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Estimating small-scale snow depth and ice thickness from total freeboard for East Antarctic sea ice

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ABSTRACT

Deriving the snow depth on Antarctic sea ice is a key factor in estimating sea-ice thickness distributions from space or airborne altimeters. Using a linear regression to model snow depth from observed 'total freeboard', or the snow/ice surface elevation relative to sea level is an efficient and promising method for the estimation of snow depth for instruments which only detect the uppermost surface of the sea-ice conglomerate (e.g. laser altimetry). However the Antarctic pack-ice zone is subject to substantial variability due to synoptic-scale weather forcing. Ice formation, motion and melt undergo large spatio-temporal variability throughout the year. In this paper we estimate snow depth from total freeboard for the ARISE (2003), SIPEX (2007) and SIPEX-II (2012) research voyages to the East Antarctic pack-ice zone. Using in situ data we investigate variability in snow depth and show that for East Antarctica, relationships between snow depth and total freeboard vary between each voyage. At a resolution of metres to tens of metres, we show how regression-based snow-depth models track total freeboard and generally over-estimate snow depth, especially on highly deformed sea ice and at sites where ice freeboard makes a substantial contribution to total freeboard. For a set of 3192 records we obtain an in situ mean snow depth of 0.21 m ($\sigma = 0.19$ m). Using a regression model derived from all in situ points we obtain the same mean, with a slightly lower variability ($\sigma = 0.16$ m). Using voyage-specific subsets of the data to derive regression models and estimate snow depth, mean snow depths ranged from 0.19 m (model derived from SIPEX observations) to 0.25 m (model derived from SIPEX-II observations). While small, these discrepancies impact ice thickness estimation using the assumption of hydrostatic equilibrium. Mean in situ ice thickness for all samples is 1.44 m ($\sigma = 1.19$ m). Using empirical models for snow depth, ice thickness varies from 1.0 to 1.8 m with the best match to the in situ mean given when snow depth is derived using a snow depth model from all observations (1.53 m, $\sigma = 1.55$ m). However, mean values only tell part of the story when investigating the sea-ice thickness distribution. Here we explicitly show how modelling snow depth and ice thickness based on a total freeboard signal compares with in situ observations. This provides insight into the confidence we place in ice thickness distributions derived using a total freeboard signal and empirically-derived models for snow depth.

1. Introduction

The Antarctic sea-ice thickness distribution is poorly understood, but has wide-ranging effects on the Southern Ocean. Due to the remoteness and size of the Antarctic pack-ice zone, estimating the circumpolar Antarctic sea-ice thickness distribution is only feasible with satellite-based instruments. Satellite altimetry offers a feasible solution for this task, since the conversion of ice freeboards to thickness is a simple computation based on an assumption of hydrostatic equilibrium between sea ice, its snow cover and the underlying seawater, and some empirical knowledge of the densities of these three materials (e.g. Alexandrov et al., 2010; Giles et al., 2008; Markus et al., 2011; Wadhams et al., 1992; Yi et al., 2011; Zwally et al., 2008).

For satellite-borne laser altimeters the only data available for estimating thickness are total freeboard estimates – meaning the elevation of ice and snow above local sea level, based on ranging

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between the altimeter and the sea-ice surface. RADAR altimeters observe the elevation of the sea ice (without snow) above the sea surface where the snowpack is dry and homogeneous, meaning that ice thickness can be estimated without accounting for snow depth. However, interpretation is difficult where icy or wet layers exist in the snowpack (e.g. Laxon, 2013; Willatt, 2010).

Over Antarctic sea ice, the historical ICESat dataset and the ongoing NASA Operation Icebridge campaign (ICEBRIDGE, e.g. Studinger et al., 2010) use laser altimetry to estimate sea-ice parameters (e.g. Markus et al., 2011; Kurtz and Markus, 2012; Kurtz et al., 2013; Kwok and Maksym, 2014; Xie et al., 2011, 2013). In East Antarctica, high resolution airborne laser altimetry has been flown over a small portion of the pack-ice zone, with the aim of investigating sea-ice parameters on the metre- to tens-of-metres scale (Lieser et al., 2013). These airborne remote sensing data approach the resolution of in situ ice measurements, and offer a potential link from drill holes at the scale of metres to satellite observations at the scale of hundreds or thousands of metres. This is critical for understanding how small-scale variability is contained in larger-scale satellite-based estimates of sea-ice parameters.

A key problem for laser altimeters is the conversion of an elevation – or total freeboard – observation to an ice thickness. A functional model for estimating sea-ice thickness using only total freeboard and sparse in situ observations is given by assuming that sea ice and its snow cover exist in hydrostatic equilibrium with surface seawater (e.g. Wadhams et al., 1992):

$$Z_i = \frac{\rho_w}{\rho_w - \rho_i} F - \frac{\rho_w - \rho_s}{\rho_w - \rho_i} Z_s \tag{1}$$

where Z_i is the ice thickness, ρ_w, ρ_i, and ρ_s are the densities of water, sea ice and snow respectively, F is the total freeboard, or elevation of the sea ice plus any snow cover above the ocean surface (reference level), and Z_s is the snow depth. There is reasonable agreement between in situ observations and sea-ice thickness estimated using altimetry (Markus et al., 2011; Xie et al., 2013; Yi et al., 2011; Zwally et al., 2008), but careful attention to the inputs for Eq. (1) is critical. Key parameters in the model must be estimated from in situ observations – snow density, ice freeboard, ice density, and seawater density, each of which vary on different spatial and temporal scales. In East Antarctica, Worby et al. (2011) provide estimates of in situ water and snow density but defer to the review of Timco and Frederking (1996) for an estimate of sea-ice density. Hutchings et al. (2015) provide a rare glimpse of East Antarctic pack-ice density from in situ observations. All studies make the point that in situ data are too sparse to reliably characterise an Antarctic- or Arctic-wide set of values for use in the estimation of sea-ice thickness from satellite and airborne altimetry.

For application to altimetry observations and Eq. (1), snow depth can be estimated from in situ observations or remote sensing methods. Field campaigns aimed at collecting in situ observations of snow depth give a highly accurate but spatially and temporally disparate dataset (e.g. Massom et al., 2006; Worby et al., 2011; Xie et al., 2011). On a regional scale, microwave brightness temperatures detected by the spaceborne Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) instrument have been used to estimate snow depth (Comiso et al., 2003; Markus et al., 2011; Worby et al., 2008). AMSR-E snow depth agrees generally with ship-based observations following the ASPeCt protocol (Worby et al., 2008), and has been used to estimate Antarctic sea-ice thickness from ICESat observations (Yi et al., 2011; Zwally et al., 2008). However, the low spatial resolution (12.5 km/pixel) and tendency to underestimate snow depth around ridged ice (Stroeve et al., 2006; Worby et al., 2008) limit the utility of this dataset for estimating ice thickness using altimeter observations and Eq. (1). Markus et al. (2011) made improvements in passive microwave estimates of snow depth to account for surface roughness, but the coarse resolution remains an issue that effectively prevents use of this dataset as a snow depth parameter for high resolution altimeters.

One approach taken for laser altimetry from ICESat missions has been to group laser shots into 25 km grid cells, matching to AMSR-E resolution (e.g. Kern and Spreen, 2015; Kurtz and Markus, 2012; Zwally et al., 2008). For oceanic basins and circumpolar estimates of ice thickness this is a reasonable approach. However, the topography of Antarctic sea ice is highly variable on much smaller scales (Hutchings et al., 2012; Markus et al., 2011; Massom et al., 2006; Worby et al., 2011; Xie et al., 2013). Airborne instruments may capture topography on the scale of metres- to tens-of-metres, but without coincident laser and RADAR altimetry (e.g. Kurtz et al., 2013; Kwok and Maksym, 2014) snow depth at these scales must be estimated from empirical knowledge of in situ snow depth and total freeboard.

Wadhams et al. (1992) worked on the principle that a relationship existed between the snow/ice/air and ice/ocean interfaces of sea ice, based on airborne laser profiling and under-ice sonar observations from submarines in the Arctic. Alexandrov et al. (2010) derived a linear regression model from in situ total freeboard and ice thickness observations, applied it to satellite altimetry observations, and found that modelled ice thickness was comparable with in situ observations. Doble et al. (2011) investigated the relationship between surface topography and ice draft using airborne LiDAR and under-ice draft measurements from upward looking sonar, finding was that the relationship improved with increasing scales of observation. They also deduced a length scale for the assumption of isostacy in Arctic sea ice of roughly 70 m for level ice. Xie et al. (2011) deduced that snow depth on sea ice in the Bellingshausen Sea could be predicted by a simple linear regression model based on in situ total freeboard and snow depth measurements. This relationship was also explored for East Antarctic sea ice (Worby et al., 2011), who found that the relationship between total freeboard and snow depth is heavily skewed by measurements where the underlying ice freeboard makes up a substantial component of the total freeboard. Ozsoy-Cicek et al. (2013) derived a set of snow depth models for broad sectors around the Antarctic continent, examining snow depth at a spatial scale of hundreds of metres or more. This extended previous work at smaller scales, providing a set of snow depth estimation models for circumpolar sea-ice thickness estimates from satellite altimetry.

Efforts to understand snow depth have largely focussed on satellite-scale observations of Antarctic sea ice, with spatial resolutions of hundreds of metres to kilometres. With few exceptions, altimetry data are used to populate much coarser grid cells. For smaller-scale missions, e.g. airborne laser altimetry focussed on a specific region and season, or proposed satellite-based instruments (e.g. ICESAT-2, Abdalati et al., 2010), using AMSR-E snow depth estimates over 25 km grid cells is not representative of reality. Xie et al. (2013) provide an example of how the inference of snow depth at different scales affects the derived ice thickness using ICESat altimetry (60–70 m diameter spots), AMSR-E snow depth (12.5 km/pixel) and snow depth derived by empirical models using in situ snow depth and total freeboard measurements. They provide compelling evidence that for higher resolution altimetry, linear regression models for estimating snow depth derived from total freeboard are an attractive method. However, no analysis of the performance of linear regression modelling to estimate snow depth at scales smaller than ICESat footprints exists.

In this paper, we focus on two questions: how well do snow depths from linear regression models match reality for sea ice off