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Quantifying vulnerability of Antarctic ice shelves to hydrofracture using microwave scattering properties

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ABSTRACT

Recent ice shelf disintegrations on the Antarctic Peninsula and subsequent increases in ice sheet mass loss have highlighted the importance of tracking ice shelf stability with respect to surface melt ponding and hydrofracture. In this study, we use active microwave scatterometry in time-series to estimate melt season duration, and winter backscatter levels as a proxy for relative concentration of refrozen ice lenses in Antarctic ice shelf firn. We demonstrate a physical relationship between melt days and firn/ice backscatter using scatterometry and field data from Greenland, and apply the observed relationship to derive and map a vulnerability index for Antarctica's ice shelves. The index reveals that some remaining Antarctic Peninsula ice shelves have already reached a firn state that is vulnerable to hydrofracture. We also show that the progression of an ice shelf towards vulnerability is affected by many factors, such as surface mass balance, internal stresses, and ice shelf geometry.

1. Introduction

Atmospheric warming can lead to ice shelf disintegration through hydrofracture (Scambos et al., 2000, 2003; Rott et al., 1996; Hughes, 1983). Hydrofracture on glaciers and ice shelves occurs when water infiltrates crevasses, filling them to a level at which water pressure at the crack tip exceeds the fracture toughness of the ice as well as any compressive stresses transverse to the fracture orientation. For the fracture to continue to propagate, the crevasse tip pressure must continue to increase to offset increasing lithostatic pressure. This is facilitated by a surface reservoir of water that drains into the propagating fracture. Ponding of meltwater on the surface of ice shelves is an effective reservoir for hydrofracture. With closely-spaced fractures, fractured blocks may then topple, initiating a runaway disintegration effect (MacAyeal et al., 2003). This mechanism likely caused the complete or partial collapse of several ice shelves on the Antarctic Peninsula, including the rapid disintegration of the Larsen B Ice Shelf in 2002 (Scambos et al., 2003).

Not all ice shelves are vulnerable to hydrofracture. In regions with high winter snow accumulation or permeable, porous firn, any meltwater produced during summer months percolates into the upper firn and refreezes. To support surface ponds that provide the necessary water reservoir to initiate hydrofracture, the firn layer must be sufficiently saturated with refrozen meltwater to prevent efficient downward percolation. Modeling studies and observations confirm that ice shelves that have collapsed on the Antarctic Peninsula in the past had very little firn air thickness preceding disintegration, indicating that they were preconditioned for the hydrofracture mechanism to operate (Holland et al., 2011; Berthier et al., 2012; Kuipers Munneke et al., 2014).

Scambos et al. (2003) performed a pilot study investigating the utility of active microwave scatterometry for assessing ice shelf vulnerability to hydrofracture by analyzing the relative concentration of refrozen meltwater in firn layers. Using selected areas from several ice shelves, they demonstrated a predictable relationship between winter backscatter and ice shelf melt season duration. They interpreted this relationship as reflecting the ice-saturation state of the firn layer, based on a study linking radar scattering and ice sheet facies in Greenland (Fahnestock et al., 1993). On most shelves, backscatter increases with average annual melt days, because small ice lenses and other discontinuous refrozen structures are efficient diffuse scatterers. However, at high numbers of melt days, when ice lenses form large, nearly-continuous, and relatively smooth layers in the firn, specular reflections direct the microwave signal away from the sensor and backscatter values decrease (Fahnestock et al., 1993). As large, continuous ice lenses also impede meltwater percolation, promoting melt pond formation, shelf areas with lowered backscatter values at high numbers of annual melt days are inferred to be the areas most susceptible to hydrofracture

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(Scambos et al., 2003).

In this study, we use gridded scatterometry data to assess the relative concentration of refrozen meltwater in the firn ("firn-ice concentration") for all Antarctic ice shelves. We assess this by examining the relationship between annual melt days and average winter backscatter. After introducing the data (Section 2), we demonstrate the relationship using scatterometry, ground-penetrating radar, and shallow firn cores in Greenland, where ice sheet facies are relatively well-mapped, and where their effect on surface meltwater ponding is well-known (Section 3). We then show that the melt days-backscatter relationship is similar for Antarctica's ice shelves, and analyze the impacts of surface mass balance on this relationship (Section 4). Finally, in Section 5 we present our results, which comprise an index that assesses ice shelf vulnerability to surface-melt-induced hydrofracture collapse. Section 6 discusses the details of the index and the implications of our assessment.

2. Data

The backscatter data used in this study come from four sensors: the C-band (5.7 cm wavelength) scatterometers ESCAT onboard the European Space Agency's Earth Remote Sensing (ERS) satellites 1 (operational 1990–1995) and 2 (1995–1999); NASA's Ku-band (2.2 cm wavelength) Seawinds instrument on the QuikSCAT satellite (2000–2009); and Eumetsat's C-band Advanced Scatterometer (ASCAT) aboard the MetOp-A satellite (2007-present). All scatterometry data were obtained through Brigham Young University's Microwave Earth Remote Sensing Laboratory Scatterometer Climate Record Pathfinder. We restricted our backscatter data analysis to austral winter months (June, July, and August) in order to avoid liquid meltwater, which significantly lowers backscatter values (Long and Drinkwater, 1994).

All backscatter data were processed using the Scatterometer Image Reconstruction (SIR) algorithm (Long et al., 1993), which uses multiple days of scatterometry data to create gridded, resolution-enhanced products. The algorithm assumes a linear model that relates the normalized radar cross-section, σ^o, which is measured in decibels, and the signal incidence angle:

$$\sigma^o = A + B(\theta - 40)$$

The model normalizes the incidence angle to 40°. This creates two images: an A image, which contains the normalized backscatter values and has units of dB, and a B image, which represents the dependence of backscatter on incidence angle and has units of dB/°. In this study, we utilize the A images.

When applied to ERS data, the algorithm combines passes from multiple orbits, which requires the assumption that backscatter is independent of azimuth. Products are provided on a 25 km grid, with an estimated effective resolution of 25–30 km. ERS images are obtained using a vertically polarized microwave signal. In this study, the subset of data between 1991 and 1996 were used, a time period that includes maximum coverage consistency in the available data.

C-band ASCAT data were obtained for both Greenland and Antarctica for the time period 2009–2013. These images also combine multiple passes, and are vertically polarized. Data are provided on 4.45 km grids, with an estimated resolution of 12–15 km. In this study, ASCAT data were down-sampled (via spatial averaging) to match the 25 km resolution of passive-microwave melt-days datasets. Ku-band QuikSCAT data are available from 2000 to 2009 as a variety of products, including both vertical and horizontal polarization, and also combine multiple passes. Data are provided on a 4.45 km grid, with an effective resolution of 8–10 km. QuikSCAT data were kept on the original 4.45 km grid for this study.

We used 10-year averages of passive microwave surface melt products for Greenland and Antarctica to document annual melt days for the periods leading up to the ASCAT and ERS datasets (Mote, 2014; Picard and Fily, 2006). We chose this time scale to establish a relatively long-term average while avoiding biases from melt season effects buried below scatterometer penetration depths. We also created a third, higher-resolution dataset for Antarctic surface melt derived from ten years of available QuikSCAT backscatter data, following the technique presented in Hicks and Long (2011).

Additional validation data for the subsurface physical processes that drive the backscatter-melt days relationship come from ground-penetrating radar and shallow firn cores. These data were collected during a field campaign in southwest Greenland in the spring of 2013 (Machguth et al., 2016).

All Antarctic data were provided as continent-wide datasets. Subsetting of ice shelf regions was carried out using the MODIS Mosaic of Antarctica (MOA) 2009-derived coastline and grounding line (Scambos et al., 2007; Haran et al., 2014). Modifications were made to the outlines of the Ross and Filchner-Ronne ice shelves for ERS-1 and -2 to exclude large no-data regions near the pole.

3. Backscatter/melt days relationship development and validation

The physical relationship presented by Scambos et al. (2003) is essentially a microwave-based documentation of snow facies for Antarctic ice shelves. The observed categories are more easily identified and described in Greenland. Benson (1962) divided the Greenland ice sheet into four snow facies (dry snow, percolation, wet snow, and bare ice zones) based on their physical characteristics using in situ summer observations. Fahnestock et al. (1993) observed these same facies using winter SAR backscatter and discussed the physical features causing the distinctive backscatter response. Similar results have been presented in other studies (e.g. Jezek et al., 1993; Long and Drinkwater, 1994).

At the highest elevations in Greenland, in the dry snow zone, little or no melt occurs throughout the year, and backscatter values are typically very low due to penetration and absorption of microwave energy in the firn. At slightly lower elevations, in the percolation zone, summer melt is more intense and cooler subsurface temperatures cause meltwater to refreeze within the firn column, forming small, discontinuous ice lenses and pipes. These are efficient scatterers of microwave energy (Jezek et al., 1994; Partington, 1998; Hall et al., 2000; Haas et al., 2001; Willmes et al., 2011), and as summer melt intensity increases (with decreasing elevation on the ice sheet, among other factors), the winter backscatter signal rises. At lower elevations, in the wet snow zone, the entire upper firn column is wetted by melt and refreezes in winter to form large ice lenses, or (lower still) a nearly uniform near-surface ice layer in the superimposed ice zone. The bare ice zone at the lowest elevations is formed where summer melt removes the entire winter snow column and firn layer, leaving smooth glacial ice at the surface. In contrast to the increasing backscatter values with decreasing elevation observed through the percolation zone, the low-elevation shift found in the superimposed ice and bare ice zones to large, continuous layers of ice creates a specular surface for microwave radiation, buried under dry snow in winter. Specular reflections redirect the active microwave signal primarily away from the sensor, causing a decrease in measured backscatter. Therefore, overall we expect a graph of winter backscatter vs. average annual melt days to show increasing backscatter with increasing melt days, until some threshold where backscatter values decrease due to specular reflections at high numbers of annual melt days.

We infer that similar processes affect the firn column on Antarctic ice shelves, with analogous effects on backscatter. Cool-summer ice shelf areas have no significant summer melting, analogous to the dry snow zone in Greenland. Some areas receive a little melt, and have small, discontinuous ice lenses in the firn, similar to Greenland's percolation zone. A few areas receive significant amounts of melt that lead to the formation of superimposed ice capable of specular reflection of microwave energy. However, unlike in Greenland, where summer melt intensity is strongly correlated with elevation, snow facies on Antarctic ice shelves are more closely tied to local summer climate, and vary