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COMPUTER MODELLING OF TEMPERATURE DISTRIBUTIONS IN POLAR ICE SHEETS

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Abstract. It is now practicable to construct complete three-dimensional primitive-equation models of ice flow in which all the input may be time dependent. The input consists of bedrock and ocean distribution, accumulation net balance, ice-surface elevation–temperature relation, and the thermal and flow parameters of the ice. The main limitations on this type of model is the extensive demand of computation time. Thus simplified two-dimensional models have been developed for detailed flow-line studies, and single-column models have been used extensively for analysing the few deep bore-hole temperature profiles.

The main feature of the measured temperature profiles reflect the current steady-state regime at each location. Deviations from the steady state are caused by time variations of any of the variables such as surface temperature, accumulation rate, ice thickness, velocity, etc.

Measurements of stable-isotope ratios in the ice cores provide an indication of past temperatures which has been confirmed by the analysis of the temperature profiles. However the temperature changes could be either due to surface elevation changes or climate changes. Gas volumes in the core show promise of providing an indication of past elevations. Annual variations of the isotopes give indications of past accumulation rates. The determination of past velocities, however, requires velocity–temperature coupled models with more precise flow-law information.

Three-dimensional models are necessary to study past variations of the flow-line pattern. Finally the sliding and surging models recently developed need to be incorporated into the cold ice-sheet models.

DISCUSSION

J. F. Nye: When computing non-steady distributions, what do you do about specifying initial conditions?

W. F. Budd: For the non-steady-state situation one can start from steady state and then apply changes to the input. Alternatively, the ice masses can be grown from zero thickness.

Nye: How do you deal with the necessary boundary condition for stress, etc., at the up-stream end of the field?

Budd: We have not worried about the tension at a divide which in non-steady state is unknown. However, our grid points are widely spaced to avoid the effects of longitudinal stresses and so the first point away from the divide is no longer affected by the unknown boundary stress.

L. Lliboutry: I wonder whether you have not forgotten some equation, since the rate of change of the surface altitude ought not to have to be put into the calculation. It should be found as an output if all the appropriate boundary conditions and equations are used.

Budd: If all the data described for the input were available, then the model would be over-prescribed as you suggest. However, we do not know the data well and have to guess or try various possible outcomes. For example, if the flow law were prescribed the velocity could be calculated. Alternatively, if a velocity profile is prescribed a flow-law parameter could be calculated. Similarly, if the accumulation is prescribed the balance (or rate of change) could be calculated or vice versa.

Lliboutry: Duval's experiments have shown that the normal ice fabric in moving ice (4 or 5 maxima forming a girdle around the compressive axis), although it allows only a quarter of the strain-rate compared with the simple-shear situation, is a very stable one. Nevertheless, in the time scale valid for ice sheets there may be a slow change in the fabric from the first to the second one. In this case the ice flow law should change with time. (A more perfect ice lattice would also lead to this result.)

Budd: From laboratory studies it seems that the girdle with 4 or 5 maxima can be caused by random sample clustering (Budd, 1972). We now have a reasonable picture of the crystal fabric distribution on the Law Dome flow line which seems to be consistent with the stress situation. If steady-state applied then the spatial distribution of fabrics through the ice sheet would be appropriate for calculating the flow. For changing ice sheets I agree that the development and change of the crystal fabrics should be considered.

G. de Q. Robin: Your paper "Derived physical characteristics" may be described as determining physical characteristics (temperature, deformation, etc.) of internal layers from given boundary conditions. Your excellent curve-fitting techniques may be described, however, as determining boundary conditions from internal physical characteristics. Would you agree that the top 800 m of "Byrd" core and temperature profile are little affected, if at all, by basal and near-basal temperature gradients, and hence provide the best test to date of the agreement of isotopically derived temperatures with a measured temperature–depth profile?

Budd: Yes, for the "Byrd" profile the indications are that the temperature variations assumed from the isotope profile give rise to the measured temperature profile provided the other parameters assumed, such as the accumulation rates and horizontal velocity, have remained at their current values. However, it needs to be noted that the temperature change could be either due to elevation, or climate change, or some as yet unknown combination of both. The effect of an ice-sheet surge in the region should also not be overlooked.

M. W. Mahaffy: In the graph showing the relation between surface and bed undulations along a cross-section, what was the relative size of the noise amplitude to the undulations?

Budd: The errors in the surface elevation were about ± 1 m relative and in the ice thickness about $\pm 1\%$, i.e. about 20 m. In both cases these errors were more than an order of magnitude below the amplitude of the undulations.

REFERENCE

Budd, W. F. 1972. The development of crystal orientation fabrics in moving ice. *Zeitschrift für Gletscherkunde und Glazialgeologie*, Bd. 8, Ht. 1–2, p. 65–105.