Massive iceberg discharges as triggers for global climate change

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Observations of large and abrupt climate changes recorded in Greenland ice cores have spurred a search for clues to their cause. This search has revealed that at six times during the last glaciation, huge armadas of icebergs launched from Canada spread across the northern Atlantic Ocean, each triggering a climate response of global extent.

In 1988 Hartmut Heinrich published an article summarizing his study of a curious set of sedimentary layers in cores from the Dreizack seamounts in the eastern North Atlantic[1]. His conclusion was that these layers record the melting of six great armadas of icebergs which flooded the northern Atlantic during the last glaciation. Each of these bursts produced a prominent sediment layer rich in Canadian-derived ice-rafted debris and poor in foraminifera shells. When Heinrich's paper was published, the attention of the palaeoclimate community was directed towards the climate response to the Earth's orbital cycles, so his discovery went largely unnoticed. Only when a nearly identical record was published[2] from a core located several hundred kilometres away, with a claim that the fresh water generated by the melting of these ice armadas might have disrupted deep-water formation in the northern Atlantic, did the palaeoclimate community recognize the possibility that Heinrich's layers were more than a curiosity. Suddenly attention was refocused on the coupling between surging ice sheets and northward heat transport by the Atlantic's thermohaline circulation.

It was already known from the Greenland ice cores[44,45] that during the last glacial period the northern Atlantic region experienced repeated large and abrupt climate changes. So far only one mechanism—changes in ocean circulation—has been put forward to explain these jumps. The idea behind this mechanism is that high-latitude climate is strongly influenced by heat released from the sea. The amounts and routings of this heat are closely tied to the global pattern of thermohaline circulation. One such route, a conveyor-like circulation operating in the Atlantic, is particularly important. The heat it carries maintains the anomalously warm climate enjoyed by western Europe. The abrupt climate changes revealed in the Greenland record seem to be telling us that the conveyor has turned on and off. Modelling efforts reveal that such changes can be triggered by inputs of fresh water. One potential source of fresh water is that released by the melting of icebergs, such as the discharges recorded in Heinrich's layers (now known as Heinrich events).

Here I review the evidence that Heinrich events are indeed connected with rapid climate variations in the North Atlantic region. The timing of the events is in striking coincidence with the pattern of climate fluctuations documented from ice cores. But the mechanism that drives the events remains a matter of debate. One possibility is that the iceberg discharges reflect an internal oscillatory feature of the dynamics of the Laurentide ice sheet, from which the icebergs come. Alternatively, Heinrich events might represent a response to, rather than a cause of, climate change—external factors may induce global cooling, causing the ice sheets to surge. Although the true picture is likely to emerge only when our understanding of ocean circulation, ice-sheet dynamics and detailed regional palaeoclimate has improved substantially, there can be no doubt that Heinrich events provide a vivid illustration of the way in which the coupled influence of the atmosphere, geosphere and cryosphere may be a dominant control on the Earth's climate.

Anatomy of Heinrich layers

Although glacial sediments of the northern Atlantic are uniformly rich in ice-rafted debris, that contained in Heinrich layers differs in three distinct ways. First, 20% of the sand-sized fragments are detrital limestone (a constituent nearly absent in ambient glacial sediment)[3]. Second, the clay-sized minerals in Heinrich layers have twofold higher K–Ar ages (~1,000 million years) than those for their ambient glacial equivalents[4-6]. Third, Heinrich layers are devoid of the basal-derived clay minerals so abundant in ambient glacial sediment[4-6]. Coupled with the observation that the detrital layers thin by more than an order of magnitude from the Labrador Sea to the European end of the 46° N iceberg route[3], these composition differences point strongly to a Canadian origin for the Heinrich ice armadas.

Surprisingly, the dominant feature of Heinrich layers is not a greatly enhanced abundance of ice-rafted debris, but rather a dearth of foraminiferal shells[2,3]. The abundance of these shells drops from its usual glacial value of thousands per gram to hundreds or less per gram in the Heinrich layers. Dilution with ice-rafted debris cannot be the sole cause of this reduction because the geographical extent of sediment sparse in foraminifera exceeds that of the Canada-derived detritus[2,3]. Rather, the low abundance of foraminifera must reflect, in part, a dramatic decrease in marine productivity. Heinrich events occurred when the northern Atlantic was at its coldest, as signalled by the geographical extent of the polar foraminifera, *Neogloboquadrina pachyderma* (left coiling) which extended all the way to 40° N. The depleted ^{18}O content in the few foraminifera present in Heinrich layers suggests the presence of a low-salinity lid[3]. These observations suggest episodes of extensive sea-ice cover similar to that of today's Arctic.

Timing of Heinrich events

Perhaps the most startling aspect of the timing of these events is their occurrence at major climate boundaries[7]. As shown in Fig. 1, Heinrich event number 6 marks the transition from the relatively warm northern Atlantic of the last interglacial (that is, marine stage 5) to the cold conditions prevailing during the last glacial (marine stages 4, 3 and 2). Heinrich event 1 marks the onset of the termination which brought the last glacial to a close. There is unpublished evidence (J. McManus, personal communication) of a seventh Heinrich event right at termination of the penultimate glaciation (that is, marine stage 6). The coincidence between Heinrich events and the major changes in the temperature regimen of the northern Atlantic leads to the speculation that fresh water released as the result of the melting of Heinrich's icebergs disrupted deep-water formation, thereby permitting switches between glacial and interglacial modes of thermohaline circulation.