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New Unified Sea Ice Thickness Climate Data Record

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With the recent dramatic record-low ice extent of 2007 and with the third-lowest extent having been recorded in 2010, the changing Arctic climate, and particularly the rapidly changing sea ice cover, is often in the news. The climate models of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report forecast that rising Arctic temperatures and the reduction of sea ice will be the earliest and strongest indications of global warming. However, these models generally underestimate the observed rate of change in summer ice cover over the past 3 decades [*Stroeve et al.,* 2007].

To better understand, predict, and adapt to the changing conditions in the Arctic, more and better organized observations of the state of the sea ice cover are needed by a variety of groups, including coastal communities, shipping interests, the fishing industry, the Arctic Council, and contributors to the IPCC's upcoming Fifth Assessment Report and the U.S. National Oceanic and Atmospheric Administration's (NOAA) ongoing Arctic Report Card.

While sea ice extent is well measured by satellite-borne instruments, monitoring ice thickness has been and remains a challenge. The amount of sea ice draft data (the distance the ice extends below the water surface) and satellite freeboard data (the distance the snow or ice extends above the water surface) available in the past 10 or so years has increased markedly, providing a large and growing resource. Existing observations of ice thickness span a variety of methods, accuracies, and temporal and spatial scales, and they are archived in different locations and in many different formats. Each data source has its own strengths in terms of sampling or accuracy. Measurement uncertainties are documented to various levels of detail for different sources, but the information about the measurement techniques and their errors is spread throughout the literature.

A concerted effort to collect as many observations as possible in one place, with consistent formats and with clear and abundant documentation, could allow the scientific community to better utilize what is now a considerable body of observations. With all of the data in one location and in a common format, it will be much easier to compare different sources with each other and with model output. The increased space and time coverage of a unified data set also could facilitate improved analyses of how and where sea ice thickness has changed over the past 3 decades.

A New Ice Thickness Data Archive

The new Unified Sea Ice Thickness Climate Data Record compiles the wealth of data that are now available from moored and submarine-based upward looking sonar (ULS) instruments, airborne electromagnetic (EM) induction instruments, and satellite laser altimeters (on the Ice, Cloud, and land Elevation Satellite (ICESat)). The data set (see Figure 1) is sponsored by the NOAA Climate Program Office and is currently maintained at the University of Washington (UW) Polar Science Center. These observations, some of which date from 1975, offer adequate sampling to establish the mean ice thickness and thickness distribution for scales generally appropriate for change detection and climate model validation. Only by using all of the available data and analyzing all of the biases will it be possible to obtain a reliable and extensive record of how the ice pack is changing. The new data set could be the best approximation to a climate reference data set that is possible to assemble for sea ice thickness.

The new data set includes point measurements of the ice draft or ice thickness as acquired from data providers, statistical summaries (means, standard deviations, and ranges), and the full draft or thickness probability distribution function (pdf). The summary values provide easy access for the change detection and modeling communities. The summaries and pdf's are calculated from approximately 1 month of moored ULS data or 50 kilometers of submarine, airborne, or satellite data. (Roughly 50 kilometers of ice pass over a typical mooring site in a month, and monthly output is commonly saved in model runs.) A Web site, indicated below, provides easy access to the point data, averaged data, pdf's, and documentation.

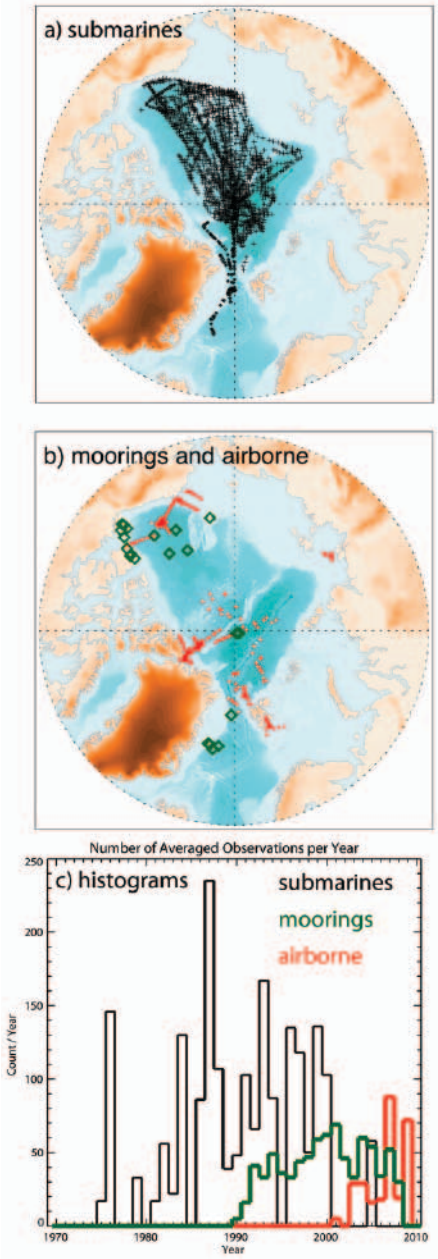

Fig. 1. (a) Map of all submarine sample locations in the Arctic. (b) Map of mooring locations (green diamonds) and airborne electromagnetic observations (red dots and lines). (c) Histograms of the number of samples per year from each of the source categories.

Many international institutions have acquired and processed ice thickness data. The following is a partial list of data sources included in the new unified data set:

- Submarine ULS data: More than 120,000 kilometers of tracks of ice draft have been processed for the Arctic Ocean since 1975 from U.S. and U.K. submarines.
- North Pole Environmental Observatory (NPEO): A U.S. National Science Foundation–sponsored oceanographic mooring with a ULS at the top has been deployed continuously at the North Pole by the University of Washington in more than 4000 meters of water since spring 2001.
- Institute of Ocean Sciences (IOS): IOS has deployed a series of ULS instruments on moorings in and around the Mackenzie Delta, in Nares Strait, and in the eastern Beaufort Sea since 1990.
- IOS Chuckchi Sea: IOS deployed a ULS-equipped mooring on the Chukchi Shelf in 2004–2005 with NOAA support.
- Woods Hole Oceanographic Institution (WHOI): The Beaufort Gyre Exploration Project has deployed between three and four moored ULS instruments in the deep water of the Beaufort Sea since 2003.
- Alfred Wegener Institute (AWI) ULS: AWI deployed moored ULS instruments in the Arctic (primarily in Fram Strait) from 1991 to 2002.
- University of Alberta (UA) and AWI helicopter EM ice thickness: Approximately 1000 kilometers of helicopter-borne surveys of the ice thickness have been made with an EM instrument in the Arctic and Antarctic since 2001.
- ICESat data: ICESat laser altimeter freeboard measurements and ice thickness estimates are available sporadically from 2003 to 2009. The smoothed and gridded ICESat data from the Jet Propulsion Laboratory (JPL) have not been reformatted.

Typical errors in the submarine and moored ULS measurements are of the order of 25 centimeters. The ICESat freeboard measurements are accurate to within about 5 centimeters, and the current evaluation of the ICESat ice thickness error is about 50 centimeters.

Sea ice thickness is an important climate state variable that has been poorly observed, poorly documented, and poorly archived. The science community can do much better, and a unified sea ice thickness data set is an important step forward. The archive will be a valuable baseline and a continuously growing resource for ongoing work by many groups in understanding, predicting, and adapting to changes in the polar regions.

Current contributors to the data set include Christian Haas, UA; Stefan Hendricks, Wolfgang Dierking, and Hannalore Witte, AWI; Ron Kwok, JPL; Andre Proshutinsky, WHOI; Humfrey Melling, IOS; Richard Moritz, UW; Peter Wadhams, University of Cambridge; and Mark Wensnahan, UW. To learn more about the data set and to contribute additional ice thickness distribution data, visit http://psc.apl.uw.edu/sea_ice_cdr.

Reference

Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze (2007), Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett., 34,* L09501, doi:10.1029/2007GL029703.

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Exploring Structural Controls on Sumatran Earthquakes

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A series of linked marine and land studies have recently targeted the Sumatra subduction zone, focusing on the 2004 and 2005 plate boundary earthquake ruptures in Indonesia. A collaborative research effort by scientists from the United Kingdom (UK Sumatra Consortium), Indonesia, United States, France, and Germany is focusing on imaging the crustal structure of the margin to examine controls on along-strike and updip earthquake rupture propagation. The fundamental science objective is to examine how margin architecture and properties control earthquake rupture location and propagation.

The project collected extensive geophysical, geological, and seismological data across the offshore and onshore parts of the subduction zone of north central Sumatra (Figures 1 and 2). Offshore data collection within the project included the largest research vessel exchange program undertaken to date, involving an exchange of research vessel time between countries to maximize efficiency. The main surveys of the project spanned two segment boundaries of the subduction zone (Figure 1): between the 2004 and 2005 ruptures at Simeulue Island, and at the southern limit of the 2005 rupture, adjacent to a segment that ruptured in 1935, at the Nias and Batu islands. The extensive geological and geophysical data examine variations, at a range of scales, in seismicity, fore-arc deformation, plate boundary properties, lithospheric structure, and sedimentary properties and processes.

Using the German R/V *Sonne,* researchers acquired 4750 kilometers of multichannel seismic reflection data and conducted an active-source refraction experiment using 95 ocean bottom seismometers (OBSs) and 50 seismometer stations on land to examine the large-scale plate structure. This phase of the project was followed by earthquake monitoring during the subsequent 10 months (April 2008 to February 2009) with up to 60 instruments, including 10 OBSs. In addition, the project collected deep-towed side-scan sonar data, multicores recovering the seabed interface, piston cores, and two heat flow transects, as well as along-track multibeam bathymetry, gravity, and magnetics data. These data sets were collected during 2008 and 2009 using 140 days of ship time (see R/V *Sonne* cruise 198-1, 198-2, and 200 reports, available at http://www.noc.soton.ac.uk/gg/sumatra/publications.html), exchanged through the European Ocean Facilities Exchange Group. Funding for this research was provided primarily by the U.K. Natural Environment Research Council (NERC), with additional funding from the U.S. National Science Foundation.

Additional passive seismic arrays were deployed in the Toba volcano area from May–October 2008 by the Deutsches GeoForschungsZentrum (Potsdam, Germany), and farther south in the area of the 2007 plate boundary rupture, from December 2007 to October 2008, funded by a NERC "urgency grant" to the U.K. scientists. In total, earthquake monitoring was conducted over nearly 800 kilometers of plate margin for a period of 6–12 months. In parallel with the onshore-offshore field data collection, researchers within the UK Sumatra Consortium (funded by NERC) are also developing new methods to refine slip distribution inversions for the earthquakes of 2004, 2005, and 2007.

The combined studies are particularly relevant given the societal impact of the December 2004 Indian Ocean earthquake and tsunami and the continued potential for great earthquakes along this margin and along other analogous subduction margins. An improved understanding of rupture processes will aid in understanding and in preparedness for future major subduction zone earthquakes. Data from the passive deployment are already helping to characterize the structural context of an earthquake within the subducting Australian plate that occurred in 2009 near the Indonesian city of Padang.

Results also are being used to identify potential borehole sites for an evolving Integrated Ocean Drilling Program (IODP) proposal, the first to target the Sumatran margin. The aim of proposed IODP drilling is to analyze sediment and fault properties and fore-arc development history, to further understand the relationship between physical properties, structure, and the earthquake rupture process. An April 2010 workshop and an upcoming workshop in 2011 are bringing together diverse international