GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 22, PAGES 3719-3722, NOVEMBER 15, 2000

Snow megadune fields on the East Antarctic Plateau: extreme atmosphere-ice interaction

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Abstract. Large dune fields occupy more than 500,000 km^2 of the East Antarctic Plateau. The "megadunes", or long-wavelength surface ripples, have amplitudes of only a few meters, wavelengths of a few kilometers, and parallel crests which can extend one hundred kilometers. They occur in areas characterized by low accumulation, extensively recrystallized snow, and strong scattering of the microwave part of the spectrum. Dune crests are oriented perpendicular to the regional katabatic wind direction. Snow megadunes are unlikely to be formed by simple wind transport of snow particles.

Background

Regularly patterned dune-like features on the East Antarctic Plateau were described in a few areas from Landsat imagery by *Swithinbank* [1988, Figure 45]. He termed the features "megadunes" based on their wavelength, and differentiated them from clouds by their stable pattern in multiple images separated in time. He suggested that their amplitudes were likely small, and that they appeared in imagery due to drifting of new snow over older firn or to subtle changes in surface slope.

We will show that these features are extensive on the East Antarctic Plateau, have small amplitudes, and are visible in imagery due to both subtle surface slopes and grain-size variations. We use Swithinbank's term "megadune" and the term "dune field" to describe the features and the areas where they occur; however, it is unlikely that they are formed by the familiar aeolian processes responsible for sand dunes.

Extent

The extent of the dune fields was determined from Advanced Very High Resolution Radiometer imagery (AVHRR) using a band-pass spatial filter to highlight regions with the unique crest-trough pattern shown by the megadunes. The largest of the dune fields, covering more than 300,000 km^2 Figure 1a, has megadunes with sub-parallel crests ten to one hundred kilometers in length, occasionally branching or merging. Wavelengths range from just under 2 to over 4 kilometers.

The total area of the three dune fields we have identified in AVHRR imagery exceeds 500,000 km^2. Field outlines are plotted (Figure 1b) on an image of average microwave emission to illustrate the close association of dune fields with areas of anomalously low emission.

Character

Field Observations

Swithinbank suggested that the features would be difficult to see from the surface due to their subtle expression; a review of the literature from the early surface traverses that crossed the features indicates the traverse parties did not recognize their ordered structure [*Cameron et al.*, 1968; *Giovinetto*, 1963; *DenHartog*, 1959; *Picciotto et al.*, 1970]. A number of traverses north of the dune fields (on the coastal side of the plateau) have made detailed measurements of topography across less-regular undulations [*Black and Budd*, 1964; *Young et al.*, 1982] which are present over most of the ice sheet. These features do not show the regular crest/trough pattern or wind orientation of megadunes.

Snow stratigraphy and accumulation measurements made on the traverses through the dune fields cannot be precisely located relative to individual dunes; however the results indicate unique firn conditions in these areas. Beta-counting-based accumulation measurements from the South Pole-Dronning Maud Land Traverse (1964-1968) [*Picciotto et al.*, 1970] show that most sites with extremely low rates (<2 cm/yr) occur within or near the identified dune fields, although rates as high as 5 cm/yr (still low even by Antarctic standards) are also found in these areas. Snow pit diagrams from the Little America-Victoria Land Traverse and the McMurdo-South Pole Traverse indicate that a number of pits consist nearly entirely of sublimation crystals (recrystallized, coarse-grained firn)[*Giovinetto*, 1963; *DenHartog*, 1959]. The two pits with the highest percentage of recrystallized firn are located in the lowest microwave emission areas of Figure 1b. Highly recrystallized firn and very large grain sizes (maximums of 0.5-1.5 cm for the entire depth of Giovinetto's pit #105) occur throughout the traversed sections of the dune fields. There is a high spatial variability in the amount of recrystallization.

Meteorological data from the interior of the Antarctic Plateau indicates the dune areas are characterized by constant katabatic wind flow, with very uniform direction and speed. Trends of the dune crests are found to be perpendicular to the predicted directions of katabatic winds[*Parish and Bromwich*, 1991].

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Paper number 1999GL011248
0094-8276/00/1999GL011248$05.00

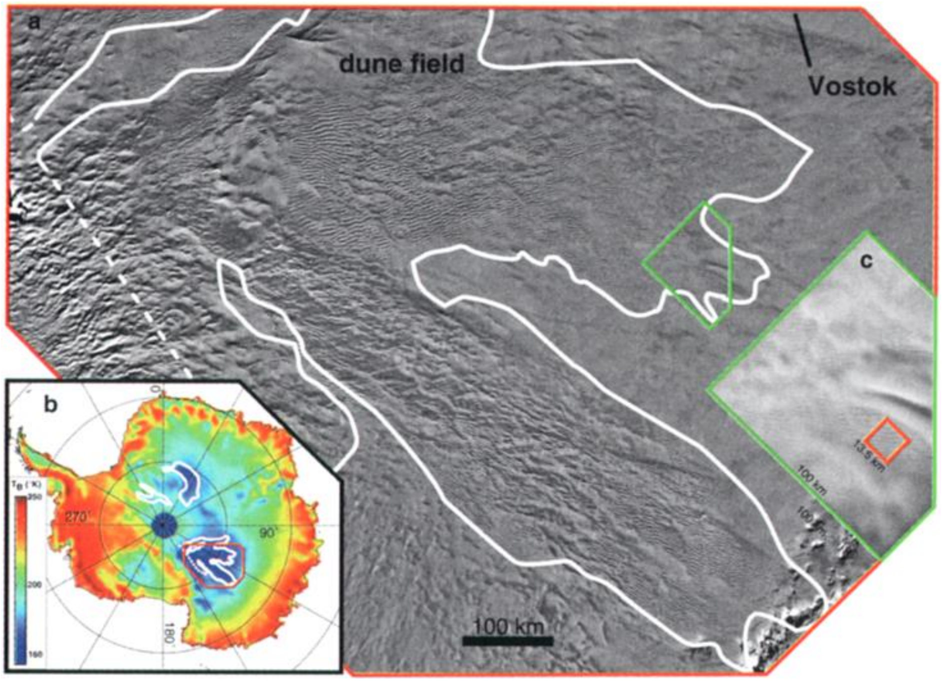

Figure 1. a) AVHRR visible-band image of the largest dune field. b) locations of identified dune fields plotted on an image of annual average of thermally-driven microwave emission from the snowpack at 37 GHz vertical polarization. c) 13.5 km x 13.5 km ERS-1 SAR image of megadunes (see Figure 2).

Remote Sensing Signatures

Microwave emission The anomalous signature of the dune fields in microwave emission is present at all frequencies and both polarizations measured by the SSM/I sensor, spanning free-air wavelengths from 3 mm to 1.4 cm (85 GHz to 19 GHz). These areas show much lower emission than would be expected for the temperature of the snowpack on the Plateau. There are two possible explanations for the low emission: the presence of firn that is much colder than the average air temperature, lowering its thermal emission; or strong scattering of upwelling energy by the firn, also lowering the energy emitted from surface. Temperatures from shallow cores [*Giovinetto*, 1963] in the dune fields, and surface temperatures from satellite thermal infrared sensors [*Comiso*, 1994] are not substantially lower than other regions of the Plateau, so there is little evidence of unusually cold firn. There is good evidence, however, that very coarse-grained firn exists in the dune fields, both from the pits examined by the traverses and from other satellite measurements.

Microwave backscatter and InSAR The intensity of backscattered microwave energy (from an actively transmitting instrument, such as a satellite radar) is strongly dependent on the character of the firn. Comparison of NSCAT measured backscatter on the Plateau [*Long and Drinkwater*, 1999] to the average emission shows that high backscatter areas correspond to the dune fields. Strong backscatter is produced either by a very rough surface or interfaces within the firn, or by strong volume scattering, such as from coarse grains.

The highest-resolution look at the megadunes in the microwave is provided by Synthetic Aperture Radar (SAR) on European ERS-1 and ERS-2 and Canadian Radarsat satellites. The dunes appear as alternating light and dark bands in the SAR imagery (Figure 1c), with narrow low-backscatter bands alternating with wider high-backscatter ones. The image in Figure 1c is one of a pair of images taken one day apart, when ERS-1 and ERS-2 where in a tandem configuration. An interferogram generated from the pair contains information about both the topography and differential ice motion within the scene [*Kwok and Fahnestock*, 1996].Figure 2 shows a perspective view of the interferometrically-derived topography of the megadune area in Figure 1c, with relative backscatter strength indicated by color. The striping is due to narrow low-backscatter bands on the uphill (windward) faces of the megadunes, and wider, high-backscatter bands on the downwind (lee) slopes. Megadune amplitudes are small, about 4 m in this area (peak to trough). Wavelengths are just under 2 km, and thus local slopes differ from regional slopes by about 0.004. We found similar amplitudes and wavelengths for megadunes 200 km south in the same dune field using photoclinometry [*Scambos and Fahnestock*, 1998] on AVHRR imagery.

Visible and near-IR Slope and grain size information is also available from AVHRR imagery. Figure 3 shows two views of an area in the middle of the largest dune field. The illumination directions were chosen so that in the top image the sun is more strongly illuminating the uphill, or windward, slopes of the megadunes, while in the bottom image the sun is illuminating the lee slopes. The image brightness in the visible band (an indication of the slope in the illumination direction) is plotted along with a ratio between the brightness in the visible and near infrared channels, an indicator of relative grain size[*Warren*, 1982]. In the lower image the slope and grain-size indicators are in phase, while the same indicators are out of phase for the image on the top. This is an independent (and shallow depth) indication of the variation in grain size across the megadunes,

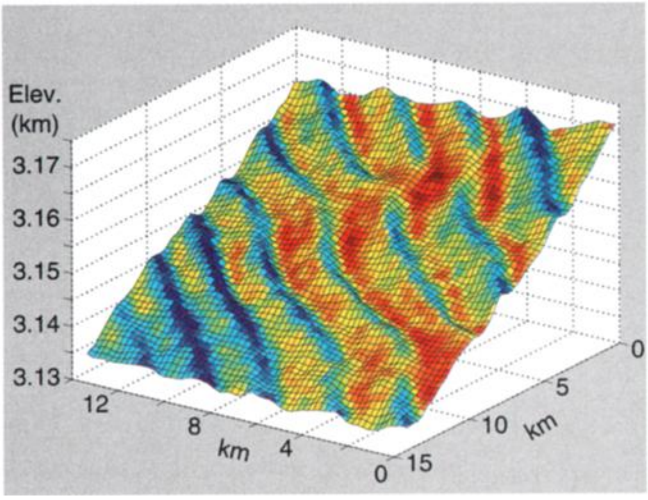

Figure 2. Perspective view of the area outlined in red in Figure 1c. Topography from SAR interferometry. Color represents relative backscatter strength (red - high, blue - low).

supporting the interpretation of backscatter patterns in SAR as grain-scale scattering.

Declassified intelligence satellite photography from 1963 shows megadune patterns in part of the largest field which are essentially unchanged in AVHRR imagery acquired 34 years later. Given the resolutions of the images, and lack of any identifiable changes, the maximum possible shift in the crests is less than 2km (or ~60 m/yr.). Moreover, both images show identical patterns of branching and megadune extent.

Possible Mechanisms and Implications

The early field reports and remote sensing information provide a detailed characterization of the dune fields, but do not provide a direct indication of the process of their formation. Clearly the atmosphere is involved, as the crests trend perpendicular to the prevailing winds. Their regular ripple-like appearance and high degree of organization seem to require some surface-atmosphere feedback, although the surface slopes involved are extremely small. The variation in grain size between the windward and lee slopes and the very large recrystallized grains observed in a number of the traverse pits indicate strong firn diagenesis, with high spatial variability. The apparent stability of patterns and the association of the dune fields with regions of very low accumulation allow the snow-atmosphere interactions to be subtle, as the firn remains exposed in the near surface for some time. The stationary aspect of the dunes may mean that regional slopes play a role in their genesis; in this respect their locations may be governed by bed topography.

Boundary layer standing waves The atmosphere on the Plateau is characterized for much of the year by a strong near-surface temperature gradient due to radiative cooling of the snow surface. This stable layer may be disturbed by strong katabatic flow, and may represent a gradient in which standing waves could develop. A detailed look at the wind velocity and temperature records from the AGO sites that are near the edges of the largest dune field show that strong winds correlate with warming near the surface, suggesting that these wind events disrupt the stratification. *Steffen et al.* [1999] have observed katabatic mixing down of warm air and related crust formation and recrystallization in Greenland. It is possible that standing waves in the strong thermal gradient of this boundary layer are the organizing phenomenon behind the structure of the megadunes. Standing waves would have to interact with the dune-field topography in a consistent manner, bringing warmer air to the surface in the regions of large-scale recrystallization.

Firn ventilation The dune fields might be generated by air moving through the snowpack, entering a megadune on the upwind face and leaving the surface on the downwind side, where saturated air would cause recrstalization and grain growth. This scenario would require very long horizontal transport driven by pressure variations across very gently sloping surfaces.

Aeolian transport A third possibility is that the dune fields are sites of migrating megadunes with shapes derived from along-flow variations in the ability of the wind to erode and transport snow particles. This scenario does not easily explain the variations in recrystallization and it is not compatible with the observed stability in dune patterns, unless the motion is extremely slow. *Black and Budd* [1964] proposed a variable deposition mechanism generating upwind migration of undulations with a low velocity, but no way to produce the strong variations in grain size. The snow megadunes bear little genetic relation to longitudinal sand dunes. Although longitudinal dunes can have similar wavelengths, their crests trend *along* the net transport direction, and they typically have slip faces on both sides and much higher crest-to-trough amplitudes. Slopes on snow megadunes are too low to be slip faces.

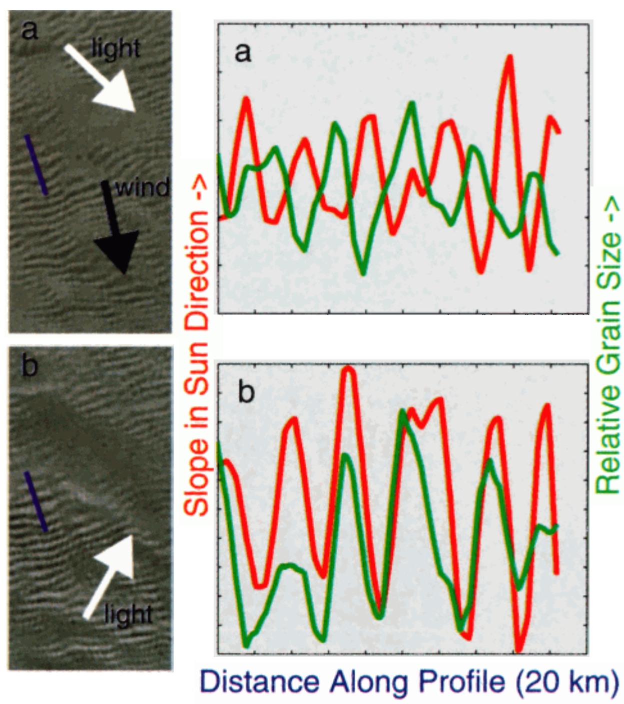

Figure 3. a) AVHRR visible-band image of part of the large dune field - illumination from the top of the figure. b) the same area as a), but with illumination from the bottom of the figure. The plots show visible-band brightness (red) and relative grain size (green) along the line in each figure.

Implications While we do not yet have a complete picture of the formation of the dune fields, we know dune fields are limited to the interior of the Plateau where there are low accumulation rates and the wind intensity and direction is determined by gravity flow, rather than by passing storm systems. This stability of conditions may be important. At the very least, the dune fields are a unique depositional environment, perhaps characteristic of the driest of firn deserts.

The extensive recrystallization associated with the dune fields leads us to favor the standing-wave mechanism. Because the megadunes occur in regions of extremely low accumulation, the recrystallized firn can represent many decades. The record preserved in the firn in these regions may vary spatially over a single megadune wavelength; such variations would be unrepresentative of climate variability when the snow fell.

Acknowledgments. The authors were supported by NASA HQ Polar Program.

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(Received November 12, 1999; revised May 5, 2000; accepted July 13, 2000.)