The Cryosphere Discuss., 5, 3113–3127, 2011
www.the-cryosphere-discuss.net/5/3113/2011/
doi:10.5194/tcd-5-3113-2011

The Cryosphere Discussions

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?

J. Alvarez-Solas[1,2,3], A. Robinson[1,3,4], and C. Ritz[5]

[1]Dpto. Astrofísica y Ciencias de la Atmósfera, Universidad Complutense, Madrid, Spain
[2]Laboratoire des Sciences du Climat et de l’Environnement (LSCE)-UMR8212, France
[3]Instituto de Geociencias (IGEO), CSIC-UCM, Spain
[4]Potsdam Institute for Climate Impact Research, Potsdam, Germany

[5]Laboratoire de Glaciologie et Géophysique de l'Environnement, UJF-Grenoble 1/CNRS, LGGE UMR 5183, Grenoble, 38041, France

Received: 28 October 2011 – Accepted: 1 November 2011 – Published: 11 November 2011

Correspondence to: J. Alvarez-Solas (jorge.alvarez.solas@fis.ucm.es)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The effects of an ice-shelf collapse on inland glacier dynamics have recently been widely studied, especially since the breakup of 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 $\sim 3K$ (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 suggested 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 revealead 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 episodes of an unusually large amount and especially widely dispersed IRDs (near the coast of Portugal) have been so-called Heinrich events (HEs). These Heinrich layers (Hemming, 2004) are primarily composed of detritical material from the areas around Hudson Bay (Bond et al., 1992). However, without strictly being considered as Heinrich events, several peaks of IRDs can be counted between the formal HEs, usually during relative minima of temperature in Greenland (i.e., during stadials) and likely reflect 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), 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, with strong implications for ice-shelf stability. Moreover, 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 strongly modulate significant ice discharges on the millennial time scale during the last glacial period.

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 (Morland, 1984; Hutter, 1983). Ice shelves are described following MacAyeal (1989) and ice streams are also treated under MacAyeal's *L1* equation, thus they are considered as *dragging ice shelves*. A more detailed description of the model's dynamics can be found in 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 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. 2). 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. 2). 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 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 years) fourfold increase in ice-shelf basal melting translates into a complete removal within 300 years (Figs. 2 and 3). 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 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, 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. 3; 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. 3; top-right panel). This effect clearly propagates upstream and begins to cease when the ice shelf buttresses again.

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. 2 and 3). 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 sensitive to buttressing as it is to 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. Firstly, 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. 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), 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 exposed (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.

Acknowledgements. We thank Marisa Montoya and Christophe Dumas for helpful discussions, Helmut Rott, Ted Scambos and Jennifer Bohlander for sharing their data concerning Larsen-B and Etor Lucio-Eceiza for assistance with the figures. We are also greatful to the PalMA group for useful comments and suggestions. This work was funded under the MOVAC and SPECT-MORE projects. J. A-S was also funded by the Spanish programme, the International Campus of Excellence (CEI).

The publication of this article is financed by CNRS-INSU.

References

Alley, R. and Whillans, I.: Changes in the West Antarctic ice sheet, Science, 254, 959–963, 1991. 3115

Alvarez-Solas, J., Charbit, S., Ramstein, G., Paillard, D., Dumas, C., Ritz, C., and Roche, D.: Millennial-scale oscillations in the Southern Ocean in response to atmospheric CO2 increase, Global Planet. Change, 76, 128–136, 2010a. 3117

Alvarez-Solas, J., Charbit, S., Ritz, C., Paillard, D., Ramstein, G., and Dumas, C.: Links between ocean temperature and iceberg discharge during Heinrich events, Nature Geoscience, 3, 122–126, 2010b. 3116

Alvarez-Solas, J., Montoya, M., Ritz, C., Ramstein, G., Charbit, S., Dumas, C., Nisancioglu, K., Dokken, T., and Ganopolski, A.: Heinrich event 1: an example of dynamical ice-sheet reaction to oceanic changes, Clim. Past Discuss., 7, 1567–1583, doi:10.5194/cpd-7-1567-2011, 2011. 3116, 3117, 3125

Arbic, B., MacAyeal, D., Mitrovica, J., and Milne, G.: PalaeoclimateOcean tides and Heinrich events, Nature, 432, 460 pp., 2004. 3116

Bond, G., Heinrich, H., Broecker, W., Labeyrie, L., McManus, J., Andrews, J., Huon, S., Jantschik, R., Clasen, S., Simet, C., Tedesco, K., Klas, M., Bonani, G., and Ivy, S.: Evidence for massive discharge of icebergs into the North Atlantic Ocean during the last glacial, Nature, 360, 245–249, 1992. 3116

Bueler, E. and Brown, J.: Shallow shelf approximation as a sliding lawin a thermomechanically coupled ice sheet model, J. Geophys. Res, 114, F03 008, 2009. 3120

Calov, R., Ganopolski, A., Petoukhov, V., Claussen, M., and Greve, R.: Large-scale instabilities of the Laurentide ice sheet simulated in a fully coupled climate-system model, Geophys. Res. Lett., 29, 69–1, 2002. 3116

Clark, P., Hostetler, S., Pisias, N., Schmittner, A., and Meissner, K.: Mechanisms for an 7-kyr Climate and Sea-Level Oscillation During Marine Isotope Stage 3, Geoph. Monog., AGU, 173, 209–246, 2007. 3116

Cook, A., Fox, A., Vaughan, D., and Ferrigno, J.: Retreating glacier fronts on the Antarctic Peninsula over the past half-century, Science, 308, 541–544, 2005. 3115

Dansgaard, W., Johnsen, S., Clausen, H., Dahl-Jensen, D., Gundestrup, N., Hammer, C., Hvidberg, C., Steffensen, J., Sveinbjornsdottir, A., Jouzel, J., and Bond, G.: Evidence for general instability of past climate from a 250-kyr ice-core record, Nature, 364, 218–220, 1993. 3116

Flückiger, J., Knutti, R., and White, J.: Oceanic processes as potential trigger and amplifying mechanisms for Heinrich events, Paleoceanography, 21, PA2014, doi:10.1029/2005PA001204, 2006. 3116

Heinrich, H.: Origin and consequences of cyclic ice rafting in the northeast Atlantic Ocean during the past 130,000 years, Quaternary Res., 29, 142–152, 1988. 3116

Hemming, S. R.: Heinrich events: Massive late Pleistocene detritus layers of the North Atlantic and their global climate imprint, Rev. Geophys, 42, RG1005, doi:10.1029/2003RG000128, 2004. 3116

Hodell, D., Evans, H., Channell, J., and Curtis, J.: Phase relationships of North Atlantic ice-rafted debris and surface-deep climate proxies during the last glacial period, Quaternary Sci. Rev., 29, 3875–3886, 2010. 3116

Hughes, T.: West Antarctic ice streams, Rev. Geophys., 15, 1–46, 1977. 3115

Hulbe, C., MacAyeal, D., Denton, G., Kleman, J., and Lowell, T.: Catastrophic ice shelf breakup as the source of Heinrich event icebergs, Paleoceanography, 19, 2004. 3116

Hulbe, C., Scambos, T., Youngberg, T., and Lamb, A.: Patterns of glacier response to disintegration of the Larsen B ice shelf, Antarctic Peninsula, Global Planet. Change, 63, 1–8, 2008.

3116

Hutter, K.: Theoretical glaciology: material science of ice and the mechanics of glaciers and ice sheets, Springer, 1983. 3117

Jacobs, S., Jenkins, A., Giulivi, C., and Dutrieux, P.: Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf, Nature Geoscience, 4, 519–523, 2011. 3115

Le Brocq, A., Payne, A., and Vieli, A.: Antarctic dataset in netCDF format, 2010. 3125

Levermann, A., Albrecht, T., Winkelmann, R., Martin, M. A., Haseloff, M., and Joughin, I.: Kinematic first-order calving law implies potential for . abrupt ice-shelf retreat, The Cryosphere Discuss., 5, 2699–2722, doi:10.5194/tcd-5-2699-2011, 2011. 3120

MacAyeal, D.: Large-scale ice flow over a viscous basal sediment- Theory and application to ice stream B, Antarctica, J. Geophys. Res., 94, 4071–4087, 1989. 3117

MacAyeal, D.: Binge/purge oscillations of the Laurentide ice sheet as a cause of the North Atlantic's Heinrich events, Paleoceanography, 8, 775–784, 1993. 3116

Marcott, S., Clark, P., Padman, L., Klinkhammer, G., Springer, S., Liu, Z., Otto-Bliesner, B., Carlson, A., Ungerer, A., Padman, J., et al.: Ice-shelf collapse from subsurface warming as a trigger for Heinrich events, P. Natl. A. Sci., 108, 13415–13419, 2011. 3116

Montoya, M. and Levermann, A.: Surface wind-stress threshold for glacial Atlantic overturning, Geophys. Res. Lett., 35, L03608, doi:10.1029/2007GL032560, 2008. 3117

Montoya, M., Griesel, A., Levermann, A., Mignot, J., Hofmann, M., Ganopolski, A., and Rahmstorf, S.: The Earth System Model of Intermediate Complexity CLIM*BER*-3α. Part I: description and performance for present day conditions, Clim. Dyn., 25, 237–263, 2005. 3117

Morland, L.: Thermomechanical balances of ice sheet flows, Geophys. Astro. Fluid, 29, 237–266, 1984. 3117

Peyaud, V., Ritz, C., and Krinner, G.: Modelling the Early Weichselian Eurasian Ice Sheets: role of ice shelves and influence of ice-dammed lakes, Clim, Past, 3, 375–386, 2007. 3117

Philippon, G., Ramstein, G., Charbit, S., Kageyama, M., Ritz, C., and Dumas, C.: Evolution of the Antarctic ice sheet throughout the last deglaciation: A study with a new coupled climate–north and south hemisphere ice sheet model, Earth Planet. Sc. Lett., 248, 750–758, 2006. 3117

Rignot, E., Casassa, G., Gogineni, P., Krabill, W., Rivera, A., and Thomas, R.: Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf, Geophys. Res. Lett, 31, L18401, doi:10.1029/2004GL020697, 2004. 3116

Ritz, C., Rommelaere, V., and Dumas, C.: Modeling the evolution of Antarctic ice sheet over the last 420,000 years: Implications for altitude changes in the Vostok region, J. Geophys. Res.-Atmos., 106, 31943–31964, 2001. 3117

Ritz, C., Navas, G., Rémy, F., Ma, Y., Durand, G., and Sacchettini, M.: Calibration and spinup of an ice sheet model: application to the Antarctic ice sheet., Geophysical Research Abstracts, 12, 11819, 2010. 3120

Rott, H., Mller, F., Nagler, T., and Floricioiu, D.: The imbalance of glaciers after disintegration of Larsen-B ice shelf, Antarctic Peninsula, The Cryosphere, 5, 125–134, doi:10.5194/tc-5-125-2011, 2011. 3116, 3118, 3126

Scambos, T., Bohlander, J., Shuman, C., and Skvarca, P.: Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica, Geophys. Res. Lett, 31, L18402, doi:10.1029/2004GL020670, 2004. 3116

Schoof, C.: Ice sheet grounding line dynamics: Steady states, stability, and hysteresis, J. Geophys. Res, 112, F03S28, doi:10.1029/2006JF000664, 2007. 3119

Shaffer, G., Olsen, S., and Bjerrum, C.: Ocean subsurface warming as a mechanism for coupling Dansgaard-Oeschger climate cycles and ice-rafting events, Geophys. Res. Lett, 31, L24202, doi:10.1029/2004GL020968, 2004. 3116

Thomas, R.: The dynamics of marine ice sheets, J. Glaciol., 24, 167–177, 1979. 3115

Vaughan, D.: Implications of the break-up of Wordie Ice Shelf, Antarctica for sea level, Antarctic Science, 5, 403–408, 1993. 3115

Vaughan, D., Marshall, G., Connolley, W., Parkinson, C., Mulvaney, R., Hodgson, D., King, J., Pudsey, C., and Turner, J.: Recent rapid regional climate warming on the Antarctic Peninsula, Climatic Change, 60, 243–274, 2003. 3115

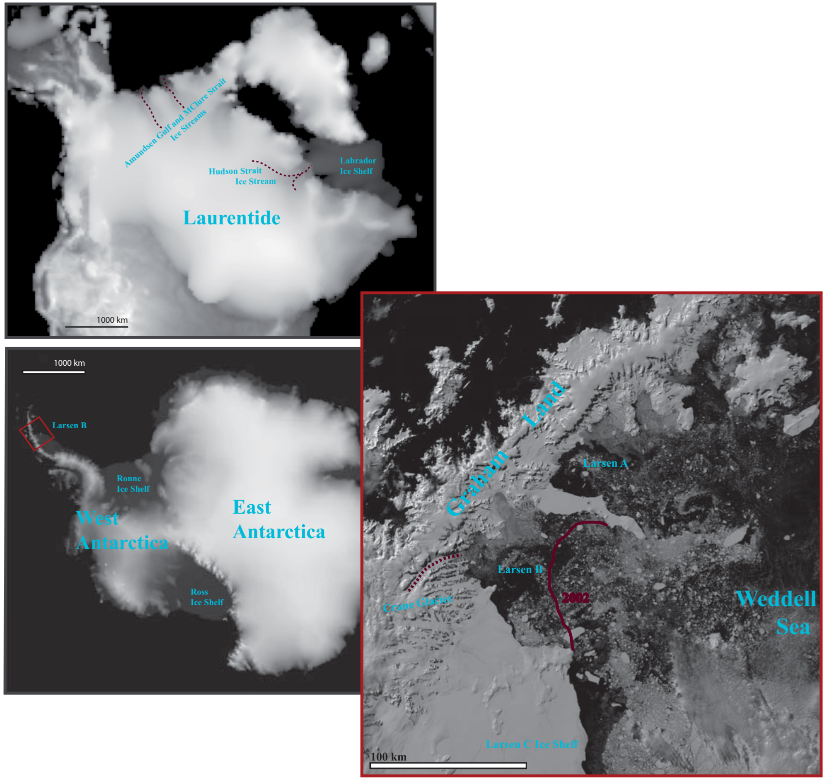

Fig. 1. Top: illustration of the Laurentide ice sheet during the last glacial period obtained from GRISLI simulations (Alvarez-Solas et al., 2011). Bottom: illustration of the present-day Antarctic ice sheet obtained from the SeaRISE data website (Le Brocq et al., 2010). Zoom: MODIS image from 18 June 2009 of the Antarctic Peninsula with 2002 Larsen-B ice-shelf extent prior to its collapse and the Crane glacier profile.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀I | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

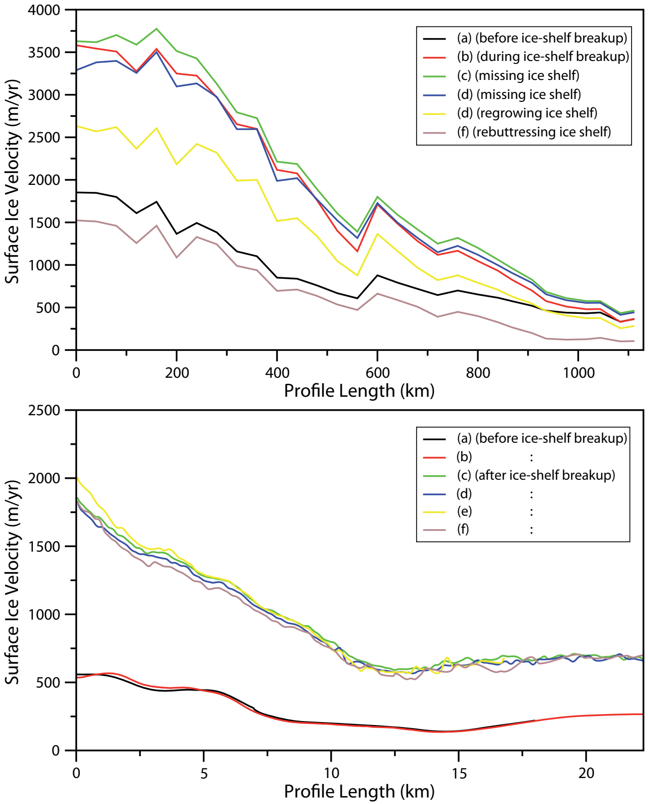

Fig. 2. Top: Surface ice velocity simulated by GRISLI for the Hudson Strait ice stream profile highlighted in Fig. 1. Colors indicate different phases of ice-stream activity with respect to the Labrador ice shelf status. Bottom: Surface ice velocity of the Crane Glacier profile as highlighted in Fig. 1; derived from the satellite data published by Rott et al. (2011) and shown in their Fig. 6. The different profiles correspond to **(a)** December 1995, **(b)** December 1999, **(c)** October 2008, **(d)** November 2008, **(e)** April 2009 and **(f)** November 2009.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▮
▶▮
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

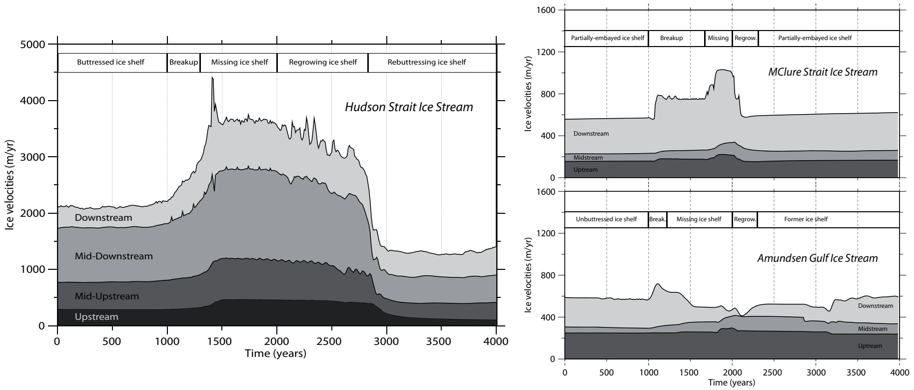

Fig. 3. Time evolution of ice velocities (in $\mathrm{m\,yr^{-1}}$) for the Hudson Strait (left), MClure Strait (top-right) and Amundsen Gulf (bottom-right) ice streams.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀
▶▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion