Retrievals of Arctic Sea-Ice Volume and Its Trend Significantly Affected by Interannual Snow Variability

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Abstract We estimate the uncertainty of satellite-retrieved Arctic sea-ice thickness, sea-ice volume, and their trends stemming from the lack of reliable snow-thickness observations. To do so, we simulate a Cryosat2-type ice-thickness retrieval in an ocean-model simulation forced by atmospheric reanalysis, pretending that only freeboard is known as model output. We then convert freeboard to sea-ice thickness using different snow climatologies and compare the resulting sea-ice thickness retrievals to each other and to the real sea-ice thickness of the reanalysis-forced simulation. We find that different snow climatologies cause significant differences in the obtained ice thickness and ice volume. In addition, we show that Arctic ice-volume trends derived from ice-thickness retrievals using any snow-depth climatology are highly unreliable because the estimated trend in ice volume can strongly be influenced by the neglected interannual variability in snow volume.

Plain Language Summary In our study, we show that the lack of snow-thickness information can cause substantial uncertainties in estimated sea-ice thickness and pan-Arctic sea-ice volume from satellites such as Cryosat2. In particular, even the sign of short-term trends can be erroneous when changes in snow thickness are ignored. The satellites measure how much the sea ice extends above the ocean surface. Current algorithms interpret any change in this quantity from one year to the next to be entirely caused by a change in the associated sea-ice thickness. This is because existing algorithms assume that the snow thickness on the sea ice is constant from one year to the next. However, in reality, the snow thickness can vary substantially, which in turn influences how much the ice extends above the ocean surface for a given sea-ice thickness. Our findings suggest that better estimates and inclusion of realistic snow depths are crucial for reliable ice-thickness retrievals from satellite altimeter data. A possible step forward is the usage of accumulated snow depth from reanalysis as a source for interannually varying snow depth data.

1. Introduction

The total Arctic sea-ice volume, an important parameter for the Earth's energy and water budget, can be assessed by combining observations of sea-ice concentration and thickness across the entire Arctic region. While consistent pan-Arctic satellite retrievals exist for sea-ice concentration since the late 1970s (e.g., Cavalieri et al., 1996; Tonboe et al., 2016), satellite retrievals of Arctic sea-ice thickness only started in the early 2000s (Kwok et al., 2009). Sea-ice thickness retrievals are commonly based on freeboard observations obtained from satellite radar or laser altimeters. Radar altimeters ideally measure the freeboard of the snow-ice interface (Laxon et al., 2013); laser altimeters obtain the freeboard of the top of the snow layer covering the ice (Kwok & Cunningham, 2008). In both cases, the observed freeboard is converted to ice thickness by assuming hydrostatic equilibrium. Snow depth is a crucial parameter for such conversion (e.g., Laxon et al., 2013), but it is usually poorly known. This lack of knowledge of snow depth is responsible for about 50% of the uncertainty of the sea-ice thickness estimate, while ~40% is caused by the freeboard measurement error (Ricker et al., 2014; Tonboe et al., 2010), and the remaining ~10% is due to uncertainty in the densities of snow, ice, and water (Giles et al., 2007). While these error sources are well known, previous studies reporting sea-ice volume estimates and trends from satellite freeboard measurements generally lack a detailed quantitative estimate of the underlying uncertainties. With our study, we aim at closing this gap.

Snow-depth estimates of state-of-the-art ice-thickness retrieval products (e.g., Laxon et al., 2013) are usually based on a 2-dimensional second-order polynomial fit through climatological snow depths compiled from 31

Soviet drifting stations located in Arctic multiyear ice regions in the period 1954–1991 (Warren et al., 1999). Over the last few decades, however, the area of Arctic sea ice and, in particular, the area of Arctic multiyear sea ice have decreased substantially (Stroeve et al., 2012). Applying the snow climatology from Warren et al. (1999; hereafter, Warren climatology) to first-year ice regions is likely to result in a positive bias for ice-thickness estimates from ice-freeboard measurements of radar altimeters. This is because the later the ice forms in the Arctic freezing period, the less snow can accumulate in a region, causing an overestimation of snow depth and thus ice thickness when a snow climatology based on multiyear ice observations is used for converting ice freeboard to thickness (see also Laxon et al., 2013). Snow-depth data from Operation IceBridge (Kurtz & Farrell, 2011) indeed show that over first-year ice regions, the snow depth is substantially reduced compared to the Warren climatology. To address this bias, in the retrieval algorithm for state-of-the-art ice-thickness products from Cryosat2, half the snow depth of the Warren climatology is used over first-year ice (Hendricks & Ricker, 2013; Laxon et al., 2013). In a more recent study, the Warren climatology was averaged over the central Arctic to obtain the snow depth used for the ice-thickness retrieval over multiyear ice, while half of that value was used over first-year ice (Tilling et al., 2016).

In this study we simulate a sea-ice thickness retrieval within the Max Planck Institute Ocean Model (MPIOM; Jungclaus et al., 2013) to test the assumptions on snow depth applied by Cryosat2-based freeboard-to-thickness conversion algorithms. To do so, we derive the ice freeboard from snow and ice thicknesses simulated in an MPIOM simulation forced with atmospheric reanalysis data over the period 1981–2016 assuming hydrostatic equilibrium. We then pretend not to know the actual modeled snow thickness and ice thickness and convert the model ice freeboard to ice thickness by using different snow climatologies. This allows us to estimate uncertainties of Arctic ice volume and its trends owing to the unknown true evolution of the snow cover.

In the following section, we first briefly summarize the strengths and limitations of our model-based approach, before giving more details on the underlying methods. We then proceed to provide estimates of the uncertainty of mean values and trends of Arctic sea-ice volume and thickness.

2. Model and Method Description

Our study has two overarching aims: First, we want to quantify the uncertainty of satellite-retrieved estimates of sea-ice volume and sea-ice thickness. And second, we want to quantify the uncertainty of the underlying trends as a function of the lengths of the satellite record. To achieve both aims, we would ideally compare satellite retrievals of sea-ice thickness based on a given snow climatology with satellite retrievals of sea-ice thickness based on the true snow thickness of Arctic sea ice for every given time and location. However, as the true snow thickness is usually unknown, we translate this approach into the model world, as there all parameters are perfectly known.

This then translates our questions into the overarching question on how well the estimates obtained in the model world can be translated to the real world. This translation is greatly simplified by the fact that we do not aim at providing accurate absolute values of sea-ice volume, as, for example, aimed for by the regional Pan-Arctic Ice-Ocean Model and Assimilation System (Zhang & Rothrock, 2003). Instead, we only aim at quantifying differences in sea-ice volume and sea-ice thickness arising from different patterns of snow thickness. Hence, for quantifying the uncertainty of the satellite-retrieved mean state of sea-ice thickness and sea-ice volume, we primarily need to ensure that the time evolution of our simulated sea-ice concentration is similar to the real sea-ice concentration, as any error in simulated sea-ice thickness will cancel out as we compare the sea-ice thickness estimates based on different snow climatologies. For quantifying differences in trends, we primarily need to ensure that the year-to-year variability of the snow cover in our reference simulation is a reasonable estimate for the year-to-year variability of the real snow cover. If these conditions are fulfilled, our results will give a reasonable estimate of the uncertainty of satellite retrievals of sea-ice volume and sea-ice thickness also for the real world.

In order to simulate a time evolution of the Arctic sea-ice coverage that agrees reasonably well with the real evolution of the sea-ice coverage, we use the European Centre for Medium-Range Weather Forecast reanalysis data set ERA-Interim (Dee et al., 2011) over the period 1981–2016 to force the MPIOM ocean/sea-ice model (Jungclaus et al., 2013). MPIOM was used with a nominal resolution of 1.5° with two poles located in South Greenland and in Antarctica. This corresponds to a horizontal resolution of 15 km near Greenland and 185 km in the tropical Pacific. In the vertical, the ocean is resolved with 40 levels, with a distance between

the centers of two levels ranging from 10 to 250 m. The sea-ice component within MPIOM consists of a dynamic/thermodynamic sea-ice model based on Hibler (1979). The mean state and variability of Arctic sea ice simulated in MPIOM is evaluated by Notz et al. (2013). In MPIOM, different ice types are not distinguished. Snow, ice, and water densities are set to constant values of 330, 910, and 1,025 kg/m^3, respectively. The accumulation of snow is obtained directly from any precipitation of snow onto the sea-ice surface. If the amount of snow accumulated on the ice surface in a grid cell would cause the ice surface to drop below the ocean surface, the snow fraction located under water is directly converted to ice. Transport of snow due to, for example, winds is neglected by the model. Snow melts in response to the surface energy balance, and the snow melt water is directly transferred into the surrounding ocean. We evaluate the resulting simulation relative to the requirements of our study in the next section.

In order to carry out a simulated satellite ice-thickness retrieval based on the "true" sea-ice evolution of the ERA-Interim-forced MPIOM simulation, we assume that we do not know the true snow thickness and try to infer the ice thickness from the simulated sea-ice freeboard and an assumed snow climatology, similar to the approach of satellite-based retrievals of sea-ice thickness. To do so, we perform the following operations:

1. We assume hydrostatic equilibrium and compute the evolution of ice freeboard in every grid cell from the simulated true snow depth and ice thickness as

$$h_{\text{fb}} = \left(1 - \frac{\rho_i}{\rho_w}\right) \cdot h_i^{\text{sim}} - \frac{\rho_s}{\rho_w} \cdot h_s^{\text{sim}}. \tag{1}$$

   Here h_i^{sim} is the simulated ice thickness, h_s^{sim} is the simulated snow thickness, h_{fb} is the freeboard of the snow/ice interface, and ρ_i, ρ_s, and ρ_w represent the densities of ice, snow, and water, respectively.

2. In order to account for the lower propagation speed of the signal in the snow layer, we subtract (in accordance with ; Kwok, 2014) 22% of the true snow depth from the obtained freeboard and add 22% of the snow depth of the snow climatology that we want to examine. The latter step accounts for the lower propagation speed of the signal based on the climatology snow depth (see also Hendricks & Ricker, 2013). For simplicity, h_{fb} hereafter refers to ice freeboard corrected in this way.

3. From here onward, we pretend not to know the true snow depth of the simulation and use a given snow climatology h_s^{clim} to estimate the "retrieved" ice thickness h_i^{retr} from the ice freeboard h_{fb} as

$$h_i^{\text{retr}} = \frac{\rho_w \cdot h_{\text{fb}} + \rho_s \cdot h_s^{\text{clim}}}{\rho_w - \rho_i}. \tag{2}$$

   We use a constant snow density of 330 kg/m^3, which is used in the standard setup of our model and lies for all months within one standard deviation of snow densities observed by Warren et al. (1999). In reality, snow density changes throughout the year, but we find that slight variations of snow densities within the uncertainty range of observations only weakly affect our results (supporting information Figure S1).

4. We compare the estimated ice thickness h_i^{retr} from step 3 with the actual simulated ice thickness h_i^{sim} to obtain the ice thickness estimation difference.

For all of our analysis, we use three different snow climatologies to retrieve sea-ice thickness: first, a *Modified Warren snow climatology*, where we use the Warren climatology (Warren et al., 1999) over multiyear ice and half the Warren snow depth over first-year ice (in accordance with Laxon et al., 2013); second, a *Tilling snow climatology*, where we use spatially averaged Warren snow depths following Tilling et al. (2016); and third, a *ERA-Interim/MPIOM snow climatology*, which is the average snow thickness for each month for the first 10 years (1981–1991) of our ERA-Interim-forced MPIOM simulation. We use the first two climatologies as they are used in the state-of-the-art Cryosat2 products with Arctic wide coverage, for example the Alfred Wegener Institute Cryosat2 Sea-Ice Thickness Data Product (http://data.meereisportal.de/gallery/index_new.php?lang=en_US). We do not use the original Warren climatology, as it is not used in any Cryosat2 sea-ice thickness product that we are aware of. We additionally examine the ERA-Interim/MPIOM snow climatology to obtain an upper limit for the accuracy of ice-thickness estimates obtained with climatological snow depths that are based on the Arctic snow coverage some decades ago. In this climatology no correction is applied to multiyear ice regions.

For the classification of sea ice into *first year* and *multiyear*, we simply classify the ice in all grid cells which were ice free in the September mean of the previous year to be first-year ice. Hence, we neglect effects originating from the transport of sea ice (including its snow cover) which we consider to be of minor importance for this investigation.

3. Evaluation of the ERA-Interim-Forced Sea-Ice State

As outlined above, the main requirement for a realistic estimate of the uncertainty of the mean state of Arctic sea-ice volume is a reasonably good estimate of the time evolution of sea-ice coverage in our ERA-Interim-forced MPIOM simulation. Notz et al. (2013) showed that forcing the model with ERA-Interim reanalyzed wind, precipitation, and surface air temperature causes both the simulated mean state and trend of the Arctic sea-ice area to agree well with Sea Ice Index data (Fetterer et al., 2002), which is based on observations.

A secondary requirement for a realistic estimate of the uncertainty of the mean state is a realistic estimate of the uncertainty of the snow climatology used for the sea-ice volume estimate. All three snow climatologies that we consider here have been assumed as "good enough" to estimate sea-ice volume in earlier studies, so their spread is a reasonable estimate of the underlying uncertainty of snow climatologies for the purpose of our study. Hence, we trust that the spread of the three estimates of sea-ice volume that we discuss is a reasonable estimate for the uncertainty of total sea-ice volume as obtained from satellite retrievals for unknown true snow thickness.

To estimate the uncertainty of the satellite-retrieved trends, we must ensure that the interannual variability of the snow cover in the ERA-Interim/MPIOM simulation is a reasonable estimate of the true variability of the snow cover. Because we do not know the evolution of the true snow cover, we can only use indirect measures to estimate the plausibility of this assumption.

First, there are several lines of evidence that the mean snow depth from an ERA-Interim-forced simulation is a reasonable estimate of the true snow depth on Arctic sea ice where measurements are available. For example, Kwok et al. (2017) showed that the mean levels of ERA-Interim accumulated snow depths agree well with Operation IceBridge data (Kurtz & Farrell, 2011) in the limited regions where observations are available. Recently, Boisvert et al. (2018) found that the ERA-Interim reanalysis *produces realistic magnitudes and temporal agreement with observed precipitation events*. To complement these existing studies, we here additionally compare the ERA-Interim/MPIOM snow depths to the modified Warren climatology (Laxon et al., 2013) where that climatology is based on actual measurements. Doing so, we find that the regional structure and temporal evolution of the modified Warren climatology and the ERA-Interim/MPIOM snow climatology agree well (Figures 1, top, and S3 to S8, top). The slightly larger snow depths shown here by the modified Warren climatology compared to the ERA-Interim/MPIOM climatology are likely to be caused by smaller snow densities (270 kg/m^3 in October to 320 kg/m^3 in April) found by Warren et al. (1999) compared to our model snow density of 330 kg/m^3, which lies for all months within one standard deviation of observed snow densities (Warren et al., 1999). In order to rule out any major impact of small variations of snow densities on our results, we repeated our analysis assuming a January snow density of 300 kg/m^3 (Warren et al., 1999). While we find, as expected, a slightly better agreement within the central Arctic, the main difference patterns remain unchanged (Figure S1). These comparisons lend credibility to our reanalyzed estimate of mean snow depth where actual measurements are available.

Second, Kwok et al. (2017) found that the variability of snow thickness from an ERA-Interim-forced sea-ice simulation is at the low end of the variability of snow-thickness estimates from Operation IceBridge. While this on the one hand suggests an overestimation of variability from the retrievals used to obtain snow thickness from Operation IceBridge data, it also suggests that the variability of ERA-Interim retrieved snow thickness on sea ice might actually be a conservative underestimation of the true variability.

Third, we believe that both these findings remain true outside the regions in the high Arctic covered by the measurement-based central region of the Warren climatology and Operation IceBridge. This is because outside of these regions, the ERA-Interim reanalysis that we use to force MPIOM is based on an increasing number of observations. We hence trust that the quality of our reanalyzed snow thickness is certainly not lower than in the areas where measurements are available.

Fourth, we repeated our simulation with National Centers of Environmental Prediction reanalysis forcing (Kalnay et al., 1996). This only slightly changes our results (Figure S17), suggesting that our analysis does not strongly depend on the atmospheric reanalysis used to drive the ocean-sea-ice model.
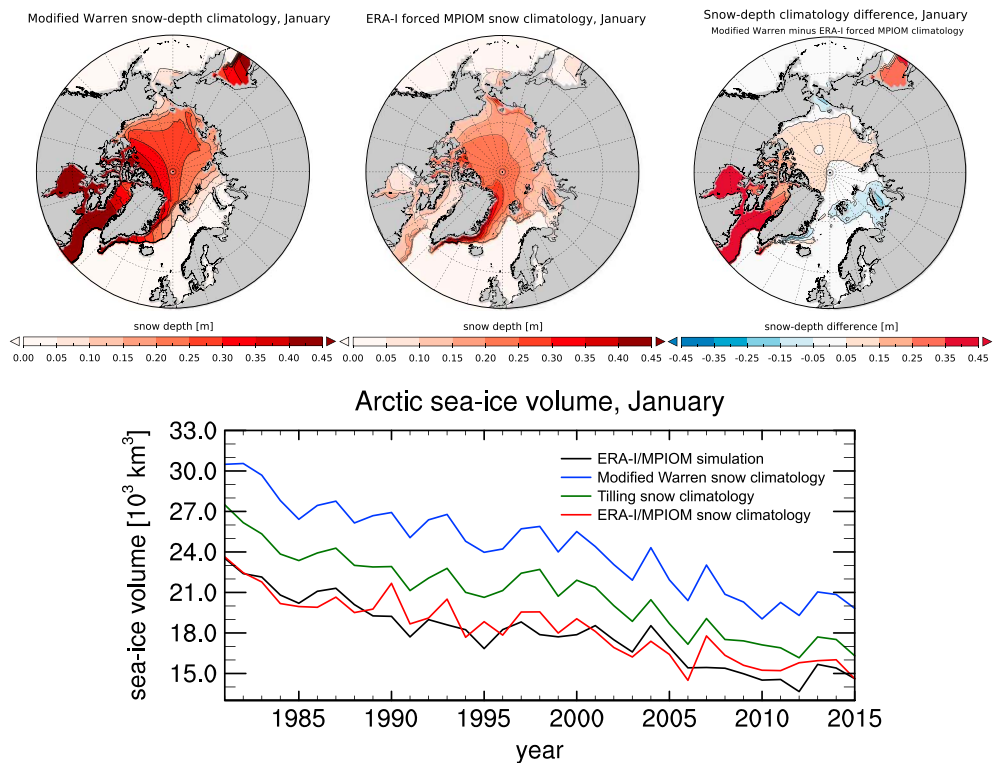
Figure 1. Modified Warren and MPIOM January snow-depth climatologies as well as the difference modified Warren minus MPIOM climatology (top, from left to right). The Arctic sea-ice volumes computed from ice-thickness estimates with Warren-based and MPIOM snow climatology are also shown (bottom). Climatological areas of first-year ice were estimated as sea ice in any grid box that had less than 15% sea-ice concentration in September, while multiyear sea ice is defined as sea ice in all grid boxes covered by more than 15% sea ice in September, based on ice-concentration data provided by the National Snow and Ice Data Center (Cavalieri et al., 1996). Using sea-ice concentrations from our reanalysis-forced model simulation, we obtain similar snow depths (Figure S2). Note that the Warren climatology was not originally designed to provide snow depth data outside the central Arctic. Nevertheless, the modified climatologies that we consider here have been used to compute ice-thickness data in these regions which is made publicly available, since other observational data products in these regions are still lacking. MPIOM = Max Planck Institute Ocean Model.

Based on this reasoning, we trust that our approach allows us to estimate both the uncertainty of mean sea-ice thickness and volume and of their trends arising from the use of a given snow climatology for the conversion of freeboard into sea-ice thickness. The results of such analysis are presented next.

4. Arctic Ice-Thickness Estimation Difference

4.1. Total Long-Term Mean Arctic Sea-Ice Volume Difference

By construction, the differences in total retrieved sea-ice volume that we identify for the different snow climatologies are primarily a reflection of total snow volume as given by the three climatologies.

We find that in all months, the ice volume estimated by converting freeboard to thickness using the 1981–1991 MPIOM/ERA-Interim snow climatology is on average very similar to the actual ice volume in the ERA-Interim-forced simulation with MPIOM. This indicates that a snow climatology from the 1980s in principle can still give a reasonable estimate of the mean sea-ice volume for today's sea-ice conditions, independent of any additional treatment of first-year ice or multiyear ice.

Because of their comparably high snow volume from October to February, we find that in these months, the modified Warren snow climatology and the Tilling snow climatology result in several thousand cubic kilometers higher estimates of Arctic sea-ice volume than the ERA-Interim/MPIOM snow climatology. (Figures 1, bottom, and S3 to S6, bottom). In March, the differences are negligible (Figure S7, bottom), and in April, the ice volume is slightly lower using the modified Warren snow climatology compared to the ERA-Interim/MPIOM-simulated snow climatology (Figure S8, bottom). Averaged over the period 2000–2016, in which the area covered by multiyear ice reduces substantially, the ice-volume difference between the
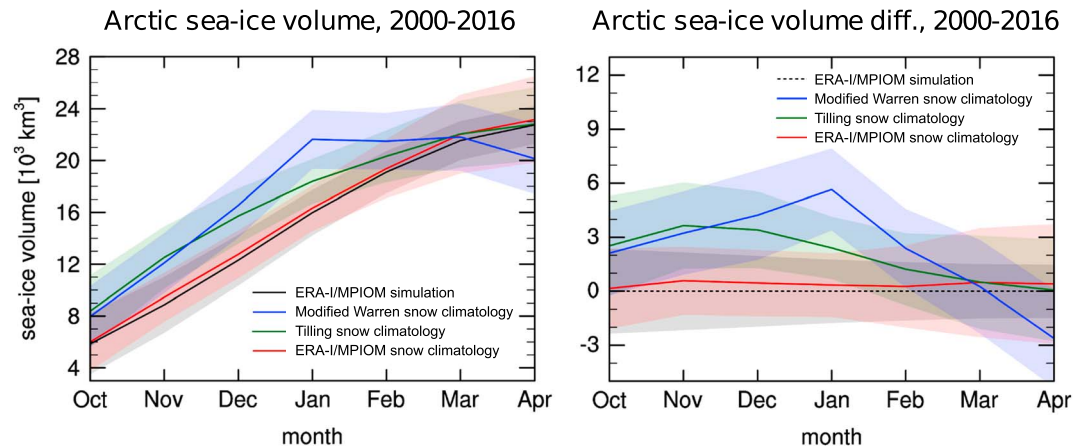
Figure 2. Total Arctic sea-ice volume (left) and the obtained difference with respect to the actual ice volume simulated in the ERA-Interim-forced MPIOM simulation (right). Data were computed over the time period 2000–2016, shaded areas indicate ±2 standard deviations (derived from the respective detrended time series). MPIOM = Max Planck Institute Ocean Model.

ice-thickness retrieved for the Tilling snow climatology and the ERA-Interim/MPIOM-simulated snow thickness is the largest in November, while the difference is the largest in January for the modified Warren snow climatology (Figure 2). The differences then decrease again until the end of the Arctic freezing period.

4.2. Regional Ice-Thickness Estimation Difference

Regional ice thicknesses retrieved with the modified Warren snow climatology result in significantly higher ice thicknesses than the "real" ice thickness in our ERA-Interim/MPIOM simulation in most regions outside the central Arctic from October to February (Figures 3a and S9a to S12a; *Warren area* refers to the region where the Warren climatology is based on observations). This explains the high estimates of sea-ice volume in these months. As the climatologies are only based on extrapolation in these regions, we believe the sea-ice volume estimate from the ERA-Interim-driven MPIOM simulation to be more realistic than those based on the Warren estimate. In March, regions with positive and negative differences largely balance (Figure S13a), leaving a negligible difference in total Arctic sea-ice volume (Figure S7, bottom). In April, the polynomial extrapolation given by the Warren climatology causes negative snow thicknesses in Hudson Bay and Hudson Strait area as well as in the Sea of Okhotsk, which we set to zero snow thickness. This missing snow cover leads to significantly lower sea-ice thickness estimates in these regions (Figure S14a), which results in a lower total Arctic sea-ice volume than the ice-thickness retrieval based on our ERA-Interim/MPIOM snow climatology
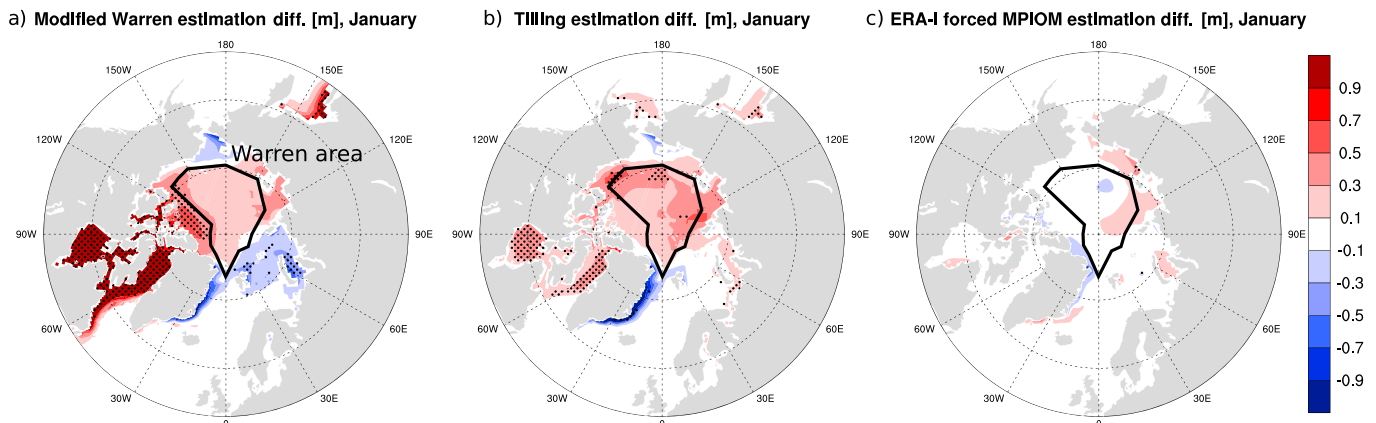

Figure 3. January-mean ice-thickness estimation difference computed over 2000–2016 obtained with the modified Warren snow climatology (a), with the Tilling estimate (b), and with the MPIOM climatology (c). Displayed ice thicknesses are mean thicknesses over the respective entire grid cells. Dotted areas indicate 95% significance for the obtained difference. Significances were computed only for grid cells which were (fully or partially) ice-covered in at least half the years. The region labeled as *Warren area* refers to the area where the Warren climatology is based on observations. MPIOM = Max Planck Institute Ocean Model.
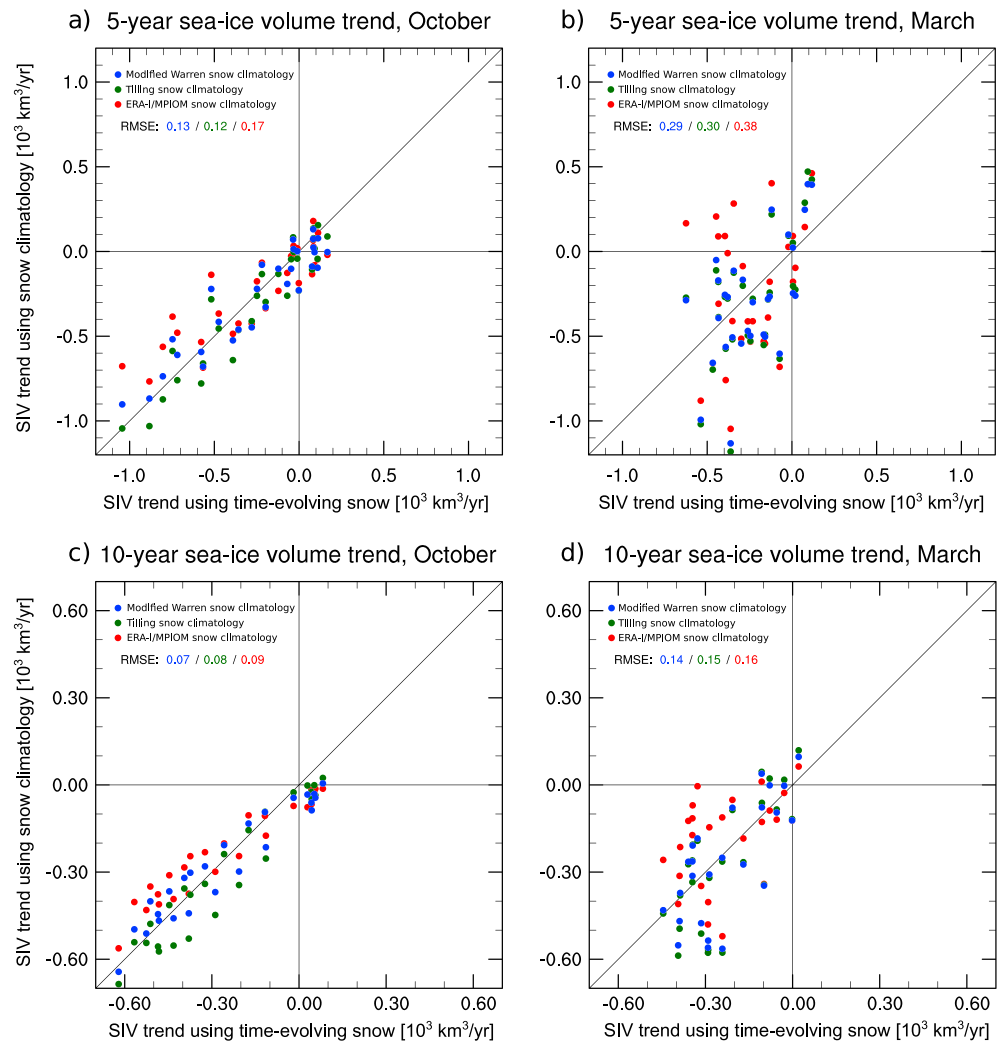
Figure 4. The 5- (top) and 10-year (bottom) trends for Arctic sea-ice volume obtained with the modified Warren snow climatology (blue), the Tilling estimate (green), and the MPIOM climatology (red), computed from all 5- and 10-year periods within 1981–2016. Trends are shown for October (a and c) and March (b and d) ice volume; the trend derived from estimated ice thicknesses is plotted over the actual trend in the ERA-Interim-forced MPIOM simulation. Root-mean square errors (RMSEs) are displayed in the respective colors. MPIOM = Max Planck Institute Ocean Model.

(Figure S8, bottom). Again, we trust the ERA-Interim-driven MPIOM simulation more than the extrapolated Warren climatology in these regions.

Estimation differences outside the central Arctic are generally smaller when the ERA-Interim/MPIOM snow climatology or the Tilling snow climatology is used. Nevertheless, the spatial averaging of Warren snow depths induces significant differences also in the central Arctic in many months. When the MPIOM snow climatology is used for freeboard-to-thickness conversion, the ice-thickness estimation difference is small for all regions and months (Figures 3b and S9b to S14b).

Inside the area where the Warren climatology is based on actual measurements, the differences between the three climatologies are relatively small in all months.

4.3. Reliability of Trends in Arctic Sea-Ice Volume

So far, we discussed only ice-thickness estimation differences averaged over several years. However, when a snow climatology is used to convert ice freeboard to thickness, interannual variations in snow depth are not accounted for. Thus, when trends for the total Arctic sea-ice volume are derived from retrieved ice-thickness data sets covering a few years, the neglected interannual snow-depth variation introduces uncertainty in these trend estimates. We quantify in the following this uncertainty for 5- and 10-year trends in total Arctic

sea-ice volume derived from ice-thickness estimates obtained with our three snow climatologies compared to the real fluctuations in sea-ice volume in our simulation.

After computing 5- and 10-year trends for all subperiods of the ERA-Interim-forced MPIOM simulation extending from 1981 to 2016, we find the derived trends to be relatively reliable for October Arctic sea-ice volume (Figures 4a and 4c). This is because the snow layer is still thin at the beginning of the freezing period, limiting the impact of snow depth on the retrieved ice thickness. In March, however, the reliability of trend estimates using any snow climatology is low for both 5- and 10-year periods, with the root-mean square error in many cases being about as large as the derived trend. For many subperiods, the magnitude of the derived trend strongly deviates from the actual trend, and in a few cases, even the obtained sign of the derived trend turns out to be wrong (Figures 4b and 4d). Evaluating 5- and 10-year trends for all months from October to April (Figures S15 and S16) shows that as soon as the accumulated snow on the ice surface reaches a certain depth (∼December), trend estimates for total Arctic sea-ice volume from retrieved ice thicknesses using a snow-depth climatology are highly uncertain. This result is independent of the snow climatology used for the ice-thickness retrieval.

5. Conclusions

The snow-depth climatology used by state-of-the-art ice-thickness retrieval algorithms yields the largest contribution to the total uncertainty of sea-ice thickness observations (Giles et al., 2007). In this study, we quantify this uncertainty through comparing the impact of different snow climatologies on estimated Arctic sea-ice volume. We find that the total Arctic sea-ice volume is systematically higher from October to February when Warren-derived snow climatologies are used for ice freeboard-to-thickness conversion rather than a reanalysis-based snow climatology. As these differences primarily arise from regions where the Warren-based snow climatologies are based on sometimes unreasonable polynomial extrapolation of snow thicknesses from the central Arctic, we have higher trust in the lower sea-ice volume estimates based on the reanalyzed snow climatology. In March, all three climatologies have similar snow volume and hence result in similar sea-ice volume, while in April, the Warren-based snow climatologies have very low snow thicknesses outside the measurement-based internal region, causing the resulting estimates of sea-ice volume to be very low. Again, we trust the reanalysis-based snow climatology and hence the resulting estimate of sea-ice volume more in these regions.

In the central Arctic, the three snow climatologies show only slightly different snow depths. These small differences result in similar estimated ice-thickness climatologies there. Hence, uncertainty of the long-term mean reduced sea-ice volume of the sea-ice within the measurement-based internal area of the original Warren climatology is much lower than the uncertainty that is induced by any extrapolation of the Warren climatology to regions outside of the central Arctic. We hence strongly caution against providing estimates of sea-ice volume and sea-ice thicknesses derived from the original or any existing modification of the Warren climatology outside of this central area.

Generally, using a snow climatology for converting ice freeboard to thickness neglects any interannual snow variability. As suggested by Kwok and Cunningham (2008), daily snow depths obtained from state-of-the-art ocean/sea-ice models forced with near-real-time observational data could be used for future satellite ice-thickness retrievals, in order to account also for interannual snow-depth variability. We find that as long as the thickness of the snow layer covering the ice surface is thin, the impact of using a snow climatology on the derived multiyear trend is small. However, as soon as the snow has reached a certain depth (usually from December onward), 5- and 10-year ice-volume trends derived even with a perfect snow climatology are highly unreliable.

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 Climate*. https://doi.org/10.1175/JCLI-D-18-0125.1

Cavalieri, D. J., Parkinson, C., Gloersen, 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, CO: NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/8GQ8LZQVL0VL

Dee, D., Uppala, S., Simmons, A., 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*(656), 553–597.

Fetterer, F., Knowles, K., Meier, W., & Savoie, M. (2002). *Sea ice index, Digital Media National Snow and Ice Data Center*. Boulder, CO.

Giles, K. A., Laxon, S. W., Wingham, D. J., Wallis, D. W., Krabill, W. B., Leuschen, C. J., et al. (2007). Combined airborne laser and radar altimeter measurements over the Fram Strait in May 2002. *Remote Sensing of Environment*, *111*(2), 182–194.

Hendricks, S., & Ricker, R. (2013). *Helm, V AWI CryoSat-2 Sea Ice Thickness Data Product*. Alfred-Wegener-Institut: Data Product Manual.

Hibler, W. (1979). A dynamic thermodynamic sea ice model. *Journal of Physical Oceanography*, *9*(4), 815–846.

Jungclaus, J., Fischer, N., Haak, H., Lohmann, K., Marotzke, J., Matei, D., et al. (2013). Characteristics of the ocean simulations in the Max Planck Institute Ocean Model (MPIOM) the ocean component of the MPI-Earth system model. *Journal of Advances in Modeling Earth Systems*, *5*, 422–446. https://doi.org/10.1002/jame.20023

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., & Gandin, L. (1996). The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, *77*(3), 437–471.

Kurtz, N. T., & Farrell, S. L. (2011). Large-scale surveys of snow depth on Arctic sea ice from Operation IceBridge. *Geophysical Research Letters*, *38*, L20505. https://doi.org/10.1029/2011GL049216

Kwok, R. (2014). Simulated effects of a snow layer on retrieval of CryoSat-2 sea ice freeboard. *Geophysical Research Letters*, *41*, 5014–5020. https://doi.org/10.1002/2014GL060993

Kwok, R., & Cunningham, G. F. (2008). ICESat over Arctic sea ice: Estimation of snow depth and ice thickness. *Journal of Geophysical Research*, *113*, C08010. https://doi.org/10.1029/2008JC004753

Kwok, R., Cunningham, G. F., Wensnahan, M., Rigor, I., Zwally, H. J., & Yi, D. (2009). Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008. *Journal of Geophysical Research*, *114*, C07005. https://doi.org/10.1029/2009JC005312

Kwok, R., Kurtz, N. T., Brucker, L., Ivanoff, A., Newman, T., Farrell, S. L., et al. (2017). Intercomparison of snow depth retrievals over Arctic sea ice from radar data acquired by Operation IceBridge. *The Cryosphere*, *11*, 2571–2593.

Laxon, S. W., Giles, K. A., Ridout, A. L., Wingham, D. J., Willatt, R., Cullen, R., et al. (2013). CryoSat-2 estimates of Arctic sea ice thickness and volume. *Geophysical Research Letters*, *40*, 732–737. https://doi.org/10.1002/grl.50193

Notz, D., Haumann, F. A., Haak, H., Jungclaus, J. H., & Marotzke, J. (2013). Arctic sea-ice evolution as modeled by Max Planck Institute for Meteorology's Earth system model. *Journal of Advances in Modeling Earth Systems*, *5*, 173–194. https://doi.org/10.1002/jame.20016

Ricker, R., Hendricks, S., Helm, V., Skourup, H., & Davidson, M. (2014). Sensitivity of CryoSat-2 Arctic sea-ice freeboard and thickness on radar-waveform interpretation. *The Cryosphere*, *8*(4), 1607–1622.

Stroeve, J. C., Serreze, M. C., Holland, M. M., Kay, J. E., Malanik, J., & Barrett, A. P. (2012). The Arctic's rapidly shrinking sea ice cover: A research synthesis. *Climatic Change*, *110*(3-4), 1005–1027.

Tilling, R. L., Ridout, A., & Shepherd, A. (2016). Near-real-time Arctic sea ice thickness and volume from CryoSat-2. *The Cryosphere*, *10*(5), 2003.

Tonboe, R. T., Eastwood, S., Lavergne, T., Srensen, A. M., Rathmann, N., Dybkjr, G., et al. (2016). The EUMETSAT sea ice concentration climate data record. *The Cryosphere*, *10*, 2275–2290.

Tonboe, R. T., Pedersen, L. T., & Haas, C. (2010). Simulation of the CryoSat-2 satellite radar altimeter sea ice thickness retrieval uncertainty, Can. *International Journal of Remote Sensing*, *36*(1), 55–67.

Warren, S. G., Rigor, I. G., Untersteiner, N., Radionov, V. F., Bryazgin, N. N., Aleksandrov, Y. I., & Colony, R. (1999). Snow depth on Arctic sea ice. *Journal of Climate*, *12*(6), 1814–1829.

Zhang, J., & Rothrock, D. A. (2003). Modeling global sea-ice with a thickness and enthalpie distribution model in generalized curvilinear coordinates. *Monthly Weather Review*, *131*(5), 845–861.