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Abrupt (or millennial or suborbital) climatic variability: Heinrich events/stadials

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Abstract :

The causes and consequences of the episodic iceberg-discharge events from the Hudson Strait Ice Stream of the Laurentide Ice Sheet, or Heinrich events (HE), are one of the most explored topics in Pleistocene palaeoclimatology. In this chapter, we summarise three decades of intense research while introducing recent results from both the European and Cordilleran Ice Sheets that could call for a paradigm shift in our understanding of the HE.

Keywords : Heinrich events, Heinrich stadials, ice sheets, Last Glacial Cycle, climate changes

Understanding the complex interactions between ice and ocean is a central topic in paleoclimate reconstructions, especially during the Pleistocene ice ages when the Northern Hemisphere ice sheets grew substantially and expand to the middle latitudes of Northern America and Europe (Ehlers and Gibbard, 2004). Marine sediments record these interactions, from the formation of thick glaciogenic deposits on continental margins (*e.g.* through-mouth fans) to the deposition of coarse-grained iceberg-rafted debris (IRD) in the open ocean. While IRD deposits were mainly limited to high-latitudes margins (*e.g.* Greenland Sea) during Pleistocene interglacials, their distribution shifted abruptly to the south down to the subpolar North Atlantic during glacial periods to form the so-called 'Ruddiman belt' (~43-53°N). This glacial shift points to a general southward extension of the location of marine ice-streams (together with ice sheets) from which debris-rich icebergs calved, as well as of the locus of iceberg melting in the ocean (Hodell et al., 2008; Ruddiman, 1977).

Long piston cores in the 'Ruddiman belt' revealed a significant variability in the flux of IRD throughout the last glacial period: layers with a high percentage of IRD (now known as 'Heinrich layers') highlight the occurrence of short-lived events ('Heinrich events' - HE) of massive iceberg discharges in the subpolar North Atlantic with a recurrence period of ~7 kyr (Bond et al., 1992; Broecker et al., 1992; Hemming, 2004; Rashid et al., 2003). Correlations between North Atlantic sediments and Greenland ice reveal that the timing of HE in the subpolar North Atlantic occurred at the extreme-cold culminations of Bond climate cycles recognized in Greenland, and preceded an abrupt shift to a warmer climate (*i.e.* interstadials) in the Northern Hemisphere (Bond et al., 1993; Broecker, 1994). In the subtropical North Atlantic, the Heinrich layers, although less evident (or even absent) in the sedimentary record, were coeval with strong sea-surface cooling and advection of low-salinity artic water masses (Bard et al., 2000). Vegetation changes suggesting extreme atmospheric cooling and continental dryness were also reported from the Iberian margin pollen records (Roucoux et al., 2001; Sanchez-Goni et al., 2000, 2002). From these correlations, the cold intervals recognized in the North Atlantic region and encompassing the HE in the 'Ruddiman belt' were defined as Heinrich Stadials (HS) (Barker et al., 2009; Sanchez-Goni & Harrison, 2010). Synchronous changes in the monsoonal precipitation (*e.g.* Brazil, Arabia, China) highlight a near-global pattern (Schulz et al., 1998; Stríkis et al., 2018; Wang et al., 2001), possibly forced by a strong rearrangement of the Atlantic Meridional Overturning Circulation (AMOC) triggered by the iceberg melting and the associated freshwater pulses (Bond et al., 1992; Broecker, 1994; McManus et al., 2004; Rahmstorf, 1994; Vidal et al., 1997). This makes the causes and consequences of HE one of the most explored topic in Pleistocene paleoclimatology since the last three decades (Hemming, 2004; Henry et al., 2016).

The debris-rich icebergs from which the Heinrich layers originate were rapidly identified as coming from the Labrador Sea region and, by extension, the eastern margin of the Laurentide Ice Sheet (LIS). This was suggested first through the geographical pattern for ice-rafted deposition in the North Atlantic (Ruddiman, 1977) and, second, through the stratigraphic signature of the abundant Paleozoic detrital carbonate (dolomite) fragments found in the Heinrich layers (Andrews & Tedesco, 1992; Broecker et al., 1992). Geochemical provenance measurements (Nd-Sr-Pb isotope composition of bulk sediments, isotopic and geochronologic measurements on individual grains) confirm this result showing that Heinrich layers (*sensu stricto*) have a Hudson Strait source (*e.g.* Grousset et al., 1993; Hemming, 2004; Huon & Ruch, 1992). Hence, HE were associated with the dynamics of the Hudson Strait Ice Stream and likely denoted considerable glaciological instability of the LIS (Andrews & Tedesco, 1992). This evidence, together with the pluri-millennial period separating the Heinrich layers, led MacAyeal et al. (1993) to suggest that HE result from internal instabilities of the Laurentide Ice Sheet (*i.e.* the 'binge-purge' mechanism) with geothermal heating being the driving force for purging the interior of the ice sheet. However, this internal process "*tied solely to a*

Laurentide ice-dynamics clock" (Hulbe et al., 2004) was challenged by subsequent petrological and geochemical investigations from deep-sea cores located in the eastern North Atlantic. They revealed that the flux of debris-rich icebergs from the Icelandic and European Ice Sheet Complex (EISC) encompasses the one from the Hudson Strait Ice Stream (Bond & Lotti, 1995; Grousset et al., 2000, 2001; Hemming et al., 1998; Peck et al., 2006; Revel et al., 1996; Snoeckx et al., 1999). More importantly, they indicate that significant increases in iceberg calving north of the 'Ruddiman belt' (*e.g.* Nordic Seas) recurred at intervals of 2-3-kyr in phase with the cold intervals (stadials) of the Dansgaard-Oeschger cycles (Bond et al., 1999; Bond & Lotti, 1995; Elliot et al., 1998; Knutz et al., 2001; Scourse et al., 2009). Hence, HE were superimposed on a millennial-scale cycle of ice-rafting events from the circum-Atlantic ice-streams that operate not due to internal but external forcing, namely climate and/or oceanographic changes (Bond & Lotti, 1995).

Climate simulations suggest that freshwater pulses in the North Atlantic and Nordic Seas can easily force the AMOC to shut down (*e.g.* Ganopolski & Rahmstorf, 2001; Menviel et al., 2014; Paillard & Labeyrie, 1994; Rahmstorf, 1994), leading to the idea that iceberg calving (including HE) could be the cause for (Heinrich and non-Heinrich) stadial conditions. However, further investigations revealed that if increased iceberg calving may enhance and/or prolong cold stadial conditions (through a positive feedback on the AMOC in response to the addition of freshwater), they were a consequence of these conditions rather than the cause (Barker et al., 2015; Clark et al., 2007; McManus et al., 1999). This evidence agrees with data and model simulations showing that the destabilization of the Hudson Strait Ice Stream and the subsequent HE (*sensu stricto*) likely result from subsurface ocean warming associated with a weakened AMOC (Alvarez-Solas et al., 2010, 2013; Bassis et al., 2017; Marcott et al., 2011; Shaffer et al., 2004).

The ultimate processes determining the initial AMOC weakening remain elusive but a close look at the sediment close to the circum-Atlantic ice sheets can help to improve our understanding of the above-mentioned scenario. Indeed, nepheloid flows and turbidity currents (leading to sedimentation rates of 1-10 m/kyr) are common depositional features of HS in ice-proximal settings of the Labrador Sea (Hesse & Khodabakhsh, 1998, 2016; Rashid et al., 2003b) and of the European margins (Lekens et al., 2005; Toucanne et al., 2008; Zaragosi et al., 2001, 2006). These processes are indicative of substantial meltwater discharges from the surrounding ice streams, implying that ice loss during HS was not restricted to calving processes alone (Andrews et al., 1994; Dowdeswell et al., 1999). The comparison of sediment flux and freshwater proxies from the LIS and EISC suggest that meltwater discharges from the two ice sheets increased as soon as the HS conditions set in, and the meltwater flux from the LIS remained high throughout the deposition of the Hudson Strait IRD (Rashid et al., 2012; Toucanne et al., 2015) (Figure 25.1). The latter fact is robustly supported by the coarse ice-rafted debris dispersed within the thick and extensive nepheloid-flow deposits (Hesse & Khodabakhsh, 1998, 2016; Rashid et al., 2003b). Thus, high fluxes of meltwater in the North Atlantic were coeval with the HS. These meltwater inputs as a whole could explain, by extension, the concomitant weakening of the AMOC responsible for the subsequent release of Hudson Strait icebergs. But one thing that remains unclear is why such meltwaters inputs occurred.

The ice loss during HS likely resulted from fast recession of ice sheets that in Europe is supported by the very rapid retreat of the Irish Sea Ice Stream (by about 400 km) during HS 2 (Chiverrell et al., 2020; Smedley et al., 2017). More generally, terrestrial-based palaeogeographical reconstructions of the EISC (Hughes et al., 2016) reveal that the Baltic Ice Stream in the continental interior of Europe retreated in phase with the meltwater inputs of Baltic origin identified in the Bay of Biscay during the last three HS (Boswell et al., 2019;

Toucanne et al., 2015). Similar results were recently obtained for the Alpine Ice Sheet (Martinez-Lamas et al., 2020). These results together demonstrate that land-terminating ice margins, together with the marine-terminating ones (including the Hudson Strait Ice Stream), were involved in the production of meltwater during HS. Thus, oceanic forcing on marine-terminating ice-streams was not a prerequisite for ice loss during these periods, and the ice melting described above likely resulted from atmospheric forcing. This is consistent with the fact that increased atmospheric temperature is today the primary driver of the rapid marine-terminating glacier retreat in the Canadian Arctic Archipelago from north of the Hudson Bay (Cook et al., 2019). The atmospheric forcing could also explain the near-synchronous reorganization of the Northern Hemisphere ice-sheets during HS, including the LIS (Palacios et al., 2020) and EISC (Hughes et al., 2016; Toucanne et al., 2015) but also the North American Cordilleran Ice Sheet. Indeed, the Cordilleran Ice Sheet released substantial volumes of meltwater into the North Pacific during HS (Hendy & Cosma, 2008; Lopes & Mix, 2009; Maier et al., 2018; Walczak et al., 2020). This is shown by increased sediment flux from both turbid plumes, turbidity currents and iceberg calving (Jaeger et al., 2014; Walczak et al., 2020). Thus, the Cordilleran Ice Sheet was likely melting, and these melting events coincide within age uncertainties with those of the Laurentide and European ice sheets (Figure 25.1). These results indicate a near-synchronous melting of the Northern Hemisphere, mid-latitude ice sheets during the HS.

Considering that glacier ablation in mid-latitudes occurs primarily during summer months (*e.g.* Oerlemans, 2001), the above conclusion implies warming summer temperatures over the North Hemisphere ice-sheets during HS. This pattern is difficult to reconcile with the existing evidences for cold polar conditions (*i.e.* cold air and SST, widespread sea ice) in the North Atlantic region at that time, although it may resemble the one described in Scotland, Arctic Norway and Greenland during the Younger Dryas event (~12.5 cal ka BP). At this time, glaciers (sensitive to summer-temperature change in these regions) were retreating (Bromley et al., 2014; Funder et al., 2021; Rinterknecht et al., 2014; Wittmeier et al., 2020) while the annual mean temperature over Greenland dropped by 5-9°C (Buizert et al., 2014). The comparison between the Younger Dryas and the HS is not straightforward. However, increased temperature seasonality (*e.g.* increased summer temperature counterbalanced by severely cold winters), not available directly from the ice core record (Buizert et al., 2014, 2018), is a mechanism that could reconcile this contrasting evidence (Boswell et al., 2019; Wittmeier et al., 2020). This assumption is consistent with the idea that seasonality switches are a critical component of abrupt glacial climate changes (Buizert et al., 2014, 2018; Denton et al., 2005). Thus, the widespread winter sea ice in the North Atlantic and the 'apparent' cold conditions in the surrounding regions during HS could be a consequence of the melting event floods that caused both the AMOC weakening and the freshening of the surface ocean (e.g. Denton et al., 2010). In other words, most of the seasonality is due to winter air temperature changes (Buizert et al., 2014; Denton et al., 2005) which makes it difficult to isolate the summer signal from marine and terrestrial palaeo-bioclimatic proxies. As a prominent example, palynological records reveal a rapid vegetation response to HS conditions in western Europe with semi-desert or steppic vegetation, particularly *Artemisia*, replacing open (boreal/temperate) forest indicating colder and drier atmospheric conditions (Fletcher et al., 2010; Sanchez-Goni et al., 2008, 2021). *Artemisia* is an interesting taxon with regard to the seasonal signal discussed above. *Artemisia* does not require necessarily warm summers to grow but some species are compatible with warm climates (Subally & Quézel, 2002). Unfortunately, we cannot discriminate warm from cold species Artemisia from pollen assemblages. *Artemisia* pollen is abundant in Chinese steppe environments that correspond with annually cold and dry climates (Hongyan et al., 2013). Furthermore, in the Near East high percentages of *Artemisia* (together with Chenopodiaceae) pollen do not necessarily indicate low annual precipitation but a highly seasonal climate with cold winters and hot, dry summers (El-Moslimany, 1987). Therefore, *Artemisia* increase can be compatible with warming (Subally & Quézel, 2002) and, particularly, in summer (El-Moslimany, 1987; Kienast et al., 2005).

In summary, lithic grains deposited in the glacial ocean by icebergs have shaken the palaeoclimatic community these last decades and moved the Quaternary science forward in a significant way. The massive discharges of icebergs from the Hudson Strait Ice Stream, or so-called HE, has long been seen as the cause for AMOC weakening and subsequent cooling of the North Atlantic region. However, it is now clear that HE may be a consequence of AMOC weakening. In this context, the HE are the ‘tip of the iceberg’. This highlights the complexity of the time intervals in which they occur, namely the HS (Boswell et al., 2019). This complexity is particularly evident in palynological records, with for example a wet-dry complex continental hydrological pattern in the western Iberian Peninsula (Fletcher & Sanchez-Goni, 2008; Naughton et al., 2009). Complex phase sequences during the HS are also reported from both the ocean (Wary et al., 2018) and ice core records (Guillevic et al., 2014). If the cause of the HS remains enigmatic, mid-latitude ice sheets in the Northern Hemisphere could have triggered the initial AMOC weakening. The study of ice-proximal settings indeed reveals huge volumes of meltwater entering the Pacific and Atlantic oceans well before the production of the Heinrich’s icebergs. This production of meltwater, although occurring at the same time of documented cold conditions in the North Atlantic region and over Greenland, necessarily involves warming summer temperatures. The mismatches between ice-core temperature oscillations in the polar regions and ice-margin fluctuations in mid-latitudes would therefore call for a paradigm shift in our understanding of past rapid climate changes.

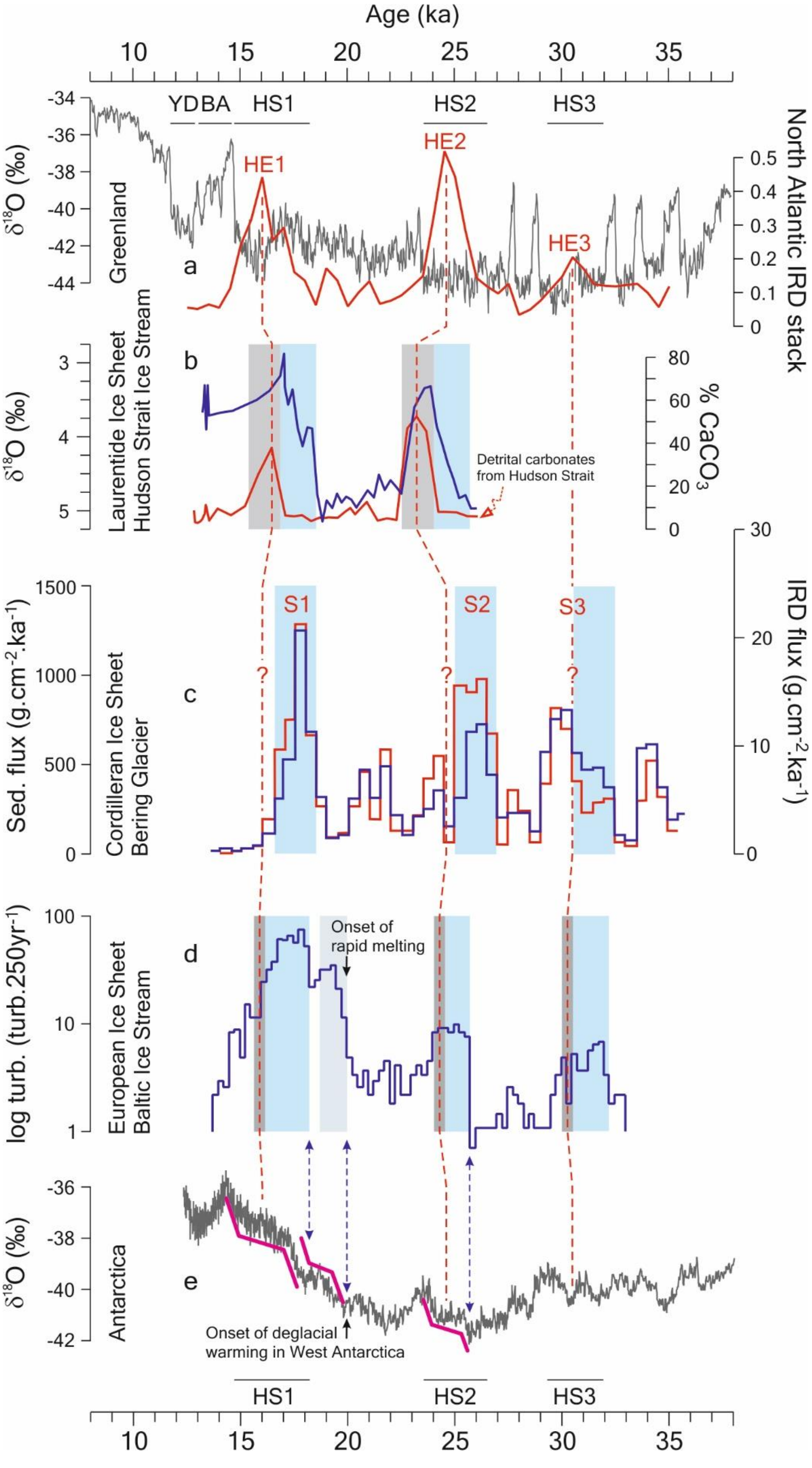
Age (ka)
10
15
20
25
30
35
YD
BA
HS1
HS2
HS3
HE1
HE2
HE3
a
δ18O (‰)
Greenland
-34
-36
-38
-40
-42
-44
North Atlantic IRD stack
0.5
0.4
0.3
0.2
0.1
0
b
δ18O (‰)
Laurentide Ice Sheet
Hudson Strait Ice Stream
3
4
5
% CaCO3
80
60
40
20
0
Detrital carbonates from Hudson Strait
c
S1
S2
S3
?
?
?
Sed. flux (g.cm-2.ka-1)
Cordilleran Ice Sheet
Bering Glacier
1500
1000
500
0
IRD flux (g.cm-2.ka-1)
30
20
10
0
d
Onset of rapid melting
log turb. (turb.250yr-1)
European Ice Sheet
Baltic Ice Stream
100
10
1
e
δ18O (‰)
Antarctica
-36
-38
-40
-42
Onset of deglacial warming in West Antarctica
HS1
HS2
HS3
10
15
20
25
30
35

Figure 25.1- Phasing of meltwater discharges into the North Atlantic and North Pacific during Heinrich Stadials, and their relationship with the Heinrich events. (a) NGRIP δ^{18}O (grey line, GICC05 chronology; Rasmussen et al., 2006; Svensson et al., 2008) and the North Atlantic IRD stack (red line; Stern & Lisiecki, 2013). Heinrich events (HE) correspond to the IRD spikes; (b) bulk carbonate as % $CaCO_3$ (red line that defines the Hudson Strait source and the HE) and δ^{18}O of the planktic polar foraminifera *Neogloboquadrina pachyderma* in core Hu97048-07, Baffin slope (Rashid et al., 2012); (c) Total mass accumulation rates (blue line) and IRD mass accumulation rates (red line; S*x* = Siku events) at IODP Site U1419, Alaskan margin (Walczak et al., 2020); (d) Turbidite flux of Baltic origin off the Channel River, western European margin (Toucanne et al., 2015); (e) West Antarctic Divide Ice Core (WDC) δ^{18}O record (WAIS Divide Project Members, 2015) with magenta lines highlighting multi-step warming episodes. All data sets are shown on their original published age models. The vertical red dashed lines show the timing of HE (*i.e.* the deposit of Hudson Strait IRD; vertical grey bars) at each sites (except in c). Vertical blue bars highlight the periods of significant meltwater releases (as suggested by sediment flux and freshwater proxies in ice-proximal settings) preceding HE (vertical grey bars in b,d). Note that (*i*) meltwater releases can continue during and after HE; (*ii*) if the timing for IRD deposits at each site (*i.e.* HE in the North Atlantic versus Siku events in the North Pacific; Walczak et al., 2020) shows a complex pattern (*i.e.* lead-lag), the Cordilleran (c), European (d) and Laurentide (a) episodes of meltwater release preceding HE are near-synchronous (within age uncertainties); (*iii*) the meltwater events in the Northern Hemisphere are coeval with multi-step warming episodes (magenta lines) in West Antarctica (e).

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