IS-ENES3 Deliverable D4.2

Development strategy for sea ice modelling in NEMO

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ABSTRACT

The NEMO consortium has recently agreed to expand the community approach to include sea ice through the collaborative development of a unified NEMO sea ice model (SI3) that will include functionality from the existing models currently used with NEMO (CICE, GELATO, LIM).

This activity, performed in conjunction with the NEMO Sea Ice Working Group (SIWG), will support SI3 development with the creation of a sustainable development strategy for sea ice in NEMO.

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Executive Summary

This document outlines a sustainable development strategy for the new NEMO sea ice model - the Sea Ice modelling Integrated Initiative (SI^3). Some key points of the strategy are as follows:

1) The SI3 sea ice model will be part of the NEMO ocean modelling framework, wholly owned by the NEMO consortium
2) The SI3 model code will be available in the NEMO repository alongside the ocean model code
3) SI3 will be developed adhering to NEMO procedures for code development as described on the NEMO Trac system, including reporting of bugs/issues and/or ideas for future SI3 code development
4) The NEMO SIWG will be responsible for the day-to-day leadership of SI3
5) The NEMO SIWG will propose the scientific direction of SI3, which will be agreed within the wider NEMO governance structure
6) In the short- to medium-term, the SI3 development strategy will be to adapt the existing LIM3 code and merge in the required features from the other sea ice models used with NEMO (namely CICE & GELATO)
7) In the longer-term, the scientific strategy of the SI3 model will be tied to the wider NEMO Development Strategy (NDS)

Particular attention has been paid to the scientific direction of the SI3 model. This has included a refresh of the sea ice section of the 2018 NDS, which is attached as an appendix to this deliverable. Further evolution of the SI3 scientific strategy will be undertaken as part of the NDS update activity performed within the wider NEMO community. Moreover, the long-term suitability of the current continuum model formulation has been appraised based upon the outcomes of the IS-ENES3 international sea ice modelling workshop "Toward defining a cutting-edge future for sea ice modelling". As well as detailing ways in which the current code should progress in terms of the representation of sea ice physics, we also make the following general points:

A. We favour smooth evolution of the existing code, but also encourage research on the feasibility of major structural changes (most notably exploring discrete element and hybrid discrete-continuum approaches)
B. We argue that the most pressing needs for SI3 are not only related to evolving the sea ice physics, but also to improving access to (or take-up of) the model. Specifically, we recommend improving code modularity, coupling interfaces and documentation (including scientific articles and in-line comments in the code)

1. Sea Ice modelling Integrated Initiative (SI^3)

Since the inception of NEMO as a pan-European ocean modelling framework – from the initial Memorandum Of Understanding in 2003 to the formal consortium signing in 2008 – the sea ice has always played a somewhat peripheral role. Although there was of course a need to include sea ice in global ocean simulations, the sea ice itself was not considered fully within the scope of the NEMO consortium. This meant that sea ice was not part of the formal NEMO strategy and development was not directly funded within the consortium member contributions. Over the years several sea ice models have been used along with the ocean component of NEMO – including the LIM2 and LIM3 models (whose codes were provided through the NEMO subversion repository), the Los Alamos sea ice model CICE, and the Météo-France/CNRM GELATO model. There was little consensus even within the NEMO consortium itself, with around half the members using LIM and half using CICE. This proliferation of sea ice models, and associated coupling infrastructure, has led to considerable wasted effort and scientific resources within the NEMO community, with duplication of effort and unnecessary competition. The need to provide coupling interfaces for multiple sea ice models has also made things technically difficult within the NEMO Surface Boundary Condition (SBC) code.

In 2016 the NEMO Sea Ice Working Group (SIWG) was formed to investigate ways to reduce the duplication of sea ice model development effort within the NEMO community. In 2017 the members of the SIWG agreed to pool resources and develop a fully unified sea ice model within the NEMO framework. This move would bring sea ice fully within the NEMO consortium, formalising existing development relationships and bringing in new (former CICE) developers. The Sea Ice modelling Integrated Initiative (SI3) was born.

The IS-ENES3 project has provided support to the NEMO SIWG for building the developer and user community necessary for a sustainable NEMO sea ice model. This deliverable report is focussed on part of this community building activity – namely creation of a sustainable development strategy for sea ice in NEMO.

2. SI^3 governance and leadership

The SI3 sea ice model will be part of the NEMO ocean modelling framework. It will be wholly owned by the NEMO consortium. The NEMO SIWG will be responsible for the day-to-day leadership of SI3, which will include representation within the NEMO System Team (NST). Sea ice model development activity will be elaborated through an annual work-plan to be developed through NEMO SIWG each year. Model developments and code changes from institutions external to the consortium can be included on the work plan (as is true for other parts of NEMO). The

NEMO SIWG will feed SI3 plans into the wider NEMO organisational structures in the same way as other NEMO working groups (NWGs) – i.e., plans are ratified by the NEMO Developer's Committee (NDC), the NEMO Scientific Advisory Committee (NSAC), and ultimately the consortium owners through the Steering Committee representatives. There will be at least one member of the NEMO Science Advisory Committee (NSAC) with a sea ice focus. Figure 1 illustrates how the various aspects of the NEMO governance structure fit together. More information can be found on the NEMO website at https://www.nemo-ocean.eu/consortium/governance/.

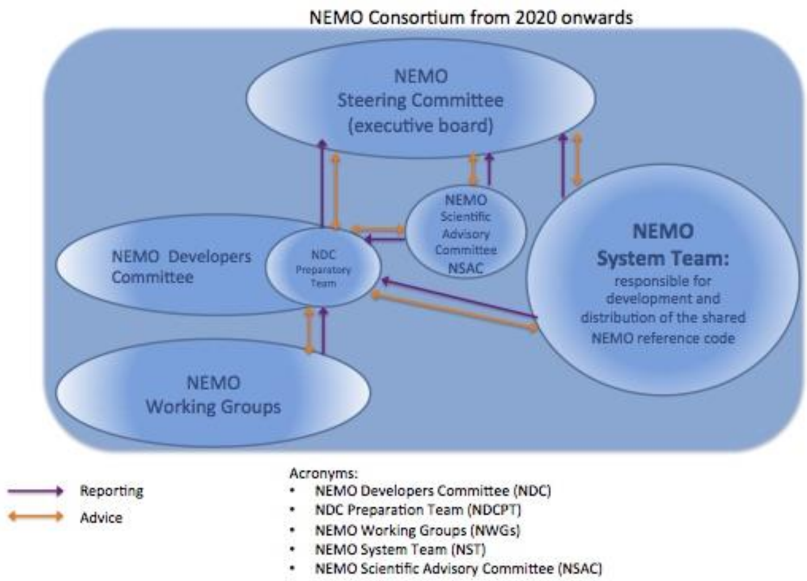

Figure 1: Illustration of NEMO's governance structures (taken from https://www.nemo-ocean.eu/consortium/governance/)

3. SI^3 technical development strategy

The SI3 model code will be available in the NEMO repository from NEMO v4.0 onwards, where it will sit in the source directories in a new 'ICE' folder alongside the ocean code in 'OCE'.

SI3 will be developed adhering to NEMO procedures for code development described on the NEMO Trac system at https://forge.ipsl.jussieu.fr/nemo/wiki/Developers. This will involve adopting NEMO practices on:

- code design and coding standards
- work-flow processes (e.g. branches, tickets, (pre)review, etc.)
- testing and evaluation strategy

Reporting of bugs/issues and/or ideas for future development of SI3 will follow what is currently done for NEMO within the NEMO Trac system.

4. SI^3 scientific direction

The NEMO SIWG will be responsible for proposing the scientific direction of SI3, which will be agreed within the wider NEMO governance structure described in Section 2 of this document (Figure 1).

4.1 Short-term direction: transition period

The transition to SI3 from LIM3, CICE and GELATO will involve starting from the LIM3 model as a base before merging back functionality from CICE and GELATO. The motivation for this approach is that LIM3 already satisfies NEMO coding standards and uses the same (Arakawa-C) grid as NEMO, making for a considerable reduction in technical development overheads. Much of this work was already planned, and some underway, before the start of the IS-ENES3 project. Although IS-ENES3 funds have been of great importance for supporting this "transition" work, the focus of this deliverable report is related to setting the longer-term strategy for sea ice modelling within the NEMO framework.

4.2 Longer-term direction: strategic planning

Most contemporary sea ice models, including all the major models used with NEMO (LIM, SI3, CICE & GELATO), describe the sea ice pack as a continuum material – a principle laid by the Arctic Ice Dynamics Joint Experiment (AIDJEX) group in the 1970s. Initially intended for climate studies, to describe the evolution of sea ice at scales of approx. 100 km over days to months, these sea ice model components are now used across a wide range of resolutions, including very high resolutions more than 100 times finer than those they were designed for. These models are also used in an increasingly wide range of applications, including operational weather and marine forecasts, that challenge the original AIDJEX model foundations. It is therefore sensible to question the applicability of contemporary sea ice models to these applications and to ask whether there are better alternatives available.

Toward defining a cutting-edge future for sea ice modelling: An international workshop

When considering the sea ice component to be used within the NEMO ocean modelling framework, we need to look much further ahead – especially given that NEMO has never really had a long-term sea ice strategy per se. In light of the above, we need to ensure that the SI3 model formulation is still relevant and the best choice to meet the varying needs of the NEMO users. Therefore, as well as considering the development strategy for NEMO/SI3 specifically, we also need to explore the relevance of the whole continuum model formulation.

In order to achieve these goals an international workshop devoted to the future direction of sea ice modelling was organised (previously reported in IS-ENES3 M4.1). The planned approach was to bring together NEMO SIWG members, with several external experts from the international sea ice modelling community, to discuss priorities, opportunities and potential threats relevant to large-scale sea ice modelling. The workshop was held in Laugarvatn, Iceland on the 23rd-26th September 2019, and was co-hosted/organised by Ed Blockley (Met Office) and Martin Vancoppenolle (CNRS-IPSL) from the IS-ENES3 project and NEMO SIWG, along with Elizabeth Hunke from the US DOE (Los Alamos National Laboratory and lead scientist for the CICE Consortium). The event was structured around a set of important motivating questions, split into 2 key themes:

Theme 1. Scientific and technical validity/limitations of the current models

A. *How relevant are the current continuum model formulations for simulating sea ice in the context of contemporary applications, given the trend towards higher horizontal resolution, the increasingly diverse applications for which sea ice models are employed today, and the warming-related changes in sea ice behaviour?*

B. *What plausible and useful alternatives could — or should — be adopted instead of the widely used continuum model approach?*

C. *What opportunities and constraints do the next generation of supercomputers provide for sea ice modelling?*

Theme 2. Physical processes and complexity: bridging the gap between weather and climate requirements

D. *What level of sea ice model complexity is required/appropriate?*

E. *Are we able to satisfy the potentially conflicting requirements for climate and operational forecasting in a coherent sea ice modelling system?*

A set of five keynote speakers, of international repute, were invited to speak to each theme and to answer selected points from the motivating questions. The keynote speakers were deliberately chosen to provide insightful and/or controversial opinions to stimulate debate. Workshop attendance comprised 32 sea ice modelling scientists, including 10 invited experts from North America and 22 from Europe – including 15 NEMO users/developers and SIWG members. Details of the keynote speakers and motivating questions can be found in the BAMS report supplementary material, reproduced in Appendix B.

The IS-ENES3 Iceland international sea ice modelling workshop was a great success and produced several important recommendations that have been useful for defining the future strategy of sea ice in NEMO. These points were written up and published as a report in BAMS entitled "The Future of Sea Ice Modeling: Where Do We Go from Here?" (Blockley et al., 2020), and are also summarised here below:

1. The continuum model formulation is still very good for describing the large-scale/average behaviour of sea ice. It will likely remain relevant for lower resolution and climate studies for many years to come.
2. However, it should be recognised that the continuum formulation does have some limitations, which mean that alternative model formulations may be beneficial for operational forecasting needs in the near future (e.g. Hunke et al., 2020):
    a. Continuum models do not seek to represent features at the grid-scale, such as individual leads, floes or ridges, only the statistical average behaviour
    b. At high resolution the continuum assumptions can be invalidated because grid-cells do not necessarily contain a representative sample of sea ice floes
3. Discrete element models (DEMs), which are becoming relatively more affordable with increases in available HPC resources, are potentially well suited for operational forecasting needs. DEM, or hybrid discrete-continuum, methods are a promising, revolutionary candidate for modelling the heterogeneous, anisotropic ice pack at fine spatio-temporal scales.
4. Recognition that varying levels of model complexity are needed – with many users wanting high complexity whilst others prefer simplicity. We should maintain a code that provides several levels of complexity in a modular fashion. However, it is also important not to have too many options – particularly for ease of ongoing code maintenance.
5. Appropriate engagement with the wider community (i.e., outside of the NEMO consortium) will be very important for SI3; it will likely improve both uptake and development of the model.

Updating the NEMO sea ice strategy

When the current NEMO Development Strategy (NDS) was written in 2018, the concept of unified sea ice modelling within NEMO was still very much in its infancy. Although the decision had already been made to pool sea ice modelling resources and expertise within the NEMO community, the details were not yet very advanced. Indeed, the SI3 name had not yet been decided upon (or even suggested!). Therefore the 2018 NDS only includes preliminary statements relating to sea ice;

the focus was mostly along the lines of stating intention to work more closely together and highlighting areas that would need to be updated in future.

As part of Task 2 within IS-ENES3 WP4, the sea ice sections of the 2018 NDS have been updated. This activity, performed in conjunction with the wider NEMO SIWG, has been heavily informed by the topics discussed at the IS-ENES sea ice modelling workshop (Iceland, September 2019), and the publications that have been spawned from it. The updated sea ice NDS chapter can be found in Appendix A attached to this deliverable report. The key points of this updated strategy are as follows:

- We favour smooth evolution of the existing code, but also encourage research on the feasibility of major structural changes (most notably exploring discrete element approaches) to address the issues raised in point #2 above.
- We argue that the most pressing needs for SI3 are not only related to evolving the sea ice physics, but also to improving access to (or take-up of) the model. Specifically improving the modularity and interfacing possibilities of the code to ensure that people can easily use SI3 with their specific applications. Another key need is to provide better communicate on the code (with documentation, scientific articles and comments in the code)
- We also detail how the current code can progress in terms of the representation of sea ice processes and physics.
- One key aspect is to ensure the circulation of information among the various stakeholders (SIWG, NEMO-ST, NEMO users and developers). In particular, before undertaking specific physical improvements, we really need to understand what the user/stakeholder needs are.

References

Blockley, E., Vancoppenolle, M., Hunke, E., and co-authors, The Future of Sea Ice Modeling: Where Do We Go from Here?, Bulletin of the American Meteorological Society, 101(8), E1304-E1311, https://doi.org/10.1175/BAMS-D-20-0073.1, 2020.

Hewitt, H.T., Blockley, E.W., and co-authors: Resolving and Parameterising the Ocean Mesoscale in Earth System Models. Curr. Clim. Change Rep., https://doi.org/10.1007/s40641-020-00164-w, 2020.

Hunke, E.C., Blockley, E.W., and co-authors, Should Sea-Ice Modeling Tools Designed for Climate Research Be Used for Short-Term Forecasting?, Curr. Clim. Change Rep., https://doi.org/10.1007/s40641-020-00162-y, 2020.

Appendices

Appendix A: updated NEMO development strategy for sea ice

The refreshed sea ice section of the NEMO Development Strategy (NDS) document is attached to this deliverable as an appendix [8 pages].

Appendix B: Iceland sea ice modelling workshop report

The key points from the IS-ENES3 sea ice modelling workshop have been published in BAMS as the article "The Future of Sea Ice Modeling: Where Do We Go from Here?". The full article and supplementary material are attached to the end of this deliverable and can be accessed online as follows:

- full article: https://doi.org/10.1175/BAMS-D-20-0073.1
- supplementary: https://doi.org/10.1175/BAMS-D-20-0073.2

Future development of the SI^3 model: NEMO Development Strategy sea ice chapter refresh

Martin Vancoppenolle and Ed Blockley, with input from the NEMO SIWG,

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1. Introduction

The representation of sea ice is important for various purposes (geophysics of sea ice, ocean and climate simulation, operational applications). NEMO now has a single sea ice model named SI^3 (Sea Ice modelling Integrated Initiative), which will be based on the best of its predecessors (LIM3, CICE and GELATO).

The SI^3 model uses a fairly standard continuum model formulation, components and physics, following principles introduced by the AIDJEX consortium in the 1970's (Coon et al., 1974). It is based on the assumption that sea ice can be represented as a 2+1D continuum drifting under the influence of friction to air, sea and seafloor, Earth rotation, and internal forces. Internal forces assume that sea ice exhibits plastic behaviour (i.e., permanent deformation after a sufficient stress is applied) (Hibler, 1979), using the aEVP method (Kimmritz et al., 2017). The subgrid-scale ice thickness distribution is resolved using ice categories, each of which has specific state variables (for snow and sea ice). 2D horizontal transport equations are used to move state variables around and redistribute them in thickness space; with a specific source/sink term designed to represent physical processes, which can be mostly considered as vertical. Vertical physics include sea ice growth and melt, cooling and warming, brine inclusion dynamics, radiative transfer, and many other parameterisations. Surface albedo is a function of surface state, in particular of melt-pond area and thickness, tracked following the approach of Flocci and Feltham (2007). For the most part, SI^3 is a sea ice model compliant with the state-of-the-art, and with representation processes identified as important by the sea ice community.

The strengths and limitations of continuum sea ice models such as SI^3, along with prospects for their evolution, are detailed in Blockley et al. (2020) and their suitability for operational forecasting applications is discussed in Hunke et al. (2020). These two publications summarise outcomes of a community workshop organised by the NEMO Sea Ice Working Group (SIWG) in Laugarvatn, Iceland, in 2019. In these papers, it is argued that:

1. The continuum model formulation is still very good for describing the large-scale/average behaviour of sea ice and will likely remain relevant for lower resolution and climate studies for many years to come. Continuum sea ice models agree well with current observations and will remain useful for the coming years to decades.

2. Continuum models are not fully appropriate for high-resolution and operational applications, which mean that alternative model formulations may be beneficial for operational forecasting needs in the near future:
    a. Continuum models do not seek to represent features at the grid-scale, such as individual leads, floes or ridges, only the statistical average behaviour
    b. At high resolution the continuum assumptions can be invalidated because grid-cells do not necessarily contain a representative sample of sea ice floes.

3. Discrete-element models, whose formulation principles are potentially well suited for operational forecasting needs, offer an exciting alternative to the continuum approach, but are not yet mature enough for implementation in large-scale ocean modelling systems such as NEMO.

In this context, we propose here a strategy for the evolution of SI^3, mostly based on the maintenance and development of the current continuum approach, but allowing research on possible alternatives such as DEM. We split our strategy along three main axes: documentation; modularity and interface to Earth System Model components; representation of sea ice processes.

The difficulties that are faced share similarities with the ocean but are also somehow specific to the sea ice. In common with the ocean, SI3 developers face specific demands from different sub-communities of users, in terms of target resolution, processes, and output diagnostics. One specific aspect of sea ice is that its physical understanding is far less advanced than that of the ocean. Governing equations are under debate (we have only a few “rules”) and increasing sea ice model resolution does not necessarily lead to a better representation of the sea ice medium. In particular, it should be stated that sea ice continuum models are mathematically similar to the standard continuum formulation used to derive the Navier-Stokes equations for Newtonian fluid flow. However, the continuum assumption is much more easily invalidated for sea ice because the sea ice floe, the analogue of a molecule in the ocean continuum, is of comparable size to the grid cell used for numerical simulation.

2. Main known issues

a. **Documentation.** There is a strong need for documentation to facilitate the uptake of SI3 users. The current documentation is only an advanced draft and so this will need to be progressed as a top priority.

b. **Modularity and interfaces.** Primary users' needs do not directly relate to model physics, but rather relate to interfacing the sea ice code with other codes/systems. A modular code structure is the best approach to allow users the capability to run SI3 with their specific applications.

c. **Representation of sea ice physical processes.** Model physics/numerics in several areas of the code could be improved. On-shelf operational solutions are rarely readily available. Physical understanding is more often the key limitation to progress, just ahead of low staff resources.

3. Plan for issue development

a. **Write and review documentation** (IS-ENES, SIWG, Dec 2021).
Activities required: (i) Report on model physics, code organisation, structure, etc. in a documentation document; (ii) Evaluate the code and document model performance in a paper; (iii) Improve inline comments within the SI3 code.

b. **Improve modularity and interfaces**
Code modularity and interfaces are important to allow users to easily use SI3, which will increase uptake of the model. Some specific issues include:

   i. **Reduced ocean physics**
   Issue: Many sea ice users need a reduced-complexity ocean (mixed layer).
   Plan: Implement bulk mixed layer from CICE (U. Reading, 2021), which paves way to more advanced schemes, likely out of the SIWG activities.

   ii. **Splitting thermodynamics and dynamics**
   Issue: Some applications would benefit from a full split of ice dynamics and thermodynamics, in order to run sea ice on a separate grid, and benefit from finite-element/volume high-order methods (e.g. DG).
   Plan: Allow full separation of thermodynamics and dynamics, and adjust the surface module accordingly (CNRS, 2021).

   iii. **Wave-ice interactions**
   Issue: There is no clearly identified interface between sea ice and waves within NEMO, although ad-hoc pieces of work have been performed in the past without much coordination. In Brest the wave-divergence term of the momentum equation (and possibly other things) have been done. NOC has implemented collisional rheology (Aksenov). Full floe size distribution (FSD) is possible but implies large extra complexity in the code and is expensive. There are basically 2 groups of stakeholders, with

different foci and interests. The WAVE research community members are interested in the effect of sea ice on waves (attenuation, reflection, …). The SEA ICE research community is interested in the effects of waves on sea ice (floe breaking, wave divergence, …).
Resolution: Launch a specific discussion with stakeholders (Reading, NOC, Waves-WG, SIWG, SASIP). 2 objectives: Identify current status of the wave-ice interface and define a strategy for wave-ice interactions that are agreeable to both waves and sea ice stakeholders. This task may benefit from a targeted workshop.

iv. **BGC-ice interactions**
Issue: The interface with tracers, in particular those used for ocean biogeochemistry (BGC), is rudimentary in the SI3 code. There has been some work done outside of the NEMO workplan to provide specific functionality, however. For instance, Hayashida and Steiner (CCCMa, Victoria) have implemented an ice algae model in NEMO 3.6. Iron in sea ice, treated as a volume tracer in ice categories, has been implemented by CNRS (Person et al., GBC 2020).
Resolution: Launch a specific discussion group with stakeholders (TOP-WG, SIWG, Victoria, CNRS). 2 problems. Define a generic strategy for tracers. Identify whether specific tracers should be incorporated and/or are needed (iron, isotopes, …)

v. **Snow on sea ice as a separate medium**
Issue: There are various advanced continental snow models (CROCUS, SnowTherm, ...). Model infrastructure is not ready to receive them, as snow is intrinsically into the sea ice model. If we want to benefit from such models, there could be a need to introduce a specific interface between sea ice and snow.
Resolution: Revise the snow-sea ice interface to better separate the two media. Interested stakeholders could be identified, in order to introduce more advanced snow models (CNRM?).

vi. Ice-atmosphere interface
Issue: Some ice-atmosphere interfaces (e.g. CNRM, CMCC) are not yet fully supported in the SI3 code.
Resolution: Interface suggestions should be sourced from the relevant groups (CMCC, CNRM). Those groups might be helped by using existing NEMO functionality to run SI3 as a separate executable coupled through OASIS. We have to see how deep an involvement of sea ice developers this requires.

c. **Representation of sea ice**

i. **Overarching model assumptions**
Issue: Current 1+2D continuum approach is designed for large-scale sea ice modelling at scales of approx. 100 km over days to months. Although it is therefore still ok for climate modelling purposes, it is not fully applicable to the 1km scales relevant for operational forecasting. Although there is no readily available alternative, discrete element (or hybrid discrete-continuum) model approaches do offer promising avenues for future research.
Resolution: Explore **discrete element** approaches (UKMO/NERC). Follow and get in contact with the many groups planning developments in that direction (UWa, Poland, SASIP).

ii. **Ice dynamics**

- **Sea ice rheology**
  Issue: Which sea ice rheology(ies) is (are) the most appropriate for climate or operational forecasting applications is an open question. SI3 currently contains the EAP and EVP rheologies.
  Resolution: Implement VP rheology and inter-compare plastic rheologies, with a particular focus on operational application (IMMERSE). Provide input regarding a brittle rheology with damage mechanism (SASIP).

- **Sea ice strength**
  Issue: Sea ice strength is highly influential and subject to large uncertainty but only the most basic strength formulation from Hibler (1979) is available in SI3.
  Resolution: Implement the “ridging” formulation of sea ice strength proposed by Rothrock (1975), which is available in CICE (UKMO, work plan 2021).

- **Horizontal transport**
  Issue: Advection remains expensive. Only the Prather ‘86 scheme is fully satisfactory. FCT4 is not performing as well numerically speaking. The incremental remapping from CICE has to be adapted to the NEMO grid to work. For these reasons, adding more tracers is not easy, which will mean cost implications for BGC, FSD and snow model developments.
  Resolution: Identify interested developers and researchers to progress.

- **Drags**
  Issue: Ice-atm/ice-ocean drag coefficients, do not yet conform to state-of-the art (Tsamados).

Resolution: UCL has routines in NEMO3.6, which need to be ported into the code at v4.2.

- **Iceberg-sea ice interactions and Antarctic land-fast sea ice**
  Issue: Antarctic land-fast ice does not currently emerge from model physics and may be important for modelling coastal polynyas and dense water formation. An ad-hoc solution has been proposed by van Achter et al. (submitted to Ocean Modelling), combining tensile strength and large icebergs as part of the sea ice mask. However, as this approach requires observations of large icebergs to be available, it is not yet easy to implement globally.
  Resolution: Implement grounded iceberg mask for sea ice model. Explore more generic parameterization of iceberg-sea ice interactions for large-scale implementation (UCL/CNRS).

iii. **Ice physics**

- **Optics**
  Issues: (i) There are questions on the current surface albedo scheme (thickness dependence of albedo). (ii) The Lebrun et la. (2019) transmittance-scheme leads to spurious surface melt reduction. (iii) Assumptions on under-ice spectral distribution of light are wrong. (iv) There exist more sophisticated optics schemes available in other sea ice models (e.g., CICE).
  Resolution: (i) Resolve disagreement on albedo scheme and amend current scheme (CNRS/Reading). (ii) Updating Lebrun et al. (2019) scheme for light attenuation with latest developments. Test multi-layer snow scheme as a solution for excess surface melt (iii) Revise infrared absorption and light fractionation under sea ice (ocean). (iv) Start discussions regarding further developments. Current broadband scheme could be revised. Two-band and delta-Eddington schemes have been introduced in CICE, but what the advantages are of these approaches is not fully clear. Therefore, we need a preliminary evaluation before we move on.

- **Melt ponds**
  Issue: Some melt pond processes are missing (under-ice ponds, refreezing)
  Resolution: Developments are ongoing in Reading (under-ice melt ponds, melt pond refreezing) and should get back reasonably soon into NEMO.

- **Salt dynamics**
  Issues: Schemes from Rees-Jones and Worster (2014) and Griewank and Notz (2013) were identified as best options by Thomas et al. (2020). However, for implementation, one would need to provide an implicit scheme, otherwise we will need to keep sub-time stepping.

- **Thermodynamic core**
  Issues: Thermodynamic phase composition formulas are inconsistent throughout the code (permeability, brine salinity, …). The linear liquidus assumption has implications everywhere. Non-linear liquidus and more general enthalpy approach would be more precise and allow for easier implementation of minerals, frazil ice, platelet ice (as per Wongpan et al., 2021). Three steps would be required: (i) fully expand the code to an enthalpy-based formulation; (ii) Rewrite heat equation with enthalpy basis; (iii) Implement various liquidus formulations. Possible compatibility with TEOS-10 (as per Vancoppenolle et al., 2019).

- **Snow on sea ice**
  Issue: Snow formulation in SI3 is very simple and a constant snow density is used.
  Resolution: Easy progress is to implement the vertical density distribution by Lecomte et al. (UCL, work plan 2021).

4. Other issues

i. There are not many test cases for sea ice.
ii. Data assimilation has been used with NEMO sea ice for several decades but is now becoming more popular with non-operational users. SI3 currently has access to the standard assimilation tools in NEMO, maintained by the DAWG, including the observation operator in 'OBS' and incremental analysis update (IAU) code in 'ASM'. The core data assimilation codes however (such as NEMOVAR) are developed and maintained separately outside of NEMO. We need to liaise with the DAWG to ensure there are appropriate links between the ICE and OBS/ASM codes.
iii. We also have a few external tools (evaluation, etc…). How should they be shared and maintained?

5. Summary

Progress in the documentation, modularity, and interfacing of SI3 is in the interest of most. Current SIWG members can do part of the job, with the help of the NEMO system team. In some cases, there is a need to link with other WG's or contact external people.

Physical progresses in the representation of sea ice will occur in the next five years. Our progress will largely be conditioned by our capacity to enrol experienced developers. An optimal organisation of the work among the different developers should be sought for.

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

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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.

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References

Coon, M. D., G. A. Maykut, R. S. Pritchard, D. A. Rothrock, and A. S. Thorndike, 1974: Modeling the pack ice as an elastic-plastic material. *AIDJEX Bull.*, No. 24, University of Washington, Seattle, WA, 105 pp.

——, R. Kwok, M. Pruis, G. Levy, D. Sulsky, and H. L. Schreyer, 2007: Arctic Ice Dynamics Joint Experiment (AIDJEX) assumptions revisited and found inadequate. *J. Geophys. Res.*, **112**, C11S90, https://doi.org/10.1029/2005JC003393.

Dansereau, V., J. Weiss, P. Saramito, and P. Lattes, 2016: A Maxwell-elasto-brittle rheology for sea ice modelling. *Cryosphere*, **10**, 1339–1359, https://doi.org/10.5194/TC-10-1339-2016.

——, ——, ——, ——, and E. Coche, 2017: Ice bridges and ridges in the Maxwell-EB sea ice rheology. *Cryosphere*, **11**, 2033–2058, https://doi.org/10.5194/tc-11-2033-2017.

Docquier, D., F. Massonnet, A. Barthélemy, N. F. Tandon, O. Lecomte, and T. Fichefet, 2017: Relationships between Arctic sea ice drift and strength modelled by NEMO-LIM3.6. *Cryosphere*, **11**, 2829–2846, https://doi.org/10.5194/tc-11-2829-2017.

Feltham, D. L., 2008: Sea ice rheology. *Annu. Rev. Fluid Mech.*, **40**, 91–112, https://doi.org/10.1146/annurev.fluid.40.111406.102151.

Girard, L., J. Weiss, J. Molines, B. Barnier, and S. Bouillon, 2009: Evaluation of high-resolution sea ice models on the basis of statistical and scaling properties of Arctic sea ice drift and deformation. *J. Geophys. Res.*, **114**, C08015, https://doi.org/10.1029/2008JC005182.

Gray, J. M. N. T., and L. W. Morland, 1994: A two-dimensional model for the dynamics of sea ice. *Philos. Trans. Roy. Soc. London*, **347A**, 219–290, https://doi.org/10.1098/rsta.1994.0045.

Heorton, H. D. B. S., D. L. Feltham, and M. Tsamados, 2018: Stress and deformation characteristics of sea ice in a high-resolution, anisotropic sea ice model. *Philos. Trans. Roy. Soc.*, **376A**, 20170349, https://doi.org/10.1098/RSTA.2017.0349.

Hibler, W. D., 1979: A dynamic thermodynamic sea ice model. *J. Phys. Oceanogr.*, **9**, 815–846, https://doi.org/10.1175/1520-0485(1979)009<0815:ADTSIM>2.0.CO;2.

Holt, J., and Coauthors, 2017: Prospects for improving the representation of coastal and shelf seas in global ocean models. *Geosci. Model Dev.*, **10**, 499–523, https://doi.org/10.5194/gmd-10-499-2017.

Hopkins, M. A., and A. S. Thorndike, 2006: Floe formation in Arctic sea ice. *J. Geophys. Res.*, **111**, C11S23, https://doi.org/10.1029/2005JC003352.

——, S. Frankenstein, and A. S. Thorndike, 2004: Formation of an aggregate scale in Arctic sea ice. *J. Geophys. Res.*, **109**, C01032, https://doi.org/10.1029/2003JC001855.

Hunke, E. C., and J. K. Dukowicz, 1997: An elastic–viscous–plastic model for sea ice dynamics. *J. Phys. Oceanogr.*, **27**, 1849–1867, https://doi.org/10.1175/1520-0485(1997)027<1849:AEVPMF>2.0.CO;2.

——, and Coauthors, 2020: CICE-Consortium/CICE: CICE version 6.1.1 (version 6.1.1). Zenodo, http://doi.org/10.5281/zenodo.3712304.

Hutter, N., and M. Losch, 2020: Feature-based comparison of sea ice deformation in lead-permitting sea ice simulations. *Cryosphere*, **14**, 93–113, https://doi.org/10.5194/tc-14-93-2020.

IPCC, 2013: Climate Change 2013: *The Physical Science Basis.* Cambridge University Press, 1535 pp., https://doi.org/10.1017/CBO9781107415324.</

Kimmritz, M., M. Losch, and S. Danilov, 2017: A comparison of viscous-plastic sea ice solvers with and without replacement pressure. *Ocean Modell.*, **115**, 59–69, https://doi.org/10.1016/j.ocemod.2017.05.006.

Koldunov, N. V., and Coauthors, 2019: Fast EVP solutions in a high-resolution sea ice model. *J. Adv. Model. Earth Syst.*, **11**, 1269–1284, https://doi.org/10.1029/2018MS001485.

Kreyscher, M., M. Harder, P. Lemke, and G. M. Flato, 2000: Results of the Sea Ice Model Intercomparison Project: Evaluation of sea ice rheology scheme for use in climate simulations. *J. Geophys. Res.*, **105**, 11 299–11 320, https://doi.org/10.1029/1999JC000016.

Kwok, R., and G. F. Cunningham, 2002: Seasonal ice area and volume production of the Arctic Ocean: November 1996 through April 1997. *J. Geophys. Res.*, **107**, 8038, https://doi.org/10.1029/2000JC000469.

——, E. C. Hunke, W. Maslowski, D. Menemenlis, and J. Zhang, 2008: Variability of sea ice simulations assessed with RGPS kinematics. *J. Geophys. Res.*, **113**, C11012, https://doi.org/10.1029/2008JC004783.

Lemieux, J.-F., D. A. Knoll, B. Tremblay, D. M. Holland, and M. Losch, 2012: A comparison of the Jacobian-free Newton–Krylov method and the EVP model for solving the sea ice momentum equation with a viscous-plastic formulation: A serial algorithm study. *J. Comput. Phys.*, **231**, 5926–5944, https://doi.org/10.1016/j.jcp.2012.05.024.

——, L. B. Tremblay, F. Dupont, M. Plante, G. C. Smith, and D. Dumont, 2015: A basal stress parameterization for modeling landfast ice. *J. Geophys. Res. Oceans*, **120**, 3157–3173, https://doi.org/10.1002/2014JC010678.

——, F. Dupont, P. Blain, F. Roy, G. C. Smith, and G. M. Flato, 2016: Improving the simulation of landfast ice by combining tensile strength and a parameterization for grounded ridges. *J. Geophys. Res. Oceans*, **121**, 7354–7368, https://doi.org/10.1002/2016JC012006.

Losch, M., A. Fuchs, J.-F. Lemieux, and A. Vanselow, 2014: A parallel Jacobian-free Newton–Krylov solver for a coupled sea ice-ocean model. *J. Comput. Phys.*, **257**, 901–911, https://doi.org/10.1016/j.jcp.2013.09.026.

Manabe, S., and R. J. Stouffer, 1980: Sensitivity of a global climate model to an increase of CO2 concentration in the atmosphere. *J. Geophys. Res.*, **85**, 5529–5554, https://doi.org/10.1029/JC085iC10p05529.

Mehlmann, C., and T. Richter, 2017: A modified global Newton solver for viscous-plastic sea ice models. *Ocean Modell.*, **116**, 96–107, https://doi.org/10.1016/j.ocemod.2017.06.001.

Newman, K., T. Jensen, B. Brown, R. Bullock, T. Fowler, and J. H. Gotway, 2019: Model evaluation tools version 8.1.2 user's guide. Developmental Testbed Center Rep., 439 pp., https://dtcenter.org/sites/default/files/community-code/met/docs/user-guide/MET_Users_Guide_v8.1.2.pdf.

Notz, D., A. Jahn, M. Holland, E. Hunke, F. Massonnet, J. Stroeve, B. Tremblay, and M. Vancoppenolle, 2016: The CMIP6 Sea-Ice Model Intercomparison Project (SIMIP): Understanding sea ice through climate-model simulations. *Geosci. Model Dev.*, **9**, 3427–3446, https://doi.org/10.5194/gmd-9-3427-2016.

Pritchard, R. S., Ed., 1980: Sea Ice Processes and Models: Proceedings of the Arctic Ice Dynamics Joint Experiment, International Commission on Snow and Ice Symposium, University of Washington Press, 474 pp.

Rampal, P., S. Bouillon, E. Ólason, and M. Morlighem, 2016: neXtSIM: A new Lagrangian sea ice model. *Cryosphere*, **10**, 1055–1073, https://doi.org/10.5194/tc-10-1055-2016.

——, V. Dansereau, E. Olason, S. Bouillon, T. Williams, A. Korosov, and A. Samaké, 2019: On the multi-fractal scaling properties of sea ice deformation. *Cryosphere*, **13**, 2457–2474, https://doi.org/10.5194/tc-13-2457-2019.

Righi, M., and Coauthors, 2020: Earth System Model Evaluation Tool (ESMValTool) v2.0—Technical overview. *Geosci. Model Dev.*, **13**, 1179–1199, https://doi.org/10.5194/gmd-13-1179-2020.

Ringeisen, D., M. Losch, L. B. Tremblay, and N. Hutter, 2019: Simulating intersection angles between conjugate faults in sea ice with different viscous–plastic rheologies. *Cryosphere*, **13**, 1167–1186, https://doi.org/10.5194/tc-13-1167-2019.

Rousset, C., and Coauthors, 2015: The Louvain-La-Neuve sea ice model LIM3.6: Global and regional capabilities. *Geosci. Model Dev.*, **8**, 2991–3005, https://doi.org/10.5194/gmd-8-2991-2015.

Tandon, N. F., P. J. Kushner, D. Docquier, J. J. Wettstein, and C. Li, 2018: Reassessing sea ice drift and its relationship to long-term Arctic sea ice loss in coupled climate models. *J. Geophys. Res. Oceans*, **123**, 4338–4359, https://doi.org/10.1029/2017JC013697.

Tsamados, M., D. L. Feltham, and A. Wilchinsky, 2013: Impact of a new anisotropic rheology on simulations of Arctic sea ice. *J. Geophys. Res. Oceans*, **118**, 91–107, https://doi.org/10.1029/2012JC007990.

Wilchinsky, A. V., and D. L. Feltham, 2006: Modelling the rheology of sea ice as a collection of diamond-shaped floes. *J. Non-Newtonian Fluid Mech.*, **138**, 22–32, https://doi.org/10.1016/j.jnnfm.2006.05.001.

WMO, 1970: Sea-ice nomenclature, terminology, codes and illustrated glossary. WMO Rep. WMO/OMM/BMO 259, 121 pp.

BAMS Supplement

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Agenda – Iceland Sea ice modelling workshop

Venue address: University of Iceland Building, Lindarbraut 4, 480 Laugarvatn, Iceland

Monday 23rd September 2019

17:00: bus transit leaves Keflavik airport to Laugarvatn (~1hr 45min)

19:00: arrival and get settled into accommodation

19:45: Informal introduction to the workshop

20.00: Dinner and reception

Tuesday 24th September 2019

07:30 - 08:15: Breakfast

08:30 - 08:50: Welcome, housekeeping, and introduction to day 1

08:50 - 12:30: Speaker presentations (15-20 min + 10 min) [Chair: Ed Blockley]

08:50 – Danny Feltham
09:20 – Martin Losch
09:50 – Pierre Rampal

10:30 - 11:00: Coffee

11:00 – Eric Maisonnave
11:30 – Adrian Turner

12:00 - 13:00: Synthesis and initial discussion

13:00 - 14:00: Lunch

14:00 - 15:30: Free time [suggestion: walk in nearby mountains]

15:30 - 1600: Coffee

16:00 - 18:30: Discussion session for day 1
Chair: Elizabeth Hunke
Rapporteurs: Andrew Roberts; Sophie Morellon

19:30: Dinner

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Wednesday 25th September 2019

07:30 - 08:15: *Breakfast*

08:30 - 08:50: Housekeeping, and introduction to day 2

08:50 - 12:30: Speaker presentations (15-20 min + 10 min) [Chair: Ed Blockley]

08:50 – Dirk Notz
09:20 – Elizabeth Hunke
09:50 – Cecilia Bitz

10:30 - 11:00: *Coffee*

11:00 – Jean-Francois Lemieux
11:30 – Steffen Tietsche

12:00 – 13:00: Synthesis and initial discussion

13:00 - 14:00: *Lunch*

14:00 - 15:30: Discussion session for day 2
Chair: Martin Vancoppenolle
Rapporteurs: François Massonnet; Sophie Morellon

15:30 - 1600: *Coffee*

16:00 - 17:00: Wrap up and exploring next steps

17:00 - 19:00: Free time [suggestion: Fontana Geothermal bath]

19:30: *Farewell dinner*

Thursday 26th September 2019

05:00: Bus transit to Keflavik airport from Laugarvatn

Emergency contacts

Sophie Morellon	Ed Blockley	Martin Vancoppenolle
		

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Iceland workshop: motivating questions (1)

Top-level questions for the workshop:

A1. What scientific questions or operational needs are driving current sea ice model development?

A2. Do we think the current continuum model formulation is still the best choice for sea ice modelling?

- **a. If no: what would be the best alternative?**
- **b. If yes: for how long will this be true? What will be the limitations?**

A3. Do we favour "evolution", "revolution", or "status quo" in relation to designing future sea ice models?

A4. What role can the sea ice model development community play to improve progress? Are there any current practices that are inhibiting scientific advancement?

Main questions for the discussion & workshop report

B1. Are we in a position to claim that any of the available sea ice modelling frameworks are better than any of the others? (e.g., Eulerian AIDJEX/Hibler, Lagrangian, Discrete Element, …)

- a. What are the key strengths and weaknesses of each approach?
- b. How is scientific validity of sea ice models established, in particular dynamics? Is there a consensus? What are the advantages vs caveats of the different evaluation methods? Which data products are to be used or precluded?
- c. Do we know what would be the "perfect" sea ice model physical framework (equivalent to Navier-Stokes for the ocean)?

B2. What level of physical complexity is necessary for sea ice modelling?

- a. Are there important missing processes in contemporary sea ice models?
- b. Why are climate models with a more complex sea ice component not clearly superior to those with a very simple sea ice model?
- c. Is there a place for very simple sea ice models for climate applications?
- d. To what extent does it make sense to increase model physics given the large uncertainties in atmospheric and oceanic forcing?

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Iceland workshop: motivating questions (2)

Main questions for the discussion & workshop report (contd.)

B3. What is the contribution of forcing *vs* physics to model uncertainty, in light of internal variability?

   a. Do we know enough how sea ice affects its own atmospheric and oceanic forcing?

   b. What are the trade-offs when considering coupling strategies to other Earth System Model components? How important are they?

B4. Which other constraints should be considered, in the context of current and upcoming applications and computing platforms?

   a. What is the finest resolution that can currently be used with current models? Are these limitations of physical, numerical, or computational origin? Is there a discrepancy between these limitations and the resolution required for operational applications?

   b. Should the same sea ice model be used for short-range forecasting and large-scale climate modelling?

   c. Will contemporary sea ice models (i.e., continuum+rheology) scale well enough for the next generation of exascale HPC systems?

   d. What are the most critical code design requirements for efficient use of new computational architectures?

Questions related to community practice & tools

C1. Are there current sea ice modelling practices slowing scientific progress?

C2. Should the sea ice modelling community improve modularity among different model sub-components to develop modular, interchangeable components that can be plugged into a generic framework? If so, how fine should the granularity be?

C3. Should the sea ice modelling community work toward one model or set of tools that everyone uses for many different purposes, or toward providing a diversity of model choices even for the same purpose?

C4. Should analysis, evaluation and calibration tools (including data assimilation) be included within sea ice modelling repositories? Could we benefit from international coordination or even collaboration?