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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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45 **1. Introduction and motivation for the workshop**

46 Earth System Models (ESMs) include a sea ice component to physically represent sea ice
47 changes and impacts on planetary albedo and ocean circulation (Manabe & Stouffer, 1980).
48 Most contemporary sea ice models describe the sea ice pack as a continuum material, a principle
49 laid by the AIDJEX (Arctic Ice Dynamics Joint EXperiment) group in the 1970s (Pritchard,
50 1980). Initially intended for climate studies, the sea ice components in ESMs are now used
51 across a wide range of resolutions, including very high resolutions more than 100 times finer
52 than those they were designed for, in an increasingly wide range of applications that challenge
53 the AIDJEX model foundations (Coon et al., 2007), including operational weather and marine
54 forecasts. It is therefore sensible to question the applicability of contemporary sea ice models
55 to these applications. Are there better alternatives available? Large advances in high
56 performance computing (HPC) have been made over the last few decades and this trend will
57 continue. What constraints and opportunities will these HPC changes provide for contemporary
58 sea ice models? Can continuum models scale well for use in exascale computing?

59
60 To address these important questions, members of the sea ice modelling community met in
61 September 2019 for a workshop in Laugarvatn, Iceland. Thirty-two sea ice modelling scientists
62 from 11 countries across Europe and North America attended, spanning 3 key areas: (i)
63 developers of sea-ice models; (ii) users of sea-ice models in an ESM context; (iii) users of sea-
64 ice models for operational forecasting and (re)analyses. The workshop was structured around 2
65 key themes:

- 66
- 67 1. Scientific and technical validity and limitations of the physics and numerical approaches
68 used in the current models

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

71
72 For each theme, 5 keynote speakers were invited to address the motivating questions and
73 stimulate debate. Further details can be found in the Supplementary Material.

74 **2. Key points and outcomes from the sea ice modelling workshop**

75 *Continuum models remain a useful tool for sea ice simulation*

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

90
91 Many studies demonstrate the ability of the continuum (E)VP models to reasonably simulate
92 key properties of the sea ice: the large-scale distribution of sea ice thickness, concentration and

93 circulation (e.g., Kreyscher et al., 1999); relationships between sea ice concentration, thickness
94 and velocity (Docquier et al., 2017); long-term trends in winter sea ice velocity (Tandon et al.,
95 2018). With modifications for grounded ridges and tensile strength, continuum models are also
96 able to realistically simulate the distribution of Arctic land-fast ice — the motionless fields of
97 sea ice attached to the coast or seabed (e.g., Lemieux et al., 2015; 2016).

98
99 However, the core assumptions of the continuum theory are appropriate only for large-scale sea
100 ice evolution, where model grid-cells contain a representative sample of floes. With the increase
101 in available computational resources over the last few decades, several sea ice model
102 configurations have grid-cell sizes of ~1-10 km. This is particularly true for short-range
103 forecasting applications and regional modelling studies, which tend to use such resolutions
104 because the Rossby radius in high-latitude waters can be close to 1 km (Holt et al., 2017). At
105 these resolutions, the continuum assumption likely breaks down (Coon et al., 2007; Feltham,
106 2008).

107
108 Nevertheless, even at kilometeric resolution, continuum-based sea ice models continue to be
109 useful. Early evaluations with synthetic aperture radar estimates of drift and deformation (Kwok
110 and Cunningham, 2002) challenged continuum sea ice models' representation of spatio-
111 temporal deformation, particularly in terms of localization and intermittency (Girard et al.,
112 2009; Kwok et al. 2008). However, simulations at kilometeric resolutions (effective 10 km)
113 reconcile the model results with observations for many drift and deformation feature statistics
114 at these resolutions (Hutter and Losch, 2020).

115
116 Solver convergence also impacts simulated deformation statistics (Lemieux et al., 2012) and
117 Linear Kinematic Features (LKF) within the ice pack (Koldunov et al., 2019). However, as the

118 spatial resolution is increased in VP continuum-based models, the numerical solution of the sea
119 ice momentum equation is increasingly difficult to obtain due to the strong nonlinearity of the
120 problem. Despite recent nonlinear solver developments (e.g. Losch et al., 2014; Kimmritz et
121 al., 2017; Mehlmann and Richter, 2017), obtaining a fast and numerically converged solution
122 remains a challenge. Another issue is that VP continuum models overestimate the prevalence
123 of large intersection angles between LKFs, which might be fixed by amending the rheological
124 formulation (Hutter and Losch, 2020; Ringeisen et al., 2019).

125
126 Alternative rheological formulations have also been proposed to address shortcomings of the
127 VP rheology; the Elastic-Anisotropic-Plastic (EAP) and Maxwell-Elasto-Brittle (MEB)
128 rheologies were discussed at the workshop. The EAP rheology (Wilchinsky and Feltham, 2006)
129 introduces a new state variable, the structure tensor, that tracks the history of past fracture
130 events and allows the orientation of these fractures to evolve at the sub-grid level due to
131 mechanical failure and melting or refreezing. In contrast, isotropic models either assume sub-
132 grid-cell cracks do not exist or are isotropically distributed. The EAP model produces realistic
133 scaling of sea ice deformation in idealised configurations and has shown promising results for
134 simulation of the basin-scale sea ice thickness distribution (Tsamados et al., 2013; Heorton et
135 al, 2018). The MEB rheology (Dansereau et al., 2016) is a damage-propagation model, different
136 from the plastic-flow approach taken by VP and EAP, simulating failure by tracking strain-
137 induced damage, which gives a high degree of stress localisation. To preserve the localised
138 fields produced by the MEB rheology, the neXtSIM model uses a continuum Lagrangian
139 formulation in which the mesh moves with the ice (Rampal et al., 2016). MEB-based models
140 reproduce some sea ice processes as emergent properties (ice bridges, ridges, land-fast ice;
141 Dansereau et al., 2017), as well as ice drift and spatio-temporal deformation statistics (Rampal
142 et al., 2019).

143

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

148

149 ***Discrete Element Modelling: a promising avenue for the future***

150 Discrete Element Models (DEMs) have long been used to model granular, discontinuous
151 materials, including ice floes (e.g., Hopkins et al., 2004; Hopkins and Thorndike, 2006). By
152 their very nature, DEMs are well suited to modelling sea ice, which - particularly around the
153 ice edge - consists of many individual ice floes.

154

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

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

174

175 *Navigating the model complexity spectrum: finding the right amount of complexity*

176 The issue of model complexity is complicated and was discussed at length at the workshop.
177 Here we take the term “model complexity” as synonymous with “number and level of detail of
178 the model’s parameterisations of physical processes”. Although there were advocates for
179 including more complexity and for using more simplified models, the general feeling was that
180 present-day continuum models capture the most important physical processes, in principle.
181 However, the representation of certain key processes is uncertain due to missing observational
182 constraints.

183

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

201

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

207

208 *HPC requirements cause uncertainty (constraints and opportunities) for future sea ice model*
209 *code structure and optimisation*

210 Current continuum formulations of sea ice dynamics require relatively high levels of
211 communication between processor domains within the rheology and advection calculations.
212 This can make sea ice components a bottleneck in coupled systems, as they tend to scale poorly
213 with increasing HPC resources due to sea ice's localization on the globe. The thermodynamic
214 components, however, rely on one-dimensional 'column' formulations that require very little
215 cross-domain communication, allowing them to scale well with increasing HPC resources.

216
217 HPC resource constraints have historically favoured continuum models, with DEMs being too
218 expensive to run. However, DEMs have the potential to scale better on newer, heterogeneous
219 HPC architectures such those using Graphical Processing Units (GPUs). DEMs benefit from a
220 natural domain decomposition via aggregates of floes, which can be moved to GPUs for
221 Lagrangian and thermodynamic calculations requiring less bandwidth for communication with
222 processors handling other parts of the domain.

223
224 Whether current continuum sea ice models will be able to take full advantage of the resources
225 available on future exascale HPC machines is currently an active area of research. Much of the
226 uncertainty comes from not knowing the form future exascale HPC systems might take, and the
227 fact that the efficiency of the sea ice model component is not likely to be a priority of those
228 people choosing the HPC resources at large modelling centres.

229

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

235

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

238 Engagement of the broad sea ice modelling community has been crucial for sea ice model
239 development, especially for large community codes such as CICE (Hunke et al., 2020) and
240 SI³/LIM (Rousset et al., 2015). Community involvement can bring considerable model
241 advances by allowing many different research and operational groups to contribute new model
242 functionality and physics, as well as thoroughly testing the code in diverse applications.
243 However, it is important to have well defined long-term plans and to communicate these
244 effectively, so that the wider community can efficiently contribute to the scientific direction of
245 the model while maintaining a streamlined and relevant code base.

246

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

250

251 One area of potential collaboration involves common model evaluation tools. Having common
252 outputs and model diagnostics, such as those defined by the SIMIP community for CMIP6
253 (Notz et al., 2016), facilitates multi-model evaluation and comparison studies. However it was

254 felt that community tools, such as ESMValTool (Righi et al., 2020) and MET (Newman et al.,
255 2019), could be better utilised for evaluation of sea ice models.

256

257 Another area that could benefit from community involvement is assessing the models at a
258 process level, for instance by formulating idealised case studies for model inter-comparison
259 (e.g., wind blowing on an ice pack in a rectangular domain). It was also felt that standard metrics
260 are required against which to compare the models with each other and with observations, and
261 to ascertain how well models capture the leading-order physical processes. For example, a
262 standard metric for measuring the performance of model thermodynamics at leading order
263 would be useful.

264 **3. Summary and recommendations**

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

275

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

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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.

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