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Snow in the changing sea-ice systems

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Snow is the most reflective, and also the most insulative, natural material on Earth. Consequently, it is an integral part of the sea-ice and climate systems. However, the spatial and temporal heterogeneities of snow pose challenges for observing, understanding and modelling those systems under anthropogenic warming. Here, we survey the snow–ice system, then provide recommendations for overcoming present challenges. These include: collecting process-oriented observations for model diagnostics and understanding snow–ice feedbacks, and 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.

Owing to its reflective and insulating properties, snow is a critical 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.

Across vast swathes of the polar oceans and beyond, sea ice intercepts snowfall that would otherwise directly enter the ocean. On accumulating, this snow cover significantly modifies the physical and radiative properties of the seasonally variable sea-ice environment, which constitutes up to 25% of Earth's snow-covered regions. In this way, snow modulates not only the critical role of sea ice in the global climate system, but also the sensitivity and response of sea ice to anthropogenic warming[6]. Considerable advances have been made in our understanding of the snow–sea ice system in recent decades (see Sturm and Masson[7]). Major questions remain, however, as to the exact role of snow, how it varies regionally and seasonally, how snow conditions on sea ice are changing and what effects these changes have on the atmosphere–sea ice–ocean interactions.

First and foremost, our limited understanding stems from the complexity of the snow–sea ice systems and the scarcity of observations. Snow on sea ice is tightly coupled to sea-ice and atmospheric conditions[6,7], and thus the physical, optical and thermal properties of snow are heterogeneous in space and time (Fig. 1). Accordingly, snow processes differ widely in occurrence, magnitude and frequency between seasons, regions and hemispheres, which underscores the difficulty in obtaining observations that are wholly representative of the snow–sea ice systems.

These factors, together with the difficulties in accessing dynamic sea-ice environments, greatly challenge our ability to observe and quantify the current state of snow on sea ice, monitor long-term changes in snow conditions, and understand snow-related processes and their feedbacks. This has, in turn, severely limited our ability to realistically represent the coupled snow–sea ice system in climate models, which undermines accurate prediction of future sea-ice coverage and conditions (and their effects) in response to climate variability and change. Given the importance of snow in sea-ice and Earth systems, addressing these challenges is a high priority in climate science. In this Perspective, we survey the snow–ice systems, synthesize recent advances in our observational and modelling capabilities and provide potential pathways to overcome these challenges through stronger coordination between the modelling, field observational and remote sensing communities. This view points towards the importance of constraining uncertainties in observations and collecting process-oriented observations as key steps for advancing our knowledge of the role of snow in the sea-ice systems and improving our understanding of polar climate change.

Snow in 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 (7 in Fig. 1a), increasing the insulating capacity of the snow[8,9]. Wind redistributes the snow to form a distinct 'snowscape' shaped by, and keyed to, Arctic and Antarctic sea-ice topographies[10–12] (6 in Fig. 1a). Open cracks, leads and polynyas within the sea ice cover act as a sink for snow during wind-driven redistribution[13,14] (11 in Fig. 1a). In any region and at any time of year, ephemeral events such as rain-on-snow (9 in Fig. 1a) and thaw can affect the amount of snow removed and reworked by the wind[15–17] and rapidly alter the snowpack's insulating and optical properties[1,18,19].

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, affecting 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 snow in the Antarctic system. Here, we provide a brief review of snow in Arctic and Antarctic environments as a yardstick with which to assess long-term changes, and highlight which processes require further scrutiny for better understanding and representation in Earth system models.

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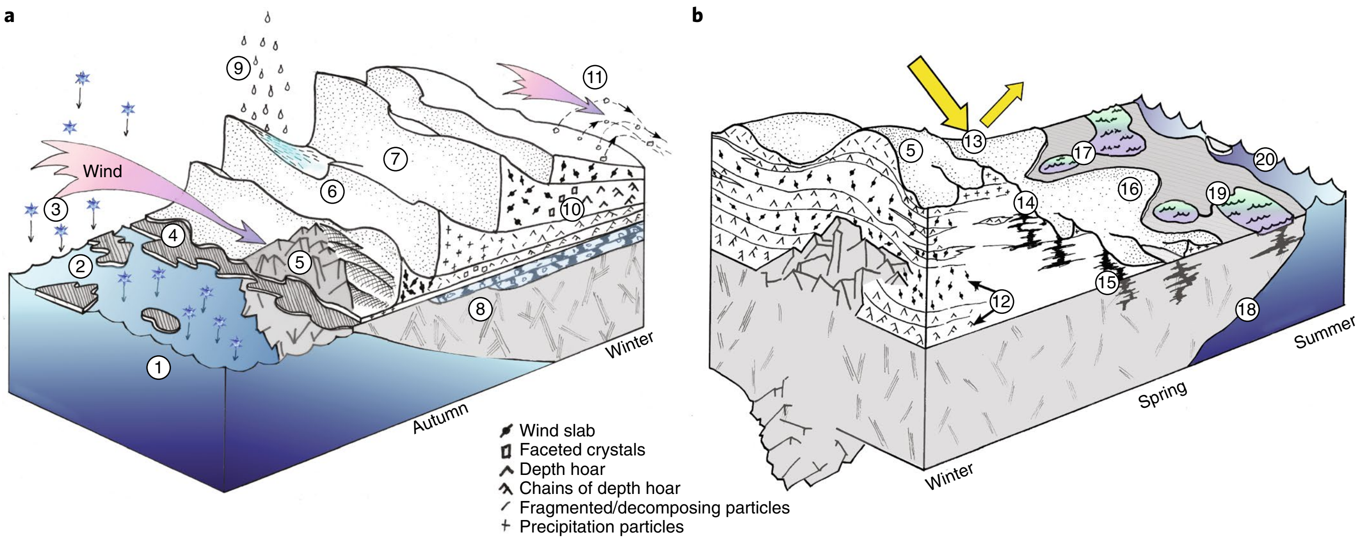

Fig. 1 | A schematic of the complex set of processes that takes place between snow and sea ice. a, Autumn to winter. **b**, Winter to summer. We exclude midwinter and mid-to-late summer from the illustrations to highlight the dominant snow processes. Box 1 contains the descriptions of the processes numbered in the figure. Certain processes are more dominant in one hemisphere than the other; for example, melt ponds in the Arctic, snow-ice formation in the Antarctic (see Box 1 and Sturm and Masson[7]). Credit: Matthew Sturm

Box 1 | Generalized sequence for snow-on-sea ice processes

Autumn to winter

1. In autumn the sea surface cools.
2. It cools to the extent that it begins to freeze, forming sea ice.
3. Snow may fall before the sea has frozen.
4. Otherwise, a thin sea-ice platform may intercept the snowfall, allowing snow to accumulate.
5. Ice deformation driven by the wind and ocean currents creates surface roughness features such as pressure ridges, which trap blowing snow in their lee 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[46,57,98].
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[1,18,19].
11. Wind continues to erode or drift the (unconsolidated) snow, increasing the heterogeneity of the snow cover[10] and blowing snow particles into leads, where they may melt, form slush or nucleate freezing[13].

Winter to summer

12. By late winter, a mature, heterogeneous snowpack covers the ice, keyed in some ways to the deformation state of the ice and its 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)[10,27].
13. By spring, increasing temperatures and solar radiation will start melting the snowpack from the top down.
14. Meltwater then percolates downwards through the snow to form internal ice layers and cause grain coarsening, which reduces the snow albedo[1,2,19].
15. Where meltwater percolation reaches the snow–ice interface, it first forms superimposed ice[38,63,99], 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 on reaching freezing-point temperatures, reducing the permeability and salinity of the ice[39].
16. Where snow dunes have formed during the winter, the snow will last longer through the melt season.
17. Melt ponds will form adjacent to these dunes[40,41] (in the Antarctic, austral summer melt is generally insufficient to remove the snow cover on surviving ice floes, and melt ponds are rare[46]). 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 basal melting by oceanic heat fluxes.
19. With all of the snow gone, the (Arctic) melt ponds expand, link up and eventually drain.
20. That is, until 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 the lack of melt ponds) may contribute to the survival of sea ice through the melt season, particularly at higher latitudes[46].

Snow on Arctic sea ice. The principal controls on snow accumulation and evolution on Arctic sea ice are the timing of sea-ice formation, duration and retreat (ice age), and the timing and magnitude of snowfall. The significance of these controls is reflected in the distinct cross-basin gradient in the distribution of snow on Arctic sea ice[20–23] (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[20,24,25]; however, for much of midwinter, Arctic cyclone intensities decrease, resulting in lower rates of snowfall[20,24–26] (4 in Fig. 1a). The seasonal tapering in snowfall differs regionally, with the Atlantic sector receiving the heaviest snowfall and rainfall year-round relative to other Arctic regions[24,26]. As a result, flooding and snow-ice formation occur in the Atlantic sector[27–31] (8 in Fig. 1a), whereas elsewhere across the Arctic, snow-ice formation rarely occurs[7] because snowfall rates are lower[26] and the snowpack thinner and drier[17,20,27,29]. The regional differences in coupled sea ice–snow–atmospheric processes lead to snow conditions that are regionally unique[17,20,27,29], 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[22] (Fig. 2b). Earlier work[20] found negative trends in snow depth for most months in 1954–1991, albeit insignificant with the exception of significant reductions in May (2 cm per decade). A thinning snow cover was also simulated in models of varying sophistication, ranging from a fully coupled global climate model[32] to snow depth reconstructions using reanalysis snowfall data[33]. Taken together, these results point to a clear and unidirectional response of the snow cover to Arctic sea-ice loss: summer ice loss increases solar absorption and warming in the upper ocean[34], which delays sea-ice formation in the subsequent autumn and reduces the total snow accumulation because snow falls into the open ocean rather than on sea ice (3 in Fig. 1a). 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[35] (13 and 14 in Fig. 1b). Increased solar absorption within the sea ice and ocean enhances sea-ice loss and ocean warming[34], to further delay sea-ice formation in the subsequent autumn and reduce snow accumulation[22,32].

In spring, Arctic melt onset has occurred earlier in recent decades due to the combined effect of higher air temperatures and larger moisture fluxes[36,37]. As melt progresses, the distribution of snow influences the occurrence, location and timing of melt pond formation due to its freshwater content[38,39] and modification of the surface topography[40,41] (15–17 in Fig. 1b). As seasonal ice becomes increasingly common and melt onset earlier[36,37,42,43], melt ponds will further promote sea-ice loss due to their low albedo[2,44,45] (17 in Fig. 1b).

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[7,46,47]. 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[46,48] and strongly influenced by frequent synoptic events and strong winds[16,49,50]. Leads and polynyas are common features and, in general, Antarctic sea ice is thinner than Arctic sea ice[51–53]. 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[54]. Accordingly, the surface albedo remains high throughout the melt season due to the persistence of snow[46,55].

Much like the Arctic[56], snow depth distributions on Antarctic sea ice are strongly coupled to the age of the ice and its surface roughness[57] (Fig. 3). However, leads in the Antarctic may serve as a more significant sink for wind-blown snow due to their greater prevalence and the high frequency of snowfall and wind events[13,58]. A recent study[58] related very thick snow (0.45 m mean) to a lack of leads in East Antarctica 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 a recent modelling study[59], 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[46] in which heavy snowfall and synoptically driven thaw events occur year-round[16,60]. The combined effect of heavy snowfall and thinner ice results in widespread flooding and snow-ice formation (8 in Fig. 1a), with the latter serving as an important positive mass contribution to Antarctic sea ice[15,57,61,62]. Although short-lived, thaw and rainfall events significantly alter the thermal and optical properties of the snowpack, and can form ice layers and crusts[57], which ‘lock in’ the snow, preventing drifting[15–17,46,63] (9 in Fig. 1a). 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[16,17,46,64]. 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[1,18,55].

Regarding the data record, Antarctic snow observations are even sparser than in the Arctic. 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[65] owing to the more structurally complex nature of the Antarctic snowpack (extensively flooded, more strongly layered, often saline and damp)[17,46,63]. Given these limitations, there is currently no climatological baseline against which to (1) identify long-term changes in snow conditions on Antarctic sea ice, or (2) gain fuller understanding of the evolution of the Antarctic snow–sea ice system over an annual cycle. Nevertheless, existing observations have revealed key differences in processes and conditions that distinguish the Antarctic snow–sea ice system from that in the Arctic. These differences include more snow-ice formation, a greater proportion of snow lost to leads, more thaw and more rain-on-snow events. Although certain Earth system models include some of these processes (the Community Earth System Model, for example), we propose that accounting for these processes in climate modelling is a necessary step towards more accurately projecting the future of the Antarctic system in a changing climate.

Key challenges and knowledge gaps

To improve predictions of polar climate change and its effects, we need to represent both the Arctic and Antarctic snow–sea ice systems more accurately in climate models. For that, two things need to happen, both of which are challenging. First, we need to determine which aspects of the complex processes shown in Fig. 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 other properties (such as density and albedo) against which model results can be compared and the 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[65–67]. However, recent advances in our observational and modelling capabilities suggest that these challenges may be surmountable.

Model treatment of snow on sea ice. Although climate models have inherent biases and uncertainties[68], they are the only means

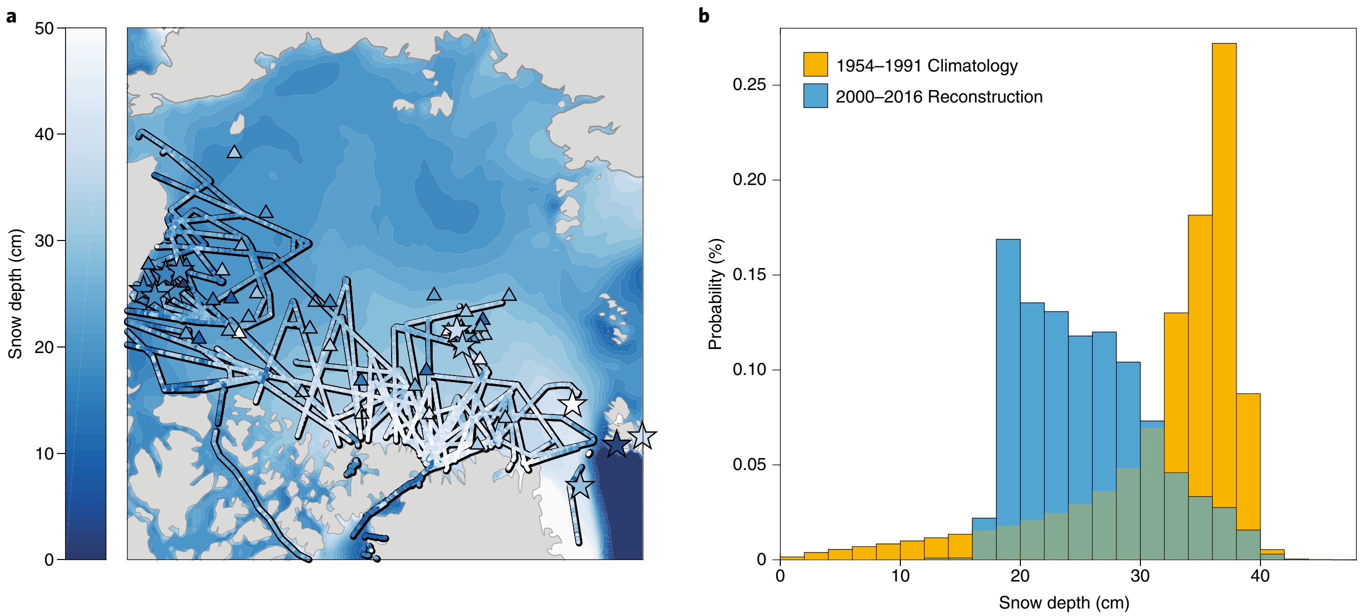

Fig. 2 | Arctic snow depth distributions. a, Snow depth reconstruction on Arctic sea ice in March–April 2000–2016 from ERA-Interim reanalysis snowfall[97]. Snow depth observations from different sources in 2000–2016 are overlaid: ice mass balance buoys[95] (triangles); mean snow depths from field campaigns (stars) and NASA Operation IceBridge aerial surveys (basin-scale lines)[85]. The Operation IceBridge retrievals exclude snow-free (zero) values. **b**, Snow depth distributions for March–April from the 1954–1991 climatology[20] and the 2000–2016 reconstruction, which show a marked reduction in depth. The bin size is 2 cm.

for understanding and predicting snow conditions on sea ice and their feedbacks at scales relevant to climate and climate change. Most of the processes shown in Fig. 1 occur at scales much smaller than those resolved by regional or global climate model meshes or sub-grid sea-ice thickness classes. They must therefore be described in terms of the larger-scale variables, represented by averages over regional or climate model grid scales. To date, the treatment of the snow–sea ice system has been relatively simplistic in climate models[69] compared with treatments for snow on land. The microscale physics that define the macroscopic thermo-optical properties of snow on sea ice are relatively well known and certain key relationships have been proposed (between effective snow thermal conductivity and bulk snow density[70], for example). However, it is unclear whether the incorporation of such relationships/processes reduces or increases 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 (vapour, 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 thermophysical parameters[71–73]. However, none have yet clearly disentangled primary from secondary processes regarding their relative importance in simulating realistic behaviour 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 to constrain (1) suffer from large uncertainties culminating from the lack of precipitation observations at high latitudes, biases associated with precipitation gauges[74], the varying sophistication of parameterized cloud physics and inherent model biases[75]. To produce (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. Snow 'loss' due to wind-blown redistribution[13] and conversion of snow to sea ice (due to flooding at the snow–ice interface) can also lead to potential discrepancies between modelled (and observed) snowfall and actual snow accumulation on sea ice[62]. The two distinct types of model evaluation needed for (3) are constrained by the differing scales between in situ snow observations and climate model resolutions and the significant uncertainties in remote sensing observations[65,76,77].

Improving the coverage and quality of large-scale snow observations is one route towards 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 the contribution of snow in feedbacks with other climate system elements, which is essential for understanding the role of snow in various climate regimes. Although such diagnostics have recently been developed for sea-ice processes and polar feedbacks[78,79], much work remains to be done regarding snow itself. Such efforts will be a leap forwards in our understanding of snow in the climate system when coincident atmosphere–ice–ocean observations appropriate for quantifying processes and feedbacks become available.

Because most snow processes occur at sub-metre scales, limited computational resources prevent direct modelling of them. Surface and near-surface fluxes associated with such processes must be estimated via sub-grid-scale approximations or sub-models that can represent the net effect of such fine-resolution processes (see Liston[80]). Improving these approximations requires

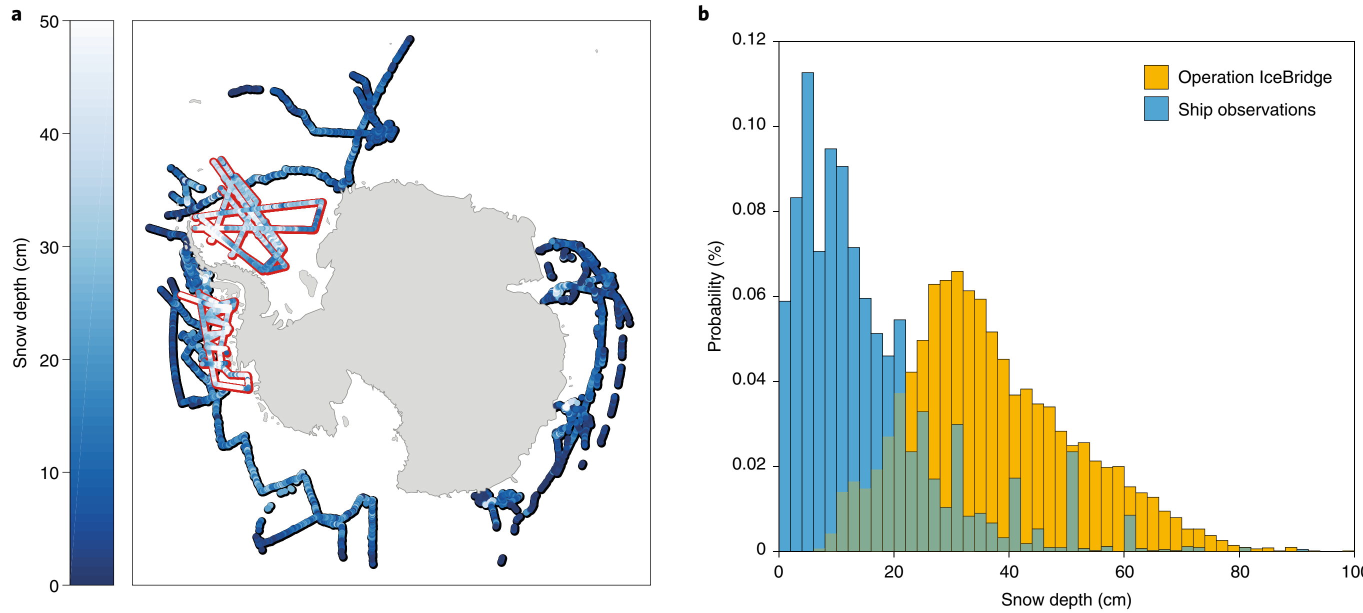

Fig. 3 | Antarctic snow depth distributions. a, September–November (austral spring) snow depth distributions on Antarctic sea ice based on ship observations[51] (black outline) and from Operation IceBridge aerial surveys[86] (red outline). The deeper snow depth retrievals from Operation IceBridge may result from greater sampling of thicker, more deformed ice later in the season relative to the ship-based observations (which tend to avoid regions of thick/deformed ice). **b**, Snow depth distributions for September–November from ship observations and Operation IceBridge. The histogram excludes snow-free values from the ship observations (~10% of the total) for an objective comparison with the airborne data, which excludes snow-free values. The bin size is 2 cm.

strong collaboration among sea-ice and remote-sensing-based observational programmes, snow- and ice-process modellers and Earth system modellers.

Snow-on-sea ice modelling can also benefit from advances made by the terrestrial snow modelling community, who have developed more comprehensive snow models[81]. 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[82]. Testing such complex snow schemes (from terrestrial snow models) on sea ice could provide valuable insight for determining the scales at which specific snow processes may become irrelevant for climate models.

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 or planned observing systems in place to routinely generate large-scale maps of snow properties on sea ice, despite the significance of snow in sea-ice mass balance[8] and thickness and volume retrievals[83]. Moreover, 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 for snow on sea ice due to physical and instrumental constraints and our limited understanding of the mechanisms governing snow accumulation and redistribution[7,13]. Remote sensing has a key role to play in addressing this issue, yet major challenges remain. On regional scales, airborne and satellite systems are subject to instrumental constraints due to range resolution issues, which create a lower bound on snow depth retrievals as there is a limited ability to separate the air–snow and snow–ice interfaces. For example, the minimum snow depth retrieval for the Operation IceBridge snow radar[84–86] is approximately 5–8 cm. Over deformed sea ice (an ice type that is typically undersampled in field observations), radar returns are scattered in several directions, resulting in an indistinct air–snow interface. In these cases, the data are often discarded[85,87]. In regions with saline snow, radar-derived snow depths may be biased low due to an erroneous detection of a shallow, saline interface[77]. Relative to radar, satellite passive microwave retrievals of snow depth provide substantial coverage of the polar sea-ice cover on a daily basis at a spatial resolution of 25 km, but they too have inadequacies[88,89]. Passive microwave snow depth retrievals are limited to areas of first-year sea ice outside the marginal ice zone and to snow depths of up to 50 cm, and also underestimate snow depth by a factor of two to three over rough surfaces[66,67,90].

Collectively, these remote sensing limitations may contribute to a poor characterization of snow specific to different ice types and their corresponding contributions to the overall distribution of snow depth. These findings 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. Technological advancements and improved instrumentation (such as finer radar range resolution) also help constrain uncertainties by allowing for more precise 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[7]. The pack ice zone continually transforms with processes relating to ice dynamics and snow thermodynamics. Accordingly, the temporal–spatial evolution of snow heterogeneity in both depth and properties is complex (Fig. 1). There is a critical need to quantify the mechanisms driving snow heterogeneity and how their magnitude of influence evolves seasonally. Key processes requiring further scrutiny include snow lost to leads[13] and lost via snow-ice formation[46,57], as well as the impact of melt[36,37,60,91]and rain-on-snow events as a function of season and region. 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, to guide field experiments for documenting, testing and better understanding these processes so that they can be readily linked with model diagnostics and development.

Future steps

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

Basin-scale sampling. There are no observational systems in place that are dedicated to basin-scale mapping of snow on sea ice. However, there are two potential opportunities to measure and monitor snow at the basin scale using remote sensing: (1) mapping with autonomous aircraft (for example, Global Hawk), which requires less support than traditional airborne missions, and (2) multisensor approaches and the merging of different satellite products[92,93]. One such avenue is the synthesis of ICESat-2 laser and CryoSat-2 radar altimeter data, which depends on their operational success, a sufficient number of cross-overs of their orbital swathes in space and time, and their 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 the basin scale[93]. Before opportunities such as this are pursued, however, it is essential to cross-communicate the differing needs (accuracy, spatial and temporal resolutions, for example) 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 of 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 multiregional arrays of coordinated field, airborne and satellite programmes would 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.

Targeting opportunities. As underscored throughout this Perspective, 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 in 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 both maintain a continual dialogue between the modelling and observational communities[94] and carry out model–observation cross-community coordination in future campaigns and missions (see http://www.mosaicobservatory.org/).

Over the last decade, autonomous observing systems (such as ice mass balance buoys[95,96], snow buoys, webcams, automated weather systems) have advanced our ability to collect a large breadth and frequency of snow and associated sea-ice and meteorological data[47]. 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[47]. Standardized autonomous systems should be strategically deployed in networks and from all ships traversing the polar sea-ice zones, coordinated with programmes such as the Southern Ocean Observing System (http://www.soos.aq), for example. Such coordination will facilitate their combination with complementary instrument packages, field campaigns, aircraft overflights and satellite overpasses. 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, interannual and regional evolution. The collection of snow, sea-ice and meteorological data can also be expanded by non-scientists travelling to the Arctic and Antarctic sea-ice environments[21]. Standardized sampling protocols have been developed and successfully implemented for cataloguing sea-ice conditions via research cruises (for example, Ice Watch; 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.

Conclusion

Snow on sea ice is a complex medium that is strongly coupled to atmospheric, oceanic and sea-ice conditions and is 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 the role of snow in the global sea-ice and climate systems. These coordinated efforts represent a quantum leap in our ability to predict the future role of snow in modulating the response of sea ice, and Earth, to a changing climate.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability, and associated accession codes are available at https://doi.org/10.1038/s41558-018-0286-7.

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Author contributions

M.W. carried out the data synthesis and led the writing. All authors contributed to the interpretation of the results and writing, each contributing to multiple aspects of the manuscript and its ideas. M.S. created Fig. 1. S.G. and D.P. provided in situ and buoy snow data in Fig. 2. R.K. provided snow depths derived from NASA's Operation IceBridge snow radar data for Figs. 2 and 3, and the ERA-Interim reconstructed snow depths in Fig. 2.

Competing interests

The authors declare no competing interests.

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Methods

The snow depth reconstruction converts reanalysis snowfall to snow depth using the climatological snow density[20] on sea-ice parcels that move with the wind and ocean currents, following methods used in earlier work[97]. The reconstruction excludes snow redistribution due to atmospheric processes and ice dynamics, which may contribute to discrepancies with observations. Nevertheless, the reconstruction was chosen for comparison due to the absence of observations in the spatial domain of the 1954–1991 climatology in Fig. 2a and the good agreement between the reconstruction and observations[100]. In Fig. 2b, a factor to consider when interpreting the frequency distributions is that the spatial averaging differs between the 1954–1991 climatology (for example, the 500 m and 1,000 m averages) and 2000–2016 reconstruction (a 25-km gridded product, for example). These differences in spatial averaging contribute to the 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 depth difference of ~10 cm between the 1954–1991 climatology and 2000–2016 reconstruction is in agreement with findings from other works[22,32,33]. Snow depth was derived from Operation IceBridge snow radar data following previous works[85,86] for Figs. 2 and 3, respectively.

Data availability

The N-ICE2015 snow data[101] are available via the Norwegian Polar Institute at https://go.nature.com/2OBliCi. The climatological snow data are available at https://doi.org/10.7265/N5MS3QNJ. The ice mass balance buoy data[102] are available at: http://imb-crrel-dartmouth.org. The ERA-Interim data[103] used for Fig. 2 are available at https://doi.org/10.1002/qj.828. The in situ data shown in Fig. 3a were provided by the SCAR Antarctic Sea Ice Processes and Climate (ASPeCt) programme (http://aspect.antarctica.gov.au). The Operation IceBridge snow radar data[104] are available at https://doi.org/10.5067/FAZTWP500V70.

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