BAMS
Meeting Summary

Workshop on Advancing NOAA's Modeling for Improved Sea Ice Forecasts

Defining Priorities and Key Collaborations

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Arctic;
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Forecasting;
Numerical weather prediction/ forecasting;
Coupled models

NOAA Sea Ice Modeling Collaboration Workshop

What: Fifty-five participants attended the workshop (34 in person and 21 online) from across NOAA research laboratories (PSL, GLERL, GFDL, PMEL) and NOAA line offices (NWS, NESDIS, NOS), other U.S. agencies/entities (DOE, NIC, NSIDC), research universities (University of Alaska Fairbanks, University of Colorado Boulder, University of Washington, Oregon State University, Colorado School of Mines, University of Maryland, Brown University, University of Michigan, etc.), and international institutions (AWI, Environment and Climate Change Canada) to discuss sea ice modeling advancements.

Where: Boulder, Colorado

When: 25–27 April 2023

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The NOAA Sea Ice Modeling Collaboration Workshop was held in Boulder, Colorado, on the University of Colorado's East Campus between 25 and 27 April 2023 amid spring blossoms and a backdrop of the snow-covered Rocky Mountain Continental Divide. Over the 2.5-day workshop, participants shared advancements and challenges in sea and lake ice modeling from NOAA's Office of Oceanic and Atmospheric Research (OAR) laboratories, other U.S. agencies, NOAA's cooperative institutes, university partners from Alaska to Maryland and many states in between, and our international colleagues from Canada and Germany. To foster new opportunities for advancing sea ice models through collaboration, presentations, exchanges, and prioritization discussions were focused around our three overriding workshop themes: advancements in coupled (sea ice–wave–ocean–atmosphere–land) modeling development, novel ways of evaluating models, and model applications and transition opportunities.

The workshop setting was an opportunity to bring together experts spanning the end-to-end enterprise of improving forecasts at high latitudes. Our discussions covered the use of observations for models [e.g., initialization, data assimilation (DA), model validation, and process evaluation], coupled sea ice–wave–ocean–atmosphere–land modeling approaches, improvements and challenges across spatiotemporal scales (weather, subseasonal to seasonal, climate, regional, global), and novel products and applications needed for stakeholders [e.g., oil spills, landfast ice, lake ice, shipping lanes, biogeochemical (BGC) modeling, ecosystem, and fisheries needs]. Through a progression of targeted presentations, round robin breakout groups, jamboard sessions, and happy hours, process observationalists, remote sensing and DA specialists, model developers, and stakeholders/users connected to build relationships and outline prioritized actions that can best advance our sea ice modeling efforts collectively.

The achievements of this workshop can be summarized as follows:

- sharing knowledge across the vast span of NOAA and NOAA-partner sea and lake ice modeling activities as a starting point for future collaborations;
- prioritizing goals and approaches for intra-OAR and cross-NOAA sea ice modeling projects;
- recommending targeted model development projects in collaboration with NOAA's university and international partners; and
- identifying transition opportunities and priorities for advancing NOAA's sea and lake ice forecasting efforts with a focus on stakeholders needs.

The NOAA sea ice forecast model landscape

To set the stage, the workshop kicked off with detailed presentations from each of the NOAA OAR research laboratories with current efforts in sea and lake ice modeling: Physical Sciences Laboratory (PSL) in Boulder, Colorado; Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey; Great Lakes Environment Research Laboratory (GLERL) in Ann Arbor, Michigan; and the Pacific Marine Environment Laboratory (PMEL) in Seattle, Washington. Each laboratory presented an overview of their current model development, forecast systems, and evaluation activities spanning regional weather-scale prediction and coupled process evaluation and understanding (PSL); seasonal predictions and climate-scale global projections (GFDL); biogeochemical sea and lake ice prediction systems (GLERL); subseasonal-to-seasonal-scale predictions (GLERL, PMEL); and fisheries/ecosystem regional modeling efforts (PMEL). Overwhelmingly, attendees were surprised and impressed to hear the number and scope of sea and lake ice modeling activities across the NOAA laboratories. Other NOAA line offices (ocean, satellite and data, and weather services), NOAA cooperative institutes, and multiple university and international partners rounded out the sessions presenting an equally impressive and broad range of modeling efforts, advances, and outstanding needs. It became very apparent that although there are substantial efforts on multiple modeling levels across the community, there is minimal active collaboration.

Plenary discussion sessions were designed to address the myriad end-to-end modeling challenges, including ice–ocean–atmosphere coupling, sea ice physics, initialization issues, parameterization development, DA, observational gaps, model skill assessment, transition to operations, and product development based on user needs. Subsequently, we broke into small focus groups to discuss ideas on priorities and collaboration projects within the NOAA laboratories, across the NOAA line offices, and with partners to facilitate progress on our shared modeling challenges and outstanding needs. The participants developed a select list of prioritized projects mapped along the three main workshop themes: model development, model assessment, and model applications and transitions (see below). A comprehensive listing of all the presentations, attendees, and prioritized recommendations can be found in the NOAA Sea Ice Workshop Report 2023 online (https://psl.noaa.gov/events/2023/sea-ice_workshop/).

Workshop highlights: Model development

Forecasting sea ice variability from days to seasons to decades is challenging due to the small-scale and complex nature of sea ice dynamics; the coupling between ocean, ice, waves, and atmosphere; and the limited observations that are needed to evaluate the models and develop the parameterizations. To address these sea ice modeling uncertainties, NOAA and partner institutions are focusing their activities in three main areas: developing new parameterizations and model physics formulations; implementing new parameterizations and coupling strategies, coupled interactions, and feedbacks; and developing new modeling tools for model physics evaluation.

Highlighted OAR activities aimed at improving models used for sea ice forecasts include developing advanced schemes to prevent numerical instabilities (GFDL), implementing tools for evaluating forecast systems such as the "replay" technique (PSL) and a coupled Arctic Single Column Model (SCM) developed using observations from recent campaigns [PSL, Environmental Modeling Center (EMC)]. Additionally, GFDL and PSL are focusing on how biases in cloud formation and the use of particular model physics impact the surface energy balance and sea ice variability. Model developments will be assessed and considered for inclusion in GFDL climate models and NOAA's emerging coupled, global Unified Forecast System (UFS) through projects such as the "UFS-Arctic" regional application currently under development at PSL in collaboration with NWS's National Centers for Environmental Prediction (NCEP) EMC.

Improving the skill of the NOAA models is dependent on model developments at partner institutions. A number of NOAA partners presented developments on modeling including sea ice dynamics and wave–ice interactions [University of Washington (UW)], new rheology schemes developed for inclusion in coupled forecast systems and climate models from Environment and Climate Change Canada (ECCC) and the U.S. Department of Energy (DOE) Los Alamos National Laboratory (LANL), and advanced modeling schemes to include floe-size distributions and the relation between floe size and ice thickness developed and evaluated by groups at UW and the Alfred Wegener Institute (AWI). Challenges in modeling sea ice variability due to biases and errors in simulating albedo, ocean circulation, and water mass properties was a recurring theme.

The coupling between sea ice models and wave models is critically important for modeling conditions in the marginal ice zone (MIZ), a regime where variability is particularly difficult to simulate and forecast. GLERL, NASA, UW, and LANL presented results of modeling studies focused on sea ice–wave interactions. Studies demonstrate that waves produce mechanical mixing to the upper ocean, which deepens the upper mixed layer depth and intensifies the thermocline layer—variability that cannot be reproduced by present ocean models without wind-wave mechanical mixing.

Improving modeled coastal representation of sea ice is an identified forecast need for stakeholders given its importance for transportation and community decision-making. Landfast ice parameterizations have been in development for a number of years but have generally not been included in operational forecast systems. A number of international operational centers are exploring the use of these parameterizations in forecast systems to address model biases and to develop more advanced forecasts to support coastal communities. Exploratory techniques such as machine learning (ML) are being used by the National Center for Atmospheric Research (NCAR), NOAA, and other centers to constrain uncertainty in parameterizations.

Workshop participants provided the following recommendations and opportunities for *model development* collaboration:

- High-latitude forecasts require models that can specifically and adequately represent the unique processes and complex couplings specific to Arctic regions. Support, develop, test, and assess a UFS-Arctic regional application (OAR, NWS, partners) to provide needed forecast guidance in this challenging area.
- Modeling groups across NOAA and partner institutions use forecast systems with differing frameworks and coupling strategies. Target funding for collaboration projects between NOAA and partners exploiting the use of shared column physics that can be applied to a range of forecast systems for evaluating and improving sea ice and atmospheric parameterizations.
- Multiple research groups reported on model errors in water mass properties, such as Atlantic inflow waters and mixed layer structure, that cause biases in sea ice forecasts. Support collaboration across NOAA and partners for ocean and sea ice physics developments that can improve Arctic ocean water mass properties.
- Many groups reported that including a parameterization for landfast ice is essential for both sea ice impacts on coastal communities and the large-scale sea ice motion. Support collaborations projects to facilitate landfast ice modeling advancements to address this important stakeholder gap and operational forecast need.

- There was a strong consensus that more direct channels for collaboration between academic, OAR, and operational centers are needed to implement and evaluate cutting-edge modeling developments. Support projects that require cross-collaboration efforts such as advancing coupled wave–ice interactions, modeling of floe-size and ice thickness distributions, and merging GFDL's SIS2 and LANL's Icepack thermodynamics.

Workshop highlights: Model assessment

Observational data across high-latitude oceans and the Great Lakes are needed to calibrate and validate any new model applications and was noted as a priority throughout the workshop. Increased partnership with observation-based science will help in diagnosing biases in models and lead to model skill improvements targeting forecast needs. Workshop participants endorsed several complementary experimental designs for leveraging in situ observations, including nudging experiments using global models (to account for internal variability, which is a significant contributor to climate model divergence from observations at subdecadal scales), process-oriented diagnostics (POD) developed from observations (to distill in situ data to the underlying physical process relationships independent from temporal variability), and detailed study of SCM configurations forced using observations (for direct access to comparable process evolution).

An efficient path forward for conducting these assessments involves prioritizing processes and properties that will be most impactful in improving model skill. Participants recognized that model sensitivity studies are a useful way to conduct this prioritization and that the needs differ among the central (consolidated) sea ice pack, MIZ, coasts, open water, and lake ice. Within the pack ice, thermodynamic sensitivities to precipitation and cloud microphysics, snow thermal conductivity, the scales of ice deformation processes, and parameters controlling aggregate albedo were thought to be most critical. In the MIZ, floe size distribution, wave–ice interactions, and complex dynamical interactions between ice and ocean were deemed essential targets for improvement. In the coastal environment, the discussion centered around evaluating landfast ice [currently, GFDL and GLERL leverage landfast ice information from shapefiles from the NWS and the National Ice Center (NIC)] and obtaining accurate estimates of freshwater input to the sea for initialization. In open water, in particular near the MIZ, discussion centered on assimilation sea surface salinity and temperature, and recent improvements to satellite retrievals. Lake ice modeling in the Great Lakes shares the identified priorities in the sea ice MIZ and thus there are distinct cross-cutting focal points for increased lake and ocean modeling collaboration.

To support model assessments and improvements, several recent advancements in observations were highlighted that could provide the basis for breakthroughs. New in situ data exist from the MOSAiC campaign, which collected spatially distributed ocean–ice–atmosphere observations during both the ice growth and melt periods of a common ice floe in 2019 and 2020. MOSAiC is already being utilized by several research groups and motivated some of the subgrid-scale focus discussed during the workshop.

While such an observational campaign is yet to emerge in the Great Lakes, lake ice research has benefited from observations leveraging existing platforms (e.g., buoys, offshore flux towers), as well as new devices (e.g., shallow water ice profilers). New and improved satellite products are also emerging. Increasing in situ observation capability in the Great Lakes would lead to improved forecasts for the ~34 million people living in the vicinity.

GFDL's data assimilation experiments for subseasonal-to-seasonal (S2S) predictions using sea ice concentration and sea ice thickness from *CryoSat-2* resulted in improved predictions of Arctic summer sea ice. NESDIS currently provides sea ice concentration operational products through the Office of Satellite Products and Operations (OSPO) and the Center for Satellite Applications and Research (STAR). Research and development work is ongoing for more advanced NOAA products including ice motion vectors, lead detection, ice type, and ice surface roughness. Better leveraging of existing satellite products of sea surface temperature (SST) and sea surface salinity (SSS) for DA in areas of open water was discussed and exploring assimilation of new variables over ice-covered areas (e.g., ice type, floe size, radiances) was discussed (STAR). Exploratory methods were presented, including sea ice thickness assimilation by GFDL and initialization of floe size using NIC data for the Great Lakes ice model by Colorado School of Mines and GLERL.

Workshop participants provided the following recommendations and opportunities for *model assessment* collaboration:

- Support projects using existing tools for conducting process-oriented model experiments (e.g., SCM, replay, nudging) to isolate processes responsible for biases in coupled forecast systems.
- Develop and share (via MDTF, MetPlus, etc.) PODs to evaluate thermodynamic sensitivities of sea ice, surface fluxes, ocean mixed layer and water mass properties, boundary layer and cloud processes, etc.
- Coordinate and design observational experiments to address specific model vulnerabilities such as wave–ice interactions and ocean–ice–atmosphere interface energy transfer.

Workshop highlights: Targeting model applications and transition opportunities

Many of the workshop presentations emphasized what the NOAA and external-partner modeling community already know to be true: the most important factors in accelerating end-to-end modeling advancements are driven by a collaborative approach linking the research community and NOAA scientists and developing and maintaining strong links between academics and the operational sectors of NOAA. The pathway for this to succeed is by communicating needs, developing ideas, and supporting collaborative projects between NOAA's operations, R&D sectors, and partners. The workshop discussions were focused on how increased collaboration and targeted attention between NOAA operations, NOAA research, academia, and stakeholders/users can be achieved.

Detailed discussions revolved around NOAA requirements and gaps for providing improved products to Alaskan coastal communities, emergency and ecosystem managers, and environmental responders who require accurate information about ice conditions and drift in the coastal regions. For example, model resolution does not capture the ice edge morphology sufficiently to support some fishing activities and models do not include landfast ice (an essential resource for coastal communities) or sufficiently represent the drift of ice and sea level in coastal regions. Another identified issue was the disconnect between specific forecaster needs at the NWS Alaska Region and National Ocean Service's Office of Response and Restoration (ORR) from the priorities of the research sector. Furthermore, the current generation of models do not capture the structure of ice in ways that can be used to differentiate lake ice from sea ice, including evolving structures such as brine channels which control ice strength (important for navigation) and vital in developing models to track pollutants such as oil.

Meeting the U.S. ice forecasting needs is a challenge that is being actively taken on by various NOAA and other federal laboratories and the academic research community, but better collaboration with current efforts are needed. For example, modifying "Icepack," LANL's widely used sea ice column model, to simulate lake ice and oil in ice can be an important development for improving Great Lake models and tracking of environmental hazards. Additionally, addressing the resolution issue and improved models for navigation in the Great Lakes can be transferred to new forecast models for the Northwest Passage and Alaskan coastal regions.

The NOAA Arctic Testbed and Proving Ground (ATPG) exists to support transition of new and/or improved sea ice products to operations. The NOAA UFS framework is encouraging cross-NOAA collaborations and can be used to move research developments into operational use. NOAA is well positioned to develop an efficient pathway from research to operations and applications (R2X), utilizing both ATPG and UFS pathways, to test experimental and new research products for operational use. However, there may still be need for other model architectures to support forecasts at the high resolutions required for coastal inundation and ice–coast interaction processes.

Workshop participants provided the following recommendations and opportunities for *model applications and transition opportunities* collaboration:

- To accelerate R2X, support should be prioritized for collaboration projects focused on model development, evaluation, and products between research (NOAA laboratories and partners) and NOAA operational line offices.
- The Arctic Testbed should be resourced to develop projects evaluating forecast skill and assess stakeholder-relevant products collaboratively between NOAA laboratories, partners, forecasters, and users.
- Promote the sharing of model advances and output across NOAA and partners for community use (e.g., UW floe size distribution module for use at GLERL; tailored CAFS output products for use at ORR; downscaled CMIP6 to project Great Lakes and Arctic sea route ice conditions to year 2100).

Conclusions

Over the past several decades, dramatic, rapid, and significant physical environmental changes in the Arctic has created a recognized need for improved forecast models and targeted and specialized products at high latitudes. Activities in remote, challenging, and hazardous Arctic waters require accurate forecasting of environmental conditions to support safe maritime transportation, search and rescue, oil spill response, commercial fishing, community, emergency and ecosystem management, environmental research, tourism, and the energy and mineral industries, to name a few. Our Sea Ice Modeling Collaboration Workshop provided an excellent opportunity to understand the state of NOAA and partners model development, research, and the needed advancements to provide skillful forecasts in sea ice conditions.

Talks highlighted the importance of coordinating efforts and a number of specific collaborations and priorities for future projects were identified. Participants conveyed their appreciation for the opportunity to exchange ideas and build relationships in an inviting environment and overwhelmingly welcomed a follow-up workshop to share advancements.

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