BAMS Meeting Summary

The Future of Sea Ice Modeling

Where Do We Go from Here?

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Toward Defining a Cutting-Edge Future for Sea Ice Modeling: An International Workshop

What: Sea ice model developers and expert users met to discuss the future of sea ice modeling.
When: 23–26 September 2019
Where: Laugarvatn, Iceland

https://doi.org/10.1175/BAMS-D-20-0073.1
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Supplemental material: https://doi.org/10.1175/BAMS-D-20-0073.2
In final form 26 March 2020

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Earth system models (ESMs) include a sea ice component to physically represent sea ice changes and impacts on planetary albedo and ocean circulation (Manabe and Stouffer 1980). Most contemporary sea ice models describe the sea ice pack as a continuum material, a principle laid by the Arctic Ice Dynamics Joint Experiment (AIDJEX) group in the 1970s (Pritchard 1980). Initially intended for climate studies, the sea ice components in ESMs are now used across a wide range of resolutions, including very high resolutions more than 100 times finer than those they were designed for, in an increasingly wide range of applications that challenge the AIDJEX model foundations (Coon et al. 2007), including operational weather and marine forecasts. It is therefore sensible to question the applicability of contemporary sea ice models to these applications. Are there better alternatives available? Large advances in high-performance computing (HPC) have been made over the last few decades and this trend will continue. What constraints and opportunities will these HPC changes provide for contemporary sea ice models? Can continuum models scale well for use in exascale computing?

To address these important questions, members of the sea ice modeling community met in September 2019 for a workshop in Laugarvatn, Iceland. Thirty-two sea ice modeling scientists from 11 countries across Europe and North America attended (Fig. 1), spanning 3 key areas: (i) developers of sea ice models, (ii) users of sea ice models in an ESM context, and (iii) users of sea ice models for operational forecasting and (re)analyses. The workshop was structured around two key themes:

1) Scientific and technical validity and limitations of the physics and numerical approaches used in the current models
2) Physical processes and complexity: Bridging the gap between weather and climate requirements

For each theme, 5 keynote speakers were invited to address the motivating questions and stimulate debate. Further details can be found in the online supplemental material (https://doi.org/10.1175/BAMS-D-20-0073.2).

Fig. 1. Workshop attendants in front of Lake Laugarvatn, Iceland.

Key points and outcomes from the sea ice modeling workshop

Continuum models remain a useful tool for sea ice simulation. Sea ice consists of moving, growing or melting, often interlocked, irregular pieces of ice, which can vary in size from a few meters up to tens of kilometers (*floes* and *plates*; see WMO 1970; Hopkins et al. 2004). In models, the representation of sea ice is divided into one-dimensional thermodynamic processes such as growth and melt, and two-dimensional, horizontal ice dynamics involving ice drift, deformation, and transport. To describe the evolution of sea ice at scales of ~100 km over days to months, the AIDJEX group proposed a framework based on an isotropic, plastic continuum approach (Coon et al. 1974), whose validity relies upon statistical averages taken over a large number of floes (Gray and Morland 1994; Feltham 2008). Assuming that sea ice behaves as a plastic material at scales of ~100 km and beyond, a viscous–plastic rheology [VP; Hibler 1979; followed by its elastic formulation EVP; Hunke and Dukowicz 1997] offered physically reasonable and numerically affordable solutions to represent sea ice dynamics. The continuum approach, as well as the (E)VP framework, have since been adopted in virtually all ESMs (IPCC 2013). The sea ice modeling community now has several decades of experience using these continuum models.

Many studies demonstrate the ability of the continuum (E)VP models to reasonably simulate key properties of the sea ice: the large-scale distribution of sea ice thickness, concentration and circulation (e.g., Kreyscher et al. 2000); relationships between sea ice concentration, thickness and velocity (Docquier et al. 2017); long-term trends in winter sea ice velocity (Tandon et al. 2018). With modifications for grounded ridges and tensile strength, continuum models are also able to realistically simulate the distribution of Arctic landfast ice—the motionless fields of sea ice attached to the coast or seabed (e.g., Lemieux et al. 2015, 2016).

However, the core assumptions of the continuum theory are appropriate only for large-scale sea ice evolution, where model grid cells contain a representative sample of floes. With the increase in available computational resources over the last few decades, several sea ice model configurations have gridcell sizes of ~1–10 km. This is particularly true for short-range forecasting applications and regional modeling studies, which tend to use such resolutions because the Rossby radius in high-latitude waters can be close to 1 km (Holt et al. 2017). At these resolutions, the continuum assumption likely breaks down (Coon et al. 2007; Feltham 2008).

Nevertheless, even at kilometric resolution, continuum-based sea ice models continue to be useful. Early evaluations with synthetic aperture radar estimates of drift and deformation (Kwok and Cunningham 2002) challenged continuum sea ice models' representation of spatiotemporal deformation, particularly in terms of localization and intermittency (Girard et al. 2009; Kwok et al. 2008). However, simulations at kilometric resolutions (effective 10 km) reconcile the model results with observations for many drift and deformation feature statistics at these resolutions (Hutter and Losch 2020).

Solver convergence also impacts simulated deformation statistics (Lemieux et al. 2012) and linear kinematic features (LKFs) within the ice pack (Koldunov et al. 2019). However, as the spatial resolution is increased in (E)VP continuum-based models, the numerical solution of the sea ice momentum equation is increasingly difficult to obtain due to the strong nonlinearity of the problem. Despite recent nonlinear solver developments (e.g., Losch et al. 2014; Kimmritz et al. 2017; Mehlmann and Richter 2017), obtaining a fast and numerically converged solution remains a challenge. Another issue is that (E)VP continuum models overestimate the prevalence of large intersection angles between LKFs, which might be fixed by amending the rheological formulation (Hutter and Losch 2020; Ringeisen et al. 2019).

Alternative rheological formulations have also been proposed to address shortcomings of the (E)VP rheology; the elastic–anisotropic–plastic (EAP) and Maxwell-elasto-brittle (MEB) rheologies were discussed at the workshop. The EAP rheology (Wilchinsky and Feltham 2006) introduces a new state variable, the structure tensor, that tracks the history of past fracture events and allows the orientation of these fractures to evolve at the subgrid level due to mechanical failure and melting or refreezing. In contrast, isotropic models either assume subgridcell cracks do not exist or are isotropically distributed. The EAP model produces realistic scaling of sea ice deformation in idealized configurations and has shown promising results for simulation of the basin-scale sea ice thickness distribution (Tsamados et al. 2013; Heorton et al. 2018). The MEB rheology (Dansereau et al. 2016) is a damage-propagation model, different from the plastic-flow approach taken by (E)VP and EAP, simulating failure by tracking strain-induced damage, which gives a high degree of stress localization. To preserve the localized fields produced by the MEB rheology, the neXtSIM model uses a continuum Lagrangian formulation in which the mesh moves with the ice (Rampal et al. 2016). MEB-based models reproduce some sea ice processes as emergent properties (ice bridges, ridges, landfast ice; Dansereau et al. 2017), as well as ice drift and spatiotemporal deformation statistics (Rampal et al. 2019).

In summary, despite their reliance on hypotheses that can become invalid at spatial resolutions typically used in modern ESM systems, these continuum-based sea ice models cannot be readily invalidated using observation-based metrics, and remain useful for large-scale, and low-resolution, modeling of sea ice.

Discrete element modeling: A promising avenue for the future. Discrete element models (DEMs) have long been used to model granular, discontinuous materials, including ice floes (e.g., Hopkins et al. 2004; Hopkins and Thorndike 2006). By their very nature, DEMs are well suited to modeling sea ice, which—particularly around the ice edge—consists of many individual ice floes.

Historically, DEMs have not been used to model sea ice within global climate models or forecasting systems because, relative to continuum sea ice models, they require extensive computational resources. However, with increases in available HPC resources, DEMs are becoming relatively more affordable and may actually be more suitable for future HPC architectures, although the uncertainties here are substantial.

The relatively large computational cost of DEMs also means that the sea ice modeling community has little experience with these models, and several unresolved issues currently present an obstacle for DEMs to be used for large-scale sea ice modeling. These include how physical processes fundamental to floe evolution, such as pressure ridging, floe aggregation, or floe splitting, can be represented in a DEM framework. Current approaches to model initialization and data assimilation also need to be rethought. Therefore, a considerable amount of time and development is needed before DEMs become usable by a large community. The workshop participants felt that DEMs are not presently able to satisfy the two-pronged criteria—both advanced enough and affordable—required to replace the continuum models used within operational forecasting and climate modeling systems. However, DEMs present a promising approach for future sea ice modeling, which should be explored further. In particular, DEMs would be particularly appealing for operational forecasting applications that require models to reproduce sea ice behavior on fine spatiotemporal scales. In this regard, a possible future avenue could be a regional DEM nested within a global continuum model.

Navigating the model complexity spectrum: Finding the right amount of complexity. The issue of model complexity is complicated and was discussed at length at the workshop. Here we take the term "model complexity" as synonymous with "number and level of detail of the model's parameterizations of physical processes." Although there were advocates for including more complexity and for using more simplified models, the general feeling was that present-day continuum models capture the most important physical processes, in principle. However, the representation of certain key processes is uncertain due to missing observational constraints.

The overall conclusion was that, given the diversity of model uses (e.g., climate projections, regional forecasts, process understanding), a large spectrum of different levels of complexity is warranted for sea ice modeling, from highly complicated to heavily simplified models. Although several physical processes were identified whose representation was considered crude or even missing in contemporary sea ice models (e.g., snow physics, wave–ice interactions, ridging processes, and intricate atmosphere-ice-ocean coupling/interactions), the impact of their absence from a model is hard to predict. In favor of more simplicity: simple models are cheaper to run and easier to use, debug, and tune, and their output is easier to understand because the likelihood of complex, nonlinear interactions is lower. Also, when considering the climate models participating in CMIP5 (44 distinct models), there is no systematic difference between the projections made by high- or low-complexity models. This suggests that sea ice sensitivity is likely related to the way key processes are treated, and that the simulated evolution of sea ice may depend more on the atmospheric and oceanographic forcing than on the complexity of the sea ice code itself. In favor of complexity: more sophisticated physical formulations are important for improved process understanding, to allow models to simulate changes in ice physics in different climate regimes, and to improve short-term predictions, particularly where there is a need to provide a detailed description of the sea ice state.

In summary, the appropriate physical complexity required strongly depends on the specific model application. Workshop participants recommend that modelers select the most appropriate tool for the job at hand, and complexity should not be used "blindly"—it is important to understand why one is including the chosen level of complexity. Code modularity is a good way to allow sea ice models to satisfy varying demands in terms of scientific complexity.

HPC requirements cause uncertainty (constraints and opportunities) for future sea ice model code structure and optimization. Current continuum formulations of sea ice dynamics require relatively high levels of communication between processor domains within the rheology and advection calculations. This can make sea ice components a bottleneck in coupled systems, as they tend to scale poorly with increasing HPC resources due to sea ice's localization on the globe. The thermodynamic components, however, rely on one-dimensional "column" formulations that require very little cross-domain communication, allowing them to scale well with increasing HPC resources.

HPC resource constraints have historically favored continuum models, with DEMs being too expensive to run. However, DEMs have the potential to scale better on newer, heterogeneous HPC architectures such as those using graphical processing units (GPUs). DEMs benefit from a natural domain decomposition via aggregates of floes, which can be moved to GPUs for Lagrangian and thermodynamic calculations requiring less bandwidth for communication with processors handling other parts of the domain.

Whether current continuum sea ice models will be able to take full advantage of the resources available on future exascale HPC machines is currently an active area of research. Much of the uncertainty comes from not knowing the form that future exascale HPC systems might take, and the fact that the efficiency of the sea ice model component is not likely to be a priority of those people choosing the HPC resources at large modeling centers.

In summary, the jury remains out on whether continuum models will be a viable choice for future HPC architectures and whether DEMs may become more favorable in the future. The answers to these questions will partly depend on the design of future exascale HPC systems, and on the continuum framework's ability to produce sensible looking results for very high-resolution simulations (say <100 m).

Community involvement plays an important role for sea ice model development, but current practices could be improved. Engagement of the broad sea ice modeling community has been crucial for sea ice model development, especially for large community codes such as CICE (Hunke et al. 2020) and Sea Ice Modelling Integrated Initiative (SI^3)/ Louvain-la-Neuve Sea Ice Model (LIM) (Rousset et al. 2015). Community involvement can bring considerable model advances by allowing many different research and operational groups to contribute new model functionality and physics, as well as thoroughly testing the code in diverse applications. However, it is important to have well defined long-term plans and to communicate these effectively, so that the wider community can efficiently contribute to the scientific direction of the model while maintaining a streamlined and relevant code base.

Although engagement of the wider community has been hugely beneficial for the evolution of large-scale sea ice models, there is scope for even better integration of community activities within the development process.

One area of potential collaboration involves common model evaluation tools. Having common outputs and model diagnostics, such as those defined by the Sea Ice Model Intercomparison Project (SIMIP) community for CMIP6 (Notz et al. 2016), facilitates multi-model evaluation and comparison studies. However, it was felt that community tools, such as Earth System Model Evaluation Tool (ESMValTool) (Righi et al. 2020) and Model Evaluation Tools (MET) (Newman et al. 2019), could be better utilized for evaluation of sea ice models.

Another area that could benefit from community involvement is assessing the models at a process level, for instance by formulating idealized case studies for model inter-comparison (e.g., wind blowing on an ice pack in a rectangular domain). It was also felt that standard metrics are required against which to compare the models with each other and with observations, and to ascertain how well models capture the leading-order physical processes.

For example, a standard metric for measuring the performance of model thermodynamics at leading order would be useful.

Summary and recommendations

Continuum sea ice models have been applied close to the presumed limits of their validity for many years, yet they remain compatible with current observations. The resolution requirements for sea ice models varies considerably depending on the application (e.g., large ensembles, paleoclimate simulations, short-range forecasting), and therefore continuum models will likely remain useful for many years to come. Meanwhile, it is highly desirable to explore the potential of DEMs. These models are expected to be more physically faithful at the highest resolutions envisioned for sea ice in ESMs, provided they incorporate all the required processes. DEMs may also prove more efficient for some new computer architectures. Such perspectives highlight the need for the sea ice modeling community to have a clear and consistent vision of the future evolution of HPC systems.

Sea ice models are used for many different purposes and therefore benefit from modularity, which allows the activation or exclusion of parameterizations and code features. Thus, users can adjust model complexity to fit their specific application.

Considering limited human resources among core sea ice modeling groups, engagement of the wider community has proven a very efficient way to advance large-scale sea ice models. However, there is still scope for further integration of the wider community in model development activities.

An important feature of the Laugarvatn sea ice modeling workshop was the open minded atmosphere in which very different views were exchanged. The workshop successfully brought together model developers and users of sea ice models for Earth system modeling, operational forecasting and (re)analyses.

International sea ice modeling workshops such as this foster collaboration and community engagement in the field of sea ice modeling. A recommendation from this workshop is that the exercise should be repeated every 2–3 years to maintain community engagement, exchange cutting-edge ideas, and reinforce collaborative momentum.

Acknowledgments. This workshop was supported through the IS-ENES3 project, funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement 824084, and by the U.S. Department of Energy's Office of Science Biological and Environmental Research programs.

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