Paper #5-6

CURRENT PRACTICE - TECHNOLOGY UTILIZED FOR CHARACTERIZING AND MEASURING ICE

Prepared for the

Technology & Operations Subgroup

On March 27, 2015, the National Petroleum Council (NPC) in approving its report, *Arctic Potential: Realizing the Promise of U.S. Arctic Oil and Gas Resources*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Technology & Operations Subgroup. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached paper is one of 46 such working documents used in the study analyses. Appendix D of the final NPC report provides a complete list of the 46 Topic Papers. The full papers can be viewed and downloaded from the report section of the NPC website (www.npc.org).

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Topic Paper

(Prepared for the National Petroleum Council Study on Research to Facilitate Prudent Arctic Development)

5-6	**Current Practice – Technology Utilized for Characterizing and Measuring Ice**
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SUMMARY

The paper provides an overarching summary of the current technologies used to characterize the ice environment to address the needs of industry. Technologies have been grouped into four main categories: satellite sensors, airborne sensors, underwater and direct (on ice) measurements.

INTRODUCTION

Characterizing and measuring ice is performed for various purposes, such as documenting the change in ice over the recent years, determining loads on vessels and structures, and for improving numerical modeling. There are several measurement parameters of interest for characterizing ice, most of which are physical properties of the ice but can be broken down into the following parameters:

- Dimensional (floe size, thickness, mass, ridging, keels)
- Dynamic (speed, stress)
- Spatial (extent, concentration, area, fast ice edge, leads)
- Temporal (seasonality, growth/decay rates, age)
- Material (composition, type, stage of development, strength, temperature, salinity)

In studying ice, the completeness or sufficiency of the characterization differs by requirements of the application. Extensive knowledge of all parameters is not absolutely necessary to develop a sufficient characterization for the purposes of prudent commercial activities. The most demanding requirements for parameters come from the numerical modeling community and academic interest. There are always parameters that are poorly defined or completely unknown, yet models exist and are useful. Additional observations, additional parameters, and long time series serve to improve model performance and reduce statistical uncertainties.

This is mentioned because there can be basic challenges to some aspects of characterizing and measuring ice that may require a combination of approaches, allowance of limitations, and statistical techniques. Thickness of a given floe of ice, for instance, can be a difficult parameter. Since the sea ice is often composed of various ice types and may be under frequent movement or stress, it is rarely undeformed. The deformations form ridges, keels, and unconsolidated layers, resulting in considerable local and regional variability. With available methods for measuring ice thickness, the greater the distance between the ice and measurement platform, the more spatial averaging becomes a factor. In a simplified example, a person can auger a hole through a piece of ice and get a fairly exact estimate of the thickness at that point (which is actually an average over the size of the ice hole). Using non-destructive methods, such as ground penetrating radar or electromagnetic systems, the effective footprint of the measurement area (i.e. area over which the thickness will be averaged) increases with altitude of the sensor. Mounted on a sled and towed across the ice, the footprint will be on the order a couple of feet, depending on the overall thickness of the ice. However a sensor used from an aircraft will have a much larger footprint. While progressing from point, to sled, to aircraft the extreme thickness features (keels) of the ice become increasingly smoothed, but more area is being sampled. Also, this ice is more than likely covered by a layer of snow, and that potentially biases the estimate, so knowledge of the snow depth may be important. To further complicate this example, altimetry methods from air or space detect the freeboard of the ice (i.e. the portion above the waterline) including the snow depth, but provide no information on the underwater thickness. Therefore, it's necessary to gain knowledge of the ice draft using sonars mounted on moorings or underwater vehicles. Since the spatial averaging (footprint) between satellite or aerial altimetry and underwater sensors will differ, and it is not likely the samples are co-registered in time and space, hence characterization of ice thickness is generally expressed as statistical distributions. In fact, distributions, such as a cumulative frequency distribution or probably density function, are suitable for describing many types of ice parameters, be it floe size or keel depth.

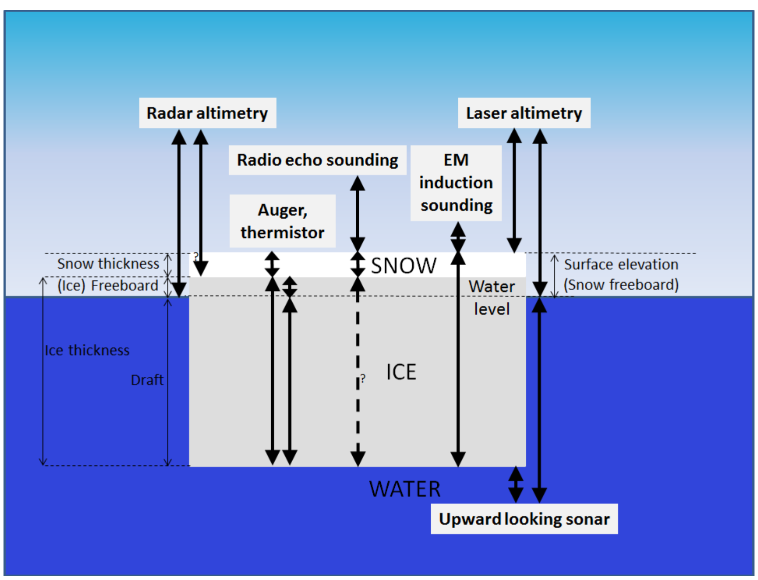

Figure 1.Schematic diagram of snow covered sea ice, showing the various dimensional parameters of interest and what various instruments measure. (H. Eicken, used with permission)

It becomes clear that when it comes to taking measurements or observations of the ice, there are distinct advantages and disadvantages to the various approaches and trade-offs or compromises are common. For example, MODIS is a freely available satellite product that can produce stunning optical imagery of wide areas of sea ice and is useful for determining location of the ice edge, sea ice extent, and location of various ice features. However, MODIS gets obscured by cloud cover and as a result there may be numerous days in a row that ice observations cannot be made with MODIS. The trade-off is that there is no cost for the imagery and the research may need to consult other satellite sources in the interim. This may have little to no impact on the strength of a long term characterization, but it could be disastrous for operational support. In an operational support case, the trade-off might be that one needs to spend significant dollars and contract Synthetic Aperture Radar (SAR) satellite imagery, which is unaffected by cloud cover.

As with numerical modeling, the spatial and temporal scales and resolutions are important factors for determining sufficiency of purpose for a particular characterization or measurement. The scales and resolutions required for pan-Arctic studies differs from those necessary for site-specific investigations and that translates into utilizing differing technologies to meet study objectives. Considering the satellite imagery example again, the resolution and areal extent are inversely proportional- the higher the pixel resolution, the smaller the image footprint. The pan-Arctic study is better served by the broad coverage of lower resolution imagery and would gain no material benefit from using higher resolution data. A site specific study, on the other hand, would find low resolution/wide area imagery of less value. The question of sufficiency is best answered by the investigator.

What does this mean for the overarching theme of characterizing and measuring ice? This goes toward pairing the observational tools to the measurement objectives and understanding where trade-offs may become necessary.

MEASUREMENT PARMETERS

The following is a list of common parameters often sought for the purpose of characterizing ice. They are presented here to provide a brief definition of the terminology and is by no means an exhaustive list.

- Extent – The area of a region that is covered by ice of at least 15% concentration.
- Area – The total are of the ice portion within a given extent. If a given extent is covered 100% by ice, then the extent and area are equal.
- Concentration – The areal ratio of ice to water over a given spatial extent.
- Drift – Displacement of ice floes and other ice features resulting from the impact of wind and currents including tidal currents and of forces transferred through the ice cover from other regions.[1]
- Thickness – The vertical measurement of ice. This would include the freeboard (thickness above the waterline) and draft (thickness below the waterline). If the ice is deformed, then ridge height and keel height would be added.
- Floe size – The area of a relatively flat contiguous piece of ice expressed in defined terms.

[1] http://www.aari.nw.ru/gdsidb/docs/wmo/nomenclature/WMO_Nomenclature_draft_version1-0.pdf

- Age – Newly formed Ice that has not experienced a summer melt season is termed First Year Ice (FYI). If that same ice survives a summer melt, it is now called second year ice. Ice that survives more than one summer melt is called Multi-Year Ice (MYI). Since it is often difficult to discern second year form MYI, all ice older than FYI is usually referred to as MYI.
- Stage of Development – As ice forms, it will go through defined stages. These stages are telling as to the appearance and thickness of the ice. FYI and MYI are considered stages of development.
- Composition – The fraction of ice types within a given floe.
- Seasonality – Timing of the arrival or departure of ice at a particular location.
- Growth/Decay Rate – The speed of development or melt of the ice.
- Deformation – Ice that has gone through a pressure process or collision and has fractured or combined with surrounding ice.
- Lead – A rectilinear or wedge-shaped crack that is more than 50 m wide and can run several kilometers to several hundreds of kilometers in length.

REMOTE SENSING

Because of the remoteness of the Arctic and the harsh climate, satellite data provide the only means to provide continuous and complete long-term monitoring of the polar regions. Fortuitously, the contrast between ice and ice-free surfaces is distinct in several bands of the electromagnetic spectrum, thus allowing numerous technologies to be employed. However, all sensor types have limitations and no single sensor can provide complete information.

SATELLITE - PASSIVE MICROWAVE

Imagery from passive microwave sensors has been available since 1972 and multi-channel radiometers have been available since November 1978. These sensors have provided one of the longest satellite climate records and have been instrumental in detecting long-term changes in the ice cover. An advantage of the microwaves is that the atmosphere is transparent at many microwave frequencies. Also, passive microwaves are emitted by earth itself and thus independent of solar radiation. So passive microwave data of sea ice can be obtained in nearly all sky conditions (except thick, precipitating clouds). This is crucial in the polar regions that are enshrouded in darkness for up to six months every year and where clouds are widespread.

Passive microwave energy is sensitive to the phase state of water and thus is ideal at discriminating ice from water. They have been employed to derive fields of sea ice concentration, extent (e.g., Cavalieri and Parkinson, 2012;), age (multi-year, seasonal), melt onset (Drobot and Anderson, 2001), and freeze-up (Markus et al., 2009). New sensors at lower frequencies are also sensitive to thickness up to a certain point (~0.5 m) and thus can be used to estimate thin ice thickness (Kaleschke et al., 2012).

The sensors are wide-swath and provide nearly complete daily coverage of the polar regions (outside of a "pole hole" resulting from the satellite orbit characteristics). The primarily limitation of passive microwave sensors is their low spatial resolution. Sensor footprints of key channels have been as large as ~50x75 km. Newer sensors have smaller footprints, but still are on the order of ~20 km. This means that small-scale features are not detectable and there is ambiguity in transition regions (e.g., sea ice edge, coast), which limits the precision needed for operational activities. Weather effects, though limited, do occur – particularly due to wind roughening of the ice-free ocean. Also because of the sensitivity to water phase, summer conditions that have liquid water on the ice surface and/or melt ponds can substantially bias retrievals.

Key sensors in the passive microwave record, and years of operation:

- Nimbus-5 Electrically Scanning Microwave Radiometer (ESMR), 1972-1977
- Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR), 1978-1987
- DMSP Special Sensor Microwave Imager [and Sounder] (SSM/I and SSMIS), 1987-present
- NASA EOS Advanced Microwave Scanning Radiometer (AMSR-E), 2002-2011
- JAXA Advanced Microwave Scanning Radiometer 2 (AMSR2), 2012-present
- ESA Soil Moisture Ocean Salinity (SMOS), 2009-present

SATELLITE - ACTIVE MICROWAVE

Like passive microwave instruments, active microwave sensors are sensitive to water phase and thus very useful for ice-covered regions. Scatterometers measure backscatter from the surface and can provide ice extent and ice edge detection and indicate melt onset. They are even more sensitive to salinity in the ice and thus more effective in winter at discriminating ice age. Scatterometer data has been employed for sea ice extent and multi-year fraction (Nghiem et al., 2007). Scatterometer resolution is similar to passive microwave sensors and there are similar limitations associated with it.

Synthetic aperture radar (SAR) is another active microwave technology. It uses the motion of the satellite to simulate a larger antenna allowing much higher spatial resolution (<<100 m). Thus SAR data can detect small-scale details such as leads, polynyas (Kwok and Cunningham, 2012). SAR beam modes can be programed to acquire wide areas (500x500 km) to small narrow swaths in a single image. In general, the larger the footprint (areal coverage), the lower the possible pixel resolution. Sea ice forecasting commonly use the ScanSAR Wide beam mode on the RADARSAT2 satellite, which covers 250,000 km^2 at 100 meter resolution.

Both scatterometers and SAR have limitations due to melt water and more ambiguity due to wind roughening than passive microwave. And especially for SAR, the backscatter characteristics of ice vary through the year, making automated detection very difficult. Typically, SAR data is analyzed manually to provide expert human interpretation.

Key active microwave sensors, and years of operation:

- ESA ERS-1/2, 1991-2011
- ESA ASCAT, 2006-present
- ESA Envisat, 2002-2012
- NASA QuikScat, 1999-2011
- JAXA ALOS/ALOS-2, 2006-2011, 2014-present
- ISRO Oceansat-2, 2009-present
- RADARSAT, 1995-present
- TerraSAR-X, 2007-present
- Cosmo-SkyMed, 2007-present

SATELLITE - VISIBLE/INFRARED

Ice and ocean/land are distinguishable in the visible spectrum due to different reflectance (ice is more reflective) and thermal (ice is colder) characteristics. The imagery is generally easy to interpret and automated algorithms have been developed. The spatial resolution is relatively high resolution (250-1000 m for freely available data from national space programs; 1-30 m resolution from defense and commercial satellites). However, visible imagery requires sunlight, limiting its use in the polar regions to between spring and fall. In summer, when ice is melting, the surface tends to be isothermic, which limits the capabilities of infrared imagery. Transition regions can be ambiguous – newly forming thin ice has nearly indistinguishable thermal and reflective characteristics than the surrounding open ocean. Clouds are also a severe constraint as neither visible nor infrared imagery can detect the surface through clouds. A further complication is that unlike mid-latitude and tropical regions, cloud masking in the high latitudes is difficult because clouds often have similar temperatures and reflectances as the underlying ice cover. Despite these issues, numerous ice parameters have been derived, including sea ice concentration, albedo, temperature (Key et al., 1997; 2001), and melt pond fraction (Tschudi et al., 2008).

Key visible/infrared sensors, and years of operation:

- NOAA Advanced Very High Resolution Radiometer (AVHRR), 1981-present
- NASA Moderate Resolution Imaging Spectroradiometer (MODIS), 1999-present
- NOAA/NASA Suomi/VIIRS (Visible Infrared Imaging Radiometer Suite), 2011-present

SATELLITE - ALTIMETERS

Ice thickness is a key parameter of interest. However, most remote sensing technologies can only determine surface properties. The exception is altimetry. Using a laser or radar, signal pulses are emitted by the sensor and the reflected signal is detected. With precise orbit determination, an accurate clock, and knowledge of the geiod, the surface height can be estimated. For sea ice, this surface height corresponds to “freeboard” or height above the ocean surface. Total sea ice thickness is calculated from freeboard using information on ice and water densities.

This technology is still relatively new, especially for sea ice and there are several limitations. First, even with precision orbit determination, there is uncertainty in the measured signal. For ice in water, because of the density differences, 80-90% of the ice is below the water line. Thus uncertainty in freeboard is magnified when converting to total thickness. Snow cover is also a significant contributor to uncertainty. Snow weighs down the ice, and its effect must be accounted for in the relative ice/water densities. Radar altimeters generally penetrate through snow to the ice surface and thus can directly retrieve ice freeboard estimates. However, the laser altimeter return is from the top of the snow surface. So the snow depth must be subtracted off to obtain sea ice freeboard. Unfortunately, snow depth measurements in the polar regions are limited and approaches are based on climatologies or snow precipitation estimates from atmospheric reanalysis fields. After falling to the surface, snow is also redistributed by winds, further complicating the issue. The small footprint size and largely nadir-viewing limit spatial coverage and limit repeat visit cycles. Thus complete fields are available only at roughly monthly timescales.

Despite these limitations, satellite altimeters are now providing important information on sea ice (Laxon et al., 2013; Kwok et al., 2009) and ice sheet thickness and will do so into the future.

Key satellite altimeters, and years of operation:

- NASA ICESat (Ice, Cloud, land Elevation Satellite), 2003-2009
- ESA CryoSat-2, 2010-present

- NASA ICESat-2, planned launch in 2017

AIRCRAFT REMOTE SENSING

Aircraft platforms can offer distinct advantages. The lower altitude provides higher spatial resolution from sensors compared to satellite platforms and aircraft have the capabilities to fly under moderate or high cloud decks to observe surfaces not detectable by similar satellite-borne sensors. Of course, there is a significant limitation in coverage. Airplanes can only fly under acceptable flight conditions and can only cover limited distances. Repeat visits are limited due to logistics and the cost of flight hours. Nonetheless, aircraft can obtain validation data for satellite products and provide valuable complementary data.

NASA's Operation IceBridge is a perfect example of complementary data. The regular aircraft missions over sea ice, glaciers, and ice sheets provides a bridge between ICESat and the CryoSat-2 and ICESat-2 missions. While coverage is limited, the flights are able to provide high-density information in key regions at yearly or bi-annual intervals. Another advantage of aircraft exemplified by IceBridge is the capability to fly much more payload. This allows simultaneous collection from several different instruments. This can help better understand and resolve ambiguities in the retrievals from individual sensors. Sea ice thickness and snow depth fields have been derived from IceBridge data (Farrell et al., 2012; Kurtz and Farrell, 2011)

Operation IceBridge is just one of many aircraft expeditions over the years. Several European campaigns have been conducted for CryoSat-2 validation. These included the use of Electromagnetic induction (EM) sensors (Haas, 2004). These sensors penetrate through sea ice to measure the ice-water interface. EM sensors provide accurate thickness data, but must be near the surface. Thus they are often deployed either on the ground (towed on sled) or near the surface by helicopters or low-flying airplanes.

LIDAR

Light detection and ranging (LIDAR) is an active remote sensing technology, similar to radar, that transmits laser pulses to a target and records the time it takes for the pulse to return to the sensor receiver. This technology is currently being used for high-resolution topographic mapping by mounting a lidar sensor, integrated with Global Positioning System (GPS) and Inertial Measurement Unit (IMU) technology, to the bottom of aircraft and measuring the pulse return rate to determine surface elevations.[2] With LIDAR mounted to an aircraft, it's possible to create swath maps of sea ice freeboard and surface elevations.

PHOTOGRAPHY

Cameras mounted or used from aircraft can provide valuable qualitative information about sea ice. This can be a useful record, since an experienced analyst can note considerable details about the ice, such as approximate size, location, and quantity of MYI floes and ridging, stages of development, descriptions of cracks, leads, polynyas, and location of the ice edge. Aerial photography has proved valuable to 'ground truth' or validate features observed in satellite products. This helps analysts to calibrate themselves for better interpretation of satellite images. However, unless flying low (<500'), it's difficult to estimate details like ridge height and rubble size, since spatial references are difficult at altitude. Another issue is that it is difficult to georeference features. Unless expensive mapping-grade cameras are utilized, where details like inertial, attitude, calibration data are captured to compensate for frame of reference orientation

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[2] http://nsidc.org/daac/projects/lidar/

and physical distortions, operators of standard photography gear must take care in recording the aircraft position at time of image acquisition at minimum. Preferably, the operator would capture additional details, such as altitude, heading and roll angle of aircraft, direction of shot (earth-fixed or with respect to aircraft heading), and angle of shot (with respect to the ground or horizontal plane), to aid in later analyses of the images.

AUTONOMOUS FLIGHT PLATFORMS
Manned flight is seen as a safety risk for many operators and investigators in the Arctic, due to frequently poor flying conditions, limited choice of airframes, range limitations, minimal aviation infrastructure, and emergency response times. The goal is to move aviation-based science observations and measurements to autonomous platforms. In recent years, there as been good progress testing Unmanned Aerial Systems (UAS), also called drones, in the Alaskan offshore. For the most part, the barrier to UAS' is not technology, rather legality. In the US, the Federal Aviation Administration has been slow to embrace general operation of UAS and evolve rules for their use. It is practical to assume that most of the observations and measurements currently possible on manned aircraft are achievable on UAS platforms. The expectations are that once fully operationalized, UAS will provide more data due to lower operating costs, longer flight times, and greater availability.

SHORE-BASED RADAR
Marine radar systems have been successfully used to monitor near-shore ice locations in Alaska. Operated by the University of Alaska Fairbanks, these 10-25 kW X-band radars are mounted on buildings near the coast in Barrow and Wales and have a range of approximately 10 km. These systems produce still images and animations for observation of ice movement, deformation, breakout events, and stability of fast ice.[3]

MARINE RADAR
An enhancement to utilizing standard marine navigation X-band radars for ice observations are specialized workstations installed on vessels that combine advanced video processing and geospatial mapping tools. Based on the Sigma S6 scan averaging video processor developed by Rutter Technologies, integrated systems like the Enfotec IceNav and Ion Narwhal allow high resolution imaging of ice, including small slow moving features, over the range of the radar-which is typically to the horizon. Using the geospatial tools, georeferenced data such as satellite imagery, weather surface maps, and ice charts can be overlaid and individual ice targets can be tracked. Shell Exploration and Production ice-capable vessels and drilling rigs operating in Alaska include IceNav systems as an ice surveillance tool.

UNDERWATER PLATFORMS

Thickness joins ice presence, concentration (i.e. fractional coverage) and type as one of the primary variables for characterizing the Arctic ice environment. Moreover the relatively small ice features of great interest to offshore operations, such as ridges leads and floes, are best delineated via detailed mapping of ice thickness.

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[3] http://seaice.alaska.edu/gi/observatories

Technology and logistics capability for wide-ranging, all-season surveillance of sea-ice thickness lags far behind that for mapping the presence, concentration and type of sea ice. There are two reasons: first, sea ice is largely opaque to electromagnetic radiation that might otherwise be used to map its thickness from aircraft or satellite; second, sea-ice thickness varies appreciably over distances of 1-10 m that are difficult to resolve from great distance in space. Although progress is now being made in the development of topside remote sensors to address these challenges, it is acoustic remote sensing from submerged platforms that has been most useful in providing information on sea-ice thickness and it variations during the past half century.

AUV/SUBMARINES

The method of using sound waves to derive the thickness of floating ice is straightforward. A single-beam sonar is positioned looking directly upward at a depth safe from moving ice (35-50 m); the depth of the sonar is determined from the difference between measured total pressure at depth and local sea-level atmospheric pressure, with knowledge of the ocean density profile enabling conversion from pressure to depth. The distance to the bottom of the ice is determined from the echo travel time, with knowledge of the ocean sound speed profile allowing conversion from travel time to distance. The ice draft (roughly 90% of it thickness) is calculated as depth minus distance to the ice and ice thickness is estimated from knowledge of the ratio of sea-ice to seawater density, assuming local isostasy.

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Figure 2. A single-beam sonar spatial profile taken by submarine showing ridges and undeformed ice.

Upward-looking sonar was deployed on nuclear submarines (USA, Russia, UK, France) in the Arctic starting in the late 1950s, for navigational purposes and later scientific analysis. Resolution has been appreciably poor for submarine systems because of wide beam-widths (2-5°) and depth of submergence (up to several hundred meters). Accuracy in draft ranges between ±0.05 and ±0.5 m, depending on how well density and sound speed are known in the overlying ocean. Observations from submarines developed a vast database of ice thickness distributions, distributions of pressure ridge depths and spacings, and occurrence of leads.

Submarine sonar surveys ice-topographic transects in the conventional manner: the navigational data from the fast-moving vessel defines the survey track below the ice, typically the slow ice drift during the surveys is ignored.

Advancements in unmanned autonomous underwater vehicle (AUV) technology enable similar observations to be made by civilian operators. These missions can be run in shallower water and have more flexibility for the survey location and study timing.

IPS/ADCP

Self-contained Ice-Profiling Sonar (IPS) was developed for scientific purposes in the 1980s and has been in routine use from fixed sub-sea moorings since 1990. A narrow acoustic beam is a key design feature of the under-ice sonar. The 1-2° beam of the IPS provides nominal 1-m resolution of under-ice topography from normal operating depth;

There has been a critical operational difference between submarine and moored deployments: submarines have provided occasional short-lived surveys of several thousand kilometres beneath Arctic ice, whereas IPS has been operated year-round from moorings at fixed locations, measuring the ice as it drifted overhead. IPS in the southern Beaufort Sea surveys 1000-3000 km of ice annually.

The IPS on a mooring measures the under-ice topography as a time series, thereby accumulating a distorted geometric picture of ice topography as the speed and direction of drift changes. If an Acoustic Doppler Current Profiler (ADCP) is positioned nearby the IPS to measure the ice drift at high temporal resolution (sub-hourly) in a Eulerian context, a pseudo-trajectory of the drift can be calculated; this differs from the true trajectory because ice velocity varies with location (i.e. pack ice deforms as it moves). A locally accurate topographic transect can be calculated by mapping the ice draft values onto the pseudo-trajectory. If the data are subsequently re-sampled to equal increments (1 m) of distance along the pseudo-trajectory, spatially weighted statistical properties of ice draft can be evaluated. Over short intervals of time (days) these statistical measures are analogous to those from submarines; over longer intervals (weeks to months) they track changes in the pack ice over forced by storms and the cycle of seasons.

An added advantage to the IPS/ADCP mooring method is that these instruments also measure profiles of the water currents and water temperature at the depth of the sensor at high temporal resolutions (<1 hour) and can estimate non-directional waves during periods of open water.

Ice measurements by sonar from submarines or sub-sea moorings share two attributes that inhibit their use in tactical (i.e. real time) support. These are the difficulty of targeting surveys where and when they are needed, and the difficulty of timely delivery of data from the survey platform to operations. In consequence, with the exception of the obvious tactical value for naval operations, data from sub-sea sonar have to date generally been used strategically, providing great value in the conceptual planning of offshore operations (e.g. rig supply, cargo transfers at sea, product loading and trans-shipment, spill counter-measures) and in defining the extreme conditions of loading that offshore structures, their foundations or anchoring systems, seabed pipelines and ships must be designed to withstand.

There are two technological developments that could be fruitful in overcoming the limitations on tactical use. Sonar could be moored at a number of locations surrounding an offshore oilfield structure, to provide information from all possible directions of ice attack. These systems could be linked to the structure via cables carrying power and telemetry, allowing real-time access to data.

AWAC

As mentioned in the previous section, an IPS measures a time series of the ice canopy and requires a secondary instrument (ADCP) to estimate a psudo-trajectory. While this system works well, it is complicated by the need of two moorings and data are recorded to separate internal loggers that require reconciliation during post processing. Recently, similar utility to the IPS/ADCP combination has been achieved using a single instrument. The Nortek AWAC

(Acoustic Waves and Current) contains the vertical sonar and inclined Doppler sonar transducers and has been demonstrated in the US Beaufort Sea (Magnell 2010). Aside from simplifying the mooring and data reconciliation issues of the IPS/ADCP, it can also estimate directional waves.

MULTIBEAM SONAR

Whereas single-beam sonars on underwater platforms provided valuable data on under ice features, they provide only a linear, two-dimensional view- a narrow spatial series of depth along the measurement track. In 2004, a multibeam sonar, commonly used for bathymetric surveys, was mounted upward looking on the Autosub AUV to survey the underside of the ice canopy. This effectively expands the field of view several tens of meters wide, capturing a 3D elevation (depth) swath of the underwater surface of the ice. With these observations, first year ice features are easily distinguished by their sharp, rough character, while older multi-year ice becomes apparent due to its smoother, weathered appearance. This cross-track view also gives a better estimate of the overall volume of submerged ice features.

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Figure 3.

SIDESCAN SONAR

Similar to the application of multibeam sonars, sidescan sonar can capture a wide cross track swath of the underside of the ice when used inverted (upward looking) on an underwater vehicle. Where multibeam sonars measure the time travel of an emitted acoustic pulse reflecting off of a surface, sidescan sonar measures the intensity of the returned pulse. Surfaces with a lot of roughness results in more reflected energy than smooth surfaces. In this way, sidescan sonar is useful for distinguishing first year from multi year ice and quantifying locations of pressure ridges and random deformations. Multibeam sonars are generally preferred, since they, unlike sidescan sonar, can estimate the depth or draft of the canopy over the entire swath. However, sidescan can outperform multibeam when it comes to resolving detail or small features. Sidescan sonar can measure range to a target and using this information, the keel depth along the path of travel can be estimated much like the upward-looking single-beam sonars discussed in earlier sections (Wadhams, 2004).

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Figure 4. Sample of sidescan sonar data take from an AUV mission in East Greenland in February 2002 (Wadhams 2004).

DIRECT MEASUREMENTS

The previous sections discussed methods that do not actually come in contact with the ice and can perform their observations or measurements at a distance. While many of the remote sensing techniques excel at supporting wide area characterizations, they tend to do so at the expense of spatial resolution- and in some cases, the results are inferences or proxies based on clever processing. Direct measurements, on the other hand, are those where the investigator or instruments are in contact with the ice it is measuring. These methods are capable of performing highly detailed measurements at a point or of a particular specimen, but they tend to be impractical for wide area characterizations. However, when combined with remote sensing methods or used as a basis for validating remote sensed estimates, reasonable characterizations over wide areas can be obtained.

ELECTROMAGNETIC SOUNDINGS

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. (Eicken (need citation))

DRILL HOLES

Direct measurement of ice thickness can be obtained by drilling a hole through the ice with an auger or corer and utilizing a tape with a deployable anchor to measure the distance from the bottom of the hole to the surface. Single-point measurements of this sort are poor characterizations of the pack ice since this yields a purely local estimate and there are likely many ice types and variations in floe thickness over short spatial distances (Wadhams 2004, Melling 2012).

Other relevant variables can also be measured while drilling, such as information on snow thickness, ice elevation, draft, thickness, but is slow and laborious and therefore unsuited for routine monitoring or wide-scale characterization (Melling pg 11, Eicken and Lange 1989).

CORING

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.

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. 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.

TEMPERATURE

Thermistor strings can deployed through ice holes and allowed to freeze in place, which will allow for measuring the vertical temperature gradient in the ice. Temperature is an important variable in determining the strength of ice, with lower temperatures suggesting stronger ice.

SALINITY

Ice salinity is obtained by measuring the electrolytical conductivity of melted samples collected in the coring process. 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.

SPECIALIZED BUOYS - MASS BALANCE

The extent of the Arctic sea ice is effectively monitored by aircraft and from satellites. Monitoring the ice thickness is more challenging. Satellites measurements of ice thickness are still in the development stage, therefore data sources are limited to on-ice mass balance measurements and submarine or seafloor-mounted upward looking sonars.[4]

[4] http://imb.crrel.usace.army.mil/intro.htm

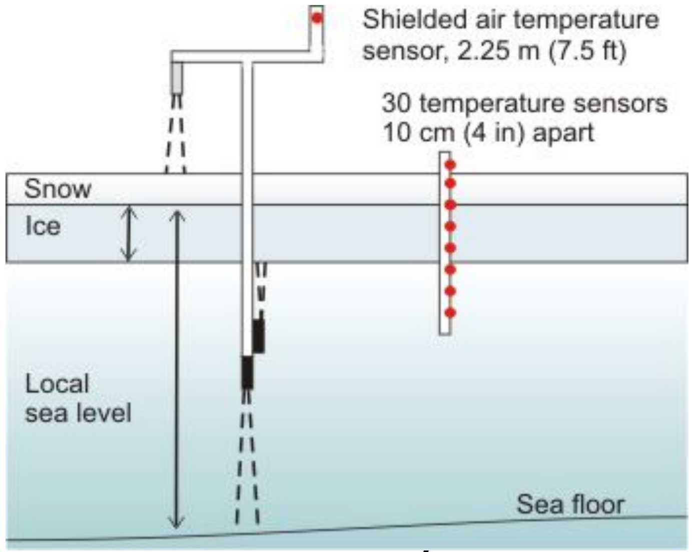

Figure 5. Mass balance measurement site sample configuration.[5] **(H. Eicken, used with permission)**

The ice mass balance is the great thermodynamic integrator. If there is net warming over time, then there will be thinning of the ice. Conversely, net cooling leads to thicker ice. Coupled with ice temperature measurements, mass balance measurements provide valuable information on the heat exchange among the air, ice and ocean.[6]

The IMB is an autonomous, ice-based system, designed to measure and attribute thermodynamic changes in the mass balance of the sea ice cover. The instrumentation of the autonomous mass balance buoys typically consists of a Campbell scientific datalogger, an Argos transmitter, a thermistor string, and above ice and below ice acoustic sounders measuring the positions of the surface and bottom within 5 mm. In addition to the mass balance instrumentation the buoys also have a GPS, a barometer, and an air temperature sensor.

Thermistor strings were PVC rod with YSI thermistors spaced every 10 cm. These rods could easily be connected to assemble strings that extended from the air through the snow and ice into the upper ocean. The thermistor accuracy is better than 0.1 C.

SATELLITE TRACKED DRIFTING BEACONS
Surface Velocity Program (SVP) beacons are small satellite tracked devices that report positional data at regular intervals (typically hourly). They can be outfitted with sensors to report sea level air pressure and surface air temperature. Depending on their construction, they can be deployed by hand, tossed from a ship, or deployed from an aircraft.

Their primary purpose is to drift with the ice in the Lagrangian sense, providing a record of vectors of the ice motion. This is used to characterize various traits of the ice movement, such frequency of movement/stasis, speed and direction, and distance traveled. If deployed in an array, study of relative movement of the ice and rotation is possible. When pressure and temperature are available, these data are assimilated into Numerical Weather Prediction (NWP) models that are

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[5] http://www.sizonet.org/research-home/mass-balance-sites

[6] http://imb.crrel.usace.army.mil/massbal.htm

used to forecast weather on synoptic time scales, and into the many long-term atmospheric reanalyses (e.g. NCEP/NCAR Reanalysis) that are used for innumerable climate studies.

SPECIALIZED BUOYS - ICE TETHERED PROFILER

Recent studies indicate that the Arctic may be both a sensitive indicator and an active agent of climate variability and change. While progress has been made in understanding the Arctic's coupled atmosphere-ice-ocean system, documentation of its evolution has been hindered by a sparse data archive. This observational gap represents a critical shortcoming of the 'global' ocean observing system. Addressing this gap, a new instrument, the 'Ice-Tethered Profiler' (ITP) was conceived to repeatedly sample the properties of the ice-covered Arctic Ocean at high vertical resolution over time periods of up to three years.

The ITP system consists of a small surface capsule that sits atop an ice flow and supports a plastic-jacketed wire rope tether that extends through the ice and down into the ocean, ending with a weight (intended to keep the wire vertical). A cylindrical underwater instrument (in shape and size much like an Argo float) mounts on this tether and cycles vertically along it, carrying oceanographic sensors through the water column. Water property data are telemetered from the ITP to shore in near-real time.[7]

SPECIALIZED BUOYS – AUTONOMOUS OCEAN FLUX BUOY

The Autonomous Ocean Flux Buoy program is being conducted to monitor and better understand the delicate balance between the upper ocean, sea ice cover, and incoming solar radiation that sustains the perennial ice cover in the Arctic Ocean. A highly specialized observation system has been developed under National Science Foundation, Arctic Observing Network sponsorship to meet this goal.

The autonomous ocean flux buoy (AOFB) is a system for measuring turbulent fluxes in the upper ocean below sea ice custom designed and fabricated at the Naval Postgraduate School (NPS). Two main components comprise the AOFBs: a surface buoy that sits on the ice and an instrument package that is suspended into the upper ocean by a series of poles from the bottom of the surface buoy. The surface buoy contains processing electronics, GPS and Iridium antennae, and batteries. The instrument package is outfitted with a downward looking 300 kHz Acoustic Doppler Current Profiler (ADCP) and a custom-built flux package. Additionally, the buoys have GPS receivers for measuring position and calculating ice velocity. After installation in the field on selected ice floes, AOFBs maintain twice-daily, two-way communications with a computer running at NPS.[8]

An acoustic travel-time current meter (Falmouth Scientific Inc. (FSI), ACM 3D current meter), an inductive conductivity cell and platinum resistance thermometer (FSI, OEM C-T Sensor), and a fast-response thermistor comprise the suite of sensors on the flux package The three flux sensors are collocated within a 0.2-m3 sample volume and are designed to directly measure the turbulent fluxes of momentum, heat, and salt using the eddy-correlation technique. The sensors are "burst-sampled" over approximately 20-minute-long Reynolds averaging periods. For each averaging period, first- and second-order statistics are calculated onboard the buoy for velocity, temperature, and salt, including the covariance of vertical velocity with horizontal velocity, temperature, and salt. In addition to the first and second moments from the Reynolds averaging

[7] http://www.whoi.edu/page.do?pid=20756

[8] http://www.oc.nps.edu/~stanton/fluxbuoy/tech/tech.html

periods, spectra of fluctuating quantities, including the vertical velocity, are calculated onboard the buoy and are included in the data transmissions.

SPECIALIZED BUOYS – UPTEMPO

The UpTempO Buoy is designed to measure the temperatures of the upper 60 m of the Arctic Ocean. These increasingly open water areas represent a tremendous storage of heat that influence summertime sea ice melt, water mass formation, marine ecosystems, the following autumn's sea ice growth, atmospheric conditions including cloud formation, and possibly the climate of nearby terrestrial ecosystems.[9]

The spherical hull contains the electronics, batteries, sea level pressure barometer, SST thermistor, and Iridium antenna. Below the hull hangs a 60m string of 12 thermistors and pressure sensors at 20m and 60m (nominal) depths.

SPECIALIZED BUOYS – AIR-DEPLOYABLE EXPENDABLE ICE BUOY

An Air-Deployable Expendable Ice Buoy (AXIB) that can withstand multiple freeze-thaw cycles and operate equally well in ice prone ocean or fresh water. The AXIB can be dropped from an airborne platform, land on an ice surface, right itself to the vertical position, anchor and stabilize itself in the ice, and continue to transmit data while anchored to the ice or floating in the ocean.

[9] http://iabp.apl.washington.edu/overview_hardware.html

References

Cavalieri, D. J. and Parkinson, C. L., 2012. Arctic sea ice variability and trends, 1979–2010, The Cryosphere, 6, 881-889, doi:10.5194/tc-6-881-2012.

Drobot, S., and M. Anderson, 2001. Comparison of interannual snowmelt onset dates with atmospheric conditions, Ann. Glaciol., 33, 79-84.

Hutchings, J., C. Geiger, J. Richter-Menge, A. Roberts, M. Doble, R. Forsberg, K. Giles, C. Haas, S. Hendriks, C. Khambhamettu, S. Laxon, T. Martin, M. Pruis, M. Thomas, P. Wadhams, D. Wilkinson, J. Zwally. 2011. SEDNA: Sea ice Experiment - Dynamic Nature of the Arctic. [indicate subset used]. Fairbanks, Alaska USA: International Arctic Research Center, UAF. http://dx.doi.org/10.7265/N5KK98PH.

Kaleschke, L., X. Tian-Kunze, N. Maaß, M. Mäkynen, and M. Drusch, 2012. Sea ice thickness retrieval from SMOS brightness temperatures during the Arctic freeze-up period, Geophys. Res. Lett., 39, L05501, doi:10.1029/2012GL050916, 2012.

Key, J., J. Collins, C. Fowler, and R. Stone, 1997. High-latitude surface temperature estimates from thermal satellite data, Rem. Sens. Environ., 61, 302-309.

Key, J.R., X. Wang, J.C. Stoeve, and C. Fowler, 2001. Estimating the cloudy-sky albedo of sea ice and snow from space, J. Geophys. Res., 106(D12), 12489–12497, doi:10.1029/2001JD900069.

Kwok, R., G.F. Cunningham, M. Wensnahan, I. Rigor, H.J. Zwally, and D. Yi, 2009. Thinning and volume loss of Arctic sea ice: 2003-2008, J. Geophys. Res., doi:10.1029/2009JC005312.

Kwok, R., G.F. Cunningham, 2012. Deformation of the Arctic Ocean ice cover after the 2007 record minimum in summer ice extent. *Cold Regions Science and Technology* **76-77**, 17-23.

Laxon S.W., K.A. Giles, A.L. Ridout, D.J. Wingham, R. Willatt, R. Cullen, R. Kwok, A. Schweiger, J. Zhang, C. Haas, S. Hendricks, R. Krishfield, N. Kurtz, S. Farrell and M. Davidson, 2013. CryoSat-2 estimates of Arctic sea ice thickness and volume, Geophys. Res. Lett., 40, 732–737, doi:10.1002/grl.50193.

Magnell, B., L. Ivanov, E. Siegel, 2010. Measurements of Ice Parameters in the Beaufort Sea using the Nortek AWAC Acoustic Doppler Current Profiler, Proceedings Oceans 2010, doi: 10.1109/OCEANS.2010.5664016.

Markus, T., J.C. Stroeve, and J. Miller, 2009. Recent changes in Arctic sea ice melt onset, freeze-up, and melt season length, J. Geophys. Res., 114, C12024, doi:10.1029/2009JC005436.

Melling, H 2012 Sea-Ice Observation: Advances and Challenges Chapter 3. In *Arctic Climate Change - The ACSYS Decade and Beyond*. Atmospheric and Oceanographic Sciences Library 43, doi 10.1007/978-94-007-2027-5_3. Springer Science+Business Media B.V. 464 pp.

Nghiem, S.V., I.G. Rigor, D.K. Perovich, P. Clemente-Colon, J.W. Weatherly, and G. Neumann, 2007. Rapid reduction of Arctic perennial sea ice, Geophys, Res. Lett., 34, L19504, doi: 10.1029/2007GL031138.

Tschudi, M.A., J.A. Maslanik, and D.K. Perovich, 2008. Derivation of melt pond coverage on Arctic sea ice using MODIS observations, Rem. Sens. Environ., 112(5), 2605-2614, doi:10.1016/j.rse.2007.12.009.

Farrell, S.L., N. Kurtz, L.N. Connor, B.C. Elder, C. Leuschen, T. Markus, D.C. McAdoo, B. Panzer, J. Richter-Menge, and J.G. Sonntag, 2012. A first assessment of IceBridge snow and ice thickness data over Arctic sea ice, IEEE Trans. Geosci. Rem. Sens., 50(6), 2098-2111, doi:10.1109/tgrs.2011.2170843.

Haas, C., 2004. Late-summer sea ice thickness variability in the Arctic Transpolar Drift 1991–2001 derived from ground-based electromagnetic sounding, Geophys. Res. Lett., 31, L09402, doi:10.1029/2003GL019394.

Kurtz, N.T., and S.L. Farrell, 2011. Large-Scale Surveys of Snow Depth on Arctic Sea Ice from Operation Icebridge. Geophys. Res. Lett., 38(L20), L20505, doi: 10.1029/2011GL049216.

Varnai, T., and R. F. Cahalan (2007), Potential for airborne offbeam lidar measurements of snow and sea ice thickness, J. Geophys. Res., 112, C12S90, doi:10.1029/2007JC004091.

Wadhams, P, J. P. Wilkinson, and A. Kaletzky, 2004: Sidescan Sonar Imagery of the Winter Marginal Ice Zone Obtained from an AUV. J. Atmos. Oceanic Technol., 21, 1462–1470. doi: http://dx.doi.org/10.1175/1520-0426(2004)021<1462:SSIOTW>2.0.CO;2