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Physics of the cryosphere

Alison F. Banwell, Justin C. Burton, Claudia Cenedese, Kenneth Golden & Jan Åström

The cryosphere — the part of Earth's climate system consisting of snow and ice — is undergoing rapid and massive perturbations due to planetary warming. For instance, almost half the summer Arctic sea-ice cover has been lost over recent decades; February 2023 saw the extent of Antarctic sea ice reach a record low. Such melting has ripple effects and feedbacks on the climate system that are powerful and can travel far, challenging efforts at modelling and prediction. Five researchers discuss how diverse physics ideas can help better understand the cryosphere.

Statistical physics in sea-ice modelling

Kenneth Golden: Improving our ability to understand and model the behaviour of sea ice is a central problem in the physics of the cryosphere and the climate system more broadly. As a material, sea ice is a hierarchical, multiscale composite with complex structure on length scales ranging from tenths of millimetres to tens of kilometres, and it exhibits rich dynamics on the scale of the Arctic Ocean. A principal modelling challenge is how to use data on smaller-scale structure to find the effective properties of sea ice on larger scales relevant to climate and process models (Box 1).

This aim parallels that of statistical mechanics. This robust theory and its extensions deftly handle complex collective behaviour such as phase transitions, transport properties and response to forcing for systems with a large number of particles or degrees of freedom. Statistical physics has seen widespread success and become a key branch of modern physics. Yet even though it provides such a natural framework for formulating and addressing key questions in the physics of sea ice, and opens up a broad array of powerful ideas and methods, it has been used in only a few contexts, albeit with unusual success.

One application of statistical physics to the macroscopic behaviour of sea ice is the use of percolation theory[1] to explain critical behaviour in data on fluid flow, snow-ice production and convection-fuelled algal blooms. The principal finding, known as the Rule of Fives, was that fluid can flow vertically when the brine volume fraction exceeds the percolation threshold of 5%, which corresponds to a critical temperature of −5 °C for a typical bulk salinity of 5 parts per thousand. Subsequent work obtained accurate predictions from percolation theory for sea-ice fluid permeability above the threshold.

Another application of a classical model in statistical physics was to adapt the Ising model, originally developed over 100 years ago to understand magnetic materials, to accurately predict the evolution and fractal geometry of Arctic melt ponds[2]. Instead of up or down spins on a lattice, water or ice patches interact with their nearest neighbours and an external field, with realistic pond configurations obtained as the Hamiltonian is minimized.

Finally, the macroscopic statistics of Brownian motion exhibited by a pollen grain in water evolve slowly compared with the microscopic collisional events driving its motion. Similarly, the rafting, ridging and other 'microscopic' mechanical events that can thicken or thin the ice cover occur over timescales that are very rapid relative to geophysical-scale changes in the macroscopic ice-thickness distribution function. Focusing not on individual events but on the transition probabilities of incrementally changing ice thickness leads to a Boltzmann-type collision integral, and a closed-form advection diffusion equation for the thickness distribution. This distribution function is a central object in sea-ice modelling and was first introduced over half a century ago, but more recently was put on a firm theoretical foundation, and recovered analytically, using classical ideas of statistical mechanics[3].

There is clear evidence that statistical physics can provide a powerful new paradigm for sea-ice modelling and prediction. In addition to the examples given above, methods of homogenization for finding the effective macroscopic behaviour of partial differential equation models with local parameters describing sea-ice microstructural characteristics[4] are similar in spirit, as well as mathematically, to theories of macroscopic behaviour in statistical physics. Hopefully these powerful ideas will be further explored and exploited in future studies of sea-ice behaviour.

Fluid dynamics of iceberg melting

Claudia Cenedese: Iceberg calving — ice breaking off the edge of an ice shelf or a glacier — accounts for half of the mass discharge from the Greenland and Antarctic ice sheets, which has increased dramatically over the past two decades. Glaciers or narrow ice streams terminating in fjords generate icebergs via the collapse of a highly crevassed glacier terminus. These relatively small icebergs drift in the fjord before entering the coastal ocean. They melt along the way and discharge freshwater, which is quickly diluted by mixing with ambient waters.

The ambient flow surrounding icebergs can be vertically sheared, especially in fjords, causing the icebergs to drift with the vertical average of the ocean currents over the iceberg height below the waterline (known as the draft of the iceberg)[5]. Submarine melting of icebergs is strongly influenced by the relative flow speed between the iceberg and the ambient flow. When this relative flow speed is small compared with that of the meltwater plumes rising uniformly around the iceberg, the plumes are attached to the iceberg's side walls and spread horizontally near the surface, or at their neutrally buoyant level, in a relatively undiluted freshwater layer. For large relative flow speeds, the meltwater plumes detach from the iceberg's side walls and mix vigorously with the ambient fluid, forming a highly diluted fresher layer over the entire draft of the iceberg. The existence of these two distinct regimes, side-attached and side-detached, results in the iceberg melt rate depending nonlinearly on the relative flow speed. In particular, the side-detached regime has a distinct increase in the dependence of melting on relative flow speed[6].

The relative flow past the iceberg influences the melting in two ways. First, it modulates the heat transport to the ice surface, resulting in the observed linear increase of melting with relative flow speed. Second, it interacts with the meltwater plumes. If the plumes are attached, the relatively cold water contained in the plumes insulates the iceberg surface from the ambient water, and the heat transport relies on the warm ambient water being pulled into the flow of the meltwater plumes. When the plumes detach from the iceberg's side wall, the iceberg comes directly in contact with the undiluted warm ambient waters, which are consistently renewed by the relative flow past the iceberg.

In the case of a tidewater glacier terminus, submarine melting increases in the presence of meltwater plumes and is proportional to their volume flux. However, the absence of meltwater plumes can result in an even greater melting, provided the warm ambient water is continually renewed by a background flow, as is the case for icebergs drifting in a sheared ambient flow. Parameterizations used in numerical models often only consider surface ocean velocities and temperatures to estimate iceberg submarine melting[7]. However, knowledge of the ocean velocity over the entire iceberg draft is crucial to describe its motion and melting accurately[5,6]. In particular, the relevant velocity to be included in submarine melting parameterizations is the meltwater plume vertical velocity when the iceberg's relative flow speed is smaller than the plume velocity, and the iceberg's relative flow speed when this is larger than the plume velocity[6].

Iceberg calving is likely to increase as the climate continues to warm. Insights into iceberg dynamics, and, in particular, the mechanisms regulating their deterioration and the associated freshwater and sediment flux, will therefore be important for understanding and predicting their impact on the climate/ocean system.

Mechanics of surface meltwater catalysing Antarctic ice-shelf collapse

Alison F. Banwell: Ice shelves, which are the floating extensions of glaciers on land, surround 75% of Antarctica. Their buttressing power gives them an important role in reducing global sea-level rise by regulating the rate that inland glacier ice is lost to the ocean. The stability of ice shelves, however, is not only threatened through calving processes at their ice fronts, as well as ice-shelf thinning due to basal melting (in response to warming ocean temperatures) and surface melting (due to rising air temperatures), but also in response to stress variations associated with surface meltwater ponding and drainage during melt seasons.

Meltwater lakes on ice shelves act as loads, causing floating ice shelves to flex downwards. These lakes can also drain, frequently via hydrofracture, a process that occurs when the hydrostatic pressure at the tip of a water-filled fracture (or crevasse) exceeds the ambient pressure enough to induce stresses at the tip of the fracture that overcome the fracture toughness of the ice. If water fills the fracture as it grows vertically, it may fracture the full ice-shelf thickness, enabling the lake's rapid drainage (on the order of hours) into the ocean below. In response, the ice shelf rebounds upwards to regain hydrostatic equilibrium.

This process of loading and unloading of surface lakes may result in sufficiently high ice-shelf stress for fractures to initiate, in ring and radial patterns, up to a kilometre or so from the lake centre. Modelling studies have shown that a chain reaction of lake drainage events could occur if these loading-induced fractures intersect adjacent lakes, as these adjacent lakes will drain into and deepen the new fractures[8,9]. For example, the rapid and widespread collapse of Antarctica's Larsen B ice shelf in 2002 has been attributed to the hydrofracture of thousands of surface meltwater lakes via a chain-reaction style process. However, chain-reaction lake drainages can only occur if lakes are close enough that fractures formed by one lake drainage event intersect an adjacent lake[9]. Additionally, stresses from further afield, including back-stress from landfast sea ice and larger-scale ice flow, can mute the impact of loading and unloading by limiting fracture initiation.

At present, predictions of future ice-shelf instability and collapse (and resultant sea-level rise) are highly uncertain, as even the most up-to-date continental-scale ice-sheet models do not explicitly account for surface-meltwater-induced ice-shelf flexure and fracture away from the ice-shelf's calving front. This omission exists partly because the physics involved in these ice dynamic processes typically occur on finer temporal and spatial scales than captured by continental ice-sheet models. One solution is to include these missing processes in ice-sheet models through the development of parameterizations, constrained by high-resolution remotely sensed and field-based observations. A variety of optical, synthetic aperture radar, microwave and lidar satellite data provides information about ice-shelf surface melt, hydrological systems and flexure and fracture dynamics, but relevant field-based observations are far more limited. Valuable observations include in situ water-pressure measurements that monitor lake depths; global navigation satellite system measurements of vertical elevation that quantify ice-shelf flexure; shallow ice and snow core data combined with in-ice thermistor strings that measure density and temperature; and seismic data that reveal information about fracturing.

It is crucial that these new observation-based parameterizations are developed to address gaps in existing modelling capability. Although changes in surface melt rates on Antarctic ice shelves have been relatively small over recent decades[10], at least compared with rapidly increasing rates of melt over the Greenland ice sheet[11], projected rates of atmospheric warming suggest that surface meltwater production on ice shelves will increase nonlinearly[12], probably making them more vulnerable to future surface-meltwater-induced instability in the future.

The contributors

Alison F. Banwell is a Research Scientist in the Cooperative Institute for Research in Environmental Sciences (CIRES), part of the University of Colorado Boulder. She has a PhD in Glaciology from the University of Cambridge (UK). Her research focuses on understanding changes in Antarctic and Greenland ice-sheet and ice-shelf melt, hydrology and dynamics using satellite remote sensing, fieldwork and process-scale modelling.

Justin C. Burton is an Associate Professor of Physics at Emory University. His research targets problems at the intersection of soft matter, fluid mechanics and geosciences. He is a past recipient of the National Science Foundation's CAREER Award and leads several K-12 STEM outreach and education activities in the Atlanta area.

Claudia Cenedese is a Senior Scientist in the Physical Oceanography Department at the Woods Hole Oceanographic Institution (MA, USA). She earned a PhD at the Department of Applied Mathematics and Theoretical Physics of the University of Cambridge (UK) after an MS + BS in Environmental Engineering at the University of Rome "La Sapienza". The focus of her research is to improve our understanding of how mesoscale and submesoscale processes, such as buoyant plumes generated by melting glaciers and icebergs, influence and modify the general circulation of the ocean.

Kenneth Golden is a Distinguished Professor of Mathematics at the University of Utah, with interests in sea ice, climate, polar ecology and composite materials. He has been on 18 polar expeditions and given over 500 invited lectures. Golden is a Fellow of the Society for Industrial and Applied Mathematics, the American Mathematical Society, the Electromagnetics Academy and the Explorers Club.

Jan Åström has a PhD in theoretical physics from Åbo Akademi university, and worked for nine years as a group leader in material physics at the University of Jyväskylä, before joining CSC, the Finnish Super-computer centre. J.Å. is a developer of scientific codes for mostly material physics, biophysical and geophysical applications.

Numerical models of disintegrating ice

Jan Åström: One major uncertainty factor related to climate-change-induced sea-level rise comes from sudden, and sometimes unexpectedly catastrophic, ice disintegration events. On a small scale, such events are common and called calvings. Much rarer and larger events, like the series of collapses of the Larsen ice shelves during 1995–2002, are suspected to become more frequent and even larger as our planet's climate warms.

These highly nonlinear disintegration process are notoriously difficult to predict, but efforts must be made in order to prepare coastal regions for future sea levels. A long-term general objective of cryospheric research is to develop generic 'calving laws' as functions of climate and ice topographic variables. Climate projection models for glaciers, ice shelves and ice sheets are typically flow models that use Stokes' equations for ice dynamics, which can stretch over hundreds of years. Such models are good for modelling the slow viscous flow of ice, but they are less capable of capturing sudden ice disintegration events. For this purpose, discrete element models (DEMs) are better suited. The fundamental reason for this difference is that viscous flow is continuous in nature, whereas fracture is intermittent. DEMs have existed for a long time, but only recently have computers become efficient enough to apply this type of model at glacier and ice-shelf scales with reasonable resolution (Supplementary Information).

Despite this progress, the development of universal calving laws is challenged by the full range of disintegration events, which span from small and infrequent winter-time calvings at tidewater glacier to the possible calving-driven collapse of the entire West Antarctic ice sheet. To highlight the vast complexity of these problems, the former could have the following dynamics. During winters, the termini of tidewater glaciers readily become stabilized by a thick and solidly frozen mélange of icebergs in the waters beyond the ice front. In the spring, the mélange may disappear and trigger intensive calving, producing new icebergs, which may, in turn, hinder further calving. At the same time, as more glacier meltwater is produced by warmer summer weather, the glacier flow easily speeds up and the glacier advances. This kind of back-and-forth dynamics can keep a glacier's terminus at a topographic stable point for decades. Eventually, in a warming climate, the stable point no longer holds, and a formerly stable glacier terminus may suddenly undergo a rapid retreat for kilometres, until a new marginally stable configuration is reached.

This type of dynamics is expected to vary significantly between tidewater glaciers, and for ice shelves and ice sheets the situation seems equally complex. The dynamics of the Thwaites eastern ice shelf, for example, is controlled by a shear zone forming against a pinning point. At others, the highly variable in-flow of warm seawater under the ice, governed by the sea bed topography, seems to be a decisive factor.

As a consequence of such complexity, generic calving laws are extremely difficult to formulate, but the situation is not hopeless. Progress is being made continuously, as high-resolution DEMs seem to be capable of simulating all the above phenomena. There remains a lot of work to do, but researchers are progressing towards a 'standard model' for ice disintegration

Box 1

Multiscale physics of sea ice

At the finest scales, sea ice is a composite material of pure ice with millimetre-scale brine inclusions whose volume fraction, geometry and connectivity depend strongly on temperature. Bulk flow through this porous microstructure controls key processes such as the evolution of complex melt ponds on the surface of Arctic sea ice, which determine its albedo, one of the most important parameters in climate modelling. Fluid transport also aids nutrient replenishment for algal communities living in the brine inclusions.

The statistical properties of the centimetre-scale polycrystalline microstructure, such as the sizes and orientations of individual grains or crystallites, are determined by ice formation conditions. The grains themselves are composites with aligned brine microstructure. These local characteristics, in turn, largely determine the effective rheological, fracture and fluid transport properties of individual ice floes on scales of metres and larger.

The ice pack itself can be considered as a granular composite of ice floes in a seawater host, where the 'grains' can range from a few centimetres to tens of kilometres across and take on myriad shapes. The floes (pictured) can break apart, melt, fuse together, raft on top of each other, or collide forming ridges and keels. Sea-ice models must incorporate the effective rheological properties of the ice pack as a multiscale, granular composite and account for various processes that statistically thicken or thin the ice cover. This system with a very large number of particles displays complex collective behaviour, and even phase transitions in its large-scale dynamics and mass transport properties, driven by atmospheric and oceanic forcing.

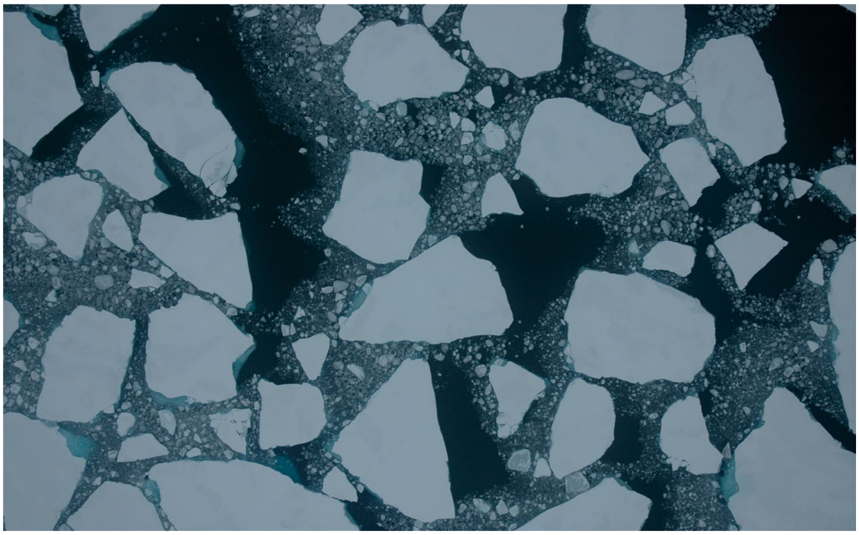

Figure courtesy of Donald K. Perovich.

that hopefully will be reliable enough to enable long-term climate projections of their contribution to sea-level rise.

Granular matter physics of ice mélange

Justin C. Burton: Dispersed throughout Earth's oceans, seas and rivers are floating granular materials. These collections of ice, trees, organisms or pollution can jam in converging flows or narrowing geometries, creating clogging hazards[13] or other ephemeral perturbations to the dynamics of Earth's aquatic ecosystems. Examples include logjams in rivers, river ice, volcanic pumice and sea ice. The fractional coverage of Earth's water bodies with floating granular materials is small, yet they are exceedingly important because crucial veins of transport can quickly become blocked with buoyant terrestrial debris.

By surface area, polar ice is the most widespread floating granular material and plays an outsized role in Earth's climate. For example, although only a few metres thick, sea ice provides a thermodynamic and hydrodynamic boundary condition for oceanic and atmospheric transport. It forms naturally as the ocean cools in the winter, reflects sunlight due to its high albedo, and insulates the ocean from the atmosphere. In contrast, ice mélange is a buoyant agglomeration of icebergs that forms through iceberg calving and discharge at marine-terminating glaciers in Greenland and parts of Antarctica. Ice mélange is the world's largest granular material[14], with individual fragments ranging from tens to hundreds of metres in size. Although less widespread than sea ice, marine-terminating glaciers act as the gateway to sea-level rise. The high uncertainty in projections of sea-level rise is largely due to a poor understanding of glacier–ocean interactions, including the ability of ice mélange to influence iceberg calving rates and modify ocean transport near glaciers.

As ice mélange is slowly pushed through Greenlandic fjords that are many kilometres wide, it jams, buckles and breaks as friction from the rocky walls transmits stress to the buoyant interior. To the human eye, ice mélange is quiescent, existing as a slowly creeping granular material. However, its flow is punctuated by the calving of cubic-kilometre-sized icebergs. During calving, icebergs are fractured from the main glacier and discharged into the floating ice mélange. Near the most active glaciers, it is possible to measure centimetre-scale iceberg displacements with ground-based radar every few minutes, revealing a period of incoherent granular flow that often precedes iceberg calving events[15]. Thus, not only can ice mélange mechanically inhibit iceberg calving, but the impending failure of this geophysical granular material can be detected in real time.

In addition to mechanically buttressing glaciers, ice mélange influences sea-level rise from below the ocean's surface. It indirectly affects submarine melting by controlling where and when icebergs release their meltwater. It acts as a physical perturbation to the stratified flow near marine-terminating glaciers, particularly altering the buoyancy-driven exchange of deep, warm water. In fact, the ability of warm ocean water to undercut and melt glaciers at depth is one of the biggest, and most uncertain, contributors to sea-level rise.

Alison F. Banwell[1]✉, **Justin C. Burton**[2]✉, **Claudia Cenedese**[3]✉, **Kenneth Golden**[4]✉ **& Jan Åström**[5]✉

[1]Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado Boulder, Boulder, CO, USA. [2]Department of Physics, Emory University, Atlanta, GA, USA. [3]Physical Oceanography Department, Woods Hole Oceanographic Institution, Woods Hole, MA, USA. [4]Department of Mathematics, University of Utah, Salt Lake City, UT, USA. [5]CSC Scientific Computing Limited, Esbo, Finland.

✉e-mail: Alison.Banwell@Colorado.edu; justin.c.burton@emory.edu; ccenedese@whoi.edu; golden@math.utah.edu; jan.astrom@csc.fi

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Competing interests

The authors declare no competing interests.

Additional information

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