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

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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

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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

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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 kilometric 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 kilometric 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 (LKFs) within the ice pack (Koldunov et al., 2019). However, as the

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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).

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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.

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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.

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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

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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.

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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 SI$^3$/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

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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.

## 3. Summary and recommendations

264

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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279

280    Considering limited human resources among core sea ice modelling groups, engagement of the

281    wider community has proven a very efficient way to advance large-scale sea ice models.

282    However, there is still scope for further integration of the wider community in model

283    development activities.

284

285    An important feature of the Laugarvatn sea ice modelling workshop was the open minded,

286    friendly and respectful atmosphere in which very different views were exchanged. The

287    workshop successfully brought together model developers and users of sea-ice models for

288    Earth-system modelling, operational forecasting and (re)analyses.

289

290    International sea ice modelling workshops such as this foster collaboration and community

291    engagement in the field of sea ice modelling. A recommendation from this workshop is that the

292    exercise should be repeated every 2-3 years to maintain community engagement, exchange

293    cutting-edge ideas, and reinforce collaborative momentum.

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

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