

## Global change on the Blue Planet

Annie Bourbonnais<sup>1,7</sup>, Sze Ling Ho<sup>2,7</sup>, Christophe Kinnard<sup>3,7</sup>,  
Jan T. M. Lenaerts<sup>4,7</sup>, Shin Sugiyama<sup>5,7</sup> & Mark Altabet<sup>6,7</sup>

Oceans and cryosphere are immediately affected by human-induced climate change. Our Editorial Board members present viewpoints on the most pressing and fruitful avenues of research on frozen and liquid water, and the transition from one to the other.

The Earth's oceans let our planet appear blue from space, and their extent is intimately linked to the amount of ice stored at the poles and in mountain glaciers. For this series of Comments that celebrate the first anniversary of the launch of *Communications Earth & Environment*, we have invited our Editorial Board members to highlight the scientific advances and questions that they are most excited about. In the oceans and cryosphere, much is in flux. The same holds true for our understanding of the underlying processes and our ability to monitor these often inaccessible environments.

### Christophe Kinnard: A thawing Earth

Changes in the cryosphere are the most salient signals of ongoing climate change. The decreasing volume and extent of sea ice, snow cover, glaciers, ice sheets and permafrost represent strong visual indicators of climate change that resonate with the public perception of climate change. This “big thaw” is having far-reaching consequences on the global hydroclimate system and human societies. The cryosphere amplifies climate change through the albedo feedback—icy surfaces tend to be bright and reflect sunlight back to space, whereas melting makes the Earth darker—and through the release of greenhouse gases from thawing soils. The disappearing Arctic sea ice slows and amplifies the jet stream, causing extreme weather patterns southward. The storage of frozen water on land and its release over various timescales from days (snow) to centuries and millennia (ice sheets) is a key component of the hydrological cycle from the global to the regional scale, and it redefines hydrological risks and resources worldwide.

The past decade has seen a rapid acceleration of cryospheric changes. In parallel, our capacity to monitor and model these changes has advanced and allows us to refine future projections. Long seen as relatively stable features, the Earth's ice sheets in Greenland and Antarctica are picking up pace, along with retreating mountain glaciers. Glacier and ice sheet mass loss is now the dominant source of the global mean sea-level rise. The Greenland ice sheet has been losing mass since the 1990s through increased surface melting and calving, at rates that match high-end climate warming projections. The West Antarctic ice sheet, which is mostly grounded below the sea level, continues to display signs of instability, with collapsing ice shelves and speeding up of its outlet glaciers. The prospect of marine ice sheet destabilization is thus becoming increasingly real and represents the largest single source of uncertainty in projections of future sea-level rise. At the regional scale, many glacierized regions of the world have already passed their point of peak water, the turning point between increasing melt rates as a result of warming and decreasing melt volumes as less and less ice is available to melt. Others are projected to do so by

<sup>1</sup>School of the Earth, Ocean and Environment, University of South Carolina, Columbia, SC, USA. <sup>2</sup>Institute of Oceanography, National Taiwan University, Taipei, Taiwan. <sup>3</sup>Canada Research Chair in Cryosphere Hydrology, Université du Québec à Trois-Rivières (UQTR), Trois-Rivières, QC, Canada. <sup>4</sup>Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, CO, USA. <sup>5</sup>Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan. <sup>6</sup>University of Massachusetts Dartmouth, New Bedford, MA, USA. <sup>7</sup>These authors contributed equally: Annie Bourbonnais, Sze Ling Ho, Christophe Kinnard, Jan T. M. Lenaerts, Shin Sugiyama, Mark Altabet. ✉email: [abourbonnais@seoe.sc.edu](mailto:abourbonnais@seoe.sc.edu); [slingho@ntu.edu.tw](mailto:slingho@ntu.edu.tw); [christophe.kinnard@uqtr.ca](mailto:christophe.kinnard@uqtr.ca); [Jan.Lenaerts@colorado.edu](mailto:Jan.Lenaerts@colorado.edu); [sugishin@lowtem.hokudai.ac.jp](mailto:sugishin@lowtem.hokudai.ac.jp)

mid-century, thus threatening local water supply in water-stressed mountain regions. The loss of snow storage is also reducing groundwater recharge and water supply in many catchments of the world—particularly those in semiarid climates where summer precipitation is scarce, such as the southwestern USA or the subtropical Andes.



**Credit: Christophe Kinnard**

Thinner snowpacks have reduced the snowmelt contribution to floods and should continue to do so in the next decades, but increased rain-on-snow events and changes in infiltration related to soil freezing make it hard to tease out the impacts of cryospheric changes on flood regimes from changes in precipitation extremes. Hence, while the thawing trend is almost ubiquitous on Earth, the hydrological consequences show a great deal of regionalism, which challenges the projection of their impacts and related adaptation strategies.

As in other areas of the Earth sciences, cryospheric science is witnessing a growing influx of diverse Earth observation data. The increased public availability of repeat satellite imagery, such as the European Space Agency's Sentinel missions has greatly increased our ability to track cryospheric changes. The use of Machine Learning and Artificial Intelligence techniques combined with cloud-based processing platforms open up new and exciting ways to study cryospheric changes in remote regions at an ever-increasing temporal and spatial resolution. Hyper-resolution models with spatial resolution <1000 m are becoming the norm. Combined with high-resolution remote-sensing this allows resolving the sometimes-formidable spatial heterogeneity of the Earth surface. This increased observational and modeling capability should help resolve some of the ongoing uncertainties in climate–cryosphere interactions in coming years—such as ice sheet stability and shifting hydrological risks and resources under future climates.

### Jan Lenaerts: The Ice Sheet Sponge

Mass loss from the Greenland and Antarctic ice sheets increasingly contributes to global sea-level rise. These ice sheets are covered with a thick layer of firn, that is, compressed snow up to hundreds of meters deep. Firn contains pockets of air and can act like a sponge that stores liquid water from melting at the ice sheet surface. Because this storage mechanism breaks the direct link between surface melt and runoff, it can delay and mitigate ice sheet mass loss. However, as the atmosphere warms and surface melt increases, the ice sheet's sponge slowly saturates. Additional effects, such as meltwater refreezing in the firn layer, can hasten along with saturation and a reduction in storage capacity. These processes can lead to mass loss in Greenland and increase the risk of destabilization of the floating ice shelves that buttress much of Antarctica's ice.

Over the past decade, field programs and airborne radar observations, particularly from NASA Operation IceBridge, have shown us that meltwater storage in Greenland and Antarctica exists in many forms, and is sensitive to the climate regime. Meltwater can be refrozen in ice lenses, stored in subsurface liquid-water lakes, or persist in firn aquifers—columns of water-saturated firn buried tens of meters under the surface. Meltwater percolation from the surface through firn is highly heterogeneous. It typically manifests as vertical pipes that rapidly route water deep below the surface. Changes in the firn structure can occur fast. Extreme melt events, especially the July 2012 event that generated surface melt in Greenland all the way to the highest, coldest areas, create spatially extensive impermeable ice slabs that prevent meltwater percolation in the deeper portion of the firn layer.

On Antarctic ice shelves, the cold climate has historically ensured that firn stores nearly all meltwater that is produced at the surface. However, recent observations show extensive ponding on the surfaces of many Antarctic ice shelves in the past decades, particularly near the grounding line, which is indicative of limited firn storage capacity. This extensive meltwater ponding has been associated with dramatic hydrofracture events, such as those leading to the collapse of the Antarctic ice shelves Larsen A in 1994 and Larsen B in 2002.

To predict the role of the firn in future ice sheet mass loss, we primarily rely on numerical models, which mostly rely on relatively simple, steady-state expressions of firn properties and percolation that are derived from past observations. Whether these expressions are still valid for the future, warmer climate conditions are unclear. In addition, current firn models represent a single firn column, which does not capture the spatial variability of meltwater processes. In order to obtain a better idea of the future role of the firn layer in ice sheet dynamics, we need to understand the contribution of horizontal water flow compared to vertical percolation, the role of nonlinear percolation processes for meltwater storage, and the impact of more frequent compound extreme melt events on firn structure and storage capacity.

To answer these questions, we need to apply high-resolution, three-dimensional firn models that represent lateral water flow and include more sophisticated treatment of localized, rapid vertical meltwater percolation—at the scale of an entire ice sheet. With such tools in hand, we will be able to investigate the firn layer's response to climate change—one of the key open questions for quantifying how much sea-level rise the ice sheets will contribute.



**Credit: Clément Miège**

### Shin Sugiyama: Beneath the ice

At the grounding zone of the Antarctic ice sheet, ice flows from the bedrock into the sea, comes afloat, and starts forming an ice shelf. The subglacial environment in this transition area is crucial for Antarctic ice loss: ice discharge across the grounding line is accelerating and subsequent melting under the floating ice shelves is rapid. The ice is moving ever faster into the sea because basal sliding is enhanced as subglacial water pressure as well as deformability of the basal sediment layer facilitate ice movement. Melting at the base of the floating ice shelves is most significant

near the grounding line, where oceanic heat is supplied by relatively warm Circumpolar Deep Water that can intrude into the cavity beneath the shelf. Under the ice in the grounding zone, a network of water channels enables active transport of meltwater, which connects subglacial lakes and exits into the ocean. Subglacial lakes as well as the cavities under the floating ice shelves host ecosystems<sup>1, 2</sup>.

Despite its importance, subglacial environments in the Antarctic grounding zone are one of the least explored areas on Earth. In situ measurements are difficult under several hundred meters of ice, and field activities are hindered by heavily crevassed ice surface conditions. Nevertheless, rapid glacier changes in West Antarctica and increasing interest in subglacial aquatic environments have inspired new initiatives. In 2019/2020, a 700-m-long borehole drilled through the floating shelf in the grounding zone of Thwaites Glacier allowed measurements of seawater properties and circulation beneath this rapidly thinning outlet glacier in the Amundson Sea Embayment. These observations can then be compared with data obtained from a glacier in a quiescent phase, the Kamb ice stream that flows into Ross Ice Shelf. Water and sediment samples were collected from Mercer Subglacial Lake under the Whillans ice stream, also in the Ross Ice Shelf region, and the sediments ~40 km upstream of the grounding line of Rutford Ice Stream were accessed through >2000 m of ice in order to investigate the basal processes driving the fast ice flow<sup>3</sup>. These extremely challenging field investigations will help us understand when, where, and how the ice sheet accelerates on its path into the ocean—a crucial piece in the puzzle of projecting sea-level rise.

The bounds of our measurement capabilities have been greatly expanded by our ability to deploy an autonomous underwater vehicle through a borehole (<https://schmidt.eas.gatech.edu/icefin/>), and by the clean hot-water drilling technique<sup>4</sup>, which enables contamination-free sampling from a borehole, and hence tackling question about life under the ice sheet. Earlier drilling and sampling in Whillans Subglacial Lake in the Ross Ice Shelf region revealed the existence of life, but much is unknown about these ecosystems in extreme environments. Subglacial observations with a variety of approaches, and undergrounding zones in different settings, will guide us to answers to the questions hidden under the ice.

### **Annie Bourbonnais and Mark Altabet: Autonomous sensing revolution**

Global change affects the biogeochemical cycling of elements in the ocean as well as the interactions between these cycles. For example, climate warming will alter ocean–atmosphere fluxes of climate-sensitive gases, such as carbon dioxide, methane, and nitrous oxide, as well as their sequestration in deep water masses. Biological communities, ecosystems, and ecosystem services are expected to respond to ocean acidification, which is the decrease in ocean pH due to its uptake of anthropogenic CO<sub>2</sub>. However, in both cases, we do not know enough about mechanistic linkages to make reliable predictions. Traditional sampling using manual methods onboard research vessels are insufficient for answering these questions. They do not resolve key time and space scales of variability. Continuous, long-term observations are required to distinguish natural from anthropogenic climate change effects. Up to now, the vast majority of the ocean has only been sampled a few times per decade, principally because of the limited capabilities of ship-based observations and their cost.

Rapid advances in autonomous chemical-sensing capabilities within the past two decades have revolutionized the field of chemical oceanography. They have allowed ocean sampling at unprecedented spatial and temporal resolutions and data

collection in challenging, remote, and rugged environments, such as undersea ice and rough seas. Sensors installed on autonomous vehicles or platforms—surface drifters, profiling floats, unmanned boats, and autonomous underwater vehicles—continuously measure key biogeochemical properties such as temperature, salinity, dissolved oxygen, pH, nitrate, and chlorophyll *a*, all in real-time for extended periods of months to years. Through the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project, the Ocean Observatories Initiative (OOI), and the Biogeochemical Argo (BGC-Argo) program and others, thousands of oceanic time series data have been collected and assembled into a remarkable database. As a result, we have learned that net community productivity undergoes strong seasonal cycles at stations in the Gulf of Alaska and the Southern Ocean<sup>5, 6</sup>. We are also now starting to better understand the importance of the Southern Ocean for global carbon fluxes<sup>7</sup>. Polar regions are particularly sensitive to climate change and ocean acidification due to higher carbon dioxide solubility at colder temperatures<sup>7</sup>.

Autonomous sensing of other important ocean chemical properties is within reach. Notably, air–sea greenhouse gas fluxes as well as water-column concentrations and stable isotopes could be continuously monitored with the help of long-term deployment of membrane inlet quadrupole mass spectrometers or laser spectrometers on autonomous platforms. With these data, processes producing or consuming key greenhouse gases, such as methane liberated from gas hydrate deposits or nitrous oxide in oxygen minimum zones, can be illuminated. Autonomous biogeochemical sensing is also increasingly used by the coastal mariculture industry and allows early detection of harmful cyanobacterial blooms and potential shellfish contamination.

Harnessing automation and big data in chemical oceanography and making full use of the very large datasets that are being generated will not be straightforward. We need to implement best practices regarding sensor calibration and performance assessment, as well as rigorous quality control of these large datasets.



Credit: Christian Lewis

### Sze Ling Ho: Models meet proxies

Ocean temperature is a key indicator of the Earth's climate system. It provides a glimpse into heat transport, equilibrium climate sensitivity, ice sheet dynamics, and sea-level change—all parameters with societal relevance. Past ocean temperature estimates routinely serve as benchmarks for global climate models. As part of the paleoclimate evidence, past ocean temperatures will also be an integral part of the next report from the Intergovernmental Panel on Climate Change, which is due for release in 2021–2022.

The past two decades have seen gradual but steady development in how we reconstruct past ocean temperatures. Technique-wise, there has been a shift from faunal and floral assemblages to geochemical indicators in sediments. Approach-wise, in addition to the conventional local reconstructions based on a single sediment record, there is an increasing number of studies based on community-led global data syntheses that integrate across archives and proxies. Global data syntheses help to bridge the gap between the models and proxy data. But they are often spatially clustered, due in part to logistics in sampling, whereas climate model simulations are coarser in resolution but with broader spatial coverage. Consequently, proxy observations need to be statistically transformed to allow an appropriate comparison with model output.

Close collaborations between proxy and model communities over the years have culminated in numerous landmark data-model comparison studies. Choices of proxy type and statistical method do matter. For instance, one data assimilation product based on geochemical proxies yields global mean surface ocean temperatures during the Last Glacial Maximum 3.1 °C cooler than the late Holocene, approximately twice the difference inferred from data compilations that are based largely on faunal assemblages. Over the years, awareness that we need to include error estimates in ocean temperature reconstructions has increased. We have seen the rise of Bayesian-based calibrations that allow the propagation of uncertainties and facilitate the integration with model output. On the flipside of model-data comparisons, there has been the rise of proxy system modeling, where instead of synthesizing the data into model-relevant formats, the models are used to simulate what may have happened at a specific site where we have proxy data.

Despite these exciting advances, inter-proxy discrepancies are not uncommon even at the same locality, hinting at yet incomplete understanding of the proxy systematics. This issue is as relevant as increasing spatial coverage of observation. Inter-proxy discrepancies stem from differences in the physiology and ecology of the proxy recorders, as well as sedimentary processes—all of which can be better understood with more observations in the laboratory and field.

Continued efforts in exploring innovative statistical methodologies and machine learning techniques along with more traditional laboratory experiments and field observations are key

to fully understanding the processes that produced the proxy data we have and to integrating them with model output.

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### Additional information

**Correspondence** and requests for materials should be addressed to A.B., S.L.H., C.K., J.T.M.L. or S.S.

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