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Synthetic aperture radar detection of the snowline on Commonwealth and Howard Glaciers, Taylor Valley, Antarctica

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ABSTRACT. Synthetic aperture radar (SAR) images of Taylor Valley, Antarctica, were acquired in January 1999 in coordination with ground-based measurements to assess SAR detection of the snowline on dry polar glaciers. We expected significant penetration of the radar wave resulting in an offset of the SAR-detected snowline relative to the true snowline. Results indicated no detectable displacement of the SAR snowline. Snow depths of 15 cm over ice can be detected on the imagery. We hypothesize that the optical depth of thin snowpacks is enhanced by reflection and refraction of the radar beam by internal snow layers. The enhanced optical depth increases the volume scattering, and thereby enhances backscatter sufficiently to be detected by the SAR. Consequently, SAR imagery may be used directly to image the position of transient snowlines in dry polar regions.

INTRODUCTION

Assessing glacier change in the polar regions, particularly in the Antarctic, has been difficult because of the distance and expense involved in conducting the fieldwork. Fieldwork also limits the spatial scope of the measurements due to the logistics of surface movement. Monitoring glaciers in the polar regions is an important component of studying the effects of climatic change because the rate and magnitude of change are expected to be greatest in those regions (Serreze and others, 2000). To monitor glacial change efficiently over broad regions requires the use of remote-observation methods. Currently, remote monitoring includes airborne laser altimetry of alpine glacier altitude (Echelmeyer and others, 1997), and satellite remote sensing (Advanced Very High Resolution Radiometer and Landsat) of ice-shelf extent (Scambos and others, 1998). An important glacial feature that can be tracked on dry polar glaciers is the position of the equilibrium line.

The equilibrium line separates the zone of net mass accumulation from the zone of net mass loss (ablation) at the end of the melt season. The equilibrium-line altitude (ELA) relative to the distribution of glacier area with altitude is an important characteristic for determining the state of the glacier's mass balance (Paterson, 1994). This presumes that the gradient of mass balance with altitude is relatively constant from year to year, but the intercept is shifted. Unlike glacier-length (terminus-position) changes, the ELA is entirely controlled by climatic processes and is not influenced by the behavior of glacier flow. In contrast to temperate or subpolar glaciers, the ELA on polar glaciers is the same as the snowline because there is no melting. One of the most attractive techniques for tracking the ELA on polar glaciers is satellite synthetic aperture radar (SAR) since it covers broad areas, it images through clouds, and it is self-illuminating. These attributes are particularly useful for the cloudy coastal conditions and long polar nights common to polar marine environments. For dry-snow conditions, typical of polar glaciers, however, the SAR beam penetrates snow (Ulaby and others, 1981, 1982, 1986; Jezek and others, 1993; Lucchitta and others, 1995) and would displace the location of the ELA up-glacier. Maximum penetration in homogeneous snow is estimated to be about 20 m (Ulaby and others, 1981, 1982, 1986; Rott and Mätzler, 1987). This effect should be quite pronounced for thin snow accumulations on low-sloping surfaces, characteristics common to polar glaciers. For example, with a small mass-balance gradient with altitude, typical of polar glaciers, we would expect roughly a 2 km shift in the apparent snowline for a glacier with a 5° slope. The purpose of our study was to examine the extent of ELA displacement on a polar glacier and determine a correction for the SAR-estimated ELA.

STUDY SITE

We examined two glaciers in Taylor Valley, one of the McMurdo Dry Valleys in Antarctica (Fig. 1). This area was chosen because of ongoing glaciological investigations in the valleys on four glaciers that include measurements of mass balance, energy balances, ice velocity and ice depth. Mean annual temperature in Taylor Valley is −17°C (Clow and others, 1988), and summer temperatures have not often exceeded freezing since 1993 (unpublished information from P.T. Doran). The glaciers show little or no evidence of melt except in the lowermost fringe near the glacier terminus and along the cliff face, which forms the terminus (Lewis and others, 1995; Fountain and others, 1998). Most of the mass loss is from sublimation, which during the summer represents 40–90% of the ablation (Lewis and others, 1995).

The two glaciers we studied were Commonwealth and Howard Glaciers. In this paper we examine Commonwealth Glacier in detail, and briefly mention the results from Howard Glacier in the discussion section. Commonwealth Glacier (Fig. 2) faces south-southeast with a gentle (5°) slope.

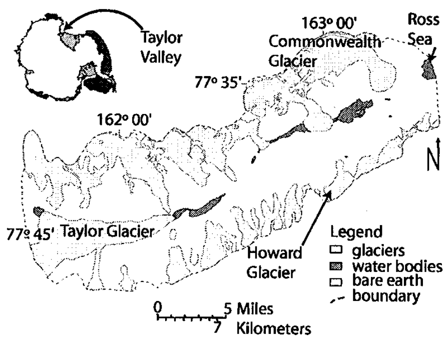

Fig. 1. Taylor Valley.

The glacier is about 2 km wide across the ELA at 350 m, with a relatively constant slope and even surface. The snow cover in the ablation zone ranges from traces to patchy, dune-like formations 4–35 cm high and covering areas of 1–20 m^2. In the accumulation zone, dry snow exists on the surface, with thin (cm or less) ice layers and hoar crystals at depth.

Methods

Mass-balance measurements are collected over the entire surface with a network of 21 stakes on Commonwealth Glacier as part of the ongoing monitoring. The stakes are typically measured twice annually, once in the spring (October–November) and once in the autumn (mid- to late January). The measurements include surface height, and snow depth if the snow covers the ice of the ablation zone. Whenever snow is present, a snow pit is dug at every stake and the snow stratigraphy is measured, including layer thickness, density and crystal shape. To supplement these measurements with precisely located measurements relative to the SAR image, we set up a transect on Commonwealth Glacier from the ablation zone, across the snowline and into the accumulation zone.

CONCLUSIONS

Glacier surfaces in Taylor Valley are generally radiometrically smooth and appear dark in the SAR image over most of the ablation zone. The snow zone images brighter because of the volume reflection from the entire depth of snow penetrated by the SAR beam. Because of the known penetration characteristics of SAR in dry snow, we expected a displacement of the SAR-inferred snowline. In contrast, the SAR-inferred and actual snowlines were very close to each other. We believe that this correspondence is due to enhanced volume reflection and can reveal the presence of snow depths of only 15 cm. Enhanced volume reflection results from layers of different densities acting as specular reflective surfaces (Ulaby and others, 1981, 1982, 1986; Mätzler and Schanda, 1984; Tsang and others, 1986). Reflection off internal layers increases the path length the beam travels (Ulaby and others, 1981, 1982, 1986), creates more opportunity to scatter in the snow and increases total reflection. Therefore thin, dry snowpacks with no internal layers will not be visible in SAR imagery.

The largest difference of backscatter between polarizations occurred in the ablation zone and reduced in the accumulation zone. On the ice surface of the ablation zone, VV polarization backscatters more than the HH polarization. In deep snow, HH backscatter increases relative to VV, and the difference in backscatter is reduced.

The corner reflectors worked very well, precisely locating the transect, adding scale and two known points to the SAR image. The reflectors were placed on smooth glacial ice, and the contrast between the dark backscatter of the ice and the brilliant reflection of the reflectors left no doubt of their locations on the image.

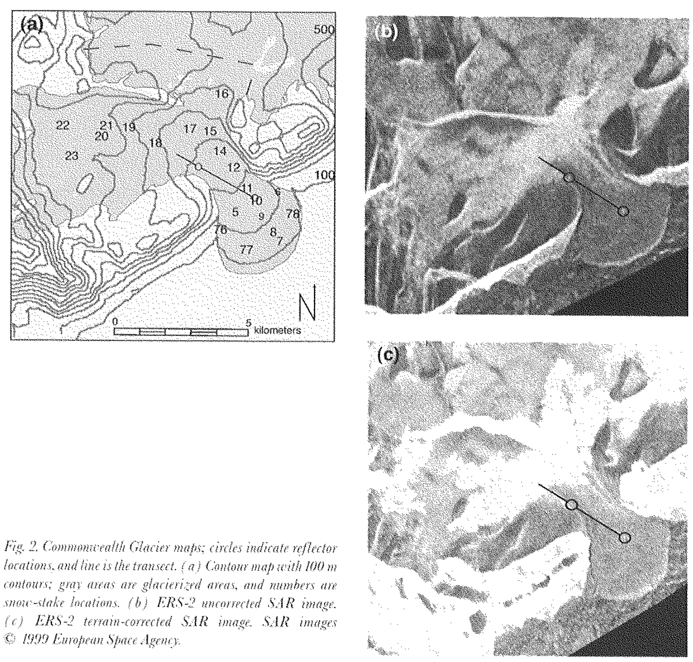

Fig. 2. Commonwealth Glacier maps; circles indicate reflector locations, and line is the transect. (a) Contour map with 100 m contours; gray areas are glacierized areas, and numbers are snow-stake locations. (b) ERS-2 uncorrected SAR image. (c) ERS-2 terrain-corrected SAR image. SAR images © 1999 European Space Agency.