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Abrupt climatic variability: Dansgaard–Oeschger events

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Abstract :

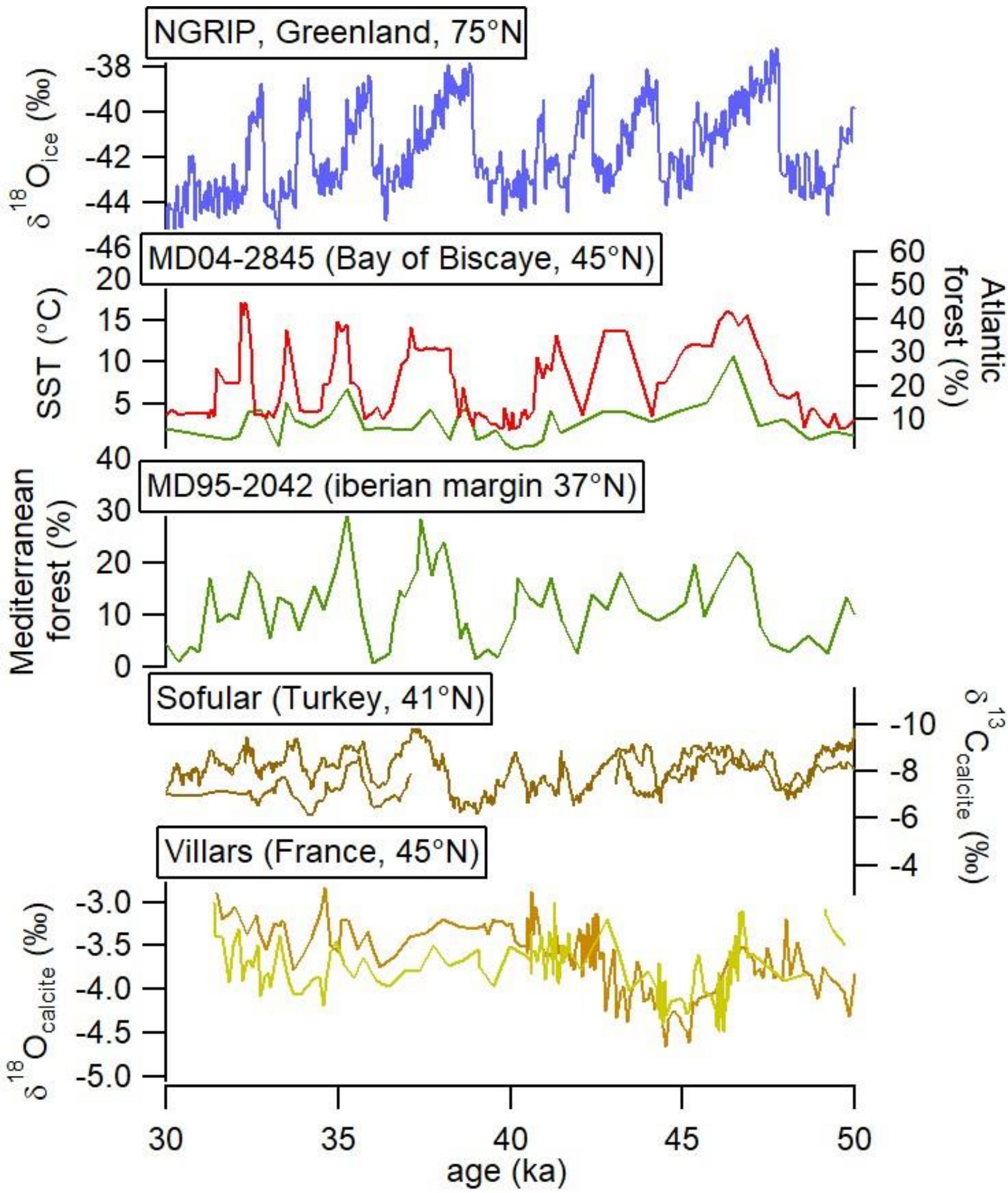
This chapter describes the millennial-scale climatic variability in the atmosphere of Greenland during the Last Glacial Cycle (MIS 5e–MIS 1, 116–14.7 cal ka BP), that is, the Dansgaard–Oeschger (D–O) cycles, and the associated global changes in greenhouse gas atmospheric concentrations, particularly CO2 and CH4, and atmospheric circulation (Ca2+ concentration and d-excess). This chapter highlights the contrasting regional impact of the D–O cycles on the North Atlantic Sea surface temperatures and the vegetation and climate across Europe, as well as the synchronicity between changes in Greenland temperature and the hydrological cycle in the tropics and midlatitudes of the Northern Hemisphere. By contrast, the shape and phasing of millennial-scale events between Greenland and Antarctica differ between the two regions. The mechanisms underlying such a variability are still under debate.

Keywords : Greenland, millennial-scale variability, atmosphere, vegetation, hydrological cycle

24.1 The Dansgaard-Oeschger cycles

Analyses of water isotopes in deep ice cores from the centre of the Greenland Ice Sheet revealed high frequency variability, which was initially attributed to strong variability of the regional climate (Dansgaard et al., 1982; Johnsen, 1992). As mentioned in the Introduction (Chapter 21), the abrupt transitions between periods with low $\delta^{18}O_{ice}$ (cold periods called stadials) to periods with high $\delta^{18}O_{ice}$ (mild periods called interstadials) in the Greenland ice cores are designed as Dansgaard-Oeschger events (D-O events) (Figure 24.1) (Rasmussen et al., 2014).

Figure 24.1- Variations of $\delta^{18}O_{ice}$ (qualitative proxy for temperature variations in Greenland ice cores, (NGRIP members, 2004)) and $\delta^{18}O_{sw}$ (proxy for sea level, (Lisiecki & Raymo, 2005). The number on top indicate the numbering of most D-O events.

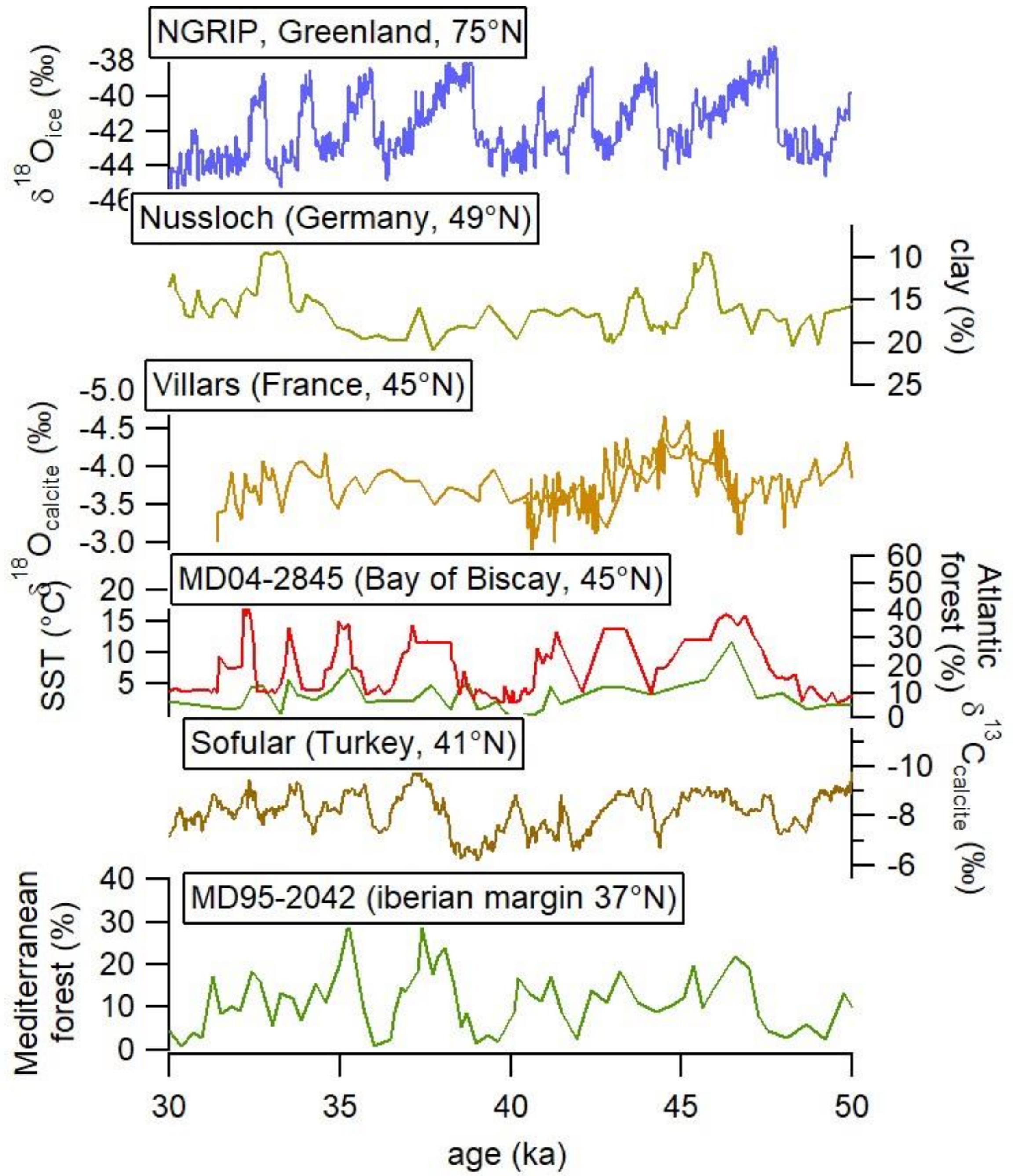


Measurements of additional proxies than δ^{18}O of ice were performed in the Greenland ice cores enabling to better document the evolution of climate and environment over these D-O events. First, CH_4 measured in air trapped in ice cores showed parallel variations to the d18Oice variations during the twenty-five D-O events suggesting a link between what is observed in Greenland and lower latitudes where methane is emitted mainly from wetlands (Brook, Sowers,

& Orchado, 1996). Second, combining $\delta^{18}O_{ice}$ records and records of proxies linked to the atmospheric circulation (Ca^{2+} concentration, d-excess defined as a combination of δD and $\delta^{18}O$ of ice) showed that the shift between stadial and interstadial is accompanied by significant changes in the atmospheric circulation (Mayewski et al., 1997) and occur in a few years to decades (Rasmussen et al., 2014). In some cases, there is a significant lag of a few decades maximum between changes in the atmospheric patterns and shifts in Greenland climate (Erhardt et al., 2019; Steffensen et al., 2008). Third, measurements of isotopes of inert gases in air trapped in ice cores ($\delta^{15}N$, $\delta^{40}Ar$) enabled the quantification of the amplitude of temperature changes over the D-O events (5 to 16°C) (Kindler et al., 2014) and the phasing between changes in temperature and changes in atmospheric methane concentration (Rosen et al., 2014; Severinghaus et al., 1998). Both temperature and methane increase in phase over most of the events but a lag of methane of a few decades has been observed over D-O events 5, 9, 10, 11, 13, 15, 19, and 20 (Baumgartner et al., 2014). Such results highlight the link between the initial observations in Greenland and the global expression of the D-O events.

Expression of D-O events is visible at lower latitudes, both in continental and marine records with a first synthesis provided by Voelker (2002). Sea surface temperature variations in the Northern Atlantic are in general in phase with temperature changes in Greenland (Waelbroeck et al., 2019). Many different archives of the northern hemisphere also show changes on land with a timing coherent with the D-O variability recorded in Greenland (Figure 24.2). Pollen counting is particularly precious in this perspective with measurements performed in lake sediments (e.g. Monticchio sequence in Italy, Allen et al., 1999; Martin-Puertas et al., 2014) but also in marine sediments that enable a direct comparison between D_O variability and modifications in the ocean (Combourieu Nebout et al., 2002; Sanchez Goñi et al., 2000, 2008; Roucoux et al., 2001). The general picture observed in Europe is a significant change in vegetation cover and soil characteristic between stadial and interstadial. The stadials was characterized by much drier and colder conditions (steppic vegetation, loess development in continental Europe – (Moine et al., 2017) and the interstadial was associated with a development of forest. Speleothems are also very useful archives both in mid-latitudes (e.g. (Fleitmann et al., 2009; Genty et al., 2003) and in the tropics (e.g. (Cruz et al., 2009; Wang et al., 2001). Isotopic composition of speleothem calcite responds to change in precipitation, temperature or in soil characteristics linked with vegetation cover. In the tropical regions, isotopes records of speleothem calcite mostly indicate modifications in the water cycle and a link to monsoon intensity in the tropics of the northern and southern hemisphere. The general pattern in the tropics is an intensification of the monsoon intensity in East Asia, while there is a weakening of the monsoon intensity in south America during Greenland interstadials and an intensification of the monsoon intensity in south America, while there is a weakening of the monsoon intensity in East Asia, during Greenland stadials (Cheng et al., 2012). A recent effort for compiling speleothem dating constraints show that there is a synchronous timing for the D-O variability between Greenland temperature and speleothem records in the tropics and mid-latitudes of the northern hemisphere (Corrick et al., 2020).

Figure 24.2- Focus on the millennial variability in Europe and Greenland over the 30 – 50 cal ka BP period which is characterized by the occurrence of several D-O events. From top to bottom: Greenland $\delta^{18}O_{ice}$ record (NorthGRIP ice core; NGRIP members, 2004); SST (red) and Atlantic forest percentage (green) from the MD04-2845 sedimentary core (Sanchez-Goñi et al., 2008); Mediterranean forest percentage from the MD95-2042 sediment core (Sánchez Goñi et al., 2002); $\delta^{18}O$ of calcite from the speleothems of the Sofular cave (Fleitmann et al., 2009); $\delta^{18}O$ of calcite from the speleothems of the Villars cave (Genty et al., 2003).



Still, not all the variability observed during the last glacial period is in phase with the Greenland temperature record. In particular, records from Antarctic ice cores and dating constraints between Greenland and Antarctica revealed an Antarctic variability associated with the Greenland D-O variability but with significant differences in the shape and phasing of events (Blunier & Brook, 2001; Landais et al., 2015; WAIS-D members, 2015). The Greenland stadials are associated with a slow Antarctic warming (~2°C in 1000 years) while Antarctic cooling occurs during Greenland interstadials. The onset of Antarctica cooling is delayed by about 200 years compared to the abrupt temperature change in Greenland, this delay being associated with long propagation time of climate change in the ocean through modification of oceanic water masses organization (Buizert et al., 2018; Pedro et al., 2018). Both polar records and oceanic records in the Atlantic suggest that this bipolar seesaw behavior strongly involves modification of the oceanic thermohaline circulation, and in particular its integrated component of deep and surface currents in the Atlantic, the Atlantic Meridional Oceanic Circulation (AMOC) (Barker et al., 2009). AMOC is characterized by a warm northward flow in the top layers and a cold southward flow in the bottom ocean layers of the Atlantic. The AMOC has an active mode during interstadials and a muted or off mode during Greenland stadials.

Despite the huge documentation of the expression of the D-O events worldwide and in the different compartments of the Earth system (atmosphere, cryosphere, ocean, land) a full explanation of their mechanism is still lacking. A central role is attributed to the AMOC variability, the AMOC being probably less stable during glacials than during interglacials (Broecker et al.1985; Sarnthein et al., 1994; Stommel, 1961). AMOC variability is strongly influenced by the water mass repartition, surface and subsurface conditions in the regions of convection in the North Atlantic and Nordic seas. Freshwater inputs in these regions can easily force the AMOC to switch to a muted or off mode as suggested by climate simulations (e.g. Ganopolski & Rahmstorf, 2001; Menviel et al., 2014). The most probable source for freshwater is the continental ice sheets (Laurentide and European Ice Sheets). However, some models are also able to produce self-sustained variability similar to the D-O variability without imposing freshwater flux through slight variability of the salinity ("salt oscillator") in the Northern Atlantic region (Broecker et al., 1990; Vettoretti & Peltier, 2016; Zhang et al., 2017).

Despite a key role attributed to the AMOC variability in some aspect of the D-O events (e.g. modification of the oceanic circulation with associated surface temperature changes), the amplitude and rapidity of temperature increases in Greenland during D-O events cannot easily be explained only with oceanic processes implying longer timescale and without taking into account the important role of the Arctic sea-ice (Gildor & Tziperman, 2003; Li et al., 2005; Vettoretti & Peltier, 2016). A recent study identifies the subpolar gyre as a key region for the onset of D-O events associated with a southward extension of the sea ice, variable water mass organization and wind patterns that participate in the amplification of smaller perturbations to produce the large D-O variability recorded in Greenland (Li and Born, 2019).

While Greenland and the Nordic seas are probably the regions with the largest expression for the D-O events, Europe is also strongly affected by variability in the AMOC. Atmospheric teleconnections associated with the latitudinal variability in sea-ice extent and the polar front position explain the large signals observed in the different environmental records (see Fletcher et al., 2010 for a review) as well as in modelling outputs (Woillez et al., 2013).

The pollen data syntheses performed by the ACER group (Sánchez Goñi et al., 2017) show the following features for the Europe vegetation during the succession of D-O events. During interstadials, forest dominates in Europe at latitudes lower than 40°N as well as north of 40°N during warmer and long interstadials (i.e. those associated with D-O events 12 and 14). In western Europe the D-O events exhibit clear different latitudinal responses one another during the interval encompassing MIS 4, 3 and 2 (73-14.7 cal ka BP). Higher Mediterranean forest developed during D-O events 17-16 and 8-7 while the Atlantic forest largely expanded during D-O events 12 and 14. D-O events 17-16 and 8-7 were probably amplified by the high seasonality induced by the minima in precession at that time. The development of the Atlantic forest during D-O events 12 and 14 was amplified by the maximum in obliquity affecting latitudes above 40°N (Sanchez-Goñi et al., 2008). A link was also proposed between the change of vegetation in the western Mediterranean area below 40°N and the Asian Monsoon, the interstadials occurring during precession minima (hence strong monsoon intervals) associated with larger development of the Mediterranean forest (Sanchez-Goñi et al., 2008). The underlying process could be linked to the Rodwell and Hoskins zonal mechanism in which desertification in the Mediterranean region is linked to diabatic heating in the Asian monsoon region (Marzin & Braconnot, 2009) or to shifts in the mean latitudinal position of the Intertropical Convergence Zone (Tzedakis et al., 2009). Some modelling studies have focused on the reconstruction of vegetation over Europe. As an example, Woillez et al. (2013) used the coupled IPSL-CM4 general circulation model equipped with the ORCHIDEE vegetation model and obtained a simulation mimicking a D-O event through a rapid shift of the AMOC. The European vegetation responds to the abrupt warming generated by the AMOC shift with a delay of 200 years to reach a new equilibrium of vegetation during the interstadial. Despite the fact that the IPSL-CM4 model produces too much forest in Europe during a glacial stage, there is a general qualitative agreement between the model and pollen estimates of a replacement of grasses by forest in western Europe during the transition from a stadial to an interstadial.

Summarizing, multi-proxy analyses in Greenland and Antarctic ice cores and high resolution records of continental and marine archives have revealed that the D-O events were global with many variations in the northern hemisphere occurring in phase. The Greenland Interstadials are associated with high temperature in the Northern Hemisphere, a northward shift of the InterTropical Convergency Zone and a vegetation dominated by forest in the western Europe. The Greenland stadials are associated with cold temperature in the Northern Hemisphere, a southern shift of the InterTropical Convergency Zone and a vegetation dominated by steppic species in the western Europe. A clear bipolar seesaw behavior is associated with the D-O event with temperature increasing in Antarctica during the Greenland stadials and then decreasing during the interstadials. The mechanism associated with the D-O events is still not fully understood but a key role has been attributed to the variations of the Atlantic Meridional Oceanic Circulation (AMOC) as well as the arctic sea-ice. An important challenge in the modelling community is to be able to model such internal climatic variability of the last glacial period without external triggering and to make the link with the Heinrich events.

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