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.

BRUCE C. DOUGLAS
ROBERT E. CHENEY
LAURY MILLER
RUSSELL W. AGREEN
WILLIAM E. CARTER
DOUGLAS S. ROBERTSON
National Ocean Service,
National Oceanic and
Atmospheric Administration,
Rockville, MD 20852

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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 we 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 ablation zone shows a spring-to-spring and summer-to-summer elevation increase that is 0.9 ± 0.4 meter when calculated relative to the average change obtained from all ice sheet crossovers.

We now have additional results from analysis of the unclassified Geosat Exact Repeat Mission (ERM) data that confirm our conclusion of ice sheet growth. This analysis uses data with all Geosat and Seasat orbits calculated by the National Aeronautics and Space Administration (NASA) with the use of the same gravity field. From a Seasat (1978)–Geosat (1987) crossover analysis, we obtained an ice sheet elevation increase of 1.55 meter, which is consistent with our previous 1.38-meter increase for 1978–1985. After we adjusted both the Geosat and Seasat orbits to our ocean reference surface, we obtained essentially the same increase. Also, our new *dH/dt* (elevation difference versus time) analysis for 1987 shows a similar ice sheet growth rate, whereas analysis of the ocean crossover data near Greenland for the same time period shows a *negative* "trend" of 0.17 meter per year.

Douglas *et al.* emphasize the use of tide gauge data and the adjustment of orbits to the ocean surface to "calibrate" the altimeter data. It should be noted that altimeter–tide-gauge comparisons sometimes show discrepancies of tens of centimeters [for example, (*2*)]. Furthermore, it is known that orbit adjustments may remove real variations in ocean topography or errors in the numerous corrections to the altimeter data over the ocean and thus introduce oceanographic-based errors over nonoceanic areas. Depending on the length of the record, such errors could appear to be several tens of centimeters per year.

The analysis of Douglas *et al.* uses Department of Defense classified data that were not available to us. We recognize, of course, that our Geosat-Geosat analysis for 1985–1986 may be influenced by undetermined secular orbit errors over the 18-month period. We now know that the data over both the ocean and the ice sheet appear to have cyclical variations that could include orbit errors as well as real variations in the ice and ocean surfaces. Although the *dH/dt* analysis used in our paper, and by Douglas *et al.* over the ocean to infer their artificial changes, can reduce the effect of cyclical variations on calculated linear trends, the calculated trends still depend on the length of the record and the phasing of the cyclical variations. An elevation time series, $H(t)$, which we obtained from sequential analysis of 18 months of ice sheet crossovers, shows a seasonal variation that we interpreted as being caused by seasonal variations in snow accumulation and firn compaction. Similarly, examination of the $H(t)$ time series over the ocean is needed to separate real surface elevation changes from possible orbit errors and to determine the effect of cyclical variations in the ocean data on deduced trends. Consequently, we do not think it is accurate to simply deduce a trend from the ocean *dH/dt* analysis alone, assume it is orbit error, and deduce that the ice sheet thinned during the 1985–1986 period.

Regarding the second line of evidence, namely the secular path of the earth's pole, (i) there are a variety of contributing sources to the observed polar motion, (ii) the water-mass for current sea level rise is not included in their calculations because its source is undetermined, and (iii) analyses of the set of possible contributing factors to polar motion have not been sufficiently constrained to deduce present ice sheet growth or shrinkage unambiguously. For example, a more recent analysis by Peltier (*3*) showed consistency of observed polar wander and rotation with model results that included recent small glacial wastage as well as North American and European glacial rebound, if there were a substantial Barents Sea ice sheet 18,000 years ago and no current changes in the ice sheets (that is, if one attributes Peltier's 1-millimeter-per-year estimate of sea level rise to thermal expansion and small glacier wastage). To further illustrate the ambiguity of such deductions, a decreasing ice mass in Wilkes Land of East Antarctica could be postulated as a counterbalance to the observed Greenland mass increase.

H. JAY ZWALLY
ANITA C. BRENNER
JUDY A. MAJOR
ROBERT A. BINDSCHADLER
JAMES G. MARSH
Oceans and Ice Branch,
Laboratory for Oceans,
Goddard Space Flight Center,
National Aeronautics and Space Administration,
Greenbelt, MD 20771

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