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Investigating snow sinks on level sea ice: A case study in the western Arctic

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ABSTRACT. We examined snow sinks on level sea ice caused by snow and sea ice interactions (snow-ice formation and sub-parcel snow mass redistribution) in the western Arctic. 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. SMLG_HS simulations of snow depth, snow-ice, and sea ice thickness were evaluated against high-resolution airborne observations from the western Arctic, highlighting the importance of snow mass changes due to snow redistribution processes. Without accounting for these processes, snow on level ice was overestimated by the model, resulting in underestimation of level ice thickness and overestimation of snow-ice thickness. In our case study, we show that snow depth on level ice needs to be reduced by up to 40 % to simulate both snow and level ice thicknesses realistically in the western Arctic in April 2017. Analysis of snow volume distribution between level and deformed sea ice using airborne radar observations supported the model results. In addition, it revealed a linear

relationship between the fraction of snow volume on level ice and the fraction of level ice along a sea ice transect in spring: $f_{V_{\mathrm{s,level}}} = (0.68 \pm 0.05) \times f_{\mathrm{level}}$.

1 INTRODUCTION

Arctic sea ice is going through unprecedented changes, decreasing dramatically both in extent (e.g. Stroeve and others, 2014) and in thickness (Maslanik and others, 2007; Kwok and others, 2009), and transitioning from a multi-year ice to a seasonal, first-year ice system (Meier and others, 2014). The role of snow in sea ice mass balance is becoming increasingly amplified in many ways, because of the higher sensitivity of sea ice to its environmental conditions. The thermal resistance of snow cover significantly reduces the atmosphere-ocean heat fluxes, regulating sea ice growth in winter (Maykut, 1978; Ledley, 1991). The high snow albedo reflects most of the solar radiation back to space, delaying sea ice from melting in spring (Perovich and others, 2017). The snow load may submerge thinner ice underneath the water level, creating negative freeboard conditions (Granskog and others, 2017; Merkouriadi and others, 2020). 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), and increases the thickness of the sea ice. 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 (Massom and others, 2001), but it was not commonly observed in situ in drifting Arctic sea ice until the Norwegian Young Sea ICE (N-ICE2015) expedition (Granskog and others, 2017; Provost and others, 2017). Snow-ice is a sink for snow, and it can positively contribute to the sea ice mass balance (Merkouriadi and others, 2017, 2020), which has implications for remote sensing retrievals of sea ice thickness. Therefore, it is essential to consider it for understanding sea ice mass balance, both in contemporary times in peripheral seas and in future scenarios where sea ice may be thinner than present-day conditions.

Accounting for different snow processes is also relevant for remote sensing applications. Satellite altimetry is the most common method for monitoring sea ice thickness, providing nearly full coverage of the Arctic Ocean (Laxon and others, 2003; Markus and others, 2017; Landy and others, 2022). Information on the snow load on sea ice is crucial for accurate 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 and others, 2003). According to Giles and others (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 and others (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 and others, 2014).

Snow depth and density estimates used in satellite altimetry applications are often derived from snow climatologies or modified versions of snow climatologies from historical observations. The most widely used snow-on-sea-ice climatology is compiled from a snow depth and density data set collected mostly over multi-year ice in 1954–1991 (Warren and others, 1999). In a changing Arctic sea ice system, snow conditions are expected to change as well (Blanchard-Wrigglesworth and others, 2015; Webster and others, 2021), and these changes are not captured by the Warren and others (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 (Warren and others, 1999; Webster and others, 2024). To account for spatiotemporal variability, efforts have focused on reanalysis-based snow depth and density reconstructions (e.g. Kwok and Cunningham, 2008; Blanchard-Wrigglesworth and others, 2018; Petty and others, 2018), i.e., simulations of snow depth and density evolution on sea ice. A recent contribution was SnowModel-LG, a state-of-the-art Lagrangian snow evolution model (Liston and others, 2020a). Compared to other reanalysis-based products, SnowModel-LG implemented Lagrangian parcel tracking and included an improved representation of snow evolution physics. It has been bias-corrected and validated against a wide observation framework in all seasons and yielded good agreement, especially with in situ measurements (Stroeve and others, 2020).

SnowModel-LG explicitly resolves many 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 and others, 2020a). However, SnowModel-LG, similarly to all the above-mentioned Arctic snow models, is not coupled to a sea ice model. Therefore, it does not account for snow sinks caused by snow-ice formation. Moreover, being configured over ice parcels of kilometer-scale, it does not resolve wind-driven 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 and others, 2018) as a result of snow redistribution by the wind. 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 examines snow sinks on level Arctic sea ice (snow-ice formation and sub-parcel snow mass redistribution), and quantifies their effect on snow depth evolution. To investigate this, we coupled SnowModel-LG with the High-Resolution Thermodynamic Sea Ice model (HIGHTSI) (Launiainen and Cheng, 1998) to produce SMLG_HS. In SMLG_HS, snow-ice forms when the ice surface is depressed below the water surface (negative freeboard). SMLG_HS outputs of snow depth, snow-ice and sea ice thickness from 1 August 2007 until 31 July 2021 were evaluated against airborne observations in the western Arctic 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 and Elder, 2006a; Liston and others, 2018). SnowModel-LG is adapted for snow depth and density reconstruction over sea ice (Liston and others, 2020a). It is implemented in a Lagrangian framework to simulate snow properties on drifting sea ice parcels. SnowModel-LG accounts for physical snow processes such as sublimation from static surfaces and blowing 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. The ice parcels are 1-D, and they do not interact with each other.

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,

$$\frac{\mathrm{d}SWE}{\mathrm{d}t} = \frac{1}{\rho_w}\left[(P_r + P_s) - (S_{ss} + S_{bs} + M) + D\right] \tag{1}$$

where t (s) is time; $\rho_w = 1000\,\mathrm{kg\,m^{-3}}$ is the water density; P_r ($\mathrm{kg\,m^{-2}\,s^{-1}}$) and P_s ($\mathrm{kg\,m^{-2}\,s^{-1}}$) are the water-equivalent rainfall and snowfall fluxes, respectively; S_{ss} ($\mathrm{kg\,m^{-2}\,s^{-1}}$) and S_{bs} ($\mathrm{kg\,m^{-2}\,s^{-1}}$) are the water-equivalent sublimation from static-surface and blowing-snow processes, respectively; M ($\mathrm{kg\,m^{-2}\,s^{-1}}$) is the melt-related mass loss; and D ($\mathrm{kg\,m^{-2}\,s^{-1}}$) represents the 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 (ρ_s), and water (ρ_w) densities,

$$SWE = \frac{\rho_s}{\rho_w} h_s. \tag{2}$$

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

$$\frac{\mathrm{d}\left(\rho_s h_s\right)}{\mathrm{d}t} = \left(P_r + P_s\right) - \left(S_{ss} + S_{bs} + M\right) + D. \tag{3}$$

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 summarized and provided in great detail in Liston and others (2020a). The model configuration in this study is identical to the one used in Liston and others (2020a), only here we have coupled it to a sea ice model (Sections 2.2–2.3). According to Stroeve and others (2020), SnowModel-LG performed well in capturing the spatial and seasonal variation of snow distributions, when evaluated against several Arctic data sets, including NASA Operation IceBridge (OIB), ice mass balance buoys, snow buoys, MagnaProbes, and ruler measurements.

In the simulations presented herein, Lagrangian parcel tracking began on 1 August 2007. At the start of the first simulation year, the model assumes no snow atop the sea ice, which is well supported by in situ observations from the contemporary period (Radionov and others, 1997; Chapman-Dutton and Webster, 2024; Webster and others, 2024); 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, described in detail in Section 2.4.

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 and Cheng, 1998) by solving the heat conduction equation for multiple ice and snow layers. The sea ice thermal conductivity is parameterized following Pringle and others (2007). HIGHTSI simulates snow-ice formation following Saloranta (2000).

HIGHTSI has been widely used in process studies and validated extensively against observations (Cheng and others, 2008b, 2013; Wang and others, 2015; Merkouriadi and others, 2017, 2020). 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 and others, 2008a). Here, we used 20 layers in the ice which is considered optimal for capturing internal thermodynamic processes (Cheng and others, 2008a,b, 2013; Wang and others, 2015). Detailed information on model parameterizations is given in Table S1 in the supplementary material.

Merkouriadi and others (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. We did this because SnowModel-LG provides a more advanced representation of snow physics compared to HIGHTSI's snow configuration. Additionally, we wanted to explore the effects of snow sinks using a publicly available snow product such as SnowModel-LG.

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 and others, 2020a). Second, SnowModel-LG's snow depth and density evolution were coupled with HIGHTSI's snow-ice and thermodynamic ice growth representations. The coupled output is hereafter referred to as being created by SMLG_HS.

For the SMLG_HS runs, snow density was simulated following Appendix C of Liston and others (2020a) and stored as a bulk density value. To represent the typical snow stratigraphy of snow on Arctic sea ice (i.e. high-density wind slab layer at the top, low-density depth hoar layer at the bottom), the vertical density profile was parameterized as being a linear fit between densities that are 20 % greater than the bulk snow density of SnowModel-LG at the top of the snowpack and 20 % less at the bottom of the snowpack. These percentages are consistent with snow-pit measurements made during the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition in 2019–2020 (Macfarlane and others, 2023). This approach was chosen to provide a best-possible fit to available snow density observations and 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 lower density 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 supplementary material (Table S1).

2.4 Input Data Sets

Daily ice concentrations (15–100 %) by the NASA team algorithm DiGirolamo and others (2022) were used to define whether an ice parcel existed and whether snow could accumulate on that parcel. Ice motion vectors from Tschudi and others (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; Global Modeling And Assimilation Office (GMAO), 2015a,b; Gelaro and others, 2017) 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 and Elder, 2006b) provided the required liquid and solid precipitation, and the downwelling shortwave and longwave radiation following Liston and others (2020a).

We applied the same bias-correction in MERRA-2 reanalysis as in Liston and others (2020a), where snow depth observations from NASA OIB (2009–2016) were used to scale the precipitation inputs. In Liston and others (2020a), 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 and others, 2020) model runs similar. Scaling factor was 1.37 for MERRA-2, indicating the need to increase the precipitation inputs in order to match the OIB observations. The same scaling factor was used in this study for the results to be comparable with the publicly available SnowModel-LG snow depth and density data set (Liston and others, 2020b).

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 and others, 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 2007 and ran through 31 July 2021. 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 daily 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 initial ice thickness conditions on 1 August 2007 were 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 14-year simulation (i.e., the model ran the first year twice and assumed the 31 July 2008 ice thickness distribution equaled the 1 August 2007 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 model spin-up procedures as implemented in Liston and others (2020a)).

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 the National Snow and Ice Data Center (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 Liston and others (2020a); Merkouriadi and others (2020).

2.6 Evaluation Exercise

To evaluate SMLG_HS snow depth and sea ice thickness, we compared them against a total of more than 100 airborne surveys from the Alfred Wegener Institute's (AWI) IceBird and NASA OIB campaigns over the western Arctic in late winter 2009–2019 (Fig. 1). Summarizing descriptions of the respective data sets are given in the Sections 2.6.1 and 2.6.2 below. We averaged the airborne measurements over the same model EASE grid when more than 50 values were present in a grid cell.

2.6.1 AWI IceBird

The AWI IceBird program carried out 11 survey flights over the western Arctic Ocean in April 2017 and 2019, monitoring the regional sea ice conditions in very high resolution (Table 1). The nominal measurement spacing along-track is 5–6 m. Snow depth data were derived from an airborne snow radar similar to OIB using the Peakiness retrieval algorithm (Jutila and others, 2021a,b, 2022b). Sea ice thickness was derived

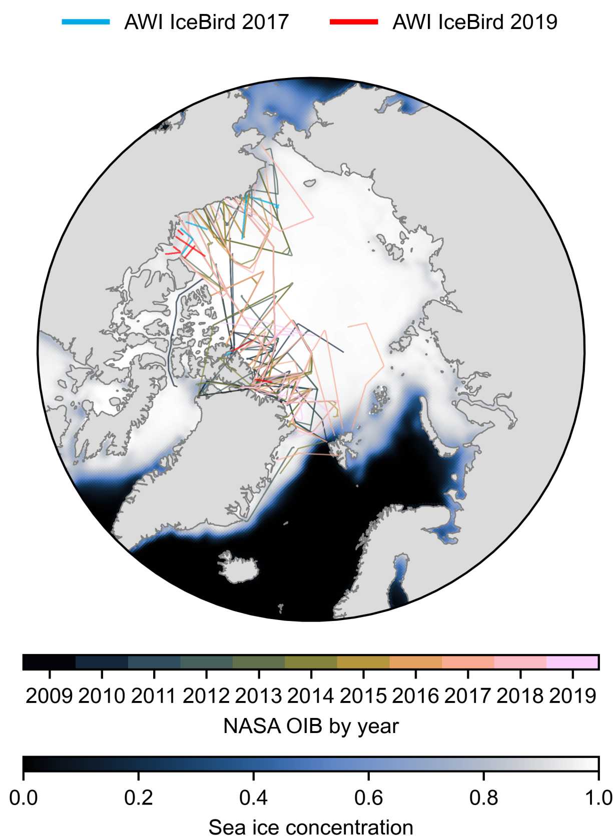

Fig. 1. Spatial and annual coverage of the 11 AWI IceBird survey flights in 2017 & 2019 (Table 1) and the 99 NASA Operation IceBridge (OIB) survey flights in 2009–2019 (Table 2 in Appendix A). The background shows the average March–April monthly sea ice concentration in 2009–2019.

Table 1. Statistics of the 11 AWI IceBird survey flights over the western Arctic Ocean in 2017 and 2019 (Fig. 1) used in this study, where L is the total length of the survey flight, $\bar{h}_{\mathrm{s,level}}$ is the average snow depth on level ice, $\bar{h}_{\mathrm{s,deformed}}$ is the average snow depth on deformed ice, $\bar{h}_{\mathrm{s,all}}$ is the average snow depth of the entire survey flight including all ice types, $\frac{\bar{h}_{\mathrm{s,level}}}{\bar{h}_{\mathrm{s,deformed}}}$ is the fraction of the average snow depth on level ice to the average snow depth on deformed ice, f_{level} is the level ice fraction of the survey flight, $f_{V_{\mathrm{s,level}}}$ is the fraction of snow volume on level ice, f_{MYI} is the fraction of multi-year ice (MYI), and f_{NaN} is the fraction of missing snow depth data

Date	L (km)	$\bar{h}_{\mathrm{s,level}}$ (m)	$\bar{h}_{\mathrm{s,deformed}}$ (m)	$\bar{h}_{\mathrm{s,all}}$ (m)	$\frac{\bar{h}_{\mathrm{s,level}}}{\bar{h}_{\mathrm{s,deformed}}}$	f_{level}	$f_{V_{\mathrm{s,level}}}$	f_{MYI}	f_{NaN}
2017-03-30	374	N/A[a]		0.327	N/A[a]				0.527
2017-04-02[b]	415	0.213	0.300	0.265	0.709	0.397	0.319	0.000	0.231
2017-04-04[b]	266	0.158	0.233	0.200	0.677	0.439	0.346	0.000	0.231
2017-04-06[b]	460	0.133	0.199	0.176	0.666	0.342	0.257	0.000	0.228
2017-04-08	619	0.080	0.162	0.136	0.490	0.323	0.189	0.000	0.308
2017-04-10	49	N/A[a]		0.226	N/A[a]				0.627
2019-04-02	408	0.361	0.377	0.375	0.956	0.128	0.123	0.808	0.446
2019-04-05	187	0.120	0.329	0.298	0.364	0.148	0.059	0.778	0.243
2019-04-07	470	0.069	0.211	0.160	0.328	0.363	0.157	0.183	0.491
2019-04-08	277	0.044	0.090	0.074	0.489	0.355	0.212	0.000	0.372
2019-04-10	415	0.080	0.216	0.166	0.371	0.369	0.178	0.219	0.256
min	49	0.044	0.090	0.074	0.328	0.128	0.059	0.000	0.228
mean	358	0.140	0.235	0.218	0.561	0.318	0.205	0.221	0.360
max	619	0.361	0.377	0.375	0.956	0.439	0.346	0.808	0.627

[a]Not applicable; no sea ice thickness measurements
[b]Used in the sensitivity experiment (Section 2.7)

by subtracting snow depth from the total (sea ice + snow) thickness data measured simultaneously with a towed electromagnetic sounding instrument (Jutila and others, 2022a; Jutila and others, 2024a,b). We distinguished measurements over level ice by 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 over continuous sections of at least 100 m long.

2.6.2 NASA OIB

Annual NASA OIB campaigns over the western Arctic Ocean took place in March–April 2009–2019 (MacGregor and others, 2021) and comprise 99 survey flights in total (Table 2 in Appendix A). We used the data products of Kurtz and others (2015, 2016) where the snow depth data were derived from airborne snow radars using the retrieval algorithms described in Kurtz and Farrell (2011); Kurtz and others (2013). The data are averaged in the along-track direction to a 40 m length scale. We did not use the OIB sea ice thickness to evaluate modeled sea ice thickness, because it is not directly measured but converted from freeboard and snow depth measurements assuming hydrostatic equilibrium. However, we did use it together with surface roughness data included in the product to guide a level ice identification similar to the IceBird data (Jutila and others, 2022a). To compensate for the increased uncertainty of sea ice thickness and the multiple times coarser along-track resolution compared to the IceBird data, we applied here more strict conditions including a sea ice thickness gradient threshold of 2 cm m^{-1} over continuous sections of at least 200 m long as well as ensuring a corresponding surface roughness value of less than 0.3 m. We determined the numerical values of these conditions through manual iteration and visually inspecting along-track sea ice transect profiles.

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, most snow models, 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 (Sturm and others, 2002; Webster and others, 2015; Itkin and others, 2023). We hypothesized that SMLG_HS would overestimate snow depth on level ice, and consequently underestimate level ice thickness and overestimate snow-ice thickness demonstrating the effect of sub-parcel snow mass redistribution processes.

To test our hypothesis, we performed a modeling sensitivity experiment, where we decreased snow depth in SMLG_HS by 10 % intervals. 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.

As an independent evaluation, we investigated the snow mass redistribution between level and deformed ice also along the 100+ airborne surveys in 2009–2019 by calculating the fraction of snow volume on level ice for each flight:

$$V_{\mathrm{s,tot}} = V_{\mathrm{s,level}} + V_{\mathrm{s,deformed}} = \bar{h}_{\mathrm{s,level}} \times f_{\mathrm{level}} + \bar{h}_{\mathrm{s,deformed}} \times (1 - f_{\mathrm{level}}) \,, \tag{4a}$$

$$f_{V_{\mathrm{s,level}}} = \frac{V_{\mathrm{s,level}}}{V_{\mathrm{s,tot}}} = \frac{\bar{h}_{\mathrm{s,level}} \times f_{\mathrm{level}}}{V_{\mathrm{s,tot}}}, \tag{4b}$$

where $V_{\mathrm{s,tot}}$ is the total snow volume, $V_{\mathrm{s,level}}$ is the snow volume on level ice, $V_{\mathrm{s,deformed}}$ is the snow volume on deformed ice, $\bar{h}_{\mathrm{s,level}}$ is the average snow depth on level ice, $\bar{h}_{\mathrm{s,deformed}}$ is the average snow depth on deformed ice, f_{level} is the level ice fraction, and $f_{V_{\mathrm{s,level}}}$ is the fraction of snow volume on level ice.

3 RESULTS

In the evaluation exercise, we compared SMLG_HS simulations of snow depth and sea ice thickness against independent airborne observations from the IceBird and OIB campaigns, and we were able to examine snow depth on level 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 0.06–0.07 m with a root-mean-square error (RMSE) of 0.10–0.11 m, but with an absolute error up to 0.45 m (Figs. 2a–d and Fig. 3a–b). For comparison, in the SMLG the maximum absolute error was even higher, 0.60 m. Therefore, SMLG_HS underestimated level ice thickness on average by 0.45 m with an RMSE of 0.62 m, but with an absolute error up to 1.76 m (Figs. 2e–h and Fig. 3e). This result was consistent in all IceBird flights examined in the evaluation exercise.

When we did not distinguish between level and deformed ice and 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 (Figs. 2a–d), with reduced RMSEs and biases compared to SMLG (Fig. 3c–d). 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?

We examined two different approaches to address the question above and to assess the sub-parcel snow mass redistribution: (1) by conducting a modeling sensitivity experiment with a subset of IceBird flights

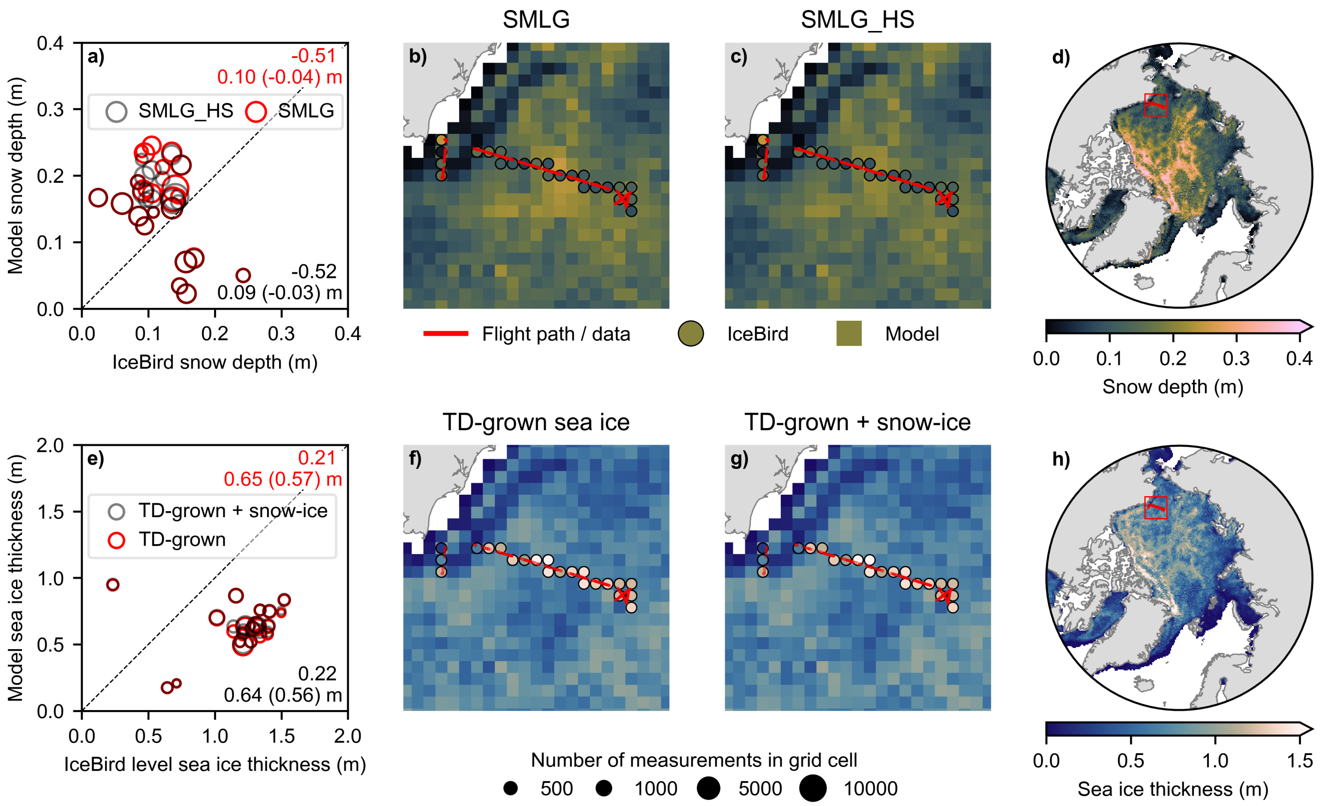

Fig. 2. Panels a)–d) show the evaluation of modeled snow depth from SMLG and SMLG_HS against airborne radar-derived snow depth measurements from the AWI IceBird survey flight on 8 April 2017. Red color refers to the original SMLG and black color to the new, coupled SMLG_HS. Panels e)–h) show the evaluation 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 same flight. The red square in panels d) and h) show the extent of panels b), c), f) and g). 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. In panels a) and e), 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.

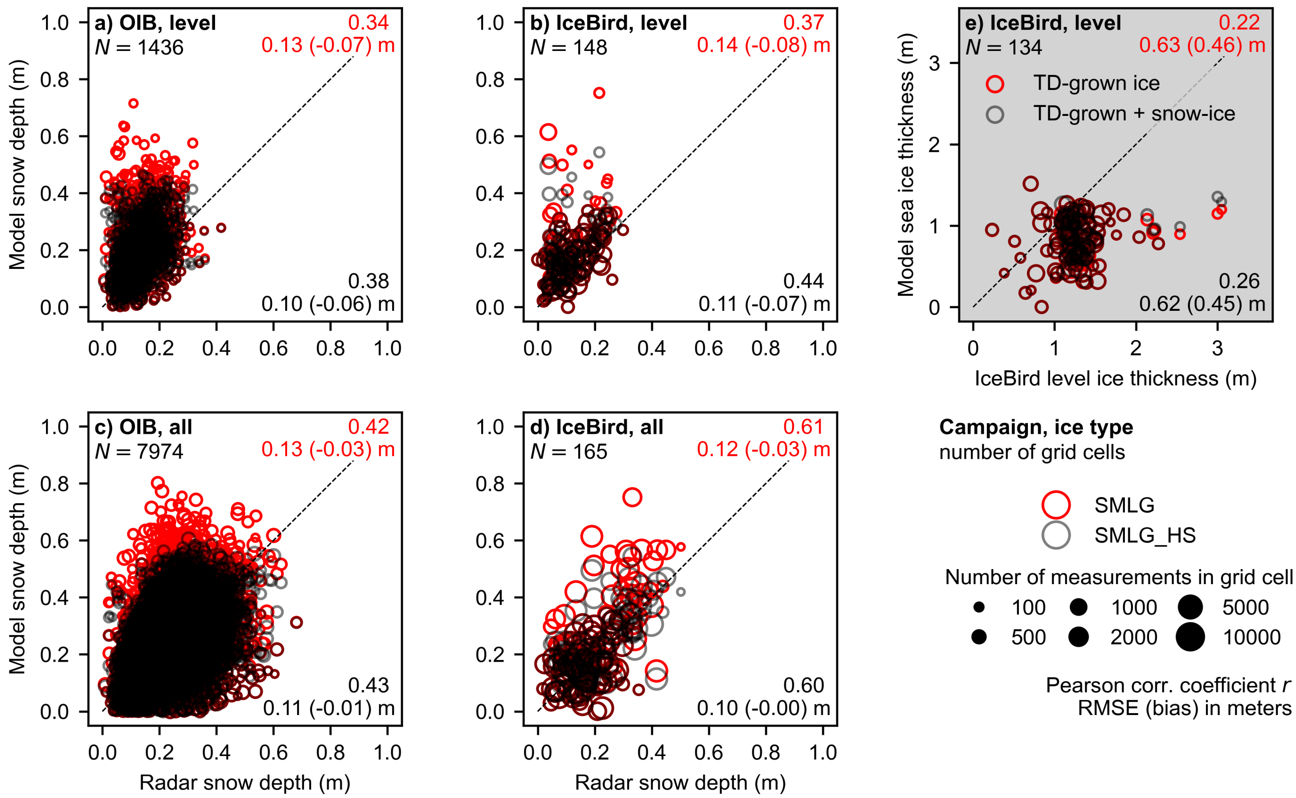

Fig. 3. Evaluation of the simulations compared against gridded airborne measurements. Panels a)–d) with white background show the modeled snow depth against radar-derived snow depth. The upper panels a)–b) show only measurements over level ice and the lower panels c)–d) show measurements over all ice types. The left-side panels a) & c) show the NASA Operation IceBridge (OIB) flights in 2009–2019 and the middle panels b) & d) show the AWI IceBird flights in 2017 & 2019. Red color refers to the original SMLG and black color to the new, coupled SMLG_HS. The upper right panel e) with grey background shows the modeled sea ice thickness compared against gridded airborne sea ice thickness measurements over level ice from the AWI IceBird campaigns in 2017 & 2019. 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. 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.

and (2) by performing an analysis of snow volume distribution between level and deformed sea ice based on all IceBird and OIB flight transects. The results of the modeling sensitivity 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, to maintain snow depth and sea ice thickness within their respective measurement uncertainties of 0.05 m and 0.12 m for the western Arctic in April 2017 (Fig. 4). This reduced the mean bias in level sea ice thickness by 53 % from 0.30 m to 0.14 m. The analysis of snow volume distribution along all the OIB and IceBird flight transects in 2009–2019 revealed a relationship between the fraction of level ice (f_{level}) along a sea ice transect and the fraction of snow volume on level ice ($f_{V_{\mathrm{s,level}}}$), demonstrating the effect of the sub-parcel snow mass redistribution (Fig. 5). This relationship is linear for fractions of level ice up to 0.5, and it can be given by

$$f_{V_{\mathrm{s,level}}} = (0.68 \pm 0.05) \times f_{\mathrm{level}}, \qquad (5)$$

where ± 0.05 represents the 95 % confidence interval of the slope.

4 DISCUSSION

We performed a modeling study to investigate snow sinks on level ice in the western Arctic. 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 1-D model, SMLG_HS considers level ice only and assumes that negative freeboard will lead to snow-ice formation. 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 and others, 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 transects 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

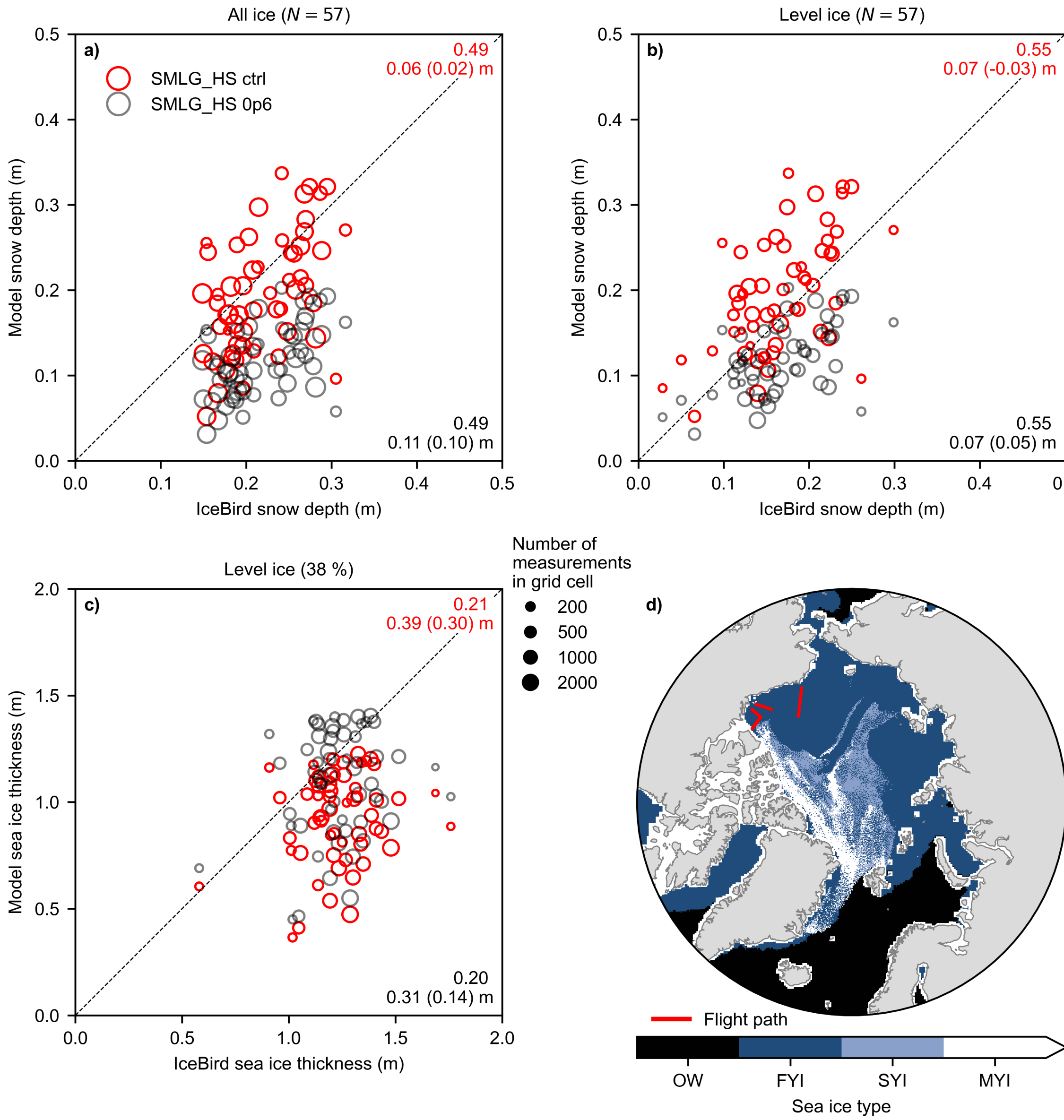

Fig. 4. Results of the sensitivity experiment showing a) snow depth over all (level and deformed) ice types, b) snow depth over level ice only, c) sea ice thickness over level ice, and d) location of the three IceBird flights (red lines; Table 1) together with the sea ice type in April 2017 at the time of the flights. The control simulation with unmodified snow depth (SMLG_HS ctrl) is shown as red circles and the simulation with snow depth reduced by 40 % (SMLG_HS 0p6) as black circles. 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. 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).

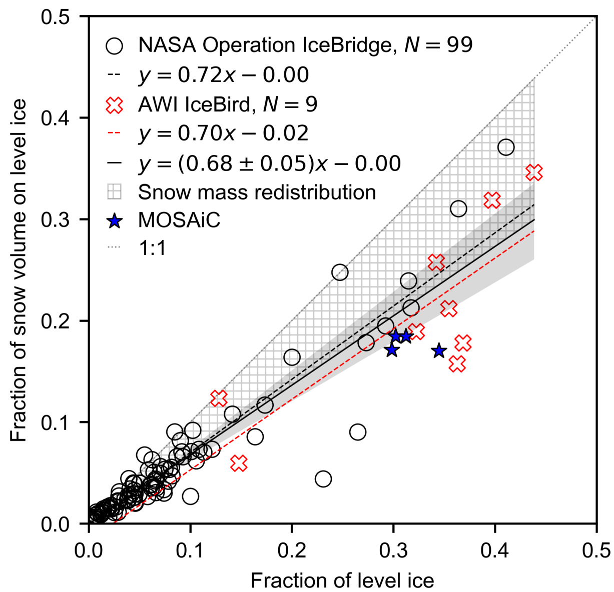

Fig. 5. The relationship between the fraction of level ice and the fraction of snow volume on level ice demonstrating the effect of snow mass redistribution (grey hatching). The NASA OIB survey flights are marked with black circles and their linear fit with a black dashed line, whereas the AWI IceBird ones are shown with red crosses and a red dashed line. The solid black line shows the linear fit of all airborne data and the grey shading is its 95 % confidence interval. The blue stars show the corresponding end-of-winter values in March–April 2020 from the MOSAiC expedition ground-based transect by Itkin and others (2023).

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 along the flight tracks. The limited level ice observations would impose a risk of unreliable conclusions, therefore we focused our analysis on flights with the largest level ice fraction in 2017. Moreover, the monitored region was occasionally close to the coast where parcel trajectory data are unavailable, rendering these regions outside the simulation domain and the sensitivity experiment.

The modeling sensitivity experiment showed that reducing snow depth by 40 % produced the best agreement between snow depth (on level ice) and level ice thickness in the western Arctic in April 2017 and reduced the mean bias in sea ice thickness by 53 %. The analysis of the snow volume distribution between level and deformed sea ice using observations from the IceBird and OIB transects was in good agreement with the model results when considering their respective limitations. The sensitivity experiment relies on a 1-D thermodynamic model that does not account for lateral conduction of heat, a factor that becomes significant when snow depth varies spatially (Clemens-Sewall and others, 2024; Zampieri and others, 2024). Regarding the airborne approach, it is not possible to account for snow sinks in snow-ice formation. Omitting snow-ice formation, that mostly occurs over level ice, would result in underestimation of the snow mass redistribution.

We argue that the snow depth decrease on level ice represents the sub-parcel snow mass redistribution process; however, this mechanism 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 across the Arctic and the different seasons to study the spatiotemporal variability of snow mass redistribution. In another, yet more local example by Itkin and others (2023), data from the MOSAiC expedition indicated that 31 % of level ice contained only 18 % of the snow volume at the end of spring (see the blue stars in Fig. 5). In the Surface Heat Budget of the Arctic Ocean (SHEBA) study in 1997–1998, snowdrifts associated with ridges occupied between 3 % and 6 % of the total study area. The drift sections had mean depths that were on average 30 % higher than the surrounding snow (Sturm and others, 2002).

Although the snow depth reduction suggested by the sensitivity experiment cannot be generalized across

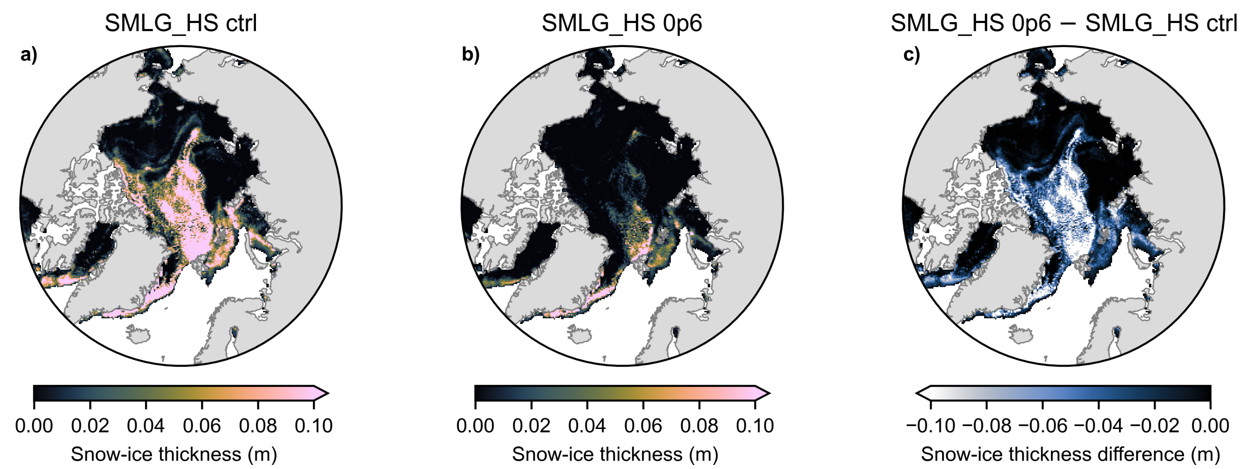

Fig. 6. Snow-ice thickness, 14-year average over the day of maximum snow-on-sea-ice volume in 2007–2021, from a) the control run (SMLG_HS ctrl), b) the run with snow depth reduced by 40 % (SMLG_HS 0p6), and c) the difference between the two simulations (reduced minus control).

the entire Arctic and across different years, as an illustrative attempt, we compared snow-ice formation results from the SMLG_HS simulation spanning the years 2007–2021, with and without a 40 % decrease in snow depth. The 14-year average snow-ice thickness on the day of maximum snow-on-sea-ice volume is shown in (Fig. 6). Even with a 40 % decrease in snow depth, snow-ice still has the potential to form and is characterized by strong seasonal and regional variations. However, 40 % less snow on level ice would greatly limit snow-ice formation in the central and western Arctic. This process would be primarily restricted to the Atlantic sector of the Arctic, particularly along Greenland's east coast and north of Svalbard underneath the North Atlantic storm track, where the N-ICE2015 campaign was conducted. Snow-ice formation has also been observed with autonomous sea ice mass balance buoys similar to Provost and others (2017) (Text S2 and Fig. S1 in the supplementary material) and in fully coupled climate models (Webster and others, 2021) in these regions in the contemporary period. Understanding the importance of sub-parcel snow mass redistribution will guide the development of necessary modeling tools that capture snow sinks properly.

5 CONCLUSIONS

We showed that a 1-D 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 in April 2017, 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 in our 2017 case study in the western Arctic, 40 % reduction in snow depth over level ice represented the sub-parcel snow mass redistribution process. Based on the analysis of more than 100 airborne survey flights spanning a full decade, the fraction of snow volume on level ice in spring is linearly related to the level ice fraction, and it is given by $f_{V_{\mathrm{s,level}}} = (0.68 \pm 0.05) \times f_{\mathrm{level}}$.

When snow models do not account for snow sinks caused by snow and sea ice interactions, 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 overestimating level ice and underestimating deformed ice thickness. Regarding sea ice modeling applications, spatial variability in snow depth will impact sea ice thermodynamic growth in winter, affecting both vertical and horizontal heat fluxes, and will influence melt pond formation in summer (Thielke and others, 2023). Therefore, snow-on-sea-ice reconstructions should be used with caution depending on the application requirements. This study emphasizes the need to account for sub-grid scale heterogeneity in snow and sea ice interactions to improve the representation of snow in remote sensing and model studies. It also highlights the crucial need for additional independent but simultaneous observations of snow depth and sea ice thickness, together with information on snow properties, to understand the mechanism behind snow mass changes due to coupled physical processes.

SUPPLEMENTARY MATERIAL

The supplementary material for this article can be found at... [LINK]

DATA

Model input

Sea ice concentration data are available at DiGirolamo and others (2022). Sea ice motion vectors are available at Tschudi and others (2019). Atmospheric forcing data are available at Global Modeling And Assimilation Office (GMAO) (2015a,b). Daily ocean heat flux data (opa0/daily_r1x1) were downloaded from ECMWF via the ECMWF ECGATE Class Service (ECS) computing facility using Teleport SSH and a personal ECMWF user account.

Evaluation

Airborne data are available at Jutila and others (2021a,b); Jutila and others (2024a,b) for AWI IceBird and at Kurtz and others (2015, 2016) for NASA OIB. Data for SIMBA buoys are available at Preußer and others (2024).

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XXX

AUTHOR CONTRIBUTIONS

Conceptualization: IM. **Data curation:** IM, AJ, GEL, AP. **Formal analysis:** IM, AJ. **Funding acquisition:** IM. **Investigation:** IM, AJ. **Methodology:** IM, GEL. **Project administration:** IM. **Resources:** IM. **Software:** GEL. **Supervision:** IM. **Validation:** IM, GEL. **Visualization:** AJ. **Writing — original draft:** IM. **Writing — review & editing:** IM, AJ, GEL, AP, MAW. Author contributions follow the Contributor Role Taxonomy (CRediT) (Brand and others, 2015; National Information Standards Organization (NISO), 2022).

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A APPENDIX – NASA OIB SURVEY STATISTICS

Table 2. Statistics of the 99 NASA Operation IceBridge survey flights over the western Arctic Ocean in 2009–2019 (Fig. 1) used in this study, where L is the total length of the survey flight, $\bar{h}_{\mathrm{s,level}}$ is the average snow depth on level ice, $\bar{h}_{\mathrm{s,deformed}}$ is the average snow depth on deformed ice, $\bar{h}_{\mathrm{s,all}}$ is the average snow depth of the entire survey flight including all ice types, $\frac{\bar{h}_{\mathrm{s,level}}}{\bar{h}_{\mathrm{s,deformed}}}$ is the fraction of the average snow depth on level ice to the average snow depth on deformed ice, f_{level} is the level ice fraction of the survey flight, $f_{V_{\mathrm{s,level}}}$ is the fraction of snow volume on level ice, f_{MYI} is the fraction of multi-year ice (MYI), and f_{NaN} is the fraction of missing snow depth data

Date	L (km)	$\bar{h}_{\mathrm{s,level}}$ (m)	$\bar{h}_{\mathrm{s,deformed}}$ (m)	$\bar{h}_{\mathrm{s,all}}$ (m)	$\frac{\bar{h}_{\mathrm{s,level}}}{\bar{h}_{\mathrm{s,deformed}}}$	f_{level}	$f_{V_{\mathrm{s,level}}}$	f_{MYI}	f_{NaN}
2009-04-02	2332	0.207	0.320	0.313	0.647	0.066	0.044	0.748	0.383
2009-04-05	2556	0.228	0.220	0.220	1.037	0.030	0.031	0.948	0.165
2009-04-21	631	0.235	0.356	0.351	0.660	0.036	0.024	0.894	0.423
2009-04-25	3050	0.168	0.277	0.273	0.605	0.038	0.024	0.341	0.783
2010-03-23	2660	0.267	0.334	0.333	0.799	0.014	0.011	0.998	0.362
2010-03-26	2822	0.107	0.240	0.232	0.443	0.058	0.027	0.858	0.425
2010-04-02	3039	0.099	0.135	0.130	0.733	0.142	0.108	0.743	0.145
2010-04-05	2796	0.126	0.228	0.222	0.552	0.062	0.035	0.952	0.321
2010-04-12	2570	0.162	0.285	0.280	0.568	0.044	0.026	0.986	0.313
2010-04-19	2028	0.152	0.229	0.223	0.660	0.082	0.055	0.982	0.140
2010-04-20	1733	0.144	0.257	0.252	0.560	0.045	0.026	0.957	0.192
2010-04-21	1885	0.107	0.249	0.238	0.432	0.074	0.033	0.985	0.496
2011-03-16	1126	0.155	0.200	0.198	0.775	0.051	0.040	0.884	0.115
2011-03-17	1869	0.175	0.227	0.226	0.771	0.029	0.022	0.791	0.074
2011-03-18	1779	0.188	0.234	0.233	0.805	0.013	0.011	0.970	0.121
2011-03-22	1159	0.142	0.210	0.207	0.676	0.041	0.028	0.949	0.058
2011-03-23	1402	0.084	0.123	0.111	0.683	0.315	0.239	1.000	0.158
2011-03-25	2248	0.228	0.199	0.200	1.142	0.007	0.008	0.929	0.135
2011-03-26	2247	0.201	0.245	0.244	0.821	0.021	0.018	0.980	0.126
2011-03-28	2669	0.150	0.237	0.235	0.631	0.023	0.014	0.769	0.202

(Continued)

Date	L (km)	$\bar{h}_{s,level}$ (m)	$\bar{h}_{s,deformed}$ (m)	$\bar{h}_{s,all}$ (m)	$\frac{\bar{h}_{s,level}}{\bar{h}_{s,deformed}}$	f_{level}	$f_{V_{s,level}}$	f_{MYI}	f_{NaN}
2012-03-14	2399	0.191	0.221	0.221	0.866	0.001	0.001	0.969	0.408
2012-03-15	2422	0.117	0.152	0.150	0.773	0.064	0.050	0.951	0.267
2012-03-16	2580	0.112	0.124	0.124	0.907	0.030	0.027	0.960	0.354
2012-03-17	2171	0.107	0.137	0.136	0.782	0.050	0.040	0.937	0.271
2012-03-19	2187	0.313	0.258	0.258	1.214	0.001	0.001	0.930	0.259
2012-03-21	2340	0.182	0.247	0.247	0.734	0.012	0.009	0.769	0.416
2012-03-22	2043	0.180	0.241	0.241	0.745	0.012	0.009	0.917	0.349
2012-03-23	2453	0.206	0.257	0.257	0.803	0.004	0.004	0.942	0.343
2012-03-26	1473	0.225	0.241	0.241	0.933	0.006	0.005	1.000	0.702
2012-03-27	1878	0.196	0.302	0.301	0.651	0.007	0.004	0.994	0.424
2012-03-28	2473	0.304	0.230	0.230	1.323	0.006	0.008	0.647	0.599
2012-03-29	2113	0.348	0.324	0.324	1.074	0.009	0.010	0.987	0.210
2012-04-02	2270	0.206	0.281	0.281	0.732	0.004	0.003	0.776	0.455
2012-04-10	1809	0.065	0.266	0.265	0.244	0.007	0.002	0.863	0.657
2013-03-21	2521	0.133	0.206	0.198	0.647	0.109	0.073	0.983	0.374
2013-03-22	2481	0.109	0.109	0.109	1.001	0.247	0.247	0.986	0.516
2013-03-23	2325	0.114	0.197	0.171	0.580	0.317	0.213	0.958	0.264
2013-03-24	2380	0.116	0.138	0.129	0.845	0.411	0.371	0.949	0.233
2013-03-26	2234	0.197	0.270	0.268	0.730	0.029	0.021	0.913	0.169
2013-03-27	2464	0.140	0.365	0.348	0.385	0.074	0.030	0.684	0.292
2013-04-22	2007	0.187	0.306	0.298	0.611	0.061	0.038	0.967	0.247
2013-04-24	2400	0.206	0.300	0.293	0.686	0.071	0.049	0.804	0.400
2013-04-25	1739	0.192	0.315	0.307	0.610	0.062	0.039	0.925	0.330
2014-03-12	1110	0.183	0.171	0.172	1.071	0.085	0.090	0.847	0.505
2014-03-13	1824	0.290	0.258	0.259	1.125	0.040	0.044	0.910	0.268
2014-03-14	2465	0.150	0.193	0.190	0.779	0.071	0.056	0.985	0.344
2014-03-15	2143	0.136	0.135	0.135	1.010	0.062	0.063	0.956	0.645
2014-03-17	2058	0.141	0.159	0.157	0.886	0.102	0.092	0.848	0.381

(Continued)

Date	L (km)	$\bar{h}_{s,level}$ (m)	$\bar{h}_{s,deformed}$ (m)	$\bar{h}_{s,all}$ (m)	$\frac{\bar{h}_{s,level}}{\bar{h}_{s,deformed}}$	f_{level}	$f_{V_{s,level}}$	f_{MYI}	f_{NaN}
2014-03-18	2386	0.129	0.145	0.144	0.894	0.059	0.053	0.946	0.563
2014-03-19	2354	0.135	0.150	0.149	0.896	0.090	0.082	0.954	0.435
2014-03-21	2225	0.301	0.253	0.253	1.187	0.005	0.006	1.000	0.412
2014-03-24	1150	0.274	0.220	0.223	1.241	0.055	0.068	0.678	0.455
2014-03-25	2232	0.065	0.108	0.107	0.602	0.027	0.016	0.014	0.422
2014-03-26	2204	0.396	0.267	0.268	1.485	0.008	0.011	0.972	0.332
2014-03-28	1495	0.250	0.287	0.286	0.872	0.015	0.013	0.960	0.289
2014-03-31	1577	0.093	0.299	0.295	0.313	0.020	0.006	0.886	0.306
2014-04-03	2994	0.216	0.277	0.276	0.779	0.019	0.015	0.955	0.209
2014-04-28	2115	0.244	0.279	0.278	0.877	0.018	0.016	0.889	0.238
2015-03-19	937	0.214	0.299	0.296	0.714	0.045	0.032	0.699	0.519
2015-03-24	1378	0.255	0.307	0.305	0.830	0.041	0.034	0.822	0.458
2015-03-25	2275	0.170	0.297	0.291	0.571	0.050	0.029	0.917	0.259
2015-03-26	2177	0.155	0.247	0.243	0.628	0.046	0.029	0.974	0.351
2015-03-27	2083	0.125	0.246	0.238	0.509	0.067	0.035	0.955	0.501
2015-03-29	2466	0.115	0.170	0.165	0.679	0.101	0.071	0.923	0.420
2015-03-30	2134	0.100	0.180	0.172	0.555	0.106	0.062	0.867	0.462
2015-04-01	1646	0.157	0.379	0.378	0.414	0.004	0.002	1.000	0.276
2015-04-03	1503	0.228	0.333	0.330	0.685	0.022	0.015	0.952	0.306
2016-04-20	2536	0.107	0.285	0.280	0.375	0.029	0.011	0.952	0.652
2016-04-21	2337	0.108	0.156	0.154	0.692	0.039	0.027	0.793	0.749
2016-04-29	2079	0.340	0.343	0.343	0.990	0.015	0.014	0.843	0.656
2016-05-03	1749	0.290	0.339	0.339	0.855	0.003	0.003	0.782	0.599
2016-05-04	1724	0.252	0.307	0.306	0.823	0.007	0.006	0.808	0.668
2017-03-09	2146	0.154	0.279	0.269	0.552	0.082	0.047	0.950	0.158
2017-03-10	2368	0.167	0.225	0.220	0.740	0.087	0.066	0.959	0.271
2017-03-11	2193	0.106	0.181	0.159	0.585	0.292	0.195	0.994	0.168
2017-03-12	2262	0.105	0.133	0.123	0.785	0.364	0.310	0.970	0.246

(Continued)

Date	L (km)	$\bar{h}_{s,\text{level}}$ (m)	$\bar{h}_{s,\text{deformed}}$ (m)	$\bar{h}_{s,\text{all}}$ (m)	$\frac{\bar{h}_{s,\text{level}}}{\bar{h}_{s,\text{deformed}}}$	f_{level}	$f_{V_{s,\text{level}}}$	f_{MYI}	f_{NaN}
2017-03-14	2378	0.193	0.247	0.236	0.782	0.200	0.164	0.881	0.049
2017-03-20	2300	0.183	0.280	0.272	0.651	0.080	0.053	0.956	0.232
2017-03-23	2096	0.172	0.390	0.380	0.441	0.045	0.020	1.000	0.317
2017-03-24	1233	0.141	0.333	0.328	0.424	0.025	0.011	0.980	0.212
2017-04-03	769	0.037	0.241	0.194	0.153	0.231	0.044	0.677	0.564
2017-04-05	2635	0.175	0.252	0.246	0.696	0.075	0.053	0.976	0.382
2017-04-06	1703	0.097	0.169	0.149	0.577	0.273	0.178	0.719	0.287
2017-04-07	2469	0.123	0.290	0.282	0.425	0.046	0.020	0.927	0.306
2017-04-11	2182	0.187	0.300	0.292	0.623	0.066	0.042	0.925	0.201
2017-04-19	1690	0.145	0.255	0.241	0.571	0.121	0.073	0.931	0.186
2018-03-22	1914	0.117	0.265	0.256	0.442	0.066	0.030	0.814	0.264
2018-04-03	1446	0.110	0.230	0.210	0.476	0.164	0.085	0.894	0.381
2018-04-04	2186	0.178	0.325	0.316	0.546	0.064	0.036	0.922	0.174
2018-04-06	2662	0.177	0.300	0.286	0.590	0.113	0.070	0.971	0.306
2018-04-07	2302	0.143	0.227	0.212	0.629	0.174	0.117	0.934	0.370
2018-04-08	2163	0.165	0.240	0.233	0.687	0.093	0.066	0.991	0.637
2018-04-14	2403	0.075	0.275	0.222	0.275	0.265	0.090	0.944	0.314
2018-04-16	2449	0.087	0.353	0.326	0.246	0.100	0.027	0.933	0.154
2019-04-06	1953	0.210	0.366	0.360	0.574	0.039	0.023	0.890	0.202
2019-04-12	1548	0.164	0.218	0.213	0.752	0.092	0.071	1.000	0.061
2019-04-19	1184	0.281	0.323	0.321	0.872	0.045	0.039	0.989	0.070
2019-04-20	1599	0.180	0.353	0.340	0.510	0.078	0.042	0.838	0.306
2019-04-22	743	0.241	0.267	0.266	0.903	0.044	0.040	0.978	0.063
min	631	0.037	0.108	0.107	0.153	0.001	0.001	0.014	0.049
mean	2062	0.174	0.249	0.243	0.714	0.074	0.051	0.894	0.336
max	3050	0.396	0.390	0.380	1.485	0.411	0.371	1.000	0.783

Supplementary material to the manuscript *"Investigating snow sinks on level sea ice: A case study in the western Arctic"*

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Contents of this file

1. Text S1 to S2
2. Figure S1
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Introduction

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

Text S1. Model parametrization. Table S1 is descriptive, and it includes the HIGHTSI model parameterization used in this study.

Text S2. Snow-ice detection with buoys. We evaluated temperature profile and heating cycle data from thermistor strings of Snow Ice Mass Balance Apparatus (SIMBA) buoys (Jackson and others, 2013) deployed in the Arctic in 2012–2020 to detect flooding (Preußer and others, 2024). Changes in thermal diffusivity, temperature, and heat propagation distinguish the temporal evolution of different layers and their thicknesses (Provost and others, 2017; Preußer and others, 2023). Figure S1 shows a summary of SIMBA buoy data, where we examined wintertime snow-ice formation. 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.

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

Parameter	**Value**	**Remarks/Source**
Extinction coefficient of sea ice (k_i)	1.5–17 m^{-1}	adopted from the paper by Grenfell and Maykut (1977)
Extinction coefficient of snow (k_s)	15–25 m^{-1}	Perovich (1996)
Surface albedo ($\alpha_{s,i}$)	Time dependent	Briegleb and others (2004)
Freezing point (T_f)	$-1.8\,°C$	
Sea ice volumetric heat capacity (ρc_i)	Function of T_i, s_i	Maykut and Untersteiner (1971)
Heat capacity of ice (c_i)	2093 $J\,kg^{-1}\,K^{-1}$	
Latent heat of freezing (L_i)	$0.33 \times 10^6\,J\,kg^{-1}$	
Oceanic heat flux (F_w)	Time dependent	ECMWF; Zuo and others (2019)
Sea ice density (ρ_i)	910 $kg\,m^{-3}$	
Snow-ice density (ρ_{si})	850 $kg\,m^{-3}$	Wang and others (2015)
Slush density (ρ_{sl})	920 $kg\,m^{-3}$	Wang and others (2015)
Sea ice salinity (s_i)	1–6	Ice core measurement Granskog and others (2017)
Snow density (ρ_s)	Time dependent	Liston and others (2020)
Surface emissivity (e)	0.97	
Sea ice heat conductivity (k_{si})	Function of T_i, s_i	Pringle and others (2007)
Thermal conductivity of ice (k_i)	2.03 $W\,m^{-2}$	Maykut and Untersteiner (1971)
Time step of model (t)	3 h	
Initial temperature in snow and ice	[$-1.25\,°C$, $-1.8\,°C$]	Cheng and others (2008)
Number of layers in the ice	20	
Number of layers in the snow	25	

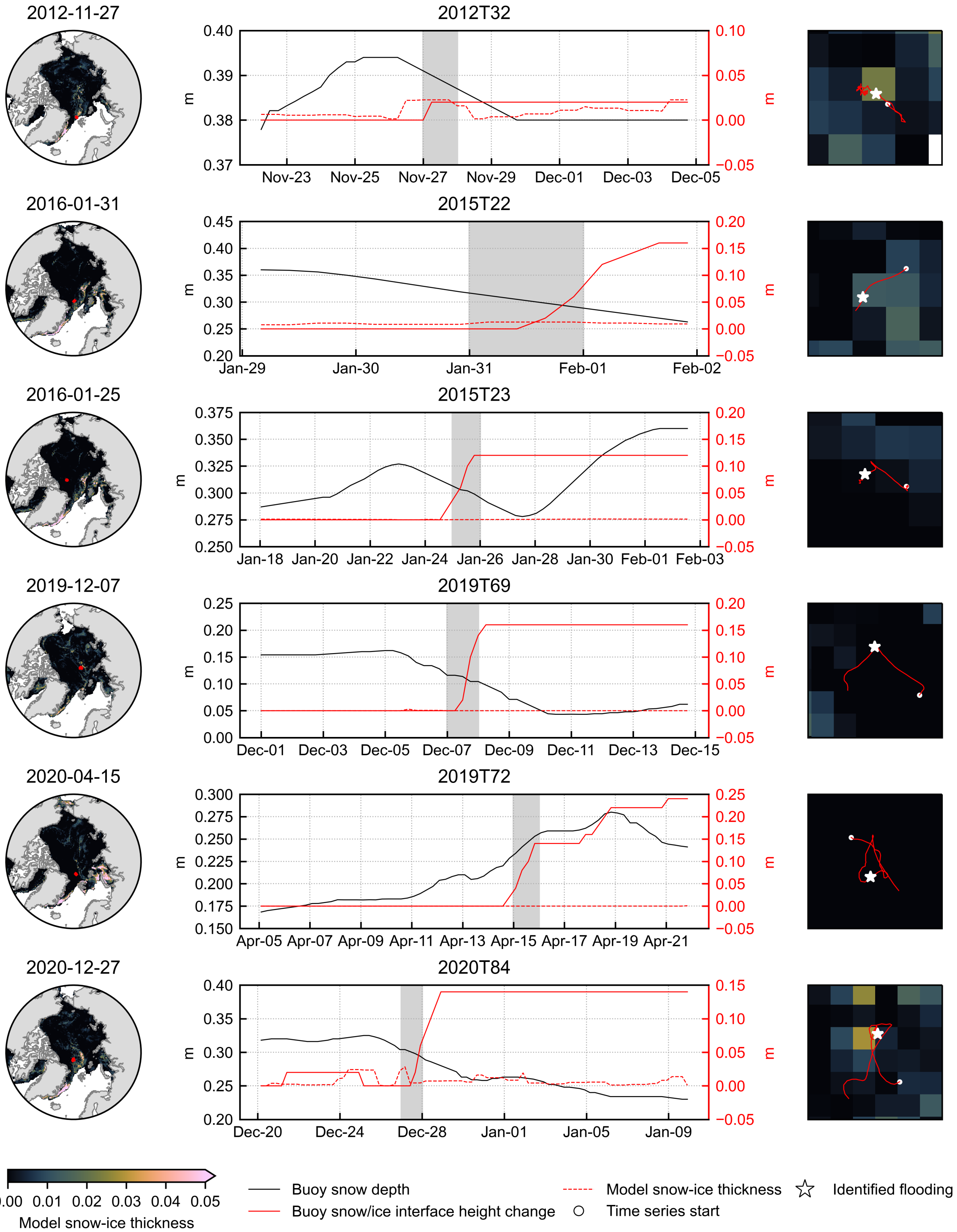
2012-11-27
2012T32
2016-01-31
2015T22
2016-01-25
2015T23
2019-12-07
2019T69
2020-04-15
2019T72
2020-12-27
2020T84
0.00 0.01 0.02 0.03 0.04 0.05
Model snow-ice thickness
Buoy snow depth
Buoy snow/ice interface height change
Model snow-ice thickness
Time series start
Identified flooding

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 × 25 km.

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