BAMS
Meeting Summary

# Why Icebergs and Their Interactions with Sea Ice Should Be Included in Earth System Models

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**KEYWORDS:**
Sea ice;
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Antarctica;
Arctic;
Climate models

**International Workshop on Icebergs, Sea Ice, and the Ocean**

***What***: A 2-day workshop to summarize recent work, identify gaps, and outline perspectives on iceberg–sea ice interactions and their implications on the ocean.

***When***: 3–4 June 2025

***Where***: Sorbonne Université, Paris, France

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## 1. Summary

Thirty-three researchers from France, Australia, Belgium, Canada, the United Kingdom, and Germany gathered in Paris for a 2-day hybrid workshop (3–4 June 2025) to discuss iceberg–sea ice interactions and their representation in Earth system models.

Icebergs and sea ice are two distinct forms of drifting ice, typically represented using different modeling approaches. Icebergs—relatively small in horizontal extent (500 m–50 km long) but up to 700 m thick—calve from continental ice shelves and marine terminating glaciers and are modeled as Lagrangian particles. In contrast, sea ice, forming from the freezing of seawater, covers vast areas, spanning thousands of kilometers, but is much thinner (about 1 m thick), and modeled as a two-dimensional continuum.

Current Earth system models generally assume that sea ice–iceberg interactions are negligible. However, mounting evidence indicates that processes essential to Antarctic sea ice and ocean dynamics—such as fast ice and coastal polynyas—arise from dynamic iceberg–sea ice interactions.

Several Earth system modeling groups are actively addressing these interactions, resulting in a series of recent studies on icebergs, sea ice, and their interplay, which motivated the workshop.

Presentations from 13 invited speakers (see the workshop program in the supplemental material), covering modeling and observational perspectives, formed the basis of discussions around the following themes:

- icebergs, sea ice, and their interactions,
- implications for the ocean, and
- perspectives on numerical and computational model infrastructure.

## 2. Workshop highlights

Iceberg–sea ice interactions have been recognized for several decades (Wright and Priestley 1922; WMO 1970; Fedotov et al. 1998; Massom et al. 2001) but until recently were not explicitly represented in Earth system models (ESMs). Discussions during the workshop reflected a shift in this perspective: Over the past decade, dynamic iceberg–sea ice interactions have gained increasing attention as potentially influential processes in polar climate systems. Key elements emerged from the workshop exchanges: Icebergs and sea ice interact thermodynamically and dynamically, which has implications for their representation in ESMs.


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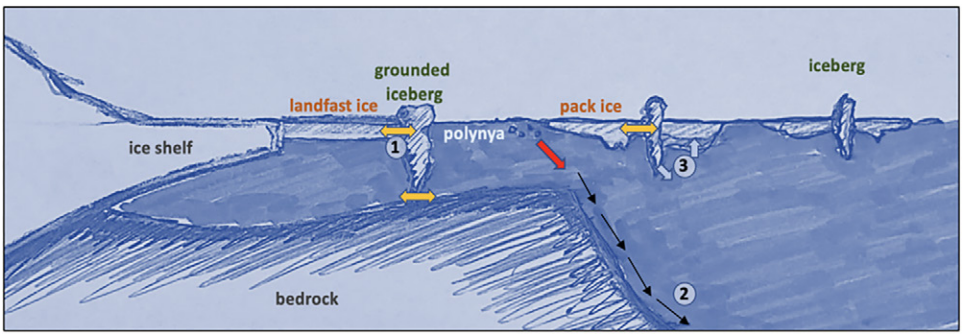



**Fig. 1. Schematic representation of key iceberg–sea ice interaction processes in the Antarctic region as detailed in this section, highlighting (1) iceberg–sea ice dynamical interactions (yellow arrows indicate contact stresses), (2) influences on dense water formation, and (3) thermodynamic coupling between iceberg melting, ocean stratification, and sea ice growth.**

***a. Icebergs and sea ice interact thermodynamically and dynamically, with impacts extending into the deep ocean.*** Three key mechanisms through which icebergs and sea ice interact, illustrated in Fig. 1, were highlighted during the workshop: dynamical coupling, ocean impacts, and thermodynamic feedbacks.

***b. Sea ice and iceberg drift are dynamically coupled: Certainly over the continental shelf and presumably also offshore.*** Several contributions presented new results on interactions between the drift of sea ice and that of icebergs, as well as their impacts. These processes are relatively new to the climate modeling community and require substantial model developments.

The Antarctic continental shelf is a critical region where icebergs and sea ice strongly interact. There, ecologically critical immobile fast ice is found (Fraser et al. 2023), and large amounts of dense water feeding the World Ocean's abyssal circulation are produced (Gordon 1971). There is now compelling evidence that grounded icebergs are key to locking in fast ice, with large impacts on coastal sea ice and hydrography. Grounded iceberg locations largely coincide with the observed fast ice distribution, known also in many cases to be associated with coastal polynyas (Massom et al. 1998; Nihashi and Ohshima 2015; Fraser et al. 2021). New modeling results show that including grounded icebergs in sea ice simulations substantially improves the representation of fast ice coverage and thickness (Van Achter et al. 2022; Olivé Abelló et al. 2025; Pirlet et al. 2025).

Offshore, two-way interactions between sea ice and icebergs are also increasingly regarded as important. First, the drift of icebergs is influenced by sea ice. In particular, icebergs can be locked within surrounding compact sea ice and drift with it, so that their velocity is very close to that of pack ice (Lichey and Hellmer 2001; Rackow et al. 2017). The study of Marson et al. (2024), focused on Baffin Bay, shows that the iceberg locking by sea ice has major large-scale effects on iceberg trajectories, diverting them from coastal currents. Iceberg locking also operates in the Southern Ocean (Rackow et al. 2017), altering iceberg melting. However, whether the iceberg locking mechanism is the same around Greenland as around Antarctica remains to be confirmed, in particular for supersized icebergs.

Conversely, pack ice could also be influenced by icebergs, as iceberg–sea ice velocity differences potentially ridge sea ice in front of icebergs, and open sea ice in the lee of icebergs, intensifying freezing as shown by Hunke and Comeau (2011). However, our understanding of such interactions remains limited to that unique study, which only included four large icebergs and ignored small ones.


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***c. The dynamical interactions between icebergs and sea ice have far-reaching consequences for the ocean, both at the surface and at depth, and for ice sheet dynamics.*** Iceberg–sea ice dynamical interactions have far-reaching impacts from sea ice down into the deep ocean. First, prescribing Antarctic grounded icebergs and/or fast ice locations in models largely benefits the representation of coastal polynyas. This was known prior to the workshop, from regional simulations (Cougnon et al. 2017; Kusahara et al. 2021; Huot et al. 2021; Van Achter et al. 2022), and has recently been confirmed to hold at circumpolar scales: Realistic fast ice implies more realistic polynya shape, larger area, and higher annual ice production (Pirlet et al. 2025).

Through improved polynyas, model representations of fast ice processes affect and even improve hydrography and water mass transformation on the Antarctic continental shelf. This has been highlighted in various regional modeling studies (Nakayama et al. 2014; Bett et al. 2020; Huot et al. 2021; Van Achter et al. 2022). New insights presented at the workshop confirm that water mass improvements are seen at circumpolar scales (Pirlet et al. 2026), and that impacts are detectable in the deep ocean, through cascading over the continental shelf.

It has also been proposed that iceberg–sea ice interactions can influence ice sheet mass loss, ocean freshening, and sea-level rise. Fast ice blocking by grounded icebergs is crucial in maintaining warm ocean conditions in regions already undergoing rapid ice sheet loss, such as the Amundsen Sea (Nakayama et al. 2014; Bett et al. 2020). This could support a feedback, where grounded icebergs foster fast ice and support warm ocean conditions, which causes ice sheet loss and more iceberg calving, hence more grounded icebergs (Bett et al. 2020). On the other hand, the presence of ice mélange can limit calving (Krug et al. 2015), and major calving events have been linked to sea ice loss, suggesting that sea ice may help protect ice shelves from ocean swell (Massom et al. 2018; Surawy-Stepney et al. 2024).

Farther offshore, the influence of iceberg–sea ice interactions is much less constrained. In Baffin Bay, iceberg locking within sea ice modulates the spatial distribution of iceberg meltwater release according to the modeling study of Marson et al. (2024). Whether similar processes are important in the Southern Ocean, we do not know. More broadly, how dynamic iceberg–sea ice interactions influence hydrography and water mass transformation is still an open question.

***d. Iceberg melt interacts with water column stability and sea ice thermodynamics.*** Several workshop presentations highlighted interactions between iceberg melting, ocean stratification, and sea ice thermodynamics. The first sea ice–ocean modeling studies with an interactive iceberg component showed that the injection at the surface of freshwater from melting icebergs stratifies near-surface waters, inhibits vertical redistribution of heat, and, in turn, promotes sea ice growth (e.g., Jongma et al. 2009; Merino et al. 2016). The large-scale spatial patterns of freshwater input and sea ice impacts are largely determined by iceberg drift (Marsh et al. 2015; Marson et al. 2024). In particular, grounding of icebergs largely concentrates freshwater release on the continental shelf (Olivé Abelló et al. 2025).

However, important details remain uncertain. In particular, the depth of iceberg meltwater injection is critical and could even reverse the iceberg effect on sea ice production. Such a possibility was recently observed in situ from an underwater glider deployed near an Antarctic giant iceberg (Lucas et al. 2025). In this case study, the meltwater injected at depth destabilized the water column by eroding the seasonally produced winter water layer—which typically acts as a strong potential energy barrier to vertical exchanges between surface and deeper waters. Ongoing work presented at the workshop by Marson et al. investigates how meltwater injected at depth in the subpolar North Atlantic produces markedly stronger changes than surface meltwater injection.


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### 3. Rapid progress is underway in modeling iceberg–sea ice interactions

Workshop participants agreed that the scientific evidence presented above is sufficient to recommend representing iceberg–sea ice interactions explicitly in models. However, this raises several challenges, as in most current modeling systems, sea ice and icebergs communicate only weakly—and in many cases, an iceberg model component is entirely absent. Rapid progress is nevertheless underway: Several groups are developing complementary approaches to improve this coupling, and their recent advances were extensively discussed during the workshop.

***a. A dedicated iceberg model component is a key prerequisite for physically realistic, internally consistent, and flexible projections of iceberg–sea ice interactions.*** Is an iceberg model component really needed? The question remains open within several research groups, as an iceberg model implies substantial numerical costs and requires dedicated code development and maintenance efforts.

Admittedly, some aspects of iceberg–sea ice interactions can be approximated by prescribing icebergs or their effects. Several studies have gained valuable insights by empirically ingesting observational knowledge into sea ice models. For instance, sea ice–ocean modeling studies have increased fast ice and coastal polynya realism by prescribing a static mask of fast ice distribution (e.g., Cougnon et al. 2017; Kusahara et al. 2021), by incorporating grounded icebergs in the land mask and increasing the sea ice tensile strength (Huot et al. 2021; Van Achter et al. 2022; Olivé Abelló et al. 2025), or by imposing zero sea ice velocity where fast ice is observed (Pirlet et al. 2025). These approaches have been instrumental in exploring the influence of grounded icebergs, fast ice, and coastal polynyas on Southern Ocean and Antarctic sea ice dynamics, in the framework of hindcast simulations over the recent past.

However, these methods remain fundamentally limited because grounded icebergs and fast ice are prescribed a priori. For simulations of the remote past or future, such constraints can become highly unrealistic, as the distribution of fast ice and icebergs—grounded or freely drifting—evolves dynamically. Furthermore, approaches that omit an explicit iceberg model can introduce unintended effects by representing two-way interaction processes only partially. For example, the iceberg–meltwater–stratification–sea ice thermodynamic feedback can be approximated without an iceberg model by prescribing a heat flux diagnosed offline (Merino et al. 2016). However, this neglects an important negative feedback: As sea ice grows, the associated oceanic latent heat loss reduces iceberg melt. In the absence of this feedback, simulations may produce unbounded sea ice growth and unrealistically thick ice, most notably in coastal bays where model icebergs sometimes accumulate.

Based on these elements, participants at the workshop agreed that the lack of an iceberg model severely limits the possibilities of representing iceberg–sea ice interactions and their effects—including dynamic fast ice, coastal polynyas, and dense water sources—in a physically consistent way.

***b. Physical, numerical, and computational developments are still required for a full representation of iceberg–sea ice interactions in ESMs.*** How can iceberg–sea ice interactions be better represented in ESMs? This requires coordinated development of the iceberg, sea ice, and ocean components and of their coupling interfaces, which is ongoing in several research groups.

**1) Iceberg realm.** A key challenge in the iceberg model component is representing grounding on the continental shelf. In this respect, Olivé Abelló et al. (2025) show that icebergs must have sufficient thickness to be able to ground on bathymetric ridges (often up to 400-m depth; Fraser et al. 2021), which they addressed by introducing iceberg thickness


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classes—linked to the thickness of their parent ice shelves. Complementing this, Kostov et al. (2026) developed and tested a physically based iceberg grounding scheme in an Amundsen Sea model configuration, accounting for sediment and bedrock friction and downslope acceleration. Both iceberg thickness classes and grounding parameterizations still need to be tested together at pan-Antarctic scales.

Another challenge is representing the drift of icebergs in the sea ice zone, particularly their observed co-drift in compact sea ice (Lichey and Hellmer 2001; Marson et al. 2024). Iceberg models include a sea ice stress term, formulated with a drag law (Bigg et al. 1997; Martin and Adcroft 2010; Marsh et al. 2015). However, several authors (Lichey and Hellmer 2001; Rackow et al. 2017; Marson et al. 2024) argue that this fails to reproduce co-drift. These authors therefore adjusted the sea ice stress at high sea ice concentration and strength, effectively locking icebergs into the sea ice to enforce co-drift. Finally, the computational cost of a Lagrangian iceberg model can be large, and simulations have been presented in which the iceberg module was externalized from the NEMO ocean model and coupled to the ocean–sea ice component via the OASIS coupler.

From an observational point of view, little is known about drifting icebergs in the sea ice zone because classical satellite methods, particularly altimetry and Synthetic Aperture Radar (SAR), struggle to distinguish them from sea ice. Recent innovations will provide crucial information to evaluate newly proposed parameterizations of iceberg physics. The first circumpolar, satellite-based dataset of grounded icebergs—currently under development—was presented at the workshop by Wongpan et al. Another recent SAR-based work (Chen et al. 2026) covers 6 years of drifting icebergs in the sea ice zone and reports substantially higher iceberg counts, especially for small icebergs, than classical altimetry-based products (Tournadre et al. 2016).

**2) Sea ice realm.** Participants at the workshop agree that a central challenge is the incorporation of iceberg information into the sea ice momentum equation. Grounded icebergs act as key pinning points for fast ice (Van Achter et al. 2022; Olivé Abelló et al. 2025), yet the best way to represent this effect remains under discussion. Existing empirical strategies (described above) provide partial solutions, but iceberg grounding effects—as well as the influence of drifting icebergs—may be better captured by explicitly including an iceberg-induced stress term in the sea ice momentum equation. Such a term is absent from current sea ice models, in line with earlier findings of Hunke and Comeau (2011), indicating that large icebergs exert only a minor influence on sea ice volume. However, that assessment neglected small icebergs, which are far more numerous than previously appreciated, especially along the coast (Chen et al. 2026), and could exert a nonnegligible, though still poorly quantified, influence on sea ice.

The internal stress term of sea ice models (their rheology) is also being revisited as a possible means to improve representations of iceberg–sea ice interactions. Introducing tensile strength into classical viscous–plastic rheology, following König Beatty and Holland (2010), improved the simulation of fast ice in a regional study of the Totten area (Van Achter et al. 2022), though only when used in combination with grounding by icebergs. More broadly, the sea ice modeling community has invested considerable effort in developing elasto-brittle rheologies (Ólason et al. 2022) which are expected to better capture the formation of ice arches and bridges—features that are central to the growth and breakup of fast ice (Plante et al. 2020). These alternative rheologies, however, have received limited evaluation in Antarctic configurations (Santana et al. 2025).

A conceptual hurdle arises in formulating tensile forces consistently across frameworks: Continuum sea ice models must interact with Lagrangian iceberg models, yet a general mathematical formalism for this coupling is still lacking. Recent scientific developments,


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presented at the workshop, have explored hybrid particle–continuum approaches for ice mélange and fast ice in idealized configurations (Kahl et al. 2025; Mehlmann and Kahl 2025). The ice-mélange framework, in particular, formalizes the combination of a continuum treatment for sea ice with a particle description for icebergs. It is compatible with existing model infrastructures and offers a promising pathway toward a more physically and numerically consistent interface between icebergs and sea ice.

Improved representations of iceberg–sea ice interactions could also come from better representations of ice–ocean interactions. A new version of the ocean modeling system NEMO has also been presented in which sea ice is embedded in the three-dimensional ocean using the Brinkman penalization framework (Kevlahan et al. 2015). Although the initial motivation of these developments was not the representation of iceberg–sea ice interactions, they may offer more flexibility for future representation of these interactions, for example, by allowing icebergs to ground without being treated as land points.

## 4. Future ESMs with interactive ice sheets should incorporate iceberg–sea ice interactions

This report summarizes a consensus among a group of sea ice, ocean, and iceberg specialists that key iceberg–sea ice interactions in the Antarctic sea ice zone have significant implications for the climate system—including their influence on dense water formation—and that representing these processes would improve ESM, climate projections, and sea ice forecasts. Implementing such interactions will require substantial development, but the timing is appropriate: Many ESM groups are now introducing interactive continental ice sheets and their interactions with the climate system, optionally including icebergs (Rocha et al. 2023; Ackermann et al. 2024; Smith et al. 2021), observational capabilities are expanding, and community interest is strong.

These interactions are also likely to become more prominent in the future, as less sea ice and more icebergs can be expected. Long-standing ESM projections of declining Antarctic sea ice (IPCC 2023) appear increasingly credible given the rapid losses observed over the past decade (Hobbs et al. 2024; Himmich et al. 2024), and Antarctic fast ice also shows signs of decline (Fraser et al. 2021). An increased iceberg calving rate is likely (Greene et al. 2022; Coulon et al. 2024), which would imply a greater abundance of icebergs. If this leads to more grounding of icebergs and more extensive fast ice, warmer ocean conditions may develop in some regions, potentially promoting ice sheet loss and feeding back to increase calving of even more icebergs (Bett et al. 2020).

Workshop participants further emphasized the need for expanded in situ and remote sensing observations of iceberg–sea ice interactions, particularly in light of forthcoming coordinated field programs [in particular, Antarctica InSync (Haumann et al. 2025) and the fifth International Polar Year in 2032 (Berkman 2025)] and satellite missions dedicated to the cryosphere [e.g., Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL); Kern et al. 2020]. Given limited resources, continued international collaboration—of the kind facilitated by the Paris workshop on iceberg–sea ice interactions—will be essential in advancing and understanding model developments in this area.

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