Impact of a New Sea Ice Thermodynamic Formulation in the CESM2 Sea Ice Component

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Key Points:
• The choice of sea ice thermodynamics impacts the sea ice mean state
• The choice of sea ice thermodynamics has a modest impact on the coupled system

Abstract: The sea ice component of the Community Earth System Model version 2 (CESM2) contains new “mushy-layer” physics that simulates prognostic salinity in the sea ice, with consequent modifications to sea ice thermodynamics and the treatment of melt ponds. The changes to the sea ice model and their influence on coupled model simulations are described here. Two simulations were performed to assess the changes in the vertical thermodynamics formulation with prognostic salinity compared to a constant salinity profile. Inclusion of the mushy layer thermodynamics of Turner et al. (2013, https://doi.org/10.1002/jgrc.20171) in a fully coupled Earth system model produces thicker and more extensive sea ice in the Arctic, with relatively unchanged sea ice in the Antarctic compared to simulations using a constant salinity profile. While this is consistent with the findings of uncoupled ice-ocean model studies, the role of the frazil and congelation growth is more important in fully coupled simulations. Melt pond drainage is also an important contribution to simulated ice thickness differences as also found in the uncoupled simulations of Turner and Hunke (2015; https://doi.org/10.1002/joc.4235). However, it is an interaction of the ponds and the snow fraction that impacts the surface albedo and hence the top melt. The changes in the thermodynamics and resulting ice state modify the ice-ocean-atmosphere fluxes with impacts on the atmosphere and ocean states, particularly temperature.

Plain Language Summary: We investigate the role of a new approach for sea ice thermodynamics in the Community Earth System Model, based on mushy-layer theory. The new approach produces thicker sea ice in the Arctic with subsequent impacts on the atmosphere and ocean.

1. Introduction

Sea ice in the real world is a combination of solid ice and salty brine trapped within the ice. The size of brine pockets and their consequent salinity and temperature can vary to maintain thermal equilibrium with the surrounding ice (Schwerdtfeger, 1963). The net salinity content of the sea ice can also change over time due to various processes such as gravity drainage and meltwater flushing (e.g., Weeks & Ackley, 1986). The resulting sea ice salinity affects the thermal properties of the ice, including its heat capacity and the heat required for melting. The ice salinity and consequent porosity also affect the flow of nutrients within sea ice with impacts on sea ice biogeochemistry (Elliott et al., 2017) and can modify the strength of the ice (Weeks & Ackley, 1986).

The influence of ice salinity on sea ice thermodynamics has been considered in modeling of the ice cover in climate simulations for quite some time (e.g., Bitz & Lipscomb, 1999; Maykut & Untersteiner, 1971; Semtner, 1976). However, traditionally this has used a prescribed and nonvarying salinity profile based on observations. Considerable previous work has assessed processes driving sea ice salinity variations, primarily in one-dimensional sea ice models. This includes work on how gravity drainage (e.g., Cox & Weeks, 1988; Griewank & Notz, 2013; Notz & Worster, 2009; Rees Jones & Worster, 2014; Turner et al., 2013), and meltwater flushing (e.g. Jeffery et al., 2011; Vancoppenolle et al., 2007) affect the sea ice salinity structure.

Several recent efforts have incorporated prognostic salinity into large-scale sea ice models. Vancoppenolle et al. (2009) simulated a variable, vertically averaged salinity within the Louvain-la-Neuve sea ice model (LIM3) and tested its use in global ice-ocean coupled simulations. While the total salinity can vary in this implementation, the vertical distribution is prescribed. More recently, Turner et al. (2013) introduced a “mushy-layer” thermodynamic scheme (hereafter MUSHY) for large-scale sea ice models. In this formulation, the vertical salinity profile in the sea ice is prognostic, and the sea ice is formed as a mass of solid ice.
and salty brine. Turner and Hunke (2015) comprehensively evaluated the change from Bitz and Lipscomb (1999), (hereafter BL99) thermodynamics, which has a prescribed vertical salinity profile, to MUSHY within the standalone Los Alamos Sea Ice Model CICE (Hunke et al., 2015) in global simulations with prescribed atmospheric and oceanic forcing, performing pairs of experiments in which the only difference was the physics change being tested. They tested nine aspects of the thermodynamics parameterization, namely, internal temperature updates; internal salinity updates; the liquidus relation; thermal conductivity; shortwave modification; thickness changes; frazil ice formation; melt pond flushing; and snow-ice formation. In these runs, the atmosphere and ocean were not able to change in response to changes in the sea ice, and their experiments produced thicker and more extensive sea ice in the Arctic with MUSHY, while in the Antarctic there was similar sea ice with MUSHY and BL99. The primary reason behind the Northern Hemisphere differences in their simulations was due to the modification of melt pond characteristics associated with the parameterization of melt pond drainage in the MUSHY configuration. Secondary factors were a shortwave modification near the melt point within the ice and differences in how ice grows (primarily basal) and melts between the formulations. In the Southern Hemisphere they found that snow-ice formation was more important but did not contribute to significant differences in the sea ice volume and area.

The Community Earth System Model version 2 (CESM2; Danabasoglu et al., 2020) is one of the first Coupled Model Intercomparison Project Phase 6 (CMIP6) models to move to this newer thermodynamic formulation. CESM2 contains version 5.1.2 of the Los Alamos Sea Ice Model (CICE; Hunke et al., 2015) and includes support for the Sea Ice Model Intercomparison Project (SIMIP) variable request (Notz et al., 2016). This version of CICE features a number of new physics options including the MUSHY thermodynamics of Turner et al. (2013) and the level-ice melt pond scheme of Hunke et al. (2013). The main change with the new MUSHY physics of Turner et al. (2013) is the inclusion of the variable, prognostic salinity profile. In the BL99 thermodynamic formulation used in CESM1, a fixed prescribed salinity profile based on observations was applied.

This manuscript examines the influence of the new sea ice thermodynamic formulation within the coupled context of CESM2. As discussed in section 2, this involves comparing fully coupled simulations with MUSHY to simulations which use BL99. An assessment of the sea ice mean state and mass budget differences between the simulations in both hemispheres is provided, and the influence on coupled simulation characteristics is discussed. Comparison of CESM2 sea ice mass budgets with other models contributed to CMIP6 are analyzed in Keen et al. (2020), and a number of characteristics of the sea ice as simulated in CESM2 runs are documented in DuVivier et al. (2020), Singh et al. (2020), and DeRepentigny et al. (2020, in press).

2. Model and Experiment Description

As described by Hunke et al. (2013), the CICE model used here is a dynamic-thermodynamic model which incorporates an ice thickness distribution. Sea ice dynamics is simulated using an elastic-viscous-plastic rheology (Hunke & Dukowicz, 2002) with a linear remapping advection scheme (Lipscomb & Hunke, 2004). The ice thickness distribution is resolved with five ice thickness categories and a single open water category.

A new aspect of the CICE model used here is the inclusion of prognostic sea ice salinity and associated changes in the ice thermodynamics. Turner and Hunke (2015) fully describe this MUSHY thermodynamic formulation, and here we highlight the primary details. The model simulates time-varying and vertically resolved prognostic salinity and its influence on thermodynamic properties of the sea ice. The migration of water and brine through the ice is handled through drainage and flushing processes, allowing the bulk salinity to change over time. This is in contrast to the BL99 scheme which has a prescribed salinity profile. In both formulations, the ice salinity impacts thermodynamic characteristics, and the internal ice energy is a function of the salt content.

With the prognostic salinity profile there are several associated differences including the freezing point calculation, the thermal conductivity in the sea ice, the growth of sea ice including frazil ice formation, snow-ice formation, gravity drainage and melt pond flushing (Turner et al., 2013). Also, for consistency with the Turner et al. (2013) thermodynamics, the salinity-dependent freezing point of Assur (1958) was used for
both the sea ice and ocean components at the sea ice-ocean interface. The melt pond formulation of Hunke et al. (2013) considers the fraction of level ice (as a tracer) versus deformed ice, which directly impacts the melt pond concentration and depth. In addition to the new physics, the vertical levels in CESM2 were increased from 4 to 8 in the sea ice and from 1 to 3 in the snow, in order to better resolve the temperature and salinity gradients in the sea ice.

The sea ice mass budget terms are also impacted by the MUSHY formulation in that sea ice forms a mass of solid ice and salty brine. This directly impacts the fluxes of water and heat between the sea ice and ocean. The salt flux is influenced by the mass of water exchange, but a salinity of 4 psu is still assumed here as in BL99 for simplicity of coupling with the ocean model. This is a limitation of the current configuration and means that we do not simulate the full impact of prognostic sea ice salinity on the coupled climate system. While not ideal, the reason for the choice of a constant coupling salinity is practical in that the ocean component of CESM2, the Parallel Ocean Program (POP) model, uses a virtual salt flux at the surface. The POP model is also responsible for computing the fluxes of freshwater and salt due to frazil ice formation. Hence, the reference salinity of 34.8 in the ocean and 4 psu in the sea ice for computing salt fluxes simplifies salt conservation. Snow ice formation occurs when the weight of the snow pushes the snow-ice interface below the waterline. In this process, the MUSHY scheme explicitly accounts for seawater flooding of the snowpack, thereby affecting the mass of snow-ice formed, whereas in BL99 the snow is just compressed into ice with no addition of seawater. Melt pond properties are also influenced by the MUSHY formulation as it allows melt ponds to drain based on the sea ice porosity, calculated with the prognostic salinity and through parameterized macroscopic holes. On the other hand, the BL99 scheme only allows drainage due to the salinity-based ice porosity.

To diagnose the influence of the new sea ice physics on CESM2, two complementary, preindustrial model experiments were performed: the first with the MUSHY thermodynamics of Turner et al. (2013) and the second with the BL99 thermodynamics of Bitz and Lipscomb (1999). In the fully coupled CESM2 experiments presented here, the only difference between the simulations is the value of the CICE parameter “ktherm,” which selects the vertical thermodynamics scheme. In other words, both experiments use eight vertical levels in the sea ice and one level in the snow, the level ice melt pond formulation, and a salinity-dependent freezing point at the base of the sea ice. These simulations were both branched from the CESM2 CMIP6 preindustrial control run (Danabasoglu et al., 2020) at year 880 and each ran for 50 years. The simulations shown here used only the single-layer snow formulation as compared to three layers in the standard CESM2 simulations, but the simulated climatology was not significantly different from the three-layer simulations (not shown). The reasons for the limited sensitivity to the number of snow layers are uncertain but could arise from the large internal variability in the system or the lack of sophistication in the snow model, which has a constant thermal conductivity and density. Additionally, in the CESM2 version of CICE5, we have added a shortwave adjustment for both thermodynamics schemes to overcome a coupled instability that can cause internal sea ice layers to melt completely in a single time step, generating very large fluxes of fresh water. By rerouting excess shortwave (when the internal temperature is very close to melting) from inside the sea ice to the top surface, this change allows the sea ice to melt more gradually. This shortwave adjustment is included in both our MUSHY and BL99 simulations.

3. Results

3.1. Sea Ice Mean State and Variability

The annual mean over 50 years shows that sea ice thickness is significantly larger in the MUSHY configuration as shown in Figure 1a. While the Southern Hemisphere thickness differences are significant in some locations (Figure 1b), they are generally small. These coupled results are consistent with Turner and Hunke (2015), and the processes/causes leading to the difference will be expanded upon in the next section. Similarly, the annual mean sea ice concentration (Figure 2) is significantly higher in the MUSHY run in the Arctic but smaller in the Antarctic. The snow depth in the Arctic is more complicated. Generally, in the central Arctic, the snow is deeper in the MUSHY run, but is thinner in some of the marginal seas area (Figure 3a). The annual northern hemispheric mean snow volume (Table 1) is quite similar in the two runs. The Southern Hemisphere snow cover is thinner in most of the pack in the MUSHY simulation (Figure 3b) due to more snow-ice formation.
Considering the annual cycle of ice conditions, we find that the Northern Hemisphere sea ice is significantly more extensive in the MUSHY simulation in all months with the largest changes in summer (Figure 4a). Although it is useful to put these results in the context of the observations, it is worth noting that the NSIDC climatology shown here (Fetterer et al., 2017) is for present day conditions, while these simulations are preindustrial. Therefore, a direct match between the model and observations should not be expected. More extensive sea ice is consistent with the thicker ice in the MUSHY experiments and the strong coupling...
between ice thickness and ice area during summer months. In the Southern Hemisphere (Figure 4b), the sea ice extent in the two simulations is statistically indistinguishable in all months.

Notably, the Northern Hemisphere differences originate almost immediately in the simulations, and the annual mean Arctic sea ice volumes (Figure 5a) and ice area (Figure 5c) are significantly larger in the MUSHY run throughout the entire 50-year experiments. In the Southern Hemisphere, the volume and area are visibly different (Figures 5b and 5d), but the differences are much smaller than in the Northern Hemisphere. The 50-year sea ice volume and snow volume mean differences (Table 1) are all significant to the 5% level in both hemispheres based on a t test. The 50-year variances (Table 1) are not significantly different in either hemisphere based on an F test. That is, the sea ice in the MUSHY simulation is thicker and more extensive overall in both hemispheres, but the variability is unchanged. In the MUSHY simulations, the annual hemispheric mean snow volume (Table 1) is much smaller in the Southern Hemisphere but slightly larger in the Northern Hemisphere. However, although these 50-year simulations are designed to account for interannual variability so as to assess differences between the experiments, they do not capture the full extent of decadal variability.

3.2. Mass Budgets

To address the question of why the MUSHY simulation has thicker ice, we examine the mass budgets in our two simulations using the SIMIP (Notz et al., 2016) variables. Figure 6 shows the overall sea ice mass budget components over the central Arctic region (standard NSIDC definition) along with differences (MUSHY minus BL99) of the mass budget terms. The differences are further quantified in Table 2. Sea ice mass budget differences can arise from both the different thermodynamic treatment in the simulations and feedbacks associated with changes in the thickness and concentration mean state due to both dynamics and thermodynamics. The sea ice mass budget is a balance of the growth, melt, and divergence of the sea ice, with divergence associated with the ice motion and considered as the “dynamic” contribution to the mass budgets. Ice melt has contributions from the ice surface, the ice base, and the lateral melting of floes. Ice growth has contributions from congelation growth at the base of the ice.
frazil ice formation associated with the supercooling of ocean water, and snow ice formation in which snow on the ice surface is flooded and freezes to sea ice. In the net (black) central Arctic seasonal mass budget (Figure 6a), the BL99 case (solid lines) has a slightly larger amplitude annual cycle as a result of more growth in winter and more melt in summer. The dynamic ice divergence term is not shown here as it is small for the central Arctic domain. The larger summer melt is the result of greater top and bottom melt in the BL99 scheme. The enhanced BL99 growth in winter is largely due to enhanced congelation growth (cyan). This is consistent with the thinner ice and snow in BL99, which allows for more conduction of heat from the ice-ocean interface. The MUSHY scheme has larger frazil ice growth (magenta) in winter, but it is not sufficiently large to lead to more total winter growth. The increased frazil formation is expected because of the way the MUSHY physics functions, forming ice as a combination of solid and liquid sea water. The liquid is trapped within the sea ice, and hence, the net thickness of sea ice

Figure 4. Climatological seasonal cycles of sea ice extent ($10^{12} \text{ m}^2$) for (a) NH and (b) SH as compared to the satellite observed NSIDC extent (Fetterer et al., 2017).

Figure 5. Annual mean sea ice volume (top) and area (bottom) time series for MUSHY (red) and BL99 (blue) NH (a and c) and SH (b and d).
and water together is thicker (Turner et al., 2013). The snow and ice mass budget annual totals for each of these components are shown in Table 2.

In the Antarctic (Figure 7), the net sea ice mass budget is similar for the two thermodynamic formulations, but the individual mass budget terms contributing to this are different in BL99 and MUSHY. MUSHY has significantly more frazil growth and snow-ice formation than BL99. This is largely compensated for by decreased congelation growth relative to BL99. There is little difference in top melt, but considerably stronger bottom melt in the MUSHY simulation. The bottom melt in the Southern Hemisphere is stronger in the MUSHY case because the sea ice is saltier than the BL99 sea ice (not shown) and hence begins to melt at a lower temperature, so it is easier to melt overall. The difference in mass budget terms, particularly the frazil ice, appears to play a role in the thinner and less extensive Antarctic sea ice in CESM2 compared to CESM1 (Singh et al., 2020).

There are regional differences in the sea ice mass budgets where frazil ice (Figure 8) is more important near the coast and snow-ice formation (Figure 9) is more important in the open pack. Figure 8 shows the frazil formation in both hemispheres. The NH frazil formation occurs largely in the marginal seas regions and near the coast (Figure 8a), and there is significantly more frazil formation in the MUSHY run as mentioned earlier. The SH frazil formation occurs almost entirely around the coast (Figure 8b). The NH snow-ice formation (Figure 9a) is generally limited to the marginal seas areas and not significant in the central Arctic as mentioned earlier. In the SH, the snow-ice formation is very important in the open pack regions, and there is significantly more frazil ice and snow-ice formation in the MUSHY run (Figure 9b). This snow-ice formation difference leads to less snow overall in the MUSHY as mentioned earlier.

3.3. Factors in the Top Melt Differences

Top melt was identified in the ice mass budgets earlier as a key component of the thicker Arctic sea ice in the MUSHY simulation. It appears that the decreased Arctic melt (less negative) in MUSHY is a direct consequence of the sea ice physics, whereas the decreased growth (less positive) is associated with the thicker and more insulating mean sea ice state. To assess why Arctic surface melt is different between the formulations, we examine the annual cycle of broadband albedo, snow fraction, and melt pond fraction in the Beaufort Sea region (Figure 10). For the seasonal cycle of albedo, it is better to focus on a smaller region, and the Beaufort Sea is partly representative of the whole Arctic. The broadband sea ice albedo (Figure 10a) is around 0.8 during the winter months when the snow is completely covered. In the spring as the snow melts, the surface albedo drops due to less snow cover and more melt ponds and bare ice.

| Table 2 | Total Annual Mass Budgets in Units of $10^9$ kg/s |
|---------|--------------------------------------------------|
|         | Total (+/−) | Congelation | Frazil | Top melt | Bot melt | Snow ice |
| BL99 NH | 4.12/4.05   | 4.58        | 0.26   | −1.27    | −2.72    | 0.02     |
| MUSHY NH| 3.74/3.65   | 4.08        | 0.69   | −1.14    | −2.58    | 0.05     |
| BL99 SH | 5.71/5.73   | 5.66        | 1.06   | −0.03    | −7.57    | 1.19     |
| MUSHY SH| 5.92/5.93   | 4.89        | 2.02   | −0.08    | −9.73    | 3.20     |
The snow fraction (Figure 10b) is higher in the MUSHY scheme, and when the minimum albedo occurs, snow fraction is about 0.3 in the MUSHY run versus about 0.1 in the BL99 simulation. The radiatively active pond coverage (i.e., the fraction of liquid water not hidden by snow, used in the shortwave radiation computation, Figure 10c) is smaller in the MUSHY simulation with a maximum of approximately 0.25 versus 0.3 in the BL99 run. The combination of reduced melt pond fraction and higher snow fraction leads to a higher broadband albedo in midsummer for MUSHY (Figure 10a). In the fall, the melt pond fraction is slightly greater in the MUSHY scheme, but the resulting lower albedo occurs when sunlight is disappearing rapidly and as a result is not as important for the surface energy balance. The broadband albedo is the sum of the fraction of different surface types multiplied by the albedo for each surface: snow, pond, or bare ice. If we assume the albedo for each surface ($a_{\text{surface\_type}}$) is approximately the same for each simulation (they use the same radiation model code and physical parameters), then the

![Figure 7](image)

*Figure 7.* SH (a) annual sea ice mass budget and (b) difference in kg/s. In (a) the MUSHY experiment is dashed, and the BL99 experiment is solid. The difference is MUSHY-BL99, and differences that are not significant at the 95% level are set to 0.

![Figure 8](image)

*Figure 8.* Total annual frazil ice formation (averaged over 50 years) in the NH (a) and SH (b) in units of $10^4$ kg/m$^2$ s. The difference is MUSHY-BL99, and differences are shown only where significant.
The difference in broadband albedo (Da) is approximately due to the fractional differences (Df_{surface\_type}) in each surface (see Equation 1).

\[ \Delta \alpha = \Delta f_{\text{snow}} \cdot \alpha_{\text{snow}} + \Delta f_{\text{pond}} \cdot \alpha_{\text{pond}} + \Delta f_{\text{ice}} \cdot \alpha_{\text{ice}} \]  

(1)

Assuming albedos of approximately 0.75, 0.6, and 0.3 for snow, bare ice, and melt ponds in midsummer, values identical in both runs, we can estimate the broadband albedo differences from Equation 1 using the difference in surface fractions between experiments (BL99 minus MUSHY). As shown in Figure 10d, despite its simplicity, this method provides a reasonable approximation to the actual albedo changes calculated in the experiments. Additionally, it allows us to calculate each surface type’s contribution (Figure 10d). BL99 has a lower broadband albedo than MUSHY, and the term associated with the snow fraction difference is the largest magnitude contribution to the broadband albedo difference. It is countered by the opposite sign bare ice albedo difference and pond albedo difference. Thus, on average the larger snow fractions in MUSHY lead to higher broadband albedo. The bare ice difference is largely due to smaller snow fraction in the BL99 run versus the MUSHY run, but the melt pond difference requires a bit more detail to understand.

As snow is an important aspect of the seasonal albedo evolution, the snow mass budget on the surface of the sea ice is shown in Figure 11. In addition to snow accumulation, melt, and snow ice formation terms, there is a dynamic loss term associated with transport and ridging of ice which deposits some snow into the ocean. Surprisingly, given the considerable difference in snow fractional coverage, the mass budget terms and the mean annual cycle of snow thickness (Figure 11c) are very similar between the simulations. Note that the snow fraction in the model depends on snow thickness and is always equal to one when snow thickness is above a threshold value of 3 cm. Thus, small differences in snow thickness around this threshold value can have a large influence on the fraction of snow-covered ice.

The primary source of melt ponds is snow melt, and melt ponds can be reduced by both the fraction of level ice and the drainage. The MUSHY scheme also allows for macroscopic drainage of melt ponds, which reduces the depth (volume) of the ponds at a rate of approximately 0.2% every time step in the model, or about 10% each day. This volume loss is offset by the surface melt providing water for the ponds. However, the snow melt and snow depth are nearly the same in each run (not shown), the level ice area is very similar, and hence the pond difference can be explained almost entirely by the drainage. Note also
Figure 10. Climatological seasonal cycle of (a) albedo, (b) snow fraction, (c) radiatively active melt pond fraction, and (d) difference in albedo and terms in Equation 1 in a Beaufort Sea region (70–85 N, −130 to −180 W), with plus and minus one standard deviation (dashed) for panels (a)–(c).

Figure 11. Central Arctic (a) annual snow mass budget and (b) difference in kg/s. In (a) the MUSHY experiment is dashed, and the BL99 experiment is solid. In panel b, the differences are MUSHY-BL99 for the entire central Arctic. Differences that are not significant at the 95% level are set to 0. Panel (c) shows the NH daily mean snow depth from the two simulations in m.
Figure 12. NH April-May-June mean (a) snow fraction and (b) radiatively active pond fraction. MUSHY is top left, and BL99 is top right. Differences, at bottom center, show MUSHY-BL99 and are only shown where significant at the 5% level.

Figure 13. NH annual mean surface air temperature (K) and difference. MUSHY is top left and BL99 is top right. Differences, at bottom center, are MUSHY-BL99 and are only shown where significant at the 5% level.
that the radiatively active pond fraction shown in Figure 10c will also be reduced from the overall pond fraction due to snow cover on the sea ice. Thus, pond coverage (Figure 12b) is a function of the snow cover, surface melt, pond drainage, and level ice fraction—as ponds are located only on level ice in the melt pond scheme used in both simulations. The MUSHY experiment has slightly less level ice in the central Arctic (not shown), which reduces pond area coverage somewhat. There is a suggestion in the Hunke et al. (2013) work that thinner ice leads to less ridging and hence more level ice area. So the thinner ice over all in the BL99 experiment would lead to more level ice. However, the difference in level ice area is quite small overall (less than 10% different). The macroscopic drainage and increased snow fraction are more important differences leading to less ponds in the MUSHY experiment as mentioned earlier. These factors lead to less pond coverage in the MUSHY experiment and hence a higher broadband albedo and less top melt of the sea ice in the central Arctic. Also, the level melt pond formulation (Hunke et al., 2013) allows for the pond water to infiltrate the snow cover and hence reduce the snow fraction. So there is an additional feedback here where the greater pond coverage in the BL99 experiment leads to less snow cover. Unfortunately, the pond depth was not saved in these simulations, and hence, the pond volume was not available. The pond depth is used to reduce the snow depth in the level melt pond scheme. When the snow depth reaches a critical threshold of 3 cm, the snow fraction is reduced linearly as mentioned earlier. However, before the critical snow depth is reached, it is also possible for the pond fraction to reduce the snow fraction when the snow fraction is close to one. It is worth noting that the level melt ponds (Hunke et al., 2013) have some limitations and potentially a more sophisticated melt pond formulation that takes into account the surface topography (e.g., Flocco et al., 2010) might lead to different results. The snow infiltration along with the slightly more rapid decline in snow thickness in the BL99 simulation (Figure 11c) leads to a smaller fraction and hence a lower albedo in BL99 compared to MUSHY. In the Southern Hemisphere, because snow remains longer on the sea ice hiding liquid water, melt ponds are not a dominant factor.

3.4. Coupled Impacts

To assess the potential coupled impacts of the change in the vertical thermodynamic schemes, the Arctic surface air temperature is shown in Figure 13. The thicker ice and deeper snow in MUSHY lead to colder conditions over the ice pack. The differences in surface air temperature (Figure 13) are significant over the central Arctic. The higher surface albedo in the MUSHY case changes the surface energy balance by reflecting more shortwave energy back to the atmosphere, which results in less surface melt, a cooler surface, and

Figure 14. NH July-August-September mean (a) sea surface temperature (°C) and (b) sea surface salinity (psu). MUSHY is top left, and BL99 is top right. Differences, at bottom center, show MUSHY-BL99 and are only shown where significant at the 5% level.
more snow cover. This change has a positive feedback on ice growth and air temperature in the coupled model, because the sea ice melts less in summer, dominating the slower growth of thicker ice in the fall. This feedback is not present in a forced ice-ocean experiment, as was shown by Turner and Hunke (2015).

Similarly, the sea surface temperature and salinity (Figure 14) show a colder and saltier central Arctic where the MUSHY has thicker ice due to enhanced ice growth. The colder temperatures are due to lower freezing point temperatures. The North Atlantic is colder and fresher due to increased sea ice export of thicker ice from the Arctic. Note that the salt fluxes are computed using a reference salinity in the ocean and sea ice as mentioned earlier, which may also impact the results here. However, the difference between the sea ice and ocean salinity is large enough that this impact would be relatively small. The differences in the ocean fields are somewhat muted as these were only 50-year simulations and there would likely have been a stronger response in longer, better ocean-equilibrated simulations.

4. Discussion and Conclusions

CESM2 (Danabasoglu et al., 2020) incorporates a new sea ice model component that includes prognostic salinity and treats sea ice as a two-phase mushy layer following Turner et al. (2013). We find that the MUSHY scheme produces thicker and more extensive ice overall in both hemispheres relative to the Bitz and Lipscomb (BL99) thermodynamics used in earlier CESM versions. While this agrees with the stand-alone sea ice results of Turner and Hunke (2015), the reasons for it differ somewhat, partly due to coupled interactions with the atmosphere and ocean. Turner and Hunke (2015) found that the difference in melt pond drainage was the leading factor for thicker ice in MUSHY, and changes in the shortwave formulation and the way thickness changes are computed (i.e., the uptake of sea water and ice in the MUSHY scheme) were also found to be important. In our fully coupled CESM2 simulations, both the MUSHY and BL99 thermodynamic schemes use the same shortwave formulation, so this radiative factor has been removed in our comparisons. While the Arctic melt pond coverage is different between the simulations, and contributes to the differences in top melt, the main factor here is the difference in snow fraction between the simulations. The MUSHY simulation has less surface melt and more frazil ice formation (by design), which is partly offset by reduced congelation growth. This balance of melt and growth leads to thicker ice in the MUSHY run. These differences are particularly important in the marginal sea ice regions, where the sea ice is both thinner and less extensive. Draining of melt ponds and reduced surface melt are key differences for the melt pond coverage and hence the surface albedo. Smaller differences in undeformed or level ice also play a role in the melt pond coverage. While the melt pond drainage is determined to be a key aspect as was found in Turner and Hunke (2015), it is the snow infiltration from ponds and accumulation of snow impacts on the snow fraction that lead to differences in the broadband albedo and hence the top melt.

Unfortunately, the pond volume was not available, but the pond fraction reduction of the snow fraction was shown to be important.

In the Southern Hemisphere, sea ice has much less top melt, and snow-ice formation plays a much larger role in these experiments. While individual mass budget terms differ in the MUSHY simulation relative to BL99, the net budget is similar, and the mean sea ice state differences are much smaller for the Antarctic than the Arctic. Despite the balance in terms being quite similar in the Antarctic sea ice, the regional differences in these terms show both positive and negative differences in the thickness and area. In particular, frazil ice formation is more important near the coast and snow-ice formation is more important in the open pack. Aspects of this are also discussed in Singh et al. (2020).

The change to the thermodynamics with the MUSHY physics does affect the sea ice thickness in CESM2. Despite the thicker sea ice in the MUSHY run, the impacts on the rest of the coupled system are relatively minor. There are small differences in the surface air temperature over the sea ice and the sea surface salinity and temperature. These differences in the atmosphere and ocean also feed back on the sea ice in the coupled system, not present in the simulations of Turner and Hunke (2015) as mentioned. However, in comparisons of CESM2 and CESM1, a number of other physics changes are present across the atmosphere and ocean components, and hence, the change to the MUSHY physics in CESM2 is not as large. These changes also have an important influence on the sea ice simulation and its feedbacks within the coupled system (DuVivier et al., 2020; Singh et al., 2020).
**Data Availability Statement**

Previous and current CESM versions are freely available online (at https://www.cesm.ucar.edu/models/cesm2/). The CESM data sets used in this study will be made available upon acceptance of the manuscript from the Earth System Grid Federation (ESGF) at https://esgf-node.llnl.gov/Fsearch/cmip6, or from the NCAR Digital Asset Services Hub (DASH) at https://data.ucar.edu, or from the links provided from the CESM website (at https://www.cesm.ucar.edu).

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