Field Techniques in Sea-Ice Research

Hajo Eicken [*] **Bodil A. Bluhm** [†] **R. Eric Collins** [†] **Rolf R. Gradinger** [†] **Christian Haas** [‡] **Malcolm Ingham** [§] **Andy Mahoney** [*] **Marcel Nicolaus** [¶] **and Don Perovich** [‖]

[*]Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska,[†]School of Fisheries and Ocean Sciences, Institute of Marine Science, University of Alaska Fairbanks, Fairbanks, Alaska,[‡]York University, Toronto, Canada,[§]School of Chemical and Physical Sciences, Victoria University of Wellington, Wellington, New Zealand,[¶]Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven, Germany, and [‖]Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire

This contribution provides a brief overview of current approaches and anticipated advances in obtaining a range of field measurements for sea ice in (sub)polar regions. The multiple uses of the ice cover and its important role in social-environmental systems at high northern and southern latitudes require a broad range of approaches and measurements to be considered. Building on a recently published monograph with detailed information about the state of the art, the present contributions provides concise summaries and updates for the following topical areas: Field research study and sampling design, snow on sea ice, ice thickness and morphology, ice coring and measurement of key physical properties, ice optics and surface energy budget, transport properties, sea ice biota and biogeochemical properties, autonomous sensors, UASs and UAVs, and ship-based observations. For each of these topics, relevant background information is provided before discussing key methodological approaches and techniques in more detail. Most of the topical sections then include an example to illustrate how the approaches are applied in specific cases. Each section then concludes with a outlook on future developments and research needs. Common to all types of field measurements is the conclusion that due to a substantial increase in human activities in ice-covered maritime regions and the impacts of rapid environmental change a great need for accurate, consistent and intercomparable sea-ice datasets has arisen. Methodological advances and scientific progress over the past few decades now puts the research and operations community in a position to develop best practices with respect to field measurements that can lead to standardized, interoperable approaches, greatly minimizing risks associated with lack of suitable, consistent datasets.

keywords: albedo | autonomous sensors | brine volume | electromagnetic sounding | energy budget | ice cores | ice thickness | landfast/shorefast ice | permeability | remote sensing | sampling design | sea ice biota | ship-based observations | snow cover | solar radiation | thermal/electrical conductivity | traditional environmental knowledge | transmittance | unmanned systems

1. Introduction

Polar and subpolar sea ice plays an important role in regulating Earth's climate, in particular as a key factor in the global surface radiation budget and its impact on global thermohaline circulation. Moreover, sea ice is an important habitat for a range of organisms, from microscopic algae to ice-associated mammals such as seals, walrus and polar bear. Finally, the past decade has brought increasing recognition of the importance of sea ice as a social-environmental system, i.e., interconnected geophysical features and processes that support or threaten a wide variety of human activities and provide services to people and ecosystems. In the Arctic, a major transformation of the ice pack has been underway for the past three decades. Not only has the total sea-ice volume been reduced by more than a factor of three, but at the same time perennial ice which occupied much of the Arctic Ocean well into the 1990s, has been reduced by more than half. With large parts of the Arctic shelf seas ice-free for much of the summer as a result of these changes, maritime shipping and offshore resource development have been on the rise.

These developments have spurred an increasing interest in and need for sea-ice research both in the Arctic and Antarctic. Field-based observations and measurement campaigns, in particular, serve to improve our understanding of important sea-ice processes, help keep track of the changing polar ice covers and complement remote sensing and modeling studies. This contribution provides a brief survey and overview of the sea-ice field measurement techniques relevant in this broader context. Given the broad scope of research relevant to the study of sea ice as a social-environmental system, a summary such as this can only scratch the surface. The team of contributors for this chapter has been guided by a few key considerations in selecting material for this chapter. First, the intent was to provide an overview of the breadth of techniques and approaches relevant to different disciplines so as to provide a framework and key references for further reading to obtain more in-depth information on the details of some of the techniques. Second, we have focused on fundamental sampling or measurement approaches that are relevant for a broad range of studies, such as measurements of ice thickness or the extraction of ice-core samples. Third, we build on a comprehensive compilation and overview of sea-ice field techniques published in 2009 (Field Techniques for Sea-Ice Research, University of Alaska Press) and see the present contribution as an update of that latter publication.

A further important consideration in compiling the material for this chapter is the recognition of an increasing need for development of best practices and standardized, interoperable approaches for sea-ice field techniques that allow for an interpretation of a given data set in different contexts or for the integration of different types of measurements into a common framework. For example, ship-based observations of ice conditions in both polar regions may be of value in validating or possibly constraining sea-ice predictions and model simulations. They can serve a similar purpose in the development and validation of sea-ice remote sensing algorithms. However, such multiple uses of data require standardized, interoperable approaches in the collection of such data, as well as clear guidance from the different data user communities as to the relative merits of different types of observations. The present contribution highlights a few key areas where progress along these lines is both needed and tractable. As an illustration of such multiple use applications, consider Figure 1.1 which provides information on the distribution and shape of community ice trails across the shorefast ice, as well as the thickness profile of the underlying ice. This information is placed in the context of a synthetic aperture radar (SAR) satellite scene to

Cite this manuscript as: Eicken, H., B.A. Bluhm, R.E. Collins, R.R. Gradinger, C. Haas, M. Ingham, A. Mahoney, M. Nicolaus, D. Perovich (2014) "Field Techniques in Sea-Ice Research" in Cold Regions Science and Marine Technology, [Ed. H. Shen], in Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO, Eolss Publishers, Paris, France, [http://www.eolss.net]

provide information about the larger-scale ice conditions at high resolution. While the primary purpose of the map is to provide information to the local community, including local search and rescue services, the underlying data are also collected to better understand long-term variations in shorefast ice mass budget and roughness.

Each of the main sections of this chapter follows a similar layout that provides a brief summary of relevant background, reviews the key approaches and techniques, discusses an example application to illustrate specific applications and then examines potential future developments and research needs.

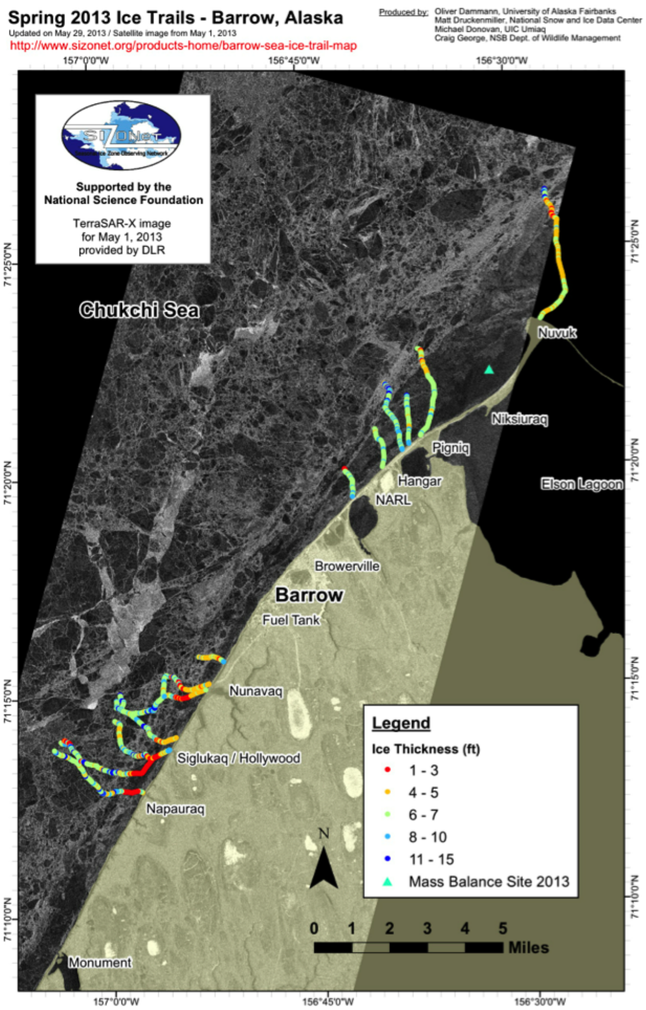

Figure 1.1: TerraSAR-X satellite scene (courtesy of DLR, Germany) for Barrow region on 1 May 2013. Also shown are thickness profiles, obtained with an EM-31 (see Section 4) along ice trails put in place by Iñupiat hunters from Barrow (data and map compiled by D.O. Dammann, University of Alaska Fairbanks). This map was compiled to serve information needs by the community of Barrow, including hunters, Barrow Search and Rescue and others. To ensure utility of the map, distances and thicknesses are provided in imperial units.

2. Field Research Study and Sampling Design

Common to all approaches described in subsequent sections in this chapter is the need to carefully consider the sampling or study design prior to commencing work in the field. While this is a broad topic that cannot be covered in detail, we illustrate a few key concepts below for a case study related to sampling shorefast sea ice. In brief, study design can help address important challenges and questions that are relevant for a broad range of sea-ice field work. These include, (1) the need to ensure that the sampled ice is representative of the process or property of interest in the study, which may target a specific ice type, aspects of the ice growth, melt and deformation history or focus on environmental factors constraining ice formation and evolution, such as the local hydrography, microclimate etc.; (2) the question of the extent to which a field site or particular period of study is representative of large-scale or long-term conditions; (3) the magnitude of spatial and temporal variability in ice properties and its impact on sampling or measurement errors.

Remote sensing, from space-based, airborne or ground-based sensors plays an important role in the compilation of data that can guide study design. Thus, remote sensing is the method of choice to scale up or down from a specific set of measurements, providing, for example, a regional context for local, point-based measurements. The aggregate nature of a sea-ice cover, typically comprising ice of different age, roughness and snow cover, requires such an approach to quantify key variables, such as the heat flux through the ice, and to evaluate the relative contribution of different ice types and processes to a regionally averaged assessment of, e.g., heat exchange. Remote sensing can also provide important information on the ice evolution from initial freeze-up to the final stages of decay. Some of this information is not easily obtained from surface-based measurements and can complement the latter. Finally, remote sensing is of key importance in the design of spatially explict sampling strategies, as well as from the perspective of field safety and logistics.

Another important source of information relevant to study design is the application of model simulations. For example, ice-growth modeling can provide important insight into the origins of spatial and temporal variations in ice properties while at the same time help constrain the age of ice horizons at different depths within an ice core. Finally, study design and site selection can benefit substantially from guidance by local and/or indigenous knowledge-holders. Often referred to as Traditional Ecological Knowledge or Traditional Environmental Knowledge (TEK) or Local and Indigenous Knowledge (LIK), such bodies of knowledge may provide a wealth of information on spatial and temporal variability of relevant ice properties or processes, interannual variability and trends, or on the potential occurrence of anomalies. Moreover, from a field safety perspective, inclusion of local or indigenous experts in the study design process and field work itself is of substantial benefit.

Let us consider a specific case study to illustrate some of these approaches and provide more detail on relevant methods. An interdisciplinary sea-ice sampling program is targeting shorefast ice near Barrow, Alaska to obtain information about key ice physical properties as well as the amount of microalgal biomass and plant nutrients present within the ice cover. Indigenous knowledge for the region and satellite remote sensing data, in particular SAR (with a high resolution of better than 10 m as well as the prerequisite temporal and regional coverage independent of cloud cover) shown in Figure 1.1, obtained for that particular year indicated that ice in relatively close proximity to the field laboratory (NARL) was broadly representative of shorefast ice in the wider region.

Such high-resolution imagery can be placed in a broader temporal and spatial context by passive microwave satellite data, in particular the Special Scanner Microwave/Imager (SSM/I), collected at a much coarser resolution of around 25 km, but on a daily basis over periods of decades. Visible and thermal-infrared range satellite images such as from the Moderate Resolution Imaging Spectrometer (MODIS) can provide information at intermediate scales but are weather and/or illumination dependent.

A sampling plan to obtain ice cores through the entire thickness of the ice (see Section 5) now has to identify specific locations. For most studies, the most appropriate sampling approach may be termed a segmented stratified random sampling scheme, which is illustrated in Figure. 2.1. Thus, by evaluating the distribution of different surface roughness, ice deformation and snow distribution patterns in the visible-range satellite scene and aerial photograph shown in Figure 2.1, different ice types and growth histories can be identified. A shore-based coastal marine radar and SAR imagery collected prior to the sampling campaign provided further information on the key ice type categories. Such an informal classification helped segment the ice cover into the key ice types to be sampled. Within these subregions, stratified random samples were now to be taken. Here, stratification refers to a subdivision of the entire area of interest into subplots. Within each of these, a random location is identified for sampling, as illustrated at bottom right in Figure 2.1. Here, quadratic subunits, parallel to the coastline and prevailing currents and ice deformation features, are chosen for convenience, but a segmented scene may well consist of irregular units that are further subdivided. The four coring locations shown in the figure would then yield intercomparable samples for the same ice type. The spatial variability in key ice properties that can be expected for such a set of samples is further discussed in Section 5.

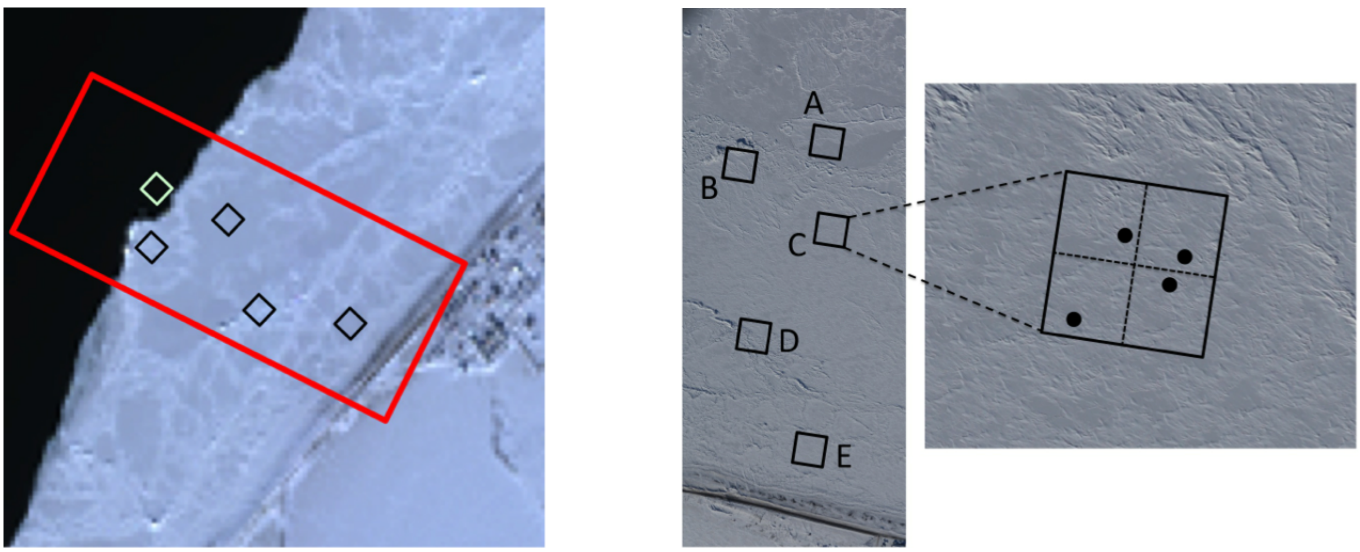

Figure 2.1: Low-resolution false-color visible-range satellite image obtained from a Digital Globe satellite scene for 16 March 2013, covering part of the Naval Arctic Research Laboratory (NARL) complex at Barrow, AK along with a stretch of shorefast ice and adjacent open ocean (top; North is up). The red rectangle delineates the extent of the aerial photograph shown in the lower left. This area of interest roughly corresponds to the trail shown in Figure 1.1 to the left of the NARL site northeast of the town of Barrow. The black quadrangles are approximately 80 m to a side and delineate the sampling regions shown in the photos below. Aerial photograph (bottom left; courtesy of S. Hendricks, Alfred Wegener Institute) for 3 April 2013 of subset of scene shown at top, showing ice of different growth and deformation history (A: new ice formed between 16 March and 3 April; B: rough, rubbled ice close to former shorefast ice edge in top figure; C: level, undeformed shorefast ice of intermediate age; D: rough ice with roughly shore-parallel pressure ridges; E: level, undeformed shorefast ice formed during early stages of freeze-up). Detail of quadrangle C, along with randomly chosen sampling sites in four sub-areas shown at bottom right.

3. Snow on sea ice

3.1. Background. Almost all sea ice in the Arctic and Antarctic is covered with snow. Even new ice rapidly acquires a snow cover due to precipitation or accumulation of blowing snow. Through its contrasting thermal, optical, and dielectric properties, the snow cover dominates the surface properties of ice-covered oceans, and hence it is of outstanding importance for the underlying sea ice. It strongly influences the energy and mass balance and determines most interactions between sea ice and the atmosphere. In the Arctic, snow on sea ice typically persists from September to June, and melts completely during summer, leaving behind a characteristic mixture of melt ponds and bare ice. In contrast, snow on Antarctic sea ice – which is typically much deeper and with lower water content in summer than Arctic snow – mostly survives summer melt, at least as long as the sea ice underneath survives the melt season.

Temperature, grain size, and wetness (liquid water content) of snow on sea ice are initially prescribed by the boundary conditions of air and ice surface temperatures. In addition, wind speed at the time of snowfall and thereafter as well as the sequence of accumulation events control the layering and density structure of the snow cover. Afterwards, changes in atmospheric conditions and additional accumulation dominate the evolution of recent snow layers. With time, snow grains and layering change as a result of metamorphism, mostly driven by temperature, temperature gradients, liquid water content, and mechanical forces due to overburden and density distributions. It has to be noted that most metamorphisms are irreversible, impacting the stratigraphy (layer sequence and properties) of the snow cover. The accumulation history and metamorphism cause strong vertical and horizontal variations in the physical properties of snow. It is of great importance to explicitly consider snow properties and processes when studying sea ice on different scales and with different methods. In that respect, the four most important aspects about snow on sea ice are

1. its thermal properties, impacting sea ice mass balance and temperatures by acting as a strong insulator between ice and atmosphere;
2. its ability to strongly scatter light, reflecting most of solar irradiance back to the atmosphere with only little energy transmitted into the sea ice and the ocean underneath. This aspect also has strong implications for high latitude ecosystems, as well as biological and biogeochemical processes;
3. its role in the freshwater budget, through transport, accumulation, and melt;
4. its dielectric properties and mass distribution, strongly affecting remote sensing (airborne and satellite) applications.

3.2. Key approaches and techniques. A most comprehensive review of the current knowledge about snow on sea ice is provided in key references compiled at the end of this chapter. In addition, a chapter by Sturm in the previously published field techniques monograph gives detailed descriptions of methods to obtain snow properties and related observations. Direct measurement of most snow properties can be difficult and/or time-consuming. In general, snow observations are made by

1. digging snow pits to reveal the stratigraphy and information about layer properties. In addition, snow samples may be taken that way;
2. performing in-situ measurements along transects to cover spatial variability and obtain distribution functions of physical properties;
3. remote sensing operations from air planes or satellites (passive and active microwave methods) to map large-scale properties or imagery.

In addition the timing of measurements is – in contrast with many other sea ice properties – most critical, since many properties underlay strong diurnal variations. Snow depth, density, and stratigraphy are the more easily, and hence most often observed properties. The optical properties of snow and sea ice are discussed in Section 6.

Snow depth is often also the only snow property that is available from field measurements, because it may be obtained either along transects or through remote observations. Snow depth measurements are as easy as using a ruler to measure the distance from the sea-ice surface to the top of the snow cover. More advanced are measurements using a Magna Probe, which automatically records snow depth measurements together with GPS data. Autonomous snow depth measurements, e.g., for high-resolution time series, may be performed through sonic range finders or from thermistor measurements. This technique is frequently applied on buoys, such as ice mass-balance buoys (Section 9).

The stratigraphy of a snow pack describes the sequence of snow layers, within which its physical properties are (assumed to be) constant. Measuring physical properties of individual snow layers is most time consuming and is performed in snow pits. Stratigraphy observations mostly consist of:

- Temperature measurements in vertical profiles with needle probes. Alternatively, snow temperatures may be obtained from thermistor chains, but these measurements may easily by impacted by absorption of solar radiation.
- Density is typically measured by volumetric measurements, when samples of defined volumes are extracted and weighed. Alternatively, capacitive measurements are possible, making use of the density dependence of dielectric properties. Using capacitive measurements, the liquid water (wetness) content of snow may be derived as well.
- Grain size and shape of snow crystals is usually determined with a lens on a mm-grid. Grain shape is classified based on reference tables, which mostly represent its genesis and status of metamorphism, and have been developed as part of an international classification of snow on the ground. In an experimental state are satellite based grain size retrieval algorithms, which exploit the spectral scattering reflection characteristics of the snow layer.
- Snow hardness is classified based on an empirical scale.
- For salinity measurements a sample (often the density sample) is melted and then electrical conductivity is measured and transferred into salinity.

3.3. Example applications. Due to the great importance of the snow cover and its physical properties, snow measurements are performed during most in-situ sea ice studies. In this case, snow observations support data analyses and interpretation of other sea ice properties. Usually, a combination of transects, time series, and snow pit measurements are performed, focusing on snow depth, density, and temperature. The exact types and frequency of measurements depend on the type, spatial and temporal variability of the main data sets.

Specific studies of snow on sea ice are often performed in connection with remote sensing applications in order to obtain ground-truth data for algorithm development and retrievals. Such studies aim for detailed snow characteristics, revealing the accumulation and metamorphosis history of the snow pack. Beyond this, studies that focus on the snow cover on sea ice as a central element are rather sparse. For example, Nicolaus and co-workers (see references for details) applied most of the above-described methods to characterize differences between first- and multi-year snow covers in the Weddell Sea (Antarctic). Beyond studies on regional snow features, large-scale experiments such as the NASA Operation Ice Bridge collect snow depth data over long transects that allow direct connections to satellite data.

3.4. Future developments and research needs. The field of remote sensing of snow on sea ice is still evolving. New and improved procedures and algorithms are constantly developed by different groups, to detect snow depths and physical properties of the snow cover. Airborne measurements of snow depth on a larger scale are performed through dedicated radar systems that are able to range the distance to the air-snow and snow-ice interfaces. While snow depth from airborne radar currently presents the most detailed snow observations on regional scales, knowledge is limited to periods with dry and cold snow as well as level ice, since the interpretation of radar echoes over deformed ice is not well constrained.

Passive microwave data sets are used to derive snow depth and melt pond fractions on sea ice. This method has the great advantage of daily coverage of the entire Arctic and Antarctic, but at the same time, data products still have remarkable uncertainties. It makes use of the surface emissivity in distinct spectral bands, and is also confined to certain physical boundary conditions, mostly temperature and sea-ice type. More regional and high-resolution information of snow covers are derived from radar satellites. The applicability of these different retrieval algorithms depends on the hemisphere, due to different snow properties in the Arctic and Antarctic. Knowledge of snow depth on basin scales, however, is implied for example in retrieval algorithms of sea-ice thickness from both radar altimeters such as Cryosat-2 and laser altimeters such as ICESat-2 or IceBridge. The lack of large-scale snow depth information is therefore currently one of the major challenges for remote sensing of sea ice, though it is the easiest property to measure on the local scale. For all these and further future remote sensing applications, ground truthing is required, using data sets from designated field studies, applying the methods above.

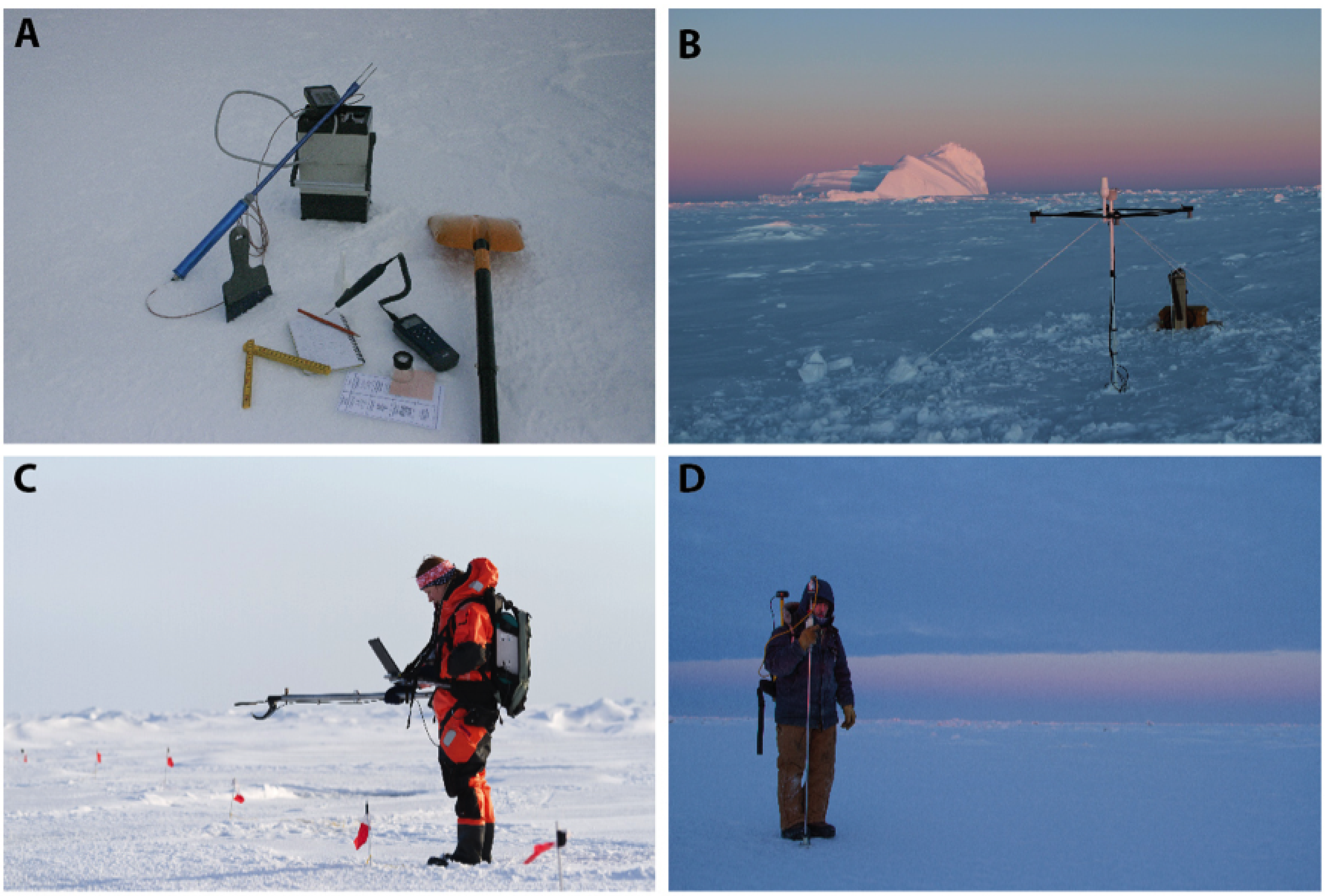

Figure 3.1: (a) tools for snow measurements in a snow pit (thermometer, density sampler, mm-grid), (b) snow depth buoy on Antarctic sea ice, (c) spectral albedo measurements with an ASD Field spec on Arctic sea ice during summer, (d) Magna Probe snow depth transect on land-fast sea ice in Barrow, Alaska.

4. Ice thickness and morphology

4.1. Background. The large-scale sea ice thickness distribution is one of the most important climate variables. It is an integral result of the combined atmospheric and oceanic energy (heat/radiation) and momentum fluxes (wind and current forcing, and resulting internal ice forces) governing the sea ice mass balance through freezing, melting, and deformation. Repeated Arctic and Antarctic-wide thickness observations are required to detect climate change, to understand its underlying causes, and to parameterize, validate, and initialize numerical models used for climate research and prediction. Thickness is also one of the most important smaller-scale sea ice properties affecting almost all sea ice services. The hazardous potential of sea ice for marine structures and ships, its suitability to safely support infrastructure and on-ice activities, its thermal and optical properties and role as a habitat all depend on ice thickness and morphology. However, despite its importance, the ice thickness distribution, i.e., its statistical properties, is still difficult to observe. This is due to the comparatively small vertical extent of the ice cover of only a few meters demanding highly sensitive and accurate methods. The large local and regional variability caused by the co-existence of refrozen leads, pressure ridges, and melt ponds requires extensive measurements to obtain statistically representative information.

4.2. Key approaches and techniques. Sea ice thickness is most commonly measured in-situ by drilling and with thermistor strings; from below the ice by means of upward-looking sonar (ULS), and from above the ice by means of ground-based and airborne electromagnetic (EM) induction sounding, as well as airborne and satellite laser and radar altimetry.

Drilling through the ice with hand-driven or motorized ice augers or hot-water drills is the most direct and most accurate method to obtain local ice thickness information. Because water fills the holes after drilling, other relevant variables related to ice thickness and the ice's isostatic balance can also be measured, i.e. ice thickness, snow thickness, ice freeboard (the height of the ice surface above the water level), and ice draft (the depth of the ice bottom under the water level). All these can be read from a tape measure lowered through the drill hole and pulled up to the ice bottom by means of a collapsible and retrievable, metal T-anchor. Drill-hole measurements are slow and tedious, and thus it is difficult to obtain representative, regional information.

Strings with closely spaced thermistors can be deployed through drill holes. Once solidly re-frozen, ice and snow thickness can be derived from the measured vertical temperature gradients which are absent in the water and air, and steeper in the snow than ice due to the snow's ten-times lower thermal conductivity. Thermistor strings can provide autonomous observations of the seasonal evolution of ice and snow thickness and temperature at individual locations.

ULS are echo-sounders measuring the range to the ice underside. Ice draft is calculated from the known depth of the ULS, and converted to ice thickness assuming isostatic equilibrium, densities of ice and snow, and snow depth. ULS can be operated from moving platforms like manned or autonomous submarines to provide regional information. If moored to the sea floor, they provide year-round ice thickness observations at individual locations. Main challenges are the knowledge of sound speed and beam divergence in the water and the identification of the water level as reference for the depth and draft measurements. With EM sounding the distance between an EM instrument and the ice/water interface can be determined by means of active induction of eddy currents in the water and measurements of the resulting secondary EM field amplitude and phase. The method relies on the strong electrical conductivity contrast between the conductive sea water and resistive sea ice and snow. No induction takes place in the latter, and the derived thickness is total thickness, i.e., ice plus snow thickness. In addition, the distance between the EM instrument and the snow/ice surface needs to be determined. EM measurements can be performed while walking or driving over the ice, e.g. by snowmobile. They can also be carried out from helicopters and airplanes, when the EM sensor is typically tethered to avoid induction in the metal of the aircraft. EM fields strongly decay with height above the water. Therefore EM sensors need to be flown low above the ice, typically less than 30 m. The used low-frequency EM fields in the Kilohertz range are diffusive and result in a large measurement footprint of 2-4 times the flying altitude, over which measurements are averaged. Therefore the maximum thickness of ridges is usually underestimated since the EM footprint averages across the maximum ice thickness in the ridge keel and adjacent thinner ridged or level ice.

Laser and radar altimetry can be employed from aircraft and satellites (e.g. ICESat, ERS, and CryoSat) to measure the height of the snow surface ("snow freeboard": lasers) or ice surface ("ice freeboard": radars) above the water level. As with ULS, ice thickness can be obtained from freeboard by assuming isostatic equilibrium, snow thickness, and the densities of snow and ice. Due to the small freeboard/thickness ratio of ice, freeboard errors and uncertainties in snow thickness and density strongly affect the accuracy of altimetric thickness estimates. Accurate freeboard retrievals are further complicated by variations of sea surface height, and, in the case of radar altimeters, variable penetration of radar waves into the snow.

4.3. Sea ice Observing System. Observations of climate-related sea ice changes require regular surveys on hemispheric scales. So far, these can only be performed by satellites using altimetric methods. However, retrieved thicknesses can possess large uncertainties, and strongly rely on calibration and validation by means of more accurate but less extensive airborne and ground measurements. Several international projects have successfully used airborne altimetry and EM sounding, moored ULS, and in-situ measurements to validate satellite products, and integrated these with results from numerical models to provide a most comprehensive best estimate of the state of the sea ice cover.

4.4. Future developments and research needs. Satellites, aircraft, and access to the polar regions are extremely expensive, limiting the amount of available data. Cost effective or autonomous platforms employing the traditional surveying methods would significantly improve our observational capabilities. Intercomparison of results obtained with different methods based on different physical concepts are complicated by different footprints. Dedicated, interdisciplinary field studies should be performed to address these issues. Snow thickness measurement techniques need to be developed and improved. There are promising attempts using ground-based and airborne broadband, frequency-modulated, continuous wave (FCMW) radio echo sounding.

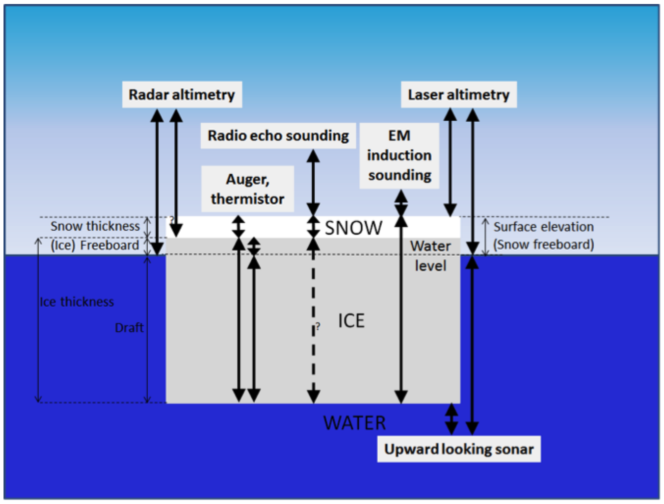

Figure 4.1: Cross section of an ice floe in isostatic equilibrium, illustrating variables comprising ice thickness. Observables retrieved by various ice thickness measurement methods are indicated by thick arrows.

5. Ice Coring and Measurements of Key Physical Properties

5.1. Background. Many studies require extraction and direct examination of samples obtained from an ice cover, in particular research into physical, chemical and biological properties of sea ice, as detailed below and in Sections 6 through 8. The relative volume fractions of ice, brine and gas (and for some applications salt precipitates) determine a range of other ice properties and constrain the volume available for biological and geochemical processes in the liquid phase. The liquid, solid and gaseous phase fractions are typically not measured directly but derived from measurements of sea-ice temperature T_{si}, bulk salinity S_{si} and density ρ_{si}, typically assuming that the ice cover formed from seawater of standard composition. Hence, these variables, T_{si}, S_{si} and ρ_{si}, can be thought of as state variables for a given ice volume. Many ice property models, describing for example the specific heat capacity, thermal conductivity or other transport properties (see Section 7), include some parameterization that requires information about the relative volume fraction of brine and gas and consequently measurements of at least T_{si} and S_{si}, with ρ_{si} often expressed in terms of the former two variables. At present, ice property models only include greatly simplified representations of ice texture, i.e., the size, shape and spatial arrangement of ice crystals and brine, gas or salt inclusions. Measurements of ice texture typically require in-depth analysis in the laboratory and are not further considered here.

5.2. Key Approaches and Techniques. The prevailing method for obtaining ice samples is to drill cylindrical ice cores by hand, with a combustion-engine powerhead or most commonly with an electric power drill (Figure 5.1). The latter minimizes contamination of the ice samples and is quieter and more efficient to operate in cold conditions. Operation of a corer represents a significant hazard in field work and requires safety precautions. Typical corer diameters are on the order of 10 cm, a compromise between obtaining ice volumes large enough to minimize sampling errors while keeping core weight and bulk at a manageable level. The standard corer design is based on a fiberglass (or less commonly carbon-fiber or metal) barrel with a metal cutting head.

Loss of brine from an extracted core, in particular in warm, permeable ice such as the lower core layers shown in Figure 5.2, and warming of the core samples are key concerns and require rapid processing of cores on site, typically starting by taking a series of core stratigraphy photos against a dark and/or white background (Figure 5.1). Temperature measurements can be obtained by drilling to the center of the core and inserting a thermistor probe; such data are associated with larger errors than in situ measurements obtained through sensors frozen in as part of autonomous systems (Section 9) but have the advantage of yielding information on the same piece of ice (or an adjacent parallel core) that is then further processed. Density measurements require intact core samples for which exact dimensions can be determined with a caliper. Typically, minimization of errors for field measurements requires core sections of well over 0.1 m length. Variations in the salinity profile indicative of different growth processes or rates justify sectioning cores into 0.05 m long segments (Figure 5.2). These samples are then transferred to tightly sealed bags or containers on site and transported to a laboratory for melting and further analysis.

Ice salinity is obtained by measuring the electrolytical conductivity of melted samples. In reporting ice salinities, in the past the practical salinity scale (pss) has been used to relate measurements of conductivity to that of standard seawater, with measurements reported in practical salinity units (psu). However, the pss is defined for standard seawater of a given composition for the interval between 1 and 42. Many measurements for sea ice fall outside of this validity interval. Recently, a new salinity reference-composition salinity scale has been developed to address some shortcomings of the pss.

Assuming standard seawater composition, thermodynamic phase relations allow the derivation of the fractions of ice, brine and air (and solid salts, if of interest) from measurements of temperature, salinity and density. Thus, brine volume fraction can be expressed as

$$\frac{V_b}{V} = \left(1 - \frac{V_a}{V}\right)\frac{\rho_i S_{si}}{F_1(T) - \rho_i S_{si} F_2(T)} \tag{5.1}$$

V_b/V is the volume fraction of brine while V_a/V is the volume fraction of air in a sample. The density of pure ice is

$$\rho_i = 0.917 - 1.403 \times 10^{-4} T \tag{5.2}$$

with ρ_i in g cm^{-3} and T in °C. $F_1(T)$ and $F_2(T)$ are empirical polynomial functions $F_i(T) = a_i + b_i\,T + c_i\,T^2 + d_i\,T^3$, based on the phase relations. The coefficients for different temperature intervals are listed in Table 5.1.

The brine salinity and density can approximated as (see Table 5.2 for coefficients)

$$S_b = a_3 + b_3 T + c_3 T^2 + d_3 T^3 \tag{5.3}$$

$$\rho_b = 1 + 8 \times 10^{-4} S_b \tag{5.4}$$

with T in °C. The volume fraction of air V_a/V can be derived from a measurement of the density of a sea ice sample ρ_{si}:

$$\frac{V_a}{V} = 1 - \frac{\rho_{si}}{\rho_i} + \rho_{si} S_{si} \frac{F_2(T)}{F_1(T)} \tag{5.5}$$

Table 5.1. Coefficients for functions *$F_1(T)$ and $F_2(T)$ for different temperature intervals, from Lepp ̈aranta and Manninen [1988], Cox and Weeks [1983, 1986]*

T, °C	$\mathbf{a_1}$	$\mathbf{b_1}$	$\mathbf{c_1}$	$\mathbf{d_1}$
$\mathbf{0 \geq T \geq -2}$	−0.041221	−18.407	0.58402	0.21454
$\mathbf{-2 \geq T \geq -22.9}$	−4.732	−22.45	−0.6397	−0.0174
$\mathbf{-22.9 > T \geq -30}$	9899	1309	55.27	0.7160
	$\mathbf{a_2}$	$\mathbf{b_2}$	$\mathbf{c_2}$	$\mathbf{d_2}$
$\mathbf{0 \geq T > -2}$	0.090312	−0.016111	1.2291×10^{-4}	1.3603×10^{-4}
$\mathbf{-2 \geq T \geq -22.9}$	0.08903	−0.01763	-5.330×10^{-4}	-8.801×10^{-6}
$\mathbf{-22.9 > T \geq -30}$	8.547	1.089	0.04518	5.819×10^{-4}

Table 5.2. Coefficients for function *$S_b(T)$ for different temperature intervals, from Leppäranta and Manninen [1988], Cox and Weeks [1983, 1986]*

T, °C	$\mathbf{a_3}$	$\mathbf{b_3}$	$\mathbf{c_3}$	$\mathbf{d_3}$
$\mathbf{0 \geq T \geq -2}$	−0.0316891	−18.3801	0.327828	0.213819
$\mathbf{-2 \geq T \geq -22.9}$	−3.9921	−22.7	−1.0015	0.019956
$\mathbf{-22.9 > T \geq -44}$	206.24	−1.8907	−0.060868	−0.0010247

5.3. Example Application. The impacts of a rain-on-snow/ice event are illustrated in an example application of ice core analysis shown in Figure 5.2. A set of full length ice cores obtained a few days prior to the event illustrates a typical salinity profile in first-year ice at the start of the melt season, with a slight reduction in ice salinity in the uppermost 0.05 m due to warming and brine drainage, comparatively small variations in ice salinity throughout the ice cover and a drastic increase at the bottom. Three replicate cores provide a measure of spatial variability, increasing towards the bottom due to loss of brine from the core sampled with air temperatures a few degrees below 0 °C. Note, however, that the internal variations in ice salinity are consistent between cores, reflecting changes in ice growth mode in the upper 0.3 m and changes in ice growth rate in the interior of the ice. Rain falling on snow at sub-freezing temperatures resulted in rapid warming of the ice and formation of a superimposed ice layer at the base of the snow pack (Figure 5.2, center and right; see also Section 4). The superimposed ice layer is clearly delineated in terms of higher density, low salinity and the absence of gas or brine inclusions evident in the core stratigraphy.

5.4. Future Developments and Research Needs. The need for improved representation of sea ice in climate and process models, as well as the importance of accurate evaluation of ice properties from the perspective of ice uses and ice hazards require increasing degrees of sophistication in determining ice properties in the field. This extends to the need to develop new sampling techniques or to combine in situ autonomous sensor systems (see Section 9) with data collected on samples obtained through coring. In the mid- to long-term, the need for near realtime, continuous ice property tracking at broad regional and pan-Arctic coverage will require additional technological advances to indirectly derive ice property data from, e.g., electric or electromagnetic measurements (see Section 7).

In the near-term, the most urgent need is for the development of best-practices and standards to ensure consistent, intercomparable observation of ice properties and derived parameters. Here, the most promising approach is to develop community-wide protocols for measuring temperature, salinity and density (and where feasible ice and pore microstructure) and uniform approaches in deriving phase fractions from such data sets. This will also require development of best practices for sampling design and replicate measurements to evaluate spatial variability. The recent development of more sophisticated geochemical models to describe the state of (frozen) seawater may also allow for more accurate representation of sea ice chemical composition in the evaluation of phase fractions. Such approaches are particularly important in cases where sea-ice property data are serving as input to the development or application of, e.g., international codes such as ISO 19906 for the design of offshore structures.

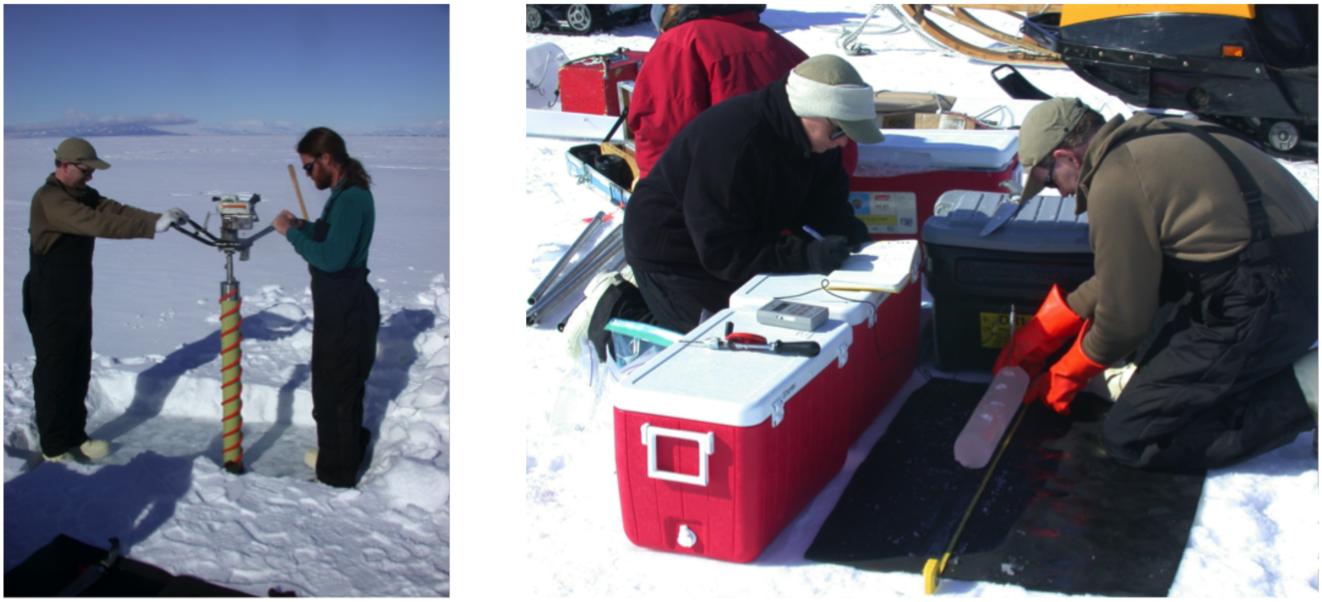

Figure 5.1: Extraction of an ice core with a gasoline-powered engine and a fiberglass-barrel corer (left). Field site (right), showing hand drill and thermometer for ice-core temperature measurements on top of the sample cooler at left and core laid out in the shade for processing.

6. Ice optics and surface energy budget

6.1. Background. How much sunlight is reflected by sea ice, absorbed in sea ice, and transmitted through sea ice to the ocean are critical elements in the heat and mass budget of sea ice. The amount of sunlight transmitted to the bottom of the ice and to the upper ocean strongly influences the marine ecosystems in ice covered waters. The interaction of sunlight with sea ice is governed by two processes; absorption and scattering. Scattering is caused primarily by brine inclusions and air bubbles in the ice. Absorption in sea ice exhibits strong wavelength dependence, while scattering is constant with wavelength. Differences in the magnitude in sea ice optical properties are due to scattering and spectral differences are due to absorption. Most optical properties of sea ice are determined through its snow cover and surface properties, because of strong scattering, which is an order of magnitude larger than the sea ice itself. Hence the optical properties of Arctic sea ice are strongly dominated by its seasonality. Changing the surface from an optically thick snow cover to bare sea ice, four times more energy is absorbed in the ice and may be transmitted further down. In the Arctic, summer melt ponds have a great impact on the surface energy budget through their low albedo and high transmittance. In the Antarctic, the strongly heterogeneous and thick snow cover dominates the optical properties and their seasonality.

6.2. Key approaches and techniques. There are many different optical properties describing the interaction of light with a material. One basic parameter is the irradiance, which is the solar energy integrated over a hemisphere and has units of W m^{-2}. The most frequently measured parameter is the albedo. The albedo is defined as the ratio of the reflected irradiance to the incident irradiance. A perfect reflector has an albedo of one and a perfect absorber has an albedo of zero. Spectral differences in albedo cause the different appearance of the sea ice surface and may be related to different physical processes that cause these difference, e.g. snow melt or contaminants (particles). For biological studies, the amount of photosynthetically active radiation (PAR) transmitted to the ocean is of particular interest. PAR is the number of photons between 400 nm and 700 nm and has units of μE m^{-2} s^{-1}, where an Einstein (E) is equal to one mole (6.02×10^{23}) of photons. However, biological processes and the amount of biomass also affect the light spectrum in and under sea ice due to characteristic absorption features.

6.3. Example application. A common type of observation is to characterize the optical properties of a single location. Ideally, the location will be uniform in thickness and surface conditions over a distance of several meters. This greatly simplifies the interpretation of the observations. A typical sequence of measurements is: i) measure the albedo; ii) carefully remove an ice core; and iii) lower a detector into the hole and measure the downwelling light every 5 cm down to the ice bottom or even beyond into the ocean underneath. Finally a detector can be mounted on an under-ice horizontal arm to measure the

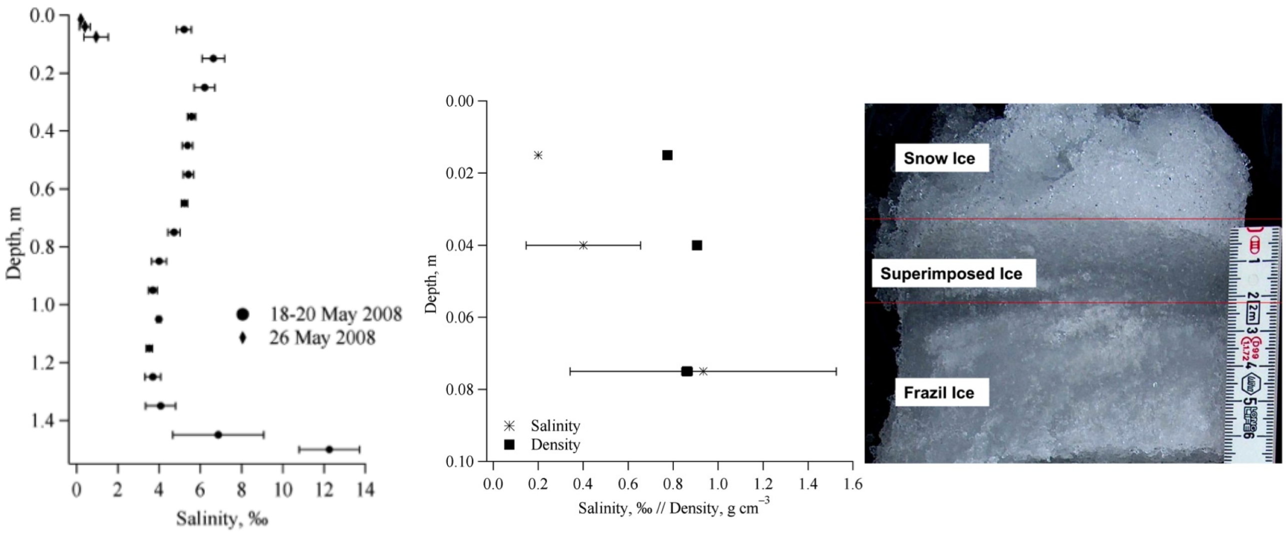

Figure 5.2: Salinity profile of first-year landfast ice (left) sampled at Barrow, Alaska before (18-20 May) and after (26 May) a rain on snow event. Salinity and density profiles of the upper 0.1 m of the core taken on 26 May shown at center, with a core photograph shown at right. Horizontal bars indicate the standard deviation of samples from three parallel cores.

amount of light transmitted through the ice cover. Depending on the detector used either spectral or wavelength-integrated measurements are made. Since sea ice is highly scattering the impact of the hole on the transmitted light field will be small below the top 20 cm of the ice. The optical observations are supplemented with descriptions of sky clouds (cloudy, sunny, sun angle) and measurements of the ice physical properties (density, salinity, brine volume).

Beyond this point measurement, transects and time series of such measurements are necessary in order to describe the spatial variability and seasonal evolution of optical properties of sea ice. Those measurements become more and more important to allow for better generalization and upscaling. Albedo transects may be performed manually along lines or using sled systems with automatic measurements. Transmittance transects require either multiple access holes or may make use of remotely operated vehicles (ROV) or autonomous underwater vehicles (AUV). Time series measurements may be performed at manned stations or through autonomous platforms (buoys).

6.4. Future developments and research needs. The changes to the Arctic sea ice cover are raising new scientific questions regarding the interaction of sunlight with sea ice. What are the optical properties of young ice? How will the shift to younger sea ice impact the partitioning of sunlight by the ice cover? What is the role of melt ponds in light reflection and absorption? What will be the impact of thinner ice on primary productivity? There is new technology that is being applied to help answer these questions. Optical instruments mounted on buoys are measuring time series of light reflection and transmission at multiple locations. Instruments mounted on autonomous vehicles are being used to investigate the spatial variability of reflected and transmitted light.

Figure 6.1: Surface-based measurement with a spectroradiometer (consisting of diffuser plate and fiber-optic detector at end of boom, laptop computer and back-pack with the radiometer).

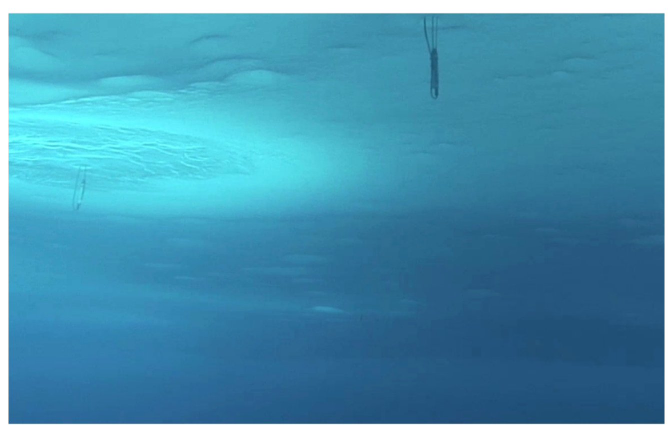

Figure 6.2: Under-ice measurements of radiative fluxes with fiber-optic detectors under level sea ice with varying snow/pond cover accounting for differences in light availability visible in the photograph.

7. Transport properties

7.1. Background. The transport properties of a material are those which describe the flow of energy and mass through it. In the case of sea ice important transport properties are thermal conductivity – which controls the flow of heat, permeability – which controls the ability of fluids to pass through the ice, and electrical conductivity – related to the passage of current.

The thermal properties of sea ice govern its growth and decay, and the manner in which it controls the transfer of heat from ocean to atmosphere. Functions of temperature and salinity of the ice, they depend on the relative sizes and geometric arrangement of the ice and brine components. Permeability controls the formation, growth and drainage of surface melt ponds, movement of brine within the ice, relevant to the salinity profile and to heat transport, and at the base of the ice is important for the exchange of fluids and nutrients between ice and the ocean. Permeability depends on the existence and size of pore connections within the ice. The electrical conductivity is primarily important because of its relationship to the dielectric permittivity - a controlling property on the interaction of sea ice with electromagnetic radiation, important in remote sensing. As electrical conductivity is highly sensitive to the existence of a connected network of brine channels in the ice it is also a physical property which can be used to probe the microstructure of sea ice.

7.2. Key approaches and techniques. Measurement of thermal conductivity (k measured in W m^{-1} K^{-1}) is best approached by determination of the thermal diffusivity (κ). This relates temporal and spatial variations in temperature through

$$\frac{\partial T}{\partial t} = \kappa \nabla^2 T \tag{7.1}$$

and is related to k, the specific heat (c) and density (ρ) through $\kappa = k/c\rho$. In-situ measurements of κ can be obtained from high precision measurements of the temporal evolution of the thermal profile of sea ice using specially designed thermistor strings embedded in the ice. Given a knowledge of the specific heat, the rate of change of temperature with time may be expressed in terms of internal energy (U)

$$\rho \frac{\partial U}{\partial t} = k \frac{\partial^2 T}{\partial z^2} + \frac{\partial k}{\partial z}\frac{\partial T}{\partial z} \tag{7.2}$$

A plot of $\rho\ \partial U/\partial t - (\partial k/\partial z)(\partial T/\partial z)$ against $(\partial^2 T/\partial z^2)$ yields a straight line of gradient k.

Measurements have led to a parameterization of k in terms of ρ, T, the density of pure ice ρ_i, and the bulk salinity S (in parts per thousand) of

$$k = \frac{\rho}{\rho_i}\left(2.11 - 0.011T + 0.09\frac{S}{T} - \frac{\rho - \rho_i}{1000}\right) \tag{7.3}$$

This gives a good overall fit to measured values of k over the ranges $0 < S < 10$ ppt and -30 °C $< T < -1.8$ °C.

The specific heat of sea ice depends only on the mass fractions of different phases present and not on their spatial arrangement. Theoretical expressions for the dependence of c on S and T can therefore be derived and yield an analytic expression

$$c = 2113 + 7.5T - 3.4S + 0.084ST + 18040\frac{S}{T^2} \tag{7.4}$$

in good agreement with values measured on core samples.

Fluid flow through porous media is described by Darcy's law which relates the specific discharge (or flux of fluid volume) q (m s^{-1}) to the pressure gradient ∇P (Pa m^{-1}) through the dynamic viscosity μ (kg m^{-1}s^{-1}) and the permeability Π (m^2) of the medium

$$q = -\frac{\Pi}{\mu}\nabla P \tag{7.5}$$

For flow through a cylindrical tube the permeability depends upon the square of the radius of the tube. This dependence on the size of brine pores is behind the experimental observation that sea ice is effectively impermeable when the brine volume fraction in the ice is below 5%. For ice of typical bulk salinity 5 ppt the transition from impermeability to permeability occurs at a temperatures of about -5 °C.

Field measurements of the vertical permeability can be made by timing the refill with seawater from below of a core hole drilled part way through the ice and sealed around the sides. Refill is driven by the difference (h) between the equilibrium sea level and the instantaneous water level in the hole, leading to a relationship for the variation of h with time (t)

$$h(t) = h_0 \exp\left(-\frac{\Pi_a g}{\mu L}t\right) \tag{7.6}$$

in which L is the ice thickness below the base of the hole. The calculated apparent permeability (Π_a) can be corrected for the effect of lateral permeability below the base of the core hole. Typical values of Π at porosities above 5% are of the order of 10^{-11} m^2 – comparable to permeability values for fine sand.

The electrical conductivity (σ in S m^{-1} $\equiv \Omega^{-1}$m^{-1}) represents the proportionality constant between current density (J in A m^{-2}) and the gradient in potential (V). Electrical conductivity is a function of frequency and depends not only on the ability of charge to pass through a material, but also on the response of permanent dipole moments in the material to an applied, time-varying, electric field. At low frequency dipole moments are able to align with the varying field, both in the ice and the brine; at high frequency they do not have time to do so in the brine, the result being a dielectric relaxation and associated dielectric loss that is governed by the properties of the brine. This process is best expressed in terms of the dielectric permittivity (ϵ^*) which is related to the electric conductivity (σ^*) by

$$\sigma^* = i\omega\epsilon_0\epsilon^* \tag{7.7}$$

where the $*$ indicates a complex quantity (one with both an amplitude and a phase), ω is the angular frequency, ϵ_0 the permittivity of free space, and $i = \sqrt{-1}$. The variation of ϵ^* through a Debye (dielectric) relaxation can be expressed as

$$\epsilon^* = \frac{\chi}{1 + i\omega\tau} + \epsilon_\infty - i\frac{\sigma_{DC}}{\epsilon_0\omega} \tag{7.8}$$

in which χ is a susceptibility, τ is a time constant characteristic of the frequency at which the relaxation occurs, ϵ_∞ is the high frequency limit of ϵ, and σ_{DC} the dc conductivity of the material. At frequencies in the GHz range, which are used in remote sensing of sea ice, ϵ^* is important because the permittivity controls the reflection, scattering, absorption and transmission of incident electromagnetic radiation.

Passage of electric current through a material depends on the availability of a connected conducting pathway. As the ice component in sea ice is almost infinitely resistive, the electrical conductivity of sea ice is entirely dependent on the degree to which a connected network of brine pores and channels exists.

Measurements of electrical conductivity (or its reciprocal resistivity) of sea ice are complicated by the fact that the vertical elongation of brine pores means that σ is highly anisotropic with the vertical component being 1-2 orders of magnitude larger than the horizontal component. As a result surface based measurements using typical geophysical techniques are extremely difficult to interpret in terms of a conductivity variation with depth. Successful dc measurements have been obtained by using four vertical strings of electrodes frozen into the ice at the corners of a 1 m $\times$ 1 m square, with individual electrodes spaced at a vertical separation of 10 cm. Passage of current between pairs of electrodes in different strings and measurement of the potential difference between electrodes also in different strings allows the anisotropic electrical conductivity to be recovered. Results, expressed as the variation of the formation factor (FF – the ratio of the measured resistivity to the resistivity of the brine in the pores) with brine volume fraction have been used to derive simple models of how the pore structure in sea ice evolves with temperature. The observed values of FF demonstrate the necessity for a connected brine fraction to exist through the ice, both vertically and horizontally, even at low temperatures when the overall brine volume fraction is small. At low temperatures horizontal connection in particular is inferred to be through intergranular brine veins. With some limitations the derived models are also quite successful in reproducing the observed dependence on temperature of both k, c and Π.

Similar cross-borehole measurements using ac have been used to make in-situ measurements of permittivity as a function of frequency in the range 10 Hz – 100 kHz. Such measurements suggest that the observed frequency at which dielectric relaxation occurs varies both with temperature and with salinity. Additionally, at low frequency, the real part of ϵ^* has a strong dependence on the microstructure of the ice. Various approaches have been used to measure ϵ^* at high frequency. The most successful techniques have used measurements of capacitance between either parallel plates embedded in the ice, or small diameter wires separated by the order of cm. However, most such measurements have been on either artificial, laboratory grown ice, or on extracted ice cores, in-situ measurements being extremely complex.

7.3. Future developments and research needs. Research needs and future developments for sea-ice transport property measurements are in line with those identified for the key state variables discussed in Section 5. In particular, standardized approaches – or more realistically, best practices – for determination of these properties have to be developed. At the same time, the combination of in situ, continuous measurements by autonomous sensor systems with direct, on-site measurements hold great potential but require substantial methodological and instrumentation advances.

8. Sea ice biota and biogeochemical properties

8.1. Background. While sea ice might appear from the human perspective to be a hostile landscape without life, it is in reality teeming with unique communities of living organisms at any time. Even in the depths of winter, many organisms make their homes within, on top of, and/or under sea ice. This section describes sampling and analysis methods for ice-associated biota.

8.2. Key approaches and techniques. Methodological approaches vary depending on habitat and targeted organism group. This contribution focuses on the invertebrate life forms associated with sea ice and excludes the study of birds and marine mammals that may use sea ice for certain parts of their life cycles. Ice corers are essential tools to sample the distribution of biota within the sea ice. They can be powered by hand or electric/gas powered drills. Samples may be taken from various ice thicknesses, typically from a few cm to several meters. For new ice, buckets or water samplers are used to scoop up ice crystals or pancake ice. Ice cores are sectioned with a stainless steel saw (Figure 8.1). For microbial sampling all sampling devices are sterilized prior to use. Core sections are stored in clean plastic bags within coolers to avoid exposure to bright light and changing temperatures. Maintaining close to in situ temperatures is critical for many biological measurements. Optical tools and nets are used to collect samples from the sea ice macrofauna which inhabits the underside of sea ice.

8.2.1. Microbial abundance, activity, and diversity

A wide range of Bacteria, Archaea, viruses, and protists occur within sea ice and contribute to the particulate organic pool. What makes them unique compared to their counterparts from lower latitudes is that they may be active at ice temperatures below −20 °C. Their abundance and activity contribute to the biogeochemical cycling in sea ice.

Because of requirements for sterility and cleanliness, ice cores collected for biogeochemical or microbiological analysis must be collected carefully to prevent contamination of the surface of the ice at the drill site, the ice corer, or the surface of the ice core once it is retrieved. These precautions may include specialized equipment and sterilized gloves, corer, shovel, and saw. Once retrieved, the surface of the ice cores should be scraped or melted off prior to further processing to ensure only the uncontaminated internal portion of the ice core is used for analysis.

Microbes in sea ice are adapted to the cold, salty brine environment they inhabit, so methods to avoid temperature and salt shock should be followed. Ice cores should be cut immediately in the field with sterilized gloves and saw, placed into sterile bags, and transported in an insulated container. Melting of ice cores is often conducted at low temperature (e.g. in a cold room) into pre-filtered seawater or an isohaline

Figure 8.1: Sectioning of an ice core with a stainless steel hand saw on site. Note the discoloration due to microalgae in the bottom-most layer, with algal cells concentrated in brine layers between lamellar ice crystals.

brine solution to avoid osmotic shock. Direct melting of ice cores – especially from very cold ice – should be avoided.

As with other microbes, abundance (and in some cases diversity) of sea ice microbes may be determined by epifluorescence microscopy. For bacteria or viruses, melted ice or brine samples are fixed and concentrated onto membrane filters, stained with a nucleic acid-specific fluorescent dye, and inspected by epifluorescence microscopy. Additional microscopic techniques applied include fluorescence in situ hybridization (FISH) to determine the abundance of specific clades of microbes, or staining with a reporter molecule as an indication of activity.

For macro-scale analyses, depth integrated abundances can be useful (typical value: 10^{11} bacteria m^{-2}), as can further conversion to biomass (typical: 10 mg bacterial C m^{-2}). For insight into the ecology of microbes, scaling to the in situ brine volume may be preferred (typical: 10^6 bacteria or 10^7 viruses mL^{-1} brine). Often results are reported scaled to ice volume, but researchers should take care to specify whether they are reporting melted ice volume or solid ice volume (typical: 10^4 protists mL^{-1} melted ice), since the density of ice and water are not the same.

While culture-dependent methods are still prevalent and important for understanding microbial diversity in sea ice, newer molecular genetic approaches are providing unique insights into sea ice microbial communities. Genome sequencing efforts are helping to identify genes and mutations that have enabled *psychrophiles* to adapt to the sea ice environment. Genetic fingerprinting techniques enable rapid identification of major microbial groups, allowing researchers to track changes in sea ice communities over time.

8.2.2. Phototrophs

Currently over one thousand algal taxa have been described for Arctic sea ice with the majority being diatoms (see Figures 8.2 and 8.3). Smaller size fractions of flagellated algae are poorly studied and require future analysis. Sea ice algae may contribute substantial amounts to total primary productivity of polar seas. Sampling follows the recommendations given for microbes above, but the lower risk of contamination makes sterility not a requirement. However controlling ice temperature and maintaining ice brine salinities is of greatest importance for any activity measurement (e.g. primary production, or nutrient uptake). After coring and melting (while controlling salinity), samples for sea ice algal diversity may be analyzed using epifluorescence microscopy (see above), or inverted microscopy. Newer approaches use extracted DNA to assess algal diversity.

For primary production estimates, trace amounts of ^{14}C-labeled dissolved inorganic carbon are added to either ice core sections or filtered sea water containing suspended sea ice pieces and processed as typically done for phytoplankton. Incubations can be done in-situ or in incubators. In situ incubations provide natural temperature and light fields that are difficult to maintain in a lab. Newer approaches using variable algal fluorescence have been successfully applied to understand the ice algal photophysiology related to the unique sea ice settings.

8.2.3. Meiofauna

Sea ice fauna consists of a wide range of protozoans and invertebrates all of which are small enough to fit into the brine filled space between the ice crystals within the ice matrix, typically ¡1 mm in diameter. Typical members include Nematoda, Polychaeta, Crustacea and Acoela with large regional differences in distribution and composition patterns. The basic sample processing follows the outlined procedure for phototrophs. After complete sample melt, the entire sample is concentrated over 20 μ m mesh and the retained organisms are flushed into a petri dish and either counted alive under a dissecting scope or fixed for later processing. Typically, abundances are 10^2–10^3 invertebrates m^{-2} and they consume less than 10% of the ice algal primary production.

8.2.4. Macrofauna

Larger crustaceans, mainly amphipods and euphausiids, use the bottom of ice floes as inverted benthic substrate. Some fish species, e.g. Boreogadus saida also live in association with sea ice. Diversity and abundance of macrofauna is assessed with optical tools (SCUBA divers, cameras, ROVs) or can be collected with under-ice trawls and pump systems. Collected specimens are typically fixed, counted and identified in the lab or from imagery.

8.3. Example applications. Studies along Arctic sea ice pressure ridges suggest that deeper layers in a ridge become accumulation regions for ice meiofauna and under-ice amphipods in summer, probably avoiding the lower surface water salini-

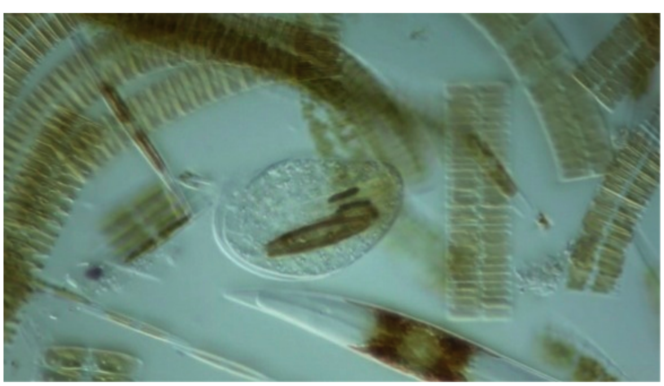

Figure 8.2: Live microscopic picture of the sea ice flora and fauna, taken in the Bering Sea. Ice algal communities are often dominated by chain forming diatoms, and protozoa (center) may be abundant.

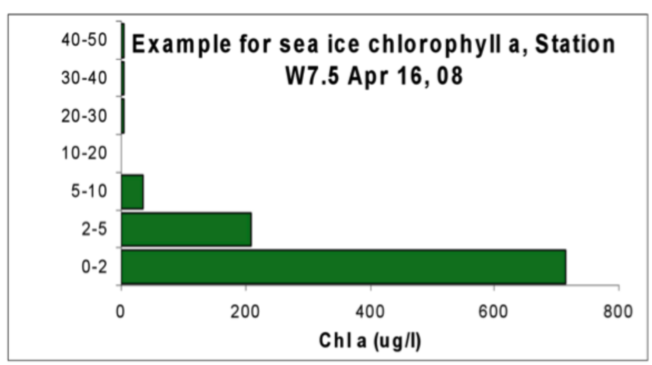

Figure 8.3: Example of the vertical distribution of sea ice algae in Arctic sea ice. Bars indicate the total algal pigment concentration (Chl a) in ice sections from the bottom of the ice (0 cm mark) to the top of the ice (50 cm mark). Highest concentrations occur in the bottom 2 cm segment.

ties. Bacterial diversity for winter communities reflects the seawater from which the ice was formed, whereas summer communities are more often associated with sea ice algal blooms. A larger fraction of bacteria (up to 60%) in summer sea ice can be grown in the lab compared to ¡1% in other environments. Many of these microbes are psychrophiles.

8.4. Future developments and research needs. Detailed information on sea ice biota is needed to develop appropriate conceptual and mathematical models to predict synergistic impacts of global climate change on polar ecosystems. The use of molecular genetic techniques holds promise for answering taxonomic, evolutionary, and ecological questions related to sea ice biota. Applied research questions could, for example, focus on the capability of some sea ice biota to change the stability and porosity of sea ice and those able to produce anti-freeze agents.

9. Autonomous sensors, UAVs and UASs

9.1. Background. The Arctic Ocean is a remote and, at times, hostile environment. There are months of total darkness, air temperatures as low as −50 °C, and a surface covered by drifting sea ice. It is also an important region as the sea ice cover is both an indicator and an amplifier of climate change. Observing and understanding the ongoing changes in this region are challenging tasks. Autonomous sensors provide a means of monitoring the environment without requiring human presence, allowing observations that would be too long or too hazardous to make with manned missions. The absence of personnel onboard can in some cases also reduce logistics costs. Mobile sensor platforms can include unmanned aircaft systems (UASs), autonomous underwater vehicles (AUVs) or even the ice itself in the case of ice-tethered profilers (ITPs) and other drifting buoys. Autonomous sensors can also be fixed in place either on land or moored to the sea floor.

9.2. Key approaches and techniques. The instruments used on autonomous sensors vary according to the platform used and the goals of the mission, but most are ruggedized or miniaturized to cope with environmental demands or payload limitations. Instruments on airborne platforms are typically chosen to observe the upper surface of sea ice and the atmosphere above it. Airborne sensors can range from a simple camera to chemical sensors, lidars, radars, and radiometers. Underwater platforms can include sensors for measuring water temperature and salinity, currents, and biogeochemistry as well as upward-looking sonars for observing the underside of sea ice. The simplest ice buoys measure position, air temperature, and barometric pressure. More complex systems examine atmospheric fluxes, snow depth, ice thickness, ice growth and decay, ocean heat flux, and upper ocean temperature, salinity, and currents.

Data retrieval is crucial to any observing system. Some autonomous sensors, in particular ice buoys, are considered expendable and therefore their data must be telemetered continuously during their deployment. In the high latitudes where sea ice is found, sensors most often rely on polar orbiting communications satellites such as Iridium. Limited bandwidth of satellite communications places additional restrictions on the sensors that can be used. Recoverable sensors can store data onboard, but this incurs the risk of complete data loss in the event of system failure. Marine-based platforms must come to the surface to transmit data, which some can be programmed to do periodically if they are not underneath sea ice. Unmanned aircraft are typically able to transmit limited amounts of data during flight and can be used as uplinks to retrieve data from sensors deployed on the surface.

9.3. Example application. One of the goals of the 2007 – 2009 International Polar Year was to develop an Arctic Observing Network. This network has many components including autonomous stations drifting in the Arctic Ocean. One such station is the North Pole Environmental Observatory (NPEO). First established in 2000, each spring an autonomous station is deployed near the North Pole. Instruments report via satellite as the station drifts southward finally reaching the open ocean in the North Atlantic several months later.

The NPEO has an array of instruments studying the atmosphere, ice, and ocean, all transmitting data via satellite. There is a meteorological station measuring air temperature, wind speed, and humidity. There is an ice mass balance buoy measuring snow depth, ice thickness, ice growth, surface and bottom ice melt, and internal snow and ice temperature. There is an ocean flux buoy that monitors the transfer of heat from the ocean to the ice and an ITP that records vertical profiles of ocean temperature and salinity. In addition, one or more web cameras are deployed so that conditions can be visually monitored.

9.4. Future developments and research needs. Autonomous sensor systems are undergoing tremendous advances thanks to improvements in computing, miniaturization, communication, and power management resulting in an increase in the types of measurements that can be made. Lower costs will allow the deployment of more stations. At the same time, regulations are being adapted to allow expanded use of UASs. Future efforts will focus on integrating results between different stations to build a network and obtain a picture of the physical and biogeochemical state of the Arctic Ocean. A key element will be instantaneous, easy access to the data for all stakeholders. This access will allow data to be used for such varied activities as weather forecasting, shipping, resource exploration, and climate change studies.

10. Ship-based observations

10.1. Background. Ship-based ice observation programs play an important role in providing information about the state of the ice cover in the context of maritime activities. At the same time, in recent years their importance as a means to obtain information about sea-ice conditions relevant for validation of sea-ice models, including ice forecasts, or ground-truthing of remote-sensing algorithms has grown steadily. In the Antarctic, challenges for satellite-remote sensing of ice thickness due to snow cover and lack of ice-profiling sonar draft records have motivated the development of a protocol and international observation program under the auspices of the Antarctic Sea Ice Processes and Climate (ASPeCt) Program. Building on these and other efforts, a group of scientists led by J. Hutchings has developed a protocol and an online database entry and archival tool for Arctic sea ice observations (IceWatch) with endorsement by the Climate and the Cryosphere (CliC) Program (http://www.iarc.uaf.edu/en/icewatch).

10.2. Key approaches and techniques. Ship-based observations are typically carried out from a suitable point on the vessel, such as the bridge, during standardized observation intervals within a defined corridor to either side of a vessel's track. Ice type, concentration, thickness, snow cover and a range of other variables describing the state and dynamics of the ice cover as well as other relevant environmental variables are recorded, typically following the World Meteorological Organization's (WMO) official sea-ice nomenclature. The observation protocol developed for the Arctic under the auspices of CliC comprises roughly 20 different classes of variables describing the ice cover and environmental conditions (Figure 10.1). Depending on whether observations record just the major ice type in abbreviated form or include a full suite of observations of all the ice types present in a particular region, each individual observation can comprise between roughly a dozen to up to one hundred individual data items. To facilitate manual or computer-based completion of standardized forms and dissemination and transmission of such data, typically (alpha)numerical codes are used for each entry (see Figure 10.1).

Recent efforts such as the Arctic IceWatch project include implementation of an online database for data entry and retrieval. Such systems also help ensure consistency and open access to observations. Further recent developments include the development of ship-based digital image acquisition systems that can provide more accurate, quantitative information about the areal coverage of different ice types, sizes of features and spatial variability along a cruise track.

10.3. Future developments and research needs. The number of voyages into the polar ice pack is increasing, both for research purposes and as part of commercial efforts such as tourism or maritime transport. With this increase come both the need for more accurate and reliable information on ice conditions and the potential for a larger number of observations obtained from vessels of opportunity. This opportunity can be taken advantage of if a standardized, accessible and ideally simple observation protocol exists that allows observers on such vessels to collect data that can then be readily disseminated and archived to be of broad use. For scientific purposes, long-term archival for later analysis may be of greater interest than it is for operators who typically require near realtime information. For the latter, great potential benefits can be derived by reporting observations and associated data (such as digital imagery) into operational networks that build on existing infrastructure and protocols, such as those developed for the Global Atmosphere Watch (GAW) program. More work on standardization and interoperability of nomenclatures, observation protocols and methodologies is required. At the same time, training of observers and generation of consistent, accurate datasets requires additional efforts. However, if done well and disseminated rapidly and widely, ship-based observations have the potential to serve a number of critical information needs in the polar regions. In this context, acquisition and near realtime processing of digital imagery, including the derivation of three-dimensional surface topographies through analysis of stereoscopic or sequential (structure from motion) imagery holds considerable promise as well.

11. Outlook

With interests and activities in the polar regions on the rise, and with the Arctic ice cover undergoing a major transformation, there is a great need for data and information about the state, dynamics and evolution of the ice cover. At the same time, the past decade or so have seen major advances in instrumentation and approaches for sea-ice field measurements. With the opportunities and challenges that come along with these recent developments arises the need for improved coordination, standardization and interoperability of different field measurement approaches. There are a number of efforts underway that likely will result in the development of best practices or codes governing human activities in the polar regions, the recent development of the ISO 19906 code for offshore Arctic structures or the evolving International Maritime Organization's Polar Code for marine vessel traffic as two prominent examples. All of these efforts and regulations require detailed and accurate information about the sea-ice cover. In this context, uncertainties or biases in datasets and derived models can have major implications for people living or working in the polar regions, as well as the broader social-environmental systems associated with sea ice. Now is the time for the research and polar operations community to come together and develop documents and resources that lead to consistent, interoperable best practices and, further down the line, standardized, well-described approaches on how to collect, process and integrate sea-ice field measurements.

Ice Type
10 Frazil
12 Grease
20 Nilas
30 Pancakes
40 Young Grey .1 - .15m
50 Young Grey/White .15 - .3m
60 First Year < .7m
70 First Year .7 - 1.2m
80 First Year > 1.2m
90 Brash
65 First Year unk
75 Second Year
85 Multiyear

Floe Size
1 Pancakes
2 New Sheet
3 Brash/Broken
4 Cake <20m
5 Small floe 20-100m
6 Med. floe 100-500m
7 Lg. floe 500-2000m
8 Vast floe >2000m
9 Bergy floe

Topography
100 Level
200 Rafted pancakes
300 Cemented pancakes
400 Finger rafting
5xy New unconsolidated ridges (no snow)
6xy New ridges filled or covered with snow
7xy Consolidated ridges, no weathering
8xy Older weathered ridges

x=Area
0 0-10%
1 11-20%
2 21-30%
3 31-40%
4 41-50%
5 51-60%
6 61-70%
7 71-80%
8 81-90%
9 91-100%

y=Avg. Sail Height
1 .5m
2 1m
3 1.5m
4 2m
5 3m
6 4m
7 5m

Sediment
0 Ice is clean
1 Spots on a few floes
2 Patches>20m
3 >1/3 ice cover is dirty

Algae
0 0% ice w/algae
1 <30% overturned ice has algae
2 30-60%
3 60-100%

Snow Type
0 No snow observation
1 No snow, no ice, or brash
2 Cold new snow, <1 day old
3 Cold old snow
4 Cold wind-packed snow
5 New melting snow (wet new snow)
6 Old melting snow
7 Glaze
8 Melt slush
9 Melt ponds
10 Saturated snow
11 Sastrugi

Stage of Melt

YOUNG ICE
0 No melt
1,2 Surface darkened, snow melt, single thaw holes
3,4 Greatly disrupted surface; thaw holes everywhere
5 Level ice completely melted; only deeply sealed-in water remains; ridges still found

FIRST YEAR ICE
0 No melt; or pack freezing, young ice forming over thaw holes
1 Some puddles on surface; ice brachia destruction begun
2 Surface darkened; snow partially melted. Big puddles; some melt ponds
3 Melt ponds everywhere; some thaw holes. Ice in stage of drying; ice color whitening
4 Greatly disrupted ice; thaw holes everywhere. Disruption of brachia complete. Underwater ramps on ice cakes
5 Rotten ice. Greatly melted formless(?) blocks. Dark grey color; greatly watered.

MULTIYEAR ICE
0 No melt; or pack freezing, young ice forming over thaw holes
1 Snow melting on top of hummocks. MPs/patches of wet snow in low places
2 Some ponding, <40% melt ponds. Snow melting, Areas with no snow
3 Well defined melt ponds everywhere. Connected freshwater output to cracks. Surface melt reduced due to output
4 Ice brachia cracked. Area melt water on surface decreased <30%. Thaw holes.
5 Floes have become cracked and blocked due to intensive melt. Rotten ice.

ADDITIONAL CODES
7 Rotten
8 Some MPs frozen
9 MPs frozen

Precipitation
Weather 1
Weather 2
see NWSOH document

Cloud Height
0 0-50m
1 50-100m
2 100-200m
3 200-300m
4 300-600m
5 600-1000m
6 1000-1500m
7 1500-2000m
8 2000-2500m
9 >2500m OR no clouds
/ Not known- obscured by fog or snow

Cloud Type
cu Cumulus
ci Cirrus
st Stratus
sc Strata-cumulus
fog Fog

Cloud Cover
0 No cloud
1 1/8 or less, but not zero
2 2/8
3 3/8
4 4/8
5 5/8
6 6/8
7 7/8
8 Sky completely covered
9 Sky obscured by fog, snow or other precip
/ Colud cover indescernible

Visibility
90 <50m
91 51-200m
92 200-500m
93 500-1000m
94 1-2km
95 2-4km
96 4-10km
97 >10km
0 Not available

Watercolor
B Blue
G Green
T Turquoise

Watersky
degree to heading

Open Water
0 No openings
1 Small cracks
2 very narrow breaks <50m
3 Narrow breaks, 50-200m
4 Wide breaks, 200-500m
5 Very wide breaks, >500m
6 Leads
7 Polynya
8 Water broken only by scattered floes
9 Open sea

Fracture
L Lead (>10m)
C Crack (<10m)

Fracture Width
vf <50m = OW2
sf 50-200m = OW3
mf 200-500m = OW4
lf >500m = OW5

Fracture Direction
direction to heading
N
NNE
NE
NEE
E
...

Fracture Spacing
distance between fractures per ship speed
1 <1km
3 1-3km
10 3-10km
11 >10km

Figure. 10.1: Ice feature categories and corresponding classification codes developed as part of the Arctic ICEWATCH Program (http://www.iarc.uaf.edu/en/icewatch).

Bibliography

Bluhm B.A., Gradinger R.A., Schnack-Schiel S.B. (2010). Sea ice meio- and macrofauna. In: Sea Ice – An Introduction to its Physics, Chemistry, Biology and Geology (Eds., D.N. Thomas & G.S. Dieckmann), pp. 357–393, Wiley-Blackwell, Oxford. [Section 8]

Cassano J.J., Maslanik J.A., Zappa C.J., Gordon A.L., Cullather R.I., Knuth S.L. (2010). Observations of Antarctic Polynya With Unmanned Aircraft Systems, Eos, Transactions American Geophysical Union 91(28), 245-246. [Section 9; summary of late-winter UAS campaign over sea ice and open water in Terra Nova Bay, Antarctica]

Colbeck S.C., Akitaya E., Armstrong R., Grubler H., Lafeuille J., Lied K., McClung D., Morris E. (1990). The international Classification for seasonal snow on the Ground. International Commission on Snow and Ice (IAHS), World Data Center A for Glaciology, University of Colorado, Boulder, CO, USA. [Section 3]

Collins R.E., Rocap G., Deming J.W. (2010). Persistence of Bacterial and Archaeal communities in sea ice through an Arctic winter. Environmental Microbiology 7:1828–1841. [Section 8]

Cox G.F.N., Weeks W.F. (1983). Equations for determining the gas and brine volumes in sea-ice samples. Journal of Glaciology 29, 306-316. [Referenced in Tables 5.1 and 5.2]

Cox G.F.N., Weeks W.F. (1986). Changes in the salinity and porosity of sea-ice samples during shipping and storage. Journal of Glaciology 32, 371-375. [Referenced in Tables 5.1 and 5.2]

Crocker E., Maslanik J.A., Palo S., Fowler C., Herzfeld U.C., Emery W.J. (2012). A sensor package for ice surface characterization using small unmanned aircraft systems, IEEE Transactions on Geoscience and Remote Sensing 50(4), 1033-1047.[Section 9]

Deming J.W. (2010). Sea ice bacteria and viruses. In: Sea Ice – An Introduction to its Physics, Chemistry, Biology and Geology (Eds., D.N. Thomas & G.S. Dieckmann), pp. 247–282. Wiley-Blackwell, Oxford. [Section 8]

Druckenmiller M.L., Eicken H., Pringle D.J., Williams C.C., Johnson M.A. (2009).Towards an integrated coastal sea-ice observatory: System components and a case studyat Barrow, Alaska. Cold Regions Science and Technology 56, 61-72. [Sections 2, 9; description of the design and implementation of a coastal sea-ice observatory, including discussion of a case study]

Eicken H., Gradinger R., Salganek M., Shirasawa K., Perovich D., Lepparanta M. (2009). Field techniques for sea ice research. University of Alaska Press, 566pp. [monograph with detailed descriptions of approaches and multimedia DVD providing documentary footage and additional resources]

Eicken H. (2010). Indigenous knowledge and sea ice science: What can we learn from indigenous ice users? In: Krupnik I., Aporta C., Gearheard S., Laidler G.J., Kielsen Holm L. (Eds.), SIKU: Knowing our ice – Documenting Inuit sea ice knowledge and use. Springer-Verlag, New York, pp. 357-376. [Section 2; perspectives on how to incorporate indigenous and local knowledge into field work design]

Freitag J., Eicken H. (2003). Melt water circulation and permeability of Arctic summer sea ice derived from hydrological field experiments. Journal of Glaciology 49, 349-358. [Section 7; describes an approach on how to measure hydraulic conductivity or permeability of sea ice in the field]

Gradinger R., Bluhm B., Iken K. (2010). Arctic sea-ice ridges-Safe heavens for sea-ice fauna during periods of extreme ice melt? Deep-Sea Research Part I 57:86-95. [Section 8]

Haas C., Hendricks S., Eicken H., Herber A. (2010). Synoptic airborne thickness surveys reveal state of Arctic sea ice cover, Geophysical Research Letters, 37, L09501, doi:10.1029/2010GL042652. [Section 4; description of electromagnetic sounding application; includes further references on method]

Haining, R., 2003. Spatial data analysis - Theory and practice. Cambridge University Press, Cambridge. [Section 2; good general overview of sampling plan design and spatial variability]

Kwok R., Rothrock D.A. (2009). Decline in Arctic sea ice thickness from submarine and ICESat records: 1958 – 2008, Geophysical Research Letters 36, L15501, doi:10.1029/2009GL039035. [Section 4; description of results from ULS and satellite laser altimetry; includes further references on methods]

LaChapelle E.R. (1969). Field Guide to Snow Crystals, University of Washington Press, reprinted by the International Glaciological Society 1992. [Section 3]

Laxon S.W., Giles K.A., Ridout A.L., Wingham D.J., Willatt R., Cullen R., Kwok R., Schweiger A., Zhang J., Haas C., Hendricks S., Krishfield R., Kurtz N., Farrel S., Davidson M. (2013). CryoSat-2 estimates of Arctic sea ice thickness and volume. Geophysical Research Letters 40, doi:10.1002/grl.50193. [Section 4; description of satellite radar altimetry and validation efforts; includes further references on methods]

Leppäranta M., Manninen T. (1988). The brine and gas content of sea ice with attention to low salinities and high temperatures. Finnish Institute of Marine Research Internal Report 88-2, Helsinki. [Referenced in Table 5.1 and 5.2]

Light B., Grenfell T.C., Perovich D.K. (2008). Transmission and absorption of solar radiation by Arctic sea ice during the melt season, Journal of Geophysical Research 113, C03023, doi:10.1029/2006JC003977. [Section 6]

Millero F.J., Feistel R., Wright D.G., McDougall T.J. (2008). The composition of Standard Seawater and the definition of the Reference-Composition Salinity Scale. Deep-SeaResearch I 55, 50-72. [Section 5]

Morison, J.A., Aagaard K., Falkner K.K., Hatakeyama K., Moritz R., Overland J.E., Perovich D.K., Shimada K., Steele M., Takizawa T., Woodgate R. (2002) North Pole Environmental Observatory Delivers Early Results. EOS, Transactions of the American Geophysical Union, 83(357), 360-361. [Section 9; describes the North Pole Environmental Observatory]

Nicolaus M., Haas C., Willmes S. (2009). Evolution of first-year and second-year snow properties on sea ice in the Weddell Sea during spring-summer transition, Journal of Geophysical Research, 114, D17109, 10.1029/2008JD011227. [Section 3]

Notz D., Wettlaufer J. S., and Worster M. G. (2005). A non-destructive method for measuring the salinity and solid fraction of growing sea ice in situ. Journal of Glaciology 51, 159-166. [Section 5; alternative, highly accurate approach to deriving in situ brine volume fraction]

Perovich D.K., Grenfell T.C., Light B., Hobbs P.V. (2002). Seasonal evolution of the albedo ofmultiyear Arctic sea ice, Journal of Geophysical Research 107(C10), 8044, doi:10.1029/2000JC000438. [Section 6]

Richter-Menge J.A., Perovich D.K., Elder B.C., Claffey K., Rigor I., Ortmeyer M. (2006). Ice mass balance buoys: A tool for measuring and attributing changes in the thickness of the Arctic sea ice cover, Annals of Glaciology 44, 205–210. [Section 9; description of ice thickness measurements with thermistor strings]

Sturm M. (2009). Field Techniques for snow observations on sea ice. In: Field techniques for sea ice research, H. Eicken, R. R. Gradinger, M. Salganek, K. Shirasawa, D. K. Perovich and M. Leppäranta (Eds.), pp. 25-47, University of Alaska Press, Fairbanks. [Section 3]

Sturm M., Massom R.A. (2009). Snow and sea ice. In: Sea ice, D. N. Thomas, G. S. Dieckmann (Eds.), pp. 153-204, Wiley-Blackwell, Chichester. [Section 3]

Thorndike A.S., Rothrock D.A., Maykut G.A., Colony R. (1975). The thickness distribution of sea ice, Journal of Geophysical Research 80(33), 4501–4513. [Section 4; description of the nature and evolution of the ice thickness distribution]

Thomas D., Fogg G., Convery P., Fritsen C., Gili J., Gradinger R. (2008). The Biology of Polar Regions, Oxford University Press, Oxford. [Section 8]

Wadhams P., Doble, M.J. (2008). Digital terrain mapping of the underside of the sea ice from a small AUV. Geophysical Research Letters 35(1), L01501, doi:10.1029/2007GL031921. [Sections 4, 9; summary of techniques and data from an icecamp-based deployment of a AUV under sea ice in the Beaufort Sea]

Weissling, B., Ackley, S., Wagner, P., Xie, H., 2009. EISCAM - Digital image acquisition and processing for sea ice parameters from ships. Cold Regions Science and Technology 57, 49-60. [Section 10; describes a ship-board system for acquisition of digital images insupport of standardized ice observations]

Worby A.P., Geiger C.A., Paget M.J., Van Woert M.L., Ackley S.F., DeLiberty T.L. (2008). Thickness distribution of Antarctic sea ice. Journal of Geophysical Research 113, C05S92, doi:10.1029/2007JV004254. [Sections 4, 10; comprehensive analysis of ship-based sea-ice observations obtained by the Antarctic ASPeCt Program]

Glossary

Albedo: The fraction of incident sunlight that is reflected from the surface. The full range of albedo is from 0 (perfectly absorbing) to 1 (perfectly reflecting).

AUV: Autonomous underwater vehicle.

Draft: Depth of the ice/water interface below the water level. Ice thickness is the sum of draft and freeboard.

Freeboard: Height of the ice ("ice freeboard") or snow surface ("snow freeboard") above the water level. Ice thickness is the sum of (ice) freeboard and draft.

ISO: International Standards Organization.

ITP: Ice-tethered profiler. An instrument designed to measured the vertical structure of the water column beneath sea ice.

LIK: Local and indigenous knowledge.

Macrofauna: in sea ice, these are small animals retained on a 200 µm mesh.

Meiofauna: in sea ice, these are small animals retained on a 20 µm mesh.

Melt pond: Pool of melt water that remains on the sea ice surface during summer. The water originates from snow and sea ice melt.

PAR: photosynthetically active radiation.

Phototrophs: organisms capable of photosynthesis.

Pressure ridge: Piles of ice blocks above ("ridge sail") and under ("ridge keel") the surrounding, undeformed level ice formed by lateral compression or shear of an ice field or ice floe. Pressure ridges and can be tens of meters thick and several meters high. Their strength and hazard potential depend on the degree of consolidation of ice blocks by freezing once formed.

psu: Practical salinity units, reported on the unitless practical salinity scale. Recently, a reference composition salinity scale based on solutes per kg of solution (reported in g/kg) has been developed.

Psychrophile: an organism that grows exclusively at low temperature.

ROV: Remotely Operated Vehicle, similar to AUV, but connected to the surface though a tether cable, which usually allows for power supply, vehicle control, and data transfer.

Sea ice thickness distribution: Histogram of the fraction $\mathrm{d}A$ of ice of certain thickness $h + \mathrm{d}h$ in a region A, where $\mathrm{d}h$ is the thickness bin width. The thickness distribution is often characterized by several modes (maxima) representing the thickness of the prevailing ice types, which differ from the mean thickness. Thickness distributions possess a long tail towards thick ice, representing the amount and thickness of pressure ridges.

Stratigraphy: Sequence of layers with characteristic properties. The stratigraphy allows conclusions about the growth history and metamorphism of the sea ice or snow pack.

TEK: Traditional environmental (or ecological) knowledge.

Transmittance: Fraction of sunlight that penetrates through the sea ice and its snow cover into the ocean underneath. It is the remaining amount of light after reflection and absorption.

Transport property: Any physical property of a material that is related to the movement of either mass or energy. In general the flux of energy or mass is equal to the transport property times the gradient of some physical state of the material. Thus the flux (rate of flow per unit area) of heat through a material equals the thermal conductivity of the material multiplied by the temperature gradient. Although a transport property of sea ice is a bulk property of the sea ice it is dependent on the properties and geometry of the individual ice and brine components.

UAS: Unmanned Aircraft Systems is the term used to include both the aircraft and the ground-based infrastructure and the personnel required to operate it.

ULS: Upward-looking sonar. Employed in determining ice draft by measuring the distance between sonar position (on a mooring or submerged vehicle) and the ice bottom. Also referred to as ice-profiling sonar (IPS).

Biographical Sketches of the Authors

Bodil Bluhm is a Research Associate Professor in Biological Oceanography and Marine Biology at the University of Alaska Fairbanks. Her research focuses on the structure and function of Arctic marine seafloor and sea ice ecosystems. She is particularly interested in who lives on Arctic shelves, slopes and in the basins in terms of species and communities, how they sustain growth, production and trophic connections in a seasonally food-limited limited system, and how these communities may be changing over time in relation to environmental forcing.

Eric Collins, Assistant Professor of Oceanography at the University of Alaska Fairbanks, has expertise utilizing environmental genomics techniques (e.g. metagenomics, transcriptomics) and computational modelling to study microbial evolution of polar marine microbes. With international arctic field experience over 10 years in both winter and summer conditions, he co-instructed "Field Techniques in Interdisciplinary Sea Ice Research" in Barrow, Alaska, and recently crossed Greenland on skis as part of the Greenland Ice Microbiome Project.

Hajo Eicken is Professor of Geophysics at the University of Alaska, Fairbanks. His research interests include field studies of the growth and properties of sea ice. He is particularly interested in determining how small-scale ice properties relate to large-scale sea-ice processes and the climate system. Through collaborative research in coastal Alaska, he has been working towards implementation of an integrated sea-ice observatory that provides an interface between geophysical and indigenous or local knowledge of ice conditions and coastal hazards.

Rolf Gradinger is Professor in Biological Oceanography at the University of Alaska Fairbanks. His main research interest focuses on the structuring role of sea ice for biological processes in Arctic waters. He conducted research on sea ice primary production and occurrence of sea ice meio- and macrofauna in a wide range of Arctic seas. He was also involved in the Arctic Ocean Diversity project as part of the Census of Marine Life.

Christian Haas received his PhD from the University of Bremen, Germany. He is a Professor and Canada Research Chair in Arctic Sea Ice Geophysics at York University, Toronto, Canada. His research focuses on in-situ, airborne, and satellite observations of the sea ice mass balance in the Arctic and Antarctic, with applications to climate research and offshore operations. Before moving to York University in 2012, he was an Alberta Ingenuity Scholar with the University of Alberta in Edmonton, Canada, since 2007.

Malcolm Ingham is a physicist at Victoria University of Wellington, New Zealand. His research concentrates on the application of electrical and electromagnetic geophysical techniques to environmental issues such as the microstructure of sea ice and the hydraulic properties of aquifers, and to the understanding of geothermal and volcanic regions.

Andy Mahoney is a Research Assistant Professor of Geophysics at the University of Alaska Fairbanks. His broad field of expertise is sea ice geophysics and his research interests encompass climate change, coastal dynamics, ice-ocean interaction and the relationship between humans and sea ice. He has spent 14 years studying sea ice in the Arctic and Antarctic using instruments from tape measures to spaced-based radar, but some of his most memorable lessons come from dogsled trips over the ice with local experts.

Marcel Nicolaus is a research scientist at the Alfred-Wegner-Institut Helmholtz-Zentrum für Polar- und Meeresforschung in Bremerhaven, Germany. As a geophysicist he works on physical properties of sea ice and snow, mostly based on field observations in the Arctic and Antarctic. He currently focuses on analyses of the energy and mass balance of sea ice with their variability and trends during different seasons.

Don Perovich is a Research Geophysicist at the Cold Regions Research and Engineering Laboratory in Hanover NH. His research focuses on the partitioning of solar radiation by a sea ice cover and the impact on sea ice mass balance.