Monitoring Changes in the Antarctic Ice Sheet from 1978 to 2007

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I. Abstract

This paper presents a study distilling radar backscatter measurements made by three Ku-band scatterometers of the Antarctic ice sheet over a nearly thirty-year study period. Backscatter signature modeling techniques are used to compensate for observation geometry and operating frequency differences among the sensors. Findings of this study include large regions of both positive and negative change in average backscatter, particularly in regions of West Antarctica and along much of the coast.

II. Introduction

The Antarctic ice sheet is an important element in the global climate system, and recent evidence suggests that the extent and composition of the ice sheet is changing [1]. In an era of increased concern about global climate patterns it is important to understand the temporal characteristics of the Antarctic ice sheet, both as an input to global climate models and as an indicator of climate change. Presently the only way to achieve a consistent Antarctic-wide long-term ice sheet record is through the use of space-borne remote sensing instruments. In this paper we compare data obtained by three scatterometers to analyze changes in the Antarctic ice sheet from 1978 to 2007. This study of nearly three decades is one of the longest active microwave continental surveys made of the Antarctic ice sheet.

III. Instruments

The three instruments we use in this study are the Seasat-A scatterometer (SASS), the NASA scatterometer (NSCAT), and Seawinds on QuikSCAT (QuikSCAT). All instruments operate in a Sun-synchronous polar orbit. Only V-pol data is considered in this report.

SASS was the first space-borne scatterometer flown by NASA and was in operation for just over three months (Julian Days 188 though 283) during the austral winter and spring of 1978. It employed four dual-pol antennas, each sweeping a nominally 500 km swath at an operating frequency of 14.6 GHz. The swaths were further divided by Doppler processing into 12 cells of approximately 50 km resolution [2].

NSCAT was a variable Doppler scatterometer launched in September 1996 and in operation until June 1997. It made observations over 600 km swaths on both sides of its ground track with eight beams from six antennas at various incidence and azimuth angles.

QuikSCAT is a scanning pencil-beam sactterometer that gathers backscatter data at 25 km resolution from two 13.6 GHz beams at distinct incidence angles and polarizations, H-pol at 46° incidence and V-pol at 54° incidence, both with dense azimuth sampling. QuikSCAT has been in nearly continuous operation since its launch in 1999.

IV. Empirical Scattering Model

Empirical models have been used in previous studies to describe normalized radar backscatter as a function of azimuth and incidence angles. The general form of such a model is

$$\sigma^0(\theta,\phi) = A + \sum_{i\in\mathcal{G}} B_i(\theta-\theta_0)^i + \sum_{j\in\mathcal{F}} C_j \cos(j\phi-\phi_j), \quad (1)$$

where σ^0 is the normalized backscatter cross-section in dB, θ is incidence angle, ϕ is azimuth angle, and θ_0 is the reference incidence angle. $\mathcal{F}$ has previously been given as $\mathcal{F}=\{2\}$, $\mathcal{F}=\{1,2\}$, and $\mathcal{F}=\{1,2,3,4\}$ in [3], [4], and [5], [6], respectively. $\mathcal{G}$ has been defined as $\mathcal{G}=\{1\}$ or $\mathcal{G}=\{1,2\}$ [7].

Model coefficients, A, B, C_j, ϕ_j, are solved for in the least squares sense. A represents the mean backscatter at the reference incidence angle, B represents the linear dependence of backscatter on incidence angle at the reference angle, and C_j and ϕ_j represent the jth order magnitude and phase, respectively, of backscatter dependence on azimuth angle. Thus, B depends on the relative contributions of surface- to-volume scattering, with a higher value corresponding to a larger surface scattering component, and C_j and θ_j depend on the presence of azimuthally oriented scatters, such as sastrugi and dunes.

Unfortunately, we find that the three sensors have insufficiently diverse observation geometries to support the full model. QuikSCAT's incidence angle is essentially fixed, leaving B_i undefined, while SASS and, to a lesser extent, NSCAT, have azimuth sampling that limits the accuracy of C_j in sparse data locations. In addition, SASS does not have enough azimuth diversity at any location to support $\mathcal{F}$ larger than $\{1,2\}$.

Thus we make some necessary modifications to the above model. With QuikSCAT data, we set $B_i = 0$, and let $\mathcal{F} = \{1,2,3,4\}$ to take advantage of dense azimuth sampling. With SASS and NSCAT data, we set $\mathcal{F}=\emptyset$, and $\mathcal{G}=\{1\}$. We also set $\theta_0 = 54.26°$, to correspond to QuikSCAT's V-pol incidence angle.

V. Frequency Adjustments

We take a straightforward approach to controlling the frequency differences between SASS, NSCAT, and QuikSCAT.

The small frequency differences and the small target size relative to wavelength suggest that the following bulk frequency adjustment is a reasonable first-order approximation,

$$\Delta\sigma^0_{dB} = -20\log_{10}\left(\frac{f_0}{f}\right). \quad (2)$$

This adjustment fails to account for the frequency dependence of σ^0, and may introduce other biases in the presence of glazed or very rough surfaces, or other larger scatterers. This bias, however, is likely small relative to the adjustment. All backscatter values from SASS and NSCAT presented in this study are adjusted by the relevant amount, see Table I.

TABLE I

ADJUSTMENTS MADE TO BACKSCATTER MEASUREMENTS DUE TO FREQUENCY DIFFERENCE, WITH QUIKSCAT AS REFERENCE.

Sensor	Frequency	Adjustment
QuikSCAT	13.600 GHz	-
SASS	14.600 GHz	0.62 dB
NSCAT	13.995 GHz	0.25 dB

VI. IMAGE COMPARISONS

As an initial comparison of the changes in the Antarctic ice sheet we consider A and B images generated from gridded σ^0 measurements observed during the Austral winter from all three sensors (for QuikSCAT, only A data is defined). The images are shown in Figures 1, 2, and 3. The pixel resolution in each image is approximately 45 km by 45 km. SASS data is from days 185 through 216, 1978; NSCAT data is from days 170 through 179, 1997; and QuikSCAT data is from days 201 through 204, 1999; and days 181 through 184 for years 2000 through 2007. These dates represent the closest seasonal match given the various times of year that the three sensors were in operation. The slight seasonal mismatch should introduce only very small inconsistencies as all occur well before the Austral melt season [8], and backscatter from snow is generally insensitive to non-melt-introducing temperature changes, as shown in Section VII-A.

The difference maps reveal a possible instrumentation bias between SASS and the other two sensors, as much of the continent, including the ice sheet crest, shows a slightly negative value. There are also regions of significant change, most notably in Ellsworth Land, the remainder of West Antarctica, and along the cost. Other regions of apparently significant backscatter change are the Ross Ice Shelf and the Amery Ice Shelf. The regions of large negative change in Wilkes Land are very likely due to uncontrolled-for azimuth modulation effects, since they appear in the SASS/QuikSCAT images (Figure 2 b,c) but not in the QuikSCAT difference image (Figure 2 d), and azimuth modulation effects in this region are well established [4], [6].

Differences in B values from SASS and NSCAT shown in Figure 3 reveal regions of change from 1978 to 1997. Again, West Antarctica exhibits the greatest difference, where NSCAT B values are consistently less (more negative) than

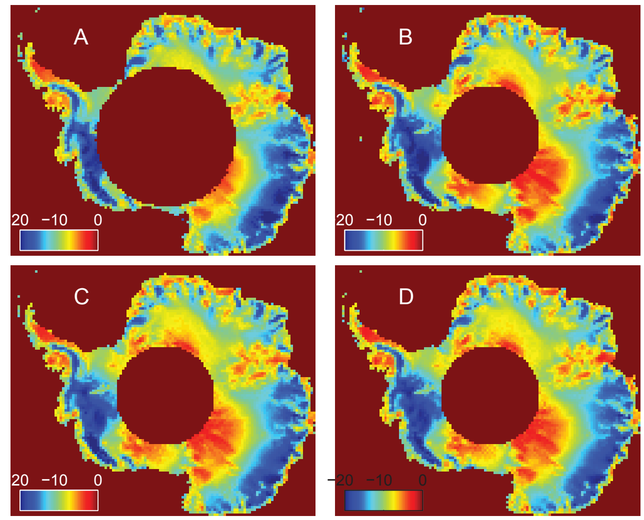

Fig. 1. Gridded A images. A) SASS, days 185 through 216, 1978. B) NSCAT, days 170 through 179, 1997. C) QuikSCAT days 201 through 208, 1999. D) QuikSCAT days 181 through 184, 2007.

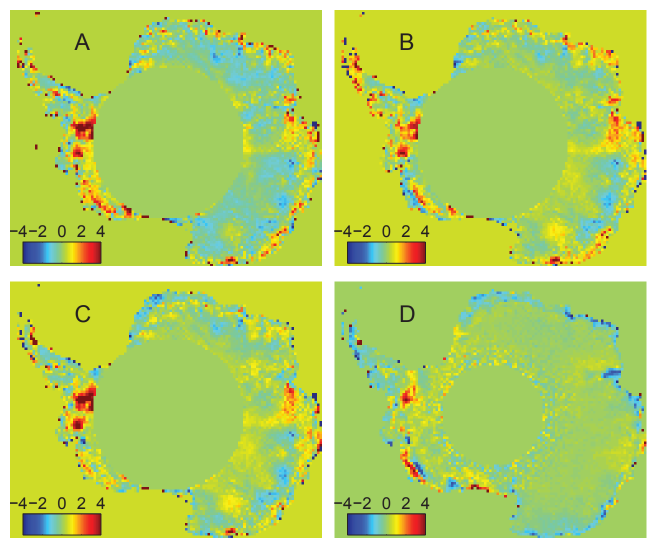

Fig. 2. Differences of the images presented in Figure 1. A) SASS 1978 - NSCAT 1996. B) SASS 1978 - QuikSCAT 1999. C) SASS 1978 - QuikSCAT 2007. D) QuikSCAT 1999 - QuikSCAT 2007.

corresponding SASS B values. Since this phenomenon is regionally variable it is unlikely the result of instrumentation differences and likely indicative of changes in the structure of the ice sheet. It is important to note that QuikSCAT's fixed incidence angle observation geometry makes estimating B values from QuikSCAT-observed data impossible.

VII. STUDY REGIONS

The purpose of displaying continent-wide data for various quantities is to conveniently encapsulate how the backscatter signature of the ice sheet as a whole has changed since 1999 and to identify regions that warrant further investigation. Figure 4 and Table II display the locations of four regions

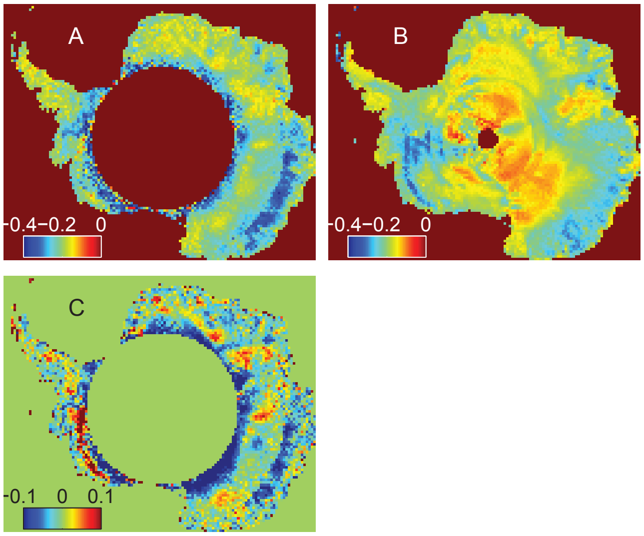

Fig. 3. B images and B difference image. A) SASS 1978. B) NSCAT 1997. C) SASS 1978 - NSCAT 1996, large negative values near the center are artifacts from insufficient SASS coverage.

chosen for detailed study. These regions are chosen subjectively because they exhibit interesting and diverse backscatter changes throughout the nearly 30 year study period.

Time series plots of A values at these study locations, computed as described in Section IV, are shown in Figure 5. Data for these plots are taken from single 45 km by 45 km pixels. QuikSCAT and NSCAT data is binned temporally every four days, whereas SASS data requires a longer eight day temporal bin to achieve sufficiently dense coverage. Despite this longer temporal bin, however, SASS data still displays somewhat higher variability than NSCAT and QuikSCAT data.

Fig. 4. Locations of the four study regions.

TABLE II

LOCATIONS OF THE FOUR STUDY REGIONS.

		Latitude	Longitude
Location 1	Dome C	-74.50	123.00
Location 2	Ellsworth Land	-76.29	-74.65
Location 3	Queen Maud Land	-71.73	-4.90
Location 4	Marie Byrd Land	-74.71	-125.87

A. Study Region 1, Dome C

Unlike the other study locations, this location is chosen because of its temporal consistency. Indeed, a previous study [4] showed that this region exhibits many desirable qualities of

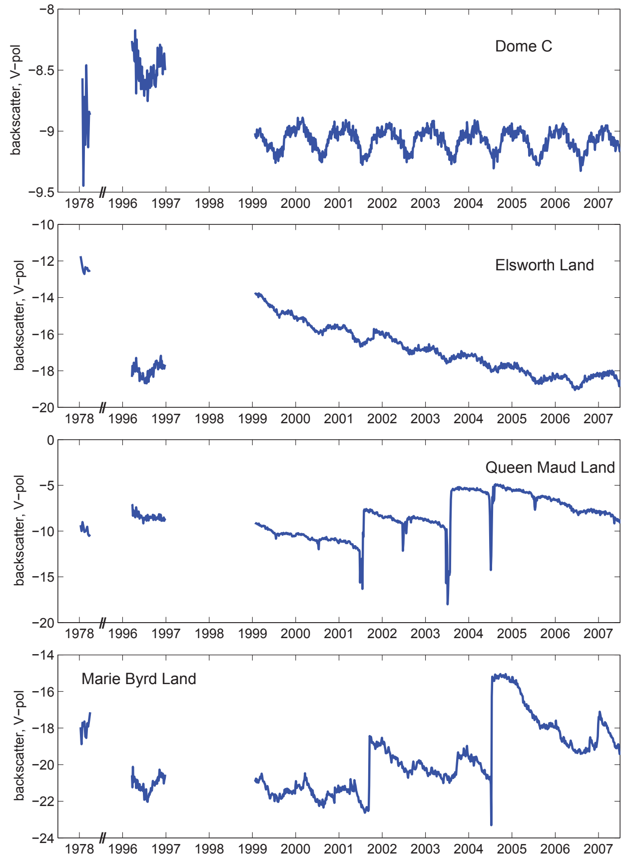

Fig. 5. Time series of average backscatter. Data in 1978 is SASS, data from 1996 through 1997 is NSCAT, and data from 1999 through 2007 is QuikSCAT. All data is adjusted for incidence angle effects, QuikSCAT data is also adjusted for azimuth angle effects. Note that different scales are used in each of the four plots to emphasize regionally distinct temporal changes in backscatter, and that there is a discontinuity in the time axis after 1978.

a calibration target. Dome C lies on the ice sheet crest, a region where latitude, elevation, and the Antarctic katabatic wind regime [9] contribute to what is perhaps the most predictable weather on Earth. Unmanned weather station records [10] confirm that despite large ($\sim$ 40 C) seasonal variations in air temperature, the climate at Dome C has been exceptionally stable since at least 2000.

If the backscatter properties at Dome C are indeed unchanging, then the data displayed in Figure 5 confirms that observations from the three sensors can be compared to within approximately 0.5 dB. It also shows that the approximately 40 C seasonal variations in air temperature correspond to an approximately 0.3 dB seasonal change in QuikSCAT-observed backscatter, and that QuikSCAT appears to maintain its V-pol intra-sensor calibration to great (perhaps to 0.01 dB) precision throughout its mission. QuikSCAT's consistency is also confirmed by the small change in backscatter observed along the ice sheet crest in the QuikSCAT 1999 and 2007 difference image, Figure 2.

B. Study Region 2, Ellsworth Land

In Ellsworth Land there is a very large magnitude (approximately 0.5 dB per year) decrease in backscatter and an approximately 0.25 dB regular seasonal variation recorded by QuikSCAT since 1999. A previous study suggests that such a temporal signature could be the result of thermal forcing and accumulation [1]. Thermal forcing due to seasonal air temperature variations subtly changes the physical and electrical properties of the snow crystals, thus affecting backscatter on a seasonal scale. Scattering models of layered firn (see [11], [12]) suggest that damping due to a 600 mm thick layer of fine-grained, high-density accumulation falling on top of an older layer of low-density, coarse-grained firn could decrease backscatter by the amount seen here.

SASS backscatter values in this region are very high, and NSCAT values very low, relative to typical QuikSCAT values. There are two plausible explanations for this behavior: (1) The NSCAT data is anomalous and there has been a consistent negative trend in backscatter at this location since at least 1978 as a result of damping due to accumulation. (2) There was a severe melt event in Ellsworth Land either during the 1997/1998 or 1998/1999 melt season (and possibly others between 1978 and 1997) that produced large ice scatterers that were subsequently buried under accumulation. In the absence of further evidence, both scenarios are equally deserving of consideration.

C. Study Region 3, Queen Maud Land

QuikSCAT time series data in Queen Maud Land shows large decreases in backscatter indicating melt events during every austral summer from 2001/2002 through 2004/2005, with smaller such decreases during the 2000/2001 and 2005/2006 melt seasons. There is little or no indication of melting during the 1999/2000 and 2006/2007 summers. The 2003/2004 melt event was both the most severe, in terms of overall backscatter decrease, and the longest. After several of the melt events, there is a substantial (up to 4 dB) increase in average backscatter. This is attributable to the formation of ice pipes and lenses and an overall increase in grain size upon refreezing [1]. In the absence of large melt events, there is a generally decreasing backscatter trend. After the large 2004/2005 melt, the magnitude of backscatter change is approximately -1.5 dB per year. As in region 2, it is reasonable to conclude that this behavior is the result of accumulation damping the backscatter from these newly-formed scatterers. These results give credence to the assertion of a severe melt even in region 2 in the recent past.

In this region, SASS and NSCAT data are consistent with later QuikSCAT observations. Although the SASS and NSCAT missions did not observe any Austral melt seasons, their observations suggest that there has perhaps been very little long-term change in this region.

D. Study Region 4, Marie Byrd Land

The QuikSCAT backscatter record at Marie Byrd Land shows indirect evidence of very short (less than four days) but very intense melt events in 2001/2002 and 2004/2005. After both of these events, the usual pattern of a large increase in backscatter followed by gradual annual decreases is seen. Compared to the previous three regions, this area has very dark backscatter returns, suggesting a different dominant backscattering mechanism. As with region 3, SASS and NSCAT data are consistent with later QuikSCAT observations

VIII. Summary

Although its possible that some of the changes observed by the three Ku-Band scatterometers used in this study are the result of unaccounted for instrumentation differences, the spatial distribution of the observed changes makes this very unlikely. The data presented here, after controlling for frequency and observation geometry differences, demonstrates that there are large-scale, spatially coherent changes in the backscatter signature of most of the Antarctic ice sheet. These changes are likely the result of changes in the composition of the ice sheet due to melting, accumulation, and thermal forcing. This study also confirms the utility of space-borne scatterometry, including combined observations from different sensors, in monitoring changes in the Antarctic ice sheet.

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