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Impacts of an accumulation hiatus on the physical properties of firn at a low-accumulation polar site

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[1] Recent field investigations of a megadune region of East Antarctica provide evidence that differences in grain size, thermal conductivity, and permeability across a megadune profile are due to spatial accumulation variability in the absence of significant microclimate variations. The megadunes are low-amplitude (2–8 m), long-wavelength (2–5 km) bands with perceptible but low accumulation (less than 40 mm water equivalent (weq) yr^{-1}) and accumulation hiatus within several kilometers proximity, as determined by remote sensing, surface feature classification, and ground-penetrating radar profiling. Our hypothesis that accumulation rate impacts the extent of temperature gradient–driven metamorphic growth in low accumulation rate sites is supported by measurements of various firn physical properties. Relatively small differences in accumulation rate (less than 40 mm weq yr^{-1}) result in large differences in physical properties, including grain size, thermal conductivity, and permeability, which are apparent in satellite-based microwave data from both passive and active sensors. The differences in physical snow structure between low-accumulation areas and accumulation hiatus areas in the near surface are sufficiently distinct that evidence of past accumulation hiatus should be observable in the physical and chemical properties of an ice core record.

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1. Introduction

[2] Polar snow and firn are sensitive indicators of local climate. The physical structure of snow and firn, including grain size, shape, and spatial distribution, influences the microwave sensor response [e.g., *Mätzler and Huppi*, 1989], the air–snow exchange processes involving atmospheric chemistry [e.g., *Dominé and Shepson*, 2002], and the chemical and physical content of the firn that becomes the ice core record [e.g., *Alley et al.*, 1993]. The purpose of this paper is to discuss the impact of extreme near-surface metamorphism resulting from accumulation hiatus on firn structure, the resulting effect on physical properties, such as permeability and thermal conductivity, and possible implications for ice core and microwave sensor interpretation. Results from field investigations in central Antarctica in 2002–2004 are presented. Our hypothesis is that spatial differences in metamorphism are dominated by accumulation rate variations with temperature and other microclimate variations having a lesser effect.

2. Background

[3] Antarctic megadunes are long-wavelength (2–5 km), low-amplitude (2–8 m) features clearly visible from airborne and space-borne platforms as alternating bright and dark bands in the visible and microwave wavelengths [*Fahnestock et al.*, 2000]. Megadunes cover up to 900,000 km^2 across central Antarctica. The largest megadune field is in the vicinity of the Vostok research station, which suggests that understanding megadune characteristics may be valuable in ice core interpretation. By comparing satellite imagery of the area spanning 34 years, *Fahnestock et al.* [2000] found that the megadune patterns appear to migrate upwind at approximately 10 to 20 m yr^{-1}.

[4] Accumulation rate variations across small-scale dune forms have been studied both in sand [e.g., *Bagnold*, 1941; *Fryberger et al.*, 1979] and in snow [e.g., *Black and Budd*, 1964; *Whillans*, 1975; *Pettre et al.*, 1986; *Liston et al.*, 2000], showing that windblown particulates tend to accumulate in local concave areas or on the lee faces of dunes. However, subsurface imaging presented by *Frezzotti et al.* [2002] shows that this is not the case in a megadune field crossed by the Italian International Trans-Antarctic Scien-

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tific Expedition (ITASE) traverse. Their measurements from ground-penetrating radar (GPR) supported by surface elevation data using GPS show internal sedimentary structures indicating that snow accumulates on the windward face of the dune and that the lee faces and troughs of the dunes experience little to no accumulation. These zones of little to no accumulation are defined here as accumulation hiatus zones. The varying accumulation modes cause the surface topography, primarily the dune face, to migrate slowly in the direction of the persistent katabatic winds. The leeward face of the dune, the region of accumulation hiatus, is slowly buried over time by accumulation on the windward face and its consequent upwind migration. The back slope is progressively ablated or "polished" by the katabatic winds. This type of enhanced accumulation on the upstream face and resulting propagation up current has been identified on the deep seafloor for low aspect ratio mud wave formation from sediment redistribution in steady currents [*Flood*, 1988; *Normark et al.*, 1980]. The upstream migration of sediment waves or dunes is a general property of a class of sediment forms know as antidunes [*Kennedy*, 1963]. For Antarctic megadunes, *Frezzotti et al.* [2002, 2005] conclude that the progressive movement of the dunes over a given location creates a periodic record that is not representative of regional or broader-scale climate phenomena. The windward faces of the dunes can have accumulation rates ranging from an estimated 20 to 30 mm weq yr^{-1}, while the leeward faces have accumulation rates ranging from an estimated 0 to 5 mm weq yr^{-1} [*Frezzotti et al.*, 2002].

[5] The leeward faces of the dunes exhibit a glaze surface during late winter months [*Albert et al.*, 2004]. This glaze surface is made up of two monograined ice crusts sandwiching a 1.5-cm-thick layer of vertically oriented recrystallized grains, as observed by earlier field work [*Albert et al.*, 2004] and at other hiatus sites [*Fujii and Kusunoki*, 1982]. The glazed region is easily recognized by its highly reflective surface when looking into the solar zenith. If buried, the glaze surfaces are preserved at depth as monograined ice crusts, as observed in previous studies of accumulation hiatus areas [*Gow*, 1968; *Fujii and Kusunoki*, 1982]. The top 2 m of the firn on the leeward faces of the megadunes consist of unusually large, well-sintered, vertically oriented growth crystals, which resemble hard depth hoar as described by *Akitaya* [1974] and *Marbouty* [1980]. We postulate that extensive temperature gradient–driven metamorphic growth observed on the leeward face is a result of decades of vapor transport at low temperature [*Albert et al.*, 2004].

3. Methods

[6] Field measurements were made during the 2003–2004 austral summer on the East Antarctic Plateau at a field camp located at 80.78°S, 124.49°E in a megadune region identified in satellite imagery and by GPS profiling during the 2002–2003 austral summer. This megadune region is characterized by low average annual temperature (−49°C), low accumulation rate (less than 40 mm weq yr^{-1}), and nearly constant katabatic wind direction and wind speed (6–12 m s^{-1}). This paper reports on measurements at two sites 3.4 km apart along a GPS-mapped line perpendicular to the dune fronts (approximately parallel to the wind direction), one on the windward face of the dune in an area of snow accumulation and redistribution, and the other in the accumulation hiatus region on the leeward side of the dune (Figure 1). The sites selected for intensive snow pit studies included low-accumulation and hiatus regions classified as such by surface features described by *Fujiwara and Endo* [1971], *Wantanabe*, [1978], and *Goodwin* [1990] and by GPR surveying of the area (T. Scambos, personal communication, 2003).

[7] Automated weather stations (AWS) were installed at each site to measure air temperatures at heights of 1 and 2.5 m, wind speeds at heights of 1 and 7 m, and firn temperatures at several depths to 10 m. Three-cup anemometers (R.M. Young), with a range of 0 to 50 m s^{-1} and an accuracy of ±0.5 m s^{-1}, were used to measure the 1-m wind speeds. Propeller-type anemometers (R.M. Young), with a range of 0–60 m s^{-1} and an accuracy of ±0.3 m s^{-1}, were used to measure the 7-m wind speeds. The temperatures were measured using resistance temperature detectors (Honeywell HEL-700 Series Platinum RTDs), which are accurate to ±0.8°C at −100°C and ±0.5°C at 0°C. Their triple point was determined in distilled water/distilled water ice, resulting in an absolute error of 0.1°C at 0°C.

7. Conclusions

[32] Near-surface firn at an accumulation hiatus site is characterized by significant (on the order of tens of centimeters and more) depths of large grained, well-sintered firn with higher permeability and higher thermal conductivity than at a nearby site experiencing the same microclimate but a slightly higher accumulation rate. At polar sites with accumulation rates less than approximately 40 mm weq yr^{-1}, accumulation rate has a first-order effect on firn microstructure, thermal conductivity, and permeability, with a smaller effect on density. Large spatial gradients in microwave signatures in megadunes areas are due to relatively small differences in accumulation rate (approximately 40 mm weq yr^{-1}), while regions with high accumulation rates (e.g., higher than 150 mm weq yr^{-1}) should not exhibit the same sensitivity to accumulation rate differences. The ice core record from an area of accumulation hiatus is expected to have a relatively thick, uniform layer of reduced internal layering due to years of temperature gradient–driven metamorphic growth in the near surface, likely to be accompanied by altered isotopic and reversibly deposited chemical species concentrations. The same temperature gradient–driven metamorphic growth process will result in very high backscatter and low microwave emission in accumulation hiatus areas.