

Improving our understanding of Antarctic sea ice with NASA's Operation IceBridge and the upcoming ICESat-2 mission

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Antarctic sea ice is a crucial component of the global climate system. Rapid sea ice production regimes around Antarctica feed the lower branch of the Southern Ocean overturning circulation through intense brine rejection and the formation of Antarctic Bottom Water (e.g., Orsi et al. 1999; Jacobs 2004), while the northward transport and subsequent melt of Antarctic sea ice drives the upper branch of the overturning circulation through freshwater input (Abernathy et al. 2016). Wind-driven trends in Antarctic sea ice (Holland & Kwok 2012) have likely increased the transport of freshwater away from the Antarctic coastline, significantly altering the salinity distribution of the Southern Ocean (Haumann et al. 2016). Conversely, weaker sea ice production and the lack of shelf water formation over the Amundsen and Bellingshausen shelf seas promote intrusion of warm Circumpolar Deep Water onto the continental shelf and the ocean-driven melting of several ice shelves fringing the West Antarctic Ice Sheet (e.g., Jacobs et al. 2011; Pritchard et al. 2012; Dutrieux et al. 2014). Sea ice conditions around Antarctica are also increasingly considered an important factor impacting local atmospheric conditions and the surface melting of Antarctic ice shelves (e.g., Scambos et al. 2017). Sea ice formation around Antarctica is responsive to the strong regional variability in atmospheric forcing present around Antarctica, driving this bimodal variability in the behavior and properties of the underlying shelf seas (e.g., Petty et al. 2012; Petty et al. 2014).

Satellite passive microwave data have provided a long-term assessment of Antarctic sea ice coverage (i.e., concentration) since the 1970s. Unfortunately, our understanding of Antarctic sea ice is limited by inadequate observations of its thickness distribution and overlying snow cover. High-resolution ice-ocean models (e.g., Holland et al. 2014; Zhang et al. 2014) and model-based sea ice reconstructions (e.g., Massonnet et al. 2013) provide important insight into the potential ice thickness variability. However, these models are being calibrated/validated against the limited observations of Antarctic sea ice thickness currently available and have arguably received less attention compared to model calibration efforts in the Arctic.

The record low Antarctic sea ice cover observed in the austral spring/summer of 2016/2017, in stark contrast to the small, but positive, long-term trend (e.g., Turner et al. 2017), has presented the Antarctic sea ice community with new questions regarding the potential variability and future trends in Antarctic sea ice and their consequences for the Southern Ocean and global climate system.

Antarctic sea ice: A challenging medium to observe

Radar and laser altimetry have been used relatively successfully in the Arctic to derive basin-scale estimates of sea ice thickness (e.g., Kwok and Cunningham 2008;

Laxon et al. 2013; Kurtz et al. 2013). The altimetry technique uses measurements of sea ice freeboard — the extension of sea ice above the local sea level — and estimates of snow depth to derive sea ice thickness (assuming the ice is in hydrostatic equilibrium). Satellite altimetry of Antarctic sea ice thickness has been hindered by uncertainty in the snow depth used to convert freeboard into thickness and, for radar altimetry (e.g., from ESA's CryoSat-2 satellite), uncertainty in the penetration of the radar signal into the overlying snow layer (e.g., Giles et al. 2008; Willatt et al. 2010).

Passive microwave derived snow depths (e.g., Markus & Cavalieri 1998), provide the only pan-Antarctic snow depth estimate currently available. The reliability of this data over different ice surfaces, however, is still uncertain. Snow accumulation models forced by reanalyses have also been used to estimate Antarctic snow depth (e.g., Maksym and Markus 2008). But due to the strong winds around Antarctica and the large coverage of leads (fractures) within the Antarctic ice pack, the fraction of snow lost to leads is thought to be significant (Leonard and Maksym 2011), increasing the challenge of this approach compared to the Arctic. The increased prevalence of flooded and refrozen snow over Antarctic sea ice (e.g., Massom et al. 2001) is also thought to increase the remote sensing challenges compared to the Arctic.

The only pan-Antarctic sea ice thickness dataset publically available is based on laser altimetry derived freeboard observations from NASA's Ice, Clouds, and Land Elevation Satellite (ICESat), using the assumption that the ice-snow interface is at sea level, i.e., that the freeboard (draft) is all snow (ice) (Kurtz and Markus 2012). The passive microwave snow depth estimates have been used to estimate sea ice thickness regionally, such as in the Weddell Sea using ICESat data (Zwally et al. 2008; Yi et al. 2011). This approach, however, has not been extended to the entire Antarctic sea ice pack. Empirical relationships between freeboard and ice thickness have also been invoked as a more relevant solution to the thick/deformed Antarctic sea ice regimes (Xie et al. 2013).

Alternative sea ice thickness datasets include: ship-based observations from the Antarctic Sea ice Processes and Climate (ASPeCt) dataset, 1980-2005 (Worby et al. 2008); upward looking sonar (ULS) measurements of ice draft in the Weddell Sea, 1990-2008 (Behrendt et al. 2013); and more localized measurements (e.g., electromagnetic sensing and *in situ* drill holes). More recently, autonomous underwater vehicle (AUV) draft measurements in localized regions around Antarctica have been used to suggest that Antarctic sea ice might be thicker than previously assumed (e.g., Williams et al. 2015).

In the Arctic, the age of the ice is often used as a proxy for ice thickness (Maslanik et al. 2011; Tschudi et al. 2016). The Antarctic sea ice pack is generally younger, however, limiting the potential for age to act as a useful proxy for thickness. The limits of seasonal ice growth are also uncertain, given the strong variability and uncertainty surrounding atmospheric and oceanic forcing around Antarctica. A 'Frontal Ice Zone' — a region of more deformed, older ice adjacent to the sea ice edge — was recently suggested by Nghiem et al. (2016), based on the analysis of satellite radar backscatter data. This utilizes the principle that older/rougher ice tends to exhibit higher radar backscatter compared to younger, flatter ice. However, more direct measurements of sea ice thickness and roughness are needed to validate this idea.

Operation IceBridge

A relatively new data source for Antarctic sea ice research is the suite of measurements provided by NASA's Operation IceBridge (OIB) mission. OIB began in 2009 with the objective to bridge the gap between ICESat and the upcoming launch of NASA's ICESat-2 satellite (Markus et al. 2017). OIB has collected data over the western Antarctic sea ice pack in austral spring since 2009 (October/November, all years except 2015). The regions profiled by the OIB Antarctic sea ice campaigns include myriad ice types, such as the thick/deformed ice of the western Weddell Sea, and the younger, drifting ice over the Ross shelf sea. The OIB Antarctic sea ice flight lines

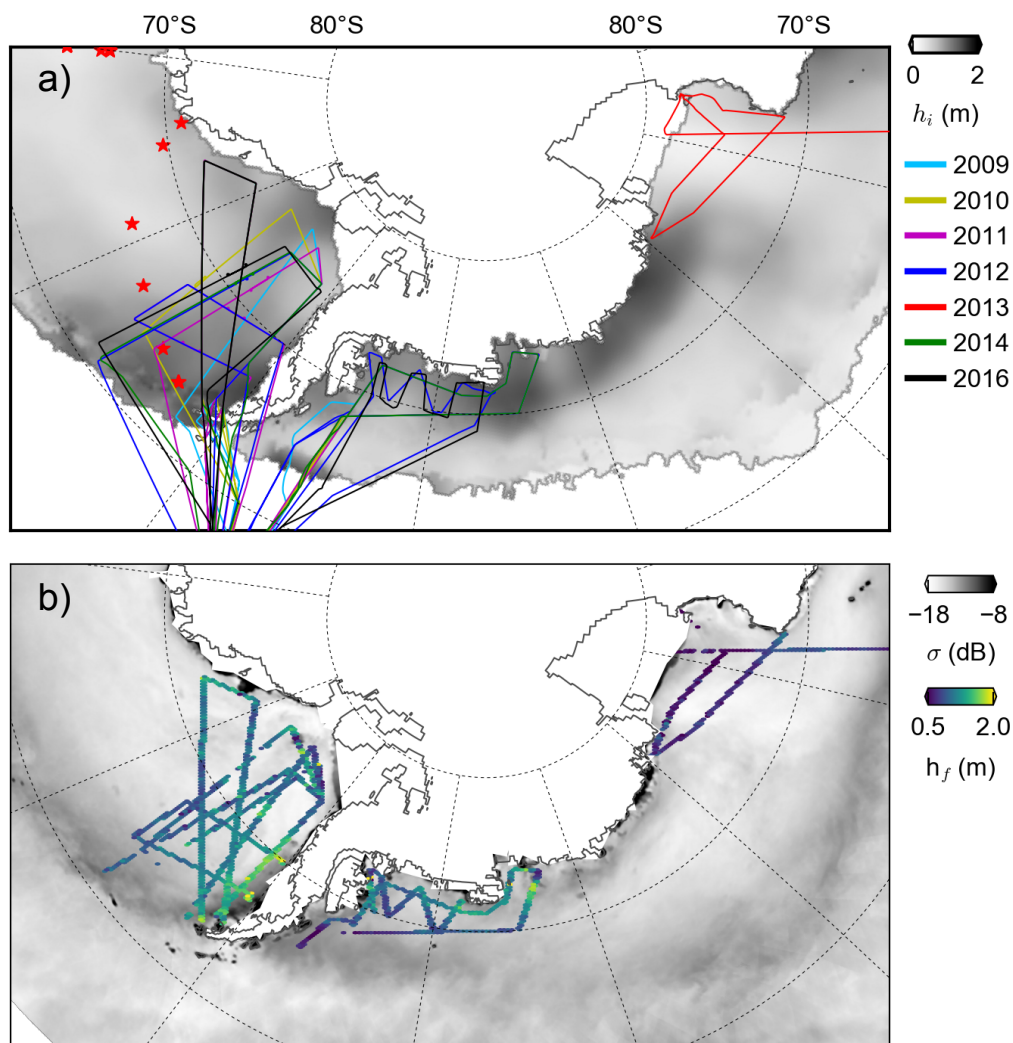


Figure 1. (a) Antarctic Operation IceBridge (OIB) sea ice flights in austral spring (October/November) overlaid on the ICESat ice thickness estimates (2003-2008 October/November mean; Kurtz and Markus 2012). The red stars indicate the location of the Weddell Sea moorings (various times of operation between 1990 and 2008). (b) Mean height of surface topography features detected from the 2009-2014 OIB ATM sea ice data overlaid on the mean ASCAT radar backscatter (σ) over the OIB sea ice campaign time periods. Ice topography processing updated for the Antarctic from Petty et al. (2016).

overlaid on the ICESat ice freeboard/thickness data (Kurtz and Markus 2012) are shown in Figure 1a.

The primary instrument onboard OIB is the conically scanning Airborne Topographic Mapper (ATM) laser altimeter (Krabill et al. 2002), which profiles the ice surface across a width of ~250 m. Each laser shot has a horizontal

footprint resolution of ~1 m and a vertical accuracy of ~10 cm. An ultra wide-band snow radar (Panzer et al. 2013) that flies with OIB is used to estimate snow depth, while coincident optical imagery helps identify leads/cracks in the ice cover; enabling the calculation of ice freeboard and thus thickness. Note that the increased prevalence and size of leads in the Antarctic ice pack make freeboard measurements easier than in the Arctic.

The Antarctic OIB data have arguably been underexploited due to the challenges of Antarctic sea ice altimetry described earlier (e.g., uncertain penetration of the OIB snow radar into the snow cover). An approach to derive snow depth from the OIB snow radar and the (snow plus ice) freeboard from the OIB ATM was presented by Kwok & Maksym (2014) for the 2010/2011 data in the Weddell and

Bellingshausen seas, providing the first assessment of snow depth and freeboard variability from the Antarctic OIB data. Unfortunately, a lack of coincident *in situ* data preclude a more thorough understanding of the uncertainties of the snow radar derived snow depths, as is currently underway for the Arctic OIB data (Kwok et al., 2017).

Despite the challenges associated with deriving Antarctic snow depth and thickness, the OIB ATM laser data can still be used to directly assess the ice (plus snow) freeboard and topography. The OIB ATM data have recently been used to assess Arctic sea ice topography (Petty et al. 2016) and its contribution to the atmospheric form drag coefficient (Petty et al. 2017). Note that these topography estimates involve the explicit detection of surface features (e.g., pressure ridges), as opposed to the more bulk metric of surface roughness (normally calculated as the standard deviation of elevations within a given window). Petty et al. (2017) also demonstrated strong correlations between satellite radar backscatter data from the Advanced Scatterometer (ASCAT) and the OIB ATM derived form drag coefficients, enabling the OIB results to be extrapolated outside of the regions directly profiled — an exciting prospect for the Antarctic OIB data.

An extension of this analysis is currently underway for the Antarctic OIB ATM sea ice data. A preliminary analysis of the OIB Antarctic ice topography is shown in Figure 1b, overlaid on the ASCAT backscatter data. The results demonstrate a broadly consistent spatial pattern of ice topography, with higher topography in the western Weddell Sea and lower topography in the Ross Sea, as expected. The ice topography results, along with other metrics of ice surface roughness, can be used to assess where we might expect smooth/thin or rough/thick ice to be prevalent, helping guide the analysis of satellite altimetry retrievals. Petty et al. (2016) also demonstrated that the OIB ice topography data can provide a reasonable, albeit crude, assessment of the total sea ice thickness, while Kwok & Maksym (2014) found a strong correlation between their OIB

estimates of ice surface roughness and snow depth, which they suggested may be due to the role of deformed ice acting as a catchment for snow.

The upcoming ICESat-2 mission

An exciting new avenue for Antarctic sea ice research will be provided by the launch of NASA's ICESat-2 mission (*scheduled for launch in 2018*). The Advanced Topographic Laser Altimeter System (ATLAS) on-board ICESat-2 is a multi-beam, photon counting laser altimeter, featuring six linear profiling beams that cover a total width of ~6 km (Markus et al. 2017; Figure 2) The three pairs of beams, together with its continuous operation, will result in about nine times better spatial coverage than the ICESat satellite. A surface elevation will be estimated from the return photon distribution — commonly referred to as a

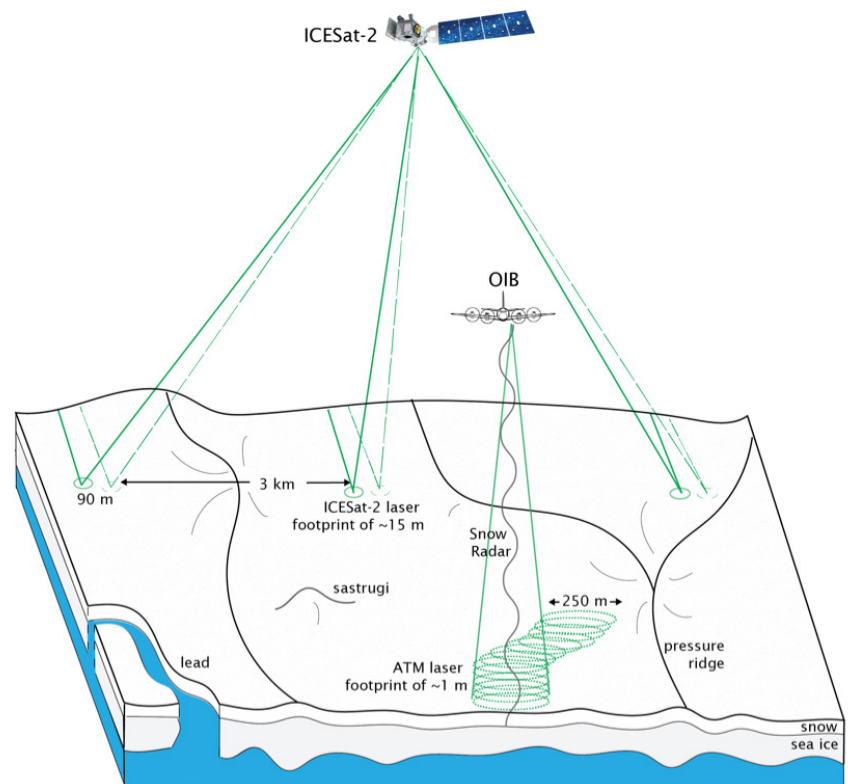


Figure 2. Schematic of Antarctic sea ice profiling with the NASA Operation IceBridge laser altimeter (ATM) and snow radar, and the expected profiling from the upcoming ICESat-2. Not to scale.

photon cloud. Measurements of sea ice freeboard (Arctic and Antarctic) are a direct mission requirement that will be provided after launch by the ICESat-2 project office. Similar to the OIB mission, one of the primary research priorities of ICESat-2 will be estimating sea ice thickness, with snow depth again expected to provide the primary source of uncertainty.

For the analysis of ice topography/roughness, the lower horizontal resolution laser footprint of ATLAS (~15 m) compared to the OIB ATM (~1 m) means it will not directly resolve the smaller surface roughness features. The Multiple Altimeter Beam Experimental Lidar (MABEL) has been deployed prior to the launch of ICESat-2 to provide relevant data for mission testing and development, especially in regards to the interpretation of the ATLAS photon cloud for sea ice elevation retrievals. Kwok et al. (2014) demonstrated that the MABEL and ATM retrievals co-vary along track and are similarly sensitive to surface elevation variability. MABEL (and thus hopefully ICESat-2) can detect surface elevation variability at this 15 m resolution, but the impact of ice topography on the photon distributions is still an open research topic.

Summary and suggestions for future research priorities

NASA's Operation IceBridge and the upcoming ICESat-2 mission will provide crucial new data to help us understand the state of the Antarctic sea ice pack. One

of the biggest remaining uncertainties is the snow depth on Antarctic sea ice. More sophisticated models of snow accumulation/redistribution could help improve the reanalysis derived snow depth estimates and provide critical context for the passive microwave and OIB derived snow depths being produced. Coincident *in situ* Antarctic sea ice campaigns to help validate these data would be invaluable.

Sea ice models provide a vital tool for understanding the variability and drivers of Antarctic sea ice mass balance, with their sophistication improving rapidly over recent years. For example, a sophisticated form drag parameterization scheme has recently been incorporated into the sea ice model CICE (Tsamados et al. 2014) to improve the atmosphere-ice-ocean coupling; however, the new parameterization scheme contains several free parameters that need to be better constrained with observations. Satellite emulators included in models (e.g., simulating sea ice freeboard) could provide an important bridge between the modeling and observational communities, along with more sophisticated calibration efforts currently underway. The depth of sea ice observations possible with OIB and the upcoming launch of ICESat-2 should provide the community with a wealth of data for advancing our knowledge of Antarctic sea ice.

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