tion bias over Greenland is 0.4 ± 0.4 m, which we treat as a correction with a systematic error. In other respects, the Geosat and Seasat altimeters are similar in design, and the same range-correction retracking algorithm was used over ice. We accounted for the ascending-descending orbit bias by analyzing the crossovers of ascending Geosat orbits with Seasat separately from those with descending Geosat orbits, and then averaging the two results. We avoided seasonal biases by comparing the Seasat data for 15 July to 10 October 1978 with Geosat data for the same period of 1985. The resulting Geosat-Seasat average elevation difference for 5906 crossovers is 1.785 ± 0.014 m. After correction for the Geosat-Seasat orbit bias, it is 1.385 ± 0.414 m. The average rate of change over the 7-year interval at these crossover locations is thus 0.20 ± 0.06 m/year. The altimeter measurements (Table I) thus show that the southern Greenland ice sheet has been thickening since the mid-1970s.

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Growth of Greenland Ice Sheet: Interpretation

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An observed 0.23 m/year thickening of the Greenland ice sheet indicates a 25% to 45% excess ice accumulation over the amount required to balance the outward ice flow. The implied global sea-level depletion is 0.2 to 0.4 mm/year, depending on whether the thickening is only recent (5 to 10 years) or longer term (<100 years). If there is a similar imbalance in the northern 60% of the ice-sheet area, the depletion is 0.35 to 0.7 mm/year. Increasing ice thickness suggests that the precipitation is higher than the long-term average; higher precipitation may be a characteristic of warmer climates in polar regions.

The mass balance of the Greenland and Antarctic ice sheets is of current interest, largely because of its direct relation to global sea level, which appears to be rising by 2.4 ± 0.9 mm/year (*1*). Although both thermal expansion of the ocean (*2*) and melting of small glaciers (*3*) contribute to sea-level rise, the major source of water is undetermined. Also, the possibility of enhanced ice-sheet melting in a warmer climate (*4*) is of concern. Glaciers respond to both precipitation and temperature in such a manner, however, that enhanced precipitation may offset increases in surface melting (*5*).

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Each year, approximately 3000 km^3 of water is exchanged between the ocean and the ice sheets of Greenland and Antarctica, a volume equivalent to 8 mm of water from the entire surface of the world's oceans. The uncertainty in ice-sheet mass balance has been at least ±30% of the annual mass exchange (*6*); this uncertainty is equivalent to ±2.4 mm/year of sea-level change. Recently, Meier *et al.* (*7*) estimated that there has been a small positive balance for both Greenland (−0.1 ± 0.4 mm/year of sea-level change) and Antarctica (−0.6 ± 0.6 mm/year). In contrast, recent total flux estimates (*8*) of annual snow accumulation, iceberg discharge, and peripheral melting of the Antarctic ice sheet indicate that the net ice loss has been 750 km^3/year, which is 35% of the mass input and equivalent to 1.9 mm/year of sea-level rise.

Satellite radar altimetry measurements show that the surface elevation of the Greenland ice sheet south of 72°N (Fig. 1) increased from 1978 to 1986 (*9*). The measured elevation change varies with latitude (Fig. 2), and the errors are larger at lower latitudes and lower ice-sheet elevations mainly because of the smaller number of crossovers (*10*). The largest elevation increases were over the southern dome around 63.5°N and in the central region near 72°N during 1985 to 1986.

The spatially averaged elevation changes, obtained by analyzing the crossover differences in ice-sheet elevation bands (Fig. 3) and weighting those values by the fractional area in each band (0.12, 0.14, 0.20, 0.31, and 0.23 for lower to higher elevations), are 0.233 ± 0.041 m/year for 1978–1985 Geosat-Seasat measurements and 0.239 ± 0.030 m/year for 1985–1986 Geosat-Geosat measurements. In southern Greenland, the equilibrium line (boundary between net ablation and net accumulation) is at ~1200 to 1500

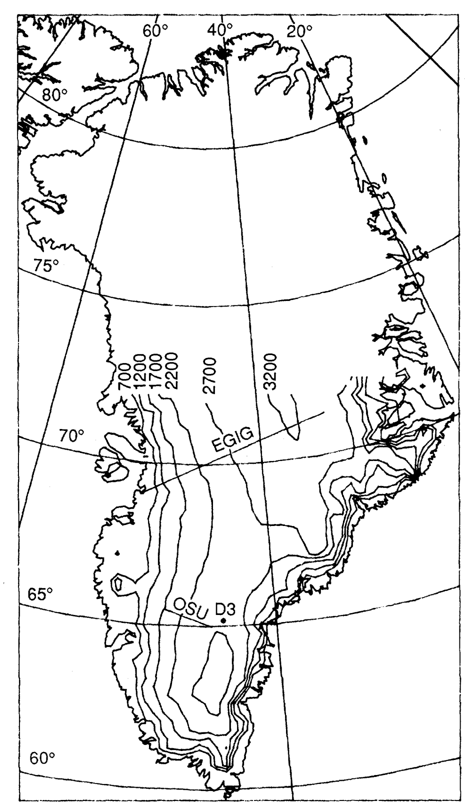

Fig. 1. Map of Greenland showing surface elevations in region covered by satellite radar altimetry and locations of surface measurements (EGIG, D3, and OSU) of elevation change.

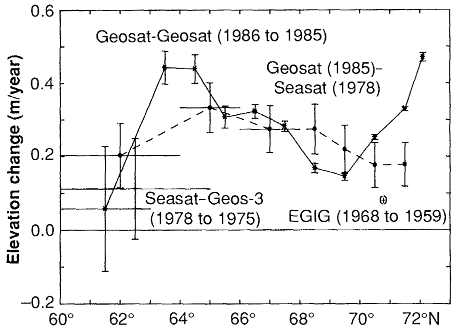

Fig. 2. Average changes in ice-sheet surface elevation in latitude bands. The 1985–1978 Geosat-Seasat values are from the difference between elevations in late summer 1985 and late summer 1978. The 1986–1985 Geosat-Geosat values are from the *dH/dt* method of analysis. The respective 1985–1978 and 1986–1985 average values for all crossovers are 0.20 m/year and 0.28 m/year (*9*). Earlier values are from EGIG traverse near 70.5°N (Fig. 1) and GEOS-3–Seasat analysis.

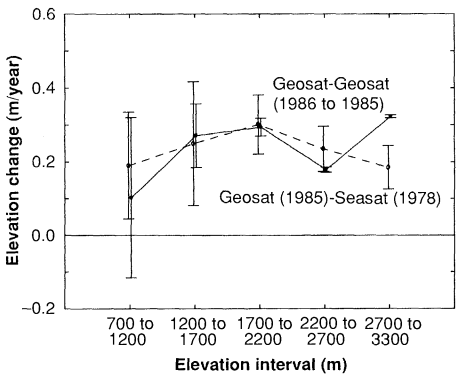

Fig. 3. Average ice-sheet surface elevation changes by elevation bands. Thickening is indicated for both time periods in both the accumulation and ablation zones (above and below ~1200 to 1500 m). Spatially averaged elevation change is 0.23 ± 0.04 m/year.

m. Therefore, thickening is indicated for both time periods in both the accumulation and ablation zones, although the errors are large for the ablation zone.

Repeat long-line leveling on traverses in 1959 and 1968 (EGIG, Fig. 1) (*11*) showed that the ice sheet was thickening by 0.09 m/year at least locally (*12*). Within the ablation zone near the western margin, the ice sheet thinned at ~0.30 m/year between 1948 and 1959 (*13*) and 0.24 m/year between 1959 and 1968 (*12*). Reeh and Gundestrup (*14*) concluded that the ice sheet was thickening at Dye 3 (D3, Fig. 1) by 0.03 ± 0.06 m/year. Kostecka and Whillans (*15*) derived a thickening rate of 0.06 ± 0.08 m/year along a transect (OSU, Fig. 1) west of Dye 3. These results consistently indicate that the accumulation zone was thickening, but the magnitudes are smaller than the spatially averaged altimeter results. In the ablation zone, the results are of opposite sign.

In general, changes in ice-sheet elevation may be caused by variations in surface balance (accumulation minus ablation), firn compression, ice flow, or crustal deformation

$$dH/dt = [A(t) - B(t)]/R_s - V_{cp} - V_i + V_b = dH'/dt + V_b \quad (1)$$

and the (net) mass balance is

$$dM/dt = A(t) - B(t) - V_i R_i \quad (2)$$

where H is surface elevation; dM/dt, A, and B are the mass-change rate, the surface-accumulation rate, and the surface-ablation rate in meters of water equivalent per year; R_s is the (relative) density of snow being added; R_i is the density of solid ice (0.92); V_{cp} is the velocity of firn compression; V_i is the downward subsurface velocity of the firn-ice transition (*16*); H' is ice-sheet thickness; and V_b is the vertical velocity of the ice base due to crustal deformation. If the surface integral of $dM/dt = 0$, over either a local area or the entire area of an ice sheet, the area is in balance.

Whereas changes in precipitation and surface ablation have immediate effects on surface elevation, changes in ice flow in response to changes in ice-sheet boundary conditions have much slower effects (*17*). Therefore, elevation changes measured over a decade could indicate either a recent change in accumulation or long-term changes in ice velocity or accumulation. Reeh and Gundestrup (*14*) suggested that the 0.03 ± 0.06 m/year thickening at Dye 3 may be caused by a slowing of the ice flow because of the downward propagation of stiffer post-Wisconsin ice. In regard to precipitation changes, accumulation time series have been obtained at only a few locations. Ice cores from the central region of the ice sheet near 71°N show that accumulation rates increased about 3.3% per 100 years over the last 300 years (*18*), and a similar change has been observed at Dye 3 (*19*). However, accumulation rates in the central region decreased about 10% from peak values between 1940 and 1985 (*18*), and the rates near Dye 3 decreased about 40% from 1935 to 1970 (*20*), while precipitation at land stations in northern mid-latitudes appeared to increase (*21*). Therefore, the specific cause of ice-sheet thickening cannot be deduced, but it is likely that the present ice velocities have been determined by the long-term (>100 years) surface conditions and that the observed ice thickening indicates that present accumulation rates are larger than the long-term average.

The rate of mass change and implied sea-level depletion can be estimated from the spatially averaged *dH/dt* values. In southern Greenland, the value of V_b due to post-glacial isostatic adjustment is between 0 and 0.009 m/year (*22*). Therefore, the average change in ice-sheet thickness, dH'/dt, is 0.23 ± 0.04 m/year. Changes in the ice velocity and the average V_{cp} over 8 years are likely to be small. The ice-sheet area south of 72°N is 0.70 × 10^6 km^2 (1/517 of global ocean area), and the measured change in volume is therefore 160 km^3/year. A lower end estimate of mass change is obtained for the situation where the elevation change is a short-term (5- to 10-year) increase in precipitation, in which case the average density of the snow being added is about 0.5 R_i. An upper-end estimate is obtained for a change from either a long-term (>100 years) increase in precipitation or a decrease in ice flow, for which the appropriate density is 0.92 R_i. The calculated global sea-level depletion thus ranges from 0.20 to 0.41 mm/year.

The average accumulation rate on the ice sheet south of 72°N is about 0.5 m/year water equivalent (*23*). Therefore, the 0.23 m/year thickness change represents a mass imbalance ranging from about 25 to 45%, depending on whether the change is short or long term. About 60% of the area of the Greenland ice sheet lies north of the radar altimeter coverage, and the average accumulation rate there is roughly half of the southern value. If the northern region has a similar positive mass balance, even though the meteorological and glaciological situation may be quite different, the northern thickening rate would be half of the southern value. In this case, the total sea-level depletion would be 0.35 to 0.7 mm/year.

A 2.4 mm/year sea-level rise (*1*) with contributions of 0.4 mm/year from small glaciers (*3*), 0.4 mm/year from ocean thermal expansion (*2*), and a −0.5 mm/year from Greenland, implies that the contribution to sea-level rise from Antarctica is 2.1 mm/year. The agreement of this value, however, with the 1.9 mm/year estimate for Antarctica based on net mass fluxes, may be fortuitous, in consideration of the large uncertainty in the flux estimates.

The relation between precipitation changes and temperature changes in polar regions is of central importance to understanding current and future behavior of the ice sheets. In polar regions, enhanced precipitation is associated with warmer temperatures because of the greater transport of moisture in warmer air (*24, 25*). Various results (*26*) suggest that the increase in precipitation is 5 to 20% per Kelvin. The effects of enhanced precipitation and warmer temperatures on ice-sheet mass balance differ in the ablation and accumulation zones. Above the equilibrium line, most surface melt water is refrozen and retained locally. Therefore, increased precipitation increases the mass input, and melting has little effect. Below the equilibrium line, increases in precipitation reduce the net summer ablation and partially offset increases in melting. Although the altitude of the equilibrium line increases with increased temperature, it decreases with increased precipitation and with increased cloudiness (*27*). Therefore, changes in position of the equilibrium line might be small as temperature and precipitation increase together. Because nearly 100% of the Antarctic ice sheet and 85% of the Greenland ice sheet are above the present equilibrium line, the dominant short-term effect is likely to be ice-sheet growth. An increase in precipitation and temperature should cause an immediate positive change in the mass balance and a gradual steepening of an ice sheet, which would continue for many years as the ice flow responded to the driving stresses.

In conclusion, Greenland ice-sheet growth is consistent with the generally warmer temperatures (*28*) experienced in this century. If climate continues to warm, enhanced precipitation in polar regions may offset increases in melting. Although the Antarctic ice sheet is a likely source of water for current sea-level rise, its mass balance is uncertain. Over much of Antarctica, which contains 91% of the earth's ice, the annual mass input is only 10% of the Greenland values, so that significant elevation changes may be ten times as small. Laser altimetry measurements (*29*) are needed there, because of its better range precision and ability to cover the critical ablation zones where radar altimeters do not adequately follow the more irregular ice surfaces.

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Thermomolecular Pressure in Surface Melting: Motivation for Frost Heave

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A thermomolecular pressure is associated with surface melting, and it can drive mass flow along an interface under a lateral temperature gradient. The pressure is a universal thermodynamic function in the limit of thick films. It may be responsible for frost heave in frozen ground.

Surface melting continues to attract considerable experimental and theoretical interest, as it involves fundamental questions in surface science and condensed matter physics and practical applications in materials processing (*1–5*). Although the phenomenon has been explored in a limited number of materials, it is believed to be a general characteristic of most classes of solid materials. The motivating force for the effect is the lowering of the interfacial free energy of a solid surface by a layer of the melted material, which occurs for all solid interfaces that are wetted by the melt liquid. Such a reduction of the free energy allows a macroscopically thick film of the liquid to be stabilized at a temperature below the normal melting point. The surface free energy of the film varies with its thickness and asymptotically approaches the value for semi-infinite liquid. This variation

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