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Increased water storage at ice-stream onsets: a critical mechanism?

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ABSTRACT. The interdependence of rapid ice flow, surface topography and the spatial distribution of subglacial water are examined by linking existing theories. The motivation is to investigate whether the acceleration of an ice-stream tributary contains a positive feedback that encourages the retention of subglacial water that leads to faster flow. Periodically varying surface and bed topographies are related through a linear ice-flow perturbation theory for various values of mean surface slope, perturbation amplitude and basal sliding speeds. The topographic variations lead to a periodic variation in hydraulic potential that is used to infer the tendency for subglacial water to be retained in local hydraulic potential minima. If water retention leads to enhanced basal sliding, a positive feedback loop is closed that could explain the transition from slower tributary flow to faster-streaming flow and the sustained downstream acceleration along the tributary–ice-stream system. A sensitivity study illustrates that the same range of topographic wavelengths most effectively transmitted from the bed to the surface also strongly influences the behavior of subglacial water. A lubrication index is defined to qualitatively measure the heterogeneity of the subglacial hydrologic system. Application of this index to field data shows that the transition from tributary to ice stream closely agrees with the location where subglacial water may be first stored.

INTRODUCTION

The rapid flow of ice streams dominates the dynamic character of ice sheets (Bentley, 1987; Alley and Bindschadler, 2001). Their demonstrated ability to stagnate (Retzlaff and Bentley, 1993; Smith and others, 2002), gradually decelerate (Bindschadler and Vornberger, 1998; Joughin and others, 2002) and suddenly stop and start on the timescale of minutes (Bindschadler and others, 2003) implies an ability to significantly alter the mass balance of the surrounding ice sheet on many timescales.

An outstanding question concerning ice streams is by what process they form. Ice streams exhibit the unusual characteristic of increasing speed downstream as driving stress decreases. Various explanations exist for this behavior (Whillans and Van der Veen, 1993; Bindschadler and others, 2001; Kamb, 2001). Many depend on a decreasing amount of basal friction downstream, although stream widening (where it occurs) also can result in faster flow (Raymond, 1996). Ice streams are fed by tributaries within which the opposite condition applies, i.e. downstream acceleration of the ice is accompanied by an increase in driving stress. The transition between flow regimes is referred to as the ice-stream 'onset' (Bindschadler and others, 2001). The change in flow mode reflects a change in the nature of the basal sliding and is likely tied to a change in the character of basal lubrication. The presence and presumably the amount of water along with the pressure of this hydraulic system and the material properties and state of the subglacial till, as influenced by the water, determine the basal friction. From analysis of bed echo strength, Blankenship and others (2001) have interpreted a change in the subglacial material from hard bedrock to soft sediments at many of the West Antarctic ice-stream onsets and attribute this change as the cause of the tributary to ice-stream flow transition. Here we consider the importance of water in explaining not only this transition from tributary to ice-stream flow, but also the more widespread gradual acceleration of flow speed along the tributary–ice-stream system.

The concept we explore includes three characteristics of ice dynamics which have not been linked previously: faster ice is more effective at transmitting basal topography to the surface topography; subglacial water pressures are much more sensitive to surface topography than to basal topography; and a more spatially variable water-pressure field will tend to include more regions of lower pressure where more subglacial water will be retained locally, reducing basal friction in these areas while increasing basal shear stress in areas of higher hydraulic potential. We work stepwise through each relationship before combining them in a 'lubrication index'. This index increases downflow along the tributary–ice-stream system, indicating a tendency for increasing water storage and, presumably, lower basal friction. Finally we discuss the possible use of this lubrication index as a useful parameterization of the positive feedback between ice-flow speed and basal lubrication, for numerical models of ice-stream flow and evolution.

TRANSMISSION OF BED TOPOGRAPHY TO SURFACE

The surface topography of ice streams is rougher than either the adjacent ice ridges or the upstream catchment areas (Bindschadler and Vornberger, 1990). The underlying reason for this relationship rests in the rheologic characteristics of ice as a viscoelastic material. These determine the specific relationship between the surface topography of the ice and the topography of the bed over which the ice flows, its speed (both sliding and deformation components) and its thickness. Numerous treatments of this problem have been published. The first correct solution was by Jóhannesson (1992). Here we employ a later treatment because it provides explicit equations for the parameters we seek to examine (Gudmundsson, 2003). Although Gudmundsson's theory also assumes a linear rheology of constant viscosity, it addresses high ratios of sliding to deformation speed for a

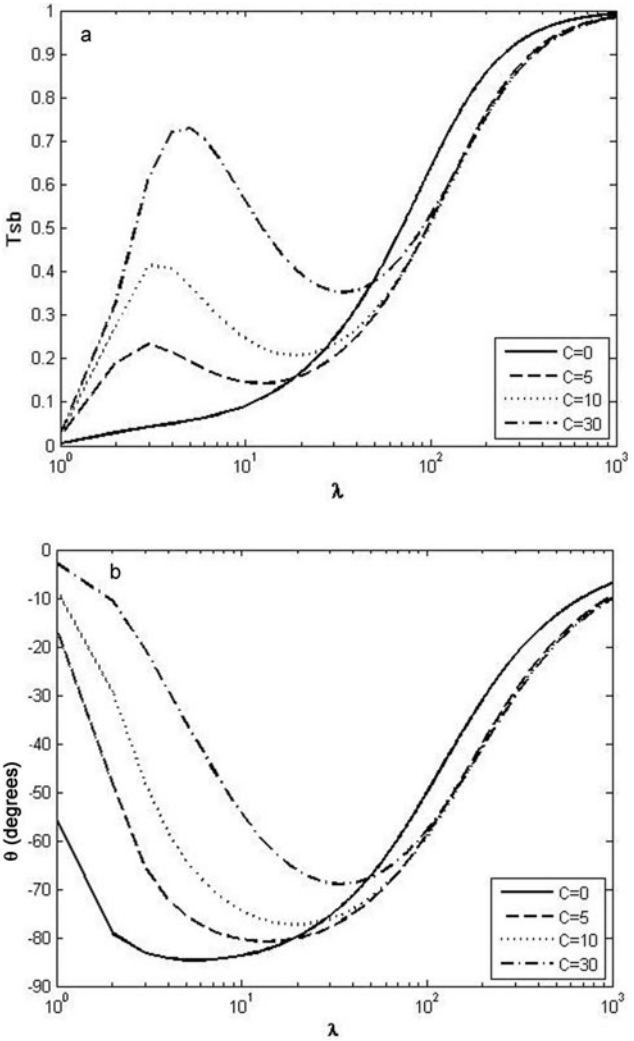

Fig. 1. Transmission efficiency, T_{sb} (a), and phase shift, θ, in degrees (b) of surface topography caused by ice flow over basal topography. Wavelength, λ, is plotted on log scale and in units of ice thickness. C refers to sliding speed (in units of surface deformation speed).

range of perturbation to ice-thickness ratios. A more complete treatment comparing non-linear ice rheologies is reported by Raymond and Gudmundsson (2005).

In the case where basal sliding dominates over the effects of internal deformation, Gudmundsson (2003, equation 70) showed that for a linear rheology the surface expression of a regular, periodically undulated bed, defined by the 'transmission efficiency', T_{sb}, is:

$$T_{sb} = \frac{k^2[Vf + (V + k^2C^2)\cosh k]}{\sqrt{[k^2V(k^2V + f\cosh k + 1)]^2 + [(f\sinh k - k)\cot\alpha]^2}}, \quad (1)$$

where $f = \cosh k + kC\sinh k$ and k is the bed wavenumber (non-dimensionalized by ice thickness, H), V is the surface speed (non-dimensionalized by deformation speed at the surface), C is the sliding speed (also non-dimensionalized by deformation speed at the surface) and α is the mean surface slope. In physical terms, T_{sb} is the ratio of the surface undulation amplitude to the bed undulation amplitude. The published theory considers both horizontal dimensions separately: here we confine ourselves to the along-flow direction only. The wavelength of the surface topography matches that of the bed, with the phase shift between the two given by:

$$\theta = \frac{-(f\sinh k - k)\cot\alpha}{k^2V(k^2V + f\cosh k + 1)}, \quad (2)$$

where a positive phase shift represents a downstream offset of the surface topography relative to the bed.

Transmission efficiency, T_{sb}, and phase shift, θ, are shown in Figure 1 for a range of bed wavelengths (in units of ice thickness). The shortest bed wavelengths are strongly damped with minor surface expression and the phase shift is least for relatively faster sliding speeds. In contrast, the longest bed wavelengths are preserved at full amplitude and with a small phase shift. These consequences are intuitive and match observations. What is less intuitive is that there is a range of intermediate wavelengths where the effective transmission of the basal amplitude to the surface is relatively enhanced and that both the range of enhanced wavelengths shifts to longer wavelengths, and the enhancement amplitude increases as the sliding speed becomes a larger multiple of the deformation speed. Within this range of enhanced bed-to-surface transmission wavelengths, the phase shift is largest for the relatively slower sliding speeds and shorter wavelengths.

CONCLUSIONS

The non-uniform filtering of basal topography to surface topography through rapidly sliding ice strongly affects the character of the subglacial hydrologic system. The larger transmission efficiency of a range of basal wavelengths was identified by Gudmundsson (2003). This range of wavelengths, the transmission efficiency and the corresponding phase shift between the surface and bed undulations depend on sliding speed, mean slope, basal wavelength and ice thickness.

Basal and surface topographies, in turn, determine the subglacial hydraulic potential, with the surface topography dominating this relationship. Wavelengths most efficiently transmitted from bed to surface are responsible for the greatest heterogeneity of the hydraulic potential. The physical interpretation of this heterogeneity is that the bed is better lubricated in areas where the subglacial hydraulic potential is lowest, while areas of highest hydraulic potential will support the majority of the driving force through basal shear stress. As speed increases, the heterogeneity of the hydraulic potential will increase, decreasing the size of the areas of high friction where driving force is concentrated. This will lead to increased basal shear stress, and thereby lead to increased sliding speeds. We surmise that this positive feedback will eventually lead to speeds where an ice stream is formed and at which the ice stream can sustain its own sliding motion through production of sufficient amounts of basal water. Although we do not examine any temporal dependence, we do define a water lubrication index and show that this is related to the lubrication factor used in a previous analysis of ice-stream energy balance (Raymond, 2000).

The sensitivity study of this hydraulic potential variation is conducted in terms of the lubrication index. In a wide range of conditions, the lubrication index exceeds unity, which corresponds to water storage in the simplified two-dimensional case. This usually occurs beneath the upstream sides of surface undulations. The dominant wavelengths in bed-to-surface transmission efficiency reach this water storage condition at the lowest sliding speeds and shallowest mean slopes.

Our single case study using field data supports our theory and indicates that the identified threshold when subglacial water is first stored is in rough agreement with the position where a tributary sliding by 'traditional' kinematics (basal shear stress positively correlated with speed) switches to 'streaming' kinematics (basal shear stress negatively correlated with speed).