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The dependence of antarctic accumulation rates on surface temperature and elevation

By ISABELLE MUSZYNSKI, *Department of Geological Sciences, Northwestern University, Locy Hall, Evanston, Illinois 60201, USA* and G. E. BIRCHFIELD, *Department of Geological Sciences and Department of Engineering Sciences and Applied Mathematics, Northwestern University, Evanston, Illinois 60201, USA*

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ABSTRACT

A study of antarctic accumulaton, surface temperature and elevation data reveals a strong correlation between the accumulation rate and the surface temperature which, in turn, is almost uniquely determined by the elevation of the ice sheet surface. The latitudinal temperature gradient seems to play a relatively minor rôle. The dependence of the accumulation rate on surface temperature and elevation is, to a very good approximation, linear. Based on our own and Robin's results, we propose two parameterizations of the accumulation rate for use in simple one-dimensional paleoclimatic models.

1. Introduction

The world's ice sheets are an integral component of the global climate system and the physics of their growth and decay may well play a critical rôle in transforming small insolation fluctuations into long-term climatic changes (see for example Birchfield et al., 1981; Denton and Hughes, 1983; Hays et al., 1976; Weertman, 1976). The most obvious climatic effect of ice sheets resides in their influence on the earth's heat budget through changes in the planetary albedo. When an ice sheet expands, it replaces a relatively low-albedo ground cover by a very high-albedo snow or ice cover. The amount of incoming solar radiation reflected back to space and thus lost to the earth is thereby increased so that the global heat budget decreases; the opposite happens when an ice sheet shrinks. Whether an ice sheet will advance or retreat depends on the net sum of precipitation, ablation and mass flux into the sea at its marine edges. Another important coupling between the ice sheets and the global climate energetics is through the small but essential latent heat fluxes expended in their growth and decay (Saltzman, 1978). A less obvious but potentially important interaction involves bedrock response to the varying ice load, the accumulation rate of snow at the surface of the ice sheet and the elevation of the ice sheet; these interact in a non-linear feedback process which may be important in producing the striking 100,000 year periodicity seen in proxy ice volume records for the late Pleistocene period (Birchfield et al., 1981; Oerlemans, 1982; Peltier and Hyde, 1984; Pollard, 1984). The speed and amplitude of the deglaciations may be influenced by the amount of meltwater present at the bottom of the ice sheet, by calving at the southern edge of the ice sheet due to the formation of proglacial lakes or to marine incursions whenever the snout drops below sea-level (Oerlemans and van der Veen, 1984; Pollard, 1984). The very simple paleoclimatic models used to explore the rôle of these mechanisms in the late Pleistocene glaciations are characterized by the absence of a closed hydrologic cycle and therefore by the use of highly parameterized mass balance prediction schemes. The present brief study was motivated by the very great sensitivity of the simple ice sheet models of Birchfield et al. (1981) and Peltier (1982) to the parameterized dependence of the accumulation rate on elevation, and should be regarded as no more than a first attempt at simplifying the complex physics involved. We report the results of a study of antarctic accumulation rates, surface temperatures and elevations which show that the accumulation rate correlates extremely well with the surface temperature which, in turn, is almost uniquely determined by the surface elevation. To a very good approximation, the dependence of the accumulation on the surface temperature and elevation is linear and we accordingly suggest two simple parameterizations for use in one-dimensional ice sheet models.

2. Data and method

We used two different data sets, one for investigating the possibility that the distance inland from the coast and the elevation have distinct effects on the accumulation, and one for studying the correlation between the accumulation and the surface temperature and elevation. The first set consists of 156 data points generated by superposing Budd et al.'s (1971) maps of surface elevation of the antarctic ice sheet and of accumulation rates over the ice sheet. The inland distance of each data point was obtained by measuring the shortest distance from the sample point to a smoothed coastal outline of the antarctic continent. The data set covers a range of accumulation rates, A, from 5 to 60 cm yr^{-1}, elevations, h, from 0 to 3500 m and distances, x, from 0 to 1730 km. The ice shelves were treated as land since they prevent the ocean beneath them from acting as a moisture source; the antarctic peninsula, on the other hand, was excluded from our idealized continental outline.

The second, 208 point data set was obtained from Budd et al.'s (1971) maps of antarctic accumulation rates, surface temperatures and elevations. The accumulation ranges from 3 to 60 cm yr^{-1}, the surface temperature, T, from -20 to -57.5 °C and the elevation from 500 to 3000 m. Sample density in both data sets is greatest in the coastal regions, reflecting the steepness of both elevation and accumulation gradients near the coast.

We calculated 1st, 2nd and 4th degree regression polynomials for the data pairs (x,A), (h,A) and (h,x) using the first data set, and (h,A), (T,A) and (h,T) using the second data set. In no case was the difference in standard deviation, σ, between the 2nd and 4th degree polynomials greater than 4%, so that in the following we will refer to the linear and quadratic regressions only.

3. Results

The surface temperature correlates very well with the elevation, the correlation coefficient, ρ, being equal to -0.86 and σ to 5.3 °C for the quadratic regression and 5.6 °C for the linear regression. The slope of the straight line is

$$T_{\mathrm{h}} = -1.40 \times 10^{-2}\ \mathrm{°C\ m^{-1}}. \tag{1}$$

The correlation between the accumulation rate and the surface temperature is also quite good: $\rho = 0.74$, $\sigma = 7.31$ cm yr^{-1} for the quadratic and 7.39 cm yr^{-1} for the linear regression. The slope of the straight line is

$$A_{\mathrm{T}} = 0.752\ \mathrm{cm\ yr^{-1}\ °C^{-1}}. \tag{2}$$

The correlation coefficient between the accumulation and the elevation is $\rho = -0.66$. For the quadratic regression, $\sigma = 8.24$ cm yr^{-1}; for the linear regression, $\sigma = 8.30$ cm yr^{-1} and the slope is

$$A_{\mathrm{h}} = -8.06 \times 10^{-3}\ \mathrm{cm\ yr^{-1}\ m^{-1}}. \tag{3}$$

To check the hypothesis that distance inland from the coast may have an effect on the accumulation which is distinct from the general decrease of A with h, we converted our (x,A) polynomial into an (h,A) polynomial by means of the (h,x) regression and compared this with the original (h,A) polynomial. The difference in accumulation rate was always well below the 9.9 cm yr^{-1} standard deviation of the original (h,A) regression.

4. Discussion

The large radiative heat losses from the surface of the antarctic ice sheet result in a surface temperature inversion layer which is permanent over most of the continent except for certain coastal areas during the short summer. From data in Schwerdtfeger (1970), the mean annual latitudinal temperature gradient over the ice sheet is of the order of $-0.25\,°C$ degree^{-1} at 500 mb while at the surface it varies from $-5.5\,°C$ degree^{-1} near the coast to $-0.5\,°C$ degree^{-1} over the antarctic plateau. The temperature inversion thus increases in strength from the coast to the continental interior, the shape and spacing of the isopleths of inversion strength being very similar to the surface isotherms (Phillpot and Zillman, 1970). The mean atmospheric circulation over antarctica consists of advection into the interior of relatively warm and moist marine air in the mid-troposphere, the cooling of this air adiabatically by topographic uplift over the ice sheet and diabatically by radiation and conduction, the subsequent slow dynamic subsidence through the lower troposphere and inversion layer and outflow at the surface (Carroll, 1984; Lysakov, 1978; Schwerdtfeger, 1970). Field studies indicate that the major part of the ice crystals received at the surface of the east antarctic plateau form in the lower troposphere, at heights of 1000–3000 m above ground (Ohtake and Yogi, 1979).

Robin (1977) compared measurements of the surface and free atmosphere temperatures at selected antarctic stations with the net accumulation and found that the variation of the accumulation rate with the free atmosphere temperature shows a trend which parallels the Clausius–Clapeyron curve for the saturation vapor pressure over ice which, over the temperature range of interest, is very nearly linear. These results thus seem to indicate that, even though the slowly subsiding air masses gain heat by adiabatic compression, the gains are more than offset by large radiative heat losses due to the presence of the surface inversion layer. Robin also found a very strong linear correlation between the accumulation and the surface temperature and related it to the increasing strength of the temperature inversion towards the center of the ice sheet.

The very strong correlation we found between the accumulation rate and the surface temperature thus confirms Robin's results. While the temperature at the 500 mb level is predominantly a function of latitude, the surface temperature also depends strongly on elevation. As shown by the meridional temperature gradient at 500 mb, the latitudinal contribution to the surface temperature is small so that the elevation effect dominates at the surface. This then explains the good correlation we find between accumulation and elevation and the impossibility of distinguishing a distance effect on the basis of our fairly scattered data set.

Both our own and Robin's results indicate that the mass balance of antarctica can adequately be represented by a linear function of either the free atmosphere temperature, the surface temperature or the surface elevation of the ice sheet. Before discussing the modelling applications of these parameterizations, we would like to briefly consider the possibility of generalizing the relations we found to other ice sheets. Antarctica differs from present-day and past northern hemisphere ice sheets by its more-or-less symmetrical location around the south pole and the pronounced parallelism between the isolines of the mean pressure field, the mean vortex field and the surface elevation. As a consequence of its high-latitude position, antarctica has no ablation zone. Northern hemisphere ice sheets, of which Greenland is the largest representative today, are not only much more irregular in shape but are situated at lower latitudes, have ablation zones at their southern edges (Barry and Kiladis, 1982; Denton and Hughes, 1983) and are fed by storm tracks which as a rule cross the topographical contour lines (Keen, 1982; Lamb and Woodroffe, 1970; Putnins, 1970). A single meridional cross section through one of these ice sheets may thus not be very representative of the entire ice sheet.

The simple paleoclimatic models we are concerned with in this paper are one-dimensional, so that there is no choice but to represent ice sheets by a north–south section and assume longitudinal symmetry. These models are of two types. The first class consists of models which include an atmospheric component (Birchfield et al., 1982; Pollard, 1983; Suarez and Held, 1979) and we propose a mass balance parameterization in which the accumulation depends linearly on a representative lower tropospheric temperature, with a slope related to the appropriate Clausius–Clapeyron curve. Such a parameterization would obviate the need for fixed latitude dependent accumulation rates normalized by present day mean zonal rates of snowfall. The second type of models do not have an atmosphere and essentially only predict surface elevations of the ice sheet. In these cases, we suggest to parameterize the accumulation rate as a linear function of the surface elevation and the latitude. The slope of the snow line will then determine the relative importance of the latitudinal gradient effect versus the elevation effect. For a polar ice cap such as antarctica, we have seen that the latitudinal effect is secondary to the elevation effect; for a typical northern hemisphere ice sheet, on the other hand, the latitudinal effect plays a crucial rôle in establishing the accumulation pattern over the northern half of the ice sheet: decreasing accumulation all the way to the polar ocean for a large latitudinal accumulation gradient, zone of increasing accumulation and possibly even ablation for a small enough latitudinal effect. The schemes used by Oerlemans (1982) and Pollard (1984) essentially incorporate these ideas. We wish to stress that the nature of our data does not enable us to draw any inferences as regards parameterization of ablation (see for example Oerlemans and van der Veen, 1984).

For the antarctic ice sheet, characterized by a strong temperature inversion and a small latitudinal temperature gradient, the slope of the (A,h) line is given by (3). In general, the weaker the inversion, the more negative this slope will be. A limiting value can be obtained from the Clausius–Clapeyron curve by assuming lapse conditions in the lower atmosphere.

5. Conclusions

We have considered the rôle of the surface temperature, the elevation and the distance inland from the coast in shaping the accumulation pattern over antarctica. Even though the free atmosphere temperature is the physically important parameter (Robin, 1977; Robin and Johnsen 1983), the accumulation correlates very well with the surface temperature which, in turn, depends almost exclusively on the elevation. The surface temperature is a function of both the elevation and the latitude. On the basis of our data, it is not possible to decide whether distance from the moisture source has an effect which is distinct from the decrease in precipitation due to the increase in latitude. We propose two parameterizations of accumulation for use in simple one-dimensional paleoclimatic models without closed hydrologic cycle. In the first, the accumulation rate is a linear function of some representative lower-troposphere temperature, with a slope related to the Clausius–Clapeyron curve for ice or water, while in the second, it depends linearly on the surface elevation and the latitude. While our results show the latitudinal contribution to be relatively minor for antarctica, which has no ablation zone, it may be more important in the northern hemisphere where the snow line may intersect the surface of the ice sheet.

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