Convergent flow of ice within the Astrolabe subglacial basin, Terre Adélie, East Antarctica: an hypothesis derived from numerical modelling experiments

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The existence of a large subglacial lake beneath the Antarctic Ice Sheet at Terre Adélie indicates the presence of basal ice at its pressure-melting temperature. A numerical model of the ice-sheet thermal regime is employed using the balance velocity of the ice sheet as an initial model input in order to calculate ice-sheet basal temperatures. However, the results from this model show the Terre Adélie area to be characterised by basal freezing. Heat in addition to that accounted for in the model is thus required at the ice-sheet base in order for pressure melting temperatures to be attained. The sources for such heat are (1) an enhanced geothermal heat flux and (2) an increase in frictional heating caused by the flow of ice. In this paper the latter possibility is expanded by hypothesising that subglacial topography induces convergent ice flow around Terre Adélie, causing enhanced basal ice velocities. Model experiments indicate that an increase in ice velocity (from 7 to at least 42 m yr^{-1}) is required to raise the temperature of the basal ice to the pressure melting value. Increased ice velocity, and consequent frictional heat production due to convergent ice flow, may therefore be important in explaining the location of the subglacial lake in this region. These results allow the process of convergent ice flow within a contemporary ice sheet to be quantified. A verification (or otherwise) of the model results may be possible if ice surface velocity measurements from modern GPS methods are made.

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Introduction

A systematic analysis of the analogue antarctic radio-echo sounding (RES) database, held at the Scott Polar Research Institute (SPRI), University of Cambridge, resulted in the identification of 77 subglacial lake-type reflectors (Siegert et al. 1996). Many (~90%) of the subglacial lakes represented by these reflectors are situated beneath major ice domes where the horizontal velocity of ice is low and ice thickness is high. However, several subglacial lakes, notably two lake-type RES reflectors (probably representing two reflections off one lake) at Terre Adélie (Fig. 1), can be found unusually far (>700 km) from the nearest ice divide along the direction of ice flow. It is assumed that the temperature of the ice-sheet base above subglacial lakes is at the pressure melting value. Consideration of the ice-sheet thermal regime above antarctic subglacial lakes indicates that the pressure melting point can be achieved beneath ice divides at, for example, Dome C and Ridge B, because of a geothermal heat component of around 54 mW m^{-2} (Siegert & Dowdeswell 1996). However, away from ice divides, as ice thickness is reduced and precipitation increased, additional heat is required to melt the ice at the ice-sheet base. For the case of the Terre Adélie subglacial lake, this extra heat term is of similar magnitude to the 54 mW m^{-2} of geothermal heat at Dome C (Siegert & Dowdeswell 1996). This additional heating may originate from a variety of sources, including (1) heat derived from basal sliding, (2) heat due to internal ice deformation and (3) spatial variation in the geothermal heat flux within the Antarctic Plate. A fourth possible source of heat is from water derived from the ice-sheet interior, channelled by subglacial topography. Although this mechanism transports heat within glaciers, it is unlikely to be effective beneath Terre Adélie because the ice-sheet base is largely frozen between Dome C and Terre Adélie (e.g. Huybrechts 1992). If the geothermal heat flux within the Astrolabe subglacial basin is of the order of 100 mW m^{-2}, then this alone may account for the attainment of

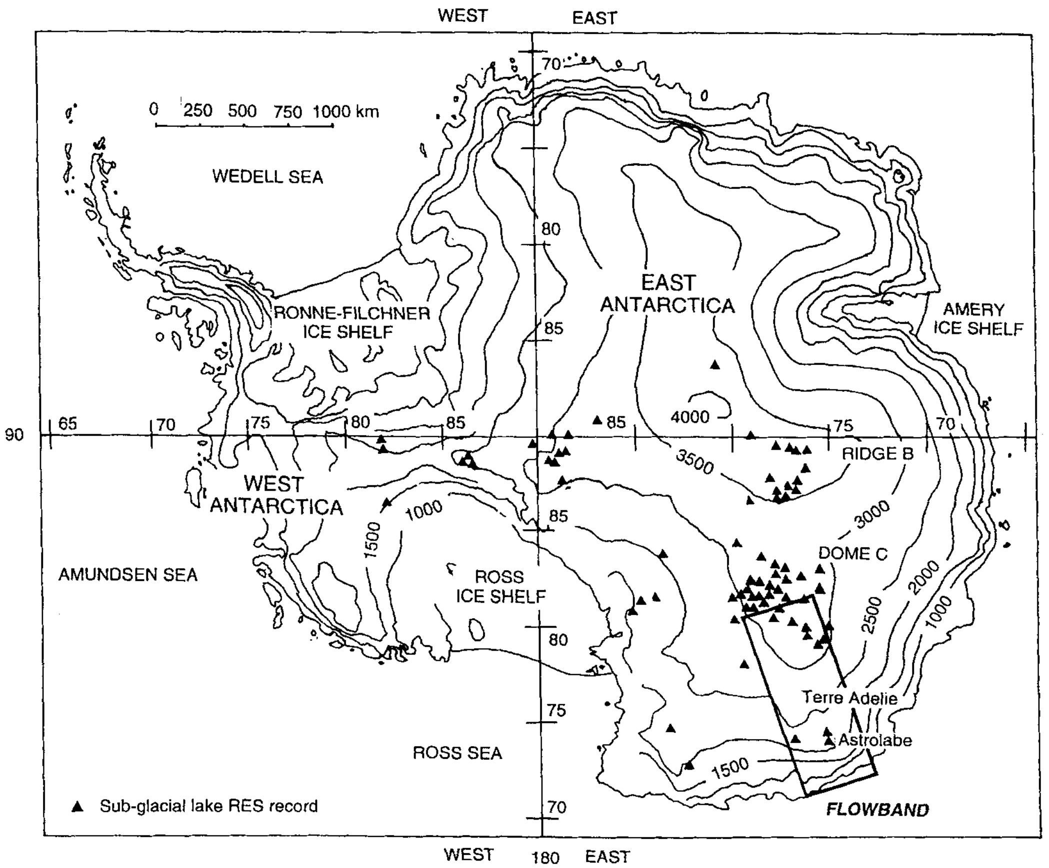

Fig. 1. Location of Terre Adélie and model flowband (after Drewry 1983). Also provided are the locations of all known antarctic subglacial lakes (after Siegert et al. 1996). The subglacial lake within the Astrolabe basin was identified by two independent RES records (Cudlip & McIntyre 1987).

pressure melting temperature (Siegert & Dowdeswell 1996). If, however, the geothermal heat input is less than this value, additional heat must be derived from ice-sheet mechanics.

The lake within Terre Adélie occupies part of a large subglacial topographic valley 250 km long, 50 km wide and 2000 m deep. The valley is named the Astrolabe subglacial basin (Drewry 1983) and runs perpendicular to the broad ice-sheet surface contour above (Fig. 1). The ice thickness within the Astrolabe basin is in excess of 4000 m (Fig. 2). The subglacial topography of the Astrolabe area has been compared with that of the Great Rift Valley in East Africa (Cudlip & McIntyre 1987). The subglacial lake beneath Terre Adélie is located at the northern end of the Astrolabe basin. The minimum length of the lake, as measured from RES data, is 43 km (Siegert et al. 1996). Other RES data from the Astrolabe region indicate generally strong, bright returns from the ice-sheet base indicative of electro-magnetic reflectors from a wet ice/bed interface. One interpretation of these data is that the ice-sheet base along most of the Astrolabe is subject to temperatures at the pressure melting value.

Topographic features such as the African Rift Valley have relatively high geothermal heat anomalies. The possibility cannot be discounted that the geothermal heat flux within the Astrolabe sub-glacial basin is significantly greater than that of the surrounding crust. Melting at the ice sheet

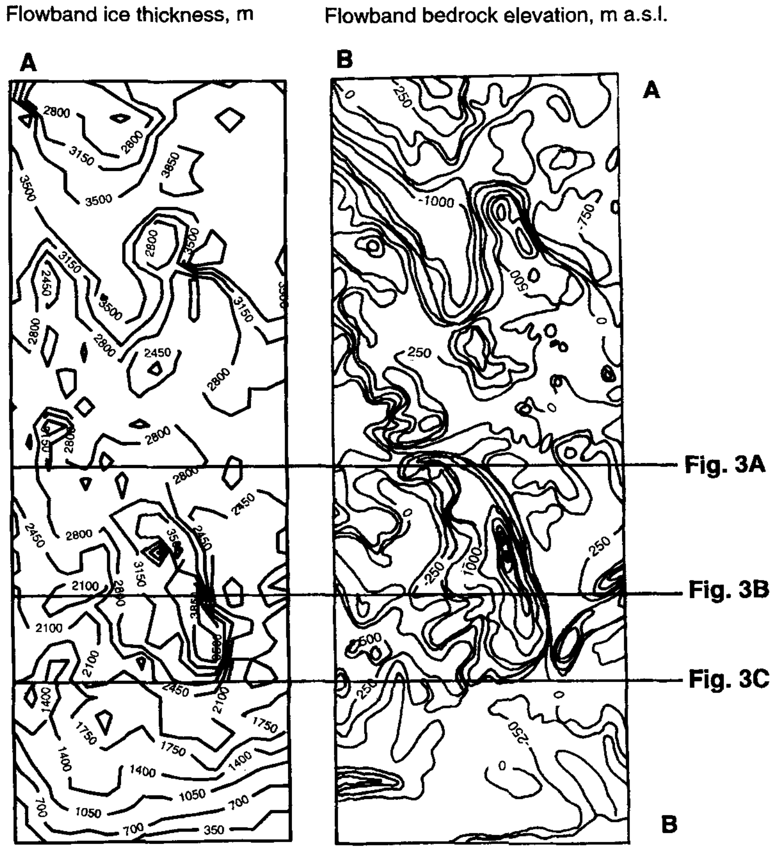

Fig. 2. A. Ice thickness within the Terre Adélie flowband used in the numerical model (after Drewry 1983). B. Bedrock elevation within the Terre Adélie flowband (after Drewry, 1983). The positions of cross sections illustrated in Fig. 3 are denoted. Central flowline (AB), over which results in Fig. 5 are calculated, is indicated.

base caused by high geothermal heat flux may be one explanation for the pressure melting temperature being attained at the ice sheet base within the Astrolabe subglacial basin. Another explanation, however, could be that this heat is generated by internal deformation and basal sliding.

The Astrolabe's topographic control on ice-sheet flow may encourage convergent ice flow from upstream. Studies where topography similar to the Astrolabe has been used within recent, appropriate numerical models of ice flow indicate that convergent flow is probable in such situations (Kerr 1993). Cross sections of the subglacial topography in the region of the Terre Adélie subglacial lake show that local ice thickness varies between 2000 and 4000 m (Figs. 2 and 3). Generally, within the centre of large ice sheets, relatively thick ice exists above topographic lows and areas of relatively thin ice cover topographic highs. Subglacial topography also influences the patterns and rates of ice flow which give rise to areas of convergent and divergent flow (McIntyre 1985; Mazo 1987; Kerr 1993). Three topographic cross sections which lie approximately perpendicular to the direction of ice flow suggest that the region around the Terre Adélie subglacial lake is an area of sufficient topographic contrast to initiate a significant convergence of ice flow (between the locations X and Y in Fig. 3).

If it is hypothesised that convergent ice flow is occurring within the Astrolabe, it is possible to model how fast the ice sheet must flow in order to produce the required basal temperatures by the use of a simple thermal model. Although more sophisticated models are available, a simple version is used in this study to ensure that model parameters, other than ice-flow-induced heating, are fixed. Thus, in this paper, the role of convergent flow of ice within the Astrolabe subglacial basin is examined. This investigation has significant implications for assessing the relative importance of convergent ice flow and geothermal heating within ancient and modern ice sheets and

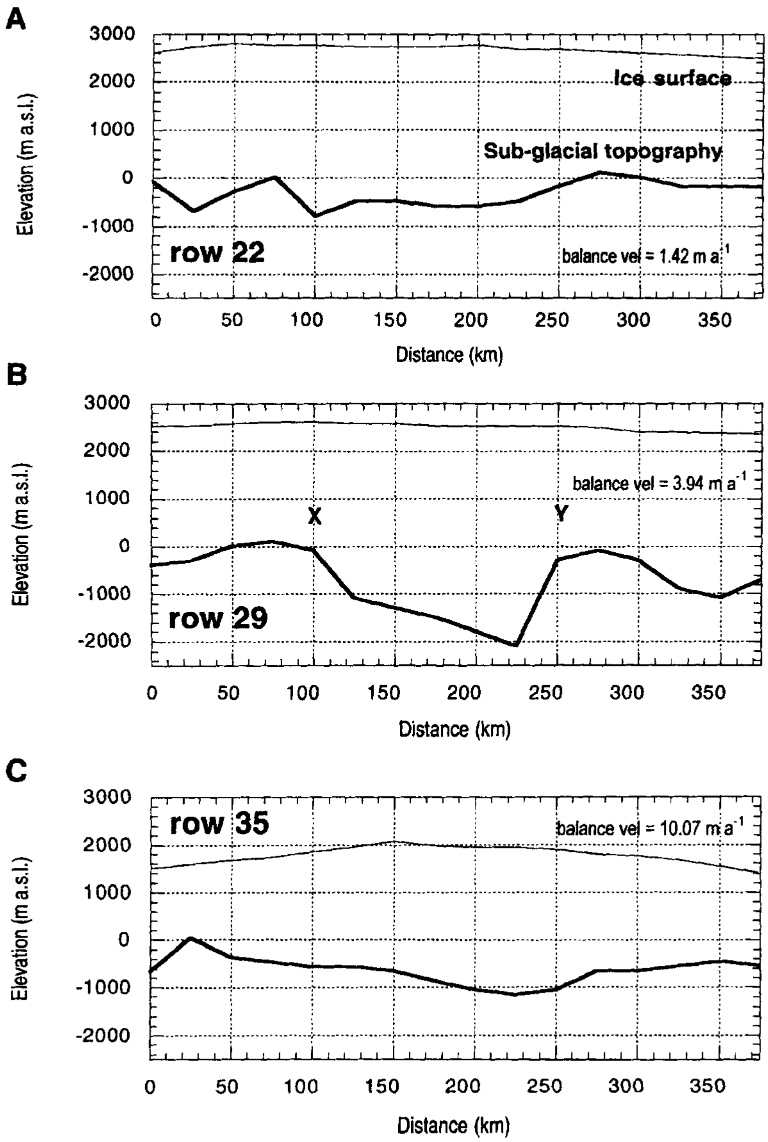

Fig. 3. Cross sections denoting the topography of the ice-sheet surface and base along three transects. A. 550 m from the ice divide at Dome C. B. 725 m from the ice divide. C. 875 m from the ice divide. The markers X and Y denote the lateral extent of the Astrolabe subglacial basin and the region in which convergent flow will occur.

for the manner in which their dynamics are modelled.

Numerical model

We have used a simple numerical model, based on that of Budd et al. (1971), to calculate the basal temperature of the ice sheet around Terre Adélie.

The basal ice temperature, T_b, is given by:

$$T_b = T_s - H\left[Y_b \frac{\mathrm{erf}(y)}{y} - Y_s 2E(y)\right] \qquad (1)$$

$$y = \left(\frac{bH}{2k}\right)^{1/2} \qquad (2)$$

$$Y_b = \frac{\Lambda_g}{K} + \frac{\tau u}{K} \qquad (3)$$

$$Y_s = \frac{u\alpha\lambda}{b} \qquad (4)$$

where T_s is the surface temperature (°C), H is the ice thickness (m), Y_b the total basal heat flux (W m^{-2}), Y_s is the surface heat gradient (°C m^{-1}), Λ_g is the geothermal heat flux (54 mW m^{-2}) and erf(y) is the error function. The basal shear stress is τ (Pa), b is the surface accumulation (m yr^{-1}), α is the surface slope of the ice sheet (in radians), K is the thermal conductivity of ice (2.1 W m^{-1} k^{-1}), λ is an altitudinal air-temperature lapse rate (0.7°C/100 m, Diamond 1960), and k is the thermal diffusivity of ice (36.29 m^2 yr^{-1}). The balance velocity u is given as:

$$u = \frac{\bar{b}(\chi)\chi}{H} \qquad (5)$$

where χ is the distance from the ice divide and $b(\chi)$ is the mean accumulation over that distance. The function E(y) is given by:

$$E(y) = \int_0^y F(\xi)\mathrm{d}\xi \qquad (6)$$

where F(ξ) is a function known as the Dawson integral. Both the error function (erf(y)) and the Dawson integral (E(y)) can be found as tabulated functions (e.g. Abramowitz & Stegun 1965).

The model calculates the basal ice temperature over a two-dimensional grid of 688 cells, 16 by 43, which have a 25 km spacing. Each cell thus represents 625 km^2 in horizontal surface area. The grid depicts a "flowband" of the ice sheet so that ice flow along the long axis of the grid (a total of 1075 km) approximates the actual flowline of the ice sheet. The position of the flowband within the Antarctic Ice Sheet is given in Fig. 1. The location of subglacial lakes that exist within the region of the flowband are indicated in Figs. 1 and 4. Most of these lakes are situated in the south of the band, in proximity with Dome C.

The model assumes a number of glaciological conditions. The first is that the ice sheet is in steady-state. The second is that heat conducted transverse to ice flow is negligible compared with that conducted along flow. We expect this assumption to hold for ice flowing through the Astrolabe Subglacial Basin. Third, advection of ice is assumed to occur in the vertical direction only. The advection rate is assumed to be constant and equal to the rate of surface warming. Fourth, all friction is assumed to apply at the base of the ice sheet; and fifth, the thermal diffusivity of ice is assumed to be constant, as is the strain rate. Thus, the only parameter that we are able to change in our model is the heat due to enhanced ice flow.

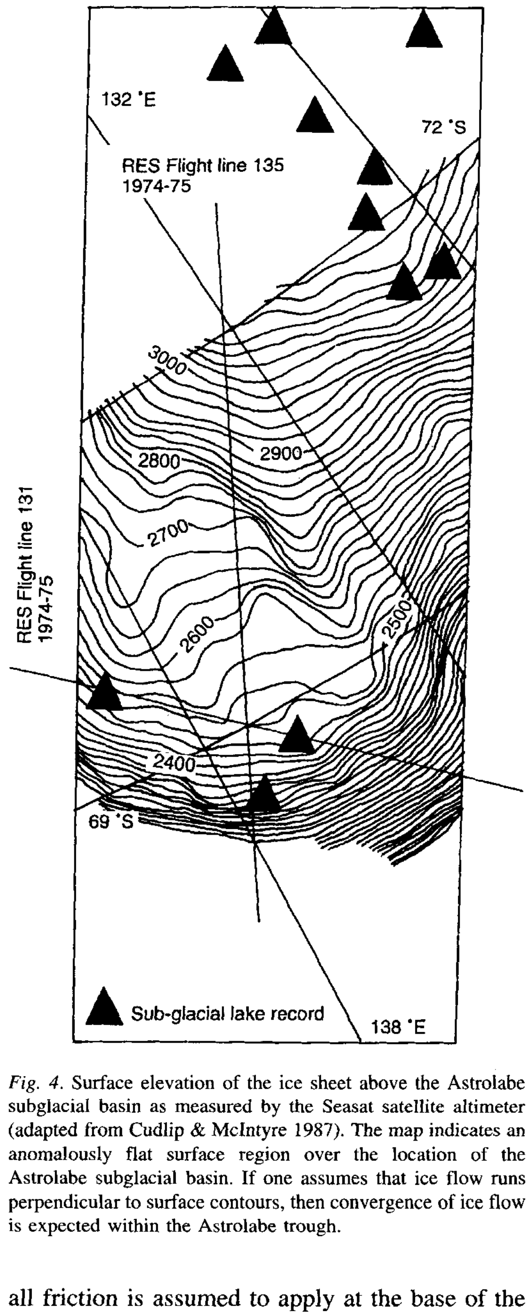

Fig. 4. Surface elevation of the ice sheet above the Astrolabe subglacial basin as measured by the Seasat satellite altimeter (adapted from Cudlip & McIntyre 1987). The map indicates an anomalously flat surface region over the location of the Astrolabe subglacial basin. If one assumes that ice flow runs perpendicular to surface contours, then convergence of ice flow is expected within the Astrolabe trough.

The main application of the Budd et al. (1971) model has been in the reconstruction of the basal thermal regime of former ice sheets. The model was used by Sugden (1977) and Gordon (1979) in

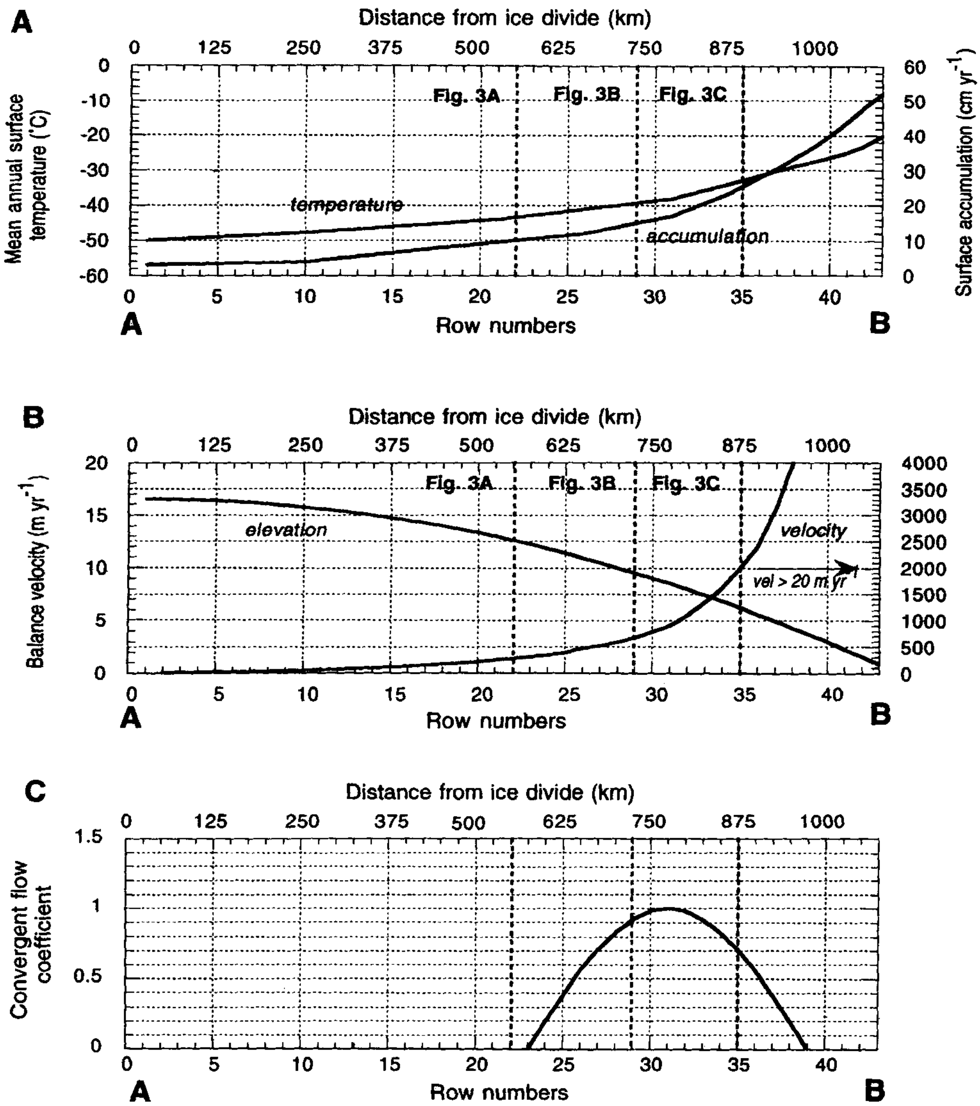

Fig. 5. A. Ice surface temperature and accumulation along the central line A–B (Fig. 2) of the flowband. B. Ice velocity and surface elevation along the central line of the flowband. C. Sine function which is used to determine the multiplication factor of the balance velocity in order to account (simply) for convergent ice flow. The lateral extent in which the Sine function is applied is given in Fig. 3B between the locations X and Y.

reconstructing steady-state ice-sheet temperatures beneath the former Laurentide and Scottish ice sheets. A criticism of the application of this model to former ice sheets is the assumption of uniform patterns of ice flow, i.e. zero migration of ice in the "y" horizontal grid cells by calculating the mean elevation of the ice sheet from surface contours in the area over which a cell is projected.

The balance velocity (Fig. 5B) is calculated assuming a flat ice-sheet base. This yields a relatively uniform flow of ice along the flowband which does not take into account the differential ice flow which occurs in response to the topography at the ice-sheet base (e.g. Kerr 1993). The velocity within the Astrolabe basin thus varies from 3 m yr^{-1} in the south to

$10\,m\,yr^{-1}$ in the north (Fig. 5B). The model was run through an initial "reference" state, where the convergent flow of ice was not accounted for. Subsequent to this model run, the velocity within the flowband was altered in a sensitivity examination of the basal temperature response to enhanced velocities within the Astrolabe basin. The manner in which ice velocity was adjusted accounted empirically for the possible convergent flow of ice. If convergent ice flow occurs within the Astrolabe basin, the flow pattern is likely to be similar to that indicated in the ice-surface contour pattern (Fig. 4). Calculated with an assumption that the ice-sheet bed is flat, the velocity of ice within the Astrolabe basin is likely to increase above the balance velocity to a maximum value at the point of most convergence around the trough centre. As divergence occurs within the downstream side of the trough, the velocity would reduce toward that of the flat-bed-derived balance velocity. We account for the change in velocity along the Astrolabe basin by multiplying the balance velocity by a Sine function which is related to position within the basin (Fig. 5C). The resulting "convergent" velocity is then added to that representing the balance velocity. The magnitude of this Sine function is varied within a sensitivity experiment on ice velocity. Ice velocity is input to the model thermal regime (eqs. 3 and 4) to yield theoretical basal ice sheet temperatures. Results thus indicate ice-sheet velocities around Terre Adelie that allow the attainment of pressure melting values at the ice-sheet base.

Model results and comparison with previous investigations

Reference model

The basal temperature distribution for the reference model run indicates that pressure melting temperatures are predicted only in the south of the grid (Fig. 6A), where a number of subglacial lakes are known to exist (Fig. 1). Since horizontal velocity in this area is low, the source of heat that causes pressure melting temperature at the ice sheet base is, principally, geothermal. Away from the Dome C ice divide, thinner ice and higher precipitation rates cause the predicted basal temperature to decrease. For example, temperatures of at least 10°C below the local pressure melting value were calculated within the centre of the flowband (Fig. 6A). However, at the Astrolabe basin, where ice thickness is in excess of 4000 m, the temperature is calculated to rise to around 10°C below the pressure melting value. The reference model run indicates that ice-sheet basal temperatures are too low beneath Terre Adélie for basal melting to occur in the region of the subglacial lake.

Model experiments

It is contended that the topographically-induced convergent flow of ice through the Astrolabe basin would cause significant increase in velocity at or near the ice-sheet base. Through frictional heating, this enhanced ice flow would cause a source of heat at the ice-sheet base. Such heat may lead to pressure melting temperature conditions within the Astrolabe basin. In order to test this contention, a series of model experiments were performed to determine the glacial conditions required to initiate basal melting. In these experiments, the magnitude of the Sine function used to multiply the balance velocity is adjusted, yielding ice velocity values which are then added to the original balance velocity.

The sensitivity of the ice-sheet basal temperature to variability in ice velocity through the Astrolabe basin is illustrated in Fig. 6. Pressure melting temperatures are attained when the velocity through the centre of the trough is multiplied by at least six-fold, i.e. to $\sim 42\,m\,yr^{-1}$ (Fig. 6B). As the velocity is increased within the trough, more basal melting occurs until large-scale basal melting of the Astrolabe region is calculated at an ice velocity of $\sim 70\,m\,yr^{-1}$ (Fig. 6C). These velocities indicate that to attain pressure melting values within the Astrolabe, convergent flow must cause a flux of ice through the subglacial trough more than 10 times that which occurs at either side of it.

The change in ice velocity between the ice sheet within and outside of the Astrolabe basin would manifest itself within the surface topography of the ice sheet. For example, the large subglacial lake at Vostok Station is overlain by an extremely flat, smooth ice surface, caused by the atypical flow of ice over it (Ridley et al. 1993; Kapitsa et al. 1996). The smooth nature of the ice-sheet surface over the Vostok lake is indicative of negligible basal shear stress (Kapitsa et al. 1996). Cudlip & McIntyre (1987) produced a surface

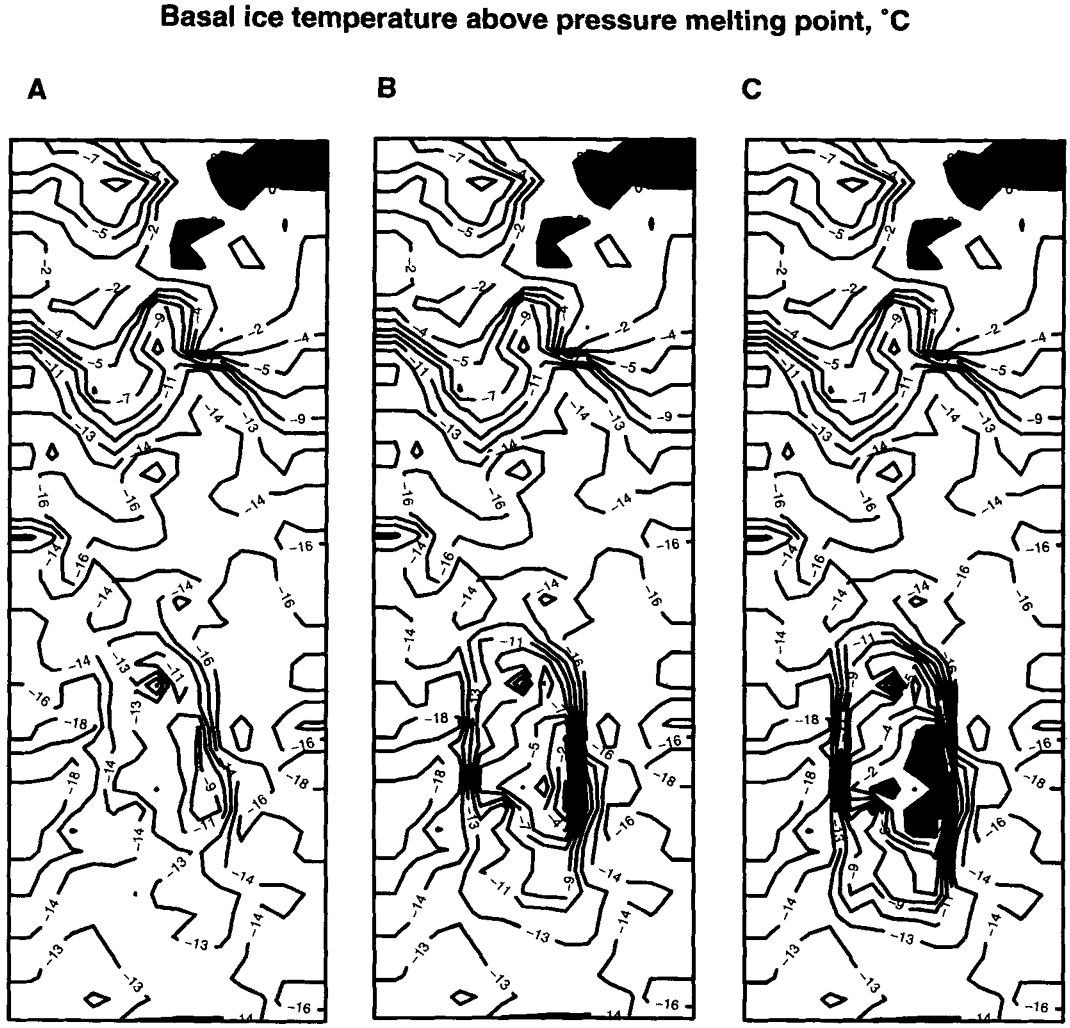

Fig. 6. Calculated basal ice temperatures (°C above the pressure melting value) in the flowband. A. Reference model (ice velocity through the trough at the location of the Sine function crest is equivalent to a balance velocity of 7 m yr^{-1}). B. Convergent ice flow yielding an ice velocity of 42 m yr^{-1} at the Sine function crest within the Astrolabe basin. C. Convergent ice flow causing ice velocity of 70 m yr^{-1} at the crest of the Sine function. Black regions indicate basal temperatures at the pressure melting value.

elevation map of the Terre Adélie region from Seasat satellite altimeter data which indicates a similarly anomalous flat contour pattern over the region of the Astrolabe subglacial trough (Fig. 4). Here the ice surface contours indicate that the ice-surface slope over the Astrolabe basin is 0.07° compared with a surrounding ice-sheet surface of 2–3 times this value. This surface morphology suggests that ice flow within the Astrolabe trough is considerably faster than either side of it, and that the flow of ice is driven by considerably low basal shear stresses. Moreover, the smoothness of the ice surface, as measured from the Seasat altimeter, suggests that longitudinal basal drag within the trough is small. Evidence for low basal stress suggests that the enhanced ice motion may be derived mainly from basal sliding or bed deformation.

Information concerning the direction of ice flow can be derived from satellite altimeter data provided it is assumed that ice flows perpendicular to surface contouring. Analysis of the Seasat altimeter data reveals a relatively steep surface slope up-stream of the subglacial basin (Fig. 4). It is assumed that ice would preferentially flow down this slope and into the Astrolabe basin. It should be noted, however, that the unusual ice dynamics that occur above subglacial lakes make the interpretation of ice flow from surface contours difficult (Kapitsa et al. 1996).

Numerical ice-sheet models utilise calculated ice surface elevations to determine ice sheet velocities. However, convergent and divergent ice flow within central ice-sheet regions are not currently accounted for by many ice-sheet models. Where the ice-sheet base is relatively flat, such models are able to describe modern ice-sheet morphologies and behaviour well. However, where large subglacial valleys are present, for example beneath Vostok Station and at the Astrolabe trough, such ice-sheet models fail to predict the satellite-altimeter-measured ice-sheet surface.

Consideration of convergent ice flow is also important for models of former ice sheets, which are commonly constructed at scales of insufficient resolution to account for basal topography. If these models are to accurately predict the spatial extent, behaviour and dynamics of former ice sheets, they must account for the effects of convergent flow of ice (Glasser 1995).

Conclusions and discussion

A numerical model of the ice sheet thermal regime (Budd et al. 1971) was employed to determine basal heat conditions within the Astrolabe subglacial basin. The model was run over a rectangular section of the Antarctic Ice Sheet which represents an ice flowband (Fig. 1). A reference model run was performed with an assumption that uniform flow of ice occurred along the flowband. The velocity was determined by the ice-sheet balance velocity. However, results from this model failed to predict basal melting in the region of the Terre Adélie subglacial lake. This experiment used a spatially uniform geothermal heat flux of $54\,\mathrm{mW\,m^{-2}}$. Model results thus indicate that to attain pressure melting temperatures at the ice-sheet base, the geothermal heat flux must be higher than $54\,\mathrm{mW\,m^{-2}}$, and/or there must be heat derived from frictional heating which is not accounted for within the model. This paper examines the role of frictional heating as a source for the heat required to cause pressure melting temperatures within the Astrolabe subglacial basin. It is hypothesised that the discrepancy between calculated basal temperatures and actual pressure melting temperatures reflects the failure of the model to account for variations in ice velocity that occur as a result of convergent ice flow. Such variability may have a significant impact on frictional heat production at the ice sheet base. The possibility cannot, however, be discounted of a geothermal heat anomaly within the Astrolabe subglacial basin contributing, at least in part, to heat at the ice sheet base.

The model was adjusted to include a term which accounted for ice flow convergence and divergence. A series of numerical experiments were then performed with this model to determine the influence of convergent ice flow on basal temperatures. Results from these experiments show that basal melting is possible in the vicinity of the Terre Adélie subglacial lake when ice velocity is greater than $42\,\mathrm{m\,yr^{-1}}$. This value compares with a balance velocity, used in the reference model, of $7\,\mathrm{m\,yr^{-1}}$. The model results could be tested by ice surface velocity measurements made using GPS methods.

This study has important geological and geomorphological implications because the rates of basal melting and ice velocity beneath ice sheets exert a strong control over rates of glacial erosion and deposition (Boulton 1979). Our calculations suggest that the location of these areas of enhanced geomorphological activity are strongly influenced by subglacial topography. Consequently, our results have implications for process models of landscape evolution beneath glaciers and ice sheets (Harbor et al. 1988; Harbor & Warburton 1992a; Harbor & Warburton 1992b). In addition, our work has ramifications for dynamic reconstructions of former and contemporary ice masses (Payne et al. 1989; Arnold & Sharp 1992; Huybrechts 1993; MacAyeal 1992; Siegert & Dowdeswell 1995).

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