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Brief communication
"Can recent ice discharges following the Larsen-B ice-shelf collapse be used to infer the driving mechanisms of millennial-scale variations of the Laurentide ice sheet?"

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Abstract. The effects of an ice-shelf collapse on inland glacier dynamics have recently been widely studied, especially since the breakup of the Antarctic Peninsula's Larsen-B ice shelf in 2002. Several studies have documented acceleration of the ice streams that were flowing into the former ice shelf. The mechanism responsible for such a speed-up lies with the removal of the ice-shelf backforce. Independently, it is also well documented that during the last glacial period, the Northern Hemisphere ice sheets experienced large discharges into the ocean, likely reflecting ice flow acceleration episodes on the millennial time scale. The classic interpretation of the latter is based on the existence of an internal thermo-mechanical feedback with the potential to generate oscillatory behavior in the ice sheets. Here we would like to widen the debate by considering that *Larsen-B-like* glacial analog episodes could have contributed significantly to the registered millennial-scale variablity.

1 Introduction

Over the last two decades climate warming has begun to noticably affect the Antarctic Peninsula. Annual mean air surface temperatures have increased by $\sim 3\,\mathrm{K}$ (e.g. Vaughan et al., 2003). Ice shelves are also responding rapidly to a warmer ocean (e.g. Cook et al., 2005; Jacobs et al., 2011) and three major sudden collapses have been observed: the Larsen A in January 1995, Wilkins in March 1998 and the Larsen B in March 2002.

The potential effect of an ice-shelf breakup on inland ice flow was already predicted some decades ago (Hughes, 1977; Thomas, 1979). A confined ice shelf exerts a backforce via longitudinal stresses on the inland glaciers that feed it. However, the quantification of this mechanism remains highly model-dependent, while at the same time, the limited observations available suggest more stable glacier–ice-shelf behavior (Alley and Whillans, 1991; Vaughan, 1993) than expected theoretically. By focusing on the Larsen-B case, several studies based on satellite observations have finally highlighted the importance of the ice-shelf buttressing effect for understanding ice sheet mass balance and also for accurately projecting sea level changes in the context of a warming ocean (Rignot et al., 2004; Scambos et al., 2004; Hulbe et al., 2008; Rott et al., 2011).

Meanwhile, the study of marine sediment cores has revealed pseudo-cyclical millennial-scale variability in the amount of ice rafted debris (IRD) present in the North Atlantic floor during last glacial period (Heinrich, 1988). Some time periods show an unusually large amount of widely dispersed IRDs (near the coast of Portugal), which are so-called Heinrich events (HEs). In the cores, these "Heinrich layers" are primarily composed of detritical material from the areas around Hudson Bay (Aksu and Mudie, 1985; Chough et al., 1987; Bond et al., 1992; Andrews, 1998; Hemming, 2004). However, without strictly being considered as Heinrich events, several peaks of IRDs can be counted between the formal HEs (Hodell et al., 2010), usually during relative minima of temperature in Greenland (i.e. during stadials). As discussed by Andrews (2000), there are three possible explanations for the peaks of IRDs found in the middle of the North Atlantic: (1) an increase in iceberg flux with a steady sediment content; (2) a change in sediment concentration with steady iceberg flux; and (3) a change in the location (and/or rate) of iceberg melting. Case (1) is commonly assumed to be the most plausible explanation and IRD peaks are then interpreted as enhanced iceberg production from the Laurentide ice sheet (LIS).

Different mechanisms have been proposed to explain these ice discharge events. The "classical" explanation considers these to be internal oscillations of the LIS associated with cyclical switching between a frozen and a temperate basal ice layer (MacAyeal, 1993; Calov et al., 2002). On the other hand, the potential effects of an ice-shelf breakup were also postulated to play an important role via atmospheric warming (Hulbe et al., 2004, see also the comment of Alley et al., 2005), tidal effects (Arbic et al., 2004), sea-level rise (Flückiger et al., 2006) and/or oceanic subsurface warming (Shaffer et al., 2004; Clark et al., 2007; Alvarez-Solas et al., 2010b, 2011; Marcott et al., 2011). Concerning the latter hypothesis, proxy studies have revealed large changes in both mid-high latitude oceanic heat content (i.e. during Dansgaard-Oescheger events) (e.g. Dansgaard et al., 1993; Hodell et al., 2010) and atmospheric temperatures. Additionally, recent modelling work (e.g. Mignot et al., 2007; Brady and Otto-Bliesner, 2011; Marcott et al., 2011) indicates that during Greenland cold periods (stadials, with weakened meridional overturning circulation) the temperature of the oceanic subsurface can rise several degrees, with strong implications for ice-shelf stability (Jonkers et al., 2010). Moreover, the presence of IRD peaks in the South Atlantic during last glacial period reflect millennial-scale iceberg discharges from Antarctica, which have been interpreted as Antarctic ice-sheet instabilties triggered by episodes of ice-shelf collapses (Kanfoush et al., 2000, see also the comment of Clark and Pisias, 2000).

Finally, the recent availability of the first generation of hybrid (ice-sheet–ice-shelf; SIA/SSA) models applied to the Laurentide makes this scenario fully testable. Here we briefly discuss results of the hybrid model GRISLI by showing that the collapse of the Laurentide ice shelves indeed had the potential to induce significant ice discharges on the millennial time scale during the last glacial period.

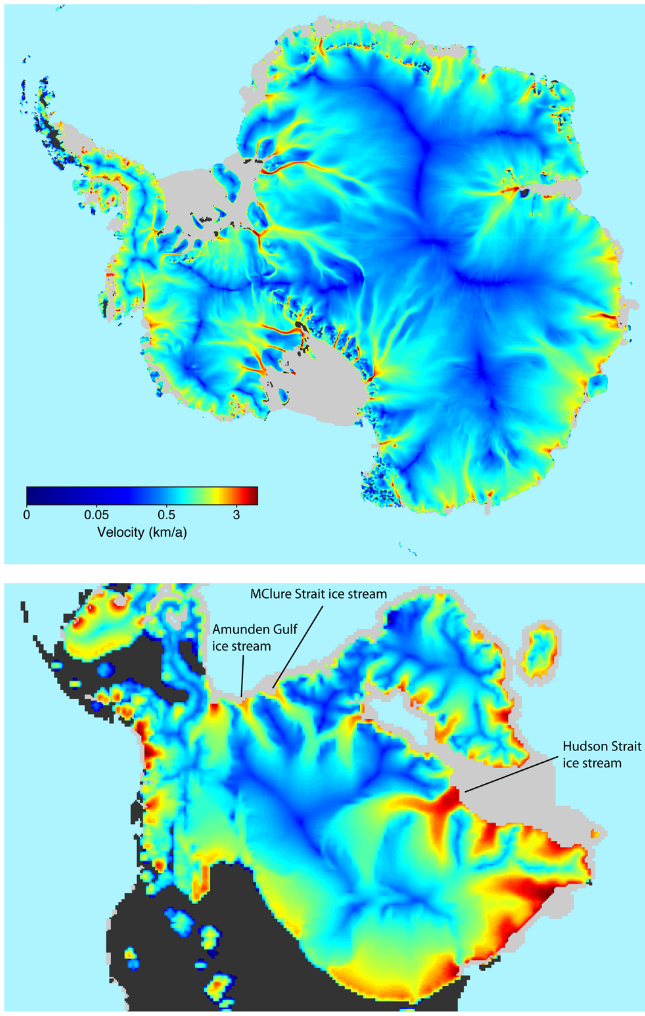

Fig. 1. Top: present-day Antarctic surface ice velocities obtained from the SeaRISE data website (Le Brocq et al., 2010). Bottom: Simulated Laurentide ice velocities during the last glacial maximum. Light grey regions denote floating ice shelves.

2 Model setup and experimental design

The three-dimensional model, GRISLI, treats both grounded and floating ice on the hemispheric scale. It was developed by Ritz et al. (2001) and validated over Antarctica (Ritz et al., 2001; Philippon et al., 2006; Alvarez-Solas et al., 2010a) over Fennoscandia (Peyaud et al., 2007) and over the Laurentide (Alvarez-Solas et al., 2011). It explicitly calculates the LIS grounding line migration, ice-stream velocities and ice-shelf behavior. Inland ice deformation is computed according to the stress balance given by the shallow ice approximation (SIA, Morland, 1984; Hutter, 1983). Thanks to its hybrid approach, ice shelves are calculated under the shallow shelf approximation (SSA) and ice streams are treated as *dragging ice shelves* (MacAyeal, 1989; Bueler and Brown, 2009). The grid resolution in this study is 40 km. A more detailed description of the model's dynamics is provided by

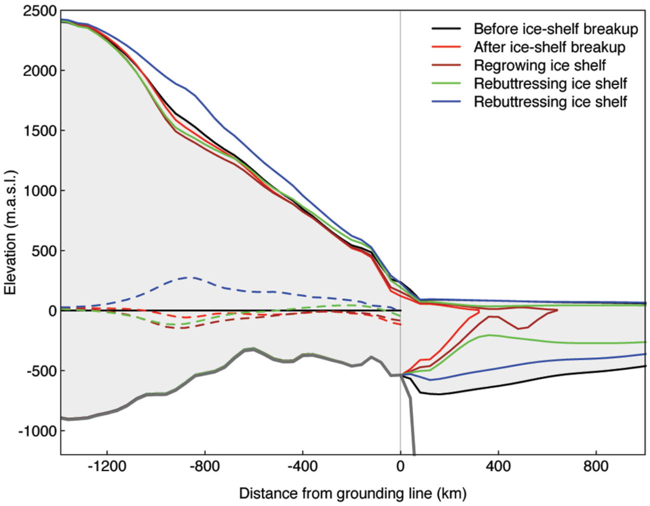

Fig. 2. Simulated along-flow profiles of surface elevation. Colors indicate different phases of the Hudson-Bay/Strait ice stream with respect to the Labrador ice shelf status and go from black (initial unperturbed steady state) to red (after 500 yr of enhanced basal melting), brown (1100 yr after the onset of the perturbation; 100 yr after the end of the enhanced basal melting period), green (1900 yr after the onset of the perturbation; 900 yr after the end of the enhanced basal melting period) and blue (3000 yr after the onset of the perturbation; 2000 yr after the end of the enhanced basal melting period). Dashed lines show the elevation anomaly relative to the steady state.

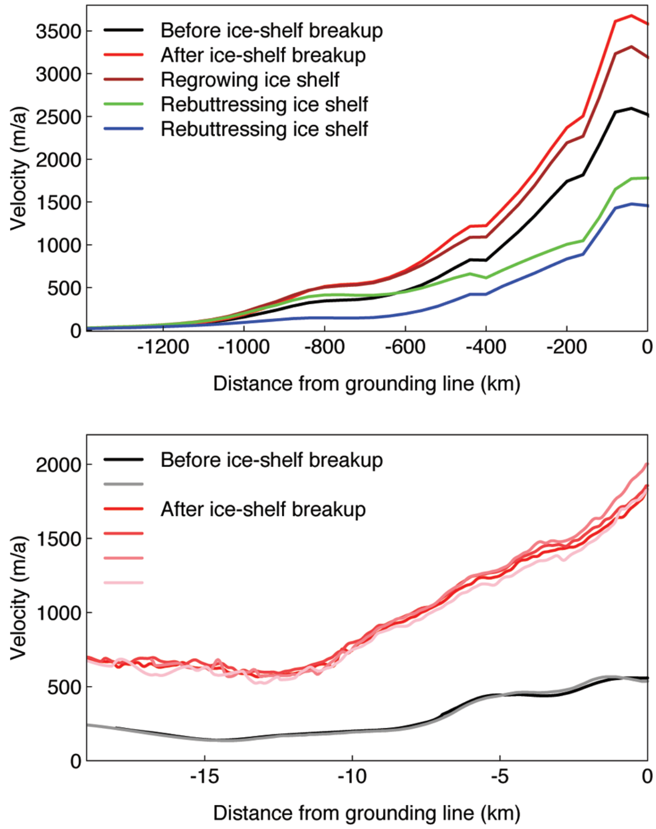

Fig. 3. Top: simulated along-flow profiles of ice velocity. The lines are color-coded for time as in Fig. 2. Bottom: surface ice velocity of the Crane Glacier profile; derived from the satellite data published by Rott et al. (2011) and shown in their Fig. 6. The different profiles, from black to light pink, correspond to December 1995, December 1999, October 2008, November 2008, April 2009 and November 2009.

Ritz et al. (2001); Peyaud et al. (2007); Alvarez-Solas et al. (2011) and references therein. In order to isolate the dynamic effects of the ice-shelf collapse, the surface climate imposed on the ice sheet is not time-evolving. Climate fields (including subsurface oceanic temperatures used for computing ice-shelf basal melt) are based on the standard CLIMBER-3α simulation of the last glacial maximum (LGM) (Montoya et al., 2005; Montoya and Levermann, 2008). Ice-shelf breakup is ensured here by quadrupling the former standard basal melt rates over all Laurentide ice shelves. The timing of the ice-shelf response to this enhanced basal melt is labelled in Figs. 2 and 3. We hereafter analyze the consequence of such an imposed ice-shelf collapse on three different Laurentide ice streams (i.e. McLure Strait, Amundsen Gulf and Hudson Strait ice streams; see Fig. 1, top), while at the same time, we compare the Crane Glacier response to the observed Larsen-B disappearance (Fig. 1, bottom).

3 Results

Despite the clear difference in size, Laurentide ice streams also react significantly to the breakup of their respective ice shelves, just as Crane Glacier did after the Larsen-B collapse (Fig. 3). Within a spatio-temporal scale two orders of magnitude larger (i.e. thousands vs. tens of kilometers; millennia vs. decades) the GRISLI model shows that the Hudson Strait ice stream accelerates similarly following the confined Labrador ice shelf breakup (Fig. 3). In the case of the Crane Glacier, satellite data indicate a large decrease in the surface elevation occurred within the post-collapse months. The stress perturbation at the glacier front associated with complete ice shelf removal to the grounding line initiates the acceleration which, in turn, stretches the ice and thins it. The associated lowering of the glacier surface then propagated upstream through dynamic coupling over the ensuing months and has continued for several years. The post-collapse period is characterized by similar velocity values along the Crane glacier profile (i.e. a speed-up of $\sim 1300\,\mathrm{m\,yr^{-1}}$ near the grounding line), suggesting that the ice flow has not yet adapted to the new boundary conditions and a balance state still has not been reached (Rott et al., 2011).

Similarly, the Labrador ice shelf thinning and enhanced calving reduce ice-shelf buttressing, which allows faster flow. This pattern is successfully captured by the GRISLI model: the imposed (over 1000 yr) fourfold increase in ice-shelf basal melting translates into a complete removal within

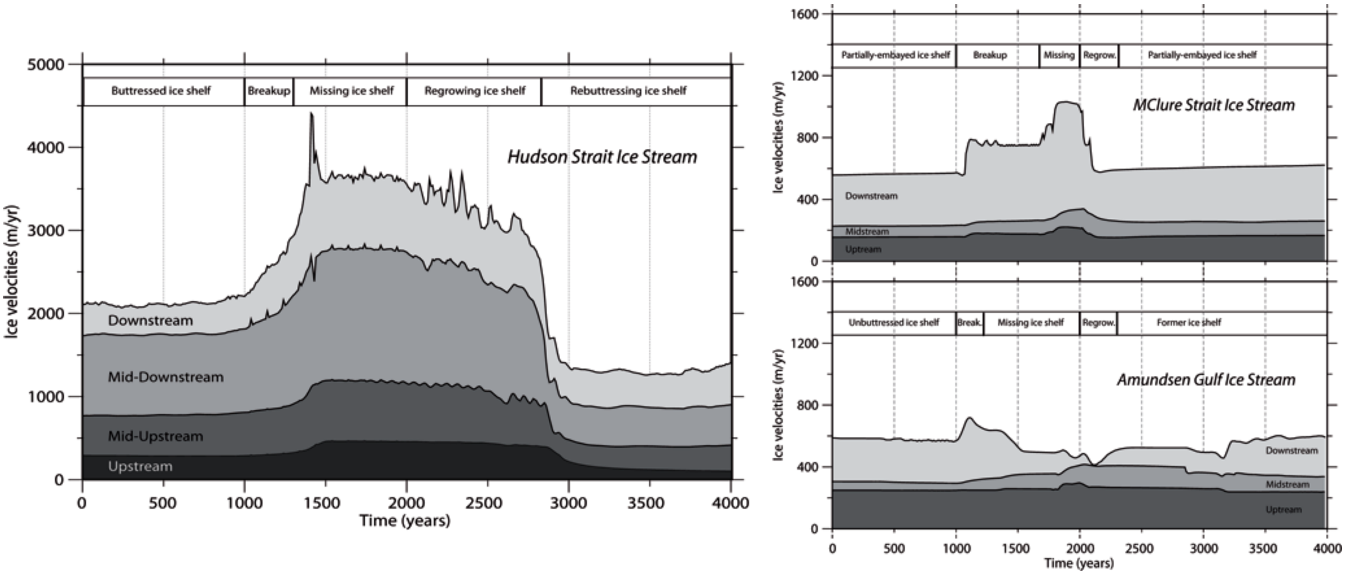

Fig. 4. Time evolution of ice velocities (in m yr^{-1}) for the Hudson Strait (left), MClure Strait (top-right) and Amundsen Gulf (bottom-right) ice streams.

300 yr (Figs. 3 and 4). A progressive acceleration is simulated near the grounded line due to ice thinning. Once the ice shelf is missing and the calving front has shifted to the grounded line, velocities appear to reach a steady state characterized by a strong increase in ice flow (i.e. a speed-up of $\sim 1800\,\mathrm{m\,yr^{-1}}$ near the grounding line). Returning to the former floating-ice basal melt rates then allows a phase of ice-shelf regrowth, which favors a gradual decrease in ice velocities. As the ice shelf regrows, inland ice flow substantially decelerates, responding to an increase in the buttressing caused by the new confinement of the Labrador ice shelf.

The simulated effects of the ice-shelf breakup on the far inland dynamics depend on the magnitude of the former ice-shelf buttressing. In the case of the Amundsen Gulf, a lack of any enbayment means that the ice shelf spreads anisotropically from the grounding line (i.e. without any stress present at the ice-shelf boundaries that determine a favored direction of spread), thus not generating any substantial backforce. An ice flow acceleration is nevertheless simulated near the grounding line as a consequence of the ice-shelf collapse and ice thinning from enhanced basal melt. But this effect only propagates inland marginally (Fig. 4; bottom-right panel). Further changes, as well as changes inland, in this ice stream's velocities are much more likely responding to internal variability than the ice-shelf collapse. Meanwhile, because of topographical characteristics, the MClure Strait ice stream flows into a partially embayed ice shelf. This results in more evident downstream acceleration following the ice-shelf's collapse (Fig. 4; top-right panel). This effect clearly propagates upstream and begins to cease when the ice shelf buttresses again.

Concerning the implications of these results for the mechanisms driving Heinrich events, it is important to note that the ice released to the ocean resulting from the acceleration of the Hudson Strait ice stream represents a mean flux of ~ 0.04 Sv during the first 1000 yr of increased ice-shelf melting, but continues during an additional 1000 yr with a weaker mean flux of ~ 0.02 Sv corresponding to the phase of a regrowing ice shelf. This ice discharge implies a sea-level rise of ~ 2.5 m for such an event, which agrees with the isotopic-modelling-based calculation of (Roche et al., 2004) and proxy-based estimations (e.g. Hemming, 2004; Arz et al., 2007).

4 Discussion

The hybrid model used here simulates different levels of ice-stream acceleration depending on the size and geometry of the former ice shelves that collapse. As a consequence of the thinning simulated along the profile, the upstream parts of the Hudson Strait ice stream suffered a thickness reduction of several hundred meters. This translates into a less pronounced surface slope along the profile and an associated decrease in the gravitational driving flow, explaining the reduced velocities during the re-buttressing period with respect to the initial state (Figs. 3 and 4). At this point, a new Labrador ice-shelf collapse would then cause a weaker acceleration, even for a similar magnitude buttressing removal; as suggested by Schoof (2007), the grounding line flux is about half as dependent on butressing as it is on ice thickness. This phenomenon of distinct responses to the same ice shelf removal depending on the inland glacier behavior prior to the collapse opens the way to speculations about oscillatory mechanisms. In other words, the existence of two different characteristic times (i.e. the time needed for ice shelf regrowth and re-buttressing and the time needed for thickening at the grounding line) gives the system a non-linearity potentially appropriate to induce oscillations.

In light of these results, our answer to the question posed in the title of this paper is certainly yes. However, several aspects likely pertinent to this analogy remain uncertain. First, the main motivation for considering that glacial ice-shelf collapses may have contributed significantly to Laurentide millennial-scale variability lies with only a single present-day example, the Larsen-B breakup. One could believe, however, that this is not a problem given that the ice-shelf buttressing effect is based on robust physics. Nevertheless, without using *Full-Stokes* models, several uncertainties remain in the numerical simulation of these physical processes. For example, as documented by Bueler and Brown (2009), the shallow shelf approximation is an effective "sliding law" for ice-stream flow within the context of hemispheric ice-sheet modeling. However, the hybrid approach used here for calculating ice velocities implies, by default, a sharp transition between areas controlled by the SIA uniquely and areas were both SIA and SSA are computed. The criterium followed here for avoiding potential numerical instabilities in this transition zone consists of computing the SSA terms of a larger area than the strict region in which these terms are applied (which is determined by the presence of basal water and sediments). Therefore, SSA terms are already computed for areas susceptible to becoming ice streams or ice shelves. Second, the grid resolution of the ice-sheet model is 40 km. This relatively coarse resolution is necessary when carrying out hemispherical-scale simulations of several thousand of years. Whereas the main ice streams simulated here are in very good agreement with geomorphologic reconstructions (Winsborrow et al., 2004) and with data-calibrated ice-shet simulations (Stokes and Tarasov, 2010; Tarasov et al., 2011), the resolution is not enough to capture small valley ice streams and glaciers.

However it does not significantly affect the upstream propagation of effects suffered by the Hudson Strait ice stream shown here. Similar responses to an imbalance at the grounded line have been noted in other modelling studies focused on finer scales both for Greenland (Nick et al., 2009) and West Antarctica (Payne et al., 2004). Our model reproduces the pattern of acceleration and thinning that results from buttressing removal shown in these studies and gives similar characteristic time responses of the kinematic and diffusive terms of upstream propagation of the imbalance at the grounded line.

On the other hand, ice-stream velocities depend here on basal dragging coefficients and indirectly on the presence of sediments. Dragging coefficients can be efficiently calibrated for Antarctica by comparing resulting ice surface velocities given by GRISLI with those measured by satellites (Ritz et al., 2010; Pollard and DeConto, 2012), but this approach cannot be used for the Laurentide, thus uncertainty remains concerning dragging coefficient values which must be explored by sensitivity tests. Finally, as recently shown (Levermann et al., 2011), the simulated ice velocities in ice streams and ice shelves strongly affect the expected calving rates.

All of these rather poorly constrained aspects explain why processes concerning ice-shelf buttressing are likely to be strongly model dependent. For this reason, this communication emphasizes the necessity for new experiments with hybrid ice sheet models. This will definitely shed light on the pertinence of considering coupled ice-stream–shelf dynamics for understanding Laurentide millennial-scale variablity, with important implications in other areas of the climate system.

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