes 1 um to 200 um 3-CCD, multispectral RGB digital camera with a thermal infrared imaging camera.
How is it operated?	
Manufacturer/Developer	As far as manufacturers, the thermal infrared camera in TRACS is Jenoptik, the RGB camera is made by JAI the IMU is made by Oxford Technologies. All of the hardware and software integration was done by Ocean Imaging. The rest of the system was built, integrated and developed (software) by Ocean Imaging and we'd prefer that certain elements of the integration remain proprietary.
Min & Max Scene Footprint size/swath width, if applicable	200-4,250 m, varies by altitude
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	0.2m to 4m, relative to altitude
Precision	Varies by incident, type of aircraft, location, how much data you want to take. Sometimes tasked to only go to one shoreline/marsh area where we go out and get the data and go back. RP or NOAA sometimes wants as much data as they can/get whole big picture, depends on what the task at hand is. Tactical information can vary by what you're doing. Can be as simple as looking at the screen, getting a Lat/Lon of where we think oil is and relaying it down to a boat over radio. Can also make mosaic imagery as GIOTIFF or KMZ or other methods. Also have quick classify that takes thermal imagery with help of RGB imagery to make 2-3 class color imagery, small file on order of KB, JPEG, KMZ, or GEOTIFF image.
Sensitivity	
Operational Procedure Available	Thickness ranges/classes examples - had a BSEE and NOAA funded study out of RAMSEE (??) 20 and compared thickness measurements to data from the boats and flew from 0 to 2 hours +/- from when they actually took the data, the ocean is very dynamic. When we were +/- 2 hours, 60% of the time was correct within 50 m of the sample spots. When we flew over precisely w/in minutes, were 70+% accurate within 10 m of the spot, 100% match within 50 to 100 m of sampling spot. Difficult to take samples, sample size isn't excellent, wouldn't pass peer reviewed paper because of the thickness ranges being fairly uncertain.
Space requirements (size, weight)	Immediate tactical oil detection and characterization. COP-ready thickness products
Power Requirements	open water, shoreline mapping, oil entrainment in marshland

Technology	**TRACS Multi Sensor System: Ocean Imaging**
Working Group Contact	**Jessica Garron**
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	Have flown in a variety of weather and wave conditions (imaged successfully using full wave height at Ohmsett). Flown cloud cover as low as 800 feet, 500 feet is lowest flown (800 during Lake Washington Spill) and got good data. Really high resolution but 500+ frames to work with, much more data. Exact Beaufort scale wind speed parameters of operation unknown.
Needs for Deployment (e.g., boats, cranes)	Can generate thickness classes for fresh crude or near fresh, not emulsified. Can detect and discriminate emulsified oil as well as estimate general level of emulsification. Can discriminate thickness for many types of fresh-near-fresh crude types: AMS, Monterey, GOM crudes, thicker fuel oils. Refined/processed fuels like jet fuel and diesel are more of a presence/absence for detection
Time for Mobilization/ Demobilization	15.5"x11.5"x13" 27 lb.
Turnaround time for data	5.5 amps, 72 watts
Permits Required for deployment	Can be shipped via fed-ex or as luggage on commercial flights. Mounts for numerous planes or helicopters, mobilized in about 4-12 hours, four systems pre-staged in the U.S. During every spill always have a backup on site in case of any situation with primary. Backup gets shipped immediately overnight to flight base of operations, always on the ready. State of Washington has mandate/statute that we have to mobilize in 12 hours.
# of people required to deployment	No special requirements, designed for aircraft of opportunity. Been on small or large helicopters, float plane in Alaska, one to two pilots (partnership with MSRC safety rule, system doesn't need two pilots)
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	4-12hours
Lab Requirements	1-8 hours, usually in 4-5 now but a bit longer 7-9 hour range for some particularly difficult spills. Based on flight times and mission objectives
Describe raw data format	No special requirements, designed for aircraft of opportunity. Been on small or large helicopters, float plane in Alaska, one to two pilots (partnership with MSRC safety rule, system doesn't need two pilots)
Describe data process workflow and requirements	1-2 pilots, 1 operator
Time required for Data Processing to data delivery (emergency vs nonemergency)	Specialized air to vessel system -- can communicate up to 10 miles in just a few minutes, don't want to send a whole lot of raw data down, want to send easy to use end products down that can be used. Antennae are used to get data off the plane as quickly as possible. Always have an MSRC person at the command center to facilitate getting that information. Sending the full load of GB data, need broadband connection for this. Part of our protocol is to make sure this is available to make this available ahead of time.
SOP available data processing	
Data size and Volume	

Technology	**TRACS Multi Sensor System: Ocean Imaging**
Working Group Contact	**Jessica Garron**
Format of Final Data File and Access Point	Some end users can't use a GEOTIFF file, now using google earth and PDFs, IMG files, etc. . Capable of delivering in whatever format the end user can use. Can't assume what they know how to use. Now protocol is to better communication with end users about what format they need. Classification type files, vector files, are all important. Tactical information products have on board software data processing, corrects for distortion and georeferenced, coregisters the bands, quick classified product and sends down from aircraft as GeoTiff, JPG or KMZ .
Format of Data delivery	5-60 minutes for digital products sent from aircraft to vessel or ICC, instant for radio, 1-8 hours for full oil characterization thematic maps
Uncertainty bounds expression	Analyst looks at situation/quality of data to decide what tools/algorithms to use. No public SOP available
Communication and transmission requirements	Varies by data product. Small for quick, tactical products. large volume, multiple gigabytes of raw data for full classification data and derived products
TRL #	geotiff,.bil/.bip,.img,JPEG, .kmz, ESRI Shapefile
How/where has technology been used to date	geotiff,.bil/.bip,.img, JPEG, .kmz, ESRI Shapefile
Next steps to get to a higher TRL and to field application	Oil thickness delivered in 50 um to 200 um wide classes. Last test during NOAA project revealed TRACS-derived thickness classes were ~70% to 100% accurate when compared to field samples depending on time and geographical proximity of sample.
Reports, articles available	TRACS incorporates an air-to-ground (or vessel) high speed data transmission system. Transferring the full, unprocessed data requires a broadband Internet connection
Strengths and weaknesses	9
Validation tests conducted to date: lab, field, test tank	DMSC (precursor to TRACS), Operational 2007 - 2014: Suisun Marsh chemical spill, McKittrick well blowout, Romic spill, California, Cosco Buson, San Francisco Bay, Platform A Santa Barbara, Deep Water Horizon, Numerous tests at Ohmsett, Santa Barbara Channel, OSPR drills, DWH data used for NOAA Technical Working Group, BSEE demo in Anchorage Alaska. TRACS, Operational 2014 – Present: Refugio, Santa Barbara, Lake Washington, LA Ohmsett tests BSEE/NOAA Oil Thickness and Emulsion project (contract E16G0023) Numerous drills and demonstrations (i.e. Chevron, OSPR, NOAA) in Santa Barbara, CA and MC20 in Gulf of Mexico Numerous training evolutions: Santa Barbara, CA, Gulf of Mexico, New Jersey Coast, Northwest Coast, Hawaii, Long Beach, CA
Oil type and condition tested	Improve in-aircraft processing, speed up thickness map generation and delivery time
Results of testing	
Testing QA/QC	Still not there with very tight oil thickness classifications, eventually we will get to hyperspectral as things scale down and units get smaller and less expensive, not there yet. Add more sensors, gets more complicated.
Vendor/Owner/ Representative and Contact Info	TBD

Technology	ACUASI - SeaHunter
Working Group Contact	**Jessica Garron**
New or Existing (number in constellation)	2
Overview of Technology (how it works). Include sensor type/description.	long-range UAS with Electo-Optical payload connected to ground station via line-of-sight and Iridium network
How is it operated?	
Manufacturer/Developer	Griffon Aerospace
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	in daylight, coldest rating undetermined
Min & Max Scene Footprint size/swath width, if applicable	Variable on sensor and height of collection
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	Variable on sensor and height of collection
Time required for taking measurements	near real-time and within minutes of landing
Accuracy	Yes
Precision	Variable based on area of survey and distance to ground station
Sensitivity	Variable on sensor and height of collection
Operational Procedure Available	Variable on sensor and height of collection
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Dependent on atmospheric conditions, sensor employed, height of data collection
Oil type and condition	No
Space requirements (size, weight)	Long-range reconnaissance, Emergency response, damage assessment, restoration monitoring marine debris identification and monitoring, long-term area observation (loitering)
Power Requirements	All
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	Daylight, low precip, low to moderate winds, VFR conditions
Needs for Deployment (e.g., boats, cranes)	On ice, on water surface
Time for Mobilization/ Demobilization	~1500 foot runway required for take-off (improved only), 300 lbs aircraft, 12-foot wingspan, sensors integrated but versatile for others
Turnaround time for data	Gasoline fueled dual engines, provides 2000 W of power to payload
Permits Required for deployment	Immediate upon request; flight to site or shipment via C-130 to hub community or trailer transport to hub community on road system
# of people required to deployment	4 crew (pilot, engineer, 2 ground station crew), ~1500 ft improved runway
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Immediate upon request; flight to site (4-8 hours) or shipment via C-130 to hub community (24-48 hours) or trailer transport to hub community on road system (24-72 hours)
Lab Requirements	near real-time (raw footage) and 1-24 hours after landing (product dependent)
Describe raw data format	Waivers for flying at night or beyond visual line of sight; runway access; permits for location of ground station;

Technology	**ACUASI - SeaHunter**
Working Group Contact	**Jessica Garron**
Describe data process workflow and requirements	4 crew (pilot, engineer, 2 ground station crew), data liaison suggested
Time required for Data Processing to data delivery (emergency vs nonemergency)	Near real-time via Iridium network, SD cards/HD upon landing
SOP available data processing	
Data size and Volume	Photos and videos
Format of Final Data File and Access Point	Raw images available during flight; transfer data to processing machines, geotag data, mosaic/full motion video creation, product delivery to end user
Format of Data delivery	real-time (raw footage) and 1-24 hours after landing (product dependent)
Uncertainty bounds expression	upon request
Communication and transmission requirements	Variable based on mission and sensor; 100s of MB
TRL #	Variable based upon user needs but typically GeoTIFF or Full motion video directly transferred to user (other transfer available when bandwidth available)
How/where has technology been used to date	Raw, GeoTiff, FMV
Next steps to get to a higher TRL and to field application	cm scale expression
Reports, articles available	Iridium network, Internet, HD delivery
Strengths and weaknesses	7
Oil type and condition tested	Perform operational missions in U.S.; integration into ERMA
Results of testing	https://acuasi.alaska.edu/missions
Testing QA/QC	Highly specialized aircraft requiring specialized pilots; sensors straightforward
Vendor/Owner/ Representative and Contact Info	Gaspe, Canada, whale identification
Technology	**ACUASI - Sentry**
Working Group Contact	**Jessica Garron**
New or Existing (number in constellation)	8
Overview of Technology (how it works). Include sensor type/description.	long-range UAS with Electro-optical and midwave infrared sensors; communications via line-of-sight
How is it operated?	
Manufacturer/Developer	US Navy Research Laboratory
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	day/night, coldest rating undetermined
Min & Max Scene Footprint size/swath width, if applicable	Variable on sensor and height of collection
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	Variable on sensor and height of collection
Time required for taking measurements	real-time and within minutes of landing
Accuracy	Yes
Precision	Variable based on area of survey and distance to ground station

Technology	ACUASI - Sentry
Working Group Contact	**Jessica Garron**
Sensitivity	Variable on sensor and height of collection
Operational Procedure Available	Variable on sensor and height of collection
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Dependent on atmospheric conditions, sensor employed, height of data collection
Oil type and condition	No
Space requirements (size, weight)	Long-range reconnaissance, Emergency response, damage assessment, restoration monitoring marine debris identification and monitoring, long-term area observation (loitering)
Power Requirements	All
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	Daylight, low precip, low to moderate winds, VFR conditions
Needs for Deployment (e.g., boats, cranes)	On ice, on water surface
Time for Mobilization/ Demobilization	~1000 foot runway required for take-off (unimproved ok), 300 lbs aircraft, 12-foot wingspan, sensor integrated
Turnaround time for data	Gasoline fuel (38 hp 2-stroke gasoline engine)
Permits Required for deployment	Immediate upon request; flight to site or shipment via C-130 to hub community or trailer transport to hub community on road system
# of people required to deployment	4 crew (pilot, engineer, 2 ground station crew), ~1000 unimproved runway
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Immediate upon request; flight to site (4-8 hours) or shipment via C-130 to hub community (24-48 hours) or trailer transport to hub community on road system (24-72 hours)
Lab Requirements	real-time (raw footage) and 1-24 hours after landing (product dependent)
Describe raw data format	Waivers for flying at night or beyond visual line of sight; runway access; permits for location of ground station;
Describe data process workflow and requirements	4 crew (pilot, engineer, 2 ground station crew), data liaison suggested
Time required for Data Processing to data delivery (emergency vs nonemergency)	Real-time via line of sight communications, SD card/HD upon landing
SOP available data processing	
Data size and Volume	Photos and videos (EO and MWIR)
Format of Final Data File and Access Point	Raw images available during flight; transfer data to processing machines, geotag data, mosaic/full motion video creation, product delivery to end user
Format of Data delivery	real-time (raw footage) and 1-24 hours after landing (product dependent)
Uncertainty bounds expression	upon request
Communication and transmission requirements	Variable based on mission and sensor; 100s of MB
TRL #	Variable based upon user needs but typically GeoTiff or Full motion video directly transferred to user (other transfer available when bandwidth available)
How/where has technology been used to date	Raw, GeoTiff, FMV

Technology	**ACUASI - Sentry**
Working Group Contact	**Jessica Garron**
Next steps to get to a higher TRL and to field application	cm scale expression
Reports, articles available	Line of sight, Internet, HD delivery
Strengths and weaknesses	7
Oil type and condition tested	Perform operational missions in U.S.; integration into ERMA
Results of testing	classified
Testing QA/QC	Highly specialized aircraft requiring specialized pilots; sensors straightforward
Vendor/Owner/ Representative and Contact Info	classified
Technology	**ACUASI - small UAS**
Working Group Contact	**Jessica Garron**
New or Existing (number in constellation)	10
Overview of Technology (how it works). Include sensor type/description.	short-range UAS with Electro-optical, longwave infrared, multispectral and in situ gas methane gas sampling capacity
How is it operated?	
Manufacturer/Developer	Multiple (DJI, in situ, ING, Autel, SkyFront)
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	in daylight, no precipitation, winds less than 20 mph
Min & Max Scene Footprint size/swath width, if applicable	Variable on sensor and height of collection
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	Higher resolution than commercially airplane or satellite-collected data sets; Variable resolution on sensor and height of collection
Time required for taking measurements	real-time and within minutes of landing
Accuracy	Yes
Precision	Variable based on area of survey and distance to ground station
Sensitivity	Variable on sensor and height of collection
Operational Procedure Available	Variable on sensor and height of collection
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Dependent on atmospheric conditions, sensor employed, height of data collection
Oil type and condition	Yes
Space requirements (size, weight)	Situational awareness, Emergency response, damage assessment, restoration monitoring marine debris identification
Power Requirements	Over land and sea ice, or within half-mile of coast for open-water missions
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	Daylight, low winds (less than 20 mph), no precipitation, half-mile visibility from ground
Needs for Deployment (e.g., boats, cranes)	On ice, on water surface
Time for Mobilization/ Demobilization	4 ft by 8 ft space for ground station and pilot to launch from, generator or power supply, large suitcase/small trunk for transfer in truck or on aircraft

Technology	**ACUASI - small UAS**
Working Group Contact	**Jessica Garron**
Turnaround time for data	Variable but primarily battery power, with one gasoline powered multi-rotor with 6 hours of endurance
Permits Required for deployment	Immediate upon request; time required for flight of equipment and pilots to area of interest
# of people required to deployment	2 crew (pilot and aerial observer)
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Immediate upon request; time required for flight of equipment and pilots to area of interest (within AK 2-24 hours)
Lab Requirements	real-time (raw footage) and 1-24 hours after landing (product dependent)
Describe raw data format	Waivers for flying at night or beyond visual line of sight or any other deviation from Part 107 flight rules; permits for location of ground station; permits for flying over special use areas or endangered animals
Describe data process workflow and requirements	2 crew (pilot and aerial observer)
Time required for Data Processing to data delivery (emergency vs nonemergency)	Real-time via line of sight communications, SD card/HD upon landing
Data size and Volume	Photos and videos (EO, LWIR, Multi-spectral images), spectral data as .csv
Format of Final Data File and Access Point	Raw images available during flight; transfer data to processing machines, geotag data, mosaic/full motion video creation, product delivery to end user
Format of Data delivery	real-time (raw footage) and 1-24 hours after landing (product dependent)
Uncertainty bounds expression	upon request
Communication and transmission requirements	Variable based on mission and sensor; 100s of MB
TRL #	Variable based upon user needs but typically GeoTiff or Full motion video directly transferred to user (other transfer available when bandwidth available)
How/where has technology been used to date	Raw, GeoTiff, FMV
Next steps to get to a higher TRL and to field application	cm scale expression; spectral signal: noise
Reports, articles available	Line of sight, Internet, HD delivery
Strengths and weaknesses	9
Oil type and condition tested	Integration into ERMA
Results of testing	numerous publications; https://acuasi.alaska.edu/missions
Testing QA/QC	Easily operated; post-processing varies in complexity by sensor and my require technical expert for manipulation and interpretation
Vendor/Owner/ Representative and Contact Info	Numerous in all operational environments

On Surface and Subsurface

Table 21: On Surface and Subsurface Tab from New and Existing Technologies Spreadsheet.

Technology	On ice profilers
Working Group Contact	Jeremy Wilkinson
New or Existing (number in constellation)	Existing
How is it operated?	install on ice and have profiling system on them and do vertical profile on ice through freezing season; using argo float that is tethered - need to fly on ice to install - measuring water CTD, dissolved oxygen, optics, cdoms
Technology	ADCP
Working Group Contact	
How is it operated?	For measuring under ice current velocity and bathymetry.
Technology	Ground penetrating radar
Working Group Contact	John Bradford (Boise State University)
How is it operated?	jbradfor@boisestate.edu
Technology	Ice auger
Working Group Contact	Chris Hall (ACS)
	No information provided.
Technology	Acoustic/Towed Ultrasound System
Working Group Contact	Jeremy Wilkinson
How is it operated?	Use ultrasound to measure brine volume. Lots of Russian literature on this.
Technology	3D laser scanner
Working Group Contact	Peter Wadhams
How is it operated?	Laser scanners to measure the change rate of ice ridging over time which tells how much bigger ridges and keels are getting.
Testing QA/QC	Timeseries to measure ice ridge development. Easy to deploy. Ice ridges change with tides. Tidal cycle short as opposed to days.
Vendor/Owner/ Representative and Contact Info	
Technology	ApRES (autonomous phase-sensitive radio-echo sounder)
Working Group Contact	John Bradford (Boise State University), same as FMCW Radar but Arctic focused -- Reach out to HP Marshall for information (cc Nathan Lamie)
How is it operated?	Glaciology -- used for thickness of ice sheets. 200-400 mhz/second. Small frequency band, different than ground penetrating radar.
Technology	Dogs
Working Group Contact	Ben Fieldhouse
How is it operated?	Ed Owens K2 Solutions: http://www.k2si.com/. Paul Bunker Chiron K9: https://chiron-k9.com/.

Under Ice and Open Water Surface

Table 22: Under Ice and Open Water Surface Tab from New and Existing Technologies Spreadsheet.

Technology	**Acoustics Thickness Sensors (Panetta)**
Working Group Contact	**CAMPRI Spreadsheet**
New or Existing	Existing - cold tested
Manufacturer/ Developer	Ultrasonic electronic equipment: PeakNDT, sensors and cables: Olympus
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	Oil in and under ice, ISB, 2C to burning, free floating, boomed, CRREL, Ohmsett, lab, waves
Min & Max Scene Footprint size/swath width, if applicable	1 meter-100m dependent on method
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	Resolution in z direction (vertical) Resolution on the x,y direction ~ 2.5 cm (1 inch) to ~20 cm (~ 8 inches) at the depth of the Ohmsett tank Minimum measurable thickness ~250 microns Maximum measurable thickness: many 10's of cm. (more than 5 inches) Slick thickness resolution: ~75 microns (measurable change in thickness)
Time required for taking measurements	instantaneous
Accuracy	66 um during ISB within 200 um from ROV
Precision	100 um to 200 um in waves
Sensitivity	100um
Operational Procedure Available	yes
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	Has been deployed for ISB, in Ohmsett, at CREEL, in oil ice fields, water needs to be deeper than 6"
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Demonstrated at over 50 sea states including sea state 2, harbor chop to 23" waves, day/night
Oil type and condition	viscosities ranging from 2 cP to over 17,000 cP Fresh to emulsified oil up to 20 wt% water Temperatures ranging from 5C to over 200C. 17 currently, wide range of oil conditions
Space requirements (size, weight)	deployable on small ROV (18" x18" x 18") sensor and electronics are ~7" long, or smaller
Power Requirements	40 watts
Needs for Deployment (e.g., boats, cranes)	ROV, glider
Time for Mobilization/ Demobilization	Deployable in hours to days

Technology	Acoustics Thickness Sensors (Panetta)
Working Group Contact	**CAMPRI Spreadsheet**
Turnaround time for results	real time
TRL #	TRL 7 for Ohmsett and CRREL (working on TRL 6/7 for open water this year)
How/where has technology been used to date	Multiple ISB measurements from ROV. Herded oil. Lab. In ice fields at Ohmsett and CRREL. Will be at Poker Flat in the fall of 2020. Previous OHMSETT testing has looked at slick thickness from moving ROV. 200 microns, we think we could do better because some oil sticks to the plate when you add it in. Also looked at glider in tank. Same oil was 7.8 mm and within 200 microns. Measured slick thickness in waves. Reasonably arbitrary shaped slick and have it contained in some way so we could put waves through it. Waves were generated and slick was contained by boom. Measured slick thickness in over 50 sea states including at sine wave and harbor chop sea state. Oil all over the place so couldn't benchmark it to see where we were. Had to use a benchmark. Benchmarking is extremely important. Put oil in an ice field at OHMSETT using oil from CRREL. Used upward looking cameras and did acoustic measurements of slick thickness in ice fields. About 5 mm thick to 7 mm thick. Also looked at herded oil at OHMSETT, released oil that flowed across sensors. As oil flowed across it was 4 - 4.5 mm thick, not uniformly thick all the way across. 1 mm to 4 or 5 mm. Just happened to be on a calm day. Another case where there was a boom and released oil through the back of the boom and measured oil as it flowed around the tank. Around 2 mm to up to 4-5-6 mm thick and then later (5 min after released oil) still around 2 mm thick.
Next steps to get to a higher TRL and to field application	Deploy offshore, integrate acoustic system with ROV (in progress)
Reports, articles available	BSEE Reports, IOSC, AMOP, Clean Gulf
Strengths and weaknesses	•Strengths •High accuracy •High precision •Direct measurement of thickness •Easy to deploy •Low cost •Instantaneous results •Usable in dark and low visibility water •Weaknesses •Small coverage (30 cm to 1 m per swath) •Need to be close to surface (~3m)
Validation tests conducted to date: lab, field, test tank	Ohmsett, open water tank, lab, ISB. See below and refs
Oil type and condition tested	Multiple Ohmsett: free floating slicks, oil-in-ice fields, oil under ice, boomed slicks Over 50 wave states and with waves to 23 inches high, oil being skimmed ISB: free floating burns, herded burning oil, boomed, and contained burns Lab: free floating, herded, confined Oil: viscosities ranging from 2 cP to over 17,000 cP Fresh to emulsified oil up to 20 wt% water Temperatures ranging from 5C to over 200C.
Results of testing	All results within specified accuracy and precision. See below and references
Testing QA/QC	Multiple: Direct comparison with mass loss during ISB (accurate to within 1%, 66 um) Direct comparison with volume during herder experiments in lab
Vendor/Owner/ Representative and Contact Info	Paul Panetta

Technology	Dip Plates
Working Group Contact	**CAMPRI Spreadsheet**
New or Existing	Existing - unknown if cold tested
Overview of Technology (how it works). Include sensor type/description.	3m T151 Sorbent Pads (analyzed for TPH and PAHs). Plexiglass plates, (weighed before and after on small battery operated field balance)
How is it operated?	
Manufacturer/Developer	3M T151 type pads
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	
Min & Max Scene Footprint size/swath width, if applicable	relative to pad size
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	NA
Temporal Resolution	
Taskable/Adaptive Sampling (yes/no)	
Time required for taking measurements	typically less than a minute
Accuracy	multiple accuracy/precision graphs, varied oil and conditions
Precision	N/A
Sensitivity	Operator identifies the floating oil
Operational Procedure Available	created procedures for Ohmsett and other conditions, old reports available
Application: Emergency response, damage assessment, restoration, marine debris, disaster preparedness, testing verification tool	testing verification tool, damage assessment, emergency response
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	Test environments, open water and shoreline
Range of sea state and other environmental conditions (e.g., day/night, clouds)	limited to conditions where people can be in field
Oil type and condition	west Texas crude, Canadian oil sands, DWH slick a, MC20, HOOPS

Technology	**Dip Plates**
Working Group Contact	**CAMPRI Spreadsheet**
Space requirements (size, weight)	relative to size of pad/plate
Power Requirements	none for collection. Small battery operated balance for processing
Needs for Deployment (e.g., boats, cranes)	boats to access site
Time for Mobilization/ Demobilization	Time required for boat deployment
Turnaround time for results	days to weeks for sorbent, immediately for plates
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	low
Uncertainty bounds expression	2x-4x
TRL #	8/9
How/where has technology been used to date	N/A
Next steps to get to a higher TRL and to field application	additional validation work to understand when it does and doesn't work
Reports, articles available	N/A
Strengths and weaknesses	Major weakness: discrete measurement. Main strength: simple to implement
Validation tests conducted to date: lab, field, test tank	Lab, field and test tank
Oil type and condition tested	see BSEE DWH Lessons learned reports here: https://www.bsee.gov/research-record/osrr-1079-deepwater-horizon-lessons-learned-methodology-and-operational-tools-to
Results of testing	see BSEE DWH Lessons learned reports here: https://www.bsee.gov/research-record/osrr-1079-deepwater-horizon-lessons-learned-methodology-and-operational-tools-to
Testing QA/QC	see BSEE DWH Lessons learned reports here: https://www.bsee.gov/research-record/osrr-1079-deepwater-horizon-lessons-learned-methodology-and-operational-tools-to
Vendor/Owner/ Representative and Contact Info	Heather Forth

Technology	Sorbent Pads -- duplicated from dip plates
Working Group Contact	**CAMPRI Spreadsheet**
New or Existing	Existing - unknown if cold tested
Overview of Technology (how it works). Include sensor type/description.	3m T151 Sorbent Pads (analyzed for TPH and PAHs). Plexiglass plates, (weighed before and after on small battery operated field balance)
Manufacturer/Developer	3M T151 type pads
Min & Max Scene Footprint size/swath width, if applicable	relative to pad size
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	NA
Time required for taking measurements	typically less than a minute
Accuracy	multiple accuracy/precision graphs, varied oil and conditions
Precision	N/A
Sensitivity	Operator identifies the floating oil
Operational Procedure Available	created procedures for Ohmsett and other conditions, old reports available
Application: Emergency response, damage assessment, restoration, marine debris, disaster preparedness, testing verification tool	testing verification tool, damage assessment, emergency response
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	Test environments, open water and shoreline
Range of sea state and other environmental conditions (e.g., day/night, clouds)	limited to conditions where people can be in field
Oil type and condition	west Texas crude, Canadian oil sands, DWH slick a, MC20, HOOPS
Space requirements (size, weight)	relative to size of pad/plate
Power Requirements	none for collection. Small battery operated balance for processing
Needs for Deployment (e.g., boats, cranes)	boats to access site
Time for Mobilization/ Demobilization	Time required for boat deployment

Technology	Sorbent Pads -- duplicated from dip plates
Working Group Contact	**CAMPRI Spreadsheet**
Turnaround time for results	days to weeks for sorbent, immediately for plates
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	low
Uncertainty bounds expression	2x-4x
TRL #	8/9
How/where has technology been used to date	N/A
Next steps to get to a higher TRL and to field application	additional validation work to understand when it does and doesn't work
Reports, articles available	N/A
Strengths and weaknesses	Major weakness: discrete measurement. Main strength: simple to implement
Validation tests conducted to date: lab, field, test tank	Lab, field and test tank
Oil type and condition tested	see BSEE DWH Lessons learned reports here: https://www.bsee.gov/research-record/osrr-1079-deepwater-horizon-lessons-learned-methodology-and-operational-tools-to
Results of testing	see BSEE DWH Lessons learned reports here: https://www.bsee.gov/research-record/osrr-1079-deepwater-horizon-lessons-learned-methodology-and-operational-tools-to
Testing QA/QC	see BSEE DWH Lessons learned reports here: https://www.bsee.gov/research-record/osrr-1079-deepwater-horizon-lessons-learned-methodology-and-operational-tools-to
Vendor/Owner/ Representative and Contact Info	Heather Forth

Technology	Tube Sampler
Working Group Contact	**CAMPRI Spreadsheet**
New or Existing	Existing - not cold tested
Overview of Technology (how it works). Include sensor type/description.	High resolution photo, Tube type
Manufacturer/Developer	Water Mapping, LLC
Min & Max Scene Footprint size/swath width, if applicable	1 inch
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	increments of 20um
Time required for taking measurements	5-10 minutes
Accuracy	assessed from calibration curve, no value
Precision	assessed from calibration curve, no value
Sensitivity	decreases with increasing thickness
Operational Procedure Available	patent pending
Range of sea state and other environmental conditions (e.g., day/night, clouds)	any as long as boat is not moving
Oil type and condition	all types
Space requirements (size, weight)	shoe box, 3 pounds
Power Requirements	small usb power supply
Needs for Deployment (e.g., boats, cranes)	minimize motion of vessel
Time for Mobilization/ Demobilization	small, can be shipped
Turnaround time for results	rapid estimate initially, takes 4 hours for calibration, 1 hour for sample processing
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	none

Technology	Tube Sampler
Working Group Contact	**CAMPRI Spreadsheet**
How/where has technology been used to date	Lake Washington spill deployed instrument. Experiment with more detailed example of the calibration and take high resolution photography of each amount -- method is very consistent where you pour known amounts of layers and comes back with very nice consistency. Experiment at Saint Petersburg ("Calibration and Digital Measurement of Thickness Layer"). Characterize thickness measurement in the but. Hard to fill donut inside the tube because of the capillary action, etc. As you increment contents regardless of if its thick enough to fill this gap...
Next steps to get to a higher TRL and to field application	Test multiple sampler configuration -- small footprint of tube. Even at OHMSETT and you get a little bit of wind and all the oil sticks against one wall -- destroying the surface at OHMSETT. Made another sampler where you can have a grid of samplers instead of one tube. 2x2 array of samples -- four samples at the same time. Haven't worked too much on that and sample in such a small area. Help to expand library of oils and get more range.
Vendor/Owner/ Representative and Contact Info	Oscar Garcia
Technology	**Remotely Manned Surface Vehicle (RMSV)**
Working Group Contact	**CAMPRI Spreadsheet**
New or Existing	In development - unknown if cold tested
Overview of Technology (how it works). Include sensor type/description.	High definition Camera
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	only open water
Min & Max Scene Footprint size/swath width, if applicable	variable, depending on how system is operated.
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	May be N/A because the system images the interface between oil-air and oil water. So it can provide very high-resolution mapping of an oil slick depending on how system is operated.
Time required for taking measurements	The system runs transects through an oil slick and physically observes the slick thickness with a camera. It provides real-time images as these measurements are taken and an immediate map of slick thickness after transects are completed.
Accuracy	variable accuracy--but as this is a physical measurement of slick thickness via an on-water camera, it will be highly accurate, if necessary.
Precision	
Sensitivity	robust
Operational Procedure Available	not yet

Technology	Remotely Manned Surface Vehicle (RMSV)
Working Group Contact	**CAMPRI Spreadsheet**
Application: Emergency response, damage assessment, restoration, marine debris, disaster preparedness, testing verification tool	emergency assessment, direct indicator of oil thickness
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	almost everywhere with water (including ice)
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Sea state range is very broad, day/night
Oil type and condition	all types, visual interpretation
Space requirements (size, weight)	400 lbs, 6'x2'x1.5'
Power Requirements	gasoline self-powered
Needs for Deployment (e.g., boats, cranes)	deployable from ship, helicopter or airplane (built in winch)
Time for Mobilization/ Demobilization	can be deployed via aircraft or vessel, and goes 65 mph (depends on storage location)
Turnaround time for results	real-time, low processing requirements
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	cellular or satellite uplink
TRL #	4-5
How/where has technology been used to date	only prototype
Next steps to get to a higher TRL and to field application	complete and test full-scale prototype with oil in the field
Reports, articles available	internal reports only
Strengths and weaknesses	Strengths • Relatively inexpensive • Direct measurement • Fast moving • Real time information • Remote operation (safe) Weaknesses • Not synoptic • Measurement speed

Technology	Remotely Manned Surface Vehicle (RMSV)
Working Group Contact	**CAMPRI Spreadsheet**
Validation tests conducted to date: lab, field, test tank	test tanks
Oil type and condition tested	vegetable oil as surrogate
Results of testing	positive
Testing QA/QC	only thick versus thin identified
Vendor/Owner/ Representative and Contact Info	Tim Nedwed
Technology	**LRAUV**
Working Group Contact	**Amy Kukulya**
New or Existing	Developed in 2009, not commercialized - cold tested, new capabilities in development
Overview of Technology (how it works). Include sensor type/description.	many sensors have been integrated to date including: ADCPs, CTDs, samplers, eDNA, SeaOwl, camera
How is it operated?	autonomously, a remote operator can track and reprogram/send commands if needed
Manufacturer/Developer	MBARI, WHOI
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	Ice and open water, fresh and salt
Min & Max Scene Footprint size/swath width, if applicable	<20 foot container (mobile, no crane needed if applicable), small boat or no boat needed
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	vehicle can yo-yo vertically, run at constant altitude or mow the lawn at predetermined spacing
Temporal Resolution	varies per sensor, please contact us
Taskable/Adaptive Sampling (yes/no)	yes
Time required for taking measurements	varies from 1 to 50 hertz or samples can be grabbed when anomaly detected
Operational Procedure Available	yes
Application: Emergency response, damage assessment, restoration, marine debris, disaster preparedness, testing verification tool	all of the above

Technology	LRAUV
Working Group Contact	**Amy Kukulya**
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	outside surf zone, open water, surface, ~2 meters from bottom, under ice, along glaciers, fresh, salt and test
Range of sea state and other environmental conditions (e.g., day/night, clouds)	limitation is only for launch and recovery sea state varies per vessel, etc.
Oil type and condition	sensor dependent
Space requirements (size, weight)	AUV is 9ft long, 12 inch diameter and weights ~250lbs
Power Requirements	contains rechargeable lithium ion batteries and requires 120 volts for recharging, 6-15 amps
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	land or sea shipping, 2 available at WHOI, MBARI has a science fleet
Needs for Deployment (e.g., boats, cranes)	can be launched from shore, dock, small or large vessel, no crane typically needed
Time for Mobilization/ Demobilization	once on site, <4hours mob and demob. Best to plan one day
Turnaround time for results	varies, sends data on a predetermined polling cycle (subset of data). Typically every two hours but can be anything. Full data download can take 1-4 hours depending on length of mission 1-14 days
Permits Required for deployment	only if working with marine mammals or in a controlled/monitored environment. Check with local authorities/agencies
# of people required to deployment	2
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	AUV has an extensive comms relay capability including Wi-Fi, RF, Iridium, Cellular and uses whatever is best
Lab Requirements	Need shore side or ship lab if vehicle needs to open (highly unlikely), small footprint
Describe raw data format	raw data is binary and can be unserialized into many formats including .mat, .xlsx, netcfd, HDF5, etc.
Describe data process workflow and requirements	varies per sensor, please contact us

Technology	**LRAUV**
Working Group Contact	**Amy Kukulya**
Time required for Data Processing to data delivery (emergency vs nonemergency)	sensors like CTD, fluorometers are minutes, imaging sensors and samples are hours to days
Data size and Volume	varies
Format of Final Data File and Access Point	user pref
Format of Data delivery	user pref
Communication and transmission requirements	see comms above (system is complete loop to phone or laptop) nothing special needed. Vehicles do benefit from iridium for long-range unattended mission
TRL #	yo-yo environmental sampling TRL 8, new capabilities vary
How/where has technology been used to date	10 years in open ocean, under-ice, fresh
Next steps to get to a higher TRL and to field application	use new capabilities more extensively, Holocam, autonomy behaviors, need real world scenarios and opportunities
Reports, articles available	yes
Strengths and weaknesses	long range, portable, not commercialized, so less vehicles available, not modular, small footprint and can be operated from a phone or ipad and data can be viewed from anywhere with a n internet connection to the data portal
Validation tests conducted to date: lab, field, test tank	lab, test, field
Oil type and condition tested	Santa Barbara Seeps
Results of testing	available
Vendor/Owner/ Representative and Contact Info	WHOI, Amy Kukulya amy@whoi.edu

Technology	**REMUS 100**
Working Group Contact	**Amy Kukulya**
New or Existing	Commercialized AUV- cold tested, WHOI owns and operates a fleet working with government, military and private sector
Overview of Technology (how it works). Include sensor type/description.	many sensors have been integrated to date including: ADCPs, CTDs, samplers, multibeam, sidescan, magnetometers, fluorometers, cameras, DO probes, turbidity, Gulpers, pH, nitrogen, holographic cameras, lasers, homing, docking, inertial navigation,
How is it operated?	autonomously, a remote operator can track and reprogram/send commands if needed
Manufacturer/Developer	WHOI, Amy Kukulya, amy@whoi.edu commercial vendor, Hydroid, Inc.
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	Ice and open water, fresh and salt
Min & Max Scene Footprint size/swath width, if applicable	<20 foot container, highly mobile, small boat, no crane needed if applicable
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	vehicle can yo-yo vertically, run at constant altitude or mow the lawn at predetermined spacing
Temporal Resolution	varies
Taskable/Adaptive Sampling (yes/no)	yes
Time required for taking measurements	varies from 1 to 50 hertz or samples can be grabbed when anomaly detected
Operational Procedure Available	yes
Application: Emergency response, damage assessment, restoration, marine debris, disaster preparedness, testing verification tool	all of the above
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	outside surf zone, open water, surface, ~2 meters from bottom, under ice, along glaciers, fresh, salt and test
Range of sea state and other environmental conditions (e.g., day/night, clouds)	limitation is only for launch and recovery sea state varies per vessel, etc.
Oil type and condition	sensor dependent
Space requirements (size, weight)	Modular ~7ft long, 7.75in diameter, 100 lbs

Technology	REMUS 100
Working Group Contact	**Amy Kukulya**
Power Requirements	contains rechargeable lithium ion batteries and requires 120 volts for recharging, 10 amps
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	air, land or sea shipment, WHOI owns 8 vehicles
Needs for Deployment (e.g., boats, cranes)	can be launched from shore, dock, small or large vessel, no crane typically needed
Time for Mobilization/ Demobilization	once on site, <4hours each mob and demob, best to plan one day
Turnaround time for results	modem data can be sent every 30 seconds with a 'snapshot of data'. Full data set download varies per sensor, CTD, Ecopuck (SeaOwl) takes minutes to send a text file with full data set.
Permits Required for deployment	only if working with marine mammals or in a controlled/monitored environment. Check with local authorities/agencies
# of people required to deployment	2
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Can use Wi-Fi and Iridium or hard-wire
Lab Requirements	minimal, laptop, power, antenna box mounted at highest point and transducer in water along side of ship if acoustic comms are needed (easy to pull out and in water)
Describe raw data format	User choice ASCII, MAT, Excel. Imaging and sonar sensors vary per manufacturer
Describe data process workflow and requirements	varies per sensor, please contact us
Time required for Data Processing to data delivery (emergency vs nonemergency)	sensors like CTD, fluorometers are minutes, imaging sensors and samples are hours to days
Data size and Volume	varies
Format of Final Data File and Access Point	user pref
Format of Data delivery	user pref
Communication and transmission requirements	see comms above (system is complete loop to phone or laptop) nothing special needed. Vehicles do benefit from iridium for long-range unattended mission
TRL #	TRL 10, new sensors and capabilities vary

Technology	**REMUS 100**
Working Group Contact	**Amy Kukulya**
How/where has technology been used to date	25 years covering the extent of the Globe in most environments including ice
Next steps to get to a higher TRL and to field application	use new capabilities more extensively, Holocam, autonomy behaviors
Reports, articles available	yes
Strengths and weaknesses	only runs for 8 hours before a recharge is needed. Multiple platforms can be used to leap frog so 24 hour testing can be achieved, is highly modular, small footprint, portable
Validation tests conducted to date: lab, field, test tank	lab, test, field
Oil type and condition tested	Santa Barbara Seeps, MC20 site
Results of testing	available
Vendor/Owner/ Representative and Contact Info	WHOI, Amy Kukulya, amy@whoi.edu commercial vendor, Hydroid, Inc.
Technology	**REMUS 600**
Working Group Contact	**Amy Kukulya**
New or Existing	Commercialized AUV, WHOI owns and operates
Overview of Technology (how it works). Include sensor type/description.	many sensors have been integrated to date including: ADCPs, CTDs, samplers, multibeam, sidescan, magnetometers, fluorometers, cameras, DO probes, turbidity, Gulpers, pH, nitrogen, holographic cameras, lasers, homing, docking, inertial navigation,
How is it operated?	autonomously, a remote operator can track and reprogram/send commands if needed
Manufacturer/Developer	WHOI, Amy Kukulya, amy@whoi.edu commercial vendor, Hydroid, Inc.
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	ice and open water, fresh and salt
Min & Max Scene Footprint size/swath width, if applicable	< 20 foot container, needs crane
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	vehicle can yo-yo vertically, run at constant altitude or mow the lawn at predetermined spacing
Temporal Resolution	varies
Taskable/Adaptive Sampling (yes/no)	yes
Time required for taking measurements	varies from 1 to 50 hertz or samples can be grabbed when anomaly detected
Operational Procedure Available	yes

Technology	REMUS 600
Working Group Contact	**Amy Kukulya**
Application: Emergency response, damage assessment, restoration, marine debris, disaster preparedness, testing verification tool	all of the above
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	outside surf zone, open water, surface, ~2 meters from bottom, under ice, along glaciers, fresh, salt and test
Range of sea state and other environmental conditions (e.g., day/night, clouds)	limitation is only for launch and recovery sea state varies per vessel, etc.
Oil type and condition	sensor dependent
Space requirements (size, weight)	Modular, ~12 ft long, 12.75 in diameter, weight varies (450-700 lbs)
Power Requirements	contains rechargeable lithium ion batteries and requires 120 volts for recharging. Some systems require 220, 30 amps
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	land or sea shipment, WHOI owns 1 vehicle and operates many for the military and has reasonable access.
Needs for Deployment (e.g., boats, cranes)	can be launched from shore or vessel with crane. Can be deployed without crane by other creative means (custom)
Time for Mobilization/ Demobilization	1-2 days (vehicle comes in modular boxes and needs to be assembled. Time varies per nature of vessel, logistics. Window can be faster. Ship needs to be set up.
Turnaround time for results	modem data can be sent every 30 seconds with a 'snapshot of data'. Full data set download varies per sensor, CTD, Ecopuck (SeaOwl) takes minutes to send a text file with full data set.
Permits Required for deployment	only if working with marine mammals or in a controlled/monitored environment. Check with local authorities/agencies
# of people required to deployment	3-Feb
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Can use Wi-Fi and Iridium or hard-wire

Technology	REMUS 600
Working Group Contact	**Amy Kukulya**
Lab Requirements	laptop, power, antenna box mounted at highest point and transducer in water along side of ship if acoustic comms are needed (easy to pull out and in water) Has large vehicle cart with wheels
Describe raw data format	User choice ASCII, MAT, Excel. Imaging and sonar sensors vary per manufacturer
Describe data process workflow and requirements	varies per sensor, please contact us
Time required for Data Processing to data delivery (emergency vs nonemergency)	sensors like CTD, fluorometers are minutes, imaging sensors and samples are hours to days
Data size and Volume	varies
Format of Final Data File and Access Point	user pref
Format of Data delivery	user pref
Communication and transmission requirements	see comms above (system is complete loop to phone or laptop) nothing special needed. Vehicles do benefit from iridium for long-range unattended mission
TRL #	TRL 10, new sensors and capabilities vary
How/where has technology been used to date	25 years covering the extent of the Globe in most environments, including cold environments
Next steps to get to a higher TRL and to field application	use new capabilities more extensively, Holocam, Gulpers, autonomy behaviors
Reports, articles available	yes
Strengths and weaknesses	modular battery packs allows for 24-72 operations and can carry many sensors at once. Larger footprint, not portable
Validation tests conducted to date: lab, field, test tank	lab, test, field
Oil type and condition tested	Santa Barbara Seeps
Results of testing	available
Vendor/Owner/ Representative and Contact Info	WHOI, Amy Kukulya, amy@whoi.edu commercial vendor, Hydroid, Inc.

Technology	**Photo Acoustic Detector**
Working Group Contact	**Ben Fieldhouse**
New or Existing	Prototype - has been tested with ice to provide indication of thickness in the oil pocket.
Overview of Technology (how it works). Include sensor type/description.	The technology developed at NRC is based on photo-acoustics, a combination of laser optics and acoustics. A pulsed laser is used as a source and ultrasonic sensors are used as detectors. It is an underwater technology that can be deployed in a Remotely Operated Vehicle (ROV) or Underwater Autonomous Vehicle (UAV). From underwater, the laser shoots upward toward ice or the surface of open water. If there is oil, the pulsed laser beam is absorbed and an ultrasonic source is created and spreads Ultrasonic waves that can be detected with ultrasound receivers on board the underwater vehicle. If there is no oil, there is no ultrasonic wave generated, so no signal; it is a binary technique. With a localized ultrasonic wave source at the oil interface, ultrasonic waves are spreading in all directions and oil thickness can be monitored. Scanning the laser beam, with scanning mirrors and moving the underwater vehicle, mapping the extent and thickness, under the ice, encapsulated in the ice or under open water surface can be obtained. Compared to conventional ultrasonic techniques to monitor oil spill from underwater, this technique has the advantages of providing a better contrast of oil extent, to provide simpler data to analyze and to be less sensitive to miss-alignment.
How is it operated?	The actual prototype is controlled via an external computer. Commands and data are transferred via an umbilicus. The actual prototype doesn't include the underwater vehicle to position or move the sensors.
Manufacturer/Developer	Prototype developed at NRC.
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	It is designed to be operated in ice covered ocean or in open ocean.
Min & Max Scene Footprint size/swath width, if applicable	If actual prototype is at a distance of 2 meters, below the ice or water surface, when immobile, the scene footprint is 1 meter by 1 meter. When moving, the swath width is 1 meters and the length will be travel distance of the underwater vehicle. Note that, the dimension can be increased by modifying the laser scanning system and optics. With AUV application, not available at this time, a working distance, sensor to ice or water surface, is expected to be 5 meters or more, and the swath width will be 2.6 meters or more for 5 meters, 5.2 meters or more for 10 meters.
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	The technique is a scanning technique and spatial resolution can be set by the operator. The min can be as low as millimeter to a max of centimeters, tens of centimeters or more for large area to map.
Temporal Resolution	When measuring only at one point, the actual prototype temporal resolution is 10 milliseconds, the laser repetition rate being 100Hz; when scanning a surface with 100 points, the temporal resolution is 1 second…
Taskable/Adaptive Sampling (yes/no)	Yes
Time required for taking measurements	Measurement can be considered real time. Data is pot processed but future development should enable real time data processing.
Accuracy	Accuracy for oil thickness measurement will depend if correct oil ultrasonic velocity is considered (oil type, oil degradation…), therefore excellent and very acceptable for this problem.

Technology	Photo Acoustic Detector
Working Group Contact	**Ben Fieldhouse**
Precision	Precision for oil thickness measurement should be as good as thickness measurement can be obtained with ultrasonic measurement, therefore excellent and very acceptable for this problem.
Sensitivity	The high sensitivity of the technique has been demonstrated in the laboratory, being able to measure as little as millimeter oil thicknesses to oil thicknesses of several inches.
Operational Procedure Available	no
Application: Emergency response, damage assessment, restoration, marine debris, disaster preparedness, testing verification tool	Application to Emergency response with a ROV, Application to area risk survey with AUV, Application to disaster preparedness, Application to restoration or recovery with a ROV, Application to satellite remote sensing calibration (open water), …
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	Ice covered region, open water
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Any sea state and environmental condition
Oil type and condition	Technology has been tested on crude oil, future work will be performed on marine diesel and diesel for remote community.
Space requirements (size, weight)	The current prototype is 32 inches in length and 8 inches in diameter, its weight is 20kg.
Power Requirements	110V, 5A.
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	1 prototype available.
Needs for Deployment (e.g., boats, cranes)	Boat, ROV.
Time for Mobilization/ Demobilization	Unknown
Turnaround time for results	Results are obtained after post processing of raw data, few minutes after data collection. Can be improved for real acquisition and data processing providing almost real time results.
Permits Required for deployment	No.
# of people required to deployment	2

Technology	Photo Acoustic Detector
Working Group Contact	**Ben Fieldhouse**
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Umbilicus from ROV to boat with Ethernet communication/cable or optical.
Lab Requirements	No.
Describe raw data format	Raw data are ultrasonic waveforms, amplitude signal function of time.
Describe data process workflow and requirements	The raw data is saved on the computer in the boat via a transfer of the submarine prototype with the umbilicus cable. Internal analysis software opens files and performs data processing: signal windowing, signal amplitude evaluation, time-of-flight measurement, and imaging of results to provide B-scans and C-scans. The B-scan is a side view or cross section of raw data that can show cross section images of the oil cavity. C-scan is a top view that can show the extent of the oil spill with signal amplitude mapping or oil thickness mapping.
Time required for Data Processing to data delivery (emergency vs nonemergency)	At this stage of development, it is about minutes, less than 10 minutes. Can be improved.
SOP available data processing	No.
Data size and Volume	Raw data files can be larges (GB), processed data are relatively small (images).
Format of Final Data File and Access Point	To be developed, jpeg…
Format of Data delivery	color-coded result mapping
Uncertainty bounds expression	
Communication and transmission requirements	Ethernet (cable/optic) from the sensor to the boat.
TRL #	4
How/where has technology been used to date	Technology used only in NRC Lab.
Next steps to get to a higher TRL and to field application	Complete some developments, tests in tanks with various conditions (turbidity, biofouling, algae, biomass), tests in large basin, Integration to ROV, tests in real conditions (open water, ice covered).
Reports, articles available	Conference presentations, conference proceeding ("Photoacoustic detection and monitoring of oil spill", C. Bescond et al.; https://doi.org/10.1063/1.5099729).

Technology	Photo Acoustic Detector
Working Group Contact	**Ben Fieldhouse**
Strengths and weaknesses	Strengths: This is a new technology which offers excellent contrast (On-off technology), easy to interpret information, is not very sensitive to misalignment and should be effective in mapping moderately complex oil spills. Weaknesses: the on-board laser induces high energy consumption, laser safety to be taken into account, high cost, large sensor volume, low to medium repetition rate; certain effects of environmental factors such as turbidity, bio-fouling, algae, biomass on the technology have not been tested (limitation of working distance, noise, sensitivity, false positives, etc.).
Validation tests conducted to date: lab, field, test tank	In laboratory (small tank, 2 meters high, 1.2 meter width)
Oil type and condition tested	Crude oil, oil on open water, below ice and Plexiglas, encapsulated within Plexiglas.
Results of testing	Mapping of oil spill extent was obtained with imaging of oil cavity and oil thickness mapping. Great contrast was obtained between areas with oil and without.
Testing QA/QC	NA.
Vendor/Owner/ Representative and Contact Info	National Research Council of Canada, Christophe.Bescond@nrc-cnrc.gc.ca
Technology	**Capacitance Thickness Sensor (Imad Elhajj)**
Working Group Contact	**Imad Elhajj**
New or Existing	New in development
Overview of Technology (how it works). Include sensor type/description.	There are 2 sensors. The first is a handheld unit (manned). The second can be mounted to a skimmer or buoy to wirelessly communicate oil thickness (unmanned).
How is it operated?	The sensor measures the thickness of oil on water by measuring the capacitance of a set of conductive electrodes that are immersed in the oil/water layer. Based on the relative differences between the capacitance values acquired by each of the sensor electrodes, interfaces separating the different layers of oil/water/air are detected. The oil thickness is calculated based on the count and geometrical dimensions of the electrodes.
Manufacturer/Developer	R&D Contract to American University of Beirut. PI is Dr. Imad Elhajj
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	Measures surface oil thickness on open water or within drift or broken ice field.
Min & Max Scene Footprint size/swath width, if applicable	Two sensors are under development. First is a hand-held unit with a telescoping pole that can be extended to measure oil thickness, either from a vessel or from the side of a test tank. The user directly reads the oil thickness in real time on the tool's handle. The second sensor mounts on a skimmer or buoy, or in the apex of a boom, and provide thickness information wirelessly to a user.
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	N/A

Technology	Capacitance Thickness Sensor (Imad Elhajj)
Working Group Contact	**Imad Elhajj**
Temporal Resolution	This is a localized measurement instrument. Multiple measurements can be taken in an area of interest.
Taskable/Adaptive Sampling (yes/no)	N/A
Time required for taking measurements	1 to 5 seconds after instrument in dipped into oil layer
Accuracy	N/A
Precision	For the hand-held sensor, +/- 3 mm For the skimmer-mount sensor, +/- 10 mm (Based on preliminary results)
Sensitivity	For the hand-held sensor, 1 mm For the skimmer-mount sensor 3 mm
Operational Procedure Available	For the hand-held sensor, 3 mm For the skimmer-mount sensor, 10 mm
Application: Emergency response, damage assessment, restoration, marine debris, disaster preparedness, testing verification tool	Not yet. These technologies are under Phase II development and will be tested at Ohmsett in Fall, 2020.
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	Emergency response, damage assessment, testing verification tool
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Could be used in marsh, shoreline, open water applications. Could be used in drift ice environment. Not for use to measure oil under ice or submerged oil. Can be used in day/night application. The remote mounted sensor is designed to handle wave conditions.
Oil type and condition	measures crude/refined oils. Calibration for oil type is not required. Will be assessing its ability to measure emulsions.
Space requirements (size, weight)	Approximate weight 5 lbs. Size is handheld.
Power Requirements	6 AA batteries
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	BSEE will own up to three prototypes of each configuration after end of project.
Needs for Deployment (e.g., boats, cranes)	None
Time for Mobilization/ Demobilization	Can be deployed immediately after power up. Negligible time.
Turnaround time for results	Does not take images

Technology	Capacitance Thickness Sensor (Imad Elhajj)
Working Group Contact	**Imad Elhajj**
Permits Required for deployment	None
# of people required to deployment	1
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	None
Lab Requirements	None
Describe raw data format	For the hand-held sensor, oil thickness is displayed on the device's screen in millimeters For the skimmer-mount sensor, oil thickness is stored in text files in millimeters and displayed on the remote PC.
Describe data process workflow and requirements	For the hand-held sensor, the user should record the results displayed on the screen. For the skimmer-mount sensor, the user should save the received measurements in separate text files using the provided software
Time required for Data Processing to data delivery (emergency vs nonemergency)	Data is delivered in real time
SOP available data processing	no SOP
Data size and Volume	Minimal data size
Format of Final Data File and Access Point	Text files containing measured oil-thickness in millimeters
Format of Data delivery	Oil-thickness in millimeters, date and time. Also ability to provide temperature and GPS.
Uncertainty bounds expression	Pending Ohmsett testing of Version II
Communication and transmission requirements	Handheld mode no transmission. The skimmer mount mode supports ZigBee.
TRL #	TRL6 expected for version II (excluding “regulatory approvals and industry standards”)
How/where has technology been used to date	Testing at AUB's laboratory and at Ohmsett for version I.
Next steps to get to a higher TRL and to field application	Conduct testing at Ohmsett

Technology	**Capacitance Thickness Sensor (Imad Elhajj)**
Working Group Contact	**Imad Elhajj**
Reports, articles available	Version I: Research Report "Development of Oil Slick Thickness Sensors," Bureau of Safety and Environmental Enforcement, 5 March 2018. https://www.bsee.gov/research-record/development-of-an-oil-thickness-sensor Mahdi Saleh, Ghassan Oueidat, Imad H. Elhajj, and Daniel Asmar, "In-situ Measurement of Oil Slick Thickness," IEEE Transactions on Instrumentation and Measurement, Vol. 68, No. 7, pp. 2635-2647, July 2019. DOI: 10.1109/TIM.2018.2866745 Abstract: Imad H. Elhajj, Mahdi Saleh, Daniel Asmar, "In situ Measurement of Oil Slick Thickness in Open Water Environments," CLEAN GULF, New Orleans, Louisiana, October 28-31, 2019.
Strengths and weaknesses	Strengths: - Does not require calibration - Is not sensitive to environmental conditions (water, temp, lighting, etc…) - Mitigates fouling and waves - Has a long life expectancy - Requires minimal maintenance and is low cost - Can be used in different use cases (handheld or mounted) Weaknesses: - Low resolution (does not measure very thin slicks) - Requires contact with the oil and is not remote
Validation tests conducted to date: lab, field, test tank	Version I: tested at Ohmsett Nov-Dec 2017. Version II: testing planned fall 2020.
Oil type and condition tested	Version I see details at: https://www.bsee.gov/research-record/development-of-an-oil-thickness-sensor
Results of testing	Version I see details at: https://www.bsee.gov/research-record/development-of-an-oil-thickness-sensor
Testing QA/QC	N/A
Vendor/Owner/ Representative and Contact Info	American University of Beirut, Imad Elhajj, imad.elhajj@aub.edu.lb

Technology	Marine Induced Polarization
Working Group Contact	**ADAC**
New or Existing	In development - simulated cold tested. Further design revisions planned for reduced form factor and power requirements.
Overview of Technology (how it works). Include sensor type/description.	manned
How is it operated?	Complex Electrical impedance anomaly detection technology: detecting phase anomalies in electrical waveforms transmitted through the water. The sensors are electrodes that are embedded in a cable that is towed behind a vessel.
Manufacturer/Developer	Induced Polarization Associates
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	Under Ice, Open Water
Min & Max Scene Footprint size/swath width, if applicable	Two transmitter electrodes to transmit a signal, and two or more receiver electrodes to record phase differences resulting from the transmit signal coming in contact with materials in the environment.
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	1- 5 m dependent on vessel towing speed and cable electrode configuration/spacing.
Temporal Resolution	Measurement swath of approximately 5-10 m (dependent on array configuration) centered on each cable sensor
Taskable/Adaptive Sampling (yes/no)	No
Time required for taking measurements	single measurements are instantaneous, multiple measurements along survey line recommended.
Accuracy	
Precision	1- 5 m dependent on vessel towing speed and cable electrode configuration/spacing.
Sensitivity	Resolves the presence/absence of contaminant; In the lab down to 2ppm concentrations reported.
Operational Procedure Available	Preliminary -- under development.
Application: Emergency response, damage assessment, restoration, marine debris, disaster preparedness, testing verification tool	Emergency response, damage assessment, restoration support, metallic marine debris
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	In-water sediments (fresh, salt, or brackish), minimum depth of 1m, maximum depth 2500m.

Technology	Marine Induced Polarization
Working Group Contact	**ADAC**
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Daytime operations, up to 3-knot currents
Oil type and condition	dilbit, crude
Space requirements (size, weight)	The cable can be 30 lbs to 150 lbs in current configurations, dependent on cable length. Topside electronics weigh approximately 30 lbs. Requires an enclosed space for data collection electronics and a minimum 10' x 10' deck space.
Power Requirements	100V - 230VAC Mains, Ship Power, Generator, 2X12V 800mAh batteries
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	One unit currently available
Needs for Deployment (e.g., boats, cranes)	Vessel of opportunity with enclosed space with a table and a seat for operator; table must be at least 3' x 2'. Equipment can be hand-carried.
Time for Mobilization/ Demobilization	From the time of arrival on site, 1 day to mobilize, deploy and collect baseline measurements
Turnaround time for results	Real-time indications of anomalies can be provided with a minor lag depending on sampling rate, and final results provided after post processing
Permits Required for deployment	No
# of people required to deployment	3
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	None
Lab Requirements	Yes. System is calibrated by obtaining a sample of the target contaminant followed by laboratory testing of the sample to understand target signal.
Describe raw data format	Raw data is collected in burst packets, format is ASCII.
Describe data process workflow and requirements	Data is processed by using instrument software to convert raw data files to ASCII and perform signal processing to resolve anomaly detection.
Time required for Data Processing to data delivery (emergency vs nonemergency)	One day for oil location yes/no
SOP available data processing	Not yet.

Technology	Marine Induced Polarization
Working Group Contact	**ADAC**
Data size and Volume	Dependent on survey track. Single raw sample approximately 500KB. Typical survey line of 100 samples approximately 52KB. Postprocessed data variable dependent on analysis techniques.
Format of Final Data File and Access Point	CSV
Format of Data delivery	CSV
Communication and transmission requirements	none
TRL #	
How/where has technology been used to date	Gulf of Mexico aboard R/V Manta; US Army CRREL Facility.
Next steps to get to a higher TRL and to field application	System is being upgraded
Reports, articles available	ADAC Year 6 Report
Strengths and weaknesses	Strengths: Noninvasive; Hand-carriable; possible to simultaneously deploy with sonar devices; integrated with GPS devices; logs data in human-readable format. Weaknesses: Currently provides only anomaly detection capabilities for metallic materials and oil contaminants; requires mains power; specific signatures of oil contamination anomalies still being characterized.
Validation tests conducted to date: lab, field, test tank	Laboratory tests, Kirkland, WA; Beach Deployment Tests, Golden Gardens Park, Seattle, WA; Ground Truthing tests, Eagle Harbor, WA; US Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, NH.
Oil type and condition tested	ANC Crude, Bunker Crude
Results of testing	Anomalies detected in CRREL Test Tank, anomalies detected in ground truthing tests.
Technology	**Upward Looking Multibeam Sonar for Under Ice Roughness**
Working Group Contact	**Ted Maksym**
New or Existing	Operational
Overview of Technology (how it works). Include sensor type/description.	Gives measure of undersurface roughness, including keel depth.
Vendor/Owner/ Representative and Contact Info	Hanu Singh
Technology	**Upward Looking Multibeam Sonar for Oil Trapped Under Ice**
Working Group Contact	**Ted Maksym**
New or Existing	Operational
TRL #	
Vendor/Owner/ Representative and Contact Info	Hanu Singh
Technology	**Single beam sonar for oil trapped under ice**
Working Group Contact	
New or Existing	Operational

Technology	**Upward Looking Lidar (video either stereo or single camera data processed)**
Working Group Contact	**Phil McGillivary**
Overview of Technology (how it works). Include sensor type/description.	Video either stereo or single camera data processed for either sequential frame stereo/Structure from Motion (SfM) data. Gives measure of undersurface roughness, including ice keel depth.
Technology	**Upward Looking Fluorescence**
Working Group Contact	**Phil McGillivary**
Overview of Technology (how it works). Include sensor type/description.	Originally developed to measure algal growth on the ice underside, depending on wavelength could likewise easily measure oil under the ice as well.
Technology	**Norbit Multibeam Sonar and LIF fluorescent laser sensor (SpiDeR –Spill Detection and Recognition system)**
Working Group Contact	**Pawel Pocwiardowski**
New or Existing	Commercialized multibeam sonar platform for AUV, ROV, SV and fixed installations. Currently being sold all around the World with multiple distributors. The added LIF sensor - Laser classifier in in RTL 8
Overview of Technology (how it works). Include sensor type/description.	NORBIT's SpiDeR is a modular sensor suite for large area bathymetric mapping capable of detecting, recognizing the source and classifying the hydrocarbon underwater leaks. The sensor suit with selectable configuration can be installed on any type of ROV vehicle and interfaces to the ROV with a single cable conducting the power and data. The complete sensor suite consist of two 3D, broad band, electronically scanning multibeam sonar systems STX, one Forward Looking Sonar FLS, fluorescent oil classifier LIF – Laser Induced Fluorescence detection unit, video camera with lights and other sensors. The most useful capability of the SpiDeR is the ability to generate 3D imagery (georeferenced bathymetry or raster image) even when the ROV is not moving. That combined with time gives 4D observable capabilities of the oil spill. The 4D capabilities have been proven during remote-sensing survey of Mississippi Canyon area in the Gulf of Mexico founded by BSEE in 2017 under solicitation number E17PS00077 as well as in OGP founded Joint Industry Program (JIP) at CRREL in 2014 and several other projects.
How is it operated?	All sonars are controlled by the single user interface with data acquisition. For SV, USV the integrated (sonar + GNSS/INS) system is provided. For ROV, AUV the external navigation needs to be used. For large area bathymetry maps the data needs to be postprocessed. For FLS and LIF the data is available for immediate observation.
Manufacturer/Developer	NORBIT A/S, pawel@norbit.com
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	Under ice and in any types of water

Technology	**Norbit Multibeam Sonar and LIF fluorescent laser sensor (SpiDeR –Spill Detection and Recognition system)**
Working Group Contact	**Pawel Pocwiardowski**
Min & Max Scene Footprint size/swath width, if applicable	The 3D wide coverage multibeam sensor is capable of illuminating 20x210 deg sector footprint. Both dimensions are programmable. The FLS sensor has 1x210 deg swath. The additional laser classifier is a point measuring device with the range roughly 10m.
Min & Max Spatial Resolution (GSD e.g. 10m/pixel), if applicable	1 x 1 deg for multibeam sensors. The 20x210deg sector consists of pings containing 512 beams distributed inside that single swath. Each beam has a footprint 1x1 deg. Therefore the entire footprint is 20 x 210 deg sector consists of 1x1 deg beams distributed inside that sector. The range of the sonar depends on conditions and selected frequency and can range from 0 to 500m.
Temporal Resolution	0.9cm for acoustic sensor (both 3D and FLS) 1m for laser classifier
Taskable/Adaptive Sampling (yes/no)	Yes
Time required for taking measurements	ping time - depends on selected range. Typically 20m range with take 30ms
Accuracy	Bathymetry system - exceeds IHO Special Order standard, exceeds USACE standard FLS systems supervised and unsupervised classification LIF laser sensor 99% probability of detection
Precision	3D sonar 3mm FLS 9mm LIF 16bit
Sensitivity	Multibeam can detect single PPM of oil in the water. Can detect oil on the seabed or on the ice surface. LIF laser can detect/classify very small amount of oil in the water or droplets.
Operational Procedure Available	Complete user manuals and training available for multibeams. For LIF sensor the documentation is under preparation.
Application: Emergency response, damage assessment, restoration, marine debris, disaster preparedness, testing verification tool	Spill emergency response, wide area coverage, oil and gas leaks. Suspended plumes in the water column detection and classification, Heavy oils on the sea bottom light oils under the ice damage assessment general high resolution bathymetry general FLS inspection general mapping and bottom sediment classification
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	Any types waters (rivers, lakes, sea, open and close waters, shallow, deep, ice, surface waters, shoreline, offshore, etc.)

Technology	Norbit Multibeam Sonar and LIF fluorescent laser sensor (SpiDeR –Spill Detection and Recognition system)
Working Group Contact	**Pawel Pocwiardowski**
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Any sea state and environmental conditions
Oil type and condition	Suspended plumes Heavy oils on the sea bottom light oils under the ice
Space requirements (size, weight)	configurable from a single multibeam sonar 1lb (wet) to complete sensor suite 40lb (wet)
Power Requirements	configurable from a single multibeam sonar 30W to complete sensor suite 100W
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	Multibeam are available with standard shipping (3-6 weeks). LIF is extended delivery time (approx. 12-24 weeks)
Needs for Deployment (e.g., boats, cranes)	ROV, AUV, SV, USV, pole mount, tripod, etc.
Time for Mobilization/ Demobilization	single sonar - 20min complete suite - depends on platform.
Turnaround time for results	Suspended plumes and gas as well as FLS - immediate heavy oil on the sea bottom or under ice with FLS - immediate with bathymetry mapping - 30min - depends on area size
Permits Required for deployment	none
# of people required to deployment	1
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Ethernet
Lab Requirements	no
Describe raw data format	sonar data - s7k Teledyne public format LIF data - NMEA data
Describe data process workflow and requirements	All sensor data along with navigation is saved on the survey PC. The PC is equipped with user interface providing user graphical images. The FLS sonar as well as LIF sensor are used as immediate supervised operation. The automatic leakage detection based on the sonar data is operating in real time and providing real-time leak detection alarms. The bathymetry data is displayed in real time and processed in real time into DTM and maps. The postprocessing is available for cleaning and map re-generation.

Technology	Norbit Multibeam Sonar and LIF fluorescent laser sensor (SpiDeR –Spill Detection and Recognition system)
Working Group Contact	**Pawel Pocwiardowski**
Time required for Data Processing to data delivery (emergency vs nonemergency)	The bathymetry and backscatter maps are generated in the real time during the survey. Non-emergency use (postprocessed data) requires typically an hour of postprocessing.
SOP available data processing	Standard Operating Procedures and manuals are available for multibeam operation (both FLS and bathy).
Data size and Volume	Depends on the sensor used and depth, a 1h of survey take approximately 10-100 GB of data.
Format of Final Data File and Access Point	Bathymetric charts, images, depending on use case
Format of Data delivery	Point cloud, images, charts
Uncertainty bounds expression	satisfies and exceeds IHO SP uncertainty standard. Combined bathymetry and navigation uncertainty models available for users.
Communication and transmission requirements	Ethernet
TRL #	Sonar - 9, fully commercialized LIF - 8
How/where has technology been used to date	Multibeam have been used for suspended oil and gas leakages all over the world. The 4D capabilities have been proven during remote-sensing survey of Mississippi Canyon area in the Gulf of Mexico founded by BSEE in 2017 under solicitation number E17PS00077 as well as in OGP founded Joint Industry Program (JIP) at CRREL in 2014 and several other projects.
Next steps to get to a higher TRL and to field application	Multibeam are readily available product. LIF sensor, if needed, requires final engineering steps and integration with more platforms (AUV, ROV, stationary)
Reports, articles available	https://www.bsee.gov/sites/bsee.gov/files/mississippi_canyon_20_final_survey_report.pdf
Strengths and weaknesses	Strengths: large area rapid monitoring and remote sensing. Instantaneous identification of spilled oil and leakages. Classification with laser fluorescent sensor to confirm gas/oil. All data is georeferenced and time stamped. Possibilities to tune and itemized the sensor suit and adjust to needs. Automatic leakage detection Interfacing to all kind of platforms and needs. Weaknesses: The sonar systems are acoustic device and as such as susceptible to other acoustic interferences.
Validation tests conducted to date: lab, field, test tank	field tests and real oil leaks.
Oil type and condition tested	Crude oil and suspended oils
Results of testing	Detection and classification confirmed oil and gas leakage in the tested area. Other testing shows detected oil spills in various situations.

Technology	**Norbit Multibeam Sonar and LIF fluorescent laser sensor (SpiDeR –Spill Detection and Recognition system)**
Working Group Contact	**Pawel Pocwiardowski**
Testing QA/QC	Possible to be tested using simulated gas leaks (air). Every sonar contains error logs and messages if something goes wrong.
Vendor/Owner/ Representative and Contact Info	NORBIT pawel@norbit.com
Technology	**Norbit Integrated Radar and Camera Sensor Application. Product name: NORBIT SeaCOP and NORBIT SECurus**
Working Group Contact	**Tony Haugen**
New or Existing	Commercialized product. Continuous development to further expand portfolio and functionality.
Overview of Technology (how it works). Include sensor type/description.	The solution is based upon input from two different sensors that are the main contributors. These are X-band radar and IR camera. The two sensors are effective on different ranges, and are complimentary in several ways. The radar processor monitor the presence of capillary waves, caused by the wind passing over the water surface. It does this by detecting the radar backscatter caused by the uneven water surface. Oil floating on the water surface suppresses the capillary waves, this in turn provides no backscatter to the radar. When an OSD Radar processor detects an area with no capillary waves it alarms this as a possible oil spill. OSD Radar will then measure the area of the suspected slick, and will go on to calculate the speed and direction of drift of the slick. To be operational, the radar needs wind between 2 and 12 m/s. Also note that x-band radar systems cannot measure relative or accurate thickness of an oil slick. To measure relative thickness, the most cost efficient is using infrared camera systems, cooled or uncooled. We also use the IR camera to classify the detected object from the radar and remove false positives, and accurately outline the slick and the varying thickness of the slick. This way we can guide the recovery operation to focus on the area where the highest density of oil is located.
How is it operated?	The SeaCOP provides the full user interface for the SECurus Camera Station.
Manufacturer/Developer	NORBIT Aptomar, tony.haugen@norbit.com
What kind of ice conditions is it designed to operate in? (Ice / Open Water)	N/A
Min & Max Scene Footprint size/swath width, if applicable	Radar typically operates 360 deg with a beamwidth that can vary from radar to radar. The radar has variable blind zone close to antenna. Standard IR Camera used in SECurus. DRI: Man: 13.1km / 4.6km / 2.3km Vehicule: 19.1km / 9.0km / 5.5km. Focal(mm) FOV(deg): Wide 18mmto narrow 430mm, Wide FOV: 29.8°(H) x 24.1°(V), Narrow FOV: 1.28°(H) x1.02°(V)
Temporal Resolution	N/A
Taskable/Adaptive Sampling (yes/no)	yes
Time required for taking measurements	Camera frame rate adjustable from 1Hz - 50 Hz
Accuracy	N/A
Precision	N/A
Sensitivity	IR Camera: Sensitivity 25mK. Ability to detect oil slick down to 5 micrometer and up.

Technology	**Norbit Integrated Radar and Camera Sensor Application. Product name: NORBIT SeaCOP and NORBIT SECurus**
Working Group Contact	**Tony Haugen**
Operational Procedure Available	Product manuals and brochures.
Application: Emergency response, damage assessment, restoration, marine debris, disaster preparedness, testing verification tool	Wide area oil spill detection from ships or shore. Oil spill recovery response, identification of area with the highest density of oil for a more effective operation. Identify and document the polluter. Management of OSD recovery operation incl. distribution of the common operational picture.
Environmental setting. Marsh, shoreline, open-water (e.g., surface water mixing layer), bottom, ice, test environment	Open sea, waters close to shore, confined waters and ports
Range of sea state and other environmental conditions (e.g., day/night, clouds)	Any visibility, light conditions and sea state (Note 1: radar has sea state limitations when used without the IR camera Note 2 : Fog, rain and snow will affect range.).
Oil type and condition	Oil on sea surface.
Space requirements (size, weight)	SECurus, Size [w x h x d] 1052 x 1070 x 686 [mm] Weight:175 [kg]. Size of X-band radar is variable. Min. 8 ft radar antenna is advised for optimal result. Shorter antennas are supported.
Power Requirements	SECurus: Power source 110-230 VAC, 50-60Hz, Power consumption, Max 2.0 kW
Availability for deployment (e.g. shipping needs, # of units available, fly over for satellites)	SECurus has standard delivery: 8 weeks. SeaCOP and radar less.
Needs for Deployment (e.g., boats, cranes)	Platform that can carry radar and Securus. This is typically a ship on 50ft or more.
Time for Mobilization/ Demobilization	Can be deployed immediately after power up. Negligible time.
Turnaround time for results	Near real-time.
Permits Required for deployment	NIL
# of people required to deployment	1
Communication and transmission requirements (e.g., SD cards, cellular communications satellite uplink, dedicated landline)	Ethernet
Lab Requirements	NIL
Describe raw data format	video, images, radar raw data, NMEA for navigation sensors

Technology	**Norbit Integrated Radar and Camera Sensor Application. Product name: NORBIT SeaCOP and NORBIT SECurus**
Working Group Contact	**Tony Haugen**
Describe data process workflow and requirements	All sensor data is presented in real time upon a electronic chart (ENC) layer or in separate windows. All data is stored, and can be replayed or further processed. A dedicated module (SeaCOP WorkFlow) is handling operational procedures to ensure "human in the loop" and quality of the process.
Time required for Data Processing to data delivery (emergency vs nonemergency)	Near real time
SOP available data processing	yes
Data size and Volume	Depending of sensors integrated, data compression and length of recording.
Format of Final Data File and Access Point	Video, images, text files based upon user preferences.
Format of Data delivery	Video, images, text files/reports.
Uncertainty bounds expression	N/A
Communication and transmission requirements	Ethernet
TRL #	SECurus/SeaCOP: TRL 9
How/where has technology been used to date	Vessels dedicated for OSD and recovery. Shore organizations for OSD operation management, aircrafts.
Next steps to get to a higher TRL and to field application	N/A. New functionality for enhanced operation in ice can be added.
Reports, articles available	TBD
Validation tests conducted to date: lab, field, test tank	TBD
Oil type and condition tested	TBD
Results of testing	TBD
Testing QA/QC	TBD
Vendor/Owner/ Representative and Contact Info	NORBIT Aptomar, tony.haugen@norbit.com
Technology	Camera with strobe
Working Group Contact	
	No information provided.
Technology	Mass spectrometer
Working Group Contact	
New or Existing	Would give signature of the oil in a plume. Used at WHOI.

Seafloor Mounted

Table 23: Seafloor Mounted Tab from New and Existing Technologies Spreadsheet.

Technology	Rotating acoustic system
Working Group Contact	Dave Palmer via Phil McGillivary
Overview of Technology (how it works). Include sensor type/description.	Measures droplet density.
Technology	Collecting solids (e.g., marine snow, in-situ burn residuals)
Working Group Contact	Vern Asper and Arne Diercks (University of Southern Mississippi)
Overview of Technology (how it works). Include sensor type/description.	vernon.asper@usm.edu, arne.diercks@usm.edu
Vendor/Owner/ Representative and Contact Info	Rebecca Brooks
Technology	Lander technology with various sensors
Working Group Contact	Kevin Hardy (Global Ocean Design) via Phil McGillivary
Overview of Technology (how it works). Include sensor type/description.	Cameras for watching oiled particles settle. Primarily used for marine snow. Also samples upper sediment layers.
Vendor/Owner/ Representative and Contact Info	Kevin Hardy