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Abstract

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P. A. Shumskii

ON THE CHANGE IN MASS OF THE ICE SHEET IN CENTRAL GREENLAND

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As is known, from the end of the nineteenth to the beginning of the twentieth century there began an epoch of general glacier shrinkage, caused, apparently, by an intensification of zonal circulation (westerly transport) of air masses and a displacement of climatic zones toward the poles ([1]). In most regions of the globe the shrinkage of glaciers continues even now, although in places, from the late 1940s to the early 1950s, a new advance of glaciers began. The glacier shrinkage of the first half of the twentieth century encompassed all latitudinal zones of both hemispheres of the Earth. The only regions for which data on changes in ice mass were completely lacking were the central parts of the continental ice sheets of Antarctica and Greenland.

Thanks to the investigations of the International Glaciological Expedition to Greenland, data have appeared for the first time that make it possible indirectly to determine the rate of change of the mass of ice in the center of the Greenland ice sheet.

The rate of change of the mass m of a vertical column of ice, firn, and snow with unit horizontal cross-sectional area is

$$\frac{\partial m}{\partial t} = \int_{z}^{z} \frac{\partial \rho}{\partial t}\, dz + \rho\, \frac{\partial z}{\partial t} - \rho\, \frac{\partial z}{\partial t} \tag{1}$$

($\rho = \rho(z, t)$ is the density of ice, firn, or snow; t is time; $z = z(t)$, $z = z(t)$ are coordinates along the vertically downward axis oz; the subscripts and indicate that the corresponding characteristics refer to the upper and lower surfaces of the glacier) may otherwise be defined as the algebraic sum of the masses passing per unit time through its external boundaries. To do this, we integrate the continuity equation of a moving continuous medium, $\partial\rho/\partial t + \operatorname{div}\rho V = 0$, with respect to oz, orienting the axis ox in the direction of the horizontal component of the vector V of the velocity of ice motion, and substitute the values of the terms from equation (1) and the two following equations, which determine the conditions at the upper and lower boundaries moving in time:

$$\partial z\,/\partial t = w\ - u\ \operatorname{tg}\alpha - \frac{a}{\rho}, \tag{2}$$

$$\partial z\,/\partial t = w\ - u\ \operatorname{tg}\beta + \frac{a}{\rho} \tag{3}$$

(u, v, w are the components of the velocity vector along the coordinate axes, a is the rate of mass passage through a unit area of the horizontal projection of the upper and lower surfaces of the glacier; α and β are the angles of inclination of the upper and lower surfaces to the ox axis). We obtain

$$\frac{\partial m}{\partial t} = a\ + a\ - \int_{z}^{z} \rho\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) dz - \int_{z}^{z} u\frac{\partial \rho}{\partial x}\,dz + \rho\,u\ \operatorname{tg}\alpha - \rho\,u\ \operatorname{tg}\beta. \tag{4}$$

At the ice divide of the ice sheet $u(z) = 0$ ([2]), and in order to determine the rate of mass change it is sufficient to know the accumulation rate and total melting, the thickness, density, and total rate of extension along two horizontal axes coinciding with the principal axes of the strain-rate tensor.

Most of the data on central Greenland had been known previously; only information on the extension rate of the ice sheet was lacking. In the period between May 1959 and August 1960 the International Glaciological Expedition to Greenland carried out repeated measurements of distances between stakes installed at the corners and at the center of squares with diagonals about 1 km long at four stations along a latitudinal profile across Greenland. On the basis of these measurements P. Gfeller calculated the extension rate of the ice-sheet surface in the west-east (ox) and north-south (oy) directions. For the Central and Jarl-Joset stations, situated approximately at 71° N, 130 km west and 140 km east of the ice divide, the results given in Table 1 were obtained.

Table 1

Station	Surface extension rate 10^{-5} yr^{-1}	Surface extension rate 10^{-5} yr^{-1}	Surface extension rate 10^{-5} yr^{-1}
Station	$\partial u_{\mathrm{p}}/\partial x$	$\partial v_{\mathrm{p}}/\partial y$	$\partial u_{\mathrm{p}}/\partial x + \partial v_{\mathrm{p}}/\partial y$
Central	25 ± 14	24 ± 12	49 ± 26
Jarl-Joset	29 ± 12	16 ± 12	45 ± 24

In view of the small difference in the total extension rate between the two stations, for the ice divide of the ice sheet in this region one may, with a sufficient degree of probability, adopt the value
$\partial u_{\mathrm{p}}/\partial x + \partial v_{\mathrm{p}}/\partial y = (4.7 \pm 2.5) \cdot 10^{-4}$ yr^{-1}. Because the axes ox and oy do not coincide with the principal axes of the strain-rate tensor, some reduction of the total rate of surface extension is possible.

The change in the rate of horizontal extension in the vertical section of the glacier is unknown. Taking into account the low temperature of the upper layers, its gradual increase with depth, and the probability of melting at the bed, there is no basis for assuming a significant decrease in extension rate with depth. But even if differences in resistance to deformation due to temperature changes are neglected and a linear increase in tensile stress is assumed from zero at the bed to a maximum at the ice surface—which is unlikely—then even in this case the mean horizontal extension rate over the profile will exceed one half of the surface rate. Consequently, the true value of the mean horizontal extension rate at the ice divide lies between one half of the surface rate and its full value: $(2.35\text{–}4.7) \cdot 10^{-4}$ yr^{-1}, probably closer to the upper limit.

The mean density of the ice sheet at the point of interest may be taken as 0.90 ± 0.01 g $\cdot$ cm^{-3} ([2]), the thickness as 3040 ± 100 m ([3]), and the sum of the accumulation rates a_T and basal melting a_n as $22 + 2$ g $\cdot$ cm$^{-2} \cdot$ yr^{-1} ([4]) (taking into account that $0 \geq a_\mathrm{n} \geq 0.5$ g $\cdot$ cm$^{-2} \cdot$ yr^{-1} ([2])).

Substituting the above data into equation (4), we obtain

$$-50 \pm 43 \geq \partial m/\partial t \geq -122 \pm 84 \text{ g} \cdot \text{cm}^{-2} \cdot \text{yr}^{-1}.$$

Thus, in the center of the Greenland ice sheet a decrease in mass is undoubtedly taking place; its most probable rate is about 0.1 kg $\cdot$ cm$^{-2} \cdot$ yr^{-1}.

In the coastal regions of Greenland in the twentieth century glacier shrinkage also predominated, but it is difficult to estimate its mean rate. Only for the glaciers of the southwestern coast of Greenland does A. Weidick ([5]) give a value for the mean thinning since the time of the last maximum (1800-1850) of about 100 m, which, taking into account the considerable acceleration in the twentieth century, apparently corresponds to the present rate of loss

mass in the amount of 0.10—0.15 kg $\cdot$ cm$^{-2} \cdot$ yr^{-1}. On the other hand, it is known that the glaciers of northeastern Greenland have been retreating extremely slowly ([6]).

For a reliable estimate of the overall rate of change in the mass of the Greenland ice sheet, these data are, of course, insufficient. There is no doubt, however, that a decrease in mass is taking place and probably at a rate considerably greater than was previously supposed. Thus, if the mean specific rate of mass loss is taken to be only 50 cm$^{-2} \cdot$ yr^{-1}, then the total rate will be $9 \cdot 10^{17}$ g $\cdot$ yr^{-1} (900 km^3 of water per year).

The additional runoff of such a quantity of water should raise the level of the World Ocean by 2.5 mm per year, and, owing to the reduction of glaciers in other regions, the overall rate of rise of ocean level should be still greater. In fact, the rise in ocean level is proceeding at a rate of 2.4 mm per year ([7]). But the change in glacier mass is not the only possible cause of fluctuations in ocean level, and the influence of other causes, in particular subsidence of the ocean floor, cannot yet be assessed with sufficient reliability. Therefore, the rate of change in ocean level can hardly serve as a check on the result obtained.

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Note: Figure translations are in progress. See original paper for figures.