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INTRODUCTION TO THE SPECIAL ISSUE ON

Ocean-Ice Interaction

By Josh K. Willis, Eric Rignot, R. Steven Nerem, and Eric Lindstrom

The end of 2016 is an uneasy moment for climate science in the United States. With a new Administration and a new Congress arriving in January 2017, future support for climate science and observing systems is uncertain. Against this backdrop, this special issue of *Oceanography* on ocean-ice interaction is timely. Although it was not our intent to highlight climate change, the fragile nature of Earth's cryosphere and how it is responding to a warming world are essential parts of each article. Many aspects of the shrinking cryosphere are not yet understood, but the research described in these pages points to larger-than-anticipated—and alarming—changes to the planet's large ice sheets, with associated future increases in global sea levels. Importantly, the articles in this special issue demonstrate the value to society of continuing vigorous scientific research that will enable us to better understand our planet's rapidly changing polar environments.

Nowhere is this better illustrated than in the paper by **Frajka-Williams et al.**, which considers the long-studied link between freshwater output from the Greenland Ice Sheet and changes in the Atlantic Meridional Overturning Circulation (AMOC). This slow-moving circulation, which carries heat through the ocean from the equator to the high northern latitudes in the Atlantic, is expected to slow as the planet warms and greater volumes of fresh meltwater from Greenland flow into the North Atlantic, with large consequences for Europe's climate. But, has this already begun? Although changes have occurred in the last decade and Greenland ice loss may soon become

Photo of an iceberg-to-be off Getz Ice Shelf, West Antarctica, taken during NASA's Operation IceBridge 2016. *Photo credit: Jeremy Harbeck, NASA/GSFC* a dominant driver of AMOC slowing, **Frajka-Williams et al.** show that a longer and more complete observational record, including data from both satellites and in situ observations, is needed to establish a definitive link between the two.

The next two articles focus on one of the most important glaciers in East Greenland and its direct interactions with the ocean. These detailed studies of Sermilik Fjord and Helheim Glacier reveal a rapidly changing ice front that sits in 600–700 m of water. Based on a sustained observing effort lasting more than seven years, **Straneo et al.** show how warm, salty water originating in the North Atlantic enters the fjord and mixes with both meltwater from the glacier front and melt that originates upstream from the front. But an obvious connection between ocean temperature and circulation and the melt, calving, or other ice loss at the front remains elusive. The results of **Holland et al.** further underscore the dynamic nature of the glacier front by providing a detailed case study of a single calving event, a process that continues to defy easy description and parameterization in models.

Given all that we know about our planet, it is always surprising to realize that basic exploration is still an important part of advancing Earth and climate science. The shapes and depths of the bedrock beneath the ocean and glaciers, important input to climate models, are being mapped for the first time. **Morlighem et al.** use ship-based sonar data collected as part of a new NASA mission called Oceans Melting Greenland (OMG) to improve maps of the seafloor and glacier beds along the east coast of Greenland. Likewise, **Fenty et al.** delve into the first year of OMG ocean and ice observations, furthering OMG's mission to make broad-scale surveys of both glacier and ocean changes through 2020. The striking thing about both studies is the vast areas of Greenland's intricate coast where few prior measurements of ocean conditions or seafloor depth have been made.

Münchow et al. is our final article dedicated to ocean-ice interaction in

A Tribute to Gordon Hamilton

To Gordon and Leigh, field glaciologists, the boats in Greenland's Tasiilaq harbor all looked seaworthy. To Dave and Fiamma, field oceanographers, they all looked worryingly tiny. A few hours later, we were gently rolling inside Sermilik Fjord on a 21-foot hunting-turned-ocean-research vessel amid towering icebergs. Elated by the new type of fieldwork, Gordon rapidly caught on as we alternated between depth soundings, velocity measurements, and CTD profiles. That first day, July 4, 2008, we found clear evidence that warm, salty waters carried by the Gulf Stream reached the margin of Helheim Glacier—one of Greenland's largest and fastest-moving glaciers. That day, the science of ocean-ice interaction took a leap forward. And that day also marked the beginning of a fruitful, exciting, and rewarding friendship and scientific collaboration among a few glaciologists and oceanographers that continues to expand, encompassing many colleagues, postdocs, and students.

Gordon Hamilton making ocean measurements in Sermilik Fjord, Southeast Greenland, July 2008.

Conducting interdisciplinary research requires something beyond what we need to succeed within our own fields. It requires trust, because we depend on our colleagues' expertise in the other discipline(s). It requires an ability to synthesize our science to make it accessible, because colleagues may have different backgrounds from our own. It requires generosity, because we may have to take a back seat to facilitate advancement in other fields. Above all, it requires a genuine excitement about advancing the science as a whole that transcends any personal achievement.

There is no doubt that throughout his career and in our work together, Gordon displayed all of these qualities. He was an amazing colleague, mentor, and friend to the many, many people with whom he worked. He was a master of logistics, he never tired of sharing his extensive field expertise to help others' research, and he always solved seemingly insurmountable problems with a smile. Gordon was driven by a keen interest in understanding why ice sheets are changing and what this would mean for future generations. He was strongly committed to engaging society and traveled the world to share what he and others were learning. He was committed to facilitating progress by creating opportunities for scientific interaction through workshops, summer schools, and international programs. Though his premature and tragic death leaves a deep void in the hearts and minds of all who had the good fortune to work side by side with him, his legacy will continue to inspire and motivate us for many years to come.

— Fiamma Straneo, Leigh Stearns, and Dave Sutherland

Gordon S. Hamilton, a 50-year-old glaciologist and climate professor at the University of Maine died tragically on October 22, 2016, when his snowmobile fell into a crevasse in Antarctica. He was investigating a shear zone, a region that is important for the stabilization of the Ross Ice Shelf, and an area he thought was key to understanding future loss of ice from Antarctica.

Greenland. Their study provides an interesting historical perspective and a careful look at new observations of the ice shelf extending from Petermann Gletscher, on Greenland's northern coast. One of only a handful of floating ice shelves in Greenland, Petermann has lost about one-third of its area since 2010—a surprising change, given its location along the far northern edge of the island. **Münchow et al.** use observations of ocean temperature and salinity from moorings placed beneath the shelf along with a variety of other data to show that warm ocean water has played an important role in melting the ice shelf from below, and they speculate about whether the shelf has reached a new equilibrium or will continue to retreat in the coming years.

Shifting to the Southern Hemisphere, the unbroken eastward flow of the Antarctic Circumpolar Current (ACC) is the dominant feature. Acting as a barrier between the warmer waters of the mid-latitudes and the massive ice sheet covering Antarctica, changes in the ACC are hypothesized to impact Antarctic ice loss in several key regions. Although the westerly winds that drive the ACC have intensified and moved south, **Gille et al.** suggest that the ACC itself has done neither of these things. Instead, they propose an increase in eddies that carry warm, salty water across the current and toward Antarctica is causing ice shelves in this region to thin.

Remarkably, even more distant features than the ACC may influence the amount of heat reaching the ice shelves through the ocean. **Jenkins et al.** describe teleconnections with the tropical Pacific Ocean that drive local changes in the Amundsen Sea. This basin is the location of some of the most dramatic changes in glacier mass balance in the world. Circulation changes there may modulate the amount of warm water that can cross the continental shelf and reach the floating ice shelves of two of the most rapidly retreating glaciers, Pine Island and Thwaites. But **Heywood et al.** remind us that even with modern data from the most extensive ship surveys, seal-tagging programs, and autonomous underwater vehicles, huge gaps remain in our understanding of the complex circulation across the continental shelf.

Although West Antarctica and the Antarctic Peninsula have long been assumed to be the regions most likely to contribute to sea level rise first, recent work suggests that large glacier systems in East Antarctica are at risk from warm ocean waters as well. **Silvano et al.** review the different types of ocean-ice shelf interactions at work around Antarctica. The volume of ice grounded below sea level in East Antarctica is enough to raise global sea levels by 19 m—a fact not accounted for in most projections of future sea level rise. **Silvano et al.** review recent evidence that much of this ice may be threatened by warming waters in the centuries to come. Given their enormous potential to affect future sea level rise, ocean observations in these regions are desperately needed in order to determine just how threatened East Antarctic glaciers may be.

One of the most urgent reasons for understanding ocean-ice interaction is the projection of future ice loss and sea level rise. Realistic projections require realistic models, and **Dinniman et al.'s** review of ice shelf-ocean modeling in Antarctica provides a broad look at where such efforts stand today. While there has been an increase in successful three-dimensional modeling of both ocean and ice shelves over the past two decades, coupling of these types of models in a realistic way remains a top priority for the next decade. But **Dinniman et al.** also highlight the need for more observations that allow models and model physics to be tested.

Though the details of understanding ocean-ice interactions can sometimes feel remote and academic, our final paper by **Leuliette and Nerem** reminds us that the consequences of these interactions can already be felt across the planet. Rising sea levels caused by human interference with climate are already noticeable on nearly every coastline in the world, and fully one-third of that rise is due to ice loss in Greenland and Antarctica.

In times of uncertainty, it is important to remember that the study of ocean-ice interaction has direct consequences for hundreds of millions of people worldwide. Our field is more than a simple effort to reduce uncertainties; it is one of discovery, exploration, and grand scientific challenges—a fact made obvious by the photographs in this issue. We hope this compilation of work stands as a reminder for us and our colleagues to speak up and speak out about the need to better understand our planet as we reshape its climate.

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