The principal conclusion of C. H. Davis et al. (1), that the elevation of the Southern Greenland ice sheet increased at a smaller rate than the 23 cm/year we previously reported (2, 3), is in qualitative agreement with our new analysis. Their statement, however, that "surface elevations above 2000 meters increased at an average rate of 1.5 ± 0.5 cm/year" is not accurate because the calculation of this average included only 70% of the area above 2000 m, as seen if one overlays elevation contours on the map in figure 1 of the report (1, p. 2087). Much of the other 30% of the area above 2000 m is adjacent to the portion where Davis et al. calculated that changes are in the range of +5 to +18 cm/year. Because 37% of the total area is below 2000 m, the average they give represents only 43% of the total area and is biased toward the higher elevations and latitudes, where the changes are smaller or negative. Of secondary importance, the average they present includes all seasons for the Geosat time period, but the seasonal changes of ±15 cm they note are usually positive (at elevations above 1700 m) during the late summer, corresponding to the Seasat period.

Because Davis et al. obtained their data from our NASA Pathfinder reprocessing project, we use the same data, altimeter corrections, and orbit calculations. We also use similar orbit correction procedures. Within the areas reported by Davis et al., we obtain essentially the same result within 1 cm/year. However, our current analysis uses more altimeter data, including that from the first 18 months of the Geosat mission, and which extends to lower elevations. As in our earlier paper (3), we calculated the average change in five 500-m elevation bands above 700 m. Our area-weighted averages are 5.4 ± 1.6 cm/year for Geosat-Seasat and 6.2 ± 2.8 cm/year for Geosat-Geosat (before correction for isostatic uplift, which may be 0.5 cm/year). Below 1700 m, the increases are less significant as a result of fewer crossovers and larger altimeter errors. For elevations above 1700 m, the thickening rates are 3.8 ± 0.2 cm/year for Geosat-Seasat and 6.4 ± 0.9 cm/year Geosat-Geosat. Therefore, our recalibrated area-weighted averages are significantly smaller (×1/4) than our previously calculated values, but also significantly larger (×3) than those given by Davis et al.

As a percentage of mass balance, a thickening rate of 5 cm/year is about 10% of the average rate of precipitation minus evaporation for Southern Greenland (4), which is a significant growth rate. Relative to climate change, 10% is within the range of predicted changes for a 1 K climate warming (5). Because there are no previous regional-scale measurements of the mass balance, it is not known whether the observed positive balance is associated with climate warming during this century. More accurate and longer term measurements of ice sheet elevation changes are needed, which should be obtained by NASA’s ICESat laser altimeter satellite starting in July 2001.

Finally, although our calculations of average elevation change are positive at most elevations, we see local areas with significant decreases as well as areas with increases. Huybrechts (6) noted that our previous results were in qualitative agreement with his three-dimensional numerical model, and our new results also show significant quantitative agreement with the spatial pattern of the modeled changes.

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Response: The map shown in figure 1 in our report delineates the regions that are represented by data in our study. We recognize that approximately 30% of the southern Greenland ice sheet above 2000 m is not covered. Zwally et al. incorrectly state that much of the missing area above 2000 m is adjacent to areas of large positive change (that is, west of the ice divide from 64° to 69° N). A majority of the missing area above 2000 m is east of the ice divide and adjacent to areas with negative change (Fig. 1A).

Although improved spatial coverage will provide a better portrait of the regional variations, we do not expect it to significantly alter our estimate of the overall rate. New results based on inclusion of data from the first 18 months of the Geosat mission (March 1995 to October 1996) support this conclusion. These data were only recently (December 1997) made available to us by the NASA Ice Altimeter Pathfinder Program, and we have now processed them in a manner consistent with the procedures described in our report. With the inclusion of these data, we obtain a preliminary estimate of +2.2 ± 0.9 cm/year for the rate of surface elevation change for the southern ice sheet from 1978 to 1988. This rate, which has not been adjusted for isostatic uplift, is consistent with the corresponding estimate of +2.0 ± 0.5 cm/year provided in our report. The new result (Fig. 1B) contains 23% more total area than our original analysis, includes new areas between 1700 to 2000 m, and improves coverage above 2000 m to about 80%. The coverage above 2000 m is nearly complete west of the ice divide, filling in most of the areas near changes from +5 to +18 cm/year noted by Zwally et al. However, the coverage is also significantly extended adjacent to areas experiencing negative change. Thus, the combined effect of the extended coverage produces a net spatial average not significantly different from our published result.

Zwally et al. state that our average includes all seasons for the Geosat time period, but do not acknowledge that we also performed the analysis using only “same season” data. The corresponding elevation change estimates are shown in table 2 in our report, and are consistent with the nominal estimate based on the full 2 years of Geosat data.

Zwally et al. cite several unpublished ice-sheet growth estimates, the larger of which includes data below 1700 m. While we start with essentially the same Pathfinder data, we use an editing procedure to eliminate data where the energy contained in the initial samples of the altimeter waveform is exceptionally large and noisy. This is caused by irregular ice-sheet topography and the inability of the satellite tracking circuit to properly position the altimeter waveform’s leading edge in the sampling window. After editing, we find that less than 1% of the total Geosat-Seasat crossover dataset lies below 1700 m. We believe that any Geosat-Seasat analysis for elevations < 1700 m cannot produce credible results because of the low quality and limited quantity of these data.

Zwally et al. state that their recalibrated area-weighted averages are three times larger than ours. One can obtain this factor, it appears, only by adopting the larger of their estimates (+6 cm/year), which are based on Geosat-only comparisons and on the inclusion of data from lower elevations. More important, this comparison is inappropriate because our average rates are close to zero. We stated in our report that our estimate may
not be significantly different from a null growth rate when one accounts for both random and systematic error sources in the data. If our estimate had been $10.2$ cm/year, a result wholly consistent with our error estimate, would Zwally et al. then have said that their recalibrated area-weighted averages were 30 times larger?

Excluding the low-elevation (<1700 m) data, Zwally et al. give a Geosat-Seasat result of 3.8 cm/year (no isostatic adjustment). Before isostatic adjustment, the rate we reported for elevations above 2000 m is 2 cm/year. Lacking information on the distribution of data in their elevation bands above 1700 m, and considering the systematic sources of error discussed in our report, we believe that these two results are not significantly different. The Geosat-Geosat results given by Zwally et al. are larger, but are less relevant to climate change because of the short time period of the data. We reported interannual variations in elevation change of $\pm 8$ cm, which could easily influence the short-term Geosat-Geosat results.

In evaluating our new results and those provided by Zwally et al., we remain steadfast in our conclusion that average elevation change from 1978 to 1988 is too small to assess whether the Greenland ice sheet is undergoing a long-term change because of a warmer polar climate. We agree that even longer term (>10-year) measurements of ice-sheet elevation change are needed. With the launch of the U.S. Navy’s Geosat—Follow On mission this year, we should soon have satellite radar altimeter data over the ice sheets spanning two decades. NASA’s ICESat laser altimeter satellite, scheduled for launch in 2001, should provide important new measurements of the lower elevations of the ice sheet where existing radar altimeter data cannot in general provide meaningful elevation-change results. The design lifetime of the ICESat laser altimeter is only 3 years, however, and it is therefore unlikely to produce “longer term” measurements of ice-sheet elevation change, as Zwally et al. state. Moreover, future laser altimeter missions, as yet unplanned, cannot produce long-term elevation change estimates of duration comparable to existing radar altimeter data until the year 2021.

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Editor's Summary

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