Snow in the Changing Sea-ice Systems

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Abstract:

As Earth's most reflective, insulative natural material, snow is critical to the sea-ice and climate systems, but its spatial and temporal heterogeneity poses challenges for observing, understanding and modelling those systems under anthropogenic warming. In this review, we survey the snow-ice system, then provide recommendations for overcoming present challenges. These include: (1) collecting process-oriented observations for model diagnostics and understanding snow-ice feedbacks, and (2) improving our remote sensing capabilities of snow for monitoring large-scale changes in snow on sea ice. These efforts could be achieved through stronger coordination between the observational, remote sensing and modelling communities, and would pay dividends through distinct improvements in predictions of polar environments

1. Introduction

Snow is the most reflective, and also the most insulative, natural material on Earth. Consequently, it is an integral component of Earth's climate. Snow regulates our planet's energy balance, reflecting 85% of incoming solar radiation back into space[1-2]. Without snow, the coupled atmosphere-land-ocean systems would gain energy through a positive feedback, and our planet would warm. As a whole, Earth's snow cover has decreased in duration and thickness under anthropogenic warming[3-5], which has serious implications for the future trajectory of our climate.

Outside of the general trend, we do not know how 25% of Earth's snow-covered regions is changing in a warming climate. This percentage represents the Arctic and Antarctic snow-sea ice systems, where snow plays a critical (and complex) role in the mass balance of sea ice and its response to a changing climate[6-7]. Snow enhances or curbs sea-ice loss depending on snow's thickness and properties, while sea-ice conditions, in turn, affect the snow (Fig. 1). Snow's physical, optical and thermal properties are heterogeneous in space and time due to snow’s high sensitivity to atmospheric and sea ice conditions, as well as its tendency to metamorphose over time. Hence, snow processes widely differ in occurrence, magnitude and frequency between seasons, regions and hemispheres.

Collectively, these and other factors (outlined below) greatly challenge our ability to observe the current state of snow on sea ice, monitor long-term changes in snow conditions and understand snow-related processes. These shortcomings limit our ability to realistically represent the coupled snow-sea ice system in climate models and thus limit our prediction of long-term changes and feedbacks in response to climate variability and change. Given the importance of snow in the sea-ice and Earth systems, addressing these challenges is a high priority in climate science, and, key to this perspective, these challenges may not be insurmountable.

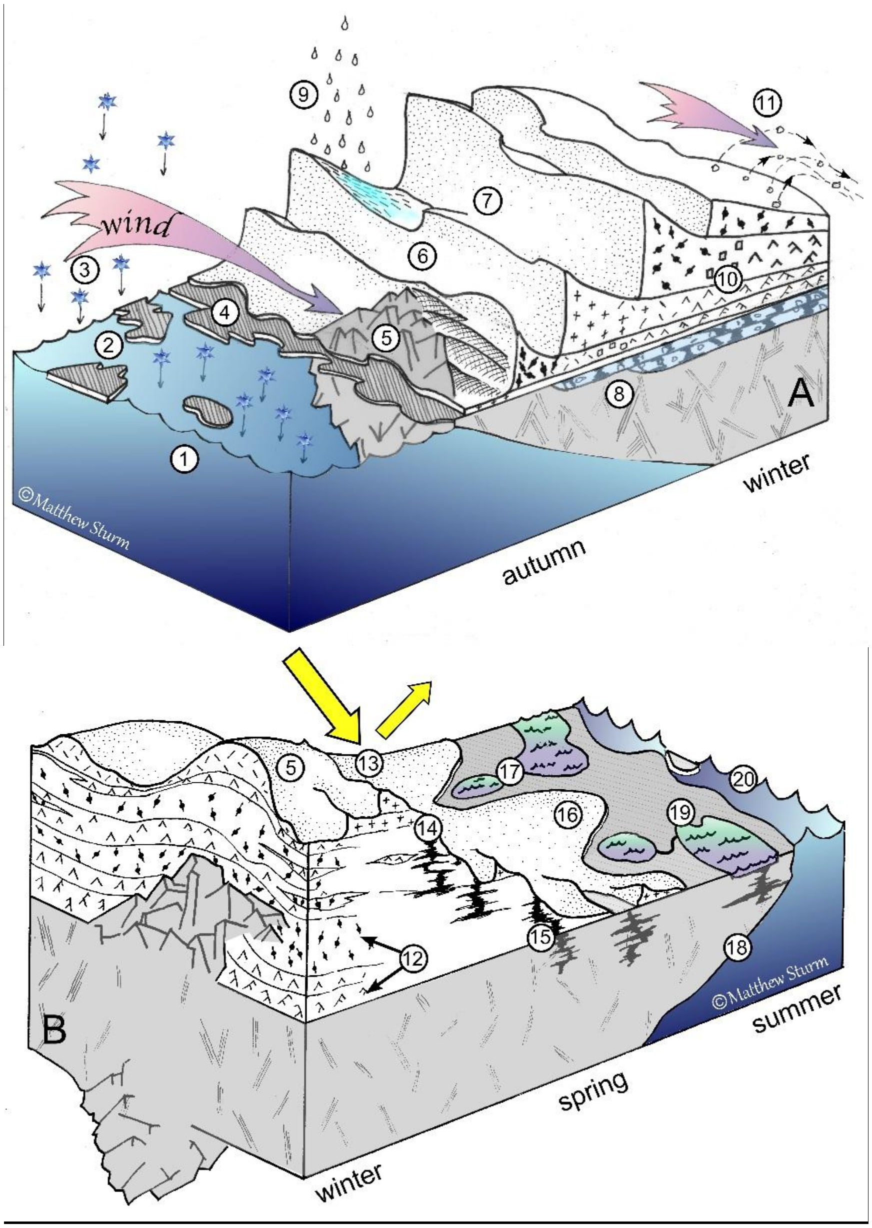

Figure 1/Box 1 Figure: An illustration conveying the complex set of processes that takes place between snow and sea ice during **(a)** autumn-winter and **(b)** winter-summer. We exclude mid-winter and mid-to-late summer from the illustration in order to highlight the dominant snow processes. Box 1 contains the descriptions of the enumerated processes marked on the figure. Note, certain processes are more dominant in one hemisphere than the other e.g., melt ponds in the Arctic, snow-ice formation in the Antarctic (see Box 1 and ref 6).

Box 1: Generalized Sequence for Snow-on-Sea-Ice Processes

Autumn to Winter: Freeze-up and growth

1. In autumn the sea surface cools,

2. to the extent that it begins to freeze, forming sea ice.

3. Snow may fall before the sea has frozen,

4. or a thin ice platform may intercept the snowfall, allowing it to accumulate.

5. Ice deformation driven by the wind and ocean currents creates surface roughness features such as pressure ridges, which trap blowing snow to create deep drifts.

6. The uneven cover of insulating snow creates spatial gradients in heat loss, leading to thermodynamic ice thickening that is heterogeneous.

7. Snow continues to deepen through a series of discrete snowfall events over the winter.

8. If thick enough, the snow overburden will exceed the buoyancy of the floe, resulting in ice-surface flooding, often followed by freezing of the slush layer creating snow-ice[8-10]*.*

9. Occasionally, rain-on-snow events glaze the snow surface and "lock" snow in place.

10. Each layer of snow deposited goes through a complex metamorphic cycle that will alter its grain size and density, and thus its physical, optical and thermal properties[1,11-12]*,*

11. Wind continues to erode or drift the snow, increasing heterogeneity of the snow cover[13]*, and blow snow particles into leads, where they may melt, form slush or nucleate freezing*[14]*.*

Winter to Summer: Transition to melt

12. By late-winter a mature, heterogeneous snowpack covers the ice, keyed in some ways to the deformation state of the ice and meteorological history. The snowpack composition includes two *of the most dissimilar types of snow: depth hoar (porous, weak and highly insulative), and wind slab (dense, hard and a relatively poor insulator)*[13]*.*

13. By spring, increasing temperatures and solar radiation will still start melting the snowpack from the top down.

14. Meltwater then percolates downward through the snow to form internal ice layers and grain coarsening that reduces the snow albedo[1-2,12]*.*

15. Where meltwater percolation reaches the snow-ice interface, it first forms superimposed ice[15-17]*, and eventually starts to collect as melt ponds (primarily in the Arctic). The snowmelt may also percolate down into the ice via brine drainage channels and refreeze upon reaching freezing-point temperatures, reducing the ice permeability and salinity*[18]*.*

16. Where snow dunes have formed during the winter, the snow will last longer through the melt season, and

17. the melt ponds will form adjacent to these dunes[19-20] *(in the Antarctic, austral summer melt is generally insufficient to remove the snow cover on surviving ice floes, and melt ponds are rare*[10]*). These freshwater features, together with the exposure of bare ice and the continued grain coarsening, will reduce the surface albedo further*[2]*.*

18. As seasonal melt progresses, the sea ice warms, which aids its basal melting by oceanic heat fluxes.

19. With all of the snow gone, the (Arctic) melt ponds expand, link up and eventually drain, until

20. the sea ice either melts in place or breaks up. Some ice may survive the summer melt season. In the Antarctic, greater snow survival in summer (and lack of melt ponds) may contribute to survival of sea ice through the melt season, particularly at higher latitudes[10]*.*

2. Snow in the sea-ice systems

Across both the Arctic and Antarctic environments, snow on sea ice is governed by the same set of physics. Strong vertical temperature gradients, for example, drive extensive snow grain metamorphism (Fig. 1A, 12), increasing the snow's insulating capacity[21-22]. Wind redistributes the snow to form a distinct "snowscape" shaped by and keyed to Arctic and Antarctic sea-ice topographies[13,23-24] (Fig. 1A, 6). Open cracks, leads and polynyas within the sea ice cover act as a sink for snow during wind-driven redistribution[14,25] (Fig. 1A, 11). In any region and at any time of year, ephemeral events such as rain-on-snow (Fig. 1A, 9) and thaw can affect the amount of snow removed and reworked by the wind[26-28] and rapidly alter the snowpack's insulating and optical properties[1,11-12].

Despite these same physics and snow-ice couplings, the unique geographical settings between the Arctic and Antarctic create marked deviations in the timing, magnitude and frequency of sea ice-atmosphere-ocean processes therein, which affects which snow processes dominate at any given time. These differences ultimately impact the mass balance of the Arctic and Antarctic sea ice covers and their responses to a changing climate. Thus, there are no "average climate properties of snow" that can be used in climate models to project the correct climate response – snow in the Arctic system will respond and contribute to climate change in a different way than the Antarctic system. Here, we provide a brief review of snow in the Arctic and Antarctic environments as a yardstick against which to assess long-term changes and highlight which processes require further scrutiny for better understanding and representation in Earth system models.

2.1 Snow on Arctic sea ice

The principal controls on snow accumulation on Arctic sea ice are the timing of sea ice formation, duration (e.g., ice age) and retreat, and the timing and magnitude of snowfall. The significance of these controls is reflected in the distinct cross-basin gradient in snow depth distribution on Arctic sea ice[29-32] (Fig. 2A). Climatologically speaking, the seasonal cycle in snow accumulation is comparable across all Arctic regions. In autumn, the snowpack grows rapidly due to frequent cyclone events[29,33-34]; however, for much of mid-winter, Arctic cyclone intensities decrease, resulting in relatively lower snowfall rates[29,33-35] (Fig. 1A, 4). The seasonal tapering in snowfall differs regionally, with the Atlantic sector receiving the heaviest snowfall and rainfall year-round relative to other Arctic regions[33,35]. As a result, flooding and snow-ice formation occur in the Atlantic sector[36-39] (Fig. 1A, 8), whereas elsewhere across the Arctic, snow-ice formation rarely occurs[6] as snowfall rates are lower[35] and the snowpack thinner and drier[28-29,38-39]. The regional differences in coupled sea ice-snow-atmospheric processes lead to snow conditions that are appreciably unique[28-29,38-39], which warrants caution when looking for general changes in Arctic snow conditions, assessing model parameterizations and tuning remote sensing approaches based on a single or even multiple sets of *in situ* observations.

Over the last half century, a decrease in spring snow depth in the western Arctic has been observed from *in situ*, buoy and airborne data, and attributed to the delayed onset of sea-ice formation in autumn[31] (Fig. 2B). Earlier work[29] found negative trends in snow depth for most months in 1954-1991, albeit insignificant with the exception of significant reductions in May (2 cm decade^{-1}). A thinning snow cover was also simulated in models of varying sophistication i.e., ranging from a fully coupled global climate model[40] to snow depth reconstructions from reanalysis snowfall[41]. Taken together, these results point to a clear and uni-directional response of the snow cover to Arctic sea ice loss: summer ice loss increases solar absorption and warming in the upper ocean[42], which delays sea-ice formation in the subsequent autumn and reduces the total amount of snow accumulation as more snow falls into open ocean than on sea ice (Fig. 1A, 3). Consequently, a thinner snow cover exposes sea ice to solar radiation earlier the following spring, which contributes to the positive albedo feedback by decreasing the surface albedo during a period of high insolation[43] (Fig. 1B, 13-14). Increased solar absorption within the sea ice and ocean enhances sea-ice loss and ocean warming[42], to further delay sea-ice formation in the subsequent autumn and reduce snow accumulation[31,40].

In spring, Arctic melt onset has trended earlier in recent decades due to the combined effect of higher air temperatures and larger moisture fluxes[44-46]. As melt progresses, the distribution of snow influences the occurrence, location and timing of melt pond formation due to its freshwater content[16,18] and modification of the surface topography[19-20] (Fig. 1B, 15-17). As seasonal ice becomes increasingly common and melt onset earlier[44-48], melt ponds will further promote sea-ice loss due to their low albedo[2,49-50] (Fig. 1B, 17).

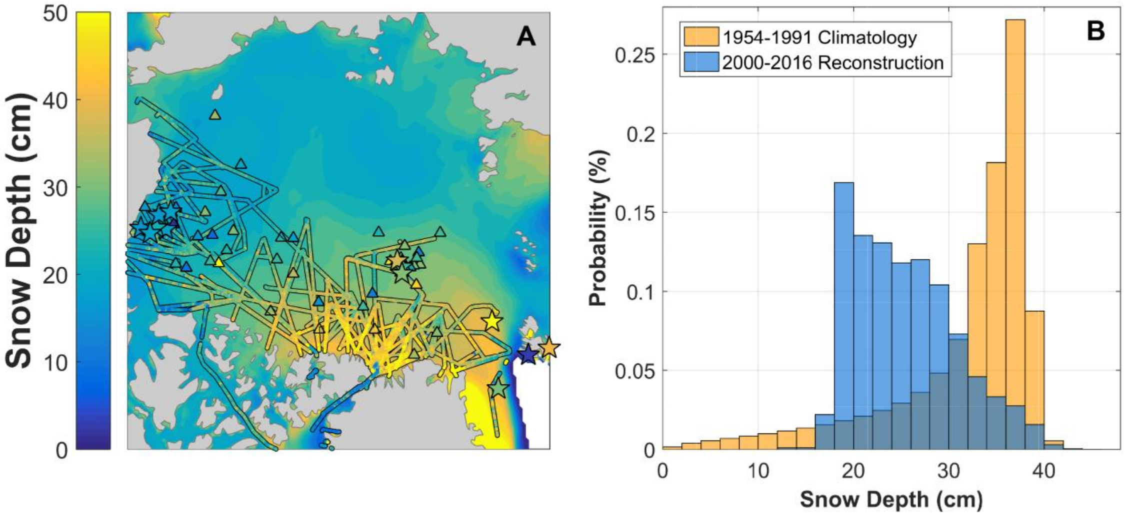

Figure 2. (A) Snow depth reconstruction for the Arctic Ocean in March-April for 2000-2016 from ERA-Interim reanalysis snowfall[51]. The reconstruction converts reanalysis snowfall to

snow depth using the climatological snow density[29] on sea-ice parcels that move with the wind and ocean currents. Snow depth observations from different sources in 2000-2016 are overlaid as symbols: Ice Mass Balance buoys[52] from 2000-2016 are triangles; mean snow depths from field campaigns are stars; and NASA Operation IceBridge 2009-2015 aerial surveys are basin-scale lines[53]. Note that the reconstruction excludes snow redistribution due to atmospheric processes and ice dynamics, which may contribute to discrepancies with the observations. The Operation IceBridge retrievals exclude snow-free (zero) values. **(B)** The snow depth distributions for March-April from the 1954-1991 climatology[29] and the 2000-2016 reconstruction showing a marked reduction in depth. The bin size is 2 cm. The reconstruction was chosen for comparison due to the absence of observations in the spatial domain of the 1954-1991 climatology and the good agreement between the reconstruction and observations[54]. A factor to consider when interpreting the frequency distributions is that the spatial averaging differs between the 1954-1991 climatology (e.g., 500-m and 1000-m averages) and 2000-2016 reconstruction (e.g., a 25-km gridded product). These differences in spatial averaging contribute to the differing shapes of the distributions, with the 1954-1991 averages retaining more variability and thus yielding a wider frequency distribution while the 25-km gridded average reduces the spatial variability and constrains the shape of the frequency distribution. The mean difference of ~10 cm between the 1954-1991 climatology and 2000-2016 reconstruction is in agreement with findings from other works[31,40-41].

2.2 Snow on Antarctic sea ice

While there are some similarities, the Antarctic snow-sea ice system differs from that of the Arctic in several fundamental ways, underpinned by key differences in the geographical settings and the associated coupled sea ice-atmosphere-ocean interactions[6,10,55]. Antarctic sea ice is mainly seasonal and exposed to the highly-dynamic circumpolar Southern Ocean. As such, the Antarctic snow-sea ice system is very mobile[10,56] and strongly influenced by frequent synoptic events and strong winds[27,57-58]. Leads and polynyas are common features and, in general, Antarctic sea ice is thinner than Arctic sea ice[59-61]. Another fundamental difference is the absence of solar-absorbing melt ponds on Antarctic sea ice and the dominance of basal melt during the relatively short melt season[62]. Accordingly, the surface albedo remains high throughout the melt season due to the persistence of snow[10,63].

Much like the Arctic[64], snow depth distributions on Antarctic sea ice are strongly coupled to the age of the ice and its surface roughness[9]. However, leads in the Antarctic may serve as a more significant sink for wind-blown snow due to their greater prevalence and high frequency of snowfall and wind events[14,65]. A recent study[65] related very thick snow (0.45-m mean) to a lack of leads in a region where, in previous years, open leads and a significantly thinner snowpack were observed. This finding underlines the importance of sea-ice dynamics and strong winds in determining the snow depth on Antarctic sea ice, as also demonstrated by recent modelling study[66], and may shed insight into processes that may play an increasingly important role in the Arctic snow-sea ice system in a changing climate.

In addition to being younger, thinner and more dynamic, the Antarctic snow-sea ice system is also characterized by highly-variable meteorological conditions[10] in which heavy snowfall and synoptically-driven thaw events occur year-round[27,67]. The combined effect of heavy snowfall and thinner ice results in widespread flooding and snow-ice formation (Fig. 1A, 8), with the latter serving as an important positive mass contribution to Antarctic sea ice[9,26,68-69]. Although short-lived, thaw and rainfall events significantly alter the snowpack's thermal and optical properties, and can form ice layers and crusts[9] which "lock in" the snow, preventing drifting[15,26-28] (Fig. 1A, 9). The upward wicking of brine from the sea-ice surface typically creates a damp, saline layer at the base of the snowpack, even in the absence of flooding[27-28,69-70]. An important consequence of wet snow, in addition to increasing its thermal conductivity, is a decrease in albedo, with this effect remaining after the wet snow refreezes[1,11,63].

Regarding the data record, Antarctic snow observations are even sparser than the Arctic's. This is due to the extreme remoteness and harshness of the Southern Ocean and the greater difficulty in accurately deriving snow characteristics from remote sensing data[71] owing to the more structurally-complex nature of the Antarctic snowpack (e.g., extensively flooded, more strongly layered, often saline and damp)[10,15,28]. Given these limitations, there is currently no climatological baseline against which to i) identify long-term changes in snow conditions on Antarctic sea ice, or ii) gain fuller understanding of the Antarctic snow-sea ice system evolution over an annual cycle. Nevertheless, existing observations have revealed key differences in processes and conditions that distinguish the Antarctic snow-sea ice system from the Arctic. These differences include: (1) more snow-ice formation, (2) more snow lost to leads, (3) more thaw and (4) more rain-on-snow events. Although some Earth system models include some of these processes (e.g., the Community Earth System Model), we propose that accounting for these processes in climate modelling will be a major step towards more accurately projecting the future of the Antarctic system in a changing climate.

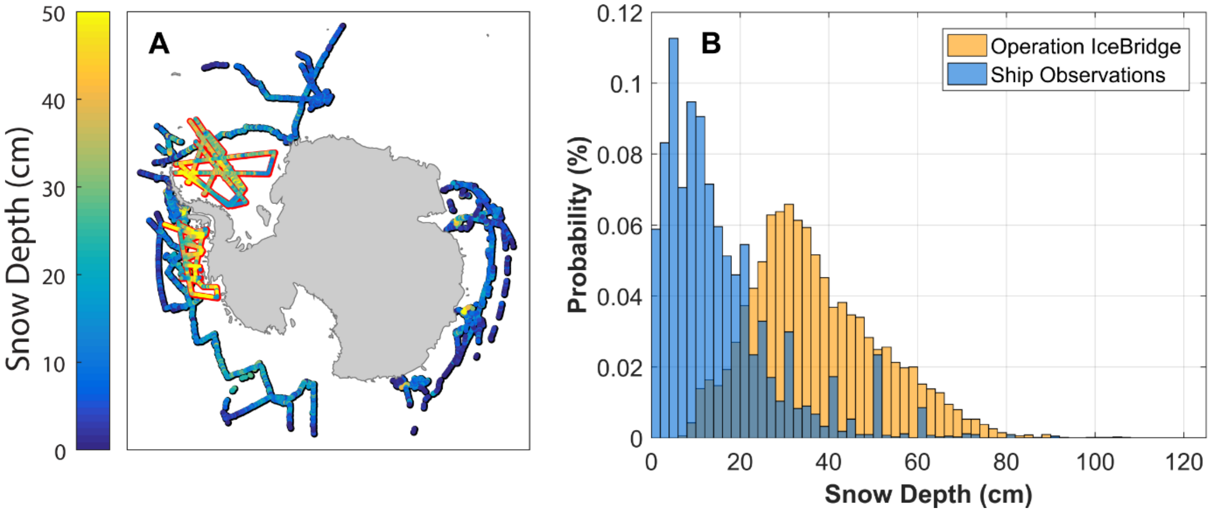

Figure 3. (A) September-November (austral spring) snow depth distributions on Antarctic sea ice based on ship observations (black outline) compiled by ref. 59 and derived from Operation IceBridge snow radar data (red outline)[72]. Note that the deeper snow depth retrievals from Operation IceBridge flights may result from greater sampling of thicker, more deformed ice later in the season relative to the ship observations. **(B)** The snow depth distributions for September-November from ship observations and Operation IceBridge. The histogram excludes snow-free values from the ship observations (making up ~10% of the total) for an objective comparison with the airborne data, which excludes snow-free values. The bin size is 2 cm.

3. Key challenges and knowledge gaps

To improve predictions of polar climate change and its effects, we need to represent the Arctic and Antarctic snow-sea ice systems accurately. For that, two things need to happen, both challenging. First, we need to know which aspects of the complex processes shown in Figure 1 need to be represented in the models (or the projections will be wrong). Second, we need to be able to obtain much-improved observations of snow processes and spatial fields of snow depth and properties against which model results can be compared and models subsequently improved. As noted earlier, considerable physical and logistical challenges limit the collection of snow observations at the spatial and temporal frequencies required for monitoring and understanding changes in snow conditions. Not only this, remote sensing of snow on sea ice remains a challenge given the complexity of the snow substrate and the heterogeneity of the underlying sea ice as both affect the electromagnetic signature[71]. However, these challenges may be surmountable.

3.1 Model treatment of snow on sea ice

Although climate models have inherent biases and uncertainties[73], they are the only means for understanding and predicting snow conditions on sea ice and their feedbacks at scales relevant to climate and climate change. To date, the treatment of the snow-sea ice system has been relatively simplistic in climate models[74] compared with treatments for snow on land. The micro-scale physics that define the macroscopic thermo-optical properties of snow on sea ice are relatively well-known and certain key relationships have been proposed (e.g., between effective snow thermal conductivity and bulk snow density[75]). However, it is unclear whether the incorporation of such relationships/processes reduce or increase current uncertainties in climate models – given the sparsity of input data, the lack of space- and time-independent observations applicable to different climate scenarios and the issue of reasonably representing small-scale processes at the aggregate-scale. For example, the treatment of different phases (vapor, liquid, solid) in the snowpack and their interactions with other physical processes have not been addressed in sea-ice models, and one can only speculate about the effective impacts of such higher-order mechanisms on large-scale climate simulations. Previous works have demonstrated the large sensitivity of sea-ice and climate simulations to thermo-physical parameters[76-78]. To date, however, none have clearly disentangled primary from secondary processes regarding their relative importance in simulating realistic behavior of the snow–sea ice system under changing climate. This is in large part due to the absence of process-oriented diagnostics from observations.

Ensuring a high-fidelity simulation of snow on sea ice requires: (1) reasonable precipitation forcing, (2) reasonable representation of factors driving snow loss and melt and (3) model evaluation methods to both assess snow in present climate simulations and pinpoint critical processes defining the snowpack in transient climate experiments. Both model- and observation-based precipitation data for (1) suffer from large uncertainties culminating from the lack of precipitation observations at high latitudes, biases associated with precipitation gauges[79], the varying sophistication of parameterized cloud physics and inherent model biases[80]. For (2), we face challenges in modelling snow melt due to the complexity of observing and simulating time-varying changes in atmospheric forcing, surface conditions and albedo. Additionally, snow "loss" due to wind-blown redistribution and snow-to-sea ice conversion (from flooding at the snow-ice interface) can lead to potential discrepancies between modeled (and observed) snowfall and actual snow accumulation on sea ice[69]. The two distinct types of model evaluation in (3) are constrained by the differing scales between *in situ* snow observations and climate model resolutions and the significant uncertainties in remote sensing observations[71,81-82].

Improving the coverage and quality of large-scale snow observations is a way forward for designing standard error metrics to evaluate the key snow state variables (depth, albedo, density) in current climate conditions. Equally important are process-oriented metrics for exposing inaccurate or missing mechanisms that drive the evolution of snow conditions in climate models.

Process-oriented metrics also allow assessment of snow's contribution in feedbacks with other climate system elements, which is essential for understanding snow's role in various climate regimes. Although such diagnostics have recently been developed for sea-ice processes and polar feedbacks[83-84], much work remains to be done regarding snow itself. Such efforts will be a leap forward in our understanding of snow's role in the climate system when coincident atmosphere-ice-ocean observations appropriate for quantifying processes and feedbacks become available.

Snow-on-sea ice modelling can also benefit from advances made by the terrestrial snow modelling community, which has developed more comprehensive snow models[85]. The fact that snow lies on a moving, deforming sea-ice platform to which it is closely coupled remains a considerable challenge. However, some snow processes are transferable to sea-ice frameworks, as recently done for wind-driven snow redistribution on level ice[86]. Testing such complex snow schemes (from terrestrial snow models) on sea ice could provide valuable insight to determine the scales at which specific snow processes might become irrelevant for climate models.

3.2 Improving observations of snow on sea ice

Ideally, we would have recurring, consistent and scalable observations that capture the seasonal evolution of snow depth, density and albedo across both polar sea-ice covers. However, there are no current observing systems in place or planned future systems to routinely generate large-scale maps of snow properties on sea ice, despite snow's significance to sea-ice mass balance and thickness retrievals[87]. More so, existing *in situ* and remote sensing observations of snow are severely limited in space, quality and time due to the spatial and temporal heterogeneity of snow, substantial year-to-year variability, the vast scales involved and difficulties in accessing extremely remote environments. Unique uncertainties are also associated with the type of observational method used, giving rise to caveats specific to data interpretation. Here, we discuss the current limitations in observing snow on sea ice and introduce priorities for extending our observational capabilities.

Snow depth distribution is one of the critical knowledge gaps of snow on sea ice due to physical and instrumental constraints and our limited understanding of the mechanisms governing snow accumulation and redistribution[6,14]. Remote sensing has a key role to play in addressing this issue, yet key challenges remain. On regional scales, airborne and satellite systems reach instrumental constraints due to range resolution issues, creating a lower-bound to snow depth retrievals based on the ability to separate the air-snow and snow-ice interfaces e.g., ~5-8 cm minimum for the Operation IceBridge snow radar[53,72,88]. Over deformed sea ice, an ice type typically under-sampled in field observations, radar returns are scattered in several directions, resulting in a rather indistinct air-snow interface. In these cases, the data are often discarded[53,89]. In regions with saline snow, radar-derived snow depths may be biased low due to an erroneous detection of a shallow, saline interface[82]. Relative to radar, satellite passive microwave retrievals of snow depth provide substantial coverage of the polar sea ice covers on a daily basis at 25-km spatial resolution[90-91], but they too have inadequacies. Passive microwave snow depth retrievals are limited to areas of first-year sea ice outside the marginal ice zone and to snow depths of 50 cm and less, and underestimate snow depth by a factor of 2 to 3 over rough surfaces[92-94].

Collectively, these remote sensing limitations may contribute to a poor characterization of snow specific to different ice types and their corresponding contribution to the overall snow depth distribution. These findings highly motivate focused efforts towards quantifying and constraining uncertainties and biases associated with remotely sensed snow properties over all ice types. This can be achieved through strategic coordination between field, airborne and satellite campaigns targeting wide-ranging snow and sea ice conditions to collect coincident, scalable data that are more representative of the heterogeneous snow-sea ice systems. Constraining uncertainties is also aided by technological advancements and improved instrumentation (e.g., finer radar range resolution) for more accurate detection of air-snow-ice interfaces.

Another major challenge to measuring snow is that it is governed by time-variant processes that operate at different spatial scales[6]. The pack ice zone continually transforms with ice dynamic and snow thermodynamic processes. Accordingly, the time-space evolution of the snow heterogeneity in both depth and properties is complex (Fig. 1). There is a critical need for quantifying the mechanisms driving snow heterogeneity and how their magnitude of influence evolves seasonally. Key processes requiring further scrutiny include snow lost to leads[14] and via snow-ice formation[9-10] and the impact of melt[44,46,67] and rain-on-snow events as a function of season and region[95]. To make progress on these priorities, collecting data specific to atmosphere-snow-sea ice interactions is essential, such as time-series of coincident meteorological (wind speed, air temperature, humidity, precipitation amount and phase), sea ice (orientation of topographic features and leads) and snowpack conditions (porosity, snow grain size and shape, the presence of liquid within the snowpack). Models can help reveal which processes may dominate in specific regions, which can be further guide field experiments for documenting, testing and better understanding these processes so that they can be readily linked with model diagnostics and development.

4. Future steps

Here, we propose two approaches to addressing critical observational and modelling needs and improving our understanding of, and ability to predict, snow on Arctic and Antarctic sea ice. These approaches are achievable through the synthesis of observational, remote sensing and modelling efforts, as shown by examples below.

4.1 Basin-scale sampling (remote sensing)

There are currently no observational systems in place dedicated to basin-scale mapping of snow on sea ice. However, there are two potential opportunities to measure and monitor snow at basin-scale: (1) mapping with autonomous aircraft (e.g., Global Hawk), which requires less support than traditional airborne missions (e.g., Operation IceBridge), and (2) multi-sensor approaches and the merging of different satellite products[87,96-97]. One such avenue of the latter is the synthesis of ICESat-2 laser and CryoSat-2 radar altimeter data, which depends on their operational success, the availability of sufficient crossovers of their orbital swaths in space and time and retrieval uncertainties. Theoretically, ICESat-2 and CryoSat-2 will detect the distance to the air-snow and snow-ice interfaces, respectively. The difference will yield snow depth. This concept has been successfully demonstrated using airborne and satellite data, and shows promise as a future source of snow depth retrievals on sea ice at basin-scale[97]. Before opportunities like this are pursued, however, it is essential to cross-communicate the differing needs (e.g., accuracy, spatial and temporal resolutions) of the modelling and remote sensing communities to ensure that the resulting uncertainties are sufficiently low to be useful. For example, a snow depth product gridded at 25-km resolution with a 5-cm uncertainty addresses the needs of the remote sensing community for accurate sea ice thickness retrievals as well as those by the modelling community as a standard error metric, and is a realistic goal within the coming decades. Algorithm development, calibration and validation using suitable surface and airborne datasets are vital to the success of such efforts. Implementing multi-regional arrays of coordinated field, airborne and satellite programs provide the means for gaining a deeper understanding of uncertainty sources over variable surface conditions and subsequently improving our remote sensing capabilities of snow on sea ice.

4.2 Targeting opportunities

As underscored throughout this review, process-oriented observations are critical for better understanding snow on sea ice and its feedbacks in the climate system. These observations can also inform parameterization development in models, ultimately leading to more robust predictive capability. Therefore, time-series of process-relevant data should be collected at every opportunity and at the necessary quantities for applying the same process-oriented diagnostics as those in models. To maximize the value of such observations, it is essential to maintain a continual dialogue between the modelling and observational communities[98] and, of equal importance, carry out model-observation cross-community coordination in future campaigns and missions (e.g., http://www.mosaicobservatory.org/).

Over the last decade, autonomous observing systems (e.g., ice mass balance buoys[52,99], snow buoys[100], webcams, automated weather systems) have advanced our ability to collect a large breadth and frequency of snow and associated sea ice and meteorological data[55]. These serve as ideal platforms for adding to our understanding of snow-sea ice processes and the evolution of snow properties as they relate to precipitation, air temperature and wind and sea-ice conditions[55]. Standardized autonomous systems should be strategically deployed in networks and from all ships traversing the polar sea ice zones e.g., coordinated within the Southern Ocean

Observing System SOOS: www.soos.aw. Such coordination will facilitate their combination with complementary instrument packages, field campaigns, aircraft overflights and satellite passes. These combined datasets yield considerable insight into the mechanisms influencing changes in the coupled snow-sea ice-atmosphere-ocean system, as well as their seasonal, inter-annual and regional evolution. The collection of snow, sea ice and meteorological data can also be expanded by non-scientists traveling to the Arctic and Antarctic sea-ice environments[30]. Standardized sampling protocols have been developed and successfully implemented for cataloguing sea-ice conditions via research cruises (e.g., https://sites.google.com/a/alaska.edu/ice-watch/), and can be readily enhanced and made accessible for non-scientists given the increase in tourism at high latitudes.

4.3 Conclusion

snow on sea ice is a complex medium strongly coupled to atmospheric, oceanic and sea ice conditions and thus heterogeneous in space and time (Fig. 1). This inherent nature of snow poses important challenges in collecting observations suitable for assessing and developing sea-ice and climate models. We have provided context and strong motivation for coordinating efforts to obtain process-oriented observations as diagnostics for sea-ice and global climate models and to improve our remote sensing capabilities of snow on sea ice. Through considered synthesis of observational, remote sensing and modelling efforts, we can attain a more complete picture of how Earth’s snow-covered regions are changing under anthropogenic warming and gain a richer understanding of snow’s role in the global sea-ice and climate systems. These coordinated efforts will leap forward our ability to predict the future role of snow in modulating the response of sea ice, and Earth, to a changing climate.

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Conflicting Interests

The authors declare no conflicting interests

Author contributions

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