FIELD TECHNIQUES IN SEA-ICE RESEARCH

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Contents

Summary

This chapter 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.

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.

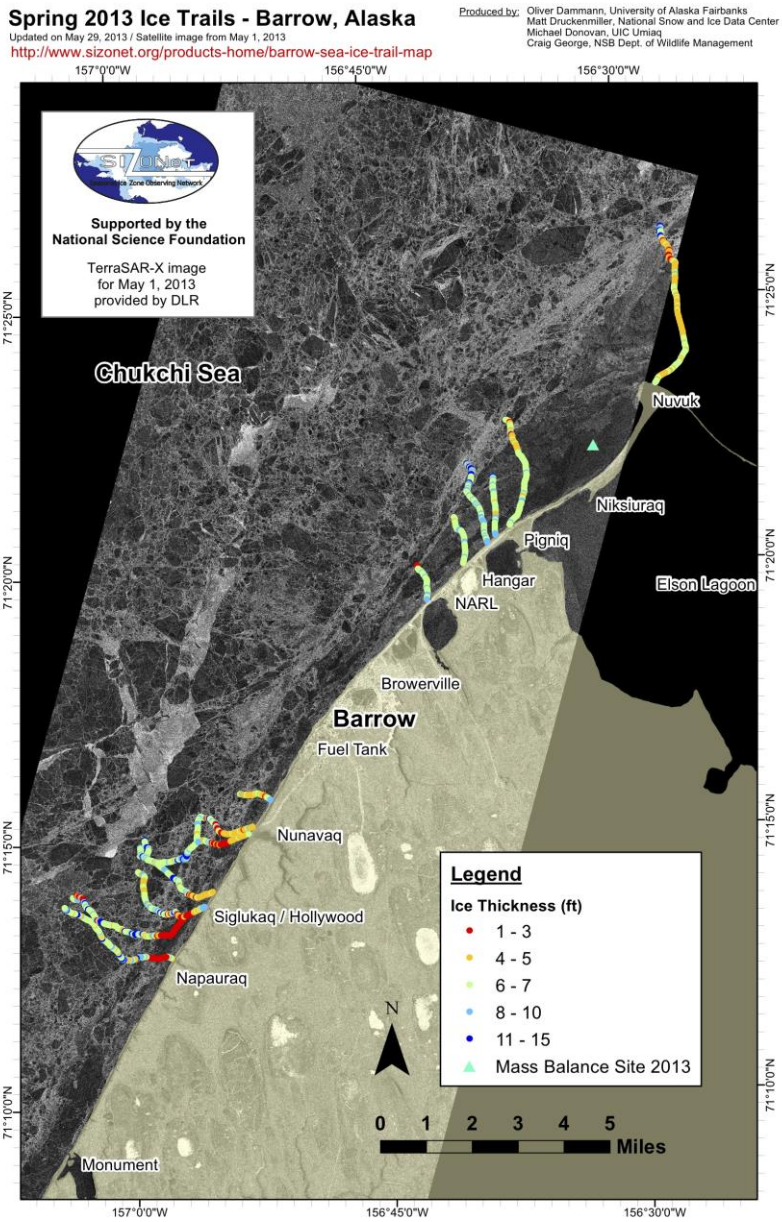

Figure 1. TerraSAR-X satellite scene (courtesy of DLR, Germany) for Barrow region on 1 May 2013. Also shown are thickness profiles, obtained with an EM-31 (see Section 4) along ice trails put in place by Iñupiat hunters from Barrow (data and map compiled by D. O. Dammann, University of Alaska Fairbanks). 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.

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 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 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.

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, inter-annual 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, 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. 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, 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. 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.

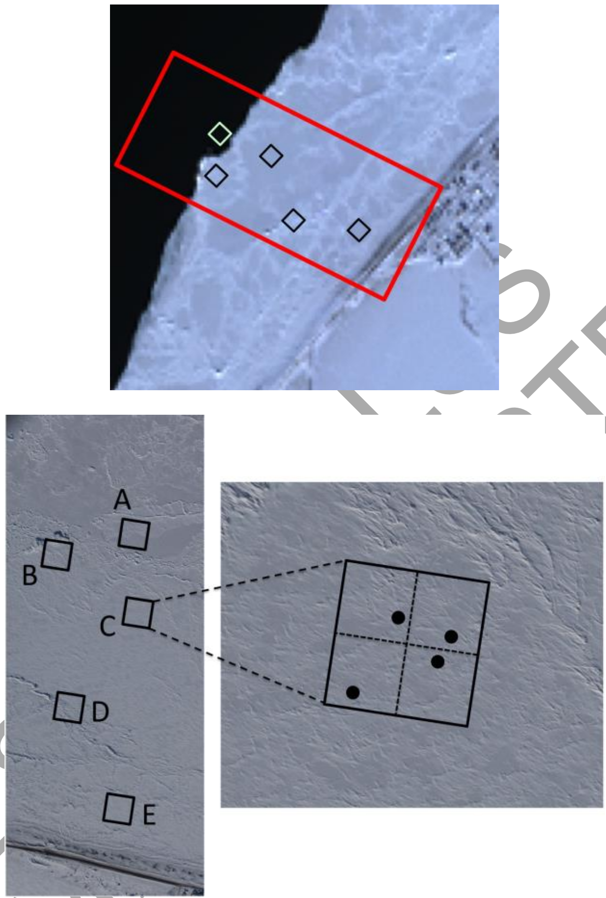

Figure 2. Low-resolution false-color visible-range satellite image obtained from a Digital Globe satellite scene for 16 March 2013, covering part of the Naval Arctic Research Laboratory (NARL) complex at Barrow, AK along with a stretch of shorefast ice and adjacent open ocean (top; North is up). The 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 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.

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Biographical Sketches

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 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 modeling 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.

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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.

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