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Comment on "Catastrophic ice shelf breakup as the source of Heinrich event icebergs" by C. L. Hulbe et al.

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[1] *Hulbe et al.* [2004] argue that the original binge-purge model of their coauthor *MacAyeal* [1993a, 1993b] is not appropriate for Heinrich events but that a new ice-shelf-collapse mechanism may work. We believe that the new collapse mechanism disagrees with important data and that MacAyeal's original model remains viable after appropriate modifications. We have enjoyed a fascinating discussion with Hulbe et al. on this topic, which is stimulating our thinking and research, and we present some of the arguments here for a wider audience.

[2] In MacAyeal's model, thermal cycling in the Hudson Strait region of the Laurentide Ice Sheet caused an alternation between long-lived ice sheet growth and short-lived ice stream draw-down. The main evidence used by *Hulbe et al.* [2004] against *MacAyeal* [1993a, 1993b] is that each Heinrich event followed widespread cooling around the North Atlantic and so was not solely controlled by the "clock" of the Laurentide Ice Sheet, that thermal processes in ice streams tend to slow their motion and so would prevent the massive ice output needed for Heinrich-layer formation, and that there exists no strong evidence for the large changes in ice sheet configuration expected from the Heinrich event surges.

[3] We agree that the Heinrich events seem to have consistently followed regional climatic cooling, but it is easy to have a faster process triggering a MacAyealian oscillator only when it is ready. Indeed, we have proposed more than one such mechanism for cooling triggering Heinrich events [*Alley et al.*, 1996, 2005], and we are confident that additional triggering mechanisms are possible [e.g., *Alley*, 1991].

[4] Thermal controls on ice stream persistence do exist, but as shown by studies (including one involving Hulbe [*Parizek et al.*, 2003]), subglacial water flow from beneath inland regions of ice sheets can both overcome this negative feedback and contribute to the debris entrainment necessary to explain the distal deposits of Heinrich events by allowing freezing of debris-bearing ice from the flowing water before any freezing to the bed. Indeed, the existence of high-speed ice streams and of thermal limits is central in the *MacAyeal* [1993a, 1993b] model.

[5] *Hulbe et al.* [2004, paragraph [56]] also questioned the MacAyeal model because they found "no obvious evidence" for "extraordinary draw-down events" of the Laurentide Ice Sheet (LIS). Yet evidence exists in the Labrador Sector of the LIS for two sector-wide reorganizations of ice flow between the Last Glacial Maximum and final deglaciation [*Dyke et al.*, 2002; *Veillette et al.*, 1999]. The first reorganization indicates an eastward shift of the main center of ice outflow by up to 900 km, with an associated lowering of the ice surface over Hudson Bay of possibly hundreds of meters. Although this extraordinary event cannot be dated precisely, *Dyke et al.* [2002] suggested that it may have resulted from Heinrich event 1.

[6] The dramatic collapse of the Larsen B ice shelf as described by *Hulbe et al.* [2004] and the subsequent speed-up of grounded ice behind [*De Angelis and Skvarca*, 2003] are of great importance in assessing stability of past and future ice sheets. However, we are cautious about applying this mechanism to the Heinrich events as done by Hulbe et al. Our first doubt is simple and indeed is noted by *Hulbe et al.* [2004]. The Larsen B mechanism requires cooling to grow an ice shelf, followed by warming at least in summer to fill ice-shelf surface crevasses with meltwater and may require oceanic warming to weaken the ice shelf from below [*Shepherd et al.*, 2003]. However, all available paleoclimatic records of which we are aware show that the distinctive sedimentary signatures of the Heinrich events began during cold intervals with no premonitory warming. Unless some unobservable short warm periods triggered Heinrich events, we have difficulty reconciling the model with the data.

[7] This requirement of warming to trigger the *Hulbe et al.* [2004] ice-shelf collapse yet lack of premonitory

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warming in the paleoclimatic record is probably the biggest difficulty for their model, but other considerations also serve to cast doubt. For example, if an ice shelf covered broad areas proximal to Hudson Strait prior to Heinrich events, we expect that severe reduction or even elimination of planktonic foraminifera from the surface waters would have resulted. A spike in planktonic numbers prior to Heinrich event 2 in cores from the SE Baffin Island slope, however, would suggest the opposite [*Jennings et al.*, 1996], placing limits on the size of any such ice shelf. Indeed, the dates that have been reported on the timing of Heinrich events in the Labrador Sea and Baffin Bay are on planktonic foraminifera [*Andrews et al.*, 1998; *Hillaire-Marcel et al.*, 1994; *Jennings et al.*, 1996]. These dates overlap those for the onset of Heinrich events obtained from the more distal area of the North Atlantic [e.g., *Bond et al.*, 1992, 1999; *Chapman and Shackleton*, 1999], thus indicating that at least seasonally ice-free conditions existed near the margin of the ice sheet at the time of the events.

[8] We further note that comparison of Greenland ice core records to marine sediment records [e.g., *Bond et al.*, 1993] indicates that many stadials lacking Heinrich layers were as cold as stadials with Heinrich layers. This is expected from the original MacAyeal model modified to allow for triggering by marginal processes (if the bed of the Hudson Strait ice stream was still frozen, no surge could be triggered [*Alley and Clark*, 1999]), whereas the ice-shelf mechanism has greater difficulty providing an explanation why some very cold times grew ice shelves that collapsed to make Heinrich layers, but other very cold times followed by abrupt warmings did not produce Heinrich layers.

[9] An important observation is that the part of each Heinrich layer proximal to the Laurentide Ice Sheet and Hudson Strait is dominated by sorted sediments 50–100 cm thick, indicating large volumes of meltwater and the production of turbidites [*Andrews et al.*, 1998; *Hesse and Khodabakhsh*, 1998; *Hesse et al.*, 1997, 2004; *Rashid et al.*, 2003] despite the evidence for persistence of climatically cold conditions during Heinrich-layer deposition. In contrast, at distal sites west of Europe, iceberg-rafted debris was being supplied to deep-sea sites [*Heinrich*, 1988]. Thus the Heinrich layers seem to require volumes of water normally associated with jokulhlaups, and the proposed origin of the sediments [*Hulbe et al.*, 2004, paragraph [38]] seems improbable. We have presented one model in which a cooling event could trigger a surge and an outburst flood from beneath an ice stream such as that in Hudson Strait [*Alley et al.*, 2005], and we expect that several other models are possible. Large incised channels are suggested on seismic profiles from the Hudson Strait seafloor and adjacent shelf [*Andrews and MacLean*, 2003; *MacLean et al.*, 2001] and may relate to these postulated outburst floods.

[10] In addition, any mechanism invoking ice shelves faces the difficulty that they generally serve as "debris filters," holding ice near the shore but out of contact with debris sources while providing time for basal debris to melt off before icebergs are formed. Melting may be caused by heat from sub-ice-shelf water or by the "ice pump," the pressure-melting effect that removes ice from deep-draft regions and deposits it in shallower-draft regions to reduce the potential energy of the system [*Lewis*, 1985]; because ice shelves thin away from their grounded debris sources, ice-pump melting preferentially attacks debris-bearing ice. Ice-shelf basal melting could be avoided by a sufficiently steep basal temperature gradient or sufficiently cold ocean water; however, to the best of our knowledge, widespread grounding-line freeze-on has not been observed across the suite of modern ice shelves studied and seems unlikely in an environment warm enough to cause surface melting triggering a Larsen B-type ice-shelf disintegration. Thus, although glaciological theory does not preclude ice-shelf mechanisms for storage and release of debris, the theory does urge caution.

[11] The phasing of IRD events from different ice sheets [e.g., *Grousett et al.*, 2000] is advanced as a major reason for an ice shelf model. However, this interpretation is based on a FennoScandanavian Ice Sheet isotopic signature [*Grousett et al.*, 2000] that *Farmer et al.* [2003] showed to be nonunique. In sediments south of the North Sea the IRD most likely came from the Gulf of St. Lawrence [*Farmer et al.*, 2003]. This suggests a phasing between the Gulf of St. Lawrence and the Hudson Strait ice streams. More definitive statements require the search for more specific, ideally unique, "fingerprints" from potential IRD sources.

[12] The reader should recognize that none of these objections is fatal to the *Hulbe et al.* [2004] model. Diffusion and bioturbation can remove sedimentary evidence of a short-lived warming, debris does exist in ice shelves, sediment cores are not available from all possible ice-shelf locations, and recognition of ice shelves from sedimentary deposits and identification of source terranes for ice-rafted debris can be equivocal. Furthermore, it is likely that ice shelves did exist at times in some places around the Laurentide Ice Sheet and contributed to its behavior, so that a complete understanding of the ice sheet and its Heinrich events will include ice shelves. Nonetheless, we believe that the weight of evidence now available argues against a warming-induced ice-shelf-disintegration model for origin of Heinrich-event layers, and we continue to favor a (modified) MacAyeal oscillator as the best model for these important and enigmatic features. We look forward to continuing discussions with Hulbe et al. on this fascinating topic.

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References

Alley, R. B. (1991), Sedimentary processes may cause fluctuations of tidewater glaciers, *Annal. Glaciol.*, *15*, 119–124.

Alley, R. B., and P. U. Clark (1999), The deglaciation of the Northern Hemisphere: A global perspective, *Annu. Rev. Earth Planet. Sci.*, *27*, 149–182.

Alley, R. B., S. Sanandakrishnan, and K. M. Cuffey (1996), Subglacial sediment transport and ice-stream behavior, *Antarct. J. U.S.*, *31*, 81–82.

Alley, R. B., T. K. Dupont, B. R. Parizek, S. Anandakrishnan, D. E. Lawson, G. J. Larson, and E. B. Evenson (2005), Outburst flooding and surge initiation in response to climatic cooling: An hypothesis, *Geomorphology*, in press.

Andrews, J. T., and B. MacLean (2003), Hudson Strait ice streams: A review of stratigraphy, chronology, and links with North Atlantic Heinrich events, *Boreas*, *32*, 4–17.

Andrews, J. T., M. E. Kirby, A. E. Jennings, and D. C. Barber (1998), Late Quaternary stratigraphy, chronology, and depositional processes on the SE Baffin Island slope, detrital carbonate and Heinrich events: Implications for onshore glacial history, *Geogr. Phys. Quat.*, *52*, 91–105.

Bond, G., et al. (1992), Evidence for massive discharges of icebergs into the glacial northern Atlantic, *Nature*, *360*, 245–249.

Bond, G., W. S. Broecker, S. Johnsen, J. McManus, L. Labeyrie, J. Jouzel, and G. Bonani (1993), Correlations between climate records from North Atlantic sediments and Greenland ice, *Nature*, *365*, 143–147.

Bond, G., W. Showers, M. Elliot, M. Evans, R. Lotti, I. Hajdas, G. Bonani, and S. Johnson (1999), The North Atlantic's 1–2 kyr climate rhythm: Relation to Heinrich events, Dansgaard/Oescher cycles and the Little Ice Age, in *Mechanisms of Global Climate Change at Millennial Time Scales*, *Geophys. Monogr. Ser.*, vol. 112, edited by P. U. Clark, R. S. Webb, and L. D. Keigwin, pp. 35–58, AGU, Washington, D. C.

Chapman, M. R., and N. J. Shackleton (1999), Global ice-volume fluctuations, North Atlantic ice-rafting events, and deep-ocean circulation changes between 130 and 70 ka, *Geology*, *27*, 795–798.

De Angelis, H., and P. Skvarca (2003), Glacier surge after ice shelf collapse, *Science*, *299*, 1560–1562.

Dyke, A. S., J. T. Andrews, P. U. Clark, J. H. England, G. H. Miller, J. Shaw, and J. J. Veillette (2002), The Laurentide and Innuitian ice sheets during the Last Glacial Maximum, *Quat. Sci. Rev.*, *21*, 9–31.

Farmer, G. L., D. C. Barber, and J. T. Andrews (2003), Provenance of late Quaternary ice-proximal sediments in the North Atlantic: Nd, Sr and Pd isotopic evidence, *Earth Planet. Sci. Lett.*, *209*, 227–243.

Grousett, F. E., C. Pujol, L. Labeyrie, G. Auffret, and A. Boelaert (2000), Were the North Atlantic Heinrich events triggered by the behavior of the European ice sheets?, *Geology*, *28*, 123–126.

Heinrich, H. (1988), Origin and consequences of cyclic ice rafting in the northeast Atlantic Ocean during the past 130,000 years, *Quat. Res.*, *29*, 143–152.

Hesse, R., and S. Khodabakhsh (1998), Depositional facies of late Pleistocene Heinrich events in the Labrador Sea, *Geology*, *26*, 103–106.

Hesse, R., et al. (1997), Ice-sheet sourced juxtaposed turbidites systems in the Labrador Sea, *Geosci. Can.*, *24*, 3–12.

Hesse, R., H. Rashid, and S. Khobabakhsh (2004), Fine-grained sediment lofting from meltwater-generated turbidity currents during Heinrich events, *Geology*, *32*, 449–452.

Hillaire-Marcel, C., A. de Vernal, G. Bilodeau, and G. Wu (1994), Isotope stratigraphy, sedimentation rates, deep circulation, and carbonate events in the Labrador Sea during the last ~200kyr, *Can. J. Earth Sci.*, *31*, 63–89.

Hulbe, C. L., D. R. MacAyeal, G. H. Denton, J. Kleman, and T. V. Lowell (2004), Catastrophic ice shelf breakup as the source of Heinrich event icebergs, *Paleoceanography*, *19*, PA1004, doi:10.1029/2003PA000890.

Jennings, A. E., K. A. Tedesco, J. T. Andrews, and M. E. Kirby (1996), Shelf erosion and glacial ice proximity in the Labrador Sea during and after Heinrich events (H-3 or 4 to H-0) as shown by foraminifera, in *Late Quaternary Palaeoceanography of the North Atlantic Margins*, edited by J. T. Andrews et al., pp. 29–49, Geol. Soc., London.

Lewis, E. L. (1985), The "ice pump," a mechanism for ice-shelf melting, glaciers, ice sheets, and sea level, in *Effect of a CO2-Induced Climate Change, Rep. DOE/EV/60235-1*, pp. 275–278, U.S. Dept. of Energy, Washington, D. C.

MacAyeal, D. R. (1993a), Binge/purge oscillations of the Laurentide Ice Sheet as a cause of North Atlantic's Heinrich events, *Paleoceanography*, *8*, 775–784.

MacAyeal, D. R. (1993b), A low-order model of growth/purge oscillations of the Heinrich-event cycle, *Paleoceanography*, *8*, 767–773.

MacLean, B., J. T. Andrews, J. T. Gray, F. R. Hall, I. Hardy, A. E. Jennings, W. F. Manley, W. T. Pfeffer, and G. Vilks (2001), Hudson Strait Quaternary sediments and late glacial and deglaciation history: A discussion and summary, in *Marine Geology of Hudson Strait and Ungava Bay, Eastern Arctic Canada: Late Quaternary Sediments, Depositional Environments, and Late Glacial-Deglacial History Derived From Marine and Terrestrial Studies*, edited by B. MacLean, pp. 181–192, Queen's Print., Ottawa, Ont.

Parizek, B. R., R. B. Alley, and C. L. Hulbe (2003), Subglacial thermal balance permits ongoing grounding-line retreat along the Siple Coast of west Antarctica, *Annal. Glaciol.*, *36*, 251–256.

Rashid, H., R. Hesse, and D. J. W. Piper (2003), Origin of unusually thick Heinrich layers in ice-proximal regions of the northwest Labrador Sea, *Earth Planet. Sci. Lett.*, *208*, 319–336.

Shepherd, A., D. Wingham, T. Payne, and P. Skvarca (2003), Larsen ice shelf has progressively thinned, *Science*, *302*, 856–859.

Veillette, J. J., A. S. Dyke, and M. Roy (1999), Ice-flow evolution of the Labrador sector of the Laurentide Ice Sheet: A review, with new evidence from northern Quebec, *Quat. Sci. Rev.*, *18*, 993–1019.

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