A Pan-Arctic Airborne Sea Ice Observation System

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Theme 2: Technology and Innovation for sustained Arctic observations

Abstract

We present an Arctic sea-ice observation system that focuses on unique direct observations of sea ice plus snow thickness. A network of research institutions, the Alfred Wegener Institute, York University and the Norwegian Polar Institute, maintain an observation system that is embedded in several national and international projects and supported by research partners. Activities in the field include the use of long-range polar research aircraft and helicopter operations from research icebreakers and bases on land. Data collections are based on electromagnetic induction sounding and consistent time series are available in key regions of the Arctic Ocean since 2001. The increased use of polar research aircrafts in recent years has resulted in several initiatives that aim for long-term observations of ice thickness during seasonal minimum and maximum sea-ice extent in the Arctic. The scientific payload of the research aircraft of type Basler BT-67 and its capability to fly low-altitude surveys makes it an ideal tool for the validation and on-going verification of various satellite remote sensing products. The availability of airborne sea-ice thickness information spans the periods of different satellite sea-ice thickness retrieval concepts, such as the radar altimeters from Envisat and CryoSat-2 as well as the laser altimeter from ICESat-1 and -2. Wherever possible, the airborne surveys are accompanied by in-situ observations on the ice surface to compile a hierarchy of validation data from local to basin scales. Results of the observation network have found broad use for studying inter-annual variability and changes of sea ice thickness as well as the validation of satellite data products. We identify a gap of observations over the multi-year sea ice zone during the melt season and early freeze-up. We also stress the need for the continuation of a coordinated observational program that has produced a time series of sea ice thickness only paralleled by submarine observations. We plan to augment the observation system by simultaneous measurements of snow depth and to investigate opportunities for technological advances, such as the utilization of unmanned aerial systems.

Objective

Sea ice plays an important role in the polar and global climate system by controlling the surface energy balance and the interaction between atmosphere and oceans in high latitude. Therefore, the polar sea ice cover is a key indicator for the variability and changes of the polar climate system. The Global Climate Observation System (GCOS) selected sea ice as an Essential Climate Variable (ECV) and its observation is the objective of several national and international observation networks and initiatives. Key observation parameters are the extent, concentration and thickness of sea ice as well as the depth of the overlying snow layer and melt pond concentration in summer. The large and remote areas of ice-covered oceans with harsh environmental condition require the use of satellite remote sensing as an observational tool. The longest and continuous time series of Arctic sea ice are based on passive microwave datasets that can be utilized to derive sea ice extent and concentration at decadal scales. Recently, remote sensing products of sea ice thickness have emerged, a key physical parameter of the sea ice cover. The main challenges for sea ice thickness observations from space are the inter-annual variability and the significant seasonal cycle of ice surface conditions. One example is the lack of snow-depth data that may create significant errors of ice thickness retrievals from satellite freeboard measurements. The assessment of uncertainties in the sea ice mass budget through independent validation data sets therefore requires the presence of an observation system throughout the year.

The scale necessary to capture gradients of sea ice thickness and to provide meaningful sections of data for comparisons require either the use of long-range observation platforms, such as submarines or aircraft, or autonomous stations that can record sea ice parameters at a location for months and years. In addition, the need for consistency among data sets is an important factor for time series of high-resolution validation data sets that may bridge between several remote sensing mission concepts. One method that provides such datasets throughout different stages of developments of sea ice is airborne electromagnetic induction sounding (AEM). The underlying geophysical principle of electromagnetic induction sounding exploits the contrast of electrical conductivity between the sea ice and ocean layers. The method provides a profile of ice thickness that is smoothed by the size of the sensor footprint. Thus, maximum thicknesses at the deepest point of a pressure ridge are usually underestimated but comparisons to other methods demonstrate that the footprint smoothing is mass conserving. Hand-held or sled-mounted sensors for high-resolution measurements are in use as well, but airborne systems deliver long-range and high-resolution direct measurements of snow plus ice thickness (henceforth ice thickness) profiles that are only paralleled by submarine draft measurements.

Implementation

Several partners carry out AEM ice thickness measurements in the Arctic with simultaneous field work (Figure 1) throughout the year with the exception of the dark winter months with no-fly conditions. The Alfred Wegener Institute spearheaded the broad use of helicopter-towed AEM sensors for climate research with a pilot project in 2001 (Haas et al., 2009). The principal design is based on pioneering work dating back to several years earlier (Kovacs et al. 1987, Kovacs and Holladay, 1990). The so-called EM-Birds are rated as a standard external sling-load and can be used by several helicopter types with minimal preparation time. In practice, AEM systems can be deployed from research icebreakers, ice camps and airports nearby sea ice. This flexibility initiated several time series of AEM ice thickness in the Lincoln (Haas et al., 2010), Beaufort and Laptev Seas, Fram Strait (Renner et al., 2014; Krumpen et al. 2015) Storfjorden (Hendricks et al., 2010) and the central Arctic. Technical advances and the use of research aircraft of the type Basler BT-67 opened the possibility for longer profiles with additional sensor equipment. The underlying principles require operations close to the ice surface in absence of conductive objects or electromagnetic sources in the very low signal frequency range. Though integration into the frame of an aircraft or helicopter have been implemented, towed systems have emerged as the commonly mode of operation for such measurements. Aircraft surveys therefore require operations at low altitudes to bring the sensor close to the ice-water interface where the bulk of the measured signal is generated. The additional scientific payload of these polar research aircraft leads to an efficient multi-purpose, multi-variable sea-ice observation platform that accommodates the need for different survey altitudes in the outgoing and return leg of the surveys, which have sufficient length due to the aircraft's operational range (Herber et al., 2012).

Today, an observational network building on various airborne assets operated by the Alfred Wegener Institute (AWI), York University (YU) and the Norwegian Polar Institute (NPI) acquires AEM ice thickness data. The observational strategy aims to assess sea ice conditions during the annual maximum ice extent in March/April, the melt season and the annual minimum in September. The field campaigns of all partners are closely tied to on-going satellite validation activities, such as the CryoSat-2 validation experiment (CryoVEx) or SMOS (SMOSice) as well as other observational programs, e.g. the Seasonal Ice Zone Observing Network (SIZONet), and the Transpolar System of the Arctic Ocean (Transdrift). In addition, we pursue other opportunities for cross-referencing and calibration such as with the U.S. Naval Research Laboratory's LiDaR surveys, NASA's IceBridge flights and the The Fram Strait Arctic Outflow Observatory. Field activities are funded either by national projects, international partnerships of participating research institutions or partners such as the European Space Agency (ESA). One example are repeated spring surveys since 2009 by aircraft of the AWI called Polar Airborne Measurements and Arctic Regional Climate Model Simulation Project (PAMARCMIP) that are supported financially and logistically by international partners like (Environment Canada, YU, University of Alaska Fairbanks through the U.S. National Science Foundation and industry and that tie into complementary observations such as those of SIZONet.

Activities

AWI operates two polar research aircraft (Polar-5 and Polar-6, see Figure 2) that are used for pan-Arctic measurements in spring ranging from the seasonal ice zone in the Beaufort/Chukchi Sea regions to the Greenland Sea and Fram Strait. In these campaigns, the aircraft are outfitted to serve multiple roles. The observation of ice thickness and morphology with an EM-Bird and scanning laser altimeter is carried out at low flight levels, while experiments on atmospheric chemistry and atmosphere-sea ice interaction on the same flights are carried out at higher altitudes. The conditions of the sea ice surface are documented with aerial photography (different automatized systems, single or stereo photography). In the melt season, the AWI observational program consists of aircraft surveys from Greenland (TIFAX: Thick Ice Feeding Arctic Export) and helicopter AEM measurements from the icebreakers R/V *Polarstern* (Germany). Here, measurements are complemented by aerial photography to document the coverage and evolution of melt ponds on the ice surface. YU operates a Basler BT-67 aircraft with an AEM system with a special regional focus in ice-covered regions of the Northwest Passage (Haas and Howell, 2015) and adjacent regions of the Canadian Archipelago in the Arctic Ocean. NPI implements AEM sea-ice thickness observations with a helicopter-based system, that operates from Norwegian research vessels (R/V *Lance*) or coast guard ships (KV *Svalbard*) with a regional focus in the Greenland Sea (Fram Strait), and Barents Seas, and the Arctic Basin north of Svalbard. Measurements are complemented with a stereo camera system. Norwegian Polar Institute's surveys are currently done every second or third year in the mentioned regions. Ship-borne activities by AWI and NPI generally include in-situ collection of sea ice parameters and the deployment of drifting buoys that measure time-series of snow and sea ice parameters beyond the period of airborne surveys.

The activities are closely coordinated between the partners to sustain time series of sea-ice thickness in key regions and maximize temporal and spatial coverage. The results spawned several studies on changes of sea-ice thickness (e.g. Haas et al., 2010, Renner et al 2014, Lindsay and Schweiger 2015), the validation of satellite sea-ice thickness retrievals from altimetry and passive microwave missions (Laxon et al. 2013, Ricker et al. 2014, Maaß et al. 2015, Kwok and Cunningham 2015, Tilling et al. 2015), the inter-calibration of different ice thickness retrieval methods (e.g. Mahoney et al. 2015), and exploration of inverse modeling approaches to determine optimal routing of measurement flights (Kaminski et al. 2015).

Outlook, Recommendations and Action Items

With the exception of one regular activity from Greenland between July and August, most of the long-range sea-ice thickness surveys by polar aircraft are carried out during spring. In summer instead, ship-borne activities become feasible that include the possibility to complete the observational hierarchy of local in-situ data collection, airborne measurement at mesoscale and satellite remote sensing data at basin scale. However, we identify a major gap in airborne surveys over the multi-year ice zone near the Canadian Archipelago during the melt season and early freeze-up; this region is mostly inaccessible to research icebreakers but represents an important part of the Arctic ice pack, including its role as a source of thick ice for the Beaufort and Chukchi Sea. This region requires additional attention and coverage. This recommendation is amplified by the need for validation of newly available monthly sea-ice thickness fields derived from the CryoSat-2 mission. Measurements during late summer or potentially early freeze-up have the potential to provide validation data for the CryoSat-2, Sentinel-3 and future ICESat-2 thickness fields early in the freezing season, at a time and location for which we are currently lacking validation data. Also, the lack of knowledge of the interannual variability of physical parameters that feed into satellite retrieval algorithms, such as snow depth or density, create the need for continued validation and verification by independent sea ice thickness information. Due to this reason, satellite products will not be able to supplant AEM measurements to a significant degree in the near future.

We therefore stress the need for the continuation and coordination of AEM sea ice thickness data acquisitions in the Arctic. AEM data provides consistent and direct observations of the ice thickness distribution that furnishes valuable information for the interpretation and validation of freeboard estimates from altimeters. As such it is the only data source other than increasingly scarce submarine data that provides profile measurements of the bulk of the total ice thickness, rather than a measurement of surface elevation or freeboard. Moreover, airborne platforms allow for the integration of a range of different measurements and instrumentation into a single airframe, fostering inter-disciplinary studies that are co-located in space and time. Through coordination among observing partners, including the use of buoys and satellite data to track ice, surveys can also be designed to allow repeat, semi-Lagrangian observations that will provide essential insight into the linkage between Arctic ice volume and dynamics. To better coordinate and support such flights, an international consortium that brings together operators, science users, private sector entities and others may help in the creation of a more robust, long-term program. Currently, not all parts of the surveys are rooted in long term funded programmes, which means that partners are depending on funding in new projects.

There is further opportunity to expand the observational network by coordinating with partners from China and Japan who also have the capability for airborne ice thickness measurements. Contributions by new partners are highly welcome since the current observation programme has a limited range of operations (see Figure 3 as an example for aircraft sea ice observations in spring). A particular lack of information exist in the Russian Arctic, mainly the Laptev and Kara Seas. The understanding of the processes that govern the inter-annual and long-term variability of sea ice thickness and extent needs measurements in these ice production regions. There is also a need to augment the capability of the observations system by simultaneous measurements of snow depth. Knowledge of snow depth is not only important for mass balance estimates from satellite remote sensing, but also as an input parameter for seasonal sea ice forecasts (Castro-Morales et al., 2014) in frameworks such as the Sea Ice Prediction Network.

While additional parameters such as snow depth will amplify the impact of the observing system for climate research, the core activity of AEM ice thickness surveys are becoming increasingly important for high-resolution, near-real-time regional studies in support of environmental assessments, ice navigation, and offshore engineering operations. Therefore, a key opportunity from the technology side is the development of AEM systems that lend themselves to deployment onboard unmanned aerial systems (UAS). As outlined above, such deployment faces key challenges with respect to miniaturization, reduction of noise and maintenance of data quality, but the potential rewards of such a system are high.

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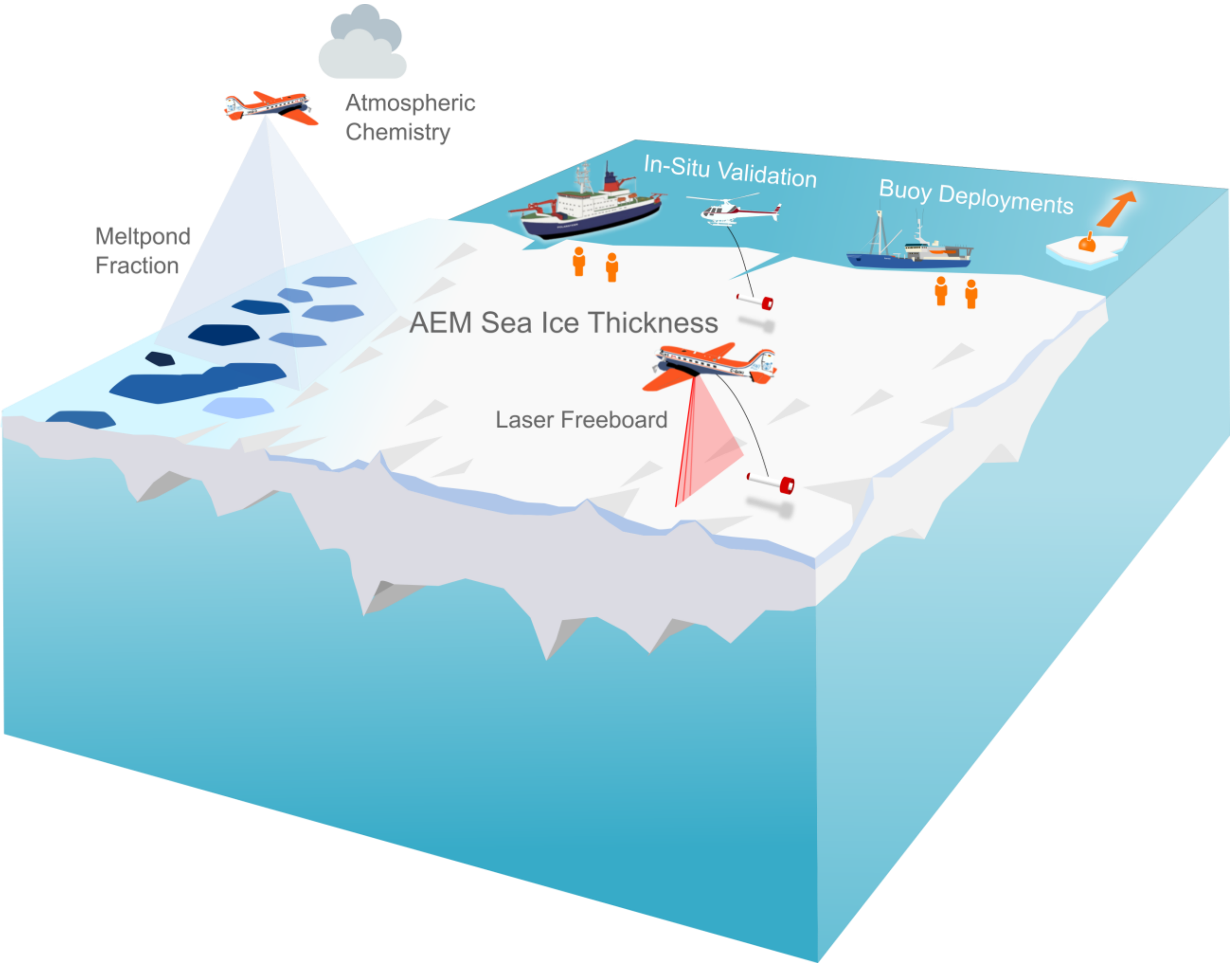

Figure 1: Schematic of a comprehensive Sea Ice Observation System with a focus on direct observations of sea-ice thickness with airborne electromagnetic induction sounding (AEM). Research aircraft and helicopters are frequently used to tow AEM sensors from early spring to late autumn in the Arctic. The scientific payload of research aircraft allows multi-role science missions that include observation of atmospheric and other parameters for the validation of satellite remote-sensing products. Coincident and high-resolution in-situ observations are available by activities that are based on research icebreakers including the deployment of drifting buoys to fill data gaps between airborne observations.

Figure 2: Polar-5, a polar research aircraft of the Alfred Wegener Institute outfitted with an AEM sensor for direct sea-ice thickness observations. York University operates are similar aircraft of the same model and scientific payload.

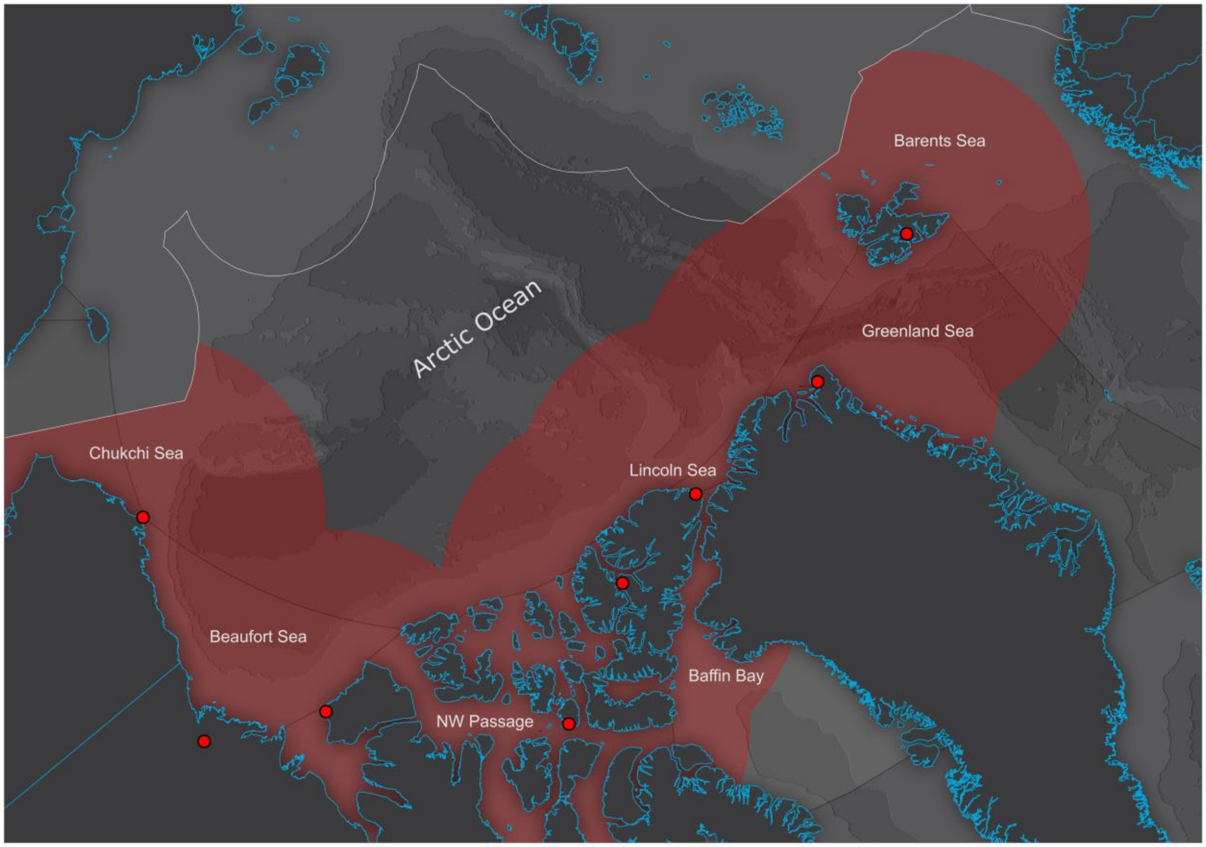

Figure 3: Current operational coverage of the sea ice observation system by polar research aircraft for sea-ice thickness surveys from logistic hubs (red dots) in the western Arctic.