Quantifying the Potential for Snow-Ice Formation in the Arctic Ocean

Ioanna Merkouriadi1, Glen E. Liston2, Robert M. Graham1, and Mats A. Granskog1

1Fram Centre, Norwegian Polar Institute, Tromsø, Norway, 2Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO, USA

Abstract We examine the regional variations and long-term changes of the potential for snow-ice formation for level Arctic sea ice from 1980 to 2016. We use daily sea ice motion data and implement a 1-D snow/ice thermodynamic model that follows the ice trajectories while forcing the simulations with Modern-Era Retrospective analysis for Research and Applications, Version 2 and ERA-Interim reanalyses. We find there is potential for snow-ice formation in level ice over most of the Arctic Ocean; this is true since the 1980s. In addition, the regional variations are very strong. The largest potential is typically found in the Atlantic sector of the Arctic Ocean, particularly in the Greenland Sea, where precipitation is highest. We surmise that, in addition to the annual amount of solid precipitation, potential for snow-ice formation is controlled by two main factors: the initial second-year/multiyear ice thickness in the autumn and the timing of first-year ice formation.

1. Introduction

Snow on sea ice is a critical factor for sea ice evolution (Sturm & Massom, 2010; Webster et al., 2014). The high reflectance and thermal insulation properties of snow modulate the growth and decay of sea ice (Maykut, 1978; Sturm & Massom, 2010). Snow can also contribute to the sea ice thickness via superimposed ice (Haas et al., 2001; Kawamura, 1997) and snow-ice (e.g., Leppäranta, 1983) formation. Superimposed ice forms when meltwater from snow or rainfall percolates downward through the snowpack and refreezes at the ice/snow interface. Snow ice forms when seawater floods and refreezes at the snow/ice interface due to a heavy snow load that submerges the ice surface below sea level. Snow ice is therefore a mixture of snow and seawater, and it can provide a habitat for snow infiltration communities, with implications on carbon export and transfer (Fernández-Méndez et al., 2018).

A younger and thinner Arctic sea ice system becomes more sensitive to snow accumulation (Liston et al., 2018). A relatively thick snow pack can limit the thermodynamic growth of sea ice and at the same time promote sea ice growth via snow-ice formation (Merkouriadi, Cheng, et al., 2017). This mechanism was observed in the Atlantic sector of the Arctic Ocean during the Norwegian young sea ICE (N-ICE2015) expedition (Granskog et al., 2017), where negative freeboards were widespread (Rösel et al., 2018). Snow ice is a common phenomenon in the seasonal sea ice zone and in the Southern Ocean (Granskog et al., 2004; Jeffries et al., 2001; Ukita et al., 2000). However, it has not been considered prevalent in the Arctic (Sturm & Massom, 2010; Vihma et al., 2014), where thick perennial sea ice once dominated. It is unclear whether the snow ice observed during N-ICE2015 is common for this part of the Arctic or became a more widespread phenomenon due to the recent thinning of Arctic sea ice (Hansen et al., 2013; Lindsay & Schweiger, 2015) and/or the increased frequency of storms that bring precipitation in the region (Graham, Cohen, et al., 2017).

Here, we attempt to shed more light into the potential for snow-ice formation on Arctic sea ice. Our purpose is to examine the regional and interannual variations of the potential for snow-ice formation, from 1980 to 2016. We look separately into the response of first-year (FYI) and second-year (or older) (SYI/MYI) ice. We use the term “potential” because we specifically examine the conditions for negative freeboard and for level ice only. Although a negative freeboard is a precondition for snow-ice formation, in itself, it is not sufficient to trigger flooding of the bottom of the snow pack (Rösel et al., 2018). We used information from ice motion and implemented a 1-D thermodynamic sea ice and snow model along these trajectories to examine the potential for snow-ice formation. The model was forced with two atmospheric reanalyses that have significant differences in precipitation amounts; one represents relatively low ERA-Interim (ERA-I) and the other...
relatively high (Modern-Era Retrospective analysis for Research and Applications, Version 2 [MERRA-2]) precipitation amounts in the Arctic Ocean (Boisvert et al., 2018).

2. Materials and Methods

We used a 1-D, HIGH-resolution Thermodynamic Sea Ice and snow model HIGHTSI (Launiainen & Cheng, 1998) to simulate sea ice thickness, snow-ice thickness, and snow depth in the Arctic Ocean. HIGHTSI is designed to resolve the evolution of snow and ice thickness and temperature profiles. It has been widely used in process studies and validated extensively against observations (Cheng et al., 2008, 2013; Merkouriadi, Cheng, et al., 2017; Wang et al., 2015). Detailed model parameterizations are given in Supporting Information Table S1 (Briegleb et al., 2004; Ebert & Curry, 1993; Grenfell & Maykut, 1977; Huwald et al., 2005; Maykut & Untersteiner, 1971; Perovich, 1996; Pringle et al., 2007; Yen, 1981).

We implemented HIGHTSI in a Lagrangian framework to examine Arctic snow-ice distributions. Ice motion vectors are derived by satellite products and are provided from the National Snow and Ice Data Center (Tschudi et al., 2016). Based on the motion vectors, we performed Lagrangian tracking of ice parcels over the Arctic Ocean and its marginal seas from 1980 to 2016. This resulted in a daily sea ice motion product of 25-km spatial resolution. Throughout this period, ice parcels disappear and new parcels are being generated. At any given time, the Arctic simulation domain can hold a total of 60,000 individual ice parcels. At each time step, the MicroMet meteorological preprocessor (Liston & Elder, 2006) was used to extract the atmospheric forcing based on the position of each ice parcel. Ice concentration data from Cavalieri et al. (1996) were used to initialize an ice parcel. We considered ice parcels initialized when ice concentration exceeded a 15% concentration threshold.

We used atmospheric data from reanalyses to force HIGHTSI, including 10-m wind speed, 2-m air temperature and relative humidity, and total precipitation, while MicroMet provided the solid precipitation, downwelling shortwave, and longwave radiation. We used ERA-I and MERRA-2 atmospheric reanalyses (Dee et al., 2011; Gelaro et al., 2017) in order to examine the snow-ice sensitivity to the magnitude of precipitation over sea ice. These reanalyses have shown relatively good agreement for air temperature and timing of precipitation events (Merkouriadi, Cheng, et al., 2017), although there is a warm bias in both products during the lowest temperatures in winter (Graham et al., 2019). But especially, they exhibit significant differences in the magnitude of precipitation (Boisvert et al., 2018; Chaudhuri et al., 2014; Merkouriadi, Cheng, et al., 2017) with ERA-I producing relatively low and MERRA-2 producing relatively high precipitation amounts (Boisvert et al., 2018; Merkouriadi, Cheng, et al., 2017).

HIGHTSI simulations began each year on 1 August (1980–2016), and run through one full year at a time, using a 3-hr time step. Based on the ice motion and concentration information, existing ice parcels on 1 August were considered SYI/MYI. On 1 August we assumed that there is no snow on SYI/MYI. We performed model experiments with four different initial thicknesses for the existing SYI/MYI parcels on 1 August ($h_0 = 0.5, 1, 1.5,$ and $2 \text{ m}$). Thus, we conducted eight experiments in total, four with ERA-I and four with MERRA-2 forcing. Initial ice thickness of 2 m was likely more common in 1980s and 1990s, whereas thickness of 1.5 m and less is becoming more typical in recent years (Kwok & Untersteiner, 2011). We acknowledge that a uniform initial SYI/MYI thickness over the entire ice-covered Arctic Ocean is not realistic. However, our purpose is to examine the interdecadal sensitivity of snow-ice formation to the regional patterns and trends of weather conditions and sea ice motion. For the same reason, we chose a constant, low ocean heat flux ($F_w = 1 \text{ W m}^{-2}$). In a similar study we carried out north of Svalbard, in a region where ocean heat flux is of greatest importance due to the proximity to the North Atlantic, we concluded that the choice of ocean heat flux did not significantly affect the results (Merkouriadi, Cheng, et al., 2017). These simplifications allow us to examine the sensitivity of snow-ice formation to a limited number of factors, keeping in mind our level ice assumption.

The outputs of the HIGHTSI model experiments for each ice parcel at each time step are snow-ice layer thickness, thermal ice thickness (i.e., total ice thickness minus snow-ice thickness), and snow depth. Here we only show results related to snow-ice thickness. Superimposed ice formation is also calculated in HIGHTSI, but it is not part of the snow-ice volume presented here. For computational efficiency, superimposed ice was not included in the analysis. Thermal ice thickness and snow depth results were analyzed to facilitate our interpretation and discussion. After we conducted the simulations, the model output was
gridded to the 25 × 25 km Equal-Area Scalable Earth grid (EASE grid), provided by National Snow and Ice Data Center. At each time step, the parcels’ location was used to calculate the overlap between the parcel and the EASE grid cell. The overlap is calculated as fractional area of the EASE grid cell. 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 conserves the examined parameters. In order to look separately into FYI and SYI/MYI, existing parcels on 1 August were considered to be SYI/MYI. New parcels that appear after 1 August each year were considered to be FYI.

Hereafter, for simplicity we show results based on MERRA-2 experiments because they generally give a better fit to observations (Merkouriadi, Cheng, et al., 2017). The results from all model experiments are summarized in the supporting information (Figures S1 and S2). First, we look at regional variations and long-term trends of snow ice in all ice types. Afterwards, we compare FYI and SYI/MYI.

3. Results and Discussion
3.1. Regional Variations
First, we examined the regional variations of the potential for snow-ice formation in the Arctic Ocean. In each year, we found the day of maximum snow-ice volume, and we extracted the snow-ice data from that day. We averaged the annual maximum snow-ice thicknesses over different decades (1980–1990, 1990–2000, and 2000–2016) because different decades are likely representative of different SYI/MYI initial thickness. The day of maximum snow-ice volume ranges from 21 March to 18 May and is on average on 30 April for the period 1980–2016. This day has shifted earlier by 1 week in recent years (2000–2016) compared to the 1980s. In Figure 1, we show results of selected experiments for all ice types, with initial SYI/MYI thickness ($h_0$) decreasing with time: $h_0 = 2$ m for 1980–1990 (Figure 1a); $h_0 = 2$ m and $h_0 = 1.5$ m for 1990–2000 (Figures 1b and 1c); and $h_0 = 1.5$ m, $h_0 = 1$ m, and $h_0 = 0.5$ m for 2000–2016 (Figure 1d, 1e, and 1f). For every 0.5 m decrease of $h_0$, the annual maximum snow-ice volume increases by 11.6% for MERRA-2 and 7.4% for ERA-I experiments, on average from all experiments.

Figure 1. Annual maximum snow-ice thickness averaged over different decades, from selected experiments with different second-year/multiyear ice initial thickness ($h_0$). Results are from Modern-Era Retrospective analysis for Research and Applications, Version 2 reanalysis.
We find that there is potential for snow-ice formation over most of the Arctic Ocean. However, regional variations are strong (Figure 1). Snow ice is much more prominent in the Atlantic sector of the Arctic Ocean. The Greenland Sea has the greatest potential for snow-ice formation, with snow-ice layer thickness mostly above 0.1 m, reaching up to 0.5 m locally. This is observed in all the experiments. The Atlantic sector receives the highest precipitation in the Arctic (Boisvert et al., 2018; Merkouriadi, Gallet, et al., 2017; Wang et al., 2019) and is characterized by a large number of storm events in autumn and winter (Graham, Rinke, et al., 2017; Graham et al., 2019; Graham, Cohen, et al., 2017; Rinke et al., 2017; Woods & Caballero, 2019) and is characterized by a large number of storm events in autumn and winter (Graham, Rinke, et al., 2017; Graham et al., 2019; Graham, Cohen, et al., 2017; Rinke et al., 2017; Woods & Caballero, 2019). These results from our model experiments are supported by the frequent observations of snow ice over the Arctic Ocean. Snow ice potential is higher in 1980–1990 compared to later years, even for $h_0 = 2$ m (Figure 1). This is likely related to the significant decrease of snow depth in Barents and Chukchi Seas in recent years, compared to the climatology by Warren et al. (1999), as a result of more seasonal ice and thus a shorter accumulation period (Webster et al., 2014). The maximum snow-ice thickness is obviously controlled by the initial SYI/MYI thickness in our model simulations. For smaller initial thickness, the area of higher potential for snow-ice formation propagates north, towards the central Arctic. Interestingly, in earlier decades, and for larger initial thickness, snow-ice potential in Barents and Kara Seas was higher compared to recent years (2000–2016; Figure 1). We observe the same for the Chukchi Sea, where snow-ice potential is higher in 1980–1990 compared to later years, even for $h_0 = 2$ m (Figure 1). This is likely related to the significant decrease of snow depth in Barents and Chukchi Seas in recent years, compared to the climatology by Warren et al. (1999), as a result of more seasonal ice and thus a shorter accumulation period (Webster et al., 2014).

3.2. Long-Term Trends

We looked into the interannual variation and long-term trends for the period 1980–2016. To do this, we first calculated the total snow-ice volume on the day of maximum snow-ice volume in each year. Then we examined the trends of the maximum potential snow-ice volume, assuming all ice is level. The annual maximum snow-ice volume in the Arctic Ocean ranges from 615 ± 95 to 856 ± 153 km$^3$ for MERRA-2 and from 367 ± 34 to 454 ± 51 km$^3$ for ERA-I experiments. Annual maximum snow-ice volume from ERA-I is about half (55%) of the snow-ice volume from MERRA-2 experiments (not shown).

In MERRA-2, there is a statistically significant decrease in snow-ice volume, ranging from $-6$ to $-12$ km$^3$/year, across experiments of different initial SYI/MYI thickness (Figure 2c). In ERA-I, there is no significant trend. Note that the trends are calculated from a constant initial SYI/MYI thickness throughout the examined period. Thus, the trends we show do not include any effect by the thinning of the SYI/MYI with time. The decreasing trends are possibly due to snow depth decline over most regions of the Arctic (except the Greenland Sea) (Webster et al., 2014). Snow depth decline is likely related to the smaller ice extent and thickness in recent years (Comiso, 2002, 2012; Gascard et al., 2019), which results in less snow accumulation on sea ice and consequent decrease of the potential for snow-ice formation. However, in reality, thinner SYI/MYI in recent years would lower the rate of decrease, rendering the trend not significant. Even though the average trend of snow-ice volume in MERRA-2 is negative, there are strong regional variations (Figure 2a). The strongest negative trends are found in the Barents and Kara Seas, possibly the result of later FYI formation contributing to less snow accumulation in late fall (Webster et al., 2014). Sporadic, strong positive trends are found in the Greenland Sea and are most likely due to the intensification of storms that bring more precipitation to this part of the Arctic (Graham et al., 2019).

We calculated the snow-ice fraction relative to sea ice thickness on the day of maximum snow-ice volume over the Arctic Ocean. Snow-ice fraction was on average 9–12% for MERRA-2 and 6–7% for the ERA-I experiments. The snow-ice fraction demonstrates strong regional variations that follow very similar patterns to the snow-ice layer thickness (Figure 1). In the Greenland Sea, the snow-ice fraction is largest. For example, in MERRA-2 and for $h_0 = 1$ m, snow-ice fraction in the Greenland Sea ranges from 10% to 50%, even up to 80% sporadically along the coast of Greenland. These high fractions along the coast of Greenland are found in all MERRA-2 and ERA-I experiments, regardless of the initial SYI/MYI thickness. There is a decline in snow-ice fraction by 0.06% per year in MERRA-2 experiments (Figure 2d). The opposite is observed in ERA-I experiments, where snow-ice fraction increases by 0.03% per year (not shown). ERA-I produces less precipitation than MERRA-2. This results in less snow on sea ice, thicker sea ice, and
therefore less snow-ice thickness in ERA-I compared to MERRA-2. Our experiments showed that the long-term trends of snow and sea ice volume are decreasing in both ERA-I and MERRA-2, but the rates are different. The increasing trends of snow-ice fraction in ERA-I indicate that the rate of snow loss (−9 km³/year) is relatively small compared to the rate of sea ice loss (−57 km³/year). For comparison, in MERRA-2, the rate of snow volume loss is −17 km³/year, and the rate of sea ice volume loss is −39 km³/year. Most of the snow volume decrease is explained by a decrease in sea ice extent. There is simply less ice for the snow to accumulate on top of.

**Figure 2.** (a) Snow-ice layer thickness trends for the period 1980–2016 (cm/decade; h₀ = 1 m), (b) snow-ice fraction on the day of maximum snow-ice volume averaged over the period 1980–2016 (h₀ = 1 m), (c) annual maximum snow-ice volume, and (d) annual mean snow-ice fraction. Results are from Modern-Era Retrospective analysis for Research and Applications, Version 2 reanalysis.

**Figure 3.** (a) Annual maximum snow-ice volume in first-year ice and (b) in second-year/multiyear ice. (c) Daily mean snow-ice thickness in first-year ice (d) and in second-year/multiyear ice. Results are from Modern-Era Retrospective analysis for Research and Applications, Version 2 reanalysis.
3.3. FYI Versus SYI/MYI

FYI has a much larger contribution to the total snow-ice volume than SYI/MYI (Figure 3a). On average, FYI contributes 79% of the total snow-ice volume in MERRA-2 and 92% in ERA-I experiments. The SYI/MYI contribution obviously shows large variations depending on the initial thickness (Figure 3b), ranging from 13% to 37% in MERRA-2 and from 4% to 23% in ERA-I experiments. The smallest contribution corresponds to the thickest SYI/MYI initial thickness \((h_0 = 2 \, \text{m})\), and the largest contribution corresponds to the thinnest SYI/MYI initial thickness \((h_0 = 0.5 \, \text{m}; \text{Figure } 3b)\). However, when we look at the snow-ice thickness, we notice that it can be larger in SYI/MYI compared to FYI but only for the thinnest initial thickness \((h_0 = 0.5 \, \text{m})\). For all other initial thickness scenarios, mean snow-ice thickness in SYI/MYI equals or is less than in FYI. Therefore, even though FYI contributes on average much more snow-ice volume, it does not consist of thicker snow ice. This is due to the fact the extent of FYI is larger than for SYI/MYI. On average, across all experiments, FYI fraction of the total ice volume is 77% on the day of maximum sea ice volume.

4. Conclusions

We examined the potential for snow-ice formation on level ice in the Arctic Ocean by implementing a 1-D ice/snow model on sea ice trajectories over the period 1980 to 2016. There is potential for snow-ice formation (i.e., negative freeboard) over most of the Arctic Ocean, even in earlier decades when thicker perennial sea ice extent was larger compared to recent years. However, regional variations are eminent. The largest potential snow-ice thicknesses are found in the Atlantic sector of the Arctic, especially in the Greenland Sea, where snow-ice is mostly above 0.1 m and locally reaching 0.5 m across all experiments. Snow-ice thickness for most of the central Arctic and the Pacific sectors is less than 0.05 m (<0.05 m probability = 61% for MERRA-2 and 85% for ERA-I). The snow-ice fraction to the sea ice thickness on the day of maximum snow-ice volume averages 10% for MERRA-2 and 6% for ERA-I experiments. The snow-ice fraction values demonstrate regional variations, with patterns similar to the snow-ice thickness variations.

The annual maximum snow-ice volume is obviously affected by the initial SYI/MYI thickness in our model experiments, ranging from 615 ± 95 to 856 ± 153 km³ for MERRA-2 and from 367 ± 34 to 454 ± 51 km³ for ERA-I experiments. For constant initial SYI/MYI thickness, we notice a significant decrease of the annual maximum snow-ice volume, ranging from −6 to −12 km³/year, across all MERRA-2 experiments. However, this is likely partly compensated by the thinning of SYI/MYI during the examined period that can increase the potential for snow-ice formation. On average, FYI contributes 79% of the total snow-ice volume in MERRA-2 and 92% in ERA-I experiments. This is mainly because FYI occupies a greater area of the Arctic Ocean that has also increased in recent years (Comiso, 2012; Maslanik et al., 2011).

The Arctic Ocean is going through a transition from a predominantly multiyear sea ice system to a thinner, younger, first-year seasonal ice system (Maslanik et al., 2007). In a previous case study, Merkouriadi, Cheng, et al. (2017) showed that snow-ice formation is controlled by the thickness of the SYI/MYI in the beginning of the growth season and the timing of the FYI formation relative to precipitation events in autumn and early winter. By expanding this experiment to the whole Arctic, we show here that FYI is likely the main contributor of snow ice. Thus, we expect to find snow ice contributing to the sea ice mass balance and acting as a sink for the snow in the future Arctic: especially in the Atlantic sector that has the largest precipitation. Snow contribution in sea ice via superimposed ice formation is accounted for in HIGHTSI model, but it is not included in our results of snow ice and was not analyzed in this study. Superimposed ice is more likely to occur in late spring or early summer (later than the date of maximum snow ice we have analyzed here), when snow is melting. However, in a warming Arctic with potential increase of rain-on-snow events, superimposed ice may become increasingly important; therefore, it should be examined more closely.

This relatively idealistic study examined conditions for level ice and assumed that snow ice forms given the condition of negative freeboard. Therefore, the absolute values of snow ice may be overestimated. Ice dynamics including ridging and opening of leads, with consequent snow loss, were not taken into account. We recommend that snow-ice formation is realistically accounted for in sea ice modeling studies in the Arctic Ocean, especially in the Atlantic sector where the potential for snow-ice formation is highest. The choice of reanalysis has a significant impact on the results, mainly due to different precipitation amounts.
This suggests that one has to be cautious interpreting studies of snow on sea ice where only a single reanalysis has been used (i.e. Castro-Morales et al., 2017).

References

Boisvert, L. N., Webster, M. A., Petty, A. A., Markus, T., Bromwich, D. H., & Cullather, R. I. (2018). Intercomparison of precipitation estimates over the Arctic Ocean and its peripheral seas from reanalyses. Journal of Climate, 31(20), 8441–8462. https://doi.org/10.1175/JCLI-D-18-0125.1

Briegleb, B., Bitz, C. M., Hunke, E. C., Lipscomb, W. H., Holland, M. M., Schramm, J., & Moritz, R. (2004). Scientific description of the sea ice component in the community climate system model, version three. NCAR TN-463 + STR, NCAR Tech Note, pp. 1–78.

Castro-Morales, K., Ricker, R., & Gerdes, R. (2017). Regional distribution and variability of model-simulated Arctic snow on sea ice. Polar Science, 13, 33–49. https://doi.org/10.1016/j.polar.2017.05.003

Cavalieri, D. J., Parkinson, C. L., Gloerson, P., & Zwally, H. J. (1996). Updated yearly. Sea ice concentrations from Nimbus 7 SMMR and DMSP SSM/I-SSMIS passive microwave data, version 1. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/8GQBLQZVQLO1

Chaudhari, A. H., Ponte, R. M., & Nguyen, A. T. (2014). A comparison of atmospheric reanalysis products for the Arctic Ocean and implications for uncertainties in air-sea fluxes. Journal of Climate, 27(14), 5411–5421. https://doi.org/10.1175/JCLI-D-13-00424.1

Cheng, B., Mäkynen, M., Similä, M., Rontu, L., & Vihma, T. (2013). Modelling snow and ice thickness in the coastal Kara Sea, Russian Arctic. Annales of Glaciology, 54(62), 105–113. https://doi.org/10.3189/2013AoG62A180

Cheng, B., Zhang, Z., Vihma, T., Johnsonson, M., Bion, L., Li, Z., & Wu, H. (2008). Model experiments on snow and ice thermodynamics in the Arctic Ocean with CHINARE 2003 data. Journal of Geophysical Research, 113, C09020. https://doi.org/10.1029/2007JC004654

Comiso, J. C. (2002). A rapidly declining perennial sea ice cover in the Arctic. Geophysical Research Letters, 29(20), 1956, 2016. https://doi.org/10.1029/2002GL015650

Comiso, J. C. (2012). Large decadal decline of the arctic multiyear ice cover. Journal of Climate, 25(4), 1176–1193. https://doi.org/10.1175/JCLI-D-11-00113.1

Des, P., Eppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-interim reanalysis: Configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137(S656), 553–597. https://doi.org/10.1002/qj.828

Ebert, E. E., & Curry, J. A. (1993). An intermediate one-dimensional thermodynamic sea ice model for investigating ice-atmosphere interaction. Journal of Geophysical Research, 98, 10,085–10,109. https://doi.org/10.1029/93JC00656

Fernández-Méndez, M., Olsen, L. M., Kauko, H. M., Meyer, A., Rösel, A., Merkouriadi, I., et al. (2018). Algal hot spots in a changing Arctic Ocean: Sea-ice ridges and the snow-ice interface. Frontiers in Marine Science, 5. https://doi.org/10.3389/fmars.2018.00077

Gascard, J.-C., Zhang, J., & Rafizadeh, M. (2019). Rapid decline of Arctic sea ice volume: Causes and consequences, Cryosph. Discuss., 1–29. https://doi.org/10.5194/tc-2019-2

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., et al. (2017). The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). Journal of Climate, 30(14), 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

Graham, R. M., Cohen, L., Petty, A. A., Boisvert, L. N., Rinke, A., Hudson, S. R., et al. (2017). Increasing frequency and duration of Arctic winter warming events. Geophysical Research Letters, 44, 6974–6983. https://doi.org/10.1002/2017GL073395

Graham, R. M., Cohen, L., Ritzhaupt, N., Segger, B., Graversen, R. G., Rinke, A., et al. (2019). Evaluation of six atmospheric reanalyses over Arctic sea ice from winter to early summer. Journal of Climate, 32(14), 4121–4143. https://doi.org/10.1175/JCLI-D-18-0643.1

Graham, R. M., Rinke, A., Cohen, L., Hudson, S. R., Walden, V. P., Granskog, M. A., et al. (2017). A comparison of the two arctic atmospheric winter states observed during N-ICE2015 and SHEBA. Journal of Geophysical Research: Atmospheres, 122, 5716–5737. https://doi.org/10.1002/2016JD025475

Granskog, M. A., Dodd, P. A., Divine, D., Gerland, S., Martma, T., & Leng, M. J. (2017). Snow contribution to first-year and second-year Arctic sea ice mass balance north of Svalbard. Journal of Geophysical Research: Oceans, 122, 2539–2549. https://doi.org/10.1002/2016JC012398

Granskog, M. A., Leppäranta, M., Kawamura, T., Ehn, J., & Shirasawa, K. (2004). Seasonal development of the properties and composition of landfast sea ice in the Gulf of Finland, the Baltic Sea. Journal of Geophysical Research, 109, C02020. https://doi.org/10.1029/ 2003JC001874

Grenfell, T. C., & Maykut, G. A. (1977). The optical properties of ice and snow in the Arctic Basin. Journal of Glaciology, 18(80), 445–463. https://doi.org/10.1017/S002214300000222

Haas, C., Thomas, D. N., & Bareiss, J. (2001). Surface properties and processes of perennial Antarctic sea ice in summer. Journal of Geophysical Research, 106(19), 613–625. https://doi.org/10.1029/2000JC000499

Hansen, E., Gerland, S., Granskog, M. A., Pavlova, O., Renner, A. H. H., Haapala, J., et al. (2013). Thinning of Arctic sea ice observed in Fram Strait: 1990–2011. Journal of Geophysical Research: Oceans, 118, 5202–5221. https://doi.org/10.1002/jgrc.20393

Huwald, H., Tremblay, L.-B., & Blatter, H. (2005). Reconciling different observational data sets from Surface Heat Budget of the Arctic Ocean (SHEBA) for model validation purposes. Journal of Geophysical Research: Oceans, 110, C05509. https://doi.org/10.1029/2004JC002221

Jeffries, M. O., Krouse, H. B., Hurst-Cushing, B., & Makemy, T. (2001). Snow-ice accretion and snow-cover depletion on Antarctic first-year sea-ice floes. Annals of Glaciology, 33, 51–60.

Kawamura, T. (1997). Physical, structural, and isotopic characteristics and growth processes of fast sea ice in Lützow-Holm Bay, Antarctica. Journal of Geophysical Research, 102(C2), 3345–3355. https://doi.org/10.1029/96JC03206

Kwok, R., & Untersteiner, N. (2011). The thinning of Arctic ice, in AIP Conference Proceedings, vol. 1401, pp. 220–231.

Launainen, J., & Cheng, B. (1998). Modelling of ice thermodynamics in natural water bodies. Cold Regions Science and Technology, 27(3), 153–178. https://doi.org/10.1016/S0165-232X(98)00009-3

Leppäranta, M. (1983). A growth model for black ice, snow ice and snow thickness in subarctic basins. Hydrology Research, 14(2), 59–70.

Lindsay, R., & Schweiger, A. (2015). Arctic sea ice thickness loss determined using subsurface, aircraft, and satellite observations. The Cryosphere, 9(1), 269–283. https://doi.org/10.5194/tc-9-269-2015

Liston, G. E., & Elder, K. (2006). A meteorological distribution system for high-resolution terrestrial modeling (MicroMet). J. Hydrometeorology, 7, 217–234.

Liston, G. E., Merkouriadi, I., & Granskog, M. A. (2019). Snow–ice, snow depth and ice thickness from HIGHTSI modeling with ice motion in the Arctic Ocean in the period 1980 to 2016 [Data set]. Norwegian Polar Institute. https://doi.org/10.21334/npolar.2019.881e423a
Liston, G. E., Polashenski, C., Rösel, A., Itkin, P., King, J., Merkouriadi, I., & Haagenaars, J. (2018). A distributed snow-evolution model for sea-ice applications (SnowModel). Journal of Geophysical Research: Oceans, 123, 3756–3810. https://doi.org/10.1002/2017JC013706

Maslanik, J., Stroeve, J., Fowler, C., & Emery, W. (2011). Distribution and trends in Arctic sea ice age through spring 2011. Geophysical Research Letters, 38, L13502. https://doi.org/10.1029/2011GL047735

Maslanik, J. A., Fowler, C., Stroeve, J., Drobot, S., Zwally, J., Yi, D., & Emery, W. (2007). A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss. Geophysical Research Letters, 34, L24501. https://doi.org/10.1029/2007GL032043

Maykut, G. A. (1978). Energy exchange over young sea ice in the central Arctic. Journal of Geophysical Research, 83(C7), 3646. https://doi.org/10.1029/JC083i007p03646

Maykut, G. A., & Untersteiner, N. (1971). Some results from a time-dependent thermodynamic model of sea ice. Journal of Geophysical Research, 76, 1550–1575. https://doi.org/10.1029/JC076i006p01550

Merkouriadi, I., Cheng, B., Graham, R. M., Rösel, A., & Granskog, M. A. (2017). Critical role of snow on sea ice growth in the Atlantic sector of the Arctic Ocean. Geophysical Research Letters, 44, 10,479–10,485. https://doi.org/10.1002/2017GL075494

Merkouriadi, I., Gallet, J.-C., Graham, R. M., Liston, G. E., Polashenski, C., Rösel, A., & Gerland, S. (2017). Winter snow conditions on Arctic sea ice north of Svalbard during the Norwegian young sea ICE (N-ICE2015) expedition. Journal of Geophysical Research: Atmospheres, 122, 10,837–10,854. https://doi.org/10.1002/2017JD026753

Perovich, D. K. (1996). The optical properties of sea ice (no. MONO-96-J). Hanover, NH: Cold regions research and engineering lab.

Pringle, D. J., Eicken, H., Trodahl, H. J., & Backstrom, L. G. E. (2007). Thermal conductivity of landfast Antarctic and Arctic sea ice. Journal of Geophysical Research, 112, C04017. https://doi.org/10.1029/2006JC003641

Rinke, A., Maturilli, M., Graham, R. M., Matthies, H., Handorf, D., Cohen, L., et al. (2017). Extreme cyclone events in the Arctic: Wintertime variability and trends. Environmental Research Letters, 12(9). https://doi.org/10.1088/1748-9326/aa7def

Rösel, A., Itkin, P., King, J., Divine, D., Wang, C., Granskog, M. A., et al. (2018). Thin sea ice, thick snow, and widespread negative freeboard observed during N-ICE2015 north of Svalbard. Journal of Geophysical Research: Oceans, 123, 1156–1176. https://doi.org/10.1002/2017JC012865

Sturm, M., & Massom, R. A. (2010). Snow and sea ice. In D. N. Thomas & G. S. Dieckmann (Eds.), Sea ice (Second ed., pp. 153–204). Hoboken, NJ: Wiley-Blackwell.

Tschudi, M., Fowler, C., Maslanik, J., Stewart, J. S., & Meier, W. (2016). Polar pathfinder daily 25 km EASE-Grid sea ice motion vectors, version 3. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/O57VAIT2AYYY

Ukita, J., Kawamura, T., Tanaka, N., Toyota, T., & Wakatsuchi, M. (2000). Physical and stable isotopic properties and growth processes of sea ice collected in the southern Sea of Okhotsk. Journal of Geophysical Research, 105(C9), 22,083–22,093. https://doi.org/10.1029/1999jc000013

Vihma, T., Pirazzini, R., Fer, I., Renfrew, I. A., Sedlar, J., Tjemström, M., et al. (2014). Advances in understanding and parameterization of small scale physical processes in the marine Arctic climate system: A review. Atmospheric Chemistry and Physics, 14(17), 9403–9450. https://doi.org/10.5194/acp-14-9403-2014

Wang, C., Cheng, B., Wang, K., Gerland, S., & Pavlova, O. (2015). Modelling snow ice and superimposed ice on landfast sea ice in Kongsfjorden, Svalbard. Polar Research, 34(1), 20828. https://doi.org/10.3402/polar.v34.20828

Wang, C., Graham, R. M., Wang, K., Gerland, S., & Granskog, M. A. (2019). Comparison of ERA5 and ERA-Interim near-surface air temperature, snowfall and precipitation over Arctic sea ice: Effects on sea ice thermodynamics and evolution. The Cryosphere, 13(6), 1661–1679. https://doi.org/10.5194/tc-13-1661-2019

Warren, S., Rigor, I. G., Untersteiner, N., Radionov, V. F., Bryazgin, N. N., Aleksandrov, Y. L., & Colony, R. (1999). Snow depth on Arctic sea ice. Journal of Climate, 18, 1814–1829.

Webster, M. A., Rigor, I. G., Nghiem, S. V., Kurtz, N. T., Farrell, S. L., Perovich, D. K., & Sturm, M. (2014). Interdecadal changes in snow depth on Arctic sea ice. Journal of Geophysical Research: Oceans, 119, 5395–5406. https://doi.org/10.1002/2014JC009985

Woods, C., & Caballero, R. (2016). The role of moist intrusions in winter arctic warming and sea ice decline. Journal of Climate, 29(12), 4473–4485. https://doi.org/10.1175/JCLI-D-15-0773.1

Yen, Y.-C. (1981). Review of thermal properties of snow, ice and sea ice. (Rep. ADA103734), pp. 35, Cold Reg. Res. and Eng. Lab, Hanover, NH.