Letters

Greenland Ice Sheet: Is It Growing or Shrinking?

In their recent report "Growth of Greenland ice sheet: Measurement" (22 Dec., p. 1587), H. Jay Zwally *et al.* write that Geosat and other satellite radar altimeter data indicate "the southern Greenland ice sheet has been thickening since the mid-1970s." We believe that these results are incorrect because inadequate attention was given to eliminating low frequency signals in surface elevation that arise from errors in satellite altitude. We offer two lines of evidence to support our position. (i) An implausible trend of sea level is observed for the ocean near Greenland when the data analysis methods of Zwally *et al.* are used, and (ii) the observed secular path of the earth's pole is inconsistent with a significant accretion of ice on Greenland.

The method of analysis outlined by Zwally *et al.* was to determine the trend of the observed height change of the ice sheet at intersections (crossovers) of altimeter profiles. The results appear compelling, but computed satellite orbits suffer from a large number of low frequency systematic errors requiring calibration of results against some standard. Thus in oceanographic applications of satellite altimeter data, the data are commonly compared with sea level variations given by island tide gauges. In the case of Geosat crossover data over Greenland, a calibration can be done by applying the analysis of Zwally *et al.* to crossovers in the surrounding oceans. For the same 18-month time span of Geosat data, we find for the average latitude of the area of Greenland considered an apparent secular increase of North Atlantic sea level of about 50 centimeters per year. Such an increase of sea level is clearly an artifact and suggests that the 28-centimeter-per-year result obtained for the Greenland ice sheet during 1985–1986 is also an artifact. Indeed, our results suggest that Greenland ice may have thinned by 22 centimeters per year ($28 - 50 = -22$) in 1985–1986. This calibrated result therefore offers a counterexample to the 20-centimeter-per-year ice thickening cited by Zwally *et al.* for the period 1978–1985 on the basis of Seosat-Geosat crossovers.

Systematic secular trends of sea level are also observed elsewhere in the unadjusted Geosat data. Southwest of New Zealand, antipodal to Greenland, we obtained an apparent sea level fall of the same magnitude. Overall, the effect has a linear dependence on latitude with near-zero values at the equator. Long wavelength, low-frequency effects are common in satellite altimetry, but do not show up in published analyses of crossover data [for example, (*1*)] because these signals are customarily removed from profiles of satellite altimeter data by adjusting each pass into a reference grid. By not treating the Geosat data in this way, Zwally *et al.* have introduced errors that undermine our confidence in the overall conclusions of the report.

Thickening of Greenland ice is also inconsistent with observed changes in the earth's pole position. In his companion report "Growth of Greenland ice sheet: Interpretation" (22 Dec., p. 1589), Zwally writes that the ice sheet is thickening 23 centimeters per year south of 72°N and half of that in the north. This would have the effect of moving the earth's pole away from Greenland at about 4 milliarc seconds (mas) per year (*2*). But the motion of the pole has been monitored for more than 90 years, and the available observational evidence (classical optical, satellite Doppler, satellite laser ranging, and very long baseline interferometric determinations) indicates that the secular motion is toward Greenland at a rate of about 3 mas per year. Peltier (*3*) has attributed this motion to the effect of glacial rebound in North America and Europe. The discrepancy between the observed polar motion and the motion inferred from the purported ice buildup in Greenland is about 7 mas per year, that is, about 20 centimeters per year. The new measurements alone, starting with satellite Doppler observations in 1972, rule out any major short-term change (in the last 5 to 10 years) in the Greenland ice mass. Although there is some uncertainty in the observed secular pole motion on longer time scales (greater than 100 years) as a result of motions of the tectonic plates, the general agreement seen in measurements from four different techniques mitigates against these uncertainties being much larger than a few centimeters per year. To explain the discrepancy as an error in the glacial rebound calculations would require an error of a factor of 2 or more. We therefore feel that the pole position measurements provide a strong indication that an ice buildup in Greenland has not been occuring.

In conclusion, we believe this use of inadequately calibrated altimeter crossover data from Geos 3, Seasat, and Geosat has not provided a reliable conclusion about accretion of ice on Greenland.

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REFERENCES

1. L. Miller, R. E. Cheney, B. C. Douglas, *Science* **239**, 52 (1988).
2. K. Lambeck, *The Earth's Variable Rotation* (Cambridge Univ. Press, Cambridge, MA, 1980), p. 273.
3. W. R. Peltier, *J. Geophys. Res.* **89**, 11303 (1984).
4. Supported in part by the NOAA Climate and Global Change program.

Response: Douglas *et al.* say we used "inadequately calibrated altimeter" crossover data from Geos-3, Seasat, and Geosat and suggest the ice sheet may have thinned during 1985–1986. Their interpretation overlooks our intersatellite comparison, neglects the effects of cyclical variations on their inferred artificial ocean-surface rise, and underestimates the ambiguities inherent in relating earth-rotation parameters to mass changes.

As described in our reports, the data were used for all the intersatellite comparisons were referenced to a common ocean surface. This referencing included the Seasat (1978)–Geosat (1985) comparison, which we believe is most significant for mass balance studies because of the 7-year interval between measurements. All our Geos-3 and Seasat data were adjusted to a reference ocean surface produced by us from Geos-3 and Seasat data. Our initial comparison between the unadjusted Geosat data and the Seasat data gave an apparent ice elevation rise of 1.785 ± 0.014 meter over 7 years. We then subtracted of 0.4 ± 0.4 meter to correct for a systematic bias between the Navy ocean reference level that is consistent with the Navy Geosat orbits and our ocean reference level, to which we adjusted the Seasat and Geos-3 orbits. For comparison, the 1959–1968 Expedition Glaciologique Internationale au Groenland (EGIG) surface leveling showed a 1-meter increase in central Greenland and thinning at the margins, as noted in our paper.

The basic conclusions on ice sheet growth are the same for both the Geosat-Geosat and the Seasat-Geostat comparisons. Our results from the 18-month Geosat (1985)–Geosat (1986) data showed a rate of ice sheet elevation change that is similar in both magnitude and spatial distribution over the ice sheet to the Seasat-Geosat values. The Geosat measurements provided more spatial detail, due to improved tracking over the steeper portions of the ice sheet. A more detailed analysis (*1*) of the 1985–1986 Geosat-Geosat crossovers in the western abla-