Effect of frequent winter warming events (storms) and snow on sea-ice growth – a case from the Atlantic sector of the Arctic Ocean during the N-ICE2015 campaign

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Abstract

We examine the relative effect of warming events (storms) and snow cover on thermodynamic growth of Arctic sea ice in winter. We use a 1-D snow and ice thermodynamic model to perform sensitivity experiments. Observations from the winter period of the Norwegian young sea ICE (N-ICE2015) campaign north of Svalbard are used to initiate and force the model. The N-ICE2015 winter was characterized by frequent storm events that brought pulses of heat and moisture, and a thick snow cover atop the sea ice (0.3–0.5 m). By the end of the winter, sea-ice bottom growth was negligible. We show that the thermodynamic effect of storms to the winter sea-ice growth is controlled by the amount of snow on sea ice. For 1.3 m initial ice thickness, the decrease in ice growth caused by the warming events ranged from −1.4% (for 0.5 m of snow) to −7.5% (for snow-free conditions). The decrease in sea-ice growth caused by the thick snow (0.5 m) was more important, ranging from −17% (with storms) to −23% (without storms). The results showcase the critical role of snow on winter Arctic sea-ice growth.

Introduction

The Arctic sea-ice system is going through a transition, from a multi-year to a thinner, seasonal, first-year ice system (Comiso, 2002; Maslanik and others, 2011; Meier and others, 2014). In wintertime, the thinner sea ice becomes more vulnerable to changes in the atmospheric boundary conditions, such as air temperature, wind speed and precipitation. These changes are often associated with storm activity. Most severe storms occur during the Arctic winter and they originate from the North Atlantic Ocean (Zhang and others, 2004; Sorteberg and Walsh, 2008). They enter the Arctic Ocean via the Fram Strait and the Barents Sea region and bring pulses of heat and moisture further north, reducing the heat loss from the ocean to the atmosphere and hindering sea-ice growth (Graham and others, 2019).

A number of studies has been carried out on investigating the relation between storms and sea-ice retreat in autumn and summer (Screen and others, 2011; Zhang and others, 2013; Babb and others, 2016). Due to the scarcity of continuous winter observations in the Arctic Ocean, winter studies rely on atmospheric reanalyses and remote-sensing products. Atmospheric reanalyses suffer from large air temperature biases during winter, and substantial precipitation spreads among different simulation products (Lindsay and others, 2014; Boisvert and others, 2018). Remote-sensing products for sea-ice thickness retrievals, rely on accurate information of snow depth on sea ice. Uncertainties in the amount of snow on sea ice can induce large errors in acquiring sea-ice thickness (Giles and others, 2007; Haapala and others, 2013; Ricker and others, 2015). This was especially evident in the Norwegian young sea ICE (N-ICE2015) study region (King and others, 2018). Therefore, winter observations become very valuable for understanding the new Arctic sea-ice system.

The N-ICE2015 is the most comprehensive, multidisciplinary campaign in the Atlantic sector of the Arctic Ocean including winter observations. N-ICE2015 observations provide a unique testbed to investigate closer the influence of the storm activity on the sea-ice growth evolution in winter. During the N-ICE2015 campaign (Granskog and others, 2018), frequent storms and thick snow on sea ice were observed from January to March 2015 north of Svalbard (Graham and others, 2019). In this study, we aim to examine the effect of snow and storm-induced warming events on Arctic sea-ice thermodynamic growth in winter. We do this by performing a modelling sensitivity study guided by observations collected during the N-ICE2015 campaign. In this study we focus on the interaction between the sea ice and the atmosphere. For that purpose we apply a low ocean heat flux, representative of deep Arctic basin conditions.

Materials and Methods

Observations during the N-ICE2015 campaign

During the winter part of the N-ICE2015 campaign, the R/V Lance was tethered to two different ice floes (Floe 1 and 2) north of Svalbard and moved passively with the ice drift. Comprehensive observations of sea-ice thickness and snow depth were collected from snow
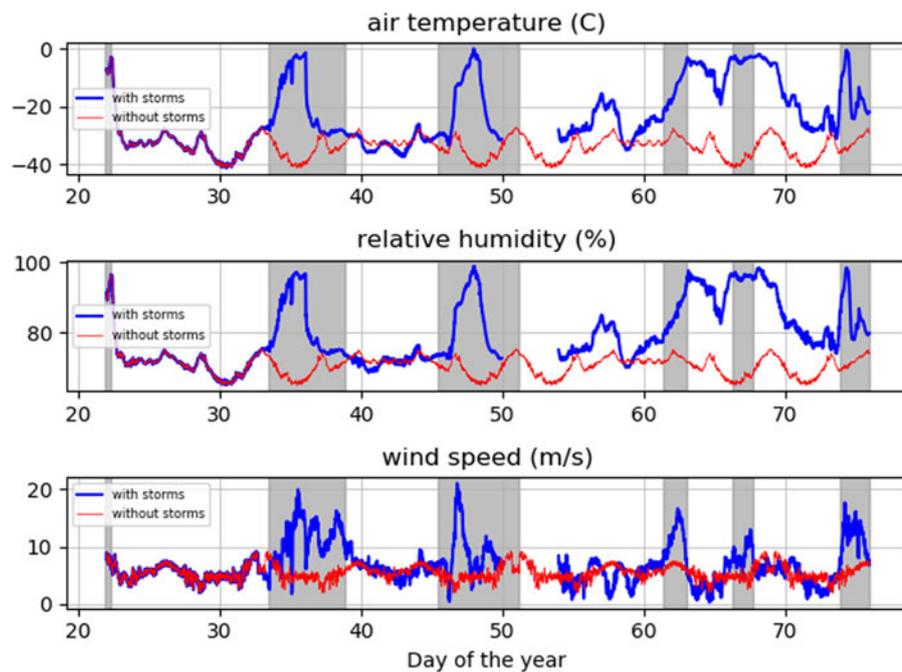
buoys, ice mass-balance buoys (IMBs), electromagnetic induction (EM) surveys (ground-based) and snow probe measurements (Rösel and others, 2018). Even though air temperature was mostly below −30°C, sea-ice thickness increased only slightly during the observation period. This was attributed to the thick snow (Rösel and others, 2018) that provided thermal insulation to the sea ice, and to the frequent synoptic storms that brought pulses of heat and moisture in the region (Cohen and others, 2017). In this study, we aim to investigate the relative importance of these two factors (snow and frequent warming events caused by storms) for the thermodynamic growth of sea ice.

Six major winter storms occurred during the N-ICE2015 campaign (Cohen and others, 2017). The storms were characterised by a considerable pressure drop, and a large increase in the air temperature, wind speed and relative humidity (Fig. 1). In most cases near-surface air temperatures rose by more than 20°C in 48 h (Cohen and others, 2017). The net longwave radiative flux rose from ∼−60 to 0 W m^{-2} in 12 h (Walden and others, 2017). The atmospheric boundary layer became warmer than the ice and snow surface, triggering downward conductive heat fluxes that warmed the snow and the upper layers of sea ice (Graham and others, 2019). The average wind speed throughout the winter was 6.8 m s^{-1}, and at instances it rose above 20 m s^{-1} during the major storms (Cohen and others, 2017). On 18 February, Floe 1 broke up. R/V Lance had to relocate, and it reached Floe 2 on 23 February. The meteorological measurements were interrupted during this period.

The model experiments

We used HIGHTSI, a 1-D, high resolution, thermodynamic ice and snow model (Launiainen and Cheng, 1998), to assess the effect of the storms and snow load on the winter sea-ice growth. HIGHTSI has been used widely in sea-ice modelling applications in the Arctic Ocean, and has been extensively validated against observations (Cheng and others, 2008, 2013; Wang and others, 2013, 2015; Merkouriadi and others, 2017). HIGHTSI resolves the evolution of snow depth, sea-ice thickness and temperature profiles in response to prescribed meteorological forcing.

Data from the winter part of the N-ICE2015 campaign (22 January–15 March) were used to guide the model experiments.

We used snow and sea-ice thickness and temperature profile data from one of the N-ICE2015 IMBs (SIMBA_2015a) to initiate the experiments (Provost and others, 2017; Rösel and others, 2018). *In situ* observations from the N-ICE2015 campaign including air temperature (2 m), wind speed (10 m), relative humidity (2 m) (Fig. 1) and downward longwave radiative flux (Fig. 2b) were used to force HIGHTSI (Hudson and others, 2015, 2016). Upward longwave radiative flux observations are also available and they were used to validate HIGHTSI modelled values. There was a very good agreement between the observed and the modelled upward longwave radiative flux (Fig. 2a). The downward solar radiative flux is available only from 3 March onward. The values remained small and the effect on the surface heat balance is negligible, therefore solar radiation was neglected in the experiments. When R/V Lance was relocated in late February to Floe 2, weather conditions remained stable without storm events. During this time, we applied linear interpolation to all parameters, to fill the gaps in the observational data.

To examine the effect of storms on the thermodynamic growth of sea ice, we created two meteorological forcing datasets. One is based on the meteorological data collected during N-ICE2015 that were characterized by frequent storms (Fig. 1). In the other one we manually removed the effect of storms on the observed parameters, by cycling through observations from the cold and calm periods (Days 24–33). Time series of air temperature, wind speed, relative humidity and downward longwave radiative flux were artificially created (Figs 1 and 2 in red) and were used as model forcing to investigate the sea-ice growth without the warming effect of storms. During the calm and cold periods, average air temperature, wind speed, relative humidity and net longwave radiative flux values were −33.6°C, 5.5 m s^{-1}, 70.8% and −41.3 W m^{-2}, respectively. These values are quite representative of the Arctic Ocean in winter (Wang and others, 2019).

Initial snow density was assumed to be uniform (350 kg m^{-3}) for the entire snowpack. The densification of snow was considered according to Anderson (1976). The snow depth during the experiments was kept constant for simplicity. A constant snow depth is not realistic; however, even though storms brought precipitation at N-ICE2015, in some locations the snow depth did not increase much, due to wind-blown snow (Rösel and others, 2018). We conducted experiments with four snow depths (h_s): $h_s = 0.50$,
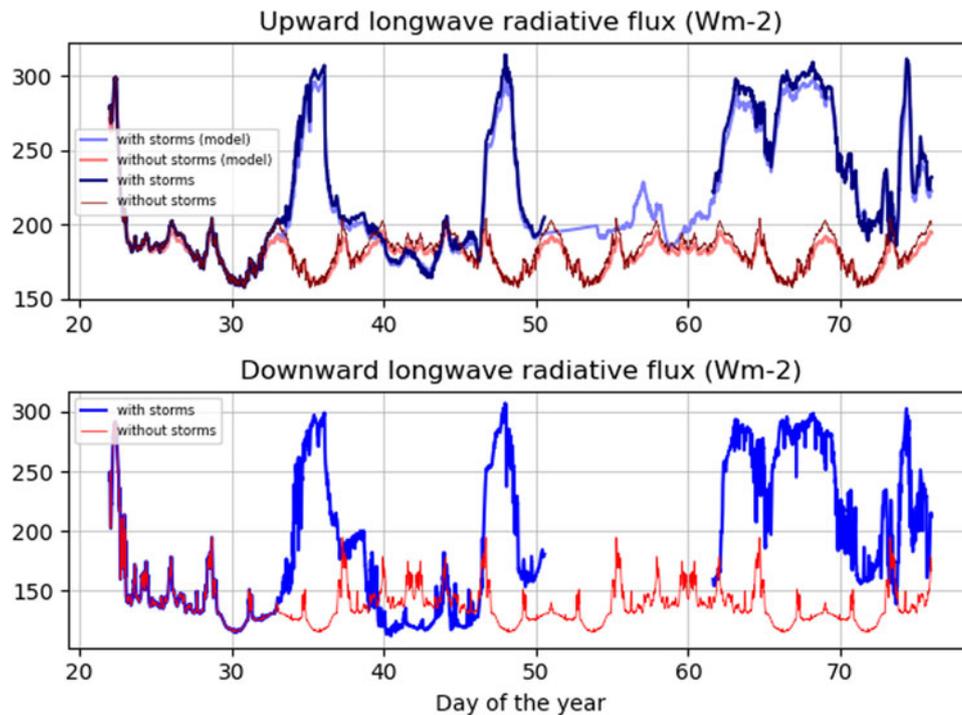
Fig. 2. Upward and downward longwave radiative flux used to perform the model experiments. The N-ICE2015 observations are in blue. The modified fluxes to remove the effect of storms are in red. The lighter coloured lines are the modelled upward longwave radiative fluxes.

0.30 0.15 and 0 m and an ice thickness of 1.3 m, which is representative of a typical ice thickness during N-ICE2015. The initial snow and ice temperature profiles were taken from the SIMBA_2015a IMB (Provost and others, 2017). For the experiments in which we used thinner initial snow depths, the snow temperature profiles were adapted by preserving the observed initial temperature gradient between the snow surface and the snow/ice interface. A snow depth of 0.50 m corresponded to the snow conditions that were observed at the start of the N-ICE2015 campaign (22 January). $h_s = 0.30$ m of snow corresponds to the climatological mean based on the snow climatology by Warren and others (1999). $h_s = 0.15$ m is considered a typical value of the western Arctic (Webster and others, 2014). Finally, we performed a snow-free experiment as a reference, in order to isolate the warming effect of storms. We repeated the same experiments for initial ice thicknesses (h_{0i}) of 0.5 and 2.0 m, to examine the sensitivity of our results to different initial ice thickness conditions. The time step of our experiments was 15 min.

Our purpose was not to reproduce the N-ICE2015 observations, but to conduct an idealistic, sensitivity study representative for the ice pack in the deep Amundsen basin during this period. For this reason, we kept a constant, low ocean heat flux ($F_w = 1$ Wm^{-2}), representative of the conditions in the deep basin (McPhee and others, 2003). We did not allow for snow-ice formation (which would have been the case for the largest snow depth), as widespread negative freeboard without flooding was observed (Rösel and others, 2018). Detailed information on the model parameterizations are given in Table 1.

Results

The simulated temperature profiles inside the ice and snow, with and without the effect of the storms, and for different snow depths, are shown in Figure 3. The pulses of heat brought by the storms have a clear signature in the snow temperature profiles (Fig. 3, left panels). Under a thick snow cover ($h_s = 0.5$ m) the heat pulses are strongly modulated in the ice temperature profiles, and

Table 1. Model parameters and constants used in this study

Parameter	Value	Remarks/source
Heat capacity of ice (c_i)	2093 J kg^{-1} K^{-1}	
Latent heat of Fusion of Arctic sea ice (L_{si})	Function of T_i, s_i	Yen (1981)
Ocean heat flux (F_w)	1 W m^{-2}	McPhee and others (2003); winter deep basin
Sea ice density (ρ_i)	910 kg m^{-3}	
Snow density (ρ_s)	350–390 kg m^{-3}	Anderson (1976)
Surface emissivity (e)	0.97	
Sea ice heat conductivity (k_{si})	Function of T_i, s_i	Pringle and others (2007)
Effective thermal conductivity of snow (k_s)	Function of ρ_s (0.39–0.44 Wm^{-1} K^{-1})	Sturm and others (1997)
Initial temperature in snow and ice	Non-linear profile in snow, Linear profile in ice	Based on SIMBA_2015a buoy data
Time step (t)	15 min	
Number of layers in the ice	20	
Number of layers in the snow	20	

they are observed mainly at the ice surface (Fig. 3). The insulation properties of snow are clearly demonstrated in Figure 3. Under snow-free conditions the average sea-ice surface temperature decreased by ∼23°C, compared to the case with 0.5 m deep snow cover.

The simulated sea-ice thickness evolution with and without the effect of the storms, and for different snow depth scenarios ($h_s = 0.5$, 0.3, 0.15 and 0) is shown in Figure 4. All experiments start on 22 January (day 22) and run until 15 March (day 74). The initial ice thickness in all of the experiments was 1.30 m, taken from N-ICE2015 observations (SIMBA_2015a). The results show that the sea-ice growth is mainly controlled by the snow depth. Under snow-free conditions and without the effect of storms, sea-ice grows 0.21 m thicker (+13%) than for 0.15 m of snow, 0.34 m thicker (+22%) than for 0.30 m of snow, and 0.42

Temperature profiles in snow and ice (°C)
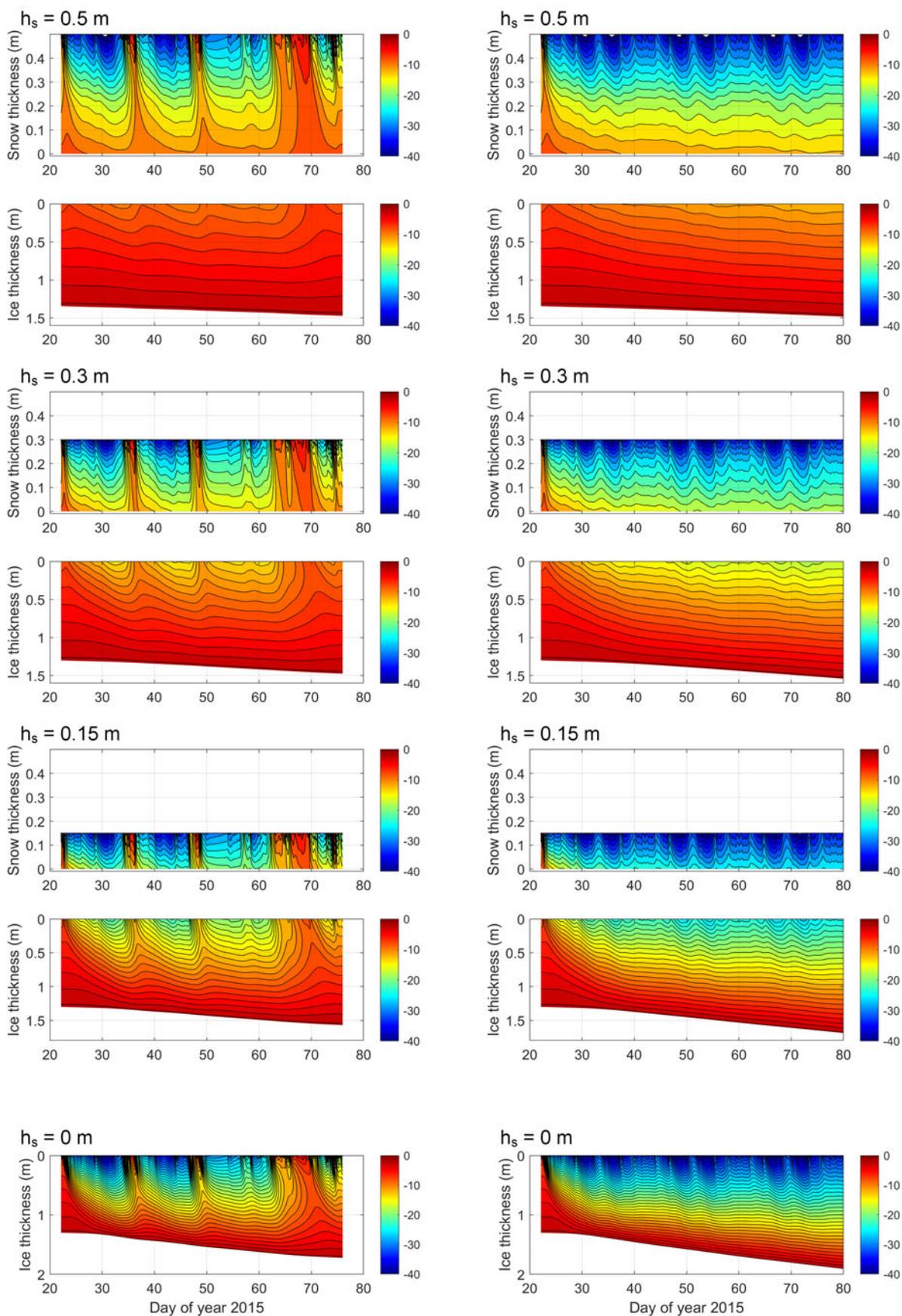
Fig. 3. Simulated ice and snow temperature profiles with (left) and without (right) the effect of storms for different snow depth scenarios, h_s = 0.5, 0.3, 0.15 and 0 m.
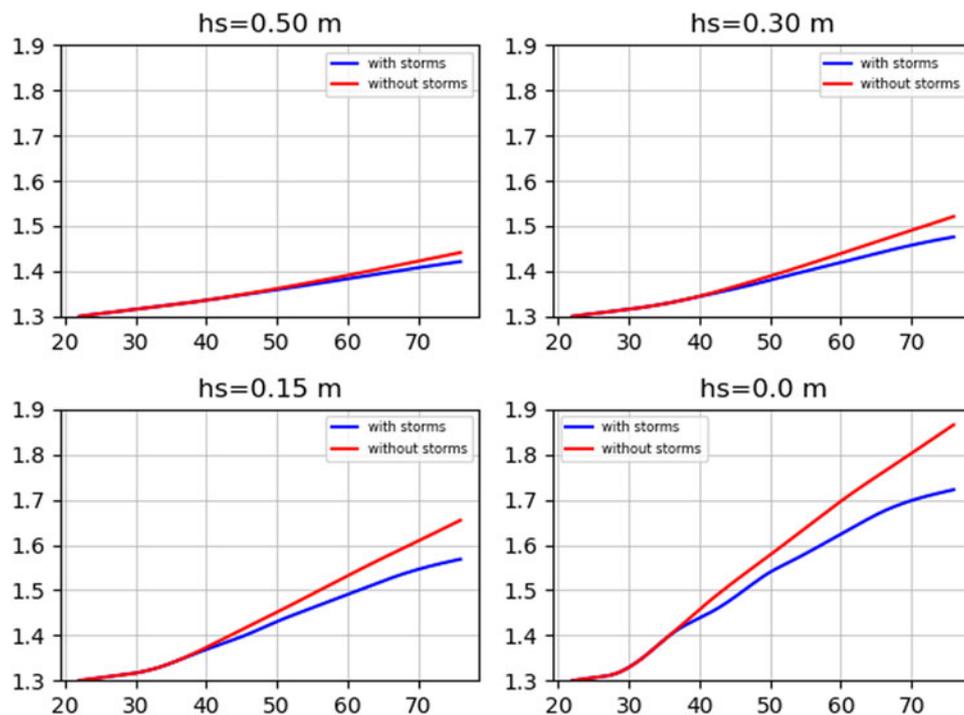
Fig. 4. Simulated sea-ice thickness evolution with (blue) and without (red) the effect of storm-induced warming events for an initial ice thickness of 1.3 m, for different snow depths: h_s = 0.5 m, 0.3, 0.15 and 0 m. Snow depth remains unchanged within the same experiment.

m thicker (+29%) than for 0.50 m of snow. When the effect of storms is taken into account, under snow-free conditions the sea ice grows 0.15 m thicker (+10%) than for 0.15 m of snow, 0.25 m thicker (+17%) than for 0.30 m of snow and 0.30 m thicker (+21%) than for 0.50 m of snow.

The effect of snow on the sea-ice growth is dominant. The effect of storms becomes more important with less snow on sea ice. For 1.3 m initial sea-ice thickness and 0.5 m of snow depth, the storms reduce the final sea-ice thickness only by 0.02 m (−1.4%). Under snow-free conditions the effect of storms maximizes, and the final sea-ice thickness is reduced by 0.14 m (−7.7%). Under snow-free conditions it takes 1 d to grow 1 cm of sea ice without the effect of the storms, and 1.3 d with the effect of the storms. For 0.5 m of snow depth it takes 3.8 d to grow 1 cm of sea ice without the effect of the storms, and 4.5 d with the effect of the storms.

The effect of both the snow and the storms in reducing the rate of sea-ice growth becomes more important in thinner ice conditions (h_{0i} = 0.5 m) and less important in thicker ice conditions (h_{0i} = 2 m). However, regardless of the initial ice thickness conditions, the effect of snow is always dominant. Results from all model experiments are summarized in Table 2.

Table 2. Results from all model experiments

Snow depth (m)	Final sea ice thickness (m)		Ice growth rate (cm d^{-1})		No of days per cm growth	
	Storms	No storms	Storms	No storms	Storms	No storms
Initial ice thickness = 1.3 m						
0	1.72	1.86	0.78	1.05	1.3	1.0
0.15	1.57	1.65	0.50	0.66	2.0	1.5
0.30	1.48	1.52	0.33	0.41	3.1	2.4
0.50	1.42	1.44	0.22	0.26	4.5	3.8
Initial ice thickness = 0.5 m						
0	1.25	1.47	1.39	1.80	0.7	0.6
0.15	0.94	1.08	0.81	1.07	1.2	0.9
0.30	0.77	0.85	0.50	0.65	2.0	1.6
0.50	0.68	0.72	0.34	0.41	3.0	2.5
Initial ice thickness = 2.0 m						
0	2.26	2.35	0.48	0.65	2.1	1.5
0.15	2.17	2.22	0.31	0.40	3.2	2.5
0.30	2.11	2.13	0.20	0.25	5.0	4.1
0.50	2.08	2.09	0.14	0.16	6.9	6.2

Discussion and Conclusions

We performed a modelling sensitivity study using a 1-D sea ice and snow thermodynamic model (HIGHTSI), to examine the relative effect of storms and snow for Arctic sea-ice growth in winter. Observational data from the N-ICE2015 campaign were used to guide the model experiments. During the winter part of the N-ICE2015 campaign (22 January–15 March) six major storm events occurred, which brought pulses of heat and moisture in the area (Fig. 1). On 22 January, the snow on sea ice was exceptionally thick (∼0.5 m). By 15 March, both the snow depth and the sea-ice thickness increased only slightly (Rösel and others, 2018). In this sensitivity experiment we evaluate the impact of storms and snow in the evolution of the sea-ice growth, (i) by

adjusting the thickness of snow on sea ice and (ii) by removing the effect of storms from the meteorological forcing. We do not take into account the increased ocean heat fluxes that occurred during some storms (Peterson and others, 2017). Instead, we use values representative of the deep Arctic basin in winter (McPhee and others, 2003), away from the warm Atlantic water inflow. Neither have we accounted for snow-ice formation that was also evident, especially for the thickest snow covers (Provost and others, 2017).

Our results show that sea-ice growth is mainly controlled by the snow depth on sea ice. The effect of storm warming events becomes more important with less snow on sea ice. For 1.3 m initial ice thickness and 0.5 m snow, similar to what was observed during N-ICE2015, the reducing effect of storms in sea-ice growth is relatively small, i.e. the difference in the final sea-ice thickness was only reduced by 0.02 m (−1.4%) due to the effect of the storms. Sea-ice growth rate was reduced from 0.26 to 0.22 cm d^{-1} (−15%). In the extreme case of snow-free conditions, the difference in the final thermodynamic sea-ice thickness caused by the storms

was 0.14 m (−7.5%). Sea-ice growth rate was reduced from 1.05 to 0.78 cm d^{-1} (−50%).

Snow depth on the other hand is strongly affecting sea-ice growth in winter. Without the effect of the storms, 0.5 m of snow cover reduced the final sea-ice thickness by 0.42 m (−23%) compared to snow-free conditions. Sea-ice growth rate was reduced from 1.05 to 0.26 cm d^{-1} (−75%). With the effect of storms, 0.5 m of snow reduced the final sea-ice thickness by 0.30 m (−17%) compared to snow-free conditions. Sea-ice growth rate was reduced from 0.78 to 0.22 cm d^{-1} (−72%).

We repeated the same experiments with different initial sea-ice thickness (h_{0i} = 0.5 and 2 m), to examine how that would affect our results (Table 2). To summarize, for 1.3 m initial ice thickness the reducing effect of storms on the sea-ice growth ranged from −1.4 to −7.5%, and the reducing effect of snow ranged from −17 to −23%. For lower initial ice thickness (h_{0i} = 0.5 m) the reducing effect of storms on the sea-ice growth becomes more important (−6 to −15%), but so does the reducing effect of snow (−46 to −51%). While, for greater initial ice thickness (h_{0i} = 2 m), the reducing effect of storms becomes less important (from −0.5 to −3.8%), but so does the reducing effect of snow (from −8 to −11%).

We should note once more that the ocean heat flux was kept low on purpose in our experiments (1 W m^{-2}), in order to simulate conditions of the deep Arctic basin and to isolate the effect of sea ice and atmosphere interactions. Observations from the IMBs deployed during N-ICE2015 capture the complete effect of the atmosphere and ocean along the drift path of the buoy. Specifically, for SIMBA_2015a sea-ice thickness decreased by 0.13 m in 30 d, due to the large ocean heat flux when the ice drifted over warm Atlantic water, where ocean heat fluxes are much larger than in the deep basin. Clearly, in this region the effect of the ocean heat flux is large, but it is likely limited to the Atlantic water pathway (Graham and others, 2019). It is also indirectly created by the increased under ice mixing caused by ice drifting and high winds. The examination of a fully coupled atmosphere-ice-ocean system is needed.

This study shows that the thermodynamic effect of warming events to the sea-ice growth is strongly connected to the snow depth on sea ice. We should note that, naturally, snowfall and storms are complementing factors that often coincide in time. However, the snow depth on sea ice does not uniformly increase after a storm event (Rösel and others, 2018). That is because, under strong winds, snow is blown away and redeposited around pressure ridges and ice blocks, which serve as topographic obstructions to the wind (Liston and others, 2018). Also, snow can be lost to leads which often form during storms. In this study, we use observations and model data to demonstrate the dual, insulating effect of snow on winter sea-ice growth. Building on previous work (Merkouriadi and others, 2017, 2020), we show that snow inhibits sea-ice growth. However, snow also reduces the effect of warm atmospheric temperatures during storms. These results emphasize the need for improved understanding and representation of snow as a critical component of the Arctic atmosphere-ice-ocean system (Webster and others, 2018).

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