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Antarctic sea ice elevation from satellite radar altimetry

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[1] In situ measurements of sea ice thickness from ship and upward-looking sonar are used to assess the potential for satellite radar altimetry to provide information on Antarctic sea ice thickness. A climatology of satellite ice elevation estimates is compared to an Antarctic sea ice thickness climatology made from the Antarctic Sea Ice Processes and Climate (ASPeCt) data set. In addition monthly, regional, satellite ice elevation estimates are compared to ULS ice draft data. The results show reasonable spatial agreement between the satellite and in-situ data, and show regional signals of change in ice elevation in line with that which would be expected. The results show some promise for providing information on Antarctic ice thickness from radar altimetry missions such as CryoSat. However, further studies into snow and ice density and the radar penetration into the Antarctic snow cover are required. **Citation:** Giles, K. A., S. W. Laxon, and A. P. Worby (2008), Antarctic sea ice elevation from satellite radar altimetry, *Geophys. Res. Lett.*, *35*, L03503, doi:10.1029/2007GL031572.

1. Introduction

[2] Changes in the thickness of the Arctic sea ice cover have been observed since the 1970s by submarine sonar measurements of ice draft [e.g., *Rothrock et al.*, 1999]. However, compared to the Arctic, measurements of Antarctic sea ice thickness are sparse, as submarines do not survey the seas around Antarctica. Therefore any changes in Antarctic sea ice thickness would currently go unnoticed. Antarctic ice thickness data are limited to measurements of ice draft from moored Upward Looking Sonar (ULS) [*Worby et al.*, 2001], ship observations and drilling [*Wadhams et al.*, 1987; A. P. Worby et al., The thickness distribution of Antarctic sea ice, submitted to *Journal of Geophysical Research*, 2007] (hereinafter referred to as Worby et al., submitted manuscript, 2007), surface measurements from airborne laser profiling [*Wadhams*, 2000] and ground based and airborne electromagnetic surveys [*Haas*, 1998; *Reid et al.*, 2006]. Although these data provide a useful description of Antarctic sea ice thickness they are spatially and temporally limited. Satellite estimates of Antarctic sea ice thickness could remove these sampling issues by providing a circumpolar wide, continuous time series of data during the ice growth season.

[3] Measurements of sea ice freeboard from the radar altimeters onboard the European Space Agency satellites ERS 1 and 2 have been used to calculate sea ice thickness in the Arctic Ocean [*Laxon et al.*, 2003], and the aim, in the context of sea ice, of the forthcoming CryoSat mission, is to measure fluctuations in Arctic sea ice thickness (http://www.esa.int/SPECIALS/Cryosat/index.html). This paper explores, for the first time, whether the same technique can be applied to Antarctic sea ice. Estimates of sea ice thickness from satellite radar altimetry in the Arctic are obtained by measuring the ice freeboard (assuming that the radar penetrates to the snow/ice interface [*Beaven et al.*, 1995]) and using estimates of snow depth and density from climatology [*Warren et al.*, 1999], and constant values of ice and water density from *Wadhams et al.* [1992], to calculate ice thickness. The nature of the Arctic climate means that the sea ice typically has a positive freeboard, and becomes entirely snow free during the summer months [*Wadhams*, 2000], which simplifies the analysis of the radar return from sea ice. However, in the Antarctic, the situation is more complicated and negative ice freeboards, and flooded and refrozen snow, are more common [*Lange*, 1988; *Lange et al.*, 1990]. In addition, a snow depth climatology, such as the one described by *Warren et al.* [1999] for the Arctic, does not exist for the Antarctic.

[4] This paper explores the potential of satellite radar altimetry to estimate sea ice thickness in the Antarctic by comparing data from ERS 2 to ASPeCt ice thickness observations and ULS ice draft measurements. Because of the complicated nature of Antarctic sea ice, and the large errors that would be introduced into the ice thickness estimate due to uncertainties in snow depth [*Giles et al.*, 2007], we compare the satellite measured Antarctic sea ice elevation (the elevation of the radar's reflecting surface above the sea level) to the in-situ data, rather than calculating ice thickness from these measurements.

2. Data

[5] The satellite radar altimetry data used in this comparison were taken from ERS 2, between 1995 and 2002. Estimates of Antarctic sea ice elevation were obtained using the same technique as *Laxon et al.* [2003]. Measurements of the sea ice height and the sea surface height [*Peacock and Laxon*, 2004] above a reference surface were obtained by reprocessing the return echoes and applying corrections for orbits, tides and atmospheric effects. Differentiation between the ocean and sea ice is possible as different shaped echoes are received from each surface [*Peacock and Laxon*, 2004]. The ice elevation above the sea surface (referred to as ice elevation from now on) was then calculated by subtracting the ice height from the sea surface height. Only measurements during the Antarctic sea ice growth season (April to September) were used in this study. The error on the estimate of average ice elevation is inversely proportional to the number of individual estimates that go into the

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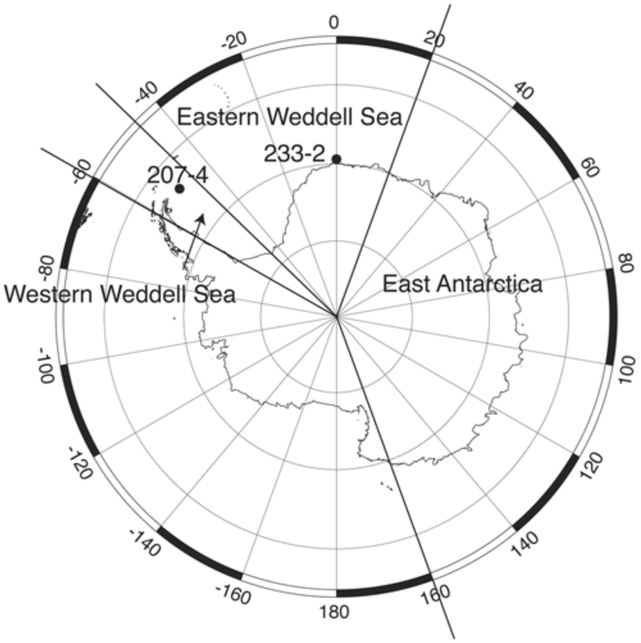

Figure 1. ULS locations in the Weddell Sea (black circles). ULS 207-4 latitude: −63.72° longitude: −50.82° and ULS 233-2 latitude: −69.40° longitude: 0.0°. The black lines show the location of the regional divisions described in section 3.2, East Antarctica (20° to 160°E), the eastern Weddell Sea (45°W to 20°E) and the western Weddell Sea (45°W to 60°W).

average. To calculate an average ice elevation, each grid cell (defined below) must contain at least ten individual elevation estimates, resulting in a maximum error of ±0.05 m [*Giles and Hvidegaard*, 2006].

[6] The ASPeCt data set is comprised of ship observations of ice thickness, concentration and snow depth, collected aboard 81 voyages to the Antarctic pack ice between 1981 and 2005 (Worby et al., submitted manuscript, 2007). In total there are 23,391 data points, but this is reduced to 14,557 once observations within 6 nautical miles of the previous observation have been removed (to avoid over sampling in areas of thick ice where the ship travels more slowly [*Worby and Allison*, 1999]). The estimated error on the ASPeCt data ranges from ±20% in level ice greater than 0.3 m to ±50% in ridged or thin ice (Worby et al., submitted manuscript, 2007).

[7] The ULS data [*Harms et al.*, 2001], of sea ice draft in the Weddell Sea, were downloaded from the National Snow and Ice Data Centre (NSIDC) at http://nsidc.org/data/g01359.html. *Harms et al.* [2001] give the error in the measured ice draft as ±0.04 m. Two sets of ULS data (ULS 207-4 and ULS 233-2) from 1997 were chosen because they were situated in different areas of the Weddell Sea, and because these areas have the highest density of ice elevation measurements. Figure 1 shows their locations along with lines showing the regional divisions discussed in section 3.2.

3. Results

3.1. Comparisons of ERS and ASPeCt Antarctic Sea Ice Climatologies

[8] We first explore the relationship between ERS ice elevation and ASPeCt ice thickness, which we would expect to be related due to hydrostatic equilibrium [*Giles et al.*, 2007]. The ERS and ASPeCt climatologies were computed by transforming the ASPeCt data and the growth season (April to September, 1995 to 2002) ERS data onto a polar stereographic map projection, and then averaging the data into 100 km grid cells. The ERS ice elevation growth season climatology (April to September, 1995 to 2002), the ASPeCt ice thickness growth season climatology (April to September, 1981 to 2005) and the ASPeCt ice thickness annual climatology (1981 to 2005) are shown in Figures 2a, 2b, and 2c, respectively. While the ERS data had full spatial coverage ASPeCt data did not. Therefore, to aid comparison, only grid cells where both ERS and ASPeCt data were present are shown. Both the ASPeCt ice thickness growth season climatology (Figure 2b) and the ERS distribution of

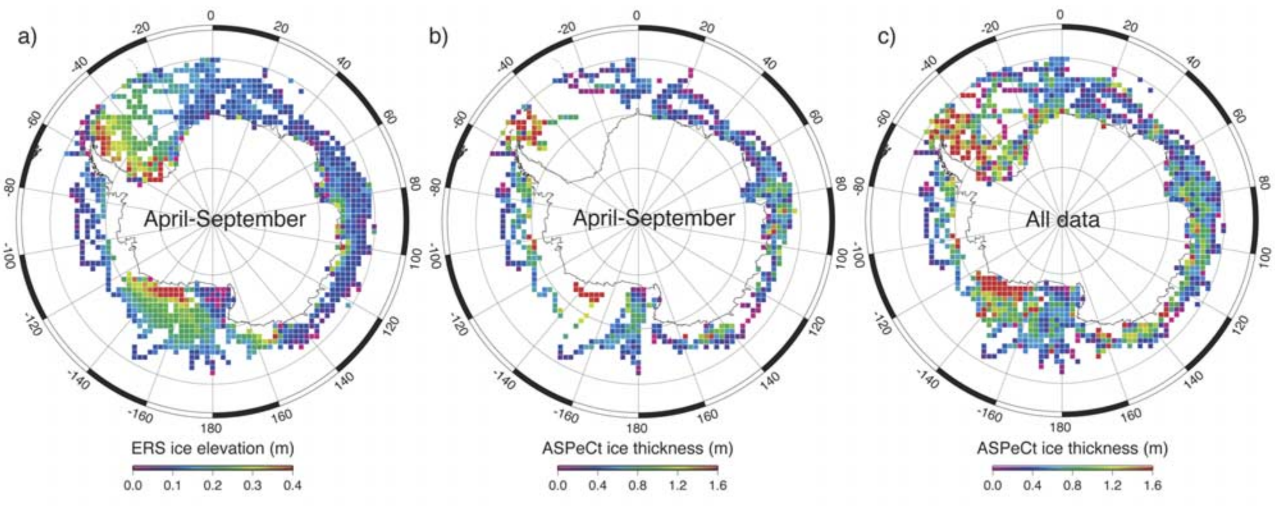

Figure 2. Plot of the (a) mean ERS measured ice elevation for April–September 1995 to 2002, (b) mean ASPeCt ice thickness for April–September data 1981 to 2005 (41% of the ASPeCt data) and (c) mean ASPeCt ice thickness for all data 1981 to 2005. Note the scale on Figure 2a is different from the scale of Figures 2b and 2c.

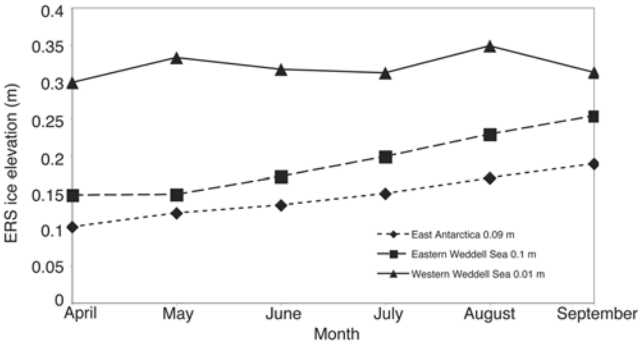

Figure 3. ERS monthly average ice elevation in the east and west Weddell Sea and around East Antarctica. The increase in ice elevation over the growth season in the around the coast of East Antarctica is 0.09 m, in the eastern Weddell Sea is 0.1 m and in the western Weddell Sea is 0.01 m.

ice elevation (Figure 2a) show thicker ice in the western Weddell Sea, and thinner ice in the eastern part of the Weddell Sea. Around the coast of East Antarctica both the ERS and the ASPeCt growth season data show thinner ice than in the western Weddell Sea. In the Ross Sea thinner ice is seen in both growth season data sets adjacent to the Ross Ice Shelf, with thicker ice to the east. In the Bellingshausen and Amundsen Seas a thickening of the ice towards the coast is seen in both growth season data sets. Comparison of the ERS ice elevation (Figure 2a) and the ASPeCt ice thickness annual climatology (Figure 2c) show similar patterns of agreement.

3.2. Monthly and Regional Change in ERS Ice Elevation

[9] To examine the monthly and regional change in the ERS measured ice elevation we averaged the ice elevation estimates in three regions (Figure 1), for each month between April and September (Figure 3). Between these months we observe a monotonic increase in the ice elevation of approximately 0.1 m in the East Antarctic and eastern Weddell Sea regions, while in the western Weddell Sea there is little change in the ice elevation over the same period. We believe that the different signals in these regions are due to a year-round presence of multi-year ice in the western Weddell Sea, whilst the eastern Weddell Sea, and East Antarctica, have largely first year ice cover. Consequently we expect more thermodynamic growth and larger percentage changes in elevation for the first year ice regions, as compared to the western Weddell. Ridging of first year ice is also likely to contribute to a net increase in ice elevation throughout the growth season. As the ice in the western Weddell Sea remains deformed all year round [*Ackley*, 1979], we would expect ridging to cause a larger percentage increase in the first year ice. For example, the ASPeCt data support these arguments. The average ice thickness in the eastern Weddell Sea for level ice is 0.29 m in autumn (March–May) and increases to 0.63 m by spring (September–November), an increase of 0.34 m, and when ridged ice is included in the average it goes from 0.44 m (autumn) to 0.89 m (spring), an increase of 0.45 m. In the western Weddell Sea the autumn average is 0.98 m and the spring average is 0.93 m for level ice (−0.05 m change) and when ridged ice is included the autumn average is 1.38 m and the spring average is 1.33 m (−0.05 m change). These averages show that there is more ice growth in the eastern Weddell Sea than the western, and that ridging contributes significantly to the increase in ice thickness over the growth season in the eastern Weddell Sea but not in the western. However, the change in the ERS ice elevation over the growth season is larger than we would expect the change in ice freeboard to be when compared with the ASPeCt data. This could be due to differences in sampling between the ASPeCt data and the ERS data, or to some yet to be observed change in the level of the scattering surface of the radar away from the snow/ice interface throughout the growth season. A complicating factor in the discussion of changes to the radar scattering surface is the formation of snow ice, which can form at the base of the snow layer as a result of snow loading and flooding from the sides of floes. It is not known how the resulting snow ice will affect the radar signal.

3.3. ERS and ULS Comparison

[10] To further investigate the seasonal change in ice elevation we compared the satellite elevations to ULS data in the Weddell Sea. The draft measurements for each ULS (excluding open water), for each month, and ERS data from the same month and within 300 km of the ULS, were then averaged. To test whether the assumption that the radar originates from the snow ice interface could be applied to Antarctic sea ice, we calculated the theoretical value of snow depth required to maintain an ice floe, with a draft (h_d) equal to the ULS draft and a freeboard (h_f), which we take to be equal to the ERS ice elevation, in hydrostatic equilibrium using equation (1):

$$h_s = \left(h_d \rho_w - h_d \rho_i - h_f \rho_i\right) / \rho_s \tag{1}$$

where h_s is the snow depth, and ρ_w, ρ_i, and ρ_s are the densities of sea-water, sea ice and snow respectively. This method assumes that there is a sharp dielectric interface between the snow and ice layers. Initially we calculated the snow depth using typical density values found by averaging the density values reported by *Massom et al.* [1998], *Sturm et al.* [1998], *Adolphs* [1998], *Fichefet and Morales Maqueda* [1999], and *Buynitskiy* [1967], which gives ρ_w = 1024 kg m^{-3}, ρ_s = 360 kg m^{-3} and ρ_i = 900 kg m^{-3}. We then recalculated the snow depths for different ice densities (ρ_i = 850 kg m^{-3} and ρ_i = 810 kg m^{-3}, the latter was the highest density we found that avoided negative snow depths), and keeping ρ_w and ρ_s constant. Figure 4 shows the average monthly ERS ice elevations and ULS ice draft, and the calculated snow depths. The calculated snow depth for ρ_i = 900 kg m^{-3} is negative for both ULS, which is unrealistic. Reducing the ice density to ρ_i = 810 kg m^{-3} results in realistic snow depths, however this is considerably lower than published ice density measurements, (e.g., *Buynitskiy* [1967], who found mean densities from East Antarctic sea ice for summer and winter of 875 kg m^{-3} and 920 kg m^{-3} respectively). These results suggest that ERS ice elevations are larger than expected the ice freeboard, given the ULS ice draft. This could be due to differences in sampling between the two instruments but it also suggests

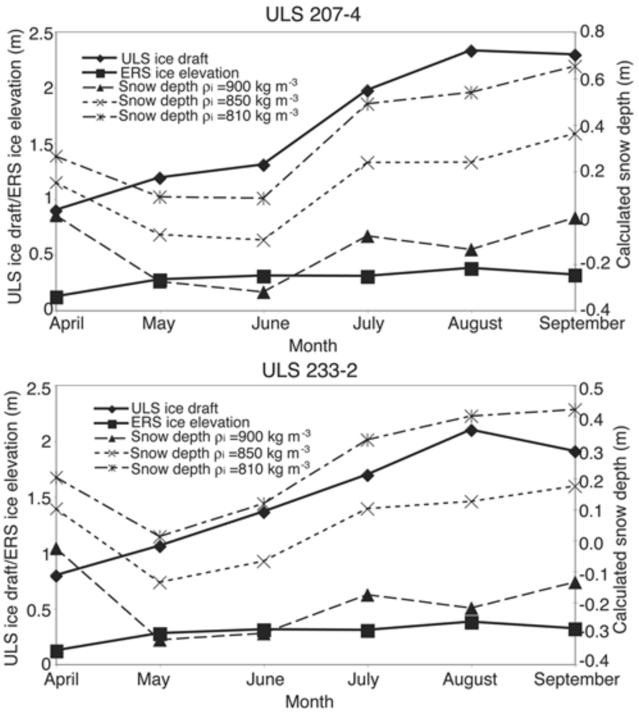

Figure 4. Average ULS ice draft and ERS ice elevation during winter 1997, with calculated snow depths for different ice densities.

that the radar is not penetrating to the snow ice interface over Antarctic sea ice, or, less-likely, that the ice densities in the Weddell Sea during 1997 were considerably lower than previously observed.

4. Discussion and Conclusions

[11] Our results show good qualitative agreement between patterns of ASPeCt ice thickness and ERS ice elevation, suggesting that satellite radar altimetry has the potential to provide some useful information on Antarctic sea ice thickness. However, the comparisons are limited by the temporal and spatial coverage of the field data.

[12] Our comparisons with ULS and ASPeCt data indicate that the ERS elevations are larger than the expected ice freeboard. Documented ice freeboards can range between zero in regions where surface flooding has occurred, to several metres in areas of heavy ridging, however are typically in a narrower range between 0.0–0.2 m over most of the pack ice [e.g., *Wadhams et al.*, 1987; *Worby et al.*, 1998], lower than the ERS elevations. There are a number of possible explanations for this. Firstly the ERS ice elevation is possibly a measurement of the ice freeboard plus part of the overlying snow, i.e. the radar doesn't penetrate to the snow/ice interface, but to somewhere between the air/snow and snow/ice interfaces over Antarctic sea ice. *Massom et al.* [2001] show that the snow cover on Antarctic sea ice, throughout the growth season, is made up of a mixture of snow types and ice layers, and the effects of these on the penetration characteristics of a radar must be explored. A detailed study of the penetration characteristics over snow covered Antarctic sea ice would fulfil this requirement. Secondly the sampling of the ASPeCt and ULS data is different from the satellite data. In particular, large ridges and highly deformed ice are under sampled in the ASPeCt data, resulting in a lower average ice thickness estimate. In addition, in some cases, data in a particular area is from a single cruise and therefore may not be representative of the average ice conditions. Investigations into the bulk density of Antarctic sea ice and snow cover, which could involve historical data and newly designed field campaigns, are also required. These further investigations will be important for exploitation of radar altimetry data, in particular from CryoSat, over Antarctic sea ice.

[13] **Acknowledgments.** ERS data were provided by the European Space Agency. The ULS data were obtained from the National Snow and Ice Data Centre (www.nsidc.org). We wish to thank A. Ridout, J. Gaudelli and N. Peacock for data processing and software development. This work was funded by the UK's National Environmental Research Council and the European Union.

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