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The future of sea ice modelling: where do we go from here?

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

What: An international workshop for sea ice model developers and expert users to discuss the future of sea ice modelling

When: 23-26 September 2019

Where: Laugarvatn, Iceland

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1. Introduction and motivation for the workshop

Earth System Models (ESMs) include a sea ice component to physically represent sea ice changes and impacts on planetary albedo and ocean circulation (Manabe & Stouffer, 1980). Most contemporary sea ice models describe the sea ice pack as a continuum material, a principle laid by the AIDJEX (Arctic Ice Dynamics Joint EXperiment) 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 modelling community met in September 2019 for a workshop in Laugarvatn, Iceland. Thirty-two sea ice modelling scientists from 11 countries across Europe and North America attended, spanning 3 key areas: (i) developers of sea-ice models; (ii) users of sea-ice models in an ESM context; (iii) users of sea-ice models for operational forecasting and (re)analyses. The workshop was structured around 2 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 Supplementary Material.

2. Key points and outcomes from the sea ice modelling 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 kilometres (*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 modelling 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

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circulation (e.g., Kreyscher et al., 1999); 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 land-fast 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 grid-cell sizes of ~1-10 km. This is particularly true for short-range forecasting applications and regional modelling 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 spatio-temporal 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 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 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 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 sub-grid level due to mechanical failure and melting or refreezing. In contrast, isotropic models either assume sub-grid-cell cracks do not exist or are isotropically distributed. The EAP model produces realistic scaling of sea ice deformation in idealised 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 VP and EAP, simulating failure by tracking strain-induced damage, which gives a high degree of stress localisation. To preserve the localised 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, land-fast ice; Dansereau et al., 2017), as well as ice drift and spatio-temporal 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, modelling of sea ice.

Discrete Element Modelling: 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 modelling 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 modelling 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 modelling. 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 initialisation 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 modelling systems. However, DEMs present a promising approach for future sea ice modelling, which should be explored further. In particular, DEMs would be particularly appealing for operational forecasting applications that require models to reproduce sea ice behaviour on fine spatio-temporal 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 parameterisations 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 modelling, 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 favour 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 favour 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 modellers 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 optimisation

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 favoured continuum models, with DEMs being too expensive to run. However, DEMs have the potential to scale better on newer, heterogeneous HPC architectures such 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 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 modelling centres.

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 favourable 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 <100m).

Community involvement plays an important role for sea ice model development, but current practices could be improved

Engagement of the broad sea ice modelling community has been crucial for sea ice model development, especially for large community codes such as CICE (Hunke et al., 2020) and SI^3/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 SIMIP community for CMIP6 (Notz et al., 2016), facilitates multi-model evaluation and comparison studies. However it was felt that community tools, such as ESMValTool (Righi et al., 2020) and MET (Newman et al., 2019), could be better utilised 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 idealised 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.

3. 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, paleo-climate 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 modelling 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 parameterisations and code features. Thus, users can adjust model complexity to fit their specific application.

Considering limited human resources among core sea ice modelling 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 modelling workshop was the open minded, friendly and respectful atmosphere in which very different views were exchanged. The workshop successfully brought together model developers and users of sea-ice models for Earth-system modelling, operational forecasting and (re)analyses.

International sea ice modelling workshops such as this foster collaboration and community engagement in the field of sea ice modelling. 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.

Acknowledgements

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References

Coon, M. D., Maykut, G. A., Pritchard, R. S., Rothrock, D. A., Thorndike, A.S.: Modeling the pack ice as an elastic-plastic material. AIDJEX Bulletin 24, 1–105, 1974.

Coon, M., Kwok, R., Pruis, M., Levy, G., Sulsky, D., and Schreyer, H. L.:. AIDJEX assumptions revisited and found inadequate. Journal of Geophysical Research 112, C11S90, doi:10.1029/2005JC003393, 2007.

Dansereau, V., Weiss, J. Saramito, P., Lattes, P. A Maxwell-elasto-brittle rheology for sea ice modelling. *The Cryosphere*, Copernicus, 10, pp.1339-1359, 2016.

Dansereau, V., Weiss, J., Saramito, P., Lattes, P., and Coche, E.: Ice bridges and ridges in the Maxwell-EB sea ice rheology, The Cryosphere, 11, 2033–2058, https://doi.org/10.5194/tc-11-2033-2017, 2017.

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

Feltham, D. L.: Sea Ice Rheology. Annual Review of Fluid Mechanics 40, 91–112. https://doi.org/10.1146/annurev.fluid.40.111406.102151, 2008.

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

Gray, J. M. N. T., and Morland, L. W.: A two-dimensional model for the dynamics of sea ice. Philosophical Transactions of the Royal Society of London. Series A: Physical and Engineering Sciences 347, 219–290. https://doi.org/10.1098/rsta.1994.0045, 1994.

Hibler, W.D.: A dynamic thermodynamic sea ice model. Journal of Physical Oceanography 9, 815–846, 1979.

Heorton, H. D. B. S., Feltham, D. L., and Tsamados, M.: Stress and deformation characteristics of sea ice in a high-resolution, anisotropic sea ice model. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 376 (2129), https://doi.org/10.1098/rsta.2017.0349, 2018.

Holt, J., Hyder, P., Ashworth, M., Harle, J., Hewitt, H. T., Liu, H., New, A. L., Pickles, S., Porter, A., Popova, E., Allen, J. I., Siddorn, J., and Wood, R.: 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, 2017.

Hopkins, M.A., Frankenstein, S., and Thorndike, A.S.: Formation of an aggregate scale in Arctic sea ice. Journal of Geophysical Research 109, C01032, 2004.

Hopkins, M.A., and Thorndike, A.S.: Floe formation in Arctic sea ice. Journal of Geophysical Research 111, C11S23. https://doi.org/doi:10.1029/2005JC003393, 2006.

Hunke, E.C., and Dukowicz, J.K.: An elastic-viscous-plastic model for sea ice dynamics. Journal of Physical Oceanography 27, 1849–1867, 1997.

Hunke, E., et al.: CICE-Consortium/CICE: CICE Version 6.1.1 (Version 6.1.1), Zenodo, http://doi.org/10.5281/zenodo.3712304, March 2020.

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

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley. ed. Cambridge University Press, Cambridge, UK and New York, USA.

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

Koldunov, N. V., Danilov, S., Sidorenko, D., Hutter, N., Losch, M., Goessling, H., et al.: Fast EVP solutions in a high- resolution sea ice model, Journal of Advances in Modeling Earth Systems, 11, 1269– 1284. https://doi.org/10.1029/2018MS001485, 2019.

Kreyscher, M., Harder, M., Lemke, P., and Flato, G.M.: Results of the Sea Ice Model Intercomparison Project: Evaluation of sea ice rheology scheme for use in climate simulations. Journal of Geophysical Research 105, 11,299–11,320, 1999.

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

Kwok, R., Hunke, E.C., Maslowski, W., Menemenlis, D., and Zhang, J.: Variability of sea ice simulations assessed with RGPS kinematics. Journal of Geophysical Research: Oceans 113. https://doi.org/10.1029/2008JC004783, 2008.

Lemieux, J.-F., Knoll, D.A., Tremblay, B., Holland, D.M., and Losch., M.: 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. Journal of Computational Physics 231, 5926–5944. http://dx.doi.org/10.1016/j.jcp.2012.05.024, 2012.

Lemieux, J.-F., Tremblay, L.B., Dupont, F., Plante, M., Smith, G.C., and Dumont, D.: A basal stress parameterization for modeling landfast ice. Journal of Geophysical Research: Oceans 120, 3157–3173. https://doi.org/10.1002/2014JC010678, 2015.

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

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

Manabe, S., and Stouffer, R.J.: Sensitivity of a Global Climate Model to an Increase of CO_2 Concentration in the Atmosphere. Journal of Geophysical Research 85, 5529–5554, 1980.

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

Newman, K., Jensen, T., Brown, B., Bullock, R., Fowler, T., and Gotway, J. H.: Model Evaluation Tools Version 8.1.2 User's Guide, Developmental Testbed Center Boulder, Colorado, https://dtcenter.org/sites/default/files/community-code/met/docs/user-guide/MET_Users_Guide_v8.1.2.pdf, October 2019 (last accessed 16th march 2020)

Notz, D., Jahn, A., Holland, M., Hunke, E., Massonnet, F., Stroeve, J., Tremblay, B., and Vancoppenolle, M.: 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, 2016.

Pritchard, R.S.: Sea Ice Processes and Models. Proceedings of the Arctic Ice Dynamics Joint Experiment International Commision on Snow and Ice Symposium. University of Washington Press, Seattle, Washington, WA, 1980.

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

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

Righi, M., Andela, B., Eyring, V., Lauer, A., Predoi, V., Schlund, M., Vegas-Regidor, J., Bock, L., Brötz, B., de Mora, L., Diblen, F., Dreyer, L., Drost, N., Earnshaw, P., Hassler, B., Koldunov, N., Little, B., Loosveldt Tomas, S., and Zimmermann, K.: 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, 2020.

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

Rousset, C., Vancoppenolle, M., Madec, G., Fichefet, T., Flavoni, S., Barthélemy, A., Benshila, R., Chanut, J., Levy, C., Masson, S., and Vivier, F.: 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, 2015.

Tandon, N.F., Kushner, P.J., Docquier, D., Wettstein, J.J., and Li, C.: Reassessing Sea Ice Drift and Its Relationship to Long-Term Arctic Sea Ice Loss in Coupled Climate Models. Journal of Geophysical Research: Oceans 123, 4338–4359, 2018.

Tsamados, M., Feltham, D.L. and Wilchinsky, A.: Impact of a new anisotropic rheology on simulations of Arctic sea ice. Journal of Geophysical Research, 118 (1). pp. 91-107. ISSN 2169-9291, doi:10.1029/2012JC007990, 2013.

Wilchinsky, A.V., and Feltham, D.L.: Modelling the rheology of sea ice as a collection of diamond-shaped floes, J. Non-Newtonian Fluid Mechanics, 138, 22-32, 2006.

WMO Sea-ice Nomenclature, Terminology, Codes and Illustrated Glossary. World Meteorological Organisation, Geneva. WMO/OMM/BMO 259, TP 145, 1970.

Figure 1: Workshop attendants in front of Lake Laugarvatn, Iceland