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Mertz and Ninnis Glacier tongues mapped from satellite radar altimeter data

Mertz and Ninnis Glaciers are two glaciers in East Antarctica (Mertz: 145° E, 67° S; Ninnis: 147.5° E, 68° S) with long tongues extending into the southernmost Indian Ocean. A contribution in a recent issue of the *Journal of Glaciology* by Wendler and others (1996) is concerned with advance and retreat of these tongues and with the description of their surface features based on satellite synthetic aperture radar (SAR) data from JERS-1.

In this letter, we note that accurate surface elevation and extent of these East Antarctic ice tongues are now available from an evaluation of Geosat Geodetic Mission (GM) radar altimeter (RA) data. A topographic map of the Ninnis and Mertz Glacier area is provided (Fig. 1), in addition to enlarged versions of Mertz Glacier (Fig. 2) and Ninnis Glacier (Fig. 3). These maps were expanded from our atlas of topographic terrain models of Antarctica, derived from Geosat GM RA data of 1985–86 using geostatistical methods (Herzfeld and Matassa, in press a).

In general, RA and SAR data can be combined to study changes in position, surface morphology and elevation of Antarctic ice streams and glaciers. The advantage of RA data over SAR data is their longer record in time (since 1978), more frequent repeat, and lesser data volume, which facilitates frequent collection and rapid evaluation for large areas.

DATA ACQUISITION, PROCESSING AND GEOSTATISTICAL EVALUATION

The advantage of Geosat data from the Geodetic Mission (1985–86) is their denser ground-track pattern resultant from the fact that the satellite was allowed to drift instead of being forced to repeat wider spaced orbits exactly (as in the Exact Repeat Mission 1987–89). Data processing, projection, the atlas-mapping problem and geostatistical evaluation are treated in Herzfeld and Matassa (in press a). We acquired data from the Ice Sheet Altimetry Group at NASA Goddard Space Flight Center (H. J. Zwally, J. DiMarzio and co-workers). Data processing at NASA GSFC included retracking, reduction using Goddard Earth Model (GEM) T2 orbits, correction for atmospheric effects, water vapour and solid Earth tides, and slope corrections (for methods see Herzfeld and Matassa, in press a). Only points with retracked and slope-corrected data are used in mapping. Geographic coordinates of data locations are converted to Universal Transverse Mercator (UTM) coordinates to facilitate rapid interpolation and to reduce distortion (Snyder, 1987; Herzfeld and Matassa, in press b).

Grid values are calculated using ordinary kriging with search algorithms developed for geophysical track-line data. Ordinary kriging is a least-squares-based optimum interpolation technique from geostatistics, the theory of regionalized variables, and proceeds in two steps, spatial analysis (variography) and estimation. The relatively high error in radar altimeter data over ice surfaces requires special precautions in the variography (see Herzfeld and Matassa, in press a). A grid spacing of 3 km is used; elevations are above the World Geodetic System 1984 (WGS84) ellipsoid.

MERTZ AND NINNIS GLACIER MAPS: PRESENTATION AND INTERPRETATION

The resultant topographic map of the Mertz and Ninnis Glacier area (142.0–148.5° E, 66.5–68.5° S) is given in Figure 1. The map is based on a digital terrain model (DTM) with 3 km grid spacing. Surface elevations are in meters above WGS84. Isohypses are drawn for 0, 10, 20, ..., 140 m (in steps of 10 m) and for 200, 400, ..., 1400 m (in steps of 200 m).

To enhance the details in the glaciers and ice tongues, enlarged, individual topographic maps of Mertz Glacier (143.5–146.0° E, 67.0–68.0° S) and Ninnis Glacier (147.0–148.5° E, 68.0–68.5° S) are given in Figures 2 and 3. In both maps, isohypses are drawn for 0, 10, 20, ..., 140 m (in steps of 10 m), for 140, 160, ..., 400m (in steps of 20 m) and for 400, 600, 800 m (in steps of 200 m). A 20 m spacing is used between 140 and 400 m to map the transition between the level of the ice cap and the level of the ice tongues.

Mertz Glacier is at UTM 360 000–440 000 E, 7 525 000–7 440 000 S. Its drainage is a broad valley that is distinguishable at the southern map boundary. The sides of the western valley are transected by erosional features. At its head, the glacier is fed by a narrow valley, approximately 4 km wide. The distance from the 80 m contour line at the head to the ice front is 85 km. In the eastern arm of Mertz Glacier there is a 20 m overdeepening, centered at (415 000, −751 000). This is located below the steepest part of the valley walls. It is not an interpolation error, since the contours are really smooth.

Mertz Glacier is about 27 km wide. The glacier tongue appears to extend about 45 km seaward of the coastline

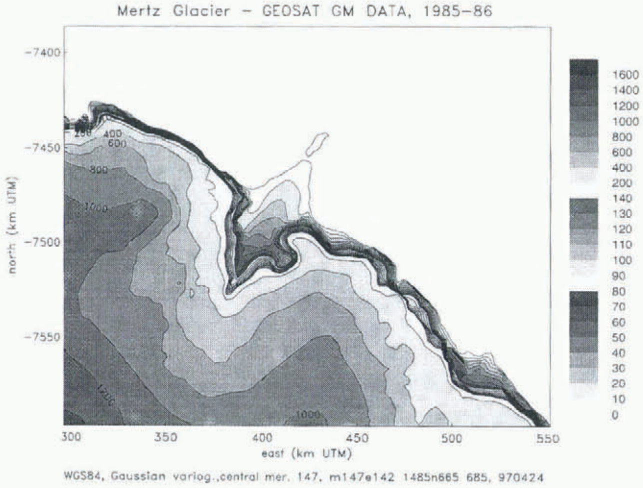

Fig. 1. Topographic map of Mertz and Ninnis Glacier area, East Antarctica (142.0–148.5° E, 66.5–68.5° S). Surface elevation in meters above WGS84, contoured from 3 km grids calculated from retracked and slope-corrected Geosat GM data (1985–86) using ordinary kriging with a Gaussian variogram; UTM coordinates, central meridian 147° E mapped to 500 000.

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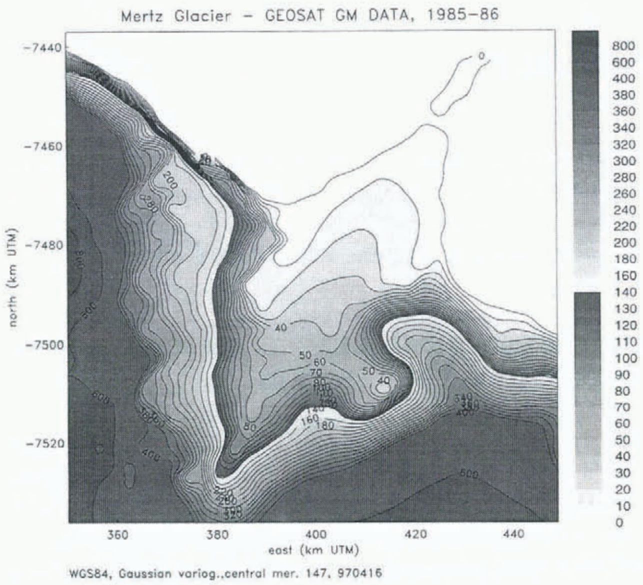

Fig. 2. Topographic map of Mertz Glacier area, East Antarctica (143.5–146.0° E, 67.0–68.0° S). Surface elevation in meters above WGS84, contoured from 3 km grids calculated from retracked and slope-corrected Geosat GM data (1985–86) using ordinary kriging with a Gaussian variogram; UTM coordinates, central meridian 147° E mapped to 500 000. Mertz Glacier is at UTM 360 000–440 000 E, 7 525 000–7 440 000 S.

(see discussion below). The grounding line of Mertz Glacier is probably located in the vicinity of the 40–50 m contour. The 60 m contour still exhibits the indentation of the valley that continues subglacially from the valley leading to the head of the glacier, while the 50 m contour does not. The 40 and 50 m contours show the signs of the eastern side valley. At 30 m, the tongue is definitely floating.

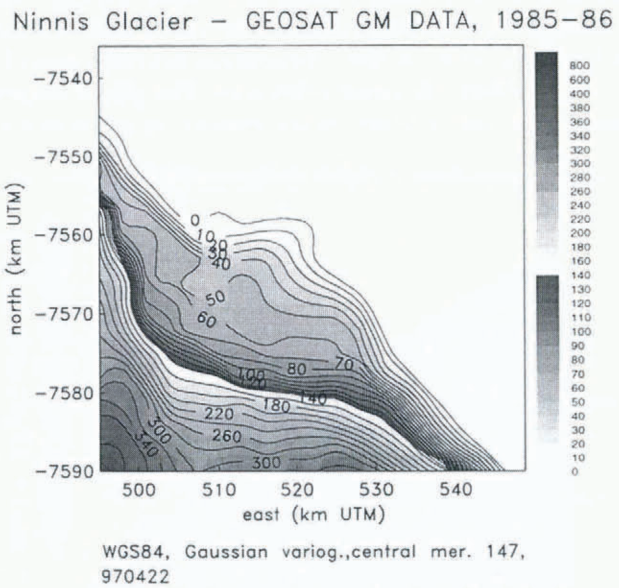

Fig. 3. Topographic map of Ninnis Glacier area, East Antarctica (147.0–148.5° E, 68.0°–68.5° S). Surface elevation in meters above WGS84, contoured from 3 km grids calculated from retracked and slope-corrected Geosat GM data (1985–86) using ordinary kriging with a Gaussian variogram; UTM coordinates, central meridian 147° E mapped to 500 000. Ninnis Glacier is at UTM 500 000–540 000 E, 7 550 000–7 580 000 S. This map is of same scale as Mertz Glacier map (Fig. 2).

The following surface slopes were calculated along local gradients of the Mertz Glacier map: 0.049° (= 8.57E-4) between the 30 and 0 m contours for the floating tongue; 0.078° in the direction of the head valley and 0.143° farther east (= 1.36E-3 and 2.5E-3, respectively) between the 40 and 70 m contours on the grounded ice; 0.286° (5E-3) between the 80 and 140 m contours in the head valley. The western side of the Mertz Glacier valley has a slope of 0.573° (= 1E-2) between 80 and 140 m, and a slope of 0.8275° (= 1.4E-2) between 140 and 400 m; above that, the slope increases with increasing elevation. The steepest area in the flanks of Mertz Glacier is located southeast of the overdeepening; it is inclined 2.0045° (= 3.5E-2) on average between 50 and 400 m, with a steeper section (2.0617° = 2.6E-2) between 50 and 140 m, and a shallower section (1.2412° = 2.16E-2) between 140 and 400 m. In this region, the slope lessens above 400 m elevation.

Ninnis Glacier is at UTM 500 000–540 000 E, 7 550 000–7 580 000 S. The glacier tongue appears to extend about 10–15 km seaward from the coastline (the coastline being identified by the steep gradient of contours). Ninnis Glacier lies below a steep cliff, at 90 m above WGS84 and lower. The entire extension from the break in slope at the foot of the cliff to the 0 m contour line is 20 km. (Notice that the 0 m contour does not coincide with sea level, because the reference level is the ellipsoid.) Ninnis Glacier is about 35 km wide. It does not really have a "tongue" anymore (as opposed to 1913), as noted by Wendler and others (1996).

DISCUSSION ON ACCURACY AND RELIABILITY

Mapping of atlas type and careful analysis of the spatial structure and the distribution of noise levels in RA data allows us to extend the limits of use of altimeter data for mapping. Bamber (1994) produced a map of Antarctica (from ERS-1 altimeter data) with 20 km grids, reliable only in areas with a slope of less than 0.65° according to the author. The drainages of Mertz Glacier and the Mertz and Ninnis Glacier area are considerably steeper than that. Accuracy depends on topographic relief, as calculated in Herzfeld and others (1993, 1994), with sub-meter accuracy on ice streams. However, the accuracy of a kriged map in areas of high topographic relief refers to the pointwise error rather than to the error of the "mean" surface elevation mapped. The "pointwise error" is the probable difference between a point on the map (estimated surface elevation) and a radar-altimetry-derived surface elevation; it depends on the averaging process of kriging. Shape and elevation of the surface at the Mertz Glacier drainage and on the glacier itself, however, are more accurate than inferred from the noise calculation, which is best conceived from inspection of the maps. The contour lines are smooth on the resolution of the 3 km grid. Smooth contour lines indicate a continuous or differentiable surface function with low error; little islands and edging contour lines indicate a rougher surface function with higher errors. That means the maps are reliable also in areas of steep terrain. An area with high relief is located on the western side of Mertz Glacier. Notice that the grid spacing of the subarea enlargements is the same 3 km as for the large map, and that a wealth of information only becomes available in the enlargement. Mertz Glacier tongue appears to extend about 40 km seaward of the coastline, Ninnis Glacier tongue about 20 km.

Neither satellite altimetry nor kriging is a tool designed to track the location of an ice cliff. Because of the effect described in Thomas and others (1983) and Partington and others (1987) (snagging of altimeter), the location of the ice edge is systematically wrong, differently so in descending and ascending orbits. Thomas and others (1983) attempted to trace the ice edge from altimeter data, designing a technique not used here. In the Ice Data Record the ice edge is in the middle of both errors. Kriging employs a moving window averaging procedure, which results in smoothing of steep edges. Consequently, the exact location of the ice edge cannot be inferred from altimetry, but the cliffs may be identifiable as a sequence of dense contours. Comparing our map with the images in Wendler and others (1996), however, we note that the results of kriging altimeter data are surprisingly good. On their map in figure 2, Mertz Glacier tongue extends about 80 km off the (averaged) coastline, Ninnis Glacier tongue 20–30 km. (Also, 1993–85 = 8 years, 0.9 km year^{-1} for 1962–93; 8 × 0.9 km = 7.2 km or 8 × 1.2 km = 9.6 km advance since 1985–86, according to Wendler and others (1996), assuming constant rate of advance.)

This indicates that, while SAR images are superior to altimetry-based maps for location of the ice edge, changes in advance/retreat can still be monitored from satellite-altimeter derived digital-terrain models (DTM), which are available for a longer time-span (since 1978; Seasat mission). SAR imagery shows surface features in the floating ice tongue. The slope and elevation of the glacier surface are lost in the grey-shaded image. Additional information on ice flux can be derived from the surface elevation in the altimetry-based DTMs, calculated for the drainage basins.

Another advantage of RA data over SAR data is that records have been available since the 1978 Seasat mission. A maximal amount of information may be expected from a quantitative combination of SAR and RA data.

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