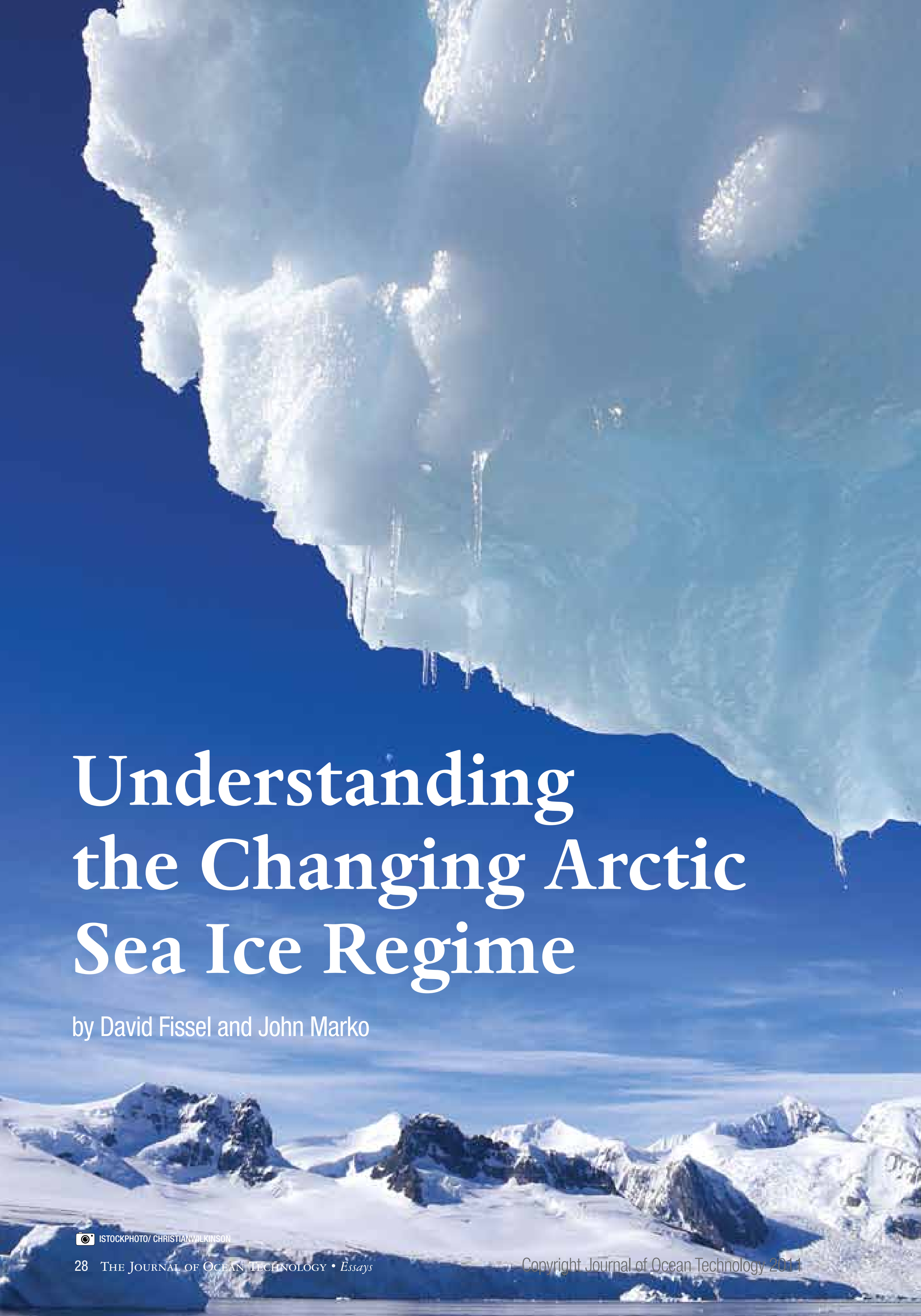

Understanding the Changing Arctic Sea Ice Regime

by David Fissel and John Marko

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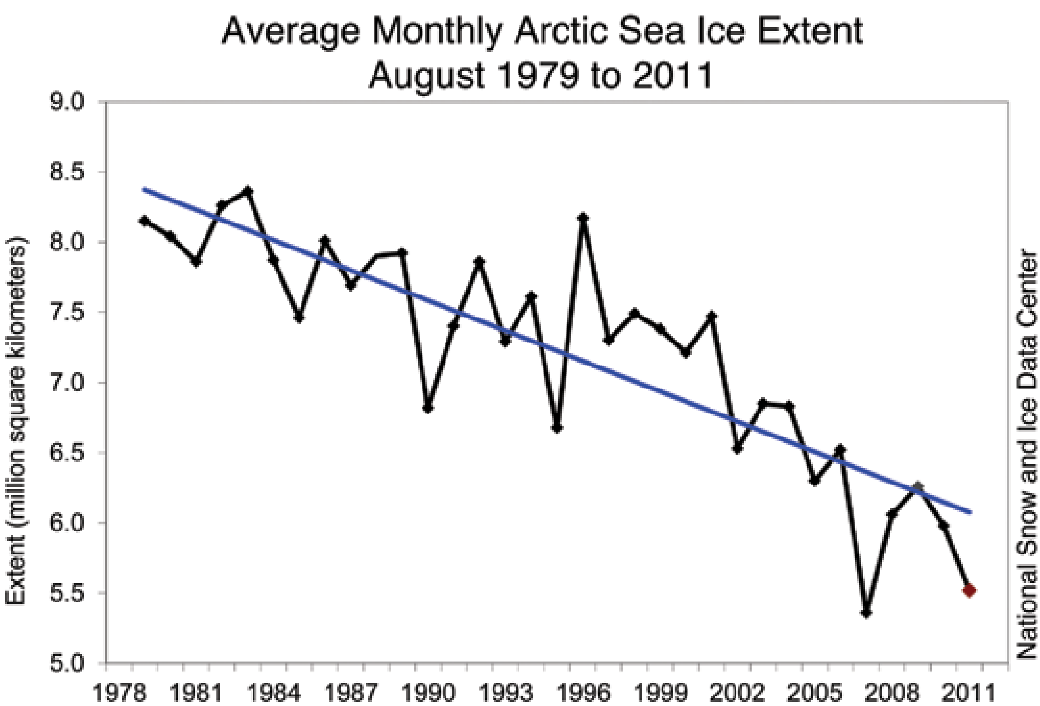
Introduction

The very large reductions in the Arctic Ocean summer sea ice observed over the past decade have captured the attention of Arctic and climate scientists, the shipping and offshore oil and gas industries, circumpolar communities, government planners and the general public. Each September, the latest Arctic Ocean sea ice area maps are closely scrutinized by scientists and, via extensive media coverage, the general public, to determine if a new record low for Arctic sea ice has occurred. The observed reductions in sea ice cover since 2002 (Figure 1) provide compelling evidence of ongoing changes in the Arctic climate and ecosystem, which may be related to greenhouse gas emissions on a global basis.

From a scientific and engineering perspective, changes in sea ice are best represented as changes in ice volume, and hence mass (mass being the product of ice volume and density), rather than in measured ice area. Ice volume is central to both assessing the extent of the observed changes and in quantifying the dynamics and thermodynamics controlling ice growth and ablation and the underlying energy exchanges with other components of the environment. Understanding of ice volume change is not only of regional and global importance but is essential for addressing local challenges involving ice breaking or oil and gas exploration operations. Ice volume (the product of ice area and thickness) is an important factor in determining whether a ship can transit through a waterway or an oil and gas platform can maintain its position in ice.

While the area of ice can be readily measured over the full Arctic region from satellites on a near-realtime basis (daily or more frequently) in all weather conditions, timely access to equivalent measurements of ice thickness is not presently feasible. In this essay, we present an overview of the capabilities and limitations of methodologies for measuring ice thickness, and the importance of ice thickness to addressing key scientific and engineering requirements in the Arctic.



SEA ICE INDEX. NATIONAL SNOW AND ICE DATA CENTER

Figure 1: Trends in August sea ice extent in the Northern Hemisphere from 1979 to 2011.

Background

The bulk of sea ice area data since the late 1970s has been derived from passive detection of surface-emitted microwave energy by satellite sensors. On regional scales, synthetic aperture radar (SAR) satellites, such as RADARSAT, can provide near-realtime measurements of sea ice extent [see Inside Out, p. 82]. In addition, optical sensors on board satellites such as the NOAA series and MODIS provide ice cover data during cloud/fog free periods. Time series of local, regional and total hemispheric sea ice area are now available online (for example http://nsidc.org/arcticseaicenews/). These data may be used to characterize seasonal variations and trends over decadal and longer time scales on a near-realtime (i.e. daily) basis.

Most of the sea ice in the Arctic Ocean is heavily deformed, as is evident from observed pressure ridging and hummocks. Ice growth, ablation, movement and deformation result in an ice cover that can exhibit large changes over short intervals in time and space. Due to this high degree of variability, accurate measurement of representative sea ice thickness requires extensive sampling over broad areas. This, in turn, presents special challenges in terms of the design and implementation of measurement and monitoring tools and techniques.

The highly variable nature of sea ice thickness is a major challenge for the oldest method of sea ice thickness measurement: mechanically drilling through the ice with ice augers. As a result, ice auger measurements are only useful in areas where sea ice deformation is minor such as coastal landfast ice zones. Manpower and logistical costs associated with collecting ice thickness data using ice augers is also a challenge.

Upward-looking sonars (ULS) on United States and British submarines were used to measure ice thickness data over large transect areas in the Arctic Ocean from the 1950s to the 1990s. These data consist of ice draft estimates derived from echoes recorded with the ULS. Since the density of sea ice is close to that of seawater, approximately 90% of the total ice volume is below the water surface. Therefore, ice thickness can be estimated from measured ice drafts under most circumstances. The accuracy and horizontal resolution of the ULS measurements vary according to the era and operational conditions of the particular submarine mission. A recently published study indicates that typical accuracies are ±0.25-0.5 m for the accuracy of ice draft, with a horizontal resolution of 1-6 m.

Historical submarine ULS data provided the first indication of the degree to which observed decreases in ice area coincided with an accompanying decrease in overall ice thickness. In the deep water portion of the central Arctic Ocean, mean ice draft at the end of the summer melt season was observed to decrease by about 40%, from 3.1 m in 1958-1976 to 1.8 m in the 1990s. It is worth noting here that the submarine ULS data did not span the entire Arctic Ocean so the rate of change could be quite different in other subregions. Nevertheless, when combined with ice extent estimates from satellites, these data have provided much of the basis for the existing tentative estimates of the total volume of Arctic sea ice from the 1950s through the 1990s.

The major shortcoming of the submarine ULS data is the relatively small number of cruises involved. Over the period 1975 to 2005 there were 34 U.S. and 3 U.K. submarine cruises on which ULS data were collected. This situation has worsened in the past decade and a half due to the considerable reduction in polar submarine traffic which followed easing of “Cold War” tensions. The political change even impacted upon the specifically science-oriented U.S. Scientific Ice Explorations (SCICEX) submarine cruise program, which ended in the 1990s just when evidence for large ice cover changes was beginning to be taken seriously. The virtual cessation of submarine-based surveys has provided a strong impetus to implement the alternative ice thickness measurement technologies and strategies which are outlined below.

Modern Approaches to Arctic Sea Ice Thickness Measurement

Upward Looking Sonar

New capabilities in the ULS method of ice draft measurements evolved out of the earlier submarine ULS methodology with the development of self-contained instruments with large data storage capacities suitable for deployment on recoverable moorings or on mobile, ROV or AUV, platforms. Progressive improvements of functionality and reliability have followed on from continuing advancements in low-power electronics, computational speed and memory design. These advances allow remote recording of high spatial resolution (horizontal and vertical) profiling data at frequencies as high as 2 Hz over typical measurement periods of one year with the capability to operate for up to three years without servicing.

A typical moored ULS installation, as sketched in Figure 2, employs both a single beam upward looking ice profiling sonar (IPS) and a multiple beam Acoustic Doppler Current Profiler (ADCP). The IPS provides instantaneous measures of ice draft, as well as the distribution of frazil (ice crystals suspended in water) and other phenomena beneath the ice. The ADCP provides water current and ice velocity data. The velocity data is an essential input for converting the IPS draft time-series into detailed profiles of the under-ice topography (Figure 2). Moored ULS ice draft monitoring systems are used by ice and ocean research institutions around the world, as well as by major oil and gas companies active in ice infested waters.

The observational network of year-long ULS mooring ice thickness measurements has expanded over the past several years to now include many locations on the periphery of the Arctic Ocean, in the Western Arctic Ocean, in the Canadian Arctic Islands, off NE Greenland and at the North Pole (Figure 3). However, there is no coverage through most of the eastern half of the Arctic Ocean or in most of the interior portions of the Arctic

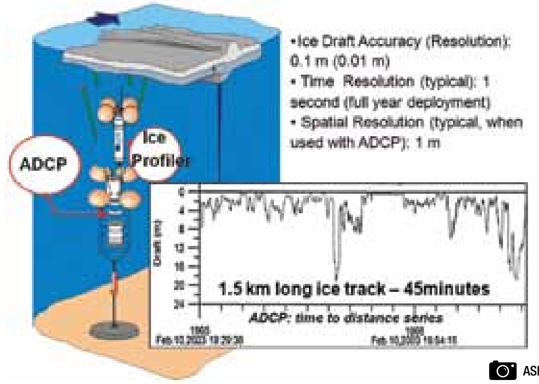


Figure 2: A typical deployment arrangement of a ULS Ice Profiler Sonar (IPS) and ADCP ice velocity measuring instruments on a single subsurface mooring as used in water depths of 40 m. Also shown is a short segment of a profile of ice cover produced by combining time series draft and ice speed.

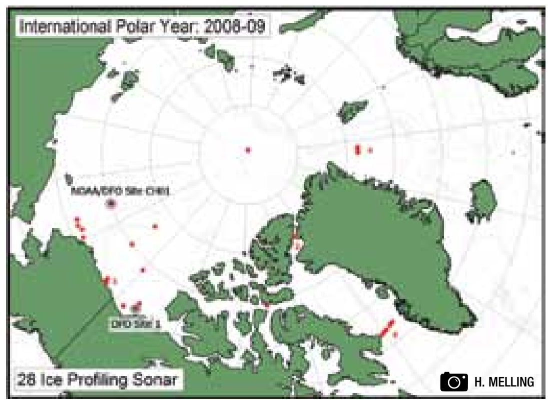


Figure 3: Locations of ULS ice moorings in 2008-2009.

Ocean and the area north of Canada and Greenland where the thickest and oldest ice occurs.

While moored ULS ice draft measurement systems provide accurate, high resolution and long duration ice thickness data, they are limited in terms of providing timely near-realtime data. This issue is being addressed by Canadian scientists with the Bedford Institute of Oceanography (in particular, Dr. Simon Prinsenberg), who are now implementing a cabled realtime ULS ice measurement system as part of the Defence Research and Development Canada Northern Watch program in Lancaster Sound in the Canadian Arctic Islands. The University of Victoria, Canada, in collaboration with ASL Environmental Sciences, has been undertaking feasibility studies for adapting the underwater ocean observatory technology of the University of Victoria's NEPTUNE Canada and VENUS observatories for data transmission over distances of tens to hundreds of kilometres for a scientific application in the Canadian Arctic Islands and for an offshore oil and gas application in the deepwater portion of the Canadian Beaufort Sea.

Equivalent ULS ice draft profiles can be produced from ROV- and AUV-deployed IPS instruments and from neutrally-buoyant floats. Accurate control and knowledge of the vertical position of the transducer is an important advantage offered by the moored instrumentation approach (5 to 10 cm accuracy) over the ROV/AUV method (20 to 30 cm). A modest deployment of ULS Ice Profilers from mid-water drifting buoys was made in 2008 as part of European Union-sponsored International Polar Year DAMOCLES (Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies) system. However, to date, no widespread deployment of mobile profilers has been achieved on the regional and larger scales required for addressing global sea ice climate change issues.

Drilling

Ice auger drilling of the ice to measure thickness is the most traditional measurement method, as discussed above. The Ice Mass Balance (IMB) System approach developed by the U.S. Army's Cold Regions Research and Engineering Laboratory uses drilling to insert instrumentation on, in and below the ice cover, allowing for continuous monitoring of changes in the ice cover and in the surrounding atmosphere and ocean. This approach yields highly local data relevant to the mechanisms effecting ice cover change and also uses realtime satellite links to provide timely data access. However, while offering significant contributions to detailed understanding of ice processes, this approach is not well suited to measurement and monitoring over broad areas.

Electromagnetic Induction

Electromagnetic (EM) induction instrumentation operated from low altitude helicopters, fixed-wing aircraft and surface sleds has been used by a number of ice research organizations including the Bedford Institute of Oceanography, Alfred Wegener Institute of Germany, Norwegian Polar Institute, and the University of Alberta. This technique utilizes short bursts of electromagnetic energy which interacts with the electrically conductive saline layer immediately beneath the ice undersurface to induce an electrical current. The strength of the induced current decreases with the distance of the antenna from the conducting layer, from which a measure of ice thickness may be inferred. The EM technique is useful for surveys of one to two hours in duration over relatively level ice, and can yield ice thickness data with a vertical accuracy of ±0.1 m, which is comparable to that obtained with ULS sensors. However, the horizontal resolution is generally a few times greater than the altitude of the sensor above the ice surface (typically 5 to 30 m) which is 1-2 orders of magnitude greater than that from moored ULS data sets. In addition, inclusions of seawater that are common in large ice keel features can introduce negative biases into the ice thickness data. It is also worth noting that EM ice thickness measurements generally require a considerable amount of effort to process the raw data resulting in a time lag of many days to a few months to deliver the final results to the end users.

Laser and Radar Altimetry

Laser and radar altimetry offer prospects for widespread, continuous ice thickness measurement from aircraft and satellites. In both cases, the sensor measures the range to the top of the ice cover and sea surface in between. From these two measurements, the ice freeboard is calculated. The data accuracy is limited by the rather large horizontal footprint of the sensor (particularly true for satellite based systems) and by the fact that the ice thickness values are derived from the freeboard estimates by assuming a 10:1 ratio between ice freeboard and ice thickness. Also, in the case of laser systems, the thickness of the snow layer, whose upper surface generates the detected returns, can be large relative to the ice freeboard. As well, the signal returns received by a radar altimeter may result from scattering at varying and unknown depths within the ice or snow layers which can pose difficulties in interpreting the location of the ice surface and sea surface. For both radar and laser systems, high ice concentrations can lead to problems with establishing the local zero-reference elevation of the sea surface.

Satellite altimetry ice thickness measurements began in 2003 with the launch of NASA's ICESat-1, which was followed by the launch of the European Space Agency CryoSat-2 in April 2010, with a planned three year mission. The functionality of the ICESat-1 satellite was seriously degraded by 2009 and its replacement, ICESat-2, is planned for a tentative launch date in 2015, so significant time gaps have and will continue to occur in these data sets.

The ground resolution for satellite-based altimeter data is 70 m x 70 m for the U.S. ICESat-1 laser altimeter and 250 m x 250 m for the ESA CryoSat-2 radar altimeter. These resolutions are coarse in comparison with EM sounding (about 50 m) and IPS (about 1 m) approaches. The nominal ice thickness measurement accuracy for ICESat-1 is generally considered to be approximately ±0.5 m or more for ice thickness, which is considerably less than either ULS or EM induction methods, both of which give vertical accuracies of around 10 cm. The CryoSat-2 has the potential to provide ice thickness measurement accuracies that are comparable to the ULS and EM methods, subject to validation studies which are presently underway. The advantage of satellite altimetry data is that they provide near-realtime monitoring of the full polar region over comparatively short time periods.

Summary and Conclusions

The limitations in our ability to measure sea ice thickness over broad areas represent a serious impediment to addressing important scientific and engineering requirements in the Arctic. A number of ice thickness measurement methods have been described in this essay. Each methodology has its strengths and weaknesses, as summarized in Table 1.

To meet the requirement for improved ice thickness data in support of better understanding of changing Arctic region sea ice conditions, expanded use of the various measurement methods described here is warranted. Ongoing development of all viable methods should be continued and, as much as possible, accelerated.

Given the advantages of using a combination of different ice thickness measurement methods, an integrated numerical framework to combine these data with daily sea ice area data could effectively address the requirement to monitor sea ice volume in a timely fashion for the Arctic region. A framework for such an integrated system exists as the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS). PIOMAS is a numerical model that simulates sea ice and the ocean with data assimilation based on sea ice concentration information from the U.S. National Snow and Ice Data Centre, as well as sea surface temperature data from NCEP/NCAR Reanalyses assimilated in ice-free areas. [Editor's note: The NCEP/NCAR Reanalysis is a continually updating gridded data set representing the state of the Earth's atmosphere jointly produced by the National Center for Environmental Prediction and the National Center for Atmospheric Research, both U.S.

Measurement Method	Vertical Accuracy	Spatial Resolution	Existing Data Coverage of Arctic Areas	Data Timeliness	Comments
ULS on submarines	± 0.25 to 0.6 m	1-6 m	Areas in the central Arctic Ocean from Bering Strait to the North Pole and to Fram Strait	Long delays for processing after mission end and security reviews	Military submarine activity has been greatly reduced for the past 10 plus years
ULS on subsurface moorings	± 0.1 m	1-2 m	Many long-term measurement locations operated in the Beaufort/Chukchi Seas; in NE Greenland and at the North Pole but very limited in the remainder of the Arctic Ocean and its peripheral seas	Data from year-round moorings require well over one year for release	Work is underway to improve data timeliness through underwater observatory cables and mobile measurement platforms
Airborne and ground based EM induction measurements	± 0.1 m (level ice); otherwise reduced	Tens to hundreds of metres	Missions are arranged as funding programs allow; subject to aircraft and ship logistic constraints	Determined by mission duration plus post processing of several weeks	Present observational systems are limited in number
Satellite altimetry	± 0.5 m (ICESat) ± 0.1 m? (CryoSat)	70 m (ICESat) 250 m (CryoSat)	The full polar region: 2003-2008 data (ICESat); 2010-2013? (CryoSat); 2015? (ICESat-2)	Potential to provide near-real time monitoring over fairly short time periods	Calibration and validation of CryoSat are underway; actual capabilities will be better known upon completion

Table 1: Ice thickness measurement methods.

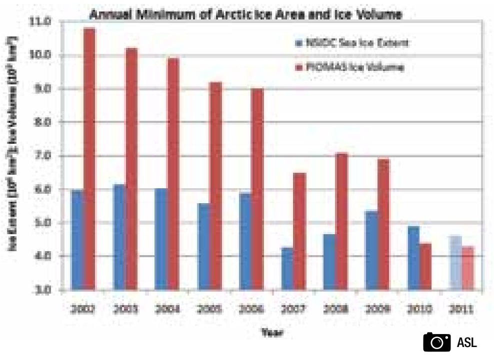


Figure 4: The yearly minimum monthly Arctic ice area (from the National Snow and Ice Data Center) and the PIOMAS ice volume. Note that the 2011 values are preliminary estimates based on data for early September 2011.

agencies.] The PIOMAS model is constantly re-calibrated and validated using various data sets, including United States Navy submarines, subsurface ULS moorings, airborne EM induction measurements and satellite altimeter data. In its present stage of development, the accuracy of the Arctic ice volumes in PIOMAS is estimated to be on the order of 1.4×10^3 km^3.

Although subject to considerable uncertainties, the PIOMAS model shows a decrease of 60% in late summer ice volume over the period from 2002 to 2011 (Figure 4). This compares with a 30% decrease in sea ice area over the same period as observed from satellite data. The difference between these two estimates reflects overall thinning of the ice cover, and underscores why it so important to have more accurate and representative (extensive) measurements of ice thickness so we can truly understand how much ice is being lost from year to year. All evidence would indicate that the amount of ice lost is more than we would estimate based on sea ice area measurements alone.

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John Marko is the Director of Ice Physics at ASL Environmental Sciences Inc. in Victoria, BC, Canada. He has physics degrees from MIT (B.Sc.) and Syracuse University (M.Sc. and PhD). He began his career as an academic specializing in solid state physics before switching interests to sea ice and remote sensing, first at the Institute of Ocean Sciences in Sidney, BC, and then as a founding partner of ASL Environmental Sciences Inc. His work has covered marine and freshwater ice issues in a large fraction of the Arctic and sub-Arctic cryosphere.