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THE SHIRASE FLOW-LINE MODEL: AN ADDITIONAL TOOL FOR INTERPRETING THE DOME-FUJI SIGNAL

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Abstract: Understanding both present and past ice dynamical behavior of the Shirase Glacier Basin (Antarctica) is an important factor for interpreting results of deep ice-core drilling at Dome Fuji Station. This paper compares preliminary flow-line model experiments with tentative ice core dating and investigates the role of ice dynamics on the age-depth profile at the ice divide. Preliminary simulations demonstrated that the model is capable of reproducing realistic age-depth profiles at the ice divide, despite its coarse resolution. Sensitivity experiments showed that a proper determination of the present surface mass balance is a key factor in determining the age-depth relationship and that it is necessary to take into account past changes in accumulation rates. Finally, changes in the dynamic behavior of the coastal ice stream (Shirase Glacier), such as enhanced flow, hardly influence the age-depth profile at the ice divide.

1. Introduction

In a previous paper PATTYN and DECLEIR (1995) presented a detailed modeling experiment of the Shirase Drainage Basin, Dronning Maud Land, Antarctica (Fig. 1), primarily focusing on the dynamics of the large continental ice stream Shirase Glacier. It was found that the rapid ice surface thinning as observed in the field (NARUSE, 1979; NISHIO *et al.*, 1989) could not be explained as a response of the ice sheet to the climatic signal alone. Another mechanism should account for this. In a subsequent paper (PATTYN, 1996) a possible scenario was put forward based on a rapid cyclic variation of the ice sheet surface due to an interaction between ice sheet thermo-mechanics and basal motion. However, we lack at present sufficient field observations regarding the ice dynamics of Shirase Glacier in order to make definite conclusions whether such a mechanism could apply.

Contrary to the lower part of the drainage basin, the upper part and the ice dome area is well covered by field observations. First, there is the deep drilling at Dome Fuji Station, which reached a depth up to 2500 m below the ice surface. Second, there is an excellent field survey of ice thickness measurements from this ice dome to the coast, which will in the future be extended by radar sounding of internal layering along the central flow line towards Shirase Glacier (K. MATSUOKA, personal communication). Ice modeling might be a useful tool for dating ice cores (REEH, 1989); the fact that the ice core is drilled on a divide (and thus less disturbed by ice flow compared to the Vostok ice cores) implies that better dating accuracy might be obtained

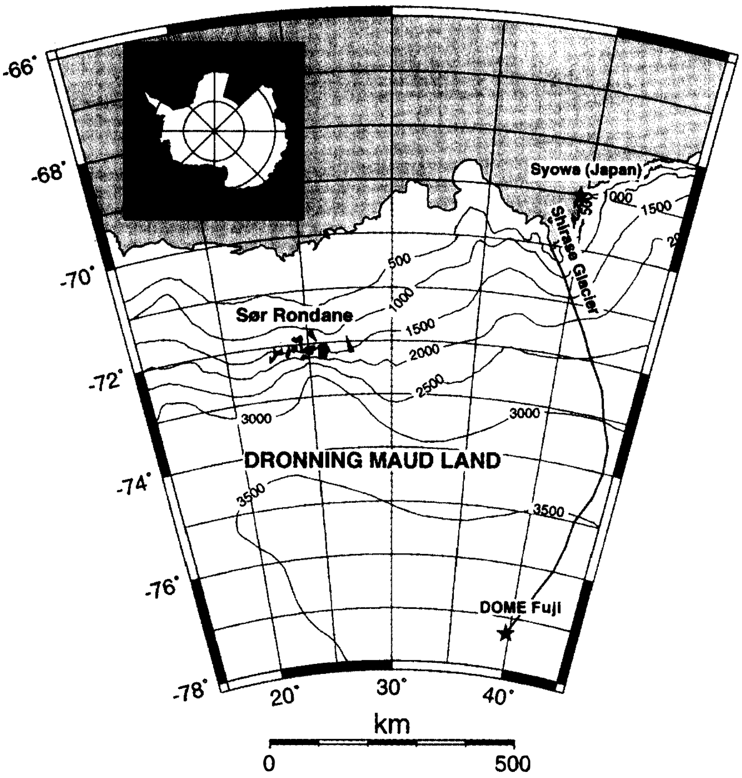

Fig. 1. Situation map of Dronning Maud Land displaying the Shirase flow-line from Dome Fuji Station to Shirase Glacier.

with experimental ice dating techniques. Flow modeling might thus offer additional information on age-depth profiles, or—concordant with radar sounding—information on the ice dynamics of the whole drainage basin.

The present paper is a first survey on how this information can be extracted and demonstrates the capabilities of the model by analyzing the sensitivity of changes in boundary conditions and ice flow parameters on the age-depth relationship in the Shirase Drainage Basin, with emphasis on the dome region.

2. Model Description

The physics and numerics of the Shirase flow line model are described in detail in PATTYN (1996). Basically, the model calculates the evolution of ice thickness along a flow line. The calculation of the velocity field is based on the full stress equilibrium (no *shallow ice approximation*), and is fully coupled to the two-dimensional temperature field through an Arrhenius relationship. Furthermore, bedrock heat conduction and isostatic adjustment are included and a freely floating ice tongue is coupled at the seaward end of the ice sheet. Basal sliding enters as a lower boundary condition and is based on subglacial water production and pressure.

A new model item is the age calculation, written as an advection equation with a small diffusion term added in order to stabilize the numerical solution (HUYBRECHTS, 1994; GREVE, 1997):

$$\frac{\partial A}{\partial t} = -u\frac{\partial A}{\partial x} - w\frac{\partial A}{\partial z} + D_{\text{art}}\frac{\partial^2 A}{\partial z^2}, \tag{1}$$

where A is the ice age (a), u and w the horizontal and vertical velocity respectively (m a^{-1}), and D_{art} a constant diffusion term (2.0 10^{-2} m^2 a^{-1}). Boundary conditions to this equation are

$$A(t) = t, \qquad \text{at the surface} \tag{2}$$

$$\frac{\partial A}{\partial t} = S\frac{\partial A}{\partial z} - u_b\frac{\partial A}{\partial x}, \qquad \text{at the bottom} \tag{3}$$

where S is the basal melting rate (m a^{-1}), taken positive when melting occurs, and u_b the basal velocity (m a^{-1}).

The model is numerically solved on a flow line fixed in space, the domain of which extends from the ice divide to the edge of the continental shelf with a horizontal spacing of 40 km and a vertical resolution of 21 layers (Figs. 1 and 2). The flow line geometry (ice thickness, bedrock elevation, flow band width), surface mass balance and temperature is taken from PATTYN and DECLEIR (1995). All experiments described below are conducted as a twofold process. First, a steady state ice sheet is developed under boundary conditions prescribed by the specific experiment, and an environmental forcing of a 5 K background temperature drop and a 50 m lower sea level compared to the present environmental conditions. These values are regarded as mean conditions for the last 200000 years. Such a steady state ice sheet was taken as initialization at 1000 ka BP. Second, forcing was applied with Vostok temperature changes for the last 200 ka (JOUZEL *et al.*, 1993), used as background temperature forcing, and Specmap sea-level changes for the same period. Between 1000 and 200 ka BP a forcing function was applied based on those two records in order to have a continuous cyclic variation of background temperature forcing and global sea-level changes. Following LORIUS *et al.* (1985) the accumulation rate in the past was calcu-

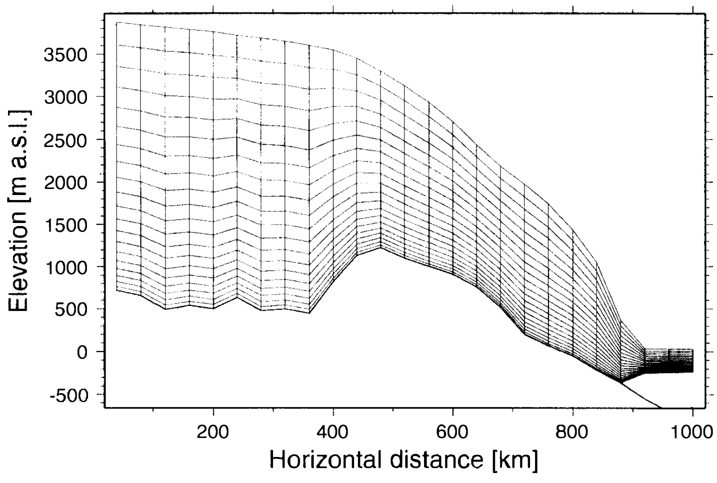

Fig. 2. Model domain on a 40 km grid with 21 layers in the vertical.

lated from its present value, related to the temperature above the inversion layer.

3. Results

The standard experiment is based on a present surface mass balance at Dome Fuji Station of 0.033 m a^{-1} water equivalent, basal melting included, without bedrock heat conduction, and a geothermal heat flux of 54 mWm^{-2} as a lower boundary condition to the temperature field. Figure 3 displays the age-depth profile at Dome Fuji Station of the standard experiment after 1000 ka of integration according to the forcing in background temperature, surface mass balance and sea-level changes as described in the previous section. Besides the standard experiment, some sensitivity experiments were carried out also: (i) with a reduced surface mass balance in the ice dome area (0.02 m a^{-1} water equivalent at the divide itself); (ii) without taking into account mass balance variations over the last million years, *i.e.* a constant surface mass balance, corresponding to a background temperature drop of 5 K, throughout the whole period of integration; (iii) excluding basal melting along the whole flow line; (iv) including heat conduction in the underlying bedrock; and (v) increased basal sliding in the Shirase Glacier stream area in order to detect the influence of enhanced sliding on the age-depth profile at the ice divide. All sensitivity experiments are compared to the standard model run and their resulting age-depth profiles also displayed in Fig. 3.

Although the present model setup is too coarse to draw any conclusions on the absolute age-depth curve at Dome Fuji Station, the standard experiment is more or less in agreement with preliminary estimates of the ice core age, *i.e.* 100 ka at a depth of 1500 m below the present ice surface and 240 ka at a depth of 2200 m (Y. Fujii,

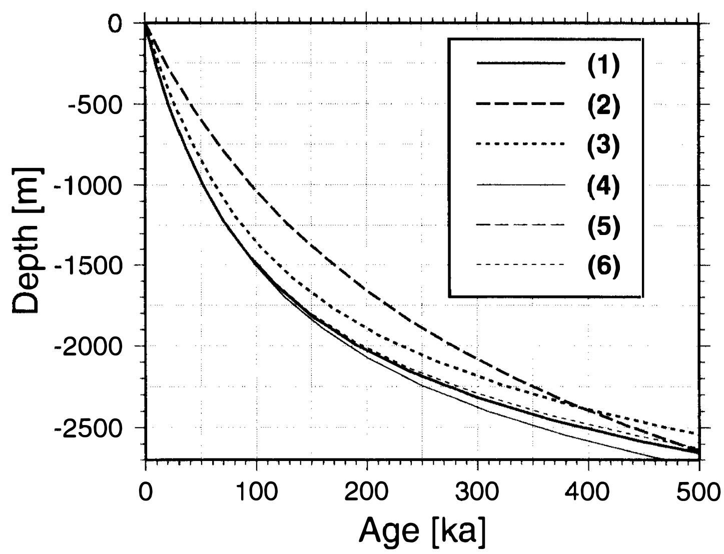

Fig. 3. Age-depth profiles for the different sensitivity experiments at Dome Fuji Station after 1000 ka of integration in time. (1) standard model run; (2) reduced surface mass balance; (3) constant surface mass balance in time; (4) without basal melting; (5) with bedrock heat conduction; (6) increased basal sliding. Curves 1 and 5 overlap.

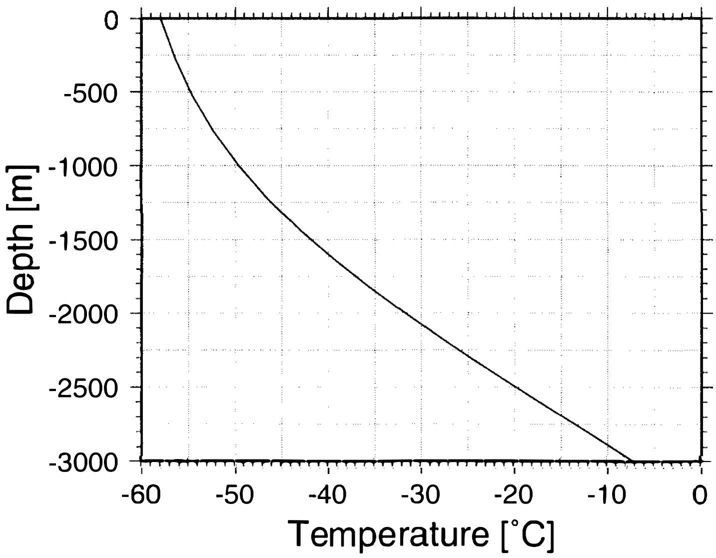

Fig. 4. Vertical temperature profile at Dome Fuji Station according to the standard experiment.

personal communication). This would imply that the present ice core bottom (at 2500 m) reaches an age of 380 ka BP according to this tentative experiment. Furthermore, the standard experiment seems to be in good agreement with the present observed ice thickness distribution along the flow line and records after 1000 ka integration in time a surface elevation at Dome Fuji Station of 3877 m a.s.l. compared to the observed value of 3810 m a.s.l. (a difference of 2% in ice thickness). According to the reference experiment, basal temperatures at the ice divide seem to be of the order of −5°C, hence close to the pressure melting point (Fig. 4).

According to Fig. 3, including heat conduction in the underlying bedrock and enhanced basal sliding in the stream area do not influence the age-depth profile at the ice divide (curve 5 and 6). Introducing enhanced basal sliding largely influences the dynamic behavior of the ice sheet in the coastal area, giving rise to a cyclic event of thinning/thickening of Shirase Glacier (PATTYN, 1996). However, this behavior seems restricted to the coastal area and hardly influences the dynamics of the central part of the ice sheet (ice divide).

Excluding basal melting also hardly influences the profile, except near the lower ice layers, as is to be expected (Fig. 3, curve 4). However, surface mass balance seems to be a decisive factor in determining the age-depth relationship, leading to differences up to 40 ka at a depth of 2000 m below the ice surface when the surface mass balance is kept constant in time, and even a difference of 70 ka at the same depth for the low mass balance scenario, both compared to the standard experiment (Fig. 3, curves 2 and 3).

The results of the standard experiment were furthermore compared to the constant vertical strain rate model of NYE (1963) and HAEFELI (1963), and known as the Nye time scale:

$$A(z)=\frac{H}{M_S}\ln\frac{H}{z}, \tag{4}$$

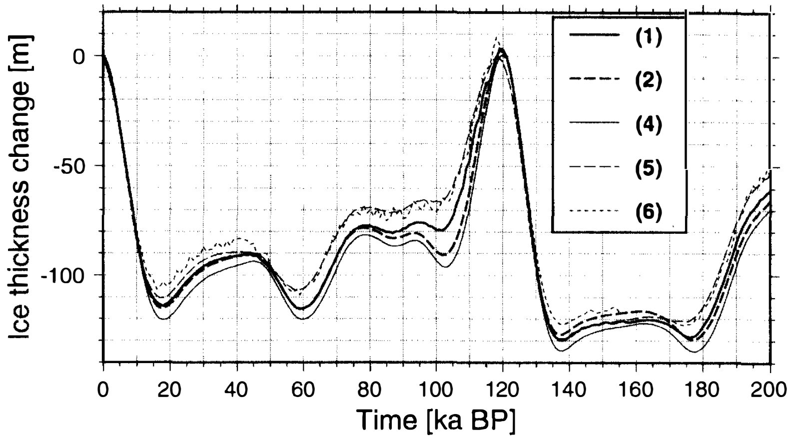

Fig. 5. Ice thickness changes for the different sensitivity experiments at Dome Fuji Station for the last 200 ka of integration in time. (1) standard model run; (2) reduced surface mass balance; (4) without basal melting; (5) with bedrock heat conduction; (6) increased basal sliding.

where $A(z)$ is the age (a BP) at a height z above the bedrock, H the ice thickness [m] and M_s the mean surface accumulation rate (m a^{-1}). Results demonstrated that with the Nye model it is not possible to produce realistic age-depth profiles that are in accord with the tentative dating and that the Nye time scale can hardly be applied to a period longer than 10 ka. Both the ice dynamics and the ice sheet climatic history seem important parameters to be considered in determining the ice sheet age, as was previously concluded by REEH (1989).

Finally, all sensitivity experiments seem in accord regarding ice sheet surface variations at the ice divide during the last 200 ka (Fig. 5). The ice surface is at present still rising and was roughly 100–120 m lower during the last glacial period. Including bedrock heating dampens the amplitude of the response of the ice sheet to the climatic signal somehow. Also these figures should be interpreted with the necessary care since they depend strongly on the accumulation regime in the whole area and not solely at the ice divide.

4. Discussion and Conclusions

The results of the model sensitivity experiments seem promising so far. The model is capable of reproducing realistic age-depth profiles at the ice divide, despite its coarse resolution. Furthermore, the sensitivity study demonstrated that the influence on the age-depth profile near the ice dome of both basal melting and the dynamics of the Shirase Glacier stream area, are negligible. On the contrary, the effect of changes in surface mass balance are considerable. Determining both present and past accumulation rates is important to obtain an accurate age-depth relationship.

The model simulations in this paper were performed on a very coarse grid, *i.e.* a horizontal resolution of 40 km. Better results can be obtained in future with high resolution data and grid sizes of the order of a few kilometers. The flow line model is capable of coping with high resolution modeling, since such a change in scale demands a higher degree of physical complexity to account for: at such a high resolution the *shallow ice approximation* is deficient and the whole Stokes problem needs to be solved, as is the case with the present model description. However, a major drawback of such a two-dimensional model is that the flow line remains fixed in space so that for instance ice divide migrations cannot be taken into account. Three-dimensional model simulations of the Antarctic ice sheet (HUYBRECHTS, 1990) demonstrated that during the last glacial-interglacial period, the Dome Fuji Station ice divide remained more or less at its present position. Nevertheless, more detailed three-dimensional modeling should give a decisive answer.

The simulations also showed that the present description of the ice sheet age calculation has some minor drawbacks. Taking the case when hardly any basal melting occurs at the ice sheets base, the ice at the bottom will be as old as the starting time of the integration (*i.e.* 1000 ka BP in our case). Therefore, age-depth profiles are not reliable in the lowermost portions of the ice sheet, as was observed when integrating over a two million year period. This is due to the fact that the advection equation used for the age determination is a conservation equation. One possibility to improve the results is to include an artificial basal boundary condition based on a prescribed thinning rate (GREVE, 1997), which will be considered in future.

Finally, the ice sheet model can be employed to determine the age of the ice core, whenever a good estimate of boundary conditions is given (surface mass balance, temperature profile), or can be employed to determine more accurate certain ice flow parameters and poorly known boundary conditions when using the experimentally derived age-depth profile and internal layer reflections along the flow line as model constraints.

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