Graduate certificate in Antarctic studies (Anta 502).

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Mechanisms and Modelling: Siple Ice Streams

Abstract

The Siple coast ice streams serve as an important observational field site for the study of the West Antarctic mass balance. Though the importance of ice stream dynamics has been understood for 15 years, the understanding of flow mechanisms is still poorly understood. This is due to the limitations enforced on research by the extreme climate and isolated locality. This limitation to research has subsequently limited the extent to which numerical models can accurately predict flow rates and the effect of climate warming. There are many uncertainties in the basal conditions of the ice streams, and various other areas of ice stream flow. Models of ice stream onset, however, have convincingly proven the potential for sporadic development of ice streams, from an initially homogenous flow.

Introduction

Ice streams are well recognised as primary transport mechanisms for the removal of mass from ice sheet accumulation. Ice streams are of interest due to their high velocities ($200ma^{-1}$) and large spatial extent (>100km wide X 300km long). Ice streams have come into the spotlight in the last 10 years, since their importance has been recognised. They are common in both Greenland and in Antarctica and develop from the edge of ice sheets. For many years their flow mechanism has been unknown though thorough research across the Siple coast is beginning to reveal the mysteries. The Siple coast contains six ice streams (*Figure 1.*) of various sizes (named A to F). This group of ice streams is regarded as an extremely important part of the Antarctic cryosphere. The stability of the West Antarctic Ice Sheet (WAIS) is of high concern and this has stemmed large investigations into the mechanisms driving this phenomena. It is a marine ice sheet (significant areas below sea level) and there is high concern for the future stability of the WAIS (. With the threat of global warming and the potential collapse of the WAIS, understanding the stability of the ice streams and their role in the Antarctic cryosphere, is important (Allison, 2003). Though ice streams are only one component of the three basic transport mechanisms (Ice sheet→ Ice stream →Ice shelf) that are present in Antarctica. Their importance stems from the high velocities (as fast as temperate valley glaciers) and subsequent mass transport ability that they display (due to their spatial extent). The ice streams contribute to about 90% of all movement in the WAIS (Shabtaie, & Bentley, 1987). The discovery of the ice streams importance in the global climate system lead to a significant movement towards ice stream research. Between 1985 and 1995 the majority of work was on ice flow rates and mapping of the velocity fields. Whillans and Van Der Veen (1993) refined techniques in determining flow rates. *Table 1.* summarises the physiology of Ice Streams B (upper and lower) and D. The depth (H), width (W) and surface slope (α) are the main driving factors that will influence U_b , the basal velocity.

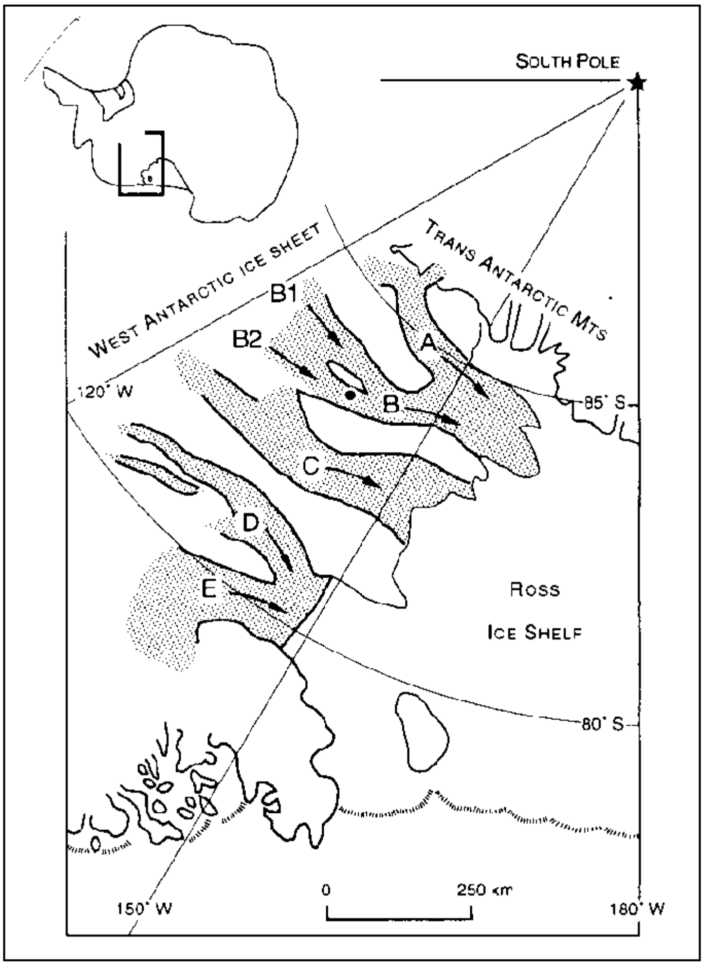

Figure 1. Siple Coast Ice Streams A-E (F not indicated) and there relative positioning to the Ross Embayment (Engelhardt and Kamb, 1996).

Table 1. Data from Raymond (2000) for Ice Streams Band D. Variables from 1 to 6 are respectively depth, width, surface slope, basal velocity, surface temperature and accumulation rate.

		UpB	*DwnB*	*D1*
Observation				
1	H (km)	1.1	0.8	0.9
2	W (km)	14	38	23
3	α (10^{-3})	1.3	0.4	[1.3, 1.7]
4	u_b (km a^{-1})	0.43	0.51	0.63
5	θ (°C)	−26	−26	−26
6	a (m a^{-1})	0.1	0.1	0.1

Most of the velocity work was completed using Geographic Positioning Systems (GPS). Remote sensing techniques were also used as the recognition of surface structures (usually crevasses) can be applied and relative displacement can be calculated. IMCORR software developed by Scambos *et al*. (1992) utilized Landsat images for this purpose and although velocity data was not as accurate as GPS (< 0.1m), a much larger area could be covered for derivation of flow fields. More recent research has focussed on the determination of onset flow mechanics (Price *et al*, 2002) and modelling of the ice streams to responses in both global warming, ice sheet surging and variable basal conditions. Models are forever adapting to new mechanisms and field data, suggesting that the requirement of raw field data will always be in demand. Only recently was the concept of sub-glacial till deformation considered, and accepted by the scientific community (Fowler, 2002). This supports a view that investigating the surface velocities fields of an ice stream that are 100km by 300km, is only scratching the surface, and that much more research is required before a thorough understanding of flow mechanisms can be accurately modelled.

This review aims to examine the extent of current knowledge on the Siple Coast ice-stream dynamics. It investigates two general areas of research to develop an over view of the extent of understanding of Ice stream research. It outlines areas that require more research (whether it be field data or modelling). The link between field research and flow models is outlined and the relevance of both types of research justified. Some modelling methods are outlined and examined. The verification of models and the various flow mechanisms suggested are also critically analysed.

History of ice streams

With a general global cooling over the last 100million years, the first Antarctic ice sheets are thought to have occurred about 40-60 million years ago (mya). A permanent ice sheet is thought to have developed 15 mya (Barret, 1999). An ice sheet stability model by Huybrechts (1993) is suggestive of an ice sheet that displays properties of slow development (tens of thousands of years), but is capable of relatively fast decay (a few thousand years). Since the last glacial maximum (~12,000 years ago) the WAIS has retreated significantly, losing up to two-thirds of its mass (Fahnestock *et al.* 2000).

Though there is no concern for current collapse in terms of global temperature rise (a 5^{o}C rise would actually increase ice volume) (Barret, 1999), the unknowns of ice stream dynamics and stability is of concern. As they are an integral part of the WAIS system. A recent history of ice stream dynamics of the Siple coast has come from

Fahnestock *et al.* (2000), who using a Advanced Very High Resolution Radiometer (AVHRR) mapped the last 1000 years of flow on the Ross Ice Shelf. Analysis proved that even in 1000 years there has been significant variation in flow regimes of the Siple coast ice streams. A major change was recognised 550 years ago (~350km of flow). Suggesting that significant changes in the flow pattern at about this time. Results also indicated that the margins of many of the ice streams (particularly Ice Stream B), have been migrating, current migration has been well documented also (Echelmeyer and Harrison, 1999). The shut down of Ice Stream C about 150 years ago (Jacobel *et al.* 2000) is of high interest, the shutdown of Ice Stream C however was not a single event, but a sequence involving stagnation of ice and migration of the ice stream boundary (Jacobel *et al.* 2000). Fahnestock *et al.* (2000) also documented a complex history of the Ice Stream C shutdown. The reduction in basal water storage through the Holocene was suggested as a possible catalyst for shutdown by Vogel *et al.* (2002).

Uncovering the history of the ice stream dynamics is important for long term modelling and future predictions of their behaviour. The tributaries to the Ross Ice Shelf can be seen in *Figure 2*. Which identifies the flow lines and extent to which the Siple coast ice streams contribute to the Ross Ice Shelf.

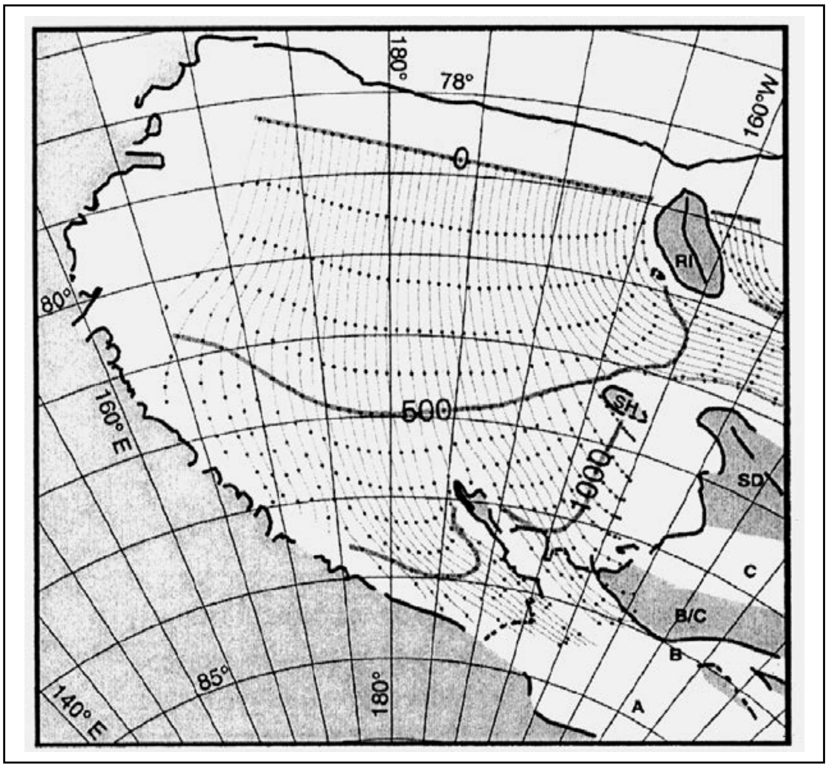

Figure 2. Flow lines across the Ross Ice Shelf and the Siple coast Ice streams (A-C) and Siple Dome (SD) to the southeast. (Fahnestock et al. *2000).*

Relict flow lines misaligned with present flow orientation have been a primary indicator that significant changes in flow have occurred.

A concern, as some models suggest, is that ice shelves restrict the flow of ice streams (buttressing effect) and that ice shelf collapse could be the first step, with subsequent ice stream enhancement followed by ice sheet collapse (Allison, 2003).

Ice stream onset and formation and flow

The ice stream onset area occurs at the margin between an ice sheet and an ice stream. It is defined by Anandakrishnan (1999) as the transition of flow mechanism from purely ice deformation (creep) to a flow dominated by basal sliding. However Ice Stream A is thought to flow mainly by a mechanism of ‘ fast creep’, which therefore eliminates the possibility of Ice Stream A having an area of onset (according to this definition). In this review ‘onset’ will be used as the region in which there is a transformation the dominant flow mechanism. This then accepts all theorised flow mechanisms (as there is debate to which mechanisms are active).

Onset areas of ice streams are poorly understood and the initiation process for their development has been in strong debate. One argument is that the onset area of ice streams is governed purely by geological boundaries and that their development is driven by basal conditions (Anandakrishnan, 1999). Another theorises that the basal water supply (from various potential sources) may increase enough to ‘drown’ controlling obstacles and enhance flow rates. This basal sliding mechanism is the most accepted. (Vogel *et al.* 2002; Vogel and Tulaczyk, 2002; Fowler and Johnson, 1996). Another method of location of the onset was defined by Bindscadler *et al.* (2000) as the most upstream transverse crevasse. As longitudinal extension is to be expected at the onset zone. This imaging technique has been well used (Stephenson and Bindschadler, 1990; Hodge and Doppelhammer, 1996). The onset area of Ice Stream D was investigated by Bindschadler *et al.* (2000), Who used GPS to determine the flow characteristics around this region. *Figure 3.* Shows the velocity field at the onset. Velocities increase from about 10 ma^{-1} to about 80 ma^{-1}, indicating a large acceleration in this area. Price *et al.* (2002) found similar results and plotted hydraulic potential and frictional melting rate maps, indicating significant changes in both over the theorised onset area proposed by Bindschadler *et al.* (2000).

The development of models to explain ice stream onset has proved that even in a completely homogenous ice cap, entirely symmetrical, spatially and thermally discontinuous flow will assume, after a given time period.

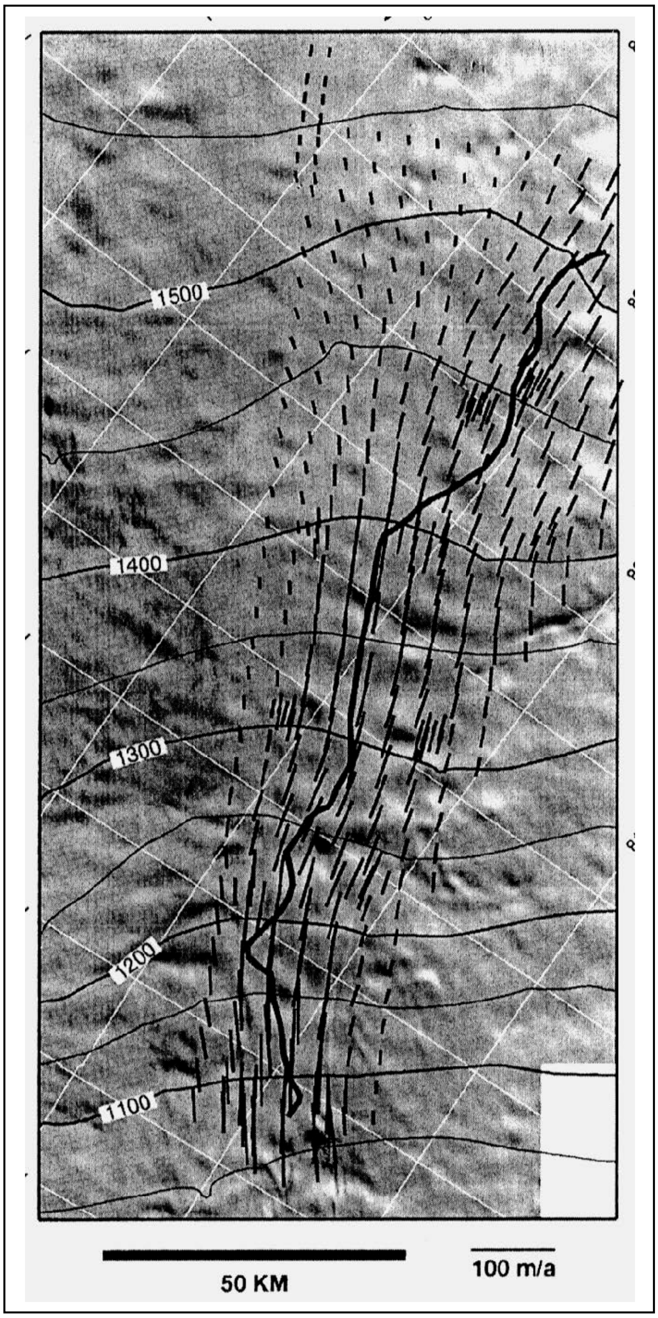

Figure 3. Onset area to Ice Stream D. Velocity vectors superimposed over a Landsat image, indicate the acceleration of ice flow through the onset region. Velocities range between 10 and 80 ma-1. Contour lines represent ice surface relative to msl. (source: Bindschadler et al. 2000.)

Hulton and Mineter (2000) produced an ice sheet model at high resolution and found that ice streams were irregularly self-organising, but had typical spacing with dependence on mass balance and thermal boundary conditions. An onset period of 10,000 years was found when the model ran. They found that ice streams were highly dynamic and proposed that even in heterogeneous terrain, ice streams have the

potential to find their own natural spacing rather than being driven by terrain features. Width spacing between 60 and 100 km were found by Hulton and Mineter (2000), similar to that of the Siple coast though there was low confidence in this aspect of their model. A similar model by Fowler and Johnson (1996) also found natural development of ice streams in a homogenous setting. They began with initial conditions similar to that of the WAIS (1ma^{-1} ice flow and 1500m ice depth). They also assumed a high ice-flow parameter and sediment based sliding dynamics.
They considered the Siple coast as a unidirectional ice flow and assumed some heterogeneity to the basal topography. The development of evenly spaced ice streams was found (*Figure 4.*), developing extending (down-stream) arms of alternating hot and cold regions, leading to enhanced and restricted sliding conditions. Their assumption were the basal conditions (wet and deformable sediment characteristics), which is still largely an uncertainty for many of the ice streams on the Siple coast.

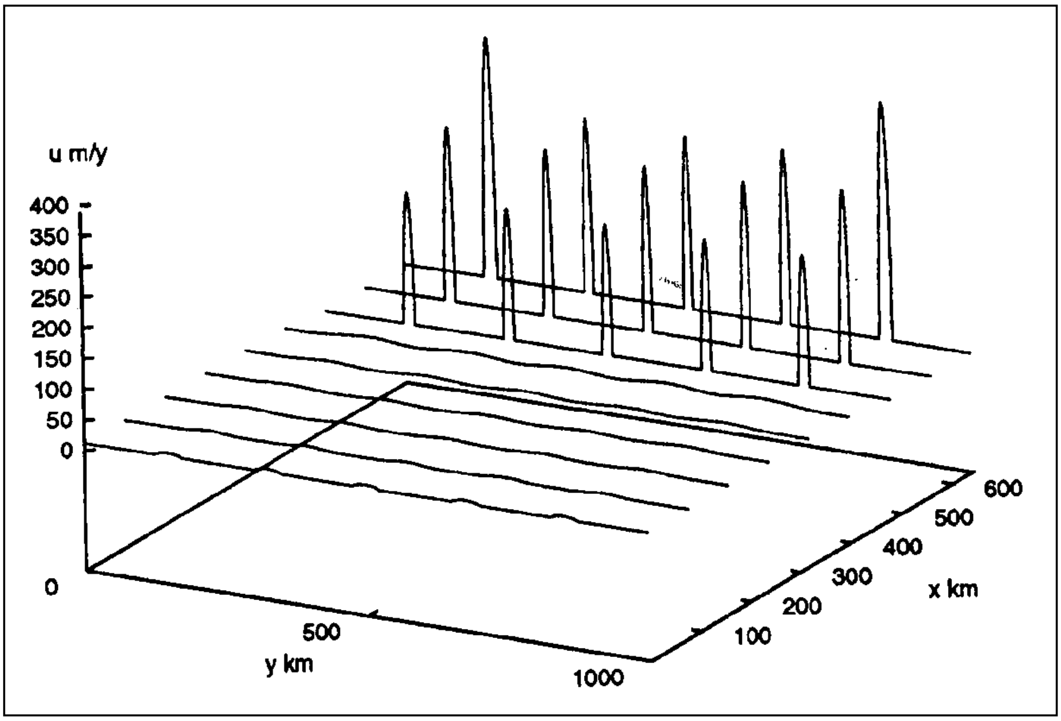

Figure 4.Development of 5 evenly spaced ice streams and the onset area (at about 400km on the x axis) The abrupt velocity increase indicates the change in flow mechanism acting on the ice stream. The extremely placid inter-stream ridges are also easy to identify. Flow direction is towards the top right. (Fowler and Johnson, 1996).

The model produced Fowler and Johnson (1996) indicates a rather rapid increase in flow rate at the onset. However recent research by Price *et al.* (2002) suggests that inland tributaries display an intermediate flow rate between that of inland and streaming-ice, and that a gradual flow increase is occurring.

Van Der Veen and Whillans (1996) produced a model that suggested an unstable wave like development that found a steady state at the time of 25,000 years after initial development period of 5000-7000 years. Basal drag is assumed only as a residual in this model suggesting that the majority of resistance to the driving stress is from lateral drag (shear stress). This supports a theory of free basal sliding on a saturated bed. Price *et al.* (2002) found that the majority of resistance in tributary flow (prior to onset) stems from basal drag. Indicating that a complete transfer of dominant resisting force. Though the study of Price *et al.* (2002) was in an onset region where ice velocities were not yet large (< $30ma^{-1}$). The main difficulties in modelling found by Van Der Veen and Whillans (1996) were in the entrainment area (onset).

Hulbe *et al.* (2000) used a combination of numerical modelling and observations to determine the tributaries to the onset of Ice Stream D. The main driving factors to the tributary were ice depth (resulting in higher basal shear and subsequent deformation) and for the ice stream was sliding. Further down stream variations in flow rate were determined by the contribution of sliding to flow (suggesting a constant creep rate), which was suggested to vary due to variations in basal water storage and sub glacial geological properties. This is in support of Anandakrishnan (1999). Though sub-glacial controls on flow is an area that requires much more research. Hulbe *et al.* (2000) found that ice stream tributaries are generally located above valley in the bedrock bathometry, which may influence the location and onset of individual ice streams.

Force/ Energy balance

Force balance analysis uses the logic that, if one can calculate the potential energy (driving force) of an ice stream, ice sheet or combination of the two, then the resistive force (from marginal shear, ice creep and basal friction and melt) must approximate the driving energy minus that of the kinetic energy within the moving ice. The force balance technique was pioneered by Van Der Veen and Whillans (1989a) and is an indirect method used to estimate force character (such as basal resistance) within the ice flow. Price *et al.* (2002) used the force balance method on the onset area of Ice Stream D. Field data was sourced from Chen *et al.* (1998) (surface velocity and elevation). Basal geometry and surface topography were first used to estimate deformation components (flow direction and rate), in comparison to observations flow orientation was accurate to ~9º and for faster flow rates (>35ma^{-1}) accurate to 5º. Calculated deformation rates can be subtracted from observed ice velocity to offer estimates of basal sliding rates and direction. Sub-glacial water flow was calculated from the hydraulic potential function, which calculates potential from both ice overburden (from depth, density of ice) and elevation (potential flow paths). Price *et al.*(2002), however chose to exclude the use of basal shear stress as they considered it was ~0.01 as much as important due to the significant depth of ice streams and the low rates of shear (creep rates). Basal water flux can be inferred from hydraulic potential as an area of higher pressure will flow towards an area of relative low pressure, this also relates to latent heat exchange and transport across the bedrock. Bed character of Ice Stream D was considered from Studinger *et al*. (2001), which proposed that the bedrock was 'draped' marine sediments. This is in some agreement with Vogel *et al.* (2002) who suggest a 12-25 meter thick dirty basal ice layer present at the ice stream-bed interface. Engelhardt and Kamb (1998) also found a 9 meter unfrozen till mixture from seismic measurements. Water has also been confirmed present from a Byrd Station (Siple Coast) borehole and the presence of a subglacial lake at the head of Ice Stream B (Siegert and Bamber, 2000) both suggest the potential of warm (wet) basal conditions.

Another possible mechanism, till deformation is known to occur in many temperate glaciers, though it is unsure whether till deformation is occurring under the Siple Coast ice streams. Engelhardt and Kamb (1998) found significant slip at the ice/ till interface and identified significant shear in the top 40 cm of the sub glacial till. The primary control on till deformation is pore water pressure though the critical pressure varies significantly with dependence on the clast characteristics of till (till shear strength) (Wu *et al.* 1996). The uncertainties with the discussed basal mechanisms are limiting to force balance analysis when modelled, though the basal friction components (slip and till deformation) can be considered generally as a single component. Van Der Veen and Whillans (1996) discussed these two possibilities and concluded that which ever mechanism was active, would not highly effect the basal flow rate, whether it be sliding or till deformation. Price *et al.* (2002) (above) calculated driving force, and separated resistance into two components (basal and lateral drag) on a longitudinal transect of Ice Stream D (*Figure 5*). These two components were used independently by Van Der Veen and Whillans.

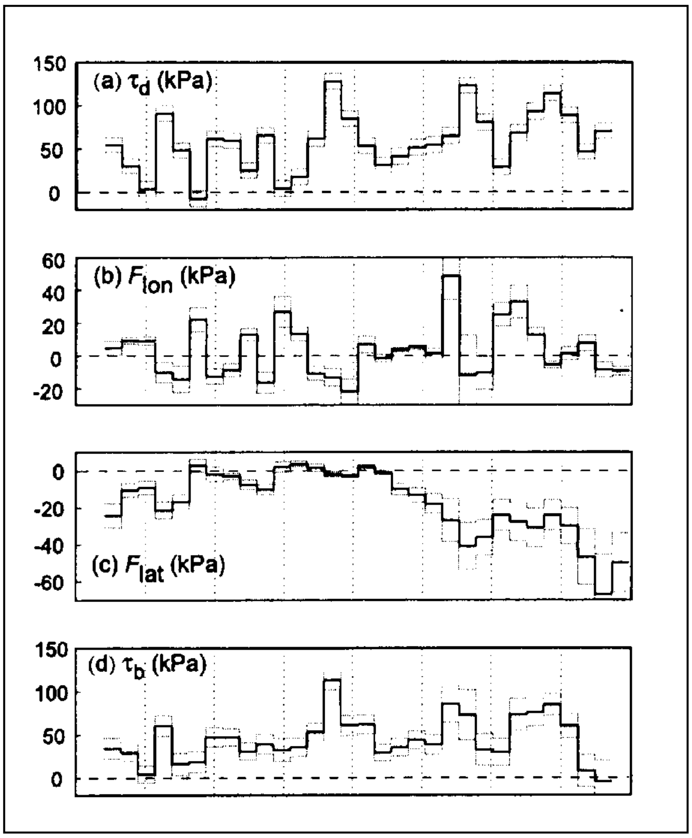

Figure 5. Driving stress (a) along a longitudinal transect to the onset area of Ice Stream D, (b) the longitudinal stress variation and (c) and (d), the partitioning of the resistive forces (lateral drag and basal drag respectively (Price et al. 2002).

Partitioning of the resistive stresses has proven to give insights into the large variation of dominant driving flow mechanisms.

Conclusions

Ice stream research has developed many avenues of investigation over the past 15 years. This development is very much due to the high concern for the stability of the West Antarctic Ice Sheet and from the understanding of the ice streams importance as the potential floodgates of the WAIS drainage system. However, the extent of understanding is somewhat limited due to various factors. The isolation, scale, expense and logistics have severely limited the research potential. Little is known about the basal mechanisms, this is limited primarily due to the depth of the ice streams (~1km). There are two main basal mechanisms. Basal slip is known to occur to some degree, this is likely but there is limited proof. The extent of water found, and hydraulic potential that has been calculated suggests the presence of water in the basal system (thus suggesting a warm based flow). Till deformation is another hypothesis and the finding of a till-ice layer confirms the potential. There is question to the geological controls on flow rates and as a possible catalyst for ice-stream onset.

Ice stream models are developing rapidly though the poor understanding of mechanisms has somewhat burdened the ability to accurately model flow. A better understanding of lateral drag and lateral entrainment of ice at the onset is also an essential gap that must be filled. Though this process has been well observed, yet models are not yet comparable.

The complete understanding of ice streams is very far away, though for a complete understanding, it is essential to compare field measurements for model verification.

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