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ABRUPT CLIMATIC CHANGES—CAUSES AND CONSEQUENCES

An Introduction

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The ICP VI meeting in Lisbon has been a superb occasion for the paleoceanographic community to meet and discuss the recent discoveries on abrupt events in oceanic records. Numerous high quality posters focused on this subject and will aliment the literature for years ahead. In the meanwhile, we intend in this introduction to present the four papers of this Chapter within the context of our present knowledge on the causes and consequences of abrupt climatic changes.

One can realize, with a glance at the volume which resulted from the first international meeting on "Abrupt Climatic Changes" in Bouviers (Berger and Labeyrie, 1987), that a most impressive abrupt change in our knowledge about past climatic variability occurred since 1987. At that time, only one really abrupt climatic event was recognized: the Younger Dryas cold event which interrupted the last deglaciation at about 10–11 kyr BP. The Younger Dryas has been recognized in European pollen records, but also in the ice (Dansgaard *et al.*, 1982) and in the ocean sediment records (Ruddiman and McIntyre, 1981; Ruddiman and Duplessy, 1985). A consensus on its cause was beginning to merge since the early work of Mercer (1969), and after Broecker *et al.* (1985). This cold event, which affected most of the Northern hemisphere and at least the low latitudes of the Southern Hemisphere, is linked to at least a decrease in the thermohaline conveyor belt and its associated northward heat transport. This decrease would have resulted from the input of large amount of meltwater from the Laurentide ice sheet when Lake Champlain emptied through the St. Laurence River (Broecker *et al.*, 1985). However

other events, such as the abruptness of the early glaciation, described by Woillard (1979) at the end of the Eemian (about 115 ky BP), were still considered highly controversial (Seret, 1983). Similarly, the rapid and large amplitude variability of the ice cores oxygen isotope ratio observed by Dansgaard *et al.* (1984) in the Greenland ice drilling of Camp Century was not getting the large attention such results should have merited.

The first change came after Heinrich published his own interpretation on the succession of sandy layers observed in sediment cores from the North Eastern Atlantic, previously described as turbiditic layers (Heinrich, 1988). He attributed these sequences to southern invasions of iceberg armadas, which he thought occurred about each 11,000 years throughout the last glacial period. It is Broecker (1992) who was the first to understand the importance of these results. He interpreted these so-called Heinrich events as catastrophic collapses of ice sheets which were able to perturb the North Atlantic ocean's hydrology. The other innovating idea of Broecker's paper was to demonstrate that hemipelagic sediment cores, even with accumulation rates of 5 to 10 cm/kyr, may provide information on the variability of climate at millennial time scale. Simultaneously, Dansgaard *et al.* (1993) and Groote *et al.* (1993) confirmed the presence of repetitive large amplitude changes in air temperature, now called Dansgaard/Oeschger events (D/O), within the new Greenland ice drillings of GRIP and GISP2. Thanks to Broecker, some of the implications of these observations were discussed in a small informal meeting organized under his umbrella in 1992 at the Lamont-Doherty Earth Observatory. One of us (Labeyrie) had the chance to be invited to that meeting, which fired the interest of our community for the study of rapid climatic changes.

Six Heinrich events were identified for the period 60 to 15 kyr BP. The North American origin of the ice rafted detritus (IRD), which correspond to most of the Heinrich events, was derived from the presence of detrital carbonate (Bond *et al.*, 1992) and minerals with high magnetic susceptibility (Grousset *et al.*, 1993). Since, geochemical studies have confirmed these results (Gwiazda *et al.*, 1996; Revel *et al.*, 1996). Large changes in surface water hydrology affected simultaneously the North Atlantic. Indeed, during each event, armadas of icebergs invaded the Northern Atlantic ocean which melted as they drifted towards the Eastern Atlantic, mostly between 40 and 55°N, at the limit between polar and sub-polar waters. This massive melting is indicated not only by the large increase of IRD flux in the sediment records, but also by the negative anomaly of the oxygen isotopic ratio of the fossil polar planktic foraminifera *Neogloboquarina pachyderma* sinistral. Bond *et al.* (1992, 1993); Grousset *et al.* (1993); Labeyrie *et al.* (1995) and Cortijo *et al.* (1997) showed that the melting of ice originating from large continental ice sheets characterized by low relative amount of Oxygen 18 isotope, could decrease by such a magnitude the isotopic ratio of surface water. Furthermore, as indicated by the relative abundance of *N. pachyderma* s. and sea surface reconstructions each Heinrich event occurred at the culmination of a cooling cycle which lasted 5 to 10 kyr, with progressive southern migration of the Polar Front, and was followed by a rapid warming (Bond *et al.*, 1992; Labeyrie *et al.*, 1999). Bond *et al.* (1992) used the general structure of these cycles, known today as the Bond cycles, to propose a correlation between the Greenland ice core and the North Atlantic sediment records. These authors postulated that the Heinrich events occurred at the culmination of a series of D/O events during the coldest stadials. Deep water hydrology was also affected, as indicated in particular by changes in the carbon isotopic ratio of benthic foraminifera (Sarnthein *et al.*, 1994; Keigwin and Lehman, 1994; Keigwin and Jones, 1994; Oppo and Lehman, 1995; Vidal *et al.*, 1997; Zahn *et al.*, 1997).

All these elements fitted with the concept developed by Broecker *et al.* (1985) and by Manabe and Stouffer (1988) after the work of Stommel (1961), that the North Atlantic thermohaline circulation could have two modes of operation. The first mode is similar to the modern pattern of oceanic circulation and is characterized by active transport of heat and salt to the high northern latitudes by the North Atlantic Current. This northward flow of surface waters is compensated by an equivalent flux of North Atlantic Deep Water to the South. The second mode corresponds to a collapse of the thermohaline circulation and the northward flux of surface waters as a result of the injection of low salinity melt water during the Heinrich events. Paillard and Labeyrie (1994) have shown, with a simple coupled two dimension model, that the non linear response of the thermohaline circulation to a fresh water flux would explain not only the drastic cooling of the high Northern latitudes during the Heinrich events, but the abrupt warming which immediately followed.

Rahmstorf (this volume) gives a detailed description of some of these modeling efforts. His paper presents a very useful and interesting review of the basic non linear behavior of the thermohaline circulation. New climate simulations for the Last Glacial Maximum are presented, using a coupled atmosphere-ocean-sea ice model. Results are conclusive, and support the earlier modeling studies. They indicate that the jump between active NADW flow and zero flow may derive from a rather low additional input of fresh water (0.2 Sv). These results have important implications for future climate evolution, as the changes in atmosphere greenhouse gases content may affect significantly the atmosphere water cycle.

What was the origin of the Heinrich events? MacAyeal (1993), with his binge/purge model, offered convincing evidence that internal ice sheet dynamic could explain, at least in part, the observations, and in particular the pseudo-periodicity of the events, each 5 to 10 kyr. However this model does not explain the apparent links between the responses of the Laurentide, the Fenno-scandian and the other northern hemisphere ice sheets (Grousset *et al.*, 1993; Fronval *et al.*, 1995; Bond and Lotti, 1995; Elliot *et al.*, 1998). Furthermore, MacAyeal's model also fails to explain the relationship between the EH and the more frequent millennial scale ice sheet instabilities and atmospheric temperature oscillations, the D/O events.

The millennial scale oscillation is indeed pervasive in North Atlantic and Norwegian sea sediments (see for example Cortijo *et al.*, 1995; Fronval *et al.*, 1995; Bond and Lotti, 1995; Elliot *et al.*, 1998), although the main characteristics of these high frequency events may be only studied accurately in areas of high sedimentation rates. Rasmussen *et al.* (1996) have shown that the general structure and morphology of the D/O cycles are well reflected in the changes of the magnetic susceptibility within a sediment core from the Southern Norwegian Sea, North of the Faeroes Islands. It has been shown that this signal monitors the changes in deep water transport of magnetic particles from the Southern Norwegian Sea to the Northern Atlantic along the modern path of North Atlantic Deep Waters (Kissel *et al.*, 1999). The magnetic minerals are probably eroded from the Denmark straight and the Wyville-Thomson sill as deep water overflow from Norwegian sea to the deep Atlantic. These results suggest that the Norwegian Sea was an active source of deep water to the North Atlantic during each warm interstadials over the last glacial period. At the opposite, each of the cold stadial events is marked in Southern Norwegian Sea by a decrease in sea surface salinity and deep water current's intensity (Rasmussen *et al.*, 1996, 1997). The North Atlantic hydrography was affected simultaneously, with large oscillations of the surface temperatures and deep water venti-

lation (Hughen *et al.*, 1998; Manthé, 1998; Elliot *et al.*, 1998; Elliot, 1999; Keigwin and Boyle, 1999). Changes in air temperature over Greenland at millennial time scale are thus, as the larger and less frequent Heinrich events, associated with oscillations of the thermohaline conveyor belt.

Adkins and Boyle (this volume) tested the hypothesis of rapid switches of the thermohaline circulation's activity at the time of the last major Heinrich event (15.4 kyBP). Their approach is very original, as they use deep-sea corals dredged at 1,800 m water depth. They couple analysis of U/Th ages done with a Thermal Ionisation mass Spectrometer and AMS ^{14}C dating, to estimate not only the time scale covered by the coral records, but the changes in water ventilation age. They show that the changes in deep water hydrology occur very fast, within the live span of one coral individual (less than 160 years). The paper complement an earlier paper by the same authors (Adkins and Boyle, 1998), by giving more detailed description of the analytical methods which will certainly serve as basis for future studies.

But what about the origin of this variability? Recent results by Blamart *et al.* (1998) and Elliot (1999) confirm the indications obtained by Fronval *et al.* (1995) and Rasmussen *et al.* (1996, 1997). The Fenno-Scandian ice sheet was oscillating on millennial time scales similar to that of the D/O events. On the other side of the North Atlantic Ocean, results from a sediment core off the Canadian coast suggest that the Laurentide ice sheet was affected at these frequencies (Labeyrie *et al.*, 1999; Elliot, 1999). In the Norwegian Sea, based on the perfect match of magnetic susceptibility variations and the ice core's atmospheric temperatures oscillations, these authors show that each stadial is marked by an invasion of icebergs from the Scandinavian ice sheet, with their load of IRD and the characteristic low oxygen 18 signal in the planktic foraminifera record. It is difficult at this point to know if internal oscillations of the relatively small Scandinavian ice sheet would be sufficient to create the large scale oscillations of the North Atlantic hydrology, or if the ice sheet variability is a consequence of the oscillations of the North Atlantic system. However, we have to keep in mind that Scandinavia was probably directly on the track of the westerly precipitation during the relatively warm interstadial events and ice may have accumulated very rapidly. Thus, the Scandinavian ice sheet could have acted as a major feedback in the ice-ocean-atmosphere interactions at the millennial time scale.

One major complication is that a millennial time scale variability with similar general morphology is now recorded in far distant places over the planet, in particular at low latitudes. Typical examples are the evolution of the oxygen minimum zone in intermediate waters of the eastern Pacific (Behl and Kennett, 1996; Hendy and Kennett, 1998), the northern Indian Ocean (Schulz *et al.*, 1998) and the Japan Sea (Tada *et al.*, 1999). It is difficult to imagine how a climatic feedback only based on high latitude processes could be at the origin of these low latitude changes in lower thermocline ventilation. One other reason to think that the evolution of ice sheets does not explain everything is the fact that these oscillations are observed, although with a smaller amplitude, during the Holocene period (Bond *et al.*, 1997; de Menocal and Bond, 1997; Labeyrie *et al.*, 1999). The problem is unresolved.

Blunier *et al.* (this volume) discuss some of the potential global teleconnections for rapid climatic changes. They present recent results, already published for the most part in Blunier *et al.* (1998) allowing a comparison of the millennial variability along the last glacial period between the Greenland and Antarctica ice cores. For this comparison, they built an inter-hemispheric chronostratigraphy for the different ice records based on the changes in CH_4 content in the air trapped within the ice. They corrected the gas corre-

lation by several hundred to thousand of years for delay in bubble closure, which depends on measured snow accumulation and temperature at the surface derived from the isotopic data. These parameters vary differently in each ice record. The error in the final correlation is of the order of few hundred years. The result is important: all the large cooling events, the major stadial events 8 and 12 and the Younger Dryas, recorded in the Greenland ice cores correspond to synchronous warm events over the Antarctic ice sheet. This results in agreement with the general idea that active thermohaline circulation and NADW formation heats the Northern Hemisphere whereas it cools the Southern Hemisphere (Crowley, 1992; Stocker *et al.*, 1992). When compared to Greenland records the Antarctic core signal appears smoothed with no significant millennial variability. The Antarctic atmospheric temperature records do not present either a significant variability in the lower frequency band which corresponds to the insolation forcing (precession band at about $1/23 \text{ kyr}^{-1}$). This would indicate that there is no direct influence of the low latitude atmospheric processes on the Antarctic climates, as the precession band is preeminent in most of the low latitude paleoclimatic records (Imbrie *et al.*, 1993). Such influence is for example apparent in the oxygen isotopic ratio of the air trapped in the ice (Bender *et al.*, 1994a), which is affected by low latitude productivity and water cycle (Bender *et al.*, 1994b) and in the CH_4 content in the ice (Blunier *et al.*, this volume), also driven largely by low latitude processes. It would thus appear from these results that at least for the area corresponding to the Bird and Vostok ice cores, Antarctic climate would be influenced by the changes in inter-hemispheric heat transfer of the thermohaline conveyor belt.

There is one period for which the mechanisms of rapid climatic changes begin to be better understood: the termination of the Last Interglacial at about 125–115 kyr BP. Imbrie *et al.* (1993) made the hypothesis that a cold climatic cycle begins at high northern latitude, with a rapid cooling following immediately the decrease in summer insolation (June perihelion and maximum obliquity, at about 120–125 kyr BP for the last glacial-interglacial cycle). The model implies that the North Atlantic conveyor belt should not be affected at that time, to allow for the large amounts of snow necessary to feed the growing Scandinavian ice sheet. Duplessy and Labeyrie (1992) and Cortijo *et al.* (1994) have shown that a rapid cooling of the surface waters occurs north of 70°N , at about 122 kyr BP when summer insolation decreases which supports this model. Simultaneously surface water salinity gets lower and deep water convection within the northern Norwegian Sea may have ceased or have been greatly reduced at that time. However, as predicted by Imbrie *et al.* (1993), the thermohaline conveyor belt was not affected for several thousands of years in the North Atlantic. The abrupt cooling and changes in North Atlantic hydrology occurred only after significant increase in the size of the ice sheet, at about 118 kyr BP (Adkins *et al.*, 1997).

Cortijo *et al.* (this volume) focus their paper on the evolution of the North Atlantic and Norwegian sea hydrology at the end of the Eemian Interglacial. They develop an idea already presented in Cortijo *et al.* (1999a), which is based on the comparison between low and high latitudes records of the changes in sea surface temperature and local solar forcing. They demonstrate that over that period, as high latitudes surface water cools down, low latitudes surface water warms. This evolution appears to be forced by insolation. At high latitudes, only summer insolation is important. At 70°N , between 127 and 115 kyr BP, integrated insolation decreases by 70 w/m^2 for the period April 15–September 15 (Berger, 1978). In the meanwhile, at 25°N , summer insolation decreases by 60 w/m^2 , but winter insolation (September 15 to March 15) increases by 45 w/m^2 . Additional heat is transferred simultaneously from the low latitude southern summer hemisphere (which

gain also 60 W/m^2 over that period), making the northern winter the more important period for northward heat transfer (Peixoto and Oort, 1992). Thus, low latitude solar forcing would have a significant role in favoring transfer of water vapor to the high latitudes during periods of ice sheet growth, in particular at the end of the Eemian. However, during Marine Isotope Stage 3, low latitude insolation is about constant. This forcing may not be considered by itself a source for the millennial variability of climate.

In conclusion, we begin to learn about the general trends of the evolution of the North Atlantic Ocean and Norwegian Sea during the last glacial-interglacial period in relation with abrupt climatic changes. There is an evident interaction between the evolution of ice sheets, the thermohaline conveyor belt, and the high latitude climate. But much more work will be needed to understand really how the ice sheet dynamic is influenced by internal and external forcing, what are the precise feedback mechanisms between the changes in thermohaline circulation, surface hydrology and climate, and what are the relationships between high- and low-latitude millennial variability.

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