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Beyond Point Measurements: Sea Ice Floes Characterized in 3-D

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A new methodology for coincident floe-scale measurements of the surface elevation, snow depth, and ice draft (the thickness below the water line) of Antarctic sea ice has been demonstrated during two recent research voyages: the Australian-led Sea Ice Physics and Ecosystem Experiment II (SIPEX II) to East Antarctica in September–November 2012 and the United Kingdom–led Ice Mass Balance in the Bellingshausen Sea (ICEBell) voyage to the Weddell and Bellingshausen Seas in November 2010 (Figure 1a).

This methodology centered on the use of a SeaBED-class autonomous underwater vehicle (AUV; Figure 1b) from the Woods Hole Oceanographic Institution (WHOI), equipped with a swath multibeam sonar to obtain the first high-resolution geolocated three-dimensional (3-D) maps of Antarctic sea ice draft. Coincident, high-resolution 3-D measurements of snow and ice surface morphology were obtained using terrestrial laser scanners (TLS) and an automated snow probe (Figure 1d). Together, these data provide a complete and coincident characterization of the floe's snow surface, ice surface, and ice bottom. Such data move beyond traditional point-based measurements, providing a wealth of additional information on the spatial variability of sea ice characteristics such as ridging, snow accumulation, and freeboard (the height of ice above the water line).

The Need for In Situ Floe-Scale Characterization

Traditionally, sea ice voyages have predominantly featured on-ice experiments (ice stations) collecting point measurements such as ice core sampling or drill lines of about 100 or so drill holes. The limited scope of these measurements has made comparison with methods that can monitor large spatial extent—such as airborne or satellite surveys—difficult. Moreover, logistical and technical challenges have made direct measurement of under-ice characteristics and processes particularly difficult to obtain except at a few isolated locations. Detailed observations of spatial variations in ice thickness, an understanding of the processes that cause and are affected by this variability, and the influence of this variability on sea ice biogeochemistry and ecology remain particularly elusive.

Simultaneous and coincident mapping of both the upper and lower surfaces of individual floes is needed to capture the morphological relationships between the ice and snow cover. To meet these needs, the new 3-D data sets will inform and provide spatial context to a variety of studies, including satellite and airborne efforts to remotely determine large-scale sea ice and snow thicknesses (e.g., NASA's Ice, Cloud, and land Elevation Satellite (ICESat) and IceBridge missions [*Koenig et al*., 2010]), the effect of ice deformation on sea ice volume, and process-based biological and biogeochemical measurements and models.

Floe-scale surveys provide the richness of a complete spatial characterization of the sampled ice floe while at the same time offering versatility of integration with a wide variety of process studies. Such surveys can be scaled up to provide a direct comparison for airborne surveys, which bridge the gap between in situ and large-scale satellite estimates of sea ice thickness. In addition, floe-scale measurements can be downscaled to smaller scales, such as those necessary in biological studies of sea ice algal distribution.

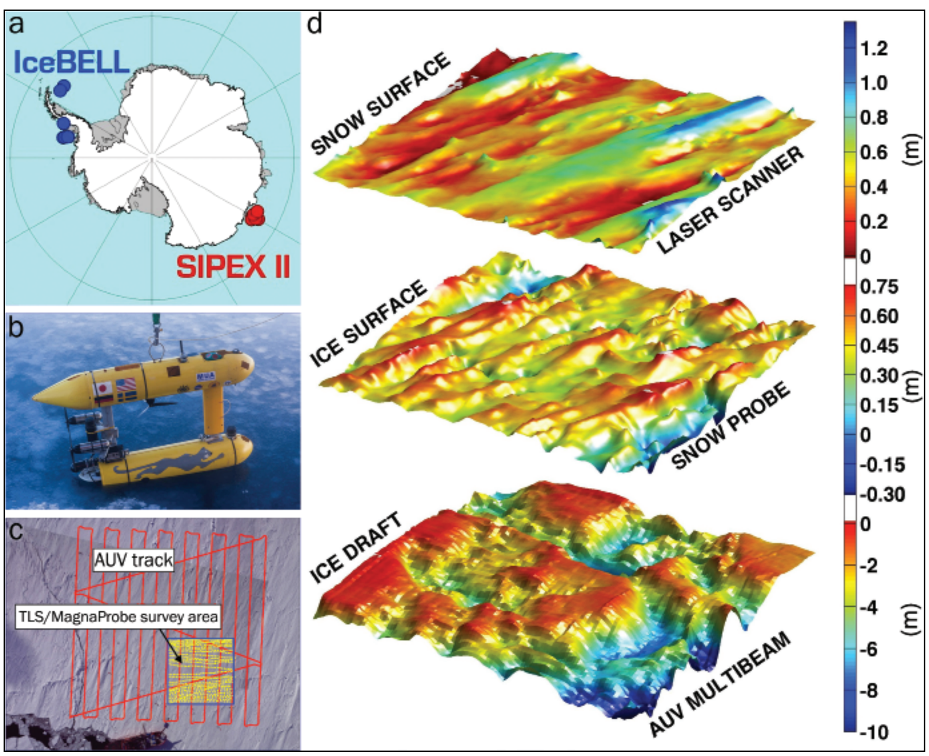

Fig. 1. An example of data obtained at a typical ice station during Sea Ice Physics and Ecosystem Experiment II (SIPEX II). (a) Location of ice stations during the SIPEX II and Ice Mass Balance in the Bellingshausen Sea (ICEBell) research voyages. (b) The Woods Hole Oceanographic Institution (WHOI) SeaBED-class autonomous underwater vehicle (AUV) Jaguar (~2 meters long) being deployed during SIPEX II. (c) Aerial photograph of an ice station from SIPEX II overlaid with AUV (300- × 300-meter, red track) and surface measurement (100- × 100-meter, yellow points and blue line) grids. (d) Corresponding ice floe maps that show, from top to bottom, snow surface (meters) from terrestrial laser scanners, with height relative to sea level; ice surface (meters) from MagnaProbe relative to sea level, corresponding to ice freeboard; and ice draft (meters) from AUV multibeam sonar relative to sea level, colocated using the GPS and total robotic station (TRS) reference grid described in the text. Note the varying vertical scale between surfaces.

Measuring the Underside of Ice

AUVs have recently opened the door to detailed measurements of the spatial variability of sea ice draft using multibeam sonars [*Wadhams et al*., 2006]. A vehicle with advanced navigational capability and easy deployment and recovery is essential when operating in a compact sea ice cover. The WHOI SeaBED-class AUV offers great flexibility in sensor integration, deployment, and operation. Its twin-hulled design and three-thruster layout provide a stable and highly maneuverable platform for deployment and recovery through small openings in the sea ice. An acoustic link between the AUV and the ship provides vehicle and mission progress information and the ability for operators to direct the vehicle to open water for recovery.

Operating at a depth of 20 to 30 meters and driving in a lawnmower pattern with overlapping swaths, a 245-kilohertz Imagenex multibeam sonar mounted on the AUV provided ice draft maps with a horizontal resolution better than 0.25 meter. This resolution enables the discrimination of individual ridge keels and rafted ice blocks in the resulting map. The AUV missions (up to 6 hours for a 400- × 400-meter grid) efficiently return preliminary maps of the underside of the ice floe that can inform other on-ice experiments conducted during the ice station.

Published in 2013 by the American Geophysical Union.

Measuring the Ice and Snow Surface

Complete characterization of ice floe morphology required coincident spatial measurements of the surface topography and snow depth at a resolution and accuracy comparable to that of the AUV ice draft maps. High-precision snow surface topographic information was obtained using a portable TLS. By acquiring scans from several locations on the floe to eliminate scan shade behind ridges and other surface features, an integrated 3-D elevation model with tens of millions of data points for areas of tens to hundreds of meters can be achieved. This operation is efficient and cost-effective, achievable by a single operator in a few hours. The snow depth distribution was measured with a GPS snow probe (SnowHydro MagnaProbe) that automatically logs snow depth and its position. Although still a labor-intensive operation, between 1000 and 2000 snow depths were recorded at spatial resolutions of 1–3 meters in a few hours.

Combining Coincident Spatial Data Sets

The precise coregistration of temporally displaced surface and subsurface measurements is important to correct for ice floe drift and rotation during the surveys. An advantage of coincident measurements at ice stations (as opposed to long-range AUV or airborne surveys) is the relatively straightforward combination of GPS and total robotic station (TRS) measurements. At each ice station a floe-centric coordinate system was established using a TRS to obtain floe-local coordinates of AUV navigation transponders, laser scanner targets, and ice thickness drill holes (the latter providing sea level reference and coregistration "tie points" for the topographic data sets). Precise location of the AUV data (<1 meter accuracy) can be achieved through a combination of bottom tracking, acoustic location, matching of overlapping multibeam swaths, and identification of ice thickness tie points [*Roman and Singh*, 2011]. The snow probe sites were placed in floe-local coordinates using either the TRS or a roving dual-frequency GPS to achieve positioning accuracy of a few centimeters.

Looking Forward

This methodology has delivered the first-ever complete coincident whole-of-floe measurements of sea ice. Importantly, this was achieved at modest cost and with logistics typical of a standard sea ice voyage, allowing a variety of additional sea ice studies to be conducted in concert. Such an approach could become standard in future sea ice research voyages, with specific AUV capability being considered in the operational requirements of the next generation of polar icebreakers. The success of these floe-scale missions could pave the way for a new era of field experiments that could eventually explore ocean and sea ice processes and phenomena on scales up to the mesoscale (10–100 kilometers). This increase in scale is important for the goal of directly linking in situ data with satellite sensor footprints, sea ice, and coupled climate model grid cells and ecosystem studies.

Acknowledgments

The SIPEX II AUV project was funded by the Antarctic Climate and Ecosystems Cooperative Research Center and contributes to Australian Antarctic Science Projects 4073 and 4116. Snow measurements were funded by U.S. National Science Foundation grant ANT-1142075 and the Swiss National Science Foundation. GPS equipment and support were provided by the University NAVSTAR Consortium (UNAVCO) and the Australian Antarctic Division. ICEBell was supported by the UK National Environmental Research Council and the British Antarctic Survey.

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