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Regional distribution and variability of model-simulated Arctic snow on sea ice

Karel Castro-Morales [a, b, *], Robert Ricker [a], Rüdiger Gerdes [a, c]

[a] Alfred Wegener Institute Helmholtz Center for Polar and Marine Research, Climate Sciences, Am Handelshafen, Bremerhaven, Germany
[b] Max Planck Institute for Biogeochemistry, Biogeochemical Integration, Jena, Germany
[c] Jacobs University, Bremen, Germany

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ABSTRACT

Numerical models face the challenge of representing the present-day spatiotemporal distribution of snow on sea ice realistically. We present modeled Arctic-wide snow depths on sea ice (h_{s_mod}) obtained with the MITgcm configured with a single snow layer that accumulates proportionally to the thickness of sea ice. When compared to snow depths derived from radar measurements (NASA Operation IceBridge, 2009–2013), the model snow depths are overestimated on first-year ice (2.5 ± 8.1 cm) and multiyear ice (0.8 ± 8.3 cm). The large variance between model and observations lies mainly in the limitations of the model snow scheme and the large uncertainties in the radar measurements. In a temporal analysis, during the peak of snowfall accumulation (April), h_{s_mod} show a decline between 2000 and 2013 associated to long-term reduction of summer sea ice extent, surface melting and sublimation. With the aim of gaining knowledge on how to improve h_{s_mod}, we investigate the contribution of the explicitly modeled snow processes to the resulting h_{s_mod}. Our analysis reveals that this simple snow scheme offers a practical solution to general circulation models due to its ability to replicate robustly the distribution of the large-scale Arctic snow depths. However, benefit can be gained from the integration of explicit wind redistribution processes to potentially improve the model performance and to better understand the interaction between sources and sinks of contemporary Arctic snow.

1. Introduction

Snow on sea ice is an important component of the climate system and effectively regulates the energy and heat fluxes between the atmosphere, ocean and ice (Blazey et al., 2013; Pedersen and Winther, 2005; Sturm et al., 2002a). This is due to its physical properties, e.g. density, grain size and texture, leading to particular thermal (e.g., low heat conductivity) and optical (high surface albedo) characteristics. Therefore, the snow contributes substantially to the Arctic Ocean heat budget and mass conservation of sea ice.

The extent and thickness decline in Arctic sea ice over the last four decades due to a warming climate (Kwok and Cunningham, 2015; Stroeve et al., 2012, 2014a) may lead to shorter periods under freezing conditions with predominance of first-year ice and, as a consequence, to a reduction of snow depth (h_s) on sea ice. A thinner snow layer leads to a decrease in surface albedo, allowing more solar radiation penetrating the snow-ice cover and heating the ocean (Hezel et al., 2012; Pedersen and Winther, 2005; Screen and Simmonds, 2012). The warmer ocean in turn leads to longer ice-free periods and a delay in the start of the freezing period.

Results of climate models from the Coupled Model Intercomparison Project 5 (CMIP5) revealed a long-term Arctic h_s decline. Hezel et al. (2012) concluded that the April h_s for the IPCC scenarios RCP2.6, RCP4.5 and RCP8.5 over the 21st century is projected to decrease between 16 and 28 cm in latitudes >70° N.

Screen and Simmonds (2012) related a reduction of Arctic h_s to a 40 % decline in summer snowfall over the Arctic Ocean and the Canadian Arctic between 1989 and 2009. This decline was observed in site level observations and in the ERA-Interim reanalysis data (Dee et al., 2011), and is suggested to be driven by low-atmosphere warming, leading to a consistent precipitation decrease in the form of snow. The results of Screen and Simmonds (2012) and Hezel et al. (2012) suggest that a projected decrease in Arctic snow cover on sea ice driven by the change of phase to more precipitation rate in the liquid form, ultimately will affect the input of fresh water content

* Corresponding author. Max Planck Institute for Biogeochemistry, Biogeochemical Integration, Hans-Knöll Str. 10, Jena, Germany.
E-mail address: kcastro@bgc-jena.mpg.de (K. Castro-Morales).

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into the Arctic Ocean. A thinner snow cover on sea ice will take shorter time to melt, thus earlier in the melt season the amount of melt ponds on sea ice might also increase (Petrich et al., 2012).

Large-scale observations of contemporary Arctic h_s on sea ice and investigations of its spatial and temporal variability are also useful for the retrieval of sea-ice thickness (h_i) using satellite altimetry. The computation of h_i derived from freeboard using observations of satellite radar or laser altimetry, requires high accuracy h_s and snow density (Kern et al., 2015; Kurtz and Farrell, 2011; Kwok et al., 2011; Ricker et al., 2014; Zygmuntowska et al., 2014). Although the number of site level h_s measurements using primarily depth probing, radar measurements and ice mass balance buoys has increased over the last twenty years (e.g., Cheng et al., 2013; Forsström et al., 2011; Iacozza and Barber, 2010; Petrich et al., 2012; Sturm et al., 2002a, 2006, 2002b), they are still scarce. Furthermore, the derivation of reliable basin scale snow and ice thickness products from remote sensing data is still a research field in progress (e.g. Maaβ et al., 2013; Ricker et al., 2014).

The work by Warren et al. (1999) (W99 hereinafter) is perhaps the most comprehensive study of large-scale Arctic h_s to date. The authors constructed a h_s climatology based on snow data from Soviet drifting stations and aircraft landings collected in 1937 and from 1954 to 1991. Their results suggested a consistent reduction of h_s by 57 % in the Beaufort and Chukchi Seas (Warren et al., 1999). It is well known that this climatology has several limitations: It lacks interannual variability and provides an unrealistic north-to-south gradient in both h_s and snow densities (Kern et al., 2015; Kwok et al., 2011). Moreover, due to the change towards a seasonal Arctic sea-ice cover, the W99 climatology overestimates the h_s in regions of first-year ice (FYI) (Kurtz and Farrell, 2011; Kwok et al., 2011; Webster et al., 2014; Markus and Cavalieri, 1998).

Remote sensing techniques are another retrieval strategies to obtain basin scale snow depths. Markus and Cavalieri (1998) demonstrated the use of satellite passive microwave data to derive the distribution of snow depths on Antarctic sea ice by using in situ h_s measurements and microwave data. However, these retrievals are associated with uncertainties and biases, particularly over rough sea ice (Markus et al., 2011; Worby et al., 2008). Recently, Maaβ et al. (2013) demonstrated the use of horizontally polarized SMOS brightness temperature measurements under cold conditions to derive snow depths on thick sea ice (>1–1.5 m)(Maaβ et al., 2013).

In 2008, Kwok and Cunningham demonstrated the use of the snowfall product, in snow water equivalent (swe), from ECMWF to obtain the sea-ice thickness from ICESat (Ice, Cloud and Land Elevation Satellite) total freeboard measurements. During their calculations, frost/rime deposition, sublimation, and wind redistribution of snow were neglected. However, due to the limited spatial resolution of large-scale sea-ice concentration and temperature fields, the actual age of the new openings was not taken into account. As a result, a correction factor was introduced because snow depths were overestimated through this approach (Kwok and Cunningham, 2008).

In the framework of the NASA Operation IceBridge (OIB) (Kurtz and Farrell, 2011), a frequency-modulated continuous-wave (FMCW) radar (Leuschen et al., 2014; Panzer et al., 2013) together with a digital camera and a laser scanner system, are all mounted on a fixed-wing aircraft to retrieve estimates of the along flight-tracks h_s distributions in Polar Regions. OIB flight campaigns have been carried out during spring (March and April) every year since 2009, providing valuable data of contemporary Arctic airborne estimates of the snow depth on sea ice (h_{s_OIB}) with larger spatial scale than in situ level h_s measurements. The OIB data bridges the gap between the ICESat mission (Abdalati et al., 2010) and ICESat-2, launching in 2018 (https://www.nasa.gov/content/goddard/about-icesat-2).

In the OIB data, the h_s retrieval algorithm is based on the detection of the air-snow and snow-ice interfaces within the radar returns. The time delay between the signals of each interface is then multiplied by the speed of light, yielding h_{s_OIB} (Farrell et al., 2011; Kwok et al., 2011). By applying a linear regression on a 40-m length scale, the spatial resolution of the h_{s_OIB} product is set to 40 m.

Webster et al. (2014) spatially interpolated the spring h_{s_OIB} data from 2009 to 2013 (following the same gridding approach of W99) and presented an updated climatology of h_s on Arctic sea ice. To evaluate changes in the last decade, and the current state of the large scale-snow cover of basically the western Arctic, the authors compared their current climatology to the one of W99. Their results showed a considerable h_s reduction between the W99 snow depth climatology and their OIB snow depth climatology from 2009 to 2013, with major snowpack thinning of about 56 % in the Beaufort and Chukchi seas (37 % in the western Arctic).

In general, h_{s_OIB} have a good agreement with in situ point h_s measurements (correlation of 0.59 and RMSE of 5.8 cm) for a wide range of snow thicknesses and ice types (Webster et al., 2014), and have an uncertainty of 5.7 cm over level ice within a 40-m length scale of the radar footprint (Kurtz et al., 2013). Recent works by Holt et al. (2015) and Kwok and Haas (2015) have demonstrated that the uncertainties in h_{s_OIB} are mainly associated to the limited range resolution of the radar measurements leading to the inability to identify snow-ice and snow-air interfaces in regions of thin snow, and to identify open leads in thin ice. Problems also arise in areas of deformed sea ice due to its rough surface and fast varying slopes. We refer to the discussion for more details on this. Recently, Sato and Inoue (2017) have compared the Climate Forecast System Reanalysis with measurements from ice mass-balance buoys and found a positive bias (i.e. thicker snow depths) during winter and spring, and a negative bias during summer and autumn, and a long term increase of snow depth in winter in Beaufort and northern Chukchi Seas (Sato and Inoue, 2017).

Changes in the snow cover on sea ice are driven by several processes, such as: melt and sublimation, snow redistribution by wind, snow fall, melting and freezing cycles, changes of grain size and density, as well as compaction of snow layers. Complex snow parameterizations are currently incorporated only in few numerical models, e.g. the Community Climate System Model, CCSM (Blazey et al., 2013); aiming to emulate partially some of these processes. Some stand-alone comprehensive snow models include multilayer snow thermal properties coupled to sea ice models (e.g., Chung et al., 2010), and metamorphic processes (e.g., Jordan et al., 1999; Nicolaus et al., 2006).

Other state-of-the-art coupled large-scale sea ice and ocean models use multilayer snow thermodynamic schemes. The thermodynamic-dynamic model LIM3 (Louvain-la-Neuve Sea Ice Model version 3), for example, provides an explicit representation of sub-grid scale ice thickness distribution (ITD) and a scheme that takes into account the vertical heat transfer through various snow layers with different thermal conductivities and densities (Lecomte et al., 2013). Few snow processes (i.e., wind redistribution and compaction) are part of large-scale sea ice general circulation models (GCMs) to date, because they are difficult to include and computationally expensive. Lecomte et al. (2015a) presented results of simulated h_s with the GCM NEMO coupled to the sea ice model LIM. This model version includes a parameterization of snow redistribution by wind and an explicit melt pond scheme. The authors evaluated their results in the context of the interaction between the snow on sea ice and their effects to melt pond formation and evolution in the Arctic (Lecomte et al., 2015a). However, the