Dynamics of the Siple Coast ice streams, West Antarctica: results from a thermomechanical ice sheet model

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Abstract. Most of the ice leaving the Antarctic Ice Sheet is discharged to the sea by ice streams. An understanding of the dynamics of these ice streams is therefore crucial if we are to predict the future evolution of the ice sheet and its effect on global sea level. The behavior of Ice Streams A to E of the Siple Coast, West Antarctica has attracted much attention with evidence of recent stagnation and numerous relict ice-flow features. Here I present results from a three-dimensional, thermodynamic ice sheet model of the West Antarctic Ice Sheet (WAIS). The model generates variability in the flow of the Siple Coast ice streams reminiscent of that mentioned above. This is caused by competition between several preferred ice flow pathways in the area. Individual ice streams interact through changes in catchment-area size: a reduction in catchment area reduces the flow of ice entering a stream and can cause stagnation through the associated reduction in deforming heating.

Introduction

At present, most of Antarctica is drained by fast-flowing ice streams [McIntyre, 1985]. The flow in these ice streams contrasts with that of the majority of the ice sheet which experiences slow flow (typically 10 compared to 600 m yr$^{-1}$). In the short term, it is the stability of these ice streams which will determine the rate and direction of ice volume change in West Antarctica, rather than gradual changes in inland ice accumulation [Whillans and van der Veen, 1993].

The ice streams of West Antarctica have been particularly well studied using a variety of geophysical and Earth-observation techniques. Two key findings have emerged from this work. First, ice streams such as the Rutford [Smith, 1997] and the Siple Coast’s Ice Stream B [Engelhardt et al., 1990] are underlain by a layer of saturated sediment whose deformation contributes a large part of the ice stream’s overall velocity. Second, individual ice streams have contrasting stabilities. Rutford Ice Stream, for instance, is thought to be stable with its position determined solely by local topography [Doake et al., 1987]. In contrast, the ice streams of the Siple Coast appear to be transient features. Ice Stream C is known to have switched from fast to slow flow some 130 years ago [Retzlaff and Bentley, 1993]. The present-day ice streams in this area are thought to have only loose topographic control [Shabtaie et al., 1988] and there are numerous indications of relict ice streams along the Siple Coast [Jacobel et al., 1996].

Description of the Ice-Flow Model

This paper uses a thermomechanical model of the WAIS and aims to understand the mechanisms which both generate ice streams and determine whether they are stable or transient features. The model uses finite differences and allows the temporal evolution of ice sheet thickness, internal temperature and flow to be simulated. Changes in ice thickness, and hence ice surface topography, arise principally through the divergence of horizontal ice flow. Ice flow occurs through both the deformation of ice and the slip of basal ice or sediment relative to the underlying bedrock. Both are assumed to be driven solely by local horizontal shear stresses, which has the important implication that ice flow is always down the line of maximum ice surface slope. The simulation of the internal temperature field of the ice sheet includes features such as diffusion, advection, heat generation by deformation within the ice mass, and geothermal and frictional heating (from sliding) at the ice/bed interface. In practice, the thermal regime of the deeper ice layers (where shear stresses are highest and most strain occurs) is controlled by the balance between geothermal and deforming heating, and the diffusive loss of heat up into the ice sheet. The results reported here are based on a 20-km horizontal grid spacing and a 10-yr time step.

Several important feedbacks operate within the ice-sheet flow system. The temperature of ice controls its viscosity such that ice near its pressure melting point is a thousand times softer than cold ice (typically 230 K) [Paterson and Budd, 1982]. This, and the importance of deforming heating in the thermal regime, leads to ‘creep instability’ [Clarke et al., 1977], which is an explosive positive feedback combining faster ice flow, increased deforming heating and reduced viscosity. Basal temperatures also control the onset of basal slip in that differential basal movement (be it sliding or sediment deformation) is only possible when the basal ice is at pressure melting point and meltwater is being generated. No attempt is made to include the details of till deformation and subglacial hydrology in the current model: where the ice sheet base is melting, basal slip occurs at a rate dependent solely on the local gravitational driving stress. However, the thermomechanical effects of basal slip are fully incorporated into the model. A fuller description of the model can be found elsewhere [Payne and Dongelmans, 1997; Payne, 1998].

It should be emphasized that the equations used in the model are not strictly applicable to ice streams, where longitudinal stresses dominate [MacAyeal, 1989]. This initial study assesses whether a thermomechanical mechanism is a viable means of explaining the temporal variability noted above. More detailed modeling will, however, be needed.

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Figure 1. Predicted basal ice temperatures in K at 94 kyr. The labels refer to known ice streams: RIS Rutford Ice Stream; IIS Institute Ice Stream; MES Mollereisstrom; FIS Foundation Ice Stream; PIG Pine Island Glacier; and TG Thwaites Glacier. The six Siple Coast ice streams are labeled ISA to ISF. The domain of the grounded ice sheet is shaded grey and the location of the transect discussed in the text is marked with a solid line. The units of the x and y axis are kilometers.

to verify the applicability of these mechanisms to ‘real’ ice streams.

This implementation of the model is forced by the present-day distributions of mean annual air temperature, snow accumulation and bedrock topography [Budd et al., 1984]. All three are held constant to isolate the effects of feedbacks internal to the ice flow system. The domain occupied by the modeled ice sheet is held constant at that of the present-day grounded WAIS. This is done so that results represent an equilibrium free of the complications of grounding line migration.

Results

Figure 1 shows the predicted basal temperatures from a 100,000 year experiment starting from a flat ice sheet with surface elevation set at sea level [Payne, 1998]. The development of ice streaming, indicated by basal pressure melting, is clearly evident and the locations of the predicted ice streams agree well with known ice stream locations. The majority of these ice streams lie within or close to troughs in the bedrock dataset. Bedrock troughs are associated with fast ice flow because they allow enhanced gravitational driving stresses and warmer ice temperatures. The concentration of flow is further increased by the effects of creep instability and the non-linear nature of the ice deformation law.

The Siple Coast ice streams are reasonably well represented. Typical surface velocities in the modeled ice streams are 100 to 200 m yr\(^{-1}\) of which 80 to 90 % is basal slip. These values are controlled by the exact parameterization of basal slip in the model but are of the same order of magnitude as estimates made from satellite imagery of the area [MacAyeal, 1992a].

Considerable temporal variability occurs throughout the simulation. This is linked almost exclusively to the Siple Coast area and centers around Ice Streams B and C [Payne, 1998]. Figure 2 shows the ice flow in this area at 90 and 100 kyr in the simulation. These times represent the two basic modes of flow in the area: a strong Ice Stream C with a weakened Ice Stream A/B complex, and strong Ice Streams A and B with a dormant Ice Stream C. The flowlines shown...
here are derived solely from the instantaneous flow field. The temporal variability of the flow means that ice does not actually follow these flowlines in the simulation, however the flowlines do serve to illustrate changes in the catchment areas of the ice streams.

The time slice shown in Figure 1 lies between those of Figure 2. At this time Ice Stream C is stagnant in the model and is frozen to its bed. Although the real Ice Stream C is currently stagnant, its bed is still thought to be wet [Bentley et al., in press]. This implies that, in addition to the two basal states which the model currently allows (frozen and immobile or melting and active), there is an intermediate state in which the bed is at melting point but does not experience slip [Fowler and Johnson, 1996].

Individual ice streams are believed to interact by capturing sections of each others’ catchment areas. This is made possible by the effect of ice flow on ice surface topography and, in particular, by the ice surface lowering occasioned by ice stream initiation [Payne and Dongelmans, 1997]. Once an ice stream begins to lose ice flow, a catastrophic stagnation occurs as the creep instability feedback operates in reverse: less flow generating reduced deformational heating and less viscous, thicker ice [Payne, 1995]. The existence of three closely-spaced bedrock troughs in the area, each of which can act as the site of ice-stream initiation, makes a repeating sequence of growth, competition and stagnation inevitable.

The behavior of the ice streams along the Siple Coast transect during the last 20 kyr of the model run is shown in Figure 3. Ice Streams A and B form a complex in the figure and exhibit cycles with a period of approximately 10 kyr. These cycles start with fast ice flow in the position currently occupied by Ice Stream A (800 km on the transect). This ice stream then migrates towards the present-day location of Ice Stream B (at 700 km). After 7.5 kyr, the ice stream splits into two ice streams centered at 700 and 800 km. Finally, the ice stream at 700 km collapses and the cycle is complete. The migration of this ice stream towards Ridge B/C is reminiscent of behavior found from repeat satellite images of the area, however the rate of modeled migration (0.01 m yr$^{-1}$) is an order of magnitude slower [Bindschadler and Vornberger, 1998].

Ice Stream C is predicted to be active only for short periods separated by long spells of quiescence (examination of the entire simulation indicates cycles with a period of approximately 20 kyr). The stagnation of Ice Stream C (not shown) proceeds very rapidly in a downstream direction and takes approximately 750 yr. Field data imply a very rapid stagnation which, however, progressed in an upstream direction [Retzlaff and Bentley, 1993]. The position of Ice Stream D remains static in the model, however it does experience pulses in flow.

Figure 4 shows a cross-section through the Siple Coast at a time when Ice Stream C is stagnant. The vertical distribution of temperature within an ice stream differs from that of adjacent ice in two ways: its base is at pressure melting point and there is a pronounced temperature inversion in its upper layers. Both arise from the faster ice flow in ice streams: the former feature is a consequence of enhanced deformational heating, while the latter arises through increased horizontal temperature advection. The location of the ice streams in relation to the underlying topography is also worthy of note. Ice Streams A and B do not lie at the centers of their respective troughs. This feature has also been found in geophysical observations of the area [Shabtaie and Bentley, 1988]. The ice surface elevations shown in Figure 4 are approximately 300 m greater than those observed in reality, which implies that the extremely low surface slopes of the Siple Coast are not well captured.
Summary

These results offer the first indication that much of the observed behavior of ice flow in the Siple Coast area can be successfully simulated using existing thermomechanical ice sheet models. This implies that the behavior relies on thermomechanical interactions and the peculiar topographic character of the area.

Although the model yields results which agree with many of the known features of the area, it is important to emphasize that the physics of ice-stream flow are poorly represented. In the model, streaming occurs because of the interaction between ice temperature and flow, which cause both reduced ice viscosity and basal melting (hence slip over the bed). However, the well-lubricated bed and the low gravitational driving stresses of the real Siple Coast ice streams imply that the model is over-estimating the heat generated by both basal friction and internal deformation. The implications of these inaccuracies for the behavior reported here are uncertain but will undoubtedly affect the time scales involved in the ice stream variability discussed above. A second major shortcoming of the model is that ice stream shutdown can only occur through basal freezing, which is in conflict with recent field evidence.

The model shows no tendency to produce large-scale surging [MacAyeal, 1992b]. Although, it is clear that much of the ice sheet is affected by large, complex patterns of ice surface elevation change which are generated internally by the ice sheet system. This has important implications for the use of satellite radar altimetry to monitor the response of ice sheets to climate change.

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