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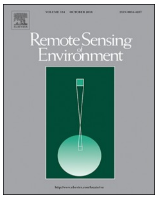

Spatio-temporal variability of Antarctic sea-ice thickness and volume obtained from ICESat data using an innovative algorithm

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ABSTRACT

We use total (sea ice plus snow) freeboard as estimated from Ice, Cloud and land Elevation Satellite (ICESat) Geophysical Laser Altimeter System (GLAS) observations to compute Antarctic sea-ice thickness and volume. In order to overcome assumptions made about the relationship between snow depth and total freeboard or biases in snow depth products from satellite microwave radiometry, we implement a new algorithm. We treat the sea ice-snow system as one layer with reduced density, which we approximate by means of a priori information about the snow depth to sea-ice thickness ratio. We derive this a priori information directly from ICESat total freeboard data using empirical equations relating in-situ measurements of total freeboard to snow depth or sea-ice thickness. We apply our new algorithm (one-layer method or OLM), which uses the buoyancy equation approach without the need for auxiliary snow depth data, to compute sea-ice thickness for every ICESat GLAS footprint from a valid total freeboard. An improved method for sea-ice volume retrieval is also used to derive ice volume at 6.25 km scale. Spatio-temporal variations of sea-ice thickness and volume are then analyzed in the circumpolar Antarctic as well as its six sea sectors: Pacific Ocean, Indian Ocean, Weddell East, Weddell West, Bell-Amund Sea, and Ross Sea, under both interannual and seasonal scales. Because the OLM algorithm relies on only one parameter, the total freeboard, and is independent of auxiliary snow depth information, it is believed to become a viable alternative sea-ice thickness retrieval method for satellite altimetry.

1. Introduction

Sea-ice thickness in polar regions is such an important indicator of global climate change that its measurements have earned endless effort among scientists, despite of the harsh weather and formidable environment. Continuous measurements of snow and sea-ice thickness have been achieved for the Arctic due to a series of in-situ approaches like submarines, buoys and sonars (Rothrock et al., 1999; Warren et al., 1999), air-borne instruments like those used during Operation IceBridge (OIB) (e.g. Kurtz et al., 2013; Holt et al., 2015), and, of course, satellite altimetry, either laser based (Kwok and Cunningham, 2008) or radar based (e.g. Laxon et al., 2003; Laxon et al., 2013; Tilling et al., 2017). However, the situation in the Antarctic is quite different. The collection of sea-ice thickness data is very limited due to a substantially smaller number of expeditions and drift stations, a smaller number of buoys, and almost no submarines in the past to collect sea-ice thickness data as compared to the Arctic. This makes it a challenge to validate snow and sea-ice thickness retrievals from satellite remote sensing. Moreover, in the Antarctic, the – compared to the Arctic – thicker snow cover on sea ice could push the snow-ice interface below the sea surface, making sea water flooding the interface and forming a slush layer (Lytle and Ackley, 1996; Golden et al., 1998; Jeffries et al., 2001) that could later refreeze to form ice. The flooding phenomenon and the caused slush layer whose depth is hard to measure with space-borne remote sensing, both influence the snow depth measurements from space-borne passive remote sensing, leading to a bias in sea-ice thickness retrieval from space.

Until now, Antarctic Sea Ice Processes and Climate (ASPeCt) data

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remains the popularly used snow and ice thickness data for the Antarctic (Worby et al., 1999; Worby et al., 2008), although many limitations exist, such as the biased low thickness due to ships tending to route through open leads and thin sea ice, and coarse spatial and temporal coverages.

Satellite remote sensing data obtained with, e.g. Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E), Ice, Cloud and land Elevation Satellite (ICESat), and European Space Agency CryoSat-2, have been used to retrieve snow depth on sea ice and sea-ice thickness. But the above-mentioned lack of validation data limits the evaluation of data products generated from these satellite sensors in the Antarctic. In addition to that, physical snow and sea-ice properties differing from those found in the Arctic limit approaches developed for the Arctic to be applied in the Antarctic (Massom et al., 2001). Based on ICESat data, the first sea-ice thickness and volume data for the circumpolar Antarctic was produced by a method with a zero sea-ice freeboard assumption (Kurtz and Markus, 2012), while Kwok and Maksym (2014) analyzed OIB observations in the Weddell Sea and Bellingshausen Sea and found a substantial fraction of non-zero sea-ice freeboard. Kern et al. (2016) compared various approaches based on ICESat data and discussed sea-ice thickness distribution in the light of the sparsely available ground truth, finding that the zero sea-ice freeboard assumption can only be a first guess solution for the Antarctic sea-ice thickness distribution given its high spatiotemporal variability. Other studies using different physically based or empirically based methods in combination with ICESat data were only applied for one or two ocean sectors or one to two years (Zwally et al., 2008; Yi et al., 2011; Xie et al., 2013). Few attempts were undertaken to use radar altimetry for sea-ice thickness retrieval in the Antarctic, all of which turned out to be less accurate than in the Arctic (Jacka and Giles, 2007; Schwegmann et al., 2016; Regan et al., 2018). As studied by Kern et al. (2016), zero sea-ice freeboard assumption is not enough to understand spatio-temporal distribution of sea-ice in the circumpolar Antarctic like was already attempted by Kurtz and Markus (2012). Therefore, it is timely to further develop circum-Antarctic, high resolution and reliable parameters of sea ice, including ice thickness and volume. Among all of these parameters, the most vital task is the retrieval of sea-ice thickness, which is a key indicator of sea-ice change, currently lacking for the Antarctic.

One of the challenges deriving a circum-Antarctic sea-ice thickness distribution from satellite altimeter data is the nature of sensing. Altimeters measure along track over a footprint size from several tens of meters (ICESat, Zwally et al., 2002; ICESat-2, Abdalati et al., 2010) to about hundreds of meters (CryoSat-2, Laxon et al., 2013; Xia and Xie, 2018) or several kilometers (Envisat, Connor et al., 2009). Also the sampling along track is an issue. Unlike for imaging satellite sensors such as AMSR-E, which covers a ~1800 km wide swath during every overpass and allows complete data coverage of the polar regions every day (except an orbit inclination determined gap at the pole), data coverage achieved with a satellite altimeter is extremely sparse. Comparing with passive microwave satellite sensors, which have wide spatial swaths and daily data coverage of the polar regions, current satellite altimetry-based sea-ice thickness datasets are so sparse that they usually have something like a monthly temporal resolution to collect data from enough satellite overpasses (e.g. Kwok and Cunningham, 2008; Tilling et al., 2015; Kern et al., 2016).

Kern et al. (2016) inter-compared a number of different methods to retrieve sea-ice thickness from ICESat data. These include methods applying empirical equations (XOC) (Xie et al., 2011; Ozsoy-Cicek et al., 2013), the zero sea-ice freeboard assumption one by Kurtz and Markus (2012) (KM), and the classical hydrostatic approach (Zwally et al., 2008; Yi et al., 2011), adopted for the entire Antarctic within the European Space Agency's Climate Change Initiative Sea Ice project (SICCI) (Kern and Spreen, 2015). The SICCI approach comes with physically-based estimates of the sea-ice thickness uncertainty. Kern et al. (2016) further introduced an alternative method, the WorBy one layer (WB) method described further below. They found that SICCI and WB methods produced a better distribution of sea-ice thickness values over the typical range than KM and XOC methods. Winter-to-spring increases in seasonal average modal with different methods are the smallest of 0.04 m from the KM method, 0.16 from the XOC method, or 0.68 m from the SICCI method, unrealistically large, while 0.17 m from the WB method, claimed as the realistic seasonal development of the circum-Antarctic sea-ice thickness distribution (Kern et al., 2016). Still, while the spatio-temporal sea-ice distribution obtained with SICCI is reasonable, at some locations the sea-ice thickness clearly is too high (over 5 m at ice edge). The SICCI approach distinguishes positive and negative sea-ice freeboard by considering the difference between total freeboard and snow depth similar to Zwally et al. (2008). However, the snow depth used by the SICCI approach (also Zwally et al., 2008; Yi et al., 2011) is based on satellite passive microwave observations of the AMSR-E sensor. Worby et al. (2008) were the first to illustrate that AMSR-E snow depth agrees well with independent snow-depth observations for level sea ice but that over deformed sea ice AMSR-E underestimates the actual snow depth by a factor of 2–3. This was confirmed by following studies, e.g. (Kern et al., 2011; Markus et al., 2011; Ozsoy-Cicek et al., 2011; Brucker and Markus, 2013; Xie et al., 2013). Note that deformation is just one reason for such a disagreement; the high variability of snow physical properties also challenges snow-depth retrieval from AMSR-E. In addition, the AMSR-E snow depth retrieval has an upper limit of about 50 cm; snow layers thicker than that will generally be under-estimated. It can hence be assumed that the AMSR-E snow depth used by the SICCI approach is underestimating the actual snow depth in certain areas, which causes an overestimation of the retrieved sea-ice thickness. We hypothesize that under these circumstances neither the assumption of zero sea-ice freeboard (KM) nor the assumption of a valid snow depth everywhere (SICCI) is providing an accurate circum-Antarctic sea-ice thickness distribution. For the KM method, ICESat total freeboard is taken as the snow depth everywhere. This leads to an overestimation of the snow depth over deformed sea ice and/or sea ice with a considerable non-zero sea-ice freeboard and hence to an underestimation of the retrieved sea-ice thickness.

The WB method tried to solve this problem by treating the sea ice-snow system as one layer with a reduced density of sea ice (Kern et al., 2016). That way no independent snow depth data would be required was the idea, as shown in Eq. (1):

$$I = \frac{\rho_w}{\rho_w - \rho_i^*}F, \text{ with } \rho_i^* = \frac{R*\rho_i + \rho_s}{R+1}, \tag{1}$$

where I is the sea-ice thickness, F is the total freeboard, ρ_w is water density, and ρ_i^* is the density of the mixed layer expressed as sea-ice density ρ_i, snow density ρ_s and sea-ice thickness to snow depth ratio R. However, for the computation of the one-layer density first-guess or climatological values of sea-ice thickness and snow depth are required. Kern et al. (2016) opted for the climatological solution. They computed R with sea-ice thickness and snow depth values from ship-based visual observations (Worby et al., 2008) separately for the three different seasons covered by the ICESat measurement periods. Their R values (6.8 in summer, 6.0 in autumn, and 5.4 in spring) therefore include some seasonal variation. However, these R-values are seasonally constant values over circum-Antarctic and do not represent small-scale or regional variability, and the in-situ observations are also potentially biased towards thinner, smoother ice.

Here, we propose an enhanced WorBy one-layer method (OLM) with dynamic R values, i.e. variable value at the pixel scale. In short, we combine the XOC methods with the WB method. Instead of using the seasonally constant circumpolar R values, our R values are computed directly from the total freeboard observations (the same we use for the final sea-ice thickness retrieval) by applying the parameters of two empirical approaches (Ozsoy-Cicek et al., 2013). Based on an