Sea ice volume and age: Sensitivity to physical parameterizations and thickness resolution in the CICE sea ice model

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Abstract

New dynamics parameterizations in Version 5 of the Los Alamos Sea Ice Model, CICE, feature an anisotropic rheology and variable drag coefficients. This study investigates their effect on Arctic sea ice volume and age simulations, along with the effects of several pre-existing model options: a parameter that represents the mean cumulative area of ice participating in ridging, the resolution of the ice thickness distribution, and the resolution of the vertical temperature and salinity profiles.

By increasing shear stress between floes, the anisotropic rheology slows the ice motion, producing a thicker, older ice pack. The inclusion of variable drag coefficients, which depend on modeled roughness elements such as deformed ice and melt pond edges, leads to thinner ice and a more realistic simulation of sea ice age. Several feedback processes act to enhance differences among the runs. Notably, if less open water is produced mechanically

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through ice deformational processes, the simulated ice thins relative to runs with more mechanically produced open water. Thermodynamic processes can have opposing effects on ice age and volume; for instance, growth of new ice increases the volume while decreasing the age of the pack. Therefore, age data provides additional information useful for differentiating among process parameterization effects and sensitivities to other model parameters.

Resolution of thicker ice types is crucial for proper modeling of sea ice volume, because the volume of ice in the thicker ice categories determines the total ice volume. Model thickness categories tend to focus resolution for thinner ice; this paper demonstrates that 5 ice thickness categories are not enough to accurately resolve the ice thickness distribution for simulations of ice volume.

Keywords: Sea Ice, Rheology, Resolution, Volume, Age, Arctic

1. Introduction

As sea ice ages, particularly as it passes through its first melt season, important physical properties change. For instance, sea ice desalinates via flushing of melt water through permeable brine networks, and deformational processes increase ice thickness through ridge-building. Freshening and thickening both enhance the probability that sea ice will survive another melt season, simply by requiring more heat to melt it (Vancoppenolle et al., 2009a). Conversely, the loss of perennial ice accelerates as younger, thinner ice replaces it.

Decline of sea ice volume in the Arctic over recent decades, and an associated shift from a largely perennial ice pack toward seasonal ice, are now

12 widely recognized (e.g., Kwok et al., 2009; Stroeve et al., 2012). The rapidity
13 and magnitude of these ongoing changes present challenges for Arctic people
14 and wildlife, as well as significant weather repercussions in lower latitudes
15 (e.g., Francis et al., 2009; Screen, 2013). On the other hand, a seasonal ice
16 pack implies simpler logistics for Arctic Ocean commerce and resource ex-
17 traction, generating safety concerns along with a stronger focus on improving
18 seasonal-to-interannual sea ice predictions.

19 Armour et al. (2011) analyze the large-scale response of sea ice to climate
20 forcing based on the seasonal partitioning and survivability characteristics
21 of first-year and multiyear (perennial) ice. They employ a reduced model
22 for theoretical guidance in interpretation of an age related tracer available in
23 CICE, namely the first-year ice area. Among their conclusions, they find that
24 the climatological seasonal cycle of sea ice area and volume can be modeled
25 accurately without correctly representing the proportions of first-year and
26 multiyear ice area and volume, with negative consequences for capturing sea
27 ice sensitivity to future climate change. They suggest that to improve models’
28 projections of trends in sea ice area and volume, data/model comparison of
29 the fractions of first-year and multiyear ice that survives melt and growth
30 seasons would be particularly useful. Fortunately, sea ice age can be deduced
31 from satellite observations. For example, Fig. 1 shows age estimates for the
32 final week of 2009 (Maslanik et al., 2007, 2011; Tschudi et al., 2010).

33 In the present study, sea ice volume and age estimates from satellite
34 observations are compared with model output. Following the work of Hunke
35 and Bitz (2009), who look at how sea ice age evolves in a 1958–2006 CICE
36 hindcast simulation, the analyses here use the chronological ice age rather

37 than first-year ice area. I apply a newer version of the model than that of
38 Hunke and Bitz (2009), but in a very similar grid and forcing configuration, to
39 explore how parameterizations of physical processes and thickness resolution
40 affect the simulation of both ice age and volume. As Armour et al. (2011)
41 suggest, sea ice age provides useful information for discriminating among the
42 sea ice processes tested.

43 Several factors affect the age of sea ice and how it evolves. Most impor-
44 tant, of course, is the incessant march of time, chronologically aging the ice
45 by an increment Δt for every Δt of time that passes. Thermodynamic pro-
46 cesses can cause the pack ice to become younger on average, as new ice freezes
47 and grows or as older ice melts and disappears. Similarly, when younger ice
48 melts, the pack ice grows older at a rate faster than by chronological aging
49 alone. These changes in ice age are evident in model simulations, such as
50 that shown in Fig. 2. During the cold months of the year, the ice pack tends
51 to grow younger (in the absence of chronological aging), while in the warm
52 months it ages markedly. The largest rates occur in July (summer melting)
53 and October (fall freeze-up) in the Arctic. Dynamic sea ice processes such
54 as transport and deformation can not change the total age or volume of the
55 ice pack, but they do move ice of various ages around the physical domain,
56 affecting the spatial patterns of ice age and volume.

57 Hunke (2010) tunes an earlier version of the CICE model based on sub-
58 marine Upward Looking Sonar measurements of ice draft, by altering pa-
59 rameters known to strongly affect sea ice thickness while maintaining albedo
60 values close to observational estimates. One conclusion of that study was
61 that similar spatial patterns of ice thickness, area and total ice volume could

62 be obtained using different combinations of model parameters, evidence that
63 the model retains sufficient flexibility to simulate observed conditions, but
64 perhaps not with the proper balance of active and important processes, as
65 suggested by Armour et al. (2011). In a detailed study of uncertainty in their
66 sea ice-ocean model that includes assimilation of ice concentration and sea
67 surface temperature, Schweiger et al. (2011) find that uncertainties in both
68 model results and measured data exhibit wide ranges, calling for better char-
69 acterization of measurement biases and additional work to understand and
70 remedy systematic modeling errors. The purpose of this paper is not to tune
71 the CICE model to observed data, but instead to highlight and explain the
72 effects of some model options and processes that contribute to modeling un-
73 certainties. This information will better constrain future tuning exercises of
74 CICE and similar sea ice models, in stand-alone and coupled configurations,
75 to better match observations of sea ice thickness and age.

76 An additional purpose of this paper is to introduce, in a unified frame-
77 work, results from several new physical parameterization options available in
78 CICE version 5, including anisotropic rheology, variable drag coefficients, and
79 vertical resolution of the temperature and salinity profiles in a new “mushy
80 layer” thermodynamic component. These options have been tested and docu-
81 mented in disparate configurations. The common framework used here allows
82 a straight-forward comparison.

83 A brief outline of the new parameterizations and pertinent numerical
84 configuration is provided in section 2, observational data descriptions in sec-
85 tion 3, and model-data comparisons plus explanations of the parameteriza-
86 tions’ effects in section 4. Feedback mechanisms that operate between ther-

87 thermodynamic and dynamic processes enhance changes due to parameterization
 88 differences, as expected, and also those changes associated with numerical
 89 resolution of the ice thickness distribution, described in section 5. Along
 90 with a discussion of the physical process results, section 6 concludes that the
 91 current thickness discretization is insufficient for resolving sea ice age and
 92 volume.

93 **2. Model Description**

94 The Los Alamos Sea Ice Model, CICE, is applied in its standard configu-
 95 ration and with selected adjustments to parameterizations. A complete de-
 96 scription of the model can be found in Hunke et al. (2013b); here I present an
 97 overview of the features pertinent to this paper. The standard configuration
 98 includes a “mushy” thermodynamic model that prognoses both temperature
 99 and salinity in 7 vertical layers (Turner et al., 2013), the elastic-viscous-
 100 plastic (EVP) dynamics scheme for computing ice velocity and deformation
 101 (Hunke and Dukowicz, 1997, 2002; Hunke, 2001), and mechanical redistribu-
 102 tion (Thorndike et al., 1975; Rothrock, 1975; Lipscomb et al., 2007) using
 103 a 5-category ice thickness distribution (ITD). CICE version 5 includes op-
 104 tions to use a form-drag parameterization (Tsamados et al., 2014) in place of
 105 the standard CICE drag coefficients and an elastic-anisotropic-plastic (EAP)
 106 rheology (Wilchinsky and Feltham, 2006; Tsamados et al., 2013) instead of
 107 EVP. I explore the effects of these two options on ice volume and age, along
 108 with sensitivity to the mean cumulative ridging area and to resolution of both
 109 the ice thickness distribution and vertical temperature and salinity profiles
 110 within the ice.

111 In the standard CICE configuration, the ocean drag coefficient and atmo-
 112 spheric *neutral* drag coefficient are constant. The atmospheric drag coefficient
 113 over each ice thickness category is then adjusted based on Monin-Obukhov
 114 theory, accounting for the stability of the atmospheric boundary layer, dur-
 115 ing the surface flux balance calculation that determines the turbulent fluxes.
 116 (Hunke et al., 2013b). The new form drag parameterization adjusts the ini-
 117 tial, neutral drag coefficients to account for structural disruptions to the flow
 118 of air or water past the ice, including ridges and keels, melt ponds and floe
 119 edges (Tsamados et al., 2014), prior to further adjustments for the surface
 120 flux balance.

121 The EAP rheology (Wilchinsky and Feltham, 2006; Tsamados et al., 2013)
 122 relates the internal ice stress tensor to the geometrical properties and orien-
 123 tation of underlying, virtual, diamond shaped floes. Local anisotropy of the
 124 sea ice cover is accounted for by an additional “structure” tensor, which in-
 125 cludes processes that tend to make the ice cover more isotropic (e.g., thermal
 126 cracking, melting, and freezing together of floes), along with a function that
 127 determines ice floe re-orientation due to fracturing under axial splitting, biax-
 128 ial tension, and biaxial compression. Geometry of the underlying diamonds
 129 alters the closing rate under convergence, and therefore the area loss rate
 130 due to ridging must also be changed for consistency with EAP. Elasticity is
 131 added in the EAP approach to create an efficient numerical algorithm, as in
 132 EVP.

133 Once the ice velocity and deformation rates are calculated using EVP or
 134 EAP, mechanical redistribution of the modeled sea ice occurs in two steps
 135 (Thorndike et al., 1975). First, a participation function defines which portion

136 of the ice thickness distribution participates in ridging. The second piece
137 is a redistribution function, which describes how the ice participating in
138 ridging is redistributed among other thickness categories, based on the initial
139 thickness and the desired height-to-area ratio of the ridge (Hunke, 2010).
140 CICE assumes an exponential distribution of ridge thicknesses, consistent
141 with observations of thick ice (Lipscomb et al., 2007). Following Rothrock
142 (1975), sea ice strength is assumed proportional to the change in ice potential
143 energy per unit area of compressive deformation.

144 The standard CICE configuration specifies 5 categories that describe the
145 areal concentration of ice within each of the 5 thickness ranges, for each grid
146 cell. The upper boundary for category n is given by the recursive formula
147 (“STD”)

$$\begin{aligned}
h_B(n) &= h_B(n-1) \\
&+ \frac{3}{N} + \frac{45}{N} \left(1 + \tanh \left[2 \left(\frac{n-1}{N} - 1 \right) \right] \right)
\end{aligned} \tag{1}$$

148 where N is the total number of categories and $h_B(0) = 0$. CICE includes
149 an alternative method for assigning category boundaries based on the World
150 Meteorological Organization (WMO) classification descriptors for sea ice.
151 These thickness ranges are shown in Fig. 3 and Table 1 for the resolution
152 cases studied in section 5. In addition, I perform a sensitivity test for vertical
153 resolution of the thermodynamic calculation, using 4 layers instead of 7.

154 Age is carried in the model as a volume-weighted tracer, transported with
155 the ice according to the conservation equation

$$\frac{\partial (v_n T_n)}{\partial t} + \nabla \cdot (v_n T_n \mathbf{u}) = 0,$$

156 where v_n is the ice volume in thickness category n , T_n is the tracer quantity

157 in category n , $\mathbf{u}$ is ice velocity and t represents time. Although aging does
 158 change physical characteristics of sea ice over time, here I assume that the
 159 age tracer is passive; i.e. it does not affect the physical evolution of the ice
 160 pack. The age tracer is initialized at age 0 upon freezing in open water and
 161 increases by the length of the time step at each step. Neither melting nor
 162 basal freezing alters the age of an ice column (thickness category), although
 163 the mean age of all ice in a grid cell may change as new ice appears or older
 164 ice disappears. As the ice pack advects and ridges, the age of ice in any given
 165 grid cell and thickness category is altered in a conservative manner following
 166 changes in ice volume. Thicknesses shown here are mean values over the grid
 167 cell, $h = \sum_{n=1}^{N_{cat}} h_n a_n$, and category age quantities are merged using volume
 168 weighting

$$T = \frac{\sum_{n=1}^{N_{cat}} v_n T_n}{\sum_{n=1}^{N_{cat}} v_n}.$$

169

170 The CICE model and forcing are applied using a 1° model configuration,
 171 as described in Hunke (2010) and Hunke et al. (2013a), but using an updated
 172 model version (CICE version 5.0.4). The thermodynamic slab-ocean mixed-
 173 layer model in CICE computes SST based on the surface energy balance of
 174 fluxes through the sea-ice and open-water interfaces. Modified NCEP forcing
 175 (CORE-II, Griffies et al., 2009; Large and Yeager, 2009) is applied for the
 176 wind, air temperature and humidity, for 1958–2009 as in Hunke et al. (2013a).
 177 Precipitation (Griffies et al., 2009), cloud fraction (Hunke and Holland, 2007)
 178 are provided as monthly mean climatologies. Ocean forcing fields (sea sur-
 179 face currents, slope, salinity, and deep ocean heat flux) are 20-year-mean
 180 climatologies from a Community Climate System Model (CCSM) climate

run (b30.009, Collins et al., 2006). In addition to SST, the turbulent heat
fluxes, wind stress, downwelling longwave radiation and shortwave radiation
are computed as described in Hunke and Holland (2007) and Hunke (2014).
Except for downwelling shortwave radiation, these fields also depend on the
state of the ice. Although air temperature is provided as an input data
set, it is adjusted in the presence of sea ice to reduce warm-temperature-
preconditioning for ice melt: if there is at least 10% sea ice cover in a grid
cell, then the air temperature is not allowed to be greater than 0.5°C (Hunke
and Holland, 2007).

The model is run for 52 years (1958–2009) for the control and all resolu-
tion tests. Sensitivities to parameterization changes are tested by branching
from the control simulation on 1 Jan 1990 and running for 20 years (Table 2).
Results for December 2009 are analyzed, along with some multidecadal aver-
ages. In December, the ice concentration is nearly 100% in the Arctic Ocean
and the ice extent is similar to that in other runs, due to the climatological
ocean forcing (Hunke and Bitz, 2009), simplifying comparison of the total
ice volume, mean thickness and age across runs. Moreover, a thickness snap-
shot represents the time-integral effect of all processes determining the ice
thickness distribution up to that time.

3. Data Description

Simulated sea ice thickness and age are compared with *in situ* and derived
observational data from satellite, submarine, mooring and airborne sources.

As described by Kwok et al. (2009), ice thickness estimates from the Ice,
Cloud, and land Elevation Satellite (ICESat) are estimated by comparing

205 returns from the ice or snow surface with that from a sea surface reference
206 within the satellite footprint. The sea surface elevation reference is deter-
207 mined using new openings in the ice where possible, otherwise using returns
208 where reflectivities are less than the snow-covered ice background reflectivity
209 and/or where elevations are lower. In addition, the sea surface elevation is
210 adjusted for biases associated with snow on thin ice and heterogeneous ice
211 coverage within the satellite footprint. Comparison of the sea surface with
212 ice/snow returns results in a freeboard estimate which is then converted to
213 ice thickness, assuming constant sea water and ice densities and a seasonally
214 varying snow density (Kwok and Cunningham, 2008). Snow thickness is es-
215 timated using precipitation rates falling onto an advecting ice cover whose
216 motion is estimated from satellite passive microwave observations (see Kwok
217 et al., 2009, for further information). Propagation of uncertainties in the
218 variables used to compute thickness yield a total uncertainty (1 standard de-
219 viation) of 0.7 m in the ICESat thickness estimates (Kwok and Cunningham,
220 2008), and differences in sea ice draft with mooring and submarine profiles
221 agree within about 0.5 m (Kwok et al., 2009).

222 Other observational data sources for 1990–2009 (submarine upward-looking
223 sonar, moorings, IceBridge flights and coastal measurements) were obtained
224 from the Unified Sea Ice Thickness Climate Data Record (Lindsay, 2013).
225 This data set consists of thickness measurements from numerous sensors and
226 sources, each with its own sampling issues and accuracy estimates (or lack
227 thereof). The data are collected in a common format with added summaries
228 calculated for time (1 month) and length (50 km) scales comparable to typical
229 model output. Submarine and moored upward-looking-sonar measurement

230 errors are typically of order 25 cm (Lindsay, 2010). Thickness uncertainties
231 in the IceBridge airborne data range up to 0.51 m.

232 Sea ice age can be deduced from satellite observations using various
233 approaches. Here I use ice age data provided by the Sea Ice Prediction
234 Network (<http://nsidc.org/data/sipn/data-sets.html>; Maslanik et al., 2007,
235 2011; Tschudi et al., 2010). Using satellite and buoy data for ice motion,
236 individual sea ice parcels are tracked from the time they form until they
237 disappear (via melt or transport out of the Arctic) at a spatial resolution
238 of 12.5 km and a time step of 1 week. The age of a parcel is the age of
239 the oldest ice within that parcel, thus biasing the data toward older ages
240 during periods when large amounts of younger ice are present. If a parcel
241 survives the summer melt season with an ice concentration of at least 15%,
242 then the parcel ages by 1 year (Maslanik et al., 2007, 2011; Tschudi et al.,
243 2010). This derivation of ice age from satellite observations differs funda-
244 mentally from the modeled ice age, in that the model ages the ice volume
245 within each thickness category chronologically on each time step and then
246 combines the resulting “age content” into a single value per grid cell. Thus,
247 modeled ice age is expected to be younger than the observational data, based
248 on definition differences alone.

249 **4. Results: Physical Parameterizations**

250 Dynamical processes have a much larger effect on spatial patterns than
251 do thermodynamic processes, which generally are smooth except near the ice
252 edge. For instance, Fig. 4 shows that during December 2009, thermodynamic
253 growth in the model increased the ice volume uniformly throughout the ice

254 pack, with larger growth rates in coastal areas and substantial melting only
255 along the ice edge in the North Atlantic. Dynamical volume rates of change
256 during the same month take both positive and negative signs (Fig. 4c). This
257 variation is loosely reflected in the rates of change of sea ice age (Fig. 4b, d).

258 Generally speaking, this configuration of the CICE model produces ice
259 that is too thin in the central and eastern Arctic Ocean and too thick near the
260 northern Canadian and Greenland coasts, as evident in Fig. 5 and Table 3.
261 Sea ice is thickest on the western side of the Arctic, north of Greenland and
262 the Canadian Archipelago, due to convergence and ridging as the Transpolar
263 Drift Stream transports ice from the eastern side and across the North Pole.
264 Some of this ice exits the Arctic Basin through Fram Strait, carrying thick ice
265 from Greenland’s north coast into the Greenland Sea. Likewise, the Beaufort
266 Gyre north of Alaska carries thicker ice into the Beaufort Sea. Fig. 5 shows
267 ICESat ice thickness estimates (Kwok et al., 2007; Kwok and Cunningham,
268 2008; Kwok et al., 2009) for October/November campaigns compared with
269 November control run output for 2005, 2006 and 2007. Prior to the dras-
270 tic sea ice retreat event during the summer of 2007, model thicknesses were
271 comparable but slightly too thin on the eastern (Siberian) side of the Arctic
272 Ocean. Propagation of uncertainties in the variables used to compute thick-
273 ness yield a total uncertainty (1 standard deviation) of 0.7 m in the ICESat
274 thickness estimates (Kwok and Cunningham, 2008); the model output is close
275 to the lower end of this range. Comparison with other observational data
276 sources for 1990–2009 (upward-looking sonar from submarine cruises, moor-
277 ings, IceBridge flights and Canadian coastal measurements, Lindsay, 2013)
278 shown in Table 3 (see Fig. 6 for locations), confirms that the simulated ice is

279 too thick on the western side of the Arctic in the control run and too thin in
 280 the central Arctic (submarines, NPEO). Notably, these biases are opposite
 281 those reported for the PIOMAS sea ice-ocean model (Schweiger et al., 2011);
 282 PIOMAS uses NCEP-based atmospheric forcing and the Parallel Ocean Pro-
 283 gram (POP) as its ocean component, the same ocean model used to generate
 284 the ocean forcing used here (albeit in a very different configuration).

285 Figs. 7 and 8 show December 2009 simulated sea ice thickness and age
 286 for the control (CNTL) and 5 sensitivity runs, as listed in Table 2. Sea ice
 287 extending from north of Greenland to the North Pole is older in the control
 288 run than indicated by observations (Fig. 1). As we will see in the sensitivity
 289 results, thicker ice tends to be older but the relationship is not strictly pro-
 290 portional. Fig. 9a provides the budget of thermodynamic melting and growth
 291 terms that contribute to ice volume changes for each parameterization option
 292 tested, along with the differences for each term relative to the control run
 293 (Fig. 9b). Congelation growth (onto the bottom of existing sea ice) and bot-
 294 tom melting dominate the thermodynamic processes, roughly balancing each
 295 other; thus small changes in any of the terms relative to the two dominant
 296 terms can determine whether the ice pack grows or shrinks (see also Kwok
 297 and Untersteiner, 2011). Because these terms affect ice age in different ways,
 298 how they vary across runs also alters the age characteristics of the simulated
 299 ice.

300 The ridging parameterization bears on a sensitivity run that tests the
 301 effect of the mean cumulative thickness distribution of ice participating in
 302 ridging, a^* (“astar”, Fig. 7b). Within the participation function, illustrated
 303 in Fig. 10 for a uniform thickness distribution, a weighting function b assigns

relative weights to the ice thickness categories, so that thinner categories tend to contribute more of their area to ridge formation:

$$b(h) = \frac{\exp[-G(h)/a^*]}{a^*[1 - \exp(-1/a^*)]} \quad (2)$$

where the cumulative ice thickness distribution $G(h)$ is the fractional area covered by ice thinner than h , $G(h) = \int_0^h g(h)dh$, and $g(h)dh$ is the fractional area of ice with thickness in the interval $(h, h+dh)$. During convergence, open water closes first. Integrating $a_P(h) = b(h)g(h)$ between category boundaries, Eq. (2) implies that the mean value of G for ice participating in ridging is a^* , and the area ratio of ice participating from each category n (or open water closing, $n = 0$) to the total area of ice ridging and open water closing is

$$a_{Pn} = \frac{\exp(-G_{n-1}/a^*) - \exp(-G_n/a^*)}{1 - \exp(-1/a^*)}, \quad (3)$$

where G_n equals G evaluated at the upper boundary of category n . For $n = 0$ we take $G_{-1} = 1$. The control run uses $a^* = 0.05$, meaning that the thinnest 5% of the ice participates in ridging, on average.

In the sensitivity run, $a^* = 0.1$. This increase in the value of a^* shifts the ridging ice toward thicker categories; less of the very thin ice ridges. For instance with the 100-category participation function shown in Fig. 10, the same amount of 0.2 m ice will ridge in both cases, but 0.1 m ice makes up only 7% of the ridge with $a^* = 0.1$, compared with 10% using $a^* = 0.05$. Thus there will be a smaller volume of ice formed from 0.1 m ice with $a^* = 0.1$, and similarly, a larger ridged ice volume formed from ice thicker than 0.2 m. When thicker ice ridges, it tends to form lower ridges that cover a larger area (Hunke, 2010). Greater ice coverage means that less open water is available with $a^* = 0.1$, initially allowing less new ice to freeze and subsequently be

326 deformed into ridges. Over time, this reduces the total volume of ice, as
 327 evident in Figs. 7b and 11a; the thinner ice pack experiences a stronger melt
 328 rate during the summer. Fig. 9b shows a small decrease in the volume of
 329 frazil ice (new ice formed in open water), relative to the control run, which
 330 is large enough to account for the overall thinner ice pack. The other terms,
 331 increased congelation growth, decreased top melting and increased bottom
 332 and lateral melting, are consistent with a thinner ice pack and generally
 333 cancel each other out. The sea ice simulated with $a^* = 0.1$ is thinner and
 334 younger (Fig. 11c) than in any of our other physical parameterization tests.

335 Activating the form drag parameterization results in thinner ice than in
 336 the control run (see Figs. 7c and 11a) and a pattern of ice age that is much
 337 closer to the observations (Fig. 1). In particular, the age pattern north of
 338 Greenland reflects the older ice near the coast, with younger ice farther north
 339 and an area of 3- to 4-year-old ice near the North Pole. Moreover, the band
 340 of older ice reaching westward in the Canadian Basin north of Alaska is more
 341 than 5 years old, as in the observations, and yet it is thinner than in CNTL.
 342 These differences result from changes to the stresses acting on the top and
 343 bottom surfaces of the ice, particularly sails and keels. Ridged ice is largely
 344 responsible for variations in the atmospheric and oceanic drag coefficients,
 345 although floe and melt pond edges also contribute in summer, and skin drag
 346 contributes throughout the year (Tsamados et al., 2014). Deformed (ridged)
 347 ice in the model is most concentrated in the thick ice areas north of Green-
 348 land (Hunke, 2010), increasing drag and accentuating the advection of ice
 349 into the Beaufort and Greenland Seas. Tsamados et al. (2014) attribute the
 350 overall decrease in sea ice volume to relative changes in the thermodynamic

351 cycle of ice growth and melt, with increased melt rates dominating increased
 352 growth. However, Figs. 11a and 9b indicate the opposite in our runs, that
 353 a reduction in congelation and frazil growth rates and increased top melt-
 354 ing in the form drag case accumulates a larger volume decrease than the
 355 increase due to changes in bottom and lateral melting and snow-ice forma-
 356 tion. (Snow-ice formation results from the conversion of snow into ice when
 357 snow loading pushes the ice freeboard below sea level, resulting in flooding of
 358 the ice.) Tsamados et al. (2014) also show that the form drag parameteriza-
 359 tion increases ice speed in most areas north of Greenland and the Canadian
 360 Arctic, while decreasing drift in regions of thinner ice.

361 The anisotropic rheology (Fig. 8a) substantially increases ice thickness
 362 on the western side of the basin, leading to an older ice pack in that area.
 363 Changes to the rheology and form drag change the mean age of the entire ice
 364 pack noticeably only in summer (Fig. 11c), indicating that thinner, younger
 365 ice in other seasons dominates pack ice age in this average measure. As
 366 Tsamados et al. (2013) discuss, the modeled anisotropy increases the shear
 367 strength of the ice, reducing the ice drift. (They found that the total ice
 368 volume in their anisotropic test could be decreased to match that in their
 369 EVP case, while largely retaining the patterns of ice thickness and area seen
 370 in the anisotropic case, by adjusting the sea ice strength frictional energy
 371 dissipation parameter C_f .) In this case, Fig. 9b indicates that freezing re-
 372 ductions and increased top melt are not large enough to offset the increased
 373 ice volume due to decreased bottom melting and growth of snow-ice. Note
 374 that even though the difference in snow-ice formation is relatively small, it
 375 is enough to account for the net difference in ice volume between the CNTL

376 and aniso runs.

377 Using both the form drag parameterization and the anisotropic rheology
378 leads to a solution with characteristics of both (Fig. 9b, 11a). The anisotropic
379 rheology tends toward thicker ice via reduction of bottom melting, while the
380 form drag parameterization produces thinner ice, especially during winter,
381 thus decreasing the amplitude of the ice thickness seasonal cycle throughout
382 the year, compared with the control run.

383 Thickening and aging of ice in runs with the anisotropic rheology are
384 strongly associated with the decrease in sea ice transport, as seen in the
385 “halfU” case shown in Fig. 8b. Here, the sea ice velocity is computed using
386 the standard EVP dynamics, but the resulting velocity components are di-
387 vided in half for advecting the ice. Deformation rates used to compute the
388 sea ice ridging rates are not changed, directly, although there are feedback ef-
389 fects that indirectly affect the ice volume as the ice slows down. For instance,
390 reduced transport of ice out of the basin through Fram Strait increases the
391 total amount of ice remaining in the Arctic Basin, leading to smaller areas of
392 open water. With less ice melting in summer (due to smaller heat absorption
393 by the ocean), the ice does not thin as much as in the control run. When
394 this thicker ice deforms, the ridges tend to cover a greater area horizontally,
395 further decreasing the amount of open water available for heat uptake. With
396 less open water available to close and a greater volume of ice overall, the ice
397 continues to slow down. Mean growth rates also decrease, but not enough to
398 compensate for the reduced melt rates (Fig. 9b).

399 Finally, the “4lyr” sensitivity simulation illustrates the effect of the ther-
400 modynamic parameterization via its vertical resolution. The standard con-

401 figuration of CICE version 5 includes a new thermodynamic model that prog-
 402 noses sea ice salinity based on mushy layer theory (Hunke et al., 2011; Turner
 403 et al., 2013), with 7 layers in the ice. In prior versions of CICE, we used the
 404 thermodynamic model of Bitz and Lipscomb (1999), which solved for temper-
 405 ature using an assumed salinity profile and 4 layers. Decreasing the number
 406 of layers in the mushy formulation to 4 causes the ice to become thicker and
 407 older, as seen in Figs. 8c and 11b, d. (Because of the differing number of
 408 layers, this run could not be branched from the control run in 1990 and there-
 409 fore was run for 1958–2009.) The additional layers in the control run better
 410 resolve the steep vertical temperature and salinity gradients near the top and
 411 bottom ice surfaces, allowing greater conductive fluxes and potentially more
 412 ice growth and melt. With fewer layers, Fig. 9d shows that top melting de-
 413 creases dramatically relative to CNTL, offset somewhat by increased bottom
 414 and lateral melting, while decreased congelation and frazil growth ensues in
 415 winter. In one-dimensional tests, Turner et al. (2013) showed that simula-
 416 tions using 4, 10 and 100 layers can reproduce the character of measured
 417 vertical salinity profiles, but the drainage region near the ice-ocean interface
 418 is too thick when resolution is low. Because tracers such as heat, salt and
 419 biological content must be carried for each additional layer, we have chosen
 420 to use 7 layers in CICE version 5 as a compromise between vertical resolution
 421 and computational efficiency.

422 **5. Results: Thickness Category Resolution**

423 In their seminal work introducing an ice thickness distribution into a cou-
 424 pled climate model, Bitz et al. (2001) performed a number of simulations to

425 study its effect, including how the number of categories affects the sea ice
426 simulation and fluxes crucial for coupling the ice and ocean models. They
427 found that 5 categories were sufficient for climate modeling purposes at that
428 time; that is, the ice area, extent and fluxes were converged, including radia-
429 tive fluxes that hinge critically on sea ice albedo. They noted that the sea
430 ice volume was not converged with just 5 categories, but that this did not
431 affect their coupled climate simulations significantly.

432 In subsequent tests, Holland et al. (2006) explored how a modeled sea
433 ice thickness distribution affects polar climate in the context of the climate
434 model CCSM3, comparing runs with different spatial resolutions (T42, T85)
435 and different numbers of thickness categories (1, 5) in present-day and dou-
436 bled CO₂ scenarios. They did not consider other ITD discretizations better
437 resolved than the 5-category case, however. The PIOMAS model and its pre-
438 decessors (e.g., Zhang and Rothrock, 2003; Lindsay et al., 2009; Schweiger
439 et al., 2011) uses 12 categories in an Eulerian framework with a fixed ice
440 thickness assigned to each thickness category. The Eulerian approach will
441 tend to be more diffusive than the Lagrangian ice thickness distribution ap-
442 proach used here, in which the ice thickness may vary within the bounds of
443 each category (Bitz et al., 2001; Lipscomb, 2001).

444 Non-convergence of the ITD resolution using 5 categories is apparent in
445 Fig. 11b and d, comparing the control run with STD 10, which uses 10
446 thickness categories (see Fig. 3). The spatial patterns shown in Fig. 12a
447 reflect thicker and older ice in the 10-category case. Because Eq. (1) does
448 not produce similarly bounded categories, to explore the thickness resolution
449 issue I utilize a second option for setting the category boundaries based on

450 the World Meteorological Organizations sea ice classification scheme. In
 451 the 5-category WMO case (WMO 5), 4 of the categories are less than 2 m
 452 thick, with the fifth category containing all ice thicker than 2 m; the thinnest
 453 category contains ice up to 0.3 m thick (Fig. 3). The 6-category case (WMO
 454 6) divides the thinnest category in half. A third case (WMO 5+), created for
 455 this study, is identical to the 5-category WMO case but adds a sixth category
 456 with ice up to 4.57 m thick, the largest category boundary in CNTL. None
 457 of the resolution runs could be branched from the control run; they were
 458 all initialized from a state of no ice in 1958 and run through 2009, like the
 459 control.

460 Because ice growth and melt rates and the participation function (Fig. 10)
 461 all exhibit the greatest variation for thinner ice (Thorndike et al., 1975), it
 462 stands to reason that increasing the resolution in this portion of the thickness
 463 distribution should matter. However, there is little difference between the
 464 WMO 5 and WMO 6 cases (they overlie each other in Fig. 11b, and their
 465 spatial patterns are so similar that WMO 6 is not shown in Fig. 12). Fig. 9d
 466 shows that in both cases, an increase in congelation growth and decrease in
 467 lateral melting is offset by increased melting at the bottom and top of the
 468 ice. In the higher-resolution WMO 6 case the increased congelation growth
 469 and decreased top melting are amplified, reflecting enhanced conduction in
 470 the thinnest ice category, which also leads to younger ice (Fig. 11d). Adding
 471 the category with ice between 2 and 4.57 m in WMO 5+ thickens the ice
 472 considerably, such that the total ice volume (Fig. 11b) and the pattern of ice
 473 thickness (Fig. 12c) are very similar to the control run. Thermodynamically,
 474 the change occurs primarily in top and lateral melting, which are decreased

475 and increased, respectively, relative to WMO 5. With more congelation
476 growth and more bottom melting than in the control run, however, WMO
477 5+ features generally younger ice than in the control, but older than in WMO
478 5 (Fig. 11d).

479 To further illustrate the importance of resolving thicker ice, Fig. 13a shows
480 the differences in thickness for ice in categories 1 and 2 of the 10-category
481 ITD minus that in category 1 of the 5-category case, and similarly for all ice
482 in the remaining, thicker categories in Fig. 13b. Although the 10-category
483 ITD resolves the thinner ice much better than does the 5-category (CNTL)
484 ITD, the difference in the thinner ice thickness is relatively small. Most of
485 the change in thickness noted between these simulations in Figs. 7, 11 and
486 12 occurs in the thicker categories.

487 This observation is borne out in the WMO tests, where the difference
488 between WMO 5+ and WMO 5 appears in the thicker categories (Fig. 13d).
489 The thinner categories have minimal differences (not shown). WMO 5+
490 shows notable differences with CNTL in the thinner categories (Fig. 13c),
491 but the thicker categories are very similar (not shown) and as a result, the
492 basin-wide ice volume in these simulations are quite similar. The volume of
493 ice in the thicker categories determines the total ice volume, and therefore
494 the discretization of the thicker ice range is crucial for proper modeling of
495 ice volume.

496 Thermodynamically, better resolution of thin ice increases heat conduc-
497 tion from the ocean to the atmosphere, which leads to increased congelation
498 growth at the bottom of the ice column and increased melting at the top of
499 the column, as illustrated in Fig. 9d. Lateral and bottom melting are both

500 fueled largely by heat accumulated in open water, but they do not vary to-
 501 gether in the model. In fact, they often show changes opposite in sign. The
 502 fraction of modeled ice that melts laterally is proportional to $\Delta T^{1.36}$ based on
 503 geometrical arguments (Maykut and Perovich, 1987; Steele, 1992), where ΔT
 504 is the difference in ocean and ice bottom temperatures. Bottom melting (and
 505 freezing), on the other hand, depends on the difference in heat flux to the
 506 bottom of the ice (proportional to ΔT) and heat conduction within the ice,
 507 away from the interface. Differences in ice area and thickness among runs will
 508 therefore affect lateral and bottom melting in different ways. Fig. 9d shows
 509 that improving resolution of thicker ice tends to decrease bottom melting and
 510 increase lateral melting, while improving thin ice resolution decreases both
 511 top melting and frazil ice growth while increasing bottom melt and congelation
 512 growth. As Kwok and Untersteiner (2011) note, the residual balance of
 513 these processes determines whether the ice pack grows or shrinks, and we do
 514 not have sufficient data at this time to understand what the proper balance
 515 should be. However, since these processes also change the simulated ice age,
 516 age data can help constrain the model parameters.

517 **6. Discussion and Conclusions**

518 The CICE model was designed for use in large-scale climate simulations,
 519 which primarily require accurate representation of the surface fluxes' annual
 520 cycle. For this purpose, Bitz et al. (2001) found that 5 thickness categories
 521 were sufficient: ice area and critical ice-ocean fluxes were converged in their
 522 model. Sea ice volume was not converged, but they reasoned that this had
 523 only a modest effect on their coupled climate simulations. Since then, two

major, relevant advances have occurred in this field of research: larger and more reliable ice thickness data sets have become available, and questions are being asked of climate models that require better simulations of ice thickness. For example, Holland et al. (2008) showed that future projections of seasonally ice-free conditions in the Arctic are sensitive to the initial mean and spatial distributions of ice thickness simulated by climate models, some of which do not resolve an ice thickness distribution at all. A major result of the present paper is the recognition that 5 ice thickness categories are not enough to accurately represent observed thickness data nor to properly model mechanical sea ice processes that control ice volume.

Prior to the drastic sea ice retreat event during the summer of 2007, the model simulations presented here resemble ICESat thickness data, but with a thin bias on the eastern side of the Arctic Ocean and a thick bias on the western side. The thick bias worsens after the 2007 minimum ice event. While resolution of thinner ice does affect its simulation, as shown in Fig. 13, the volume of ice in thicker categories determines the total ice volume, and therefore resolution of the thicker ice range is crucial for accurate representation of ice volume. Total ice volume in the WMO 5 and WMO 6 simulations, having identical ITDs except for ice thinner than 0.3 m, are practically indistinguishable. Results from the WMO 5+ test are more similar to CNTL because of the extra resolution of 2–4.5 m ice. In STD 10, resolution increases for both thin and thick ice, and ice volume shifts toward thicker ice in the central and eastern Arctic associated largely with a decrease in top melting (Fig. 9).

Even though the total volume and thickness patterns of WMO5+ and

549 CNTL are quite similar, the age of the ice pack at the end of those simulations
550 are notably different. Thus, ice age provides a practical data set that can be
551 used to distinguish among parameterizations and, eventually, to tune model
552 parameters. A prime example is the formdrag parameterization test, in which
553 reduced or increased drag in different regions of the Arctic produce thinner
554 ice overall, some being older and some younger than in CNTL. In this case,
555 the inclusion of variable drag coefficients that depend on modeled roughness
556 elements such as deformed ice and melt pond edges leads to a more realistic
557 simulation of sea ice age.

558 Age is a volume-based tracer in CICE, which means that it is conserved
559 under volume-conserving processes such as ridging. Alternatively, age could
560 be tracked based on ice area, which would make comparisons with satellite
561 observations more natural (Vancoppenolle et al., 2009b). Hunke and Bitz
562 (2009) argue that age can not be considered an ice surface property in a full-
563 physics sea ice model. They included a test in which bottom (congelation)
564 ice growth decreased ice age. This change makes the ice pack younger as a
565 whole, but it has not been adopted for other runs because the converse effect,
566 aging under melting conditions, can not be accounted for without tracking
567 the age of individual layers of the vertical ice column. Lietaer et al. (2011)
568 have proposed a new method for defining and tracking the vertical profile of
569 ice age.

570 Age does not scale proportionally with thickness, because ridging ice
571 thickens without commensurate aging and because thermodynamic sources
572 and sinks of ice, namely growth in open water areas and complete melting of
573 thinner ice, also cause ice age and volume values to diverge. Dynamic effects

574 alter spatial patterns in ice age and volume, often initiating or modifying lo-
575 cal or regional feedback mechanisms that enhance age and volume differences.
576 For instance, in the formdrag simulation, sea ice rounding the Beaufort Gyre
577 north of Alaska is both thinner and older than in the control run. This ice is
578 older because of its origin north of Canada and Greenland, but it is moving
579 faster because of increased drag, which tends to cause thinning via increased
580 opening and melt rates (the opposite of the halfU case).

581 A negative feedback associated with ridging contributes to differences
582 among several runs but is particularly evident in the astar simulation, in
583 which ridging of thicker ice creates wider, shorter ridges with less open water
584 available for new ice freezing (frazil), leading eventually to a thinner ice pack.
585 As the ice thins and the ice-ocean albedo feedback becomes active, melting
586 begins to predominate.

587 Thermodynamic processes are key to differences in both volume and age
588 among runs. In particular, we see in the parameterization tests that bottom
589 melting and congelation/frazil formation tend to act in concert to decrease
590 or increase ice volume, often counteracted by top melt. The net effect is due
591 to small differences in these large terms, which means that small terms like
592 snow-ice formation and lateral melting can play an important role. Thermo-
593 dynamic ice growth and melting act most vigorously in the thin ice range,
594 altering ice volumes by small amounts that can build over time. In con-
595 trast, inaccuracy due to insufficient resolution of the ice thickness distribu-
596 tion quickly affects the larger volumes of thicker ice categories by altering
597 the participation (and redistribution) of ice in those categories.

598 As the complexity of sea ice models escalates with the inclusion of ever

599 more detailed processes, the need for more and better sea ice measurements
600 from the field and laboratory compounds. Sea ice models contain many
601 more parameters than can be constrained with currently available data, con-
602 founding validation efforts and lending doubt to modeled process fidelity.
603 Increasing the number of degrees of freedom associated with higher resolu-
604 tion demands yet more data for model validation. Fortunately, the addition
605 of new data types combined with a detailed comparison of fundamental pro-
606 cesses can shed light on physical and model sensitivities to more complex
607 processes and their controlling parameters. Sea ice age is such a data set,
608 discriminating among the effects of parameterizations that are not easily
609 distinguished in terms of ice area or volume alone. As indicated by the sen-
610 sitivity tests presented here, selectively combining model parameterizations
611 and suitably tuning their parameters have the potential to improve simula-
612 tion fidelity of the fields for which we have reliable observational data while
613 we wait for more discriminating data sets.

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category	CNTL	STD 10	WMO 5	WMO 5+	WMO 6
1	0.00	0.00	0.00	0.00	0.00
2	0.64	0.32	0.30	0.30	0.15
3	1.39	0.66	0.70	0.70	0.30
4	2.47	1.03	1.20	1.20	0.70
5	4.57	1.47	2.00	2.00	1.20
6		2.01		4.57	2.00
7		2.73			
8		3.78			
9		5.36			
10		7.74			

Table 1: Lower boundary values for thickness categories (m).

label	N_{cat}	ITD	years	description
CNTL	5	standard	1958–2009	$a^* = 0.5$ form drag parameterization OFF elastic-viscous-plastic dynamics 7 vertical layers
<i>Physical Parameterizations</i>				
astar	5	standard	1990–2009	$a^* = 0.1$
formdrag	5	standard	1990–2009	form drag parameterization ON
aniso	5	standard	1990–2009	elastic-anisotropic-plastic (EAP) dynamics
aniso+formdrag	5	standard	1990–2009	EAP and form drag parameterizations ON
halfU	5	standard	1990–2009	$0.5\mathbf{U}_i$ applied for horizontal transport
<i>Vertical Resolution</i>				
4lyr	5	standard	1958–2009	4 vertical layers
<i>Thickness Category Resolution</i>				
STD 10	10	standard	1958–2009	as CNTL but with 10 categories
WMO 5	5	WMO	1958–2009	World Meteorological Organization categories
WMO 5+	6	WMO	1958–2009	same as WMO5 plus one thick category
WMO 6	6	WMO	1958–2009	same as WMO5 plus one thin category

Table 2: Control and sensitivity simulations. N_{cat} is the number of ice thickness distribution (ITD) categories. The standard ITD is given by Eq. 1; see Table 1 and Fig. 3 for category boundary values.

Data Source	Data	CNTL	astar	formdrag	STD 10	WMO 5	WMO 5+
Submarines ^a	2.52874	2.31325	1.97063	2.15990	2.52277	1.95785	2.26214
Airborne ^{†b}	3.13818	3.58993	3.07307	3.09780	3.96628	2.95049	3.48772
Coastal ^{†c}	1.34916	5.39137	4.14398	3.73605	6.26804	3.91331	5.41778
Moorings	1.38138	1.72851	1.63750	1.57504	1.88735	1.34602	1.71345
BGEP ^d	1.53632	2.08128	1.70255	1.79518	2.25713	1.59307	1.97489
NPEO ^e	2.88623	1.78872	1.55387	1.61870	2.02563	1.69882	1.80673
IOS-EBS ^f	1.29336	1.66659	1.72068	1.51531	1.81412	1.28048	1.70565
IOS-CHK ^g	1.19654	1.92455	1.45411	1.54079	2.09728	1.31790	1.79942
AWI-GS ^h	1.02940	1.27805	1.39385	1.31636	1.37537	1.11209	1.26467
BIO-LS ⁱ	0.879722	2.55032	2.39715	2.81366	2.98289	1.18660	2.58016
Davis St ^j	0.762295	1.06866	1.13605	0.877247	1.16990	0.943930	1.06779
All data	1.98030	2.27632	1.98355	2.02528	2.50613	1.84068	2.24381

Table 3: Sea ice draft ([†]thickness) measurements (m) from observations (Lindsay, 2013) and selected model simulations for grid cells containing the observation locations (see Fig. 6), for 1990–2009. Bold font indicates model output is thinner than the observations. ^aNational Snow and Ice Data Center (1998, updated 2006). ^bKurtz et al. (2009) ^cCanadian Ice Thickness Program. ^dThe data were collected and made available by the Beaufort Gyre Exploration Project based at the Woods Hole Oceanographic Institution (<http://www.whoi.edu/beaufortgyre>). ^eNorth Pole Environmental Observatory. ^fMelling and Riedel (2008). ^gIOS Chukchi Sea. ^hWitte and Fahrback (2005). ⁱPrinsenbergh and Pettipas (2008); Pettipas and Prinsenbergh (2008). ^jR. E. Moritz, Davis Strait Freshwater Flux Array, NSF Grant OPP-02300381.

Figure 1: Satellite derived estimate of Arctic sea ice age (years) for week 52 of 2009, courtesy of C. Fowler, J. Maslanik, and M. Tschudi, Dept. of Aerospace Engr., University of Colorado, Boulder CO.

Figure 2: Derivative of sea ice age with respect to time (days per day), averaged for 1990–2009 over Arctic grid cells with ice concentration greater than 50%, from the control run (CNTL). Chronological aging is not included in the derivative.

Figure 3: Category boundaries for the ITD resolution study in section 5.

Figure 4: Derivatives with respect to time of sea ice volume (left, cm/day) and age (right, days per day), due to (top) thermodynamic and (bottom) dynamical processes, from the control run. Chronological aging is not included. The black contour represents 15% ice concentration, and the red line is the 15% concentration contour from passive microwave satellite data (Cavalieri et al., 1996, updated 2009).

Figure 5: (left) Sea ice thickness estimates (m) from ICESat for October/November 2005–2007, compared with (right) model output from the control run for each year. ICESat periods covered Oct 21–Nov 24, 2005, Oct 25–Nov 27, 2006, and Oct 2–Nov 5, 2007. The black contour represents 15% model ice⁴² concentration, and the red line is the 15% concentration contour from passive microwave satellite data (Cavalieri et al., 1996, updated 2009). Missing ICESat data are shown as zero values here.

Figure 6: Locations and types of data used for the comparison in Table 3 (Lindsay, 2013).
Data points coinciding with land grid cells in the model were not used.

Figure 7: Sea ice model thickness (left, m) and age (right, years) for the (a) CNTL, (b) astar and (c) formdrag simulations. The black (left) and white (right) lines are the 15% ice concentration contours from the model, and the red lines are the 15% concentration contours from passive microwave satellite data (Cavalieri et al., 1996, updated 2009). Black age contours encompass ice older than 10 years.

Figure 8: As in Fig. 7 for the (a) anisotropic, (b) halfU and (c) 4-layer sensitivity tests.

Figure 9: Mean annual volume of ice gained or lost through thermodynamic processes associated with (a) parameterization options for 1990–2009 and (c) resolution tests for 1958–2009. The incremental differences from the control run volume for each process are shown in (b) and (d); e.g., positive melt terms indicate increased ice volume due to decreased melting, relative to CNTL. Horizontal black lines represent the net change in volume from the control run for all processes. Note the differing scales in (b) and (d).

Figure 10: Participation function for two values of the parameter a^* , which represents the mean cumulative area fraction of ice participating in the ridging process. These participation functions assume a uniform cumulative ice thickness distribution with 100 STD categories (lower boundary of thickest category is 12.67 m).

Figure 11: Mean annual cycle of sea ice (left) thickness and (right) age for the control run and (a, c) 5 physical parameterization tests and (b, d) 5 resolution tests for 1990–2009. Thickness output is plotted from daily model diagnostics, while age is plotted using monthly history files.

Figure 12: As in Fig. 7 for the (a) STD 10, (b) WMO 5 and (c) WMO 5+ ice thickness distribution discretizations.

Figure 13: Difference in mean thickness (m) for (left) thinner and (right) thicker categories for (a, b) STD minus CNTL, (c) WMO 5+ minus CNTL and (d) WMO 5+ minus WMO 5. “Thinner” means category 1 in CNTL (up to 0.64 m) and the sum of categories 1 and 2 in STD 10 (up to 0.66 m), WMO 5 and WMO 5+ (up to 0.70 m); the remaining ice is “thicker”. Black contours trace the 15% ice concentration in the control. Differences are taken only in grid cells where the ice area fraction in both simulations is greater than 15%. Note the difference in scales.