Investigating snow sinks on level sea ice in the Arctic

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June 03, 2024

Abstract

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Investigating snow sinks on level sea ice in the Arctic

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Key Points:

• We examined the changes in modeled snow-on-sea-ice depth and density caused by snow sinks on level Arctic sea ice.
• Accounting for snow sinks on level ice markedly reduces snow depth on Arctic sea ice regionally.
• Snow mass changes due to sub-parcel snow redistribution processes must be considered when examining snow sinks in snow-ice formation.

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Plain Language Summary
The amount of snow on sea ice is important for monitoring sea ice thickness, which
is one of the key factors in a changing climate. Recent advances in snow-on-sea-ice mod-
eling have made it possible to simulate snow depth and density over Arctic sea ice. How-
ever, these simulations often do not consider how much snow is lost from atop level ice
in processes such as snow-ice formation and snow’s tendency to leave level ice areas and
pile up over rough ice areas (sub-parcel snow mass redistribution process). Snow-ice forms
when snow becomes part of the sea ice, after seawater floods the sea ice surface and freezes
inside the snow. In this study, we combined a snow model with a sea ice model to un-
derstand how snow-on-sea-ice mass changes when snow-ice formation and sub-parcel snow
mass redistribution are accounted for. Our results show that snow depth decreases, and
snow density commonly increases. The differences are highest in the Atlantic sector of
the Arctic, where snow-ice is more likely to form due to high annual snowfall.

1 Introduction
Arctic sea ice is going through unprecedented changes, decreasing dramatically both
in extent (e.g. Stroeve et al., 2014) and in thickness (Kwok et al., 2009; Maslanik et al.,
2007), and transitioning from a multiyear ice to a seasonal, first-year ice system (Meier
et al., 2014). The role of snow cover over thinner, seasonal sea ice is amplified in many
ways. First, the thermal resistance of snow cover becomes a dominant control over the
atmosphere-ocean heat fluxes, regulating sea ice growth in winter. Second, the snow load
becomes more likely to submerge thinner ice underneath the water level, creating neg-
ative freeboard conditions. If sea water floods at the ice/snow interface and freezes there,
snow-ice is formed that is a mixture of frozen seawater and snow (e.g. Leppäranta, 1983).
Snow-ice is a common phenomenon in seas that are seasonally covered by ice (i.e., Baltic
Sea, Sea of Okhotsk) and in large parts of the Antarctic sea ice, but it was not commonly
observed in drifting Arctic sea ice until the Norwegian Young Sea ICE (N-ICE2015) ex-
pedition (Granskog et al., 2017; Provost et al., 2017). Snow-ice is a sink for snow, and
it can contribute significantly to the sea ice mass balance (Merkouriadi et al., 2017, 2020).
Therefore, it is essential to consider it for improving Arctic sea ice forecasts.
Satellite altimetry is the most common method for monitoring sea ice thickness,
providing nearly full coverage of the Arctic Ocean (Landy et al., 2022; Laxon et al., 2003;
Markus et al., 2017). Information on the snow load exerted on sea ice is crucial for al-
timetry retrievals of sea ice thickness, because radar and laser altimeters, in principle,
measure ice or snow freeboard; the elevation of the ice or snow surface from the water
surface. Snow depth and density are required to convert freeboard to sea ice thickness
information (e.g. Laxon et al., 2003). According to Giles et al. (2007), uncertainties in
snow depth and density contribute 48 % and 14 %, respectively, to the total error of sea
ice thickness retrievals from radar altimetry. A more recent study by Landy et al. (2020)
estimated these uncertainties at 11 % for snow depth and 16 % for density. Similarly, snow
depth and density uncertainties were found to contribute 70 % and 30–35 %, respectively,
to the total error of sea ice thickness retrievals from laser altimetry (Zygmuntowska et al., 2014).

Snow depth and density estimates used in satellite altimetry applications are often derived from snow climatologies or their modified versions. The most widely used snow-on-ice climatology is compiled from a snow depth and density data set collected decades ago mostly over multiyear ice (Warren et al., 1999). In a changing Arctic sea ice system, snow conditions are expected to change as well (Blanchard-Wrigglesworth et al., 2015; Webster et al., 2014), and these changes are not captured by the Warren et al. (1999) climatology. In addition to the long-term changes, climatology overlooks the spatio-temporal differences and interannual variability of snow conditions in the Arctic, which are evidently strong (Webster et al., 2019). Addressing the imperative need for better representation of snow on sea ice, efforts have focused on reanalysis-based snow depth and density reconstructions (e.g. Blanchard-Wrigglesworth et al., 2018; Kwok & Cunningham, 2008; Petty et al., 2018). A recent contribution was SnowModel-LG, a state-of-the-art Lagrangian snow evolution model (Liston, Itkin, et al., 2020). Compared to other reanalysis-based products, SnowModel-LG implemented higher resolution Lagrangian parcel tracking and included an improved representation of snow evolution physics. It has been bias-corrected and validated against a wide observation framework, and yielded good agreement, especially with in situ measurements (Stroeve et al., 2020).

SnowModel-LG explicitly resolves snow mass sources and sinks, such as blowing snow, static-surface sublimation, and melt, by performing a snow mass-budget calculation in each time step (Liston, Itkin, et al., 2020). However, SnowModel-LG, similarly to all the above-mentioned Arctic snow models, is not coupled to a sea ice model. Therefore, it does not consider snow sinks caused by snow-ice formation. Moreover, being configured over ice parcels of kilometer-scale, it does not resolve sub-parcel snow mass redistribution. The latter describes the tendency of snow to accumulate on the lee side of pressure ridges and other roughness elements (e.g. Liston et al., 2018) as a result of snow redistribution by the wind and ice topography. This process results in uneven snow load over a sea ice floe (i.e., reduced snow over level ice areas and increased snow over deformed ice). Because in this study we are examining level ice only, we will be referring to the sub-parcel snow mass redistribution process as a snow sink.

This study aims to examine snow sinks on level Arctic sea ice (snow-ice formation and sub-parcel snow mass redistribution), and their effect in snow-on-ice models, from 1 August 1980 through 31 July 2022. To investigate this, we coupled SnowModel-LG with the High-Resolution Thermodynamic Sea Ice model (HIGHTSI) (Launiainen & Cheng, 1998) to produce SMLG_HS. In SMLG_HS, snow-ice forms when the ice surface is depressed below the water surface (negative freeboard), with the assumption that all negative freeboard will result in flooding and, consequently, snow-ice formation. SMLG_HS does not account for dynamic thickening of the sea ice, therefore it considers level ice only. SMLG_HS outputs of snow depth, snow-ice and sea ice thickness were evaluated against observations to examine and to mitigate the biases introduced when sub-parcel snow mass redistribution processes are ignored.

2 Materials and Methods

2.1 SnowModel-LG

SnowModel is a collection of snow distribution and snow evolution modeling tools, applicable to any environment experiencing snow, including sea ice applications (Liston & Elder, 2006a; Liston et al., 2018). SnowModel-LG is adapted for snow depth and density reconstruction over sea ice (Liston, Itkin, et al., 2020). It is implemented in a Lagrangian framework to simulate snow properties on drifting sea ice. SnowModel-LG accounts for physical snow processes such as sublimation from static surfaces and blow-
ing snow, snow melt, evolution of snow density and temperature profiles, energy and mass transfers within the snowpack, and superimposed ice formation in a multi-layer configuration.

At each time step (3-hour here), SnowModel-LG performs a mass-budget calculation, where snow water equivalent (SWE) depth (m) is defined by snow mass gains, losses, and ice parcel dynamics,

\[
dSWE/dt = 1/\rho_w \left[ (P_r + P_s) - (S_{ss} + S_{bs} + M) + D \right]
\]

where \(t\) (s) is time; \(\rho_w = 1,000\) kg m\(^{-3}\) is the water density; \(P_r\) (kg m\(^{-2}\) s\(^{-1}\)) and \(P_s\) (kg m\(^{-2}\) s\(^{-1}\)) are the water-equivalent rainfall and snowfall fluxes, respectively; \(S_{ss}\) (kg m\(^{-2}\) s\(^{-1}\)) and \(S_{bs}\) (kg m\(^{-2}\) s\(^{-1}\)) are the water-equivalent sublimation from static-surface and blowing-snow processes, respectively; \(M\) (kg m\(^{-2}\) s\(^{-1}\)) is melt-related mass losses; and \(D\) (kg m\(^{-2}\) s\(^{-1}\)) is mass losses and gains from sea ice dynamics processes (i.e., parcels being created and lost with ice motion, divergence, and convergence).

Snow depth \(h_s\) (m) is related to SWE through the ratio of snow \((\rho_s)\), and water \((\rho_w)\) densities,

\[
SWE = \frac{\rho_s}{\rho_w} h_s.
\]

Therefore, the evolution of snow depths and densities are calculated by

\[
\frac{d(\rho_s h_s)}{dt} = (P_r + P_s) - (S_{ss} + S_{bs} + M) + D.
\]

In SnowModel-LG, snow density evolves and changes in response to compaction (weight of the above snow layers), wind force, freezing of liquid water, and vapor flux through the snowpack. Additional information on the components and the configuration of SnowModel-LG are provided in great detail in Liston, Itkin, et al. (2020). The model configuration in this study is identical to the one used in Liston, Itkin, et al. (2020), only here we have extended the simulation for another four years. According to Stroeve et al. (2020), SnowModel-LG performed well in capturing the spatial and seasonal variation of snow distributions, when evaluated against several Arctic data sets.

In the simulations presented herein, Lagrangian parcel tracking began on 1 August 1980. At the start of the first simulation year the model assumes no snow atop the sea ice; the following years carry available snow from 31 July to 1 August. Essential inputs are atmospheric reanalysis estimates of near-surface air temperature, relative humidity, precipitation, wind speed and direction, and sea ice motion and concentration products.

### 2.2 HIGHTSI

HIGHTSI is a 1-D thermodynamic sea ice model designed to simulate the evolution of snow and sea ice thickness and temperature profiles (Launiainen & Cheng, 1998) by solving the heat conduction equation for multiple ice and snow layers. The sea ice thermal conductivity is parameterized following Pringle et al. (2007). HIGHTSI simulates snow-ice formation following Saloranta (2000).

HIGHTSI has been widely used in process studies and validated extensively against observations (Cheng, Zhang, et al., 2008; Cheng et al., 2013; Merkouriadi et al., 2017, 2020; Wang et al., 2015). In this study, we used a model configuration that is derived from validation studies on Arctic sea ice. The model’s vertical resolution has been found to be critical for its performance in the Arctic (Cheng, Vihma, et al., 2008). Here, we used 20 layers in the ice which is considered optimal for capturing internal thermodynamic processes (Cheng, Vihma, et al., 2008; Cheng, Zhang, et al., 2008; Cheng et al., 2013; Wang et al., 2015). Detailed information on model parameterizations is given in Table S1 in the supporting information (Briegleb et al., 2004; Cheng, Vihma, et al., 2008;
Merkouriadi et al. (2020) implemented HIGHTSI in a Lagrangian framework to examine pan-Arctic snow-ice distributions. In the study presented herein, HIGHTSI was modified further, so that snow depth and bulk density evolution were simulated by SnowModel-LG in a 25-layer configuration.

2.3 SMLG_HS

We performed two separate snow-on-sea-ice simulations. First, we simulated snow depth and density with SnowModel-LG (i.e. Liston, Itkin, et al., 2020). Second, SnowModel-LG’s snow depth and density evolution were coupled with HIGHTSI’s snow-ice and thermodynamic ice growth representations. The coupled modeling products are hereafter referred to as being created by SMLG_HS.

For the SMLG_HS runs, snow density was simulated following Appendix C of Liston, Itkin, et al. (2020), with the vertical density profile parameterized as being a linear fit between densities that are 20% greater than the mean at the top of the snowpack (assumed to be wind slab), and 20% less at the bottom of the snowpack (assumed to be depth hoar). These percentages are consistent with snow-pit measurements made during the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition (Macfarlane et al., 2023). This approach was chosen to provide a best-possible fit to available snow density observations, as opposed to relying completely on SMLG_HS’s representation of the vertical density evolution. To account for changes in snow density in response to snow-ice formation, when snow-ice was formed, the corresponding snow-depth amount was removed from the bottom layers of the snowpack, and the bulk density was recalculated based on the depth and density of the remaining snow. Additional model specifications are presented in the supporting information (Table S1).

2.4 Input Data Sets

Daily ice concentrations (15–100%) by DiGirolamo et al. (2022) were used to define whether an ice parcel existed and whether snow could accumulate on that parcel. Ice motion vectors from the National Snow and Ice Data Center (NSIDC) (Tschudi et al., 2019, 2020) gridded over 25-km spatial resolution were used as Lagrangian ice parcel tracks. NASA’s Modern Era Retrospective Analysis for Research and Application Version 2 (MERRA-2; Gelaro et al., 2017; Global Modeling And Assimilation Office (GMAO), 2015a, 2015b) was used as atmospheric forcing to SMLG_HS. Specifically, SMLG_HS was forced with 10-m wind speed and direction, 2-m air temperature and relative humidity, and total water-equivalent precipitation from MERRA-2. During these simulations, MicroMet (Liston & Elder, 2006b) provided the required liquid and solid precipitation, and the downwelling shortwave and longwave radiation following Liston, Itkin, et al. (2020).

We applied the same bias-correction in MERRA-2 reanalysis as in Liston, Itkin, et al. (2020), where observations from NASA Operation IceBridge (OIB: 2009–2016) were used to scale the precipitation inputs. In Liston, Itkin, et al. (2020), 8-year averages of precipitation scaling factors were calculated and they were applied over all ice parcels and through the whole simulation period, making the results of MERRA-2 and the European Centre for Medium-Range Weather Forecasts (ECMWF) ReAnalysis-5th Generation (ERA5; Hersbach et al., 2020) model runs similar. Scaling factors were 1.37 for MERRA-2 and 1.58 for ERA5, indicating the need to increase the precipitation inputs in order to match the OIB observations. The same scaling factors were used in this study for the results to be comparable with the publicly available SnowModel-LG snow depth and density data set (Liston, Stroeve, & Itkin, 2020).
For the ocean boundary forcing, at the ice/ocean interface, we used ocean heat flux from the Ocean Reanalysis System 5 (ORAS5) provided at the ECMWF (Zuo et al., 2019). ORAS5 resolution is eddy-permitting (0.25° latitude and longitude) horizontally and 1 m vertically. ORAS5 includes five ensemble members and covers the period from 1979 onward. In our study, we used the ensemble mean, providing one unique value on a 1° grid for each simulation day.

### 2.5 Model Configuration and Outputs

The simulations began on 1 August 1980 and ran through 31 July 2022. Temporal resolution was 3 h to capture diurnal variations, and the parcel-specific outputs (e.g., snow depth, snow bulk density, sea ice thickness and snow-ice thickness) were saved at the end of each day. Ice parcel trajectories were linearly interpolated from weekly to 3-hourly time steps. On 1 August of each year (except in the first year), the multi-year ice thicknesses were calculated from the sea ice thickness distribution on 31 July. The 1 August 1980 ice thickness initial condition was defined by performing a one-year simulation with a domain-wide initial condition of 1 m, and then using the ice thickness distribution at the end of the first simulation year as the initial condition for the beginning of the 42-year simulation (i.e., the model ran the first year twice and assumed the 31 July 1981 ice thickness distribution equaled the 1 August 1980 distribution). In addition, any snow remaining at 00:00 UTC on 1 August (the last time step on 31 July) was used as the initial condition for the following simulation year that started at 03:00 UTC on 1 August (these are the standard procedures implemented in Liston, Itkin, et al. (2020)).

The daily simulation outputs for each parcel (approximately 61,000 parcels each year) were gridded to the 25 km × 25 km Equal-Area Scalable Earth (EASE) grid, provided by NSIDC. The location of each parcel was used to calculate the overlap between that parcel and the EASE grid cell, i.e. the fractional area of the EASE grid cell that was occupied by the parcel. The fractional area was then multiplied by the sea ice concentration of the parcel, and the result was used to weigh the parcels’ contribution to each EASE grid cell. This procedure of area- and concentration-weighted averages within the EASE grid cells conserved the examined parameters, similar to Merkouriadi et al. (2020).

### 2.6 Evaluation Exercise

To evaluate SMLG_HS snow depth and sea ice thickness, we compared them against independent airborne data from NASA OIB and Alfred Wegener Institute’s (AWI) IceBird campaigns over the western Arctic in late-winter. Snow depth data were derived from airborne snow radars similar on both OIB (99 flights in 2009–2019; Kurtz et al., 2015, 2016; MacGregor et al., 2021) and IceBird campaigns (11 flights in 2017 and 2019, see Table 1; Jutila et al., 2021a, 2021b; Jutila, King, et al., 2022), whereas sea ice thickness could be simultaneously and independently observed only on IceBird with a towed electromagnetic sounding instrument (Jutila et al., 2024a, 2024b; Jutila, Hendricks, et al., 2022). We averaged the airborne measurements over the same EASE grid when more than 50 values were present in a grid cell. For sea ice thickness, we included only level ice measurements using the flag in the data product that implements a sea ice thickness gradient threshold of 4 cm within an along-track distance of 1 m and identifies continuous sections of at least 100 m long.

In addition, we evaluated temperature profile and heating cycle data from thermistor strings of Snow Ice Mass Balance Apparatus (SIMBA) buoys (Jackson et al., 2013) deployed in the Arctic in 2012–2020 to detect flooding (Grosfeld et al., 2016; Lei et al., 2021, 2022, 2023). Changes in thermal diffusivity, temperature, and heat propagation distinguish the temporal evolution of different layers and their thicknesses (Provost et al., 2017; Preußer et al., 2024).
Table 1. AWI IceBird flights in 2017 and 2019, their geographical regions, lengths, as well as percentages of first-year ice (FYI) and level ice. Flights not included in the sensitivity experiment were due to the presence of multi-year ice or the region being at or outside the edge of the simulation domain.

<table>
<thead>
<tr>
<th>Date</th>
<th>Region</th>
<th>Length (km)</th>
<th>FYI (%)</th>
<th>Level ice (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 March 2017</td>
<td>Arctic Ocean</td>
<td>374</td>
<td>N/Aa</td>
<td>N/Aa</td>
</tr>
<tr>
<td>2 April 2017</td>
<td>Beaufort Sea</td>
<td>416</td>
<td>100</td>
<td>40b</td>
</tr>
<tr>
<td>4 April 2017</td>
<td>Beaufort Sea</td>
<td>265</td>
<td>100</td>
<td>44b</td>
</tr>
<tr>
<td>6 April 2017</td>
<td>Chukchi Sea</td>
<td>463</td>
<td>100</td>
<td>34b</td>
</tr>
<tr>
<td>8 April 2017</td>
<td>Chukchi Sea</td>
<td>619</td>
<td>100</td>
<td>32</td>
</tr>
<tr>
<td>10 April 2017</td>
<td>Chukchi Sea</td>
<td>49</td>
<td>100</td>
<td>N/Aa</td>
</tr>
<tr>
<td>2 April 2019</td>
<td>Arctic Ocean</td>
<td>294</td>
<td>33</td>
<td>3</td>
</tr>
<tr>
<td>5 April 2019</td>
<td>Lincoln Sea</td>
<td>189</td>
<td>33</td>
<td>15</td>
</tr>
<tr>
<td>7 April 2019</td>
<td>Beaufort Sea</td>
<td>470</td>
<td>89</td>
<td>36</td>
</tr>
<tr>
<td>8 April 2019</td>
<td>Amundsen Gulf</td>
<td>279</td>
<td>100</td>
<td>35</td>
</tr>
<tr>
<td>10 April 2019</td>
<td>Beaufort Sea</td>
<td>415</td>
<td>83</td>
<td>37</td>
</tr>
</tbody>
</table>

a No sea ice thickness measurements.

b Used in the sensitivity experiment (Section 2.7).

2.7 Sensitivity Experiment

Arctic sea ice floes are a mix of level and deformed ice features that affect the meter-scale spatial distribution of snow properties. However, snow modeling products, such as SnowModel-LG, consider snow properties to be evenly distributed within grid cells of a given size (e.g., 25 km × 25 km). Therefore, by not considering the sub-grid distribution of snow properties, they are expected to overestimate snow thickness over level ice and underestimate it over deformed ice. We anticipated the evaluation exercise to reveal the biases introduced when sub-parcel snow mass redistribution processes are not accounted for. We hypothesized that SMLG_HS would overestimate snow depth on level ice, and consequently underestimate level ice thickness and overestimate snow-ice thickness.

To test our hypothesis, we performed a modeling sensitivity experiment. We decreased snow depth in SMLG_HS by 10% intervals, from 100% down to 18%, following relevant observations from the MOSAiC observatory (Itkin et al., 2023). We derived a snow depth fraction that resulted in best fitting of both snow depth and level ice thickness simulations to the observations. We argue that this snow depth decrease represents the sub-parcel snow mass redistribution process and, based on that, we recalculated snow-ice formation.

3 Results

In this section, we present the results of the evaluation exercise and the sensitivity experiment. In the evaluation exercise we compared SMLG_HS simulations of snow depth and sea ice thickness against independent airborne observations, and we were able to examine snow depth on level ice and snow depth on deformed ice separately. The results of the evaluation exercise confirmed our hypothesis. They indicated that SMLG_HS overestimated snow depth over level ice on average by 0.08–0.13 m (Figures 1a–d and Figure 2), and therefore underestimated level ice thickness on average by 0.68–1.11 m (Figures 1e–h and Figure 3). This result was consistent in all IceBird flights examined in the evaluation exercise. When we did not distinguish between level and deformed ice and
Figure 1. Panels a)–d) show the evaluation of modeled snow depth from SMLG and SMLG_HS against airborne radar-derived snow depth measurements from the AWI IceBird survey flight on 30 March 2017. The red square in panel d) shows the extent of panels b) and c). Panels e)–h) show the evaluation of thermodynamically-grown (TD-grown) sea ice and snow-ice modeled with SMLG_HS against airborne sea ice thickness measurements over level ice from the AWI IceBird survey flight on 2 April 2017. The red square in panel h) shows the extent of panels f) and g).

We evaluated SMLG_HS simulations against the total snow depth observations instead (over all ice types), SMLG_HS demonstrated better fit to the snow depth observations from both IceBird and OIB flights (Figures 1a–d), with reduced root-mean-square-errors and biases compared to SMLG (Figure 2). This is an important result, because it indicates that total snow-on-sea-ice amounts given by SMLG_HS are realistic, but they do not account for the sub-grid spatial variations of snow depth (25 km × 25 km). Without considering the sub-grid snow distribution, SMLG_HS overestimated snow depth on level ice resulting in thinner level ice thickness, that is more prone to snow-ice formation. The question now becomes: how much snow is lost from the level ice due to snow mass redistribution?

To address this question and assess the sub-parcel snow mass redistribution, we performed a direct comparison of snow depth on level ice to snow depth on deformed ice along the 2017 IceBird flight transects that had the largest fraction of level ice observations. The fraction of average snow depth over level ice to average snow depth over deformed ice was 0.67, indicating that at least 33% of the snow was removed from the level to the deformed ice by April (without accounting for snow sinks to snow-ice formation). The modeling sensitivity experiment was designed to answer the same question. The results of the experiment revealed that snow depth on level ice should be reduced by at least 40% to simulate level ice thickness realistically and, at the same time, maintain snow depth and sea ice thickness within their measurement uncertainties of 0.05 m and 0.12 m, respectively (Figure 4). Guided by the results of the evaluation study and of the sensitivity experiment, we performed an additional SMLG_HS run, this time with
Figure 2. Evaluation of the modeled snow depth, compared against gridded airborne radar-derived snow depth measurements. Panels with white background show the NASA OIB campaigns in 2009–2019 and the bottom panels with grey background show the AWI IceBird campaigns in 2017 and 2019. The size of the data point reflects the relative number of airborne measurements in the grid cell. Upper and lower right corners of each panel show the statistics of the corresponding year: Pearson correlation coefficient $r$, root-mean-square error (RMSE), and lastly mean bias in parenthesis. Red color refers to the original SMLG and black color to the new, coupled SMLG_HS.
Figure 3. Evaluation of the modeled sea ice thickness, compared against gridded airborne sea ice thickness measurements over level ice from the AWI IceBird campaigns in 2017 & 2019. The size of the data point reflects the relative number of airborne measurements in the grid cell. Upper and lower right corners of each panel show the statistics of the corresponding year: Pearson correlation coefficient $r$, root-mean-square error (RMSE), and lastly mean bias in parenthesis. Red color refers to only thermodynamically-grown (TD-grown) sea ice, black color indicates the sum of TD-grown sea ice and snow-ice, i.e. total sea ice thickness.

Results from the SMLG HS simulation with 40% decrease in snow depth are presented herein. They indicated that snow-ice still has the potential to form every year in the Arctic Ocean, and it is characterized by strong seasonal and regional variations. The seasonality and long-term trends of snow-ice thickness calculated in this study were consistent with earlier findings (Merkouriadi et al., 2020). The seasonal and interannual evolution of all simulated parameters is presented in Figure 5. On average, snow-ice maximum volume occurred on the day-of-the-year 90±17 (30/31 March), whereas the maximum snow volume was on day 117±15 (26/27 April) and the maximum level ice thickness on day 128±15 (7/8 May). The pan-Arctic average snow bulk density varied around 300±50 kg m$^{-3}$ in the accumulation season and it increased as the snowpack got thicker and older, until it reached a threshold in the model (450 kg m$^{-3}$) prior to the melting season. Snow-ice volume demonstrated a negative long-term trend ($-2.36$ km$^3$ a$^{-1}$) that is partly explained by the long-term decrease of sea ice volume in the Arctic Ocean. While the fraction of the snow-ice volume to the total sea ice volume indicated strong interannual variability and it was typically reaching its maximum already in the fall (Figure 6a) governed by the timing of early season snowfall, the long-term evolution of the fraction at the end of winter showed an overall decrease of $-0.02$ % a$^{-1}$ (Figure 6b).

Based on the results from the latest SMLG HS run (with a 40% decrease in snow depth), we examined the impact of snow-ice formation on snow depth and bulk density from SMLG (Figure 7). Snow-ice formation occurred throughout the 42-year simulation period (1980–2022), and it was more prominent in the Atlantic sector of the Arctic Ocean, north of Svalbard, and across the east coast of Greenland. Here, we show results averaged across the 42-year period on the day of maximum snow-on-sea-ice volume. There was no significant long-term trend of that date across the simulation period. The snow depth and density differences (SMLG HS minus SMLG) were calculated on the date of maximum snow-on-sea-ice volume and they were averaged over the 42-year period (e.g., Figures 7c and f). Across the Arctic Ocean, accounting for snow-ice formation produced a 3.5% snow depth average decrease and a 2.3% snow density average increase, corresponding to 0.8 cm of snow depth and 7.9 kg m$^{-3}$ of snow density. In some years regional
Figure 4. Results of the sensitivity experiment showing a) snow depth over all (level and deformed) ice types, b) snow depth over level ice only, c) sea ice thickness over level ice, and d) location of the three IceBird flights (red lines; Table 1) together with the sea ice type in April 2017 at the time of the flights. OW stands for open water, FYI for first-year ice, SYI for second-year ice (i.e. sea ice that has survived one melt season), and MYI for multi-year ice (i.e. sea ice that has survived at least two or more melt seasons). The size of the data point reflects the relative number of airborne measurements in the grid cell. While 38% of the total data are from the level ice, the total number of the grid cells \(N = 57\) is not reduced. Upper and lower right corners of panels a)–c) show the statistics of the data sets: the number above is the Pearson correlation coefficient \(r\), while below are the root-mean-square error and lastly mean bias in parenthesis. The control simulation with unmodified snow depth is shown as red transparent circles and the simulation with snow depth reduced by 40% as black crosses.

and interannual variations were strong, especially in the Atlantic sector of the Arctic, yielding over 58 cm decrease in snow depth and 296 kg m\(^{-3}\) increase in snow density, when compared to the original SMLG product (not shown).

Mid-winter flooding events at the snow/ice interface detected by IMBs (Figure S1) indicated more snow-ice formation than SMLG_HS simulated with 40% decrease in snow depth. However, IMBs are point measurements and, considering the time-varying inhomogeneity of their surroundings due to ice dynamics, do not necessarily reflect the situation over larger spatial domains.

4 Discussion

We performed a modeling study to investigate snow sinks in Arctic sea ice. We coupled SnowModel-LG snow depth and density evolution with HIGHTSI thermodynamic sea ice and snow-ice growth, to create SMLG_HS. Being in fact a 1D model, SMLG_HS considers level ice only; it does not account for dynamic ice thickening, nor for sub-parcel snow mass redistribution processes, i.e., the preference of snow to accumulate over ice deformations (Liston et al., 2018). Therefore, it is expected to overestimate snow depth on level ice. Being a very effective insulator, this additional snow decelerates level ice growth, resulting in underestimation of level ice thickness and overestimation of snow-ice thickness. This hypothesis was confirmed when we compared SMLG_HS simulations to airborne observations of snow depth over level ice and level ice thicknesses. SMLG_HS did, however, match the overall snow depth observations from airborne radars better compared to SMLG, with reduced root-mean-square-errors and biases.

AWI IceBird data are ideal for evaluating SMLG_HS, because they offer simultaneous snow depth and sea ice thickness observations over hundreds of kilometers of tran-
Figure 5. Seasonal cycle of the modeled parameters: a) snow, b) snow density, c) snow-ice, d) thermodynamically-grown (TD-grown) sea ice, and e) total sea ice. They are expressed in volume summed over the Arctic (note the varying scale of the vertical axes), except for snow density in panel b), which is a pan-Arctic average. Each individual greyscale line shows the daily evolution through the year for each of the 42 simulated years, while the red dashed line shows the daily mean of those 42 years.
Figure 6. a) Seasonal cycle of the fraction of the snow-ice volume to the total level ice volume. Each individual greyscale line shows the daily evolution through the year for each of the 42 simulated years, while the red dashed line shows the daily mean of those 42 years. b) The fraction of the snow-ice volume to the total level ice volume on the day of maximum snow-ice volume shows a statistically significant long-term trend of $-0.02\%$ per year (red solid line) with a Pearson correlation coefficient of $r = -0.73$ and a $p$-value of $p \ll 0.001$. The year 2003 (red cross) is excluded from the trend calculation, because the maximum snow-ice volume occurred anomalously already in the fall.

Figure 7. Snow depth (top) and snow density (bottom) on the day of maximum snow-on-sea-ice volume (42-year average) from (a, d) SMLG, (b, e) SMLG_HS, and (c, f) the difference between the two products (SMLG_HS minus SMLG).
sects in high resolution, with a possibility to examine level and deformed ice conditions separately. However, IceBird campaigns that provide a concrete data set of both snow depth and sea ice thickness observations are limited to the western Arctic and in April 2017 and 2019 only. In 2019, IceBird flew over multi-year ice that was heavily deformed, resulting in small fractions of level ice within the flight tracks. The limited level ice observations would impose risk of unreliable conclusions, therefore we focused our analysis on flights with the largest level ice fraction in 2017. Moreover, the monitored region in 2019 was occasionally close to the coast where parcel trajectory data are unavailable, rendering these regions outside the simulation domain.

The modeling sensitivity experiment revealed that reducing snow depth by 40% resulted in the best agreement between snow depth (on level ice) and level ice thickness. We applied a 40% snow depth reduction in SMLG_HS to simulate level ice and snow-ice more realistically across the Arctic Ocean. It should be emphasized again that this reduction was derived by comparisons to IceBird observations from one year (2017) and from the western Arctic only. The mechanism of sub-parcel snow mass redistribution is not yet fully understood. The deformation rate of a sea ice floe, together with the atmospheric conditions (e.g. wind, warm intrusions) and the properties of snow cover (density, wetness, sintering level, and snow-surface shear strength) are expected to affect the snow redistribution, i.e., the amount of snow removed from the level to deformed ice. Ice and snow conditions are not uniform across the Arctic Ocean, but they vary regionally and temporally. Therefore, a 40% reduction of snow depth on level ice is empirical and more data is needed from across the Arctic and the different seasons to support it. In another, yet more local example, data from the MOSAiC observatory indicated that only 18% of the total snow-on-sea-ice volume remained on level ice by the end of spring (Itkin et al., 2023).

Due to the lack of information regarding several aspects of snow on sea ice, this study comes with some additional limitations. First, we assumed that negative freeboard always results in snow-ice formation. In reality, for flooding to occur, water pathways such as sea ice thermal cracks or leads are required. Even though these pathways become increasingly common in a thinner and more dynamic icescape (Kwok et al., 2013; Ram- pal et al., 2009), our assumption likely resulted in overestimation of snow-ice formation. Second, we did not account for snow loss into leads. Recent observations from the MOSAiC expedition demonstrated that this is likely an insignificant snow sink in winter, due to quick refreezing of the leads (Clemens-Sewall et al., 2023). This is further supported by the arguments put forth by Liston, Itkin, et al. (2020).

5 Conclusions

We showed that a 1D sea ice and snow thermodynamic model approach would overestimate snow sink in snow-ice formation. Even though the total snow depth (over both deformed and level ice) matched well with both OIB and IceBird observations, not accounting for snow redistribution from level to deformed ice resulted in overestimation of snow depth over level ice. As expected, this additional snow decelerated thermodynamic ice growth in the model, resulting in thinner level ice that is more prone to snow-ice formation. Based on the evaluation of our simulations against IceBird data, fitting both snow on level ice and level ice thickness simulations to the IceBird observations, snow depth in SMLG_HS should be reduced by 40%. We argue that this 40% reduction represented the sub-parcel snow mass redistribution process.

Snow-ice was recalculated based on the 40% reduction of snow depth on level ice. When snow-ice was accounted for, snow depth in SMLG decreased and, in most cases, snow bulk density increased. Averaged across the entire Arctic Ocean on the day of maximum snow-on-sea-ice volume, and for the period 1980–2022, snow depth given by SMLG_HS was 3.5% lower than SMLG, and snow density was 2.3% higher. Due to the large re-


Data Availability Statement

Model input

Sea ice concentration data are available at DiGirolamo et al. (2022). Sea ice motion vectors are available at Tschudi et al. (2019). Atmospheric forcing data are available at Global Modeling And Assimilation Office (GMAO) (2015a, 2015b). Daily ocean heat flux data were downloaded from ECMWF.

Evaluation

Airborne data are available at Jutila et al. (2021a, 2021b); Jutila et al. (2024a, 2024b) for AWI IceBird and at Kurtz et al. (2015, 2016) for NASA OIB. SIMBA buoy data were obtained from https://www.meereisportal.de and Lei et al. (2021, 2022, 2023).

Acknowledgments

IM was supported by the ESA grant CCI+ 4000126449/19/I-NB. IM and AJ were supported by the Research Council of Finland grant 341550. GEL was supported by the United States National Science Foundation grant 1820927. AP was supported by the European Union’s Horizon 2020 research and innovation programme under grant 101003472. The authors are grateful for Bin Cheng for providing the software code for the model HIGH-TSI. Autonomous sea ice measurements (temperature profile and heating cycle data) from 2012 to 2020 were obtained from https://www.meereisportal.de (grant: REKLM-2013-04). Scientific, color-vision deficiency friendly, and perceptually-uniform color maps used in the figures of this manuscript were provided by Crameri (2023).
References


Acknowledgment

The authors gratefully acknowledge support from the Office of Naval Research (ONR) Grant N00014-20-1-2352, which enabled the development of the SnowModel system. The SnowModel system was deployed in the Arctic Ocean as part of the MOSAiC expedition (http://mosaic.awi.de), which was financed by the German Research Foundation (DFG) under Grant No. KU 1771/17-1. The authors also acknowledge the support of the European Space Agency (ESA) through the CryoSat-2 mission (http://www.cryosat.esa.int), which provided valuable data for model validation. The authors would like to thank the MOSAiC team, particularly R. Kwok, F. Cunningham, M. Wensnahan, I. Rigor, H. J. Zwally, and D. Yi, for their contributions to the study. The authors also thank the anonymous reviewers for their constructive comments, which greatly improved the manuscript.

References


Investigating snow sinks on level sea ice in the Arctic

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Key Points:

• We examined the changes in modeled snow-on-sea-ice depth and density caused by snow sinks on level Arctic sea ice.
• Accounting for snow sinks on level ice markedly reduces snow depth on Arctic sea ice regionally.
• Snow mass changes due to sub-parcel snow redistribution processes must be considered when examining snow sinks in snow-ice formation.

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Abstract
We examined snow sinks caused by snow and sea ice interactions (snow-ice formation and sub-parcel snow mass redistribution) on Arctic level ice. We coupled SnowModel-LG, a modeling system adapted for snow depth and density reconstruction over sea ice, with HIGHTSI, a 1-D thermodynamic sea ice model, to create SMLG_HS. Pan-Arctic model simulations spanned from 1 August 1980 through 31 July 2022. Evaluation of SMLG_HS against snow depth, snow-ice, and sea ice thickness observations highlighted the importance of snow mass changes due to snow redistribution processes. The findings suggest that neglecting snow-ice formation and sub-parcel snow mass redistribution processes in models can lead to substantial overestimation of snow depth over level ice.

Plain Language Summary
The amount of snow on sea ice is important for monitoring sea ice thickness, which is one of the key factors in a changing climate. Recent advances in snow-on-sea-ice modeling have made it possible to simulate snow depth and density over Arctic sea ice. However, these simulations often do not consider how much snow is lost from atop level ice in processes such as snow-ice formation and snow’s tendency to leave level ice areas and pile up over rough ice areas (sub-parcel snow mass redistribution process). Snow-ice forms when snow becomes part of the sea ice, after seawater floods the sea ice surface and freezes inside the snow. In this study, we combined a snow model with a sea ice model to understand how snow-on-sea-ice mass changes when snow-ice formation and sub-parcel snow mass redistribution are accounted for. Our results show that snow depth decreases, and snow density commonly increases. The differences are highest in the Atlantic sector of the Arctic, where snow-ice is more likely to form due to high annual snowfall.

1 Introduction
Arctic sea ice is going through unprecedented changes, decreasing dramatically both in extent (e.g. Stroeve et al., 2014) and in thickness (Kwok et al., 2009; Maslanik et al., 2007), and transitioning from a multiyear ice to a seasonal, first-year ice system (Meier et al., 2014). The role of snow cover over thinner, seasonal sea ice is amplified in many ways. First, the thermal resistance of snow cover becomes a dominant control over the atmosphere-ocean heat fluxes, regulating sea ice growth in winter. Second, the snow load becomes more likely to submerge thinner ice underneath the water level, creating negative freeboard conditions. If sea water floods at the ice/snow interface and freezes there, snow-ice is formed that is a mixture of frozen seawater and snow (e.g. Leppäranta, 1983). Snow-ice is a common phenomenon in seas that are seasonally covered by ice (i.e., Baltic Sea, Sea of Okhotsk) and in large parts of the Antarctic sea ice, but it was not commonly observed in drifting Arctic sea ice until the Norwegian Young Sea ICE (N-ICE2015) expedition (Granskog et al., 2017; Provost et al., 2017). Snow-ice is a sink for snow, and it can contribute significantly to the sea ice mass balance (Merkouriadi et al., 2017, 2020). Therefore, it is essential to consider it for improving Arctic sea ice forecasts.

Satellite altimetry is the most common method for monitoring sea ice thickness, providing nearly full coverage of the Arctic Ocean (Landy et al., 2022; Laxon et al., 2003; Markus et al., 2017). Information on the snow load exerted on sea ice is crucial for altimetry retrievals of sea ice thickness, because radar and laser altimeters, in principle, measure ice or snow freeboard; the elevation of the ice or snow surface from the water surface. Snow depth and density are required to convert freeboard to sea ice thickness information (e.g. Laxon et al., 2003). According to Giles et al. (2007), uncertainties in snow depth and density contribute 48 % and 14 %, respectively, to the total error of sea ice thickness retrievals from radar altimetry. A more recent study by Landy et al. (2020) estimated these uncertainties at 11 % for snow depth and 16 % for density. Similarly, snow depth and density uncertainties were found to contribute 70 % and 30–35 %, respectively,
to the total error of sea ice thickness retrievals from laser altimetry (Zygmuntowska et al., 2014).

Snow depth and density estimates used in satellite altimetry applications are often derived from snow climatologies or their modified versions. The most widely used snow-on-sea-ice climatology is compiled from a snow depth and density data set collected decades ago mostly over multiyear ice (Warren et al., 1999). In a changing Arctic sea ice system, snow conditions are expected to change as well (Blanchard-Wrigglesworth et al., 2015; Webster et al., 2014), and these changes are not captured by the Warren et al. (1999) climatology. In addition to the long-term changes, climatology overlooks the spatio-temporal differences and interannual variability of snow conditions in the Arctic, which are evidently strong (Webster et al., 2019). Addressing the imperative need for better representation of snow on sea ice, efforts have focused on reanalysis-based snow depth and density reconstructions (e.g. Blanchard-Wrigglesworth et al., 2018; Kwok & Cunningham, 2008; Petty et al., 2018). A recent contribution was SnowModel-LG, a state-of-the-art Lagrangian snow evolution model (Liston, Itkin, et al., 2020). Compared to other reanalysis-based products, SnowModel-LG implemented higher resolution Lagrangian parcel tracking and included an improved representation of snow evolution physics. It has been bias-corrected and validated against a wide observation framework, and yielded good agreement, especially with in situ measurements (Stroeve et al., 2020).

SnowModel-LG explicitly resolves snow mass sources and sinks, such as blowing snow, static-surface sublimation, and melt, by performing a snow mass-budget calculation in each time step (Liston, Itkin, et al., 2020). However, SnowModel-LG, similarly to all the above-mentioned Arctic snow models, is not coupled to a sea ice model. Therefore, it does not consider snow sinks caused by snow-ice formation. Moreover, being configured over ice parcels of kilometer-scale, it does not resolve sub-parcel snow mass redistribution. The latter describes the tendency of snow to accumulate on the lee side of pressure ridges and other roughness elements (e.g. Liston et al., 2018) as a result of snow redistribution by the wind and ice topography. This process results in uneven snow load over a sea ice floe (i.e., reduced snow over level ice areas and increased snow over deformed ice). Because in this study we are examining level ice only, we will be referring to the sub-parcel snow mass redistribution process as a snow sink.

This study aims to examine snow sinks on level Arctic sea ice (snow-ice formation and sub-parcel snow mass redistribution), and their effect in snow-on-sea-ice models, from 1 August 1980 through 31 July 2022. To investigate this, we coupled SnowModel-LG with the High-Resolution Thermodynamic Sea Ice model (HIGHTSI) (Launiainen & Cheng, 1998) to produce SMLG_HS. In SMLG_HS, snow-ice forms when the ice surface is depressed below the water surface (negative freeboard), with the assumption that all negative freeboard will result in flooding and, consequently, snow-ice formation. SMLG_HS does not account for dynamic thickening of the sea ice, therefore it considers level ice only. SMLG_HS outputs of snow depth, snow-ice and sea ice thickness were evaluated against observations to examine and to mitigate the biases introduced when sub-parcel snow mass redistribution processes are ignored.

2 Materials and Methods

2.1 SnowModel-LG

SnowModel is a collection of snow distribution and snow evolution modeling tools, applicable to any environment experiencing snow, including sea ice applications (Liston & Elder, 2006a; Liston et al., 2018). SnowModel-LG is adapted for snow depth and density reconstruction over sea ice (Liston, Itkin, et al., 2020). It is implemented in a Lagrangian framework to simulate snow properties on drifting sea ice. SnowModel-LG accounts for physical snow processes such as sublimation from static surfaces and blow-
ing snow, snow melt, evolution of snow density and temperature profiles, energy and mass transfers within the snowpack, and superimposed ice formation in a multi-layer configuration.

At each time step (3-hour here), SnowModel-LG performs a mass-budget calculation, where snow water equivalent (SWE) depth (m) is defined by snow mass gains, losses, and ice parcel dynamics,

\[
\frac{d \text{SWE}}{dt} = \frac{1}{\rho_w} [(P_r + P_s) - (S_{ss} + S_{bs} + M) + D]
\]

(1)

where \( t \) (s) is time; \( \rho_w = 1,000 \text{ kg m}^{-3} \) is the water density; \( P_r \) (kg m\(^{-2}\) s\(^{-1}\)) and \( P_s \) (kg m\(^{-2}\) s\(^{-1}\)) are the water-equivalent rainfall and snowfall fluxes, respectively; \( S_{ss} \) (kg m\(^{-2}\) s\(^{-1}\)) and \( S_{bs} \) (kg m\(^{-2}\) s\(^{-1}\)) are the water-equivalent sublimation from static-surface and blowing-snow processes, respectively; \( M \) (kg m\(^{-2}\) s\(^{-1}\)) is melt-related mass losses; and \( D \) (kg m\(^{-2}\) s\(^{-1}\)) is mass losses and gains from sea ice dynamics processes (i.e., parcels being created and lost with ice motion, divergence, and convergence).

Snow depth \( h_s \) (m) is related to SWE through the ratio of snow (\( \rho_s \)), and water (\( \rho_w \)) densities,

\[
\text{SWE} = \frac{\rho_s}{\rho_w} h_s.
\]

(2)

Therefore, the evolution of snow depths and densities are calculated by

\[
\frac{d (\rho_s h_s)}{dt} = (P_r + P_s) - (S_{ss} + S_{bs} + M) + D.
\]

(3)

In SnowModel-LG, snow density evolves and changes in response to compaction (weight of the above snow layers), wind force, freezing of liquid water, and vapor flux through the snowpack. Additional information on the components and the configuration of SnowModel-LG are provided in great detail in Liston, Itkin, et al. (2020). The model configuration in this study is identical to the one used in Liston, Itkin, et al. (2020), only here we have extended the simulation for another four years. According to Stroeve et al. (2020), SnowModel-LG performed well in capturing the spatial and seasonal variation of snow distributions, when evaluated against several Arctic data sets.

In the simulations presented herein, Lagrangian parcel tracking began on 1 August 1980. At the start of the first simulation year the model assumes no snow atop the sea ice; the following years carry available snow from 31 July to 1 August. Essential inputs are atmospheric reanalysis estimates of near-surface air temperature, relative humidity, precipitation, wind speed and direction, and sea ice motion and concentration products.

### 2.2 HIGHTSI

HIGHTSI is a 1-D thermodynamic sea ice model designed to simulate the evolution of snow and sea ice thickness and temperature profiles (Launiainen & Cheng, 1998) by solving the heat conduction equation for multiple ice and snow layers. The sea ice thermal conductivity is parameterized following Pringle et al. (2007). HIGHTSI simulates snow-ice formation following Saloranta (2000).

HIGHTSI has been widely used in process studies and validated extensively against observations (Cheng, Zhang, et al., 2008; Cheng et al., 2013; Merkouriadi et al., 2017, 2020; Wang et al., 2015). In this study, we used a model configuration that is derived from validation studies on Arctic sea ice. The model’s vertical resolution has been found to be critical for its performance in the Arctic (Cheng, Vihma, et al., 2008). Here, we used 20 layers in the ice which is considered optimal for capturing internal thermodynamic processes (Cheng, Vihma, et al., 2008; Cheng, Zhang, et al., 2008; Cheng et al., 2013; Wang et al., 2015). Detailed information on model parameterizations is given in Table S1 in the supporting information (Briegleb et al., 2004; Cheng, Vihma, et al., 2008;
Merkouriadi et al. (2020) implemented HIGHTSI in a Lagrangian framework to examine pan-Arctic snow-ice distributions. In the study presented herein, HIGHTSI was modified further, so that snow depth and bulk density evolution were simulated by SnowModel-LG in a 25-layer configuration.

2.3 SMLG_HS

We performed two separate snow-on-sea-ice simulations. First, we simulated snow depth and density with SnowModel-LG (i.e. Liston, Itkin, et al., 2020). Second, SnowModel-LG’s snow depth and density evolution were coupled with HIGHTSI’s snow-ice and thermodynamic ice growth representations. The coupled modeling products are hereafter referred to as being created by SMLG_HS.

For the SMLG_HS runs, snow density was simulated following Appendix C of Liston, Itkin, et al. (2020), with the vertical density profile parameterized as being a linear fit between densities that are 20% greater than the mean at the top of the snowpack (assumed to be wind slab), and 20% less at the bottom of the snowpack (assumed to be depth hoar). These percentages are consistent with snow-pit measurements made during the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition (Macfarlane et al., 2023). This approach was chosen to provide a best-possible fit to available snow density observations, as opposed to relying completely on SMLG_HS’s representation of the vertical density evolution. To account for changes in snow density in response to snow-ice formation, when snow-ice was formed, the corresponding snow-depth amount was removed from the bottom layers of the snowpack, and the bulk density was recalculated based on the depth and density of the remaining snow. Additional model specifications are presented in the supporting information (Table S1).

2.4 Input Data Sets

Daily ice concentrations (15–100%) by DiGirolamo et al. (2022) were used to define whether an ice parcel existed and whether snow could accumulate on that parcel. Ice motion vectors from the National Snow and Ice Data Center (NSIDC) (Tschudi et al., 2019, 2020) gridded over 25-km spatial resolution were used as Lagrangian ice parcel tracks. NASA’s Modern Era Retrospective Analysis for Research and Application Version 2 (MERRA-2; Gelaro et al., 2017; Global Modeling And Assimilation Office (GMAO), 2015a, 2015b) was used as atmospheric forcing to SMLG_HS. Specifically, SMLG_HS was forced with 10-m wind speed and direction, 2-m air temperature and relative humidity, and total water-equivalent precipitation from MERRA-2. During these simulations, MicroMet (Liston & Elder, 2006b) provided the required liquid and solid precipitation, and the downwelling shortwave and longwave radiation following Liston, Itkin, et al. (2020).

We applied the same bias-correction in MERRA-2 reanalysis as in Liston, Itkin, et al. (2020), where observations from NASA Operation IceBridge (OIB: 2009–2016) were used to scale the precipitation inputs. In Liston, Itkin, et al. (2020), 8-year averages of precipitation scaling factors were calculated and they were applied over all ice parcels and through the whole simulation period, making the results of MERRA-2 and the European Centre for Medium-Range Weather Forecasts (ECMWF) ReAnalysis-5th Generation (ERA5; Hersbach et al., 2020) model runs similar. Scaling factors were 1.37 for MERRA-2 and 1.58 for ERA5, indicating the need to increase the precipitation inputs in order to match the OIB observations. The same scaling factors were used in this study for the results to be comparable with the publicly available SnowModel-LG snow depth and density data set (Liston, Stroeve, & Itkin, 2020).
For the ocean boundary forcing, at the ice/ocean interface, we used ocean heat flux from the Ocean Reanalysis System 5 (ORAS5) provided at the ECMWF (Zuo et al., 2019). ORAS5 resolution is eddy-permitting (0.25° latitude and longitude) horizontally and 1 m vertically. ORAS5 includes five ensemble members and covers the period from 1979 onward. In our study, we used the ensemble mean, providing one unique value on a 1° grid for each simulation day.

### 2.5 Model Configuration and Outputs

The simulations began on 1 August 1980 and ran through 31 July 2022. Temporal resolution was 3 h to capture diurnal variations, and the parcel-specific outputs (e.g. snow depth, snow bulk density, sea ice thickness and snow-ice thickness) were saved at the end of each day. Ice parcel trajectories were linearly interpolated from weekly to 3-hourly time steps. On 1 August of each year (except in the first year), the multi-year ice thicknesses were calculated from the sea ice thickness distribution on 31 July. The 1 August 1980 ice thickness initial condition was defined by performing a one-year simulation with a domain-wide initial condition of 1 m, and then using the ice thickness distribution at the end of the first simulation year as the initial condition for the beginning of the 42-year simulation (i.e., the model ran the first year twice and assumed the 31 July 1981 ice thickness distribution equaled the 1 August 1980 distribution). In addition, any snow remaining at 00:00 UTC on 1 August (the last time step on 31 July) was used as the initial condition for the following simulation year that started at 03:00 UTC on 1 August (these are the standard procedures implemented in Liston, Itkin, et al. (2020)).

The daily simulation outputs for each parcel (approximately 61,000 parcels each year) were gridded to the 25 km × 25 km Equal-Area Scalable Earth (EASE) grid, provided by NSIDC. The location of each parcel was used to calculate the overlap between that parcel and the EASE grid cell, i.e. the fractional area of the EASE grid cell that was occupied by the parcel. The fractional area was then multiplied by the sea ice concentration of the parcel, and the result was used to weigh the parcels’ contribution to each EASE grid cell. This procedure of area- and concentration-weighted averages within the EASE grid cells conserved the examined parameters, similar to Merkouriadi et al. (2020).

### 2.6 Evaluation Exercise

To evaluate SMLG_HS snow depth and sea ice thickness, we compared them against independent airborne data from NASA OIB and Alfred Wegener Institute’s (AWI) IceBird campaigns over the western Arctic in late-winter. Snow depth data were derived from airborne snow radars similar on both OIB (99 flights in 2009–2019; Kurtz et al., 2015, 2016; MacGregor et al., 2021) and IceBird campaigns (11 flights in 2017 and 2019, see Table 1; Jutila et al., 2021a, 2021b; Jutila, King, et al., 2022), whereas sea ice thickness could be simultaneously and independently observed only on IceBird with a towed electromagnetic sounding instrument (Jutila et al., 2024a, 2024b; Jutila, Hendricks, et al., 2022). We averaged the airborne measurements over the same EASE grid when more than 50 values were present in a grid cell. For sea ice thickness, we included only level ice measurements using the flag in the data product that implements a sea ice thickness gradient threshold of 4 cm within an along-track distance of 1 m and identifies continuous sections of at least 100 m long.

In addition, we evaluated temperature profile and heating cycle data from thermistor strings of Snow Ice Mass Balance Apparatus (SIMBA) buoys (Jackson et al., 2013) deployed in the Arctic in 2012–2020 to detect flooding (Grosfeld et al., 2016; Lei et al., 2021, 2022, 2023). Changes in thermal diffusivity, temperature, and heat propagation distinguish the temporal evolution of different layers and their thicknesses (Provost et al., 2017; Preußer et al., 2024).
Table 1. AWI IceBird flights in 2017 and 2019, their geographical regions, lengths, as well as percentages of first-year ice (FYI) and level ice. Flights not included in the sensitivity experiment were due to the presence of multi-year ice or the region being at or outside the edge of the simulation domain.

<table>
<thead>
<tr>
<th>Date</th>
<th>Region</th>
<th>Length (km)</th>
<th>FYI (%)</th>
<th>Level ice (%)</th>
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</thead>
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<td>374</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
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<td>Beaufort Sea</td>
<td>416</td>
<td>100</td>
<td>40b</td>
</tr>
<tr>
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<td>Beaufort Sea</td>
<td>265</td>
<td>100</td>
<td>44b</td>
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<td>Chukchi Sea</td>
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<td>415</td>
<td>83</td>
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</table>

aN/A: No sea ice thickness measurements.

bUsed in the sensitivity experiment (Section 2.7).

2.7 Sensitivity Experiment

Arctic sea ice floes are a mix of level and deformed ice features that affect the meter-scale spatial distribution of snow properties. However, snow modeling products, such as SnowModel-LG, consider snow properties to be evenly distributed within grid cells of a given size (e.g., 25 km × 25 km). Therefore, by not considering the sub-grid distribution of snow properties, they are expected to overestimate snow thickness over level ice and underestimate it over deformed ice. We anticipated the evaluation exercise to reveal the biases introduced when sub-parcel snow mass redistribution processes are not accounted for. We hypothesized that SMLG_HS would overestimate snow depth on level ice, and consequently underestimate level ice thickness and overestimate snow-ice thickness.

To test our hypothesis, we performed a modeling sensitivity experiment. We decreased snow depth in SMLG_HS by 10% intervals, from 100% down to 18%, following relevant observations from the MOSAiC observatory (Itkin et al., 2023). We derived a snow depth fraction that resulted in best fitting of both snow depth and level ice thickness simulations to the observations. We argue that this snow depth decrease represents the sub-parcel snow mass redistribution process and, based on that, we recalculated snow-ice formation.

3 Results

In this section, we present the results of the evaluation exercise and the sensitivity experiment. In the evaluation exercise we compared SMLG_HS simulations of snow depth and sea ice thickness against independent airborne observations, and we were able to examine snow depth on level ice and snow depth on deformed ice separately. The results of the evaluation exercise confirmed our hypothesis. They indicated that SMLG_HS overestimated snow depth over level ice on average by 0.08–0.13 m (Figures 1a–d and Figure 2), and therefore underestimated level ice thickness on average by 0.68–1.11 m (Figures 1e–h and Figure 3). This result was consistent in all IceBird flights examined in the evaluation exercise. When we did not distinguish between level and deformed ice and...
Figure 1. Panels a)–d) show the evaluation of modeled snow depth from SMLG and SMLG_HS against airborne radar-derived snow depth measurements from the AWI IceBird survey flight on 30 March 2017. The red square in panel d) shows the extent of panels b) and c). Panels e)–h) show the evaluation of thermodynamically-grown (TD-grown) sea ice and snow-ice modeled with SMLG_HS against airborne sea ice thickness measurements over level ice from the AWI IceBird survey flight on 2 April 2017. The red square in panel h) shows the extent of panels f) and g).

we evaluated SMLG_HS simulations against the total snow depth observations instead (over all ice types), SMLG_HS demonstrated better fit to the snow depth observations from both IceBird and OIB flights (Figures 1a–d), with reduced root-mean-square-errors and biases compared to SMLG (Figure 2). This is an important result, because it indicates that total snow-on-sea-ice amounts given by SMLG_HS are realistic, but they do not account for the sub-grid spatial variations of snow depth (25 km × 25 km). Without considering the sub-grid snow distribution, SMLG_HS overestimated snow depth on level ice resulting in thinner level ice thickness, that is more prone to snow-ice formation. The question now becomes: how much snow is lost from the level ice due to snow mass redistribution?

To address this question and assess the sub-parcel snow mass redistribution, we performed a direct comparison of snow depth on level ice to snow depth on deformed ice along the 2017 IceBird flight transects that had the largest fraction of level ice observations. The fraction of average snow depth over level ice to average snow depth over deformed ice was 0.67, indicating that at least 33 % of the snow was removed from the level to the deformed ice by April (without accounting for snow sinks to snow-ice formation). The modeling sensitivity experiment was designed to answer the same question. The results of the experiment revealed that snow depth on level ice should be reduced by at least 40 % to simulate level ice thickness realistically and, at the same time, maintain snow depth and sea ice thickness within their measurement uncertainties of 0.05 m and 0.12 m, respectively (Figure 4). Guided by the results of the evaluation study and of the sensitivity experiment, we performed an additional SMLG_HS run, this time with
Figure 2. Evaluation of the modeled snow depth, compared against gridded airborne radar-derived snow depth measurements. Panels with white background show the NASA OIB campaigns in 2009–2019 and the bottom panels with grey background show the AWI IceBird campaigns in 2017 and 2019. The size of the data point reflects the relative number of airborne measurements in the grid cell. Upper and lower right corners of each panel show the statistics of the corresponding year: Pearson correlation coefficient $r$, root-mean-square error (RMSE), and lastly mean bias in parenthesis. Red color refers to the original SMLG and black color to the new, coupled SMLG_HS.
a 40% decrease in snow depth, to quantify snow loss in snow-ice formation over level ice more realistically.

Results from the SMLG_HS simulation with 40% decrease in snow depth are presented herein. They indicated that snow-ice still has the potential to form every year in the Arctic Ocean, and it is characterized by strong seasonal and regional variations. The seasonality and long-term trends of snow-ice thickness calculated in this study were consistent with earlier findings (Merkouriadi et al., 2020). The seasonal and interannual evolution of all simulated parameters is presented in Figure 5. On average, snow-ice maximum volume occurred on the day-of-the-year 90±17 (30/31 March), whereas the maximum snow volume was on day 117±15 (26/27 April) and the maximum level ice thickness on day 128±15 (7/8 May). The pan-Arctic average snow bulk density varied around 300±50 kg m\(^{-3}\) in the accumulation season and it increased as the snowpack got thicker and older, until it reached a threshold in the model (450 kg m\(^{-3}\)) prior to the melting season. Snow-ice volume demonstrated a negative long-term trend (−2.36 km\(^3\) a\(^{-1}\)) that is partly explained by the long-term decrease of sea ice volume in the Arctic Ocean. While the fraction of the snow-ice volume to the total sea ice volume indicated strong interannual variability and it was typically reaching its maximum already in the fall (Figure 6a) governed by the timing of early season snowfall, the long-term evolution of the fraction at the end of winter showed an overall decrease of −0.02% a\(^{-1}\) (Figure 6b).

Based on the results from the latest SMLG_HS run (with a 40% decrease in snow depth), we examined the impact of snow-ice formation on snow depth and bulk density from SMLG (Figure 7). Snow-ice formation occurred throughout the 42-year simulation period (1980–2022), and it was more prominent in the Atlantic sector of the Arctic Ocean, north of Svalbard, and across the east coast of Greenland. Here, we show results averaged across the 42-year period on the day of maximum snow-on-sea-ice volume. There was no significant long-term trend of that date across the simulation period. The snow depth and density differences (SMLG_HS minus SMLG) were calculated on the date of maximum snow-on-sea-ice volume and they were averaged over the 42-year period (e.g., Figures 7c and f). Across the Arctic Ocean, accounting for snow-ice formation produced a 3.5% snow depth average decrease and a 2.3% snow density average increase, corresponding to 0.8 cm of snow depth and 7.9 kg m\(^{-3}\) of snow density. In some years regional
Results of the sensitivity experiment showing a) snow depth over all (level and deformed) ice types, b) snow depth over level ice only, c) sea ice thickness over level ice, and d) location of the three IceBird flights (red lines; Table 1) together with the sea ice type in April 2017 at the time of the flights. OW stands for open water, FYI for first-year ice, SYI for second-year ice (i.e. sea ice that has survived one melt season), and MYI for multi-year ice (i.e. sea ice that has survived at least two or more melt seasons). The size of the data point reflects the relative number of airborne measurements in the grid cell. While 38% of the total data are from the level ice, the total number of the grid cells ($N = 57$) is not reduced. Upper and lower right corners of panels a)–c) show the statistics of the data sets: the number above is the Pearson correlation coefficient $r$, while below are the root-mean-square error and lastly mean bias in parenthesis. The control simulation with unmodified snow depth is shown as red transparent circles and the simulation with snow depth reduced by 40% as black crosses.

and interannual variations were strong, especially in the Atlantic sector of the Arctic, yielding over 58 cm decrease in snow depth and 296 kg m$^{-3}$ increase in snow density, when compared to the original SMLG product (not shown).

Mid-winter flooding events at the snow/ice interface detected by IMBs (Figure S1) indicated more snow-ice formation than SMLG HS simulated with 40% decrease in snow depth. However, IMBs are point measurements and, considering the time-varying inhomogeneity of their surroundings due to ice dynamics, do not necessarily reflect the situation over larger spatial domains.

4 Discussion

We performed a modeling study to investigate snow sinks in Arctic sea ice. We coupled SnowModel-LG snow depth and density evolution with HIGHTSI thermodynamic sea ice and snow-ice growth, to create SMLG_HS. Being in fact a 1D model, SMLG_HS considers level ice only; it does not account for dynamic ice thickening, nor for sub-parcel snow mass redistribution processes, i.e., the preference of snow to accumulate over ice deformations (Liston et al., 2018). Therefore, it is expected to overestimate snow depth on level ice. Being a very effective insulator, this additional snow decelerates level ice growth, resulting in underestimation of level ice thickness and overestimation of snow-ice thickness. This hypothesis was confirmed when we compared SMLG_HS simulations to airborne observations of snow depth over level ice and level ice thicknesses. SMLG_HS did, however, match the overall snow depth observations from airborne radars better compared to SMLG, with reduced root-mean-square-errors and biases.

AWI IceBird data are ideal for evaluating SMLG_HS, because they offer simultaneous snow depth and sea ice thickness observations over hundreds of kilometers of tran-
Figure 5. Seasonal cycle of the modeled parameters: a) snow, b) snow density, c) snow-ice, d) thermodynamically-grown (TD-grown) sea ice, and e) total sea ice. They are expressed in volume summed over the Arctic (note the varying scale of the vertical axes), except for snow density in panel b), which is a pan-Arctic average. Each individual grey scale line shows the daily evolution through the year for each of the 42 simulated years, while the red dashed line shows the daily mean of those 42 years.
Figure 6.  a) Seasonal cycle of the fraction of the snow-ice volume to the total level ice volume. Each individual greyscale line shows the daily evolution through the year for each of the 42 simulated years, while the red dashed line shows the daily mean of those 42 years. b) The fraction of the snow-ice volume to the total level ice volume on the day of maximum snow-ice volume shows a statistically significant long-term trend of $-0.02 \%$ per year (red solid line) with a Pearson correlation coefficient of $r = -0.73$ and a $p$-value of $p \ll 0.001$. The year 2003 (red cross) is excluded from the trend calculation, because the maximum snow-ice volume occurred anomalously already in the fall.

Figure 7.  Snow depth (top) and snow density (bottom) on the day of maximum snow-on-sea-ice volume (42-year average) from (a, d) SMLG, (b, e) SMLG_HS, and (c, f) the difference between the two products (SMLG_HS minus SMLG).
sects in high resolution, with a possibility to examine level and deformed ice conditions separately. However, IceBird campaigns that provide a concrete data set of both snow depth and sea ice thickness observations are limited to the western Arctic and in April 2017 and 2019 only. In 2019, IceBird flew over multi-year ice that was heavily deformed, resulting in small fractions of level ice within the flight tracks. The limited level ice observations would impose risk of unreliable conclusions, therefore we focused our analysis on flights with the largest level ice fraction in 2017. Moreover, the monitored region in 2019 was occasionally close to the coast where parcel trajectory data are unavailable, rendering these regions outside the simulation domain.

The modeling sensitivity experiment revealed that reducing snow depth by 40 % resulted in the best agreement between snow depth (on level ice) and level ice thickness. We applied a 40 % snow depth reduction in SMLG_HS to simulate level ice and snow-ice more realistically across the Arctic Ocean. It should be emphasized again that this reduction was derived by comparisons to IceBird observations from one year (2017) and from the western Arctic only. The mechanism of sub-parcel snow mass redistribution is not yet fully understood. The deformation rate of a sea ice floe, together with the atmospheric conditions (e.g. wind, warm intrusions) and the properties of snow cover (density, wetness, sintering level, and snow-surface shear strength) are expected to affect the snow redistribution, i.e., the amount of snow removed from the level to deformed ice. Ice and snow conditions are not uniform across the Arctic Ocean, but they vary regionally and temporally. Therefore, a 40 % reduction of snow depth on level ice is empirical and more data is needed from across the Arctic and the different seasons to support it. In another, yet more local example, data from the MOSAiC observatory indicated that only 18 % of the total snow-on-sea-ice volume remained on level ice by the end of spring (Itkin et al., 2023).

Due to the lack of information regarding several aspects of snow on sea ice, this study comes with some additional limitations. First, we assumed that negative freeboard always results in snow-ice formation. In reality, for flooding to occur, water pathways such as sea ice thermal cracks or leads are required. Even though these pathways become increasingly common in a thinner and more dynamic icescape (Kwok et al., 2013; Rampal et al., 2009), our assumption likely resulted in overestimation of snow-ice formation. Second, we did not account for snow loss into leads. Recent observations from the MOSAiC expedition demonstrated that this is likely an insignificant snow sink in winter, due to quick refreezing of the leads (Clemens-Sewall et al., 2023). This is further supported by the arguments put forth by Liston, Itkin, et al. (2020).

5 Conclusions

We showed that a 1D sea ice and snow thermodynamic model approach would overestimate snow sink in snow-ice formation. Even though the total snow depth (over both deformed and level ice) matched well with both OIB and IceBird observations, not accounting for snow redistribution from level to deformed ice resulted in overestimation of snow depth over level ice. As expected, this additional snow decelerated thermodynamic ice growth in the model, resulting in thinner level ice that is more prone to snow-ice formation. Based on the evaluation of our simulations against IceBird data, fitting both snow on level ice and level ice thickness simulations to the IceBird observations, snow depth in SMLG_HS should be reduced by 40 %. We argue that this 40 % reduction represented the sub-parcel snow mass redistribution process.

Snow-ice was recalculated based on the 40 % reduction of snow depth on level ice. When snow-ice was accounted for, snow depth in SMLG decreased and, in most cases, snow bulk density increased. Averaged across the entire Arctic Ocean on the day of maximum snow-on-sea-ice volume, and for the period 1980–2022, snow depth given by SMLG_HS was 3.5 % lower than SMLG, and snow density was 2.3 % higher. Due to the large re-
Regional variations of snow-ice formation, snow depth decreased locally by up to 58 cm and
bulk density increased locally by up to 296 kg m$^{-3}$. The largest differences were found
in the Atlantic sector of the Arctic Ocean, where snow-ice has the highest potential to
form (Merkouriadi et al., 2020).

Although snow depth, and the associated snow-ice formation, have decreased Arctic-
wide, modeling studies have indicated increasing trends in snow depth (Webster et al.,
2019) and snow-ice (Merkouriadi et al., 2020) regionally in the Atlantic sector of the Arc-
tic Ocean, especially along the east coast of Greenland, north of Svalbard, and at the
Lincoln Sea since the 1980s. The regional increase is significant and it is associated with
the intensification of storms that bring more precipitation to this part of the Arctic (Graham
et al., 2017; Rinke et al., 2017; Woods & Caballero, 2016).

When snow models do not account for snow sinks caused by snow and sea ice in-
teractions, such as snow-ice formation or sub-parcel snow mass redistribution processes,
they overestimate snow depth on level ice. Uneven snow-on-sea-ice load within a sub-
grid area will result in biases in altimetry retrievals of sea ice thickness by overestimat-
ing level ice and underestimating deformed ice thickness. Regarding sea ice modeling ap-
plications, spatial variability in snow depth will impact sea ice thermodynamic growth
in winter, affecting both vertical and horizontal heat fluxes (Clemens-Sewall et al., 2024;
Zampieri et al., 2024), and will influence meltpond formation in summer. Therefore, snow-
on-sea-ice reconstructions should be used with caution depending on the application re-
quirements. This study emphasizes the need to account for snow and sea ice interactions
to improve the representation of snow on sea ice in both numerical modeling and remote
sensing applications. It also highlights the crucial need for additional independent ob-
servations of snow depth and sea ice thickness, together with information on snow prop-
erties to understand the mechanism behind snow mass changes due to ice dynamics pro-
cesses better.

Data Availability Statement

Model input

Sea ice concentration data are available at DiGirolamo et al. (2022). Sea ice mo-
tion vectors are available at Tschudi et al. (2019). Atmospheric forcing data are avail-
able at Global Modeling And Assimilation Office (GMAO) (2015a, 2015b). Daily ocean
heat flux data were downloaded from ECMWF.

Evaluation

Airborne data are available at Jutila et al. (2021a, 2021b); Jutila et al. (2024a, 2024b)
for AWI IceBird and at Kurtz et al. (2015, 2016) for NASA OIB. SIMBA buoy data were
obtained from https://www.meereisportal.de and Lei et al. (2021, 2022, 2023).

Acknowledgments

IM was supported by the ESA grant CCI+ 4000126449/19/I-NB. IM and AJ were sup-
ported by the Research Council of Finland grant 341550. GEL was supported by the United
States National Science Foundation grant 1820927. AP was supported by the European
Union’s Horizon 2020 research and innovation programme under grant 101003472. The
authors are grateful to Bin Cheng for providing the software code for the model HIGH-
TSI. Autonomous sea ice measurements (temperature profile and heating cycle data) from
2012 to 2020 were obtained from https://www.meereisportal.de (grant: REKLIM-
2013-04). Scientific, color-vision deficiency friendly, and perceptually-uniform color maps
used in the figures of this manuscript were provided by Crameri (2023).
References


Supporting Information for “Investigating snow sinks on Arctic sea ice”

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Contents of this file

1. Text S1 to S2
2. Figures S1
3. Table S1

Introduction

The supporting information includes two short supporting texts (S1–S2) explaining one table (S1) and one figure (S1).

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May 27, 2024, 11:45am
Text S1. Model parametrization. Table S1 is descriptive, and it includes the HIGH- TSI model parameterization used in this study.

Text S2. Evaluation. Figure S1 shows a summary of the data from the Snow Ice Mass Balance Apparatus (SIMBA) buoys, where we examined wintertime formation of snow-ice. The height change of the snow/ice interface shows a shift upward together with a decrease in snow depth at the presence of modeled snow-ice formation. Decrease in modeled snow-ice thickness is due to the nearest-neighbour method of extracting the closest gridded model data based on the sub-daily drift track data of the SIMBA buoys.

References


May 27, 2024, 11:45am


Table S1. Model parameters and constants used in this study.

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Figure S1. Evaluation of the snow-ice formation using Snow Ice Mass Balance Apparatus (SIMBA) buoys. The left panels show the pan-Arctic simulated snow-ice thickness with the buoy location marked with a red dot on the day of identified flooding events. The middle panels show the time series of the snow depth measured by the buoy (black solid line, left vertical axes), of the snow/ice interface height change derived from the buoy data (red solid line, right vertical axes), and of the modeled snow-ice thickness of the nearest grid cell (red dashed line, right vertical axes) around the time of identified flooding events. The buoy names are given as the titles. Note the varying scales of the axes, both left and right vertical axes as well as the horizontal time axes. The gray background indicates the day depicted in the maps. The right panels show the drift track of the buoys with the start of the middle panel time series marked with a white dot and the time of identified flooding with a white star. Note the varying scale: however, a single grid cell is always 25 km $\times$ 25 km.