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The three lost millennia of the last deglaciation (Alfred Wegener Medal Lecture)

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Looking back more than thirty years, climate history over the last period of deglaciation was seen to portray a smooth transition between the last glacial maximum (LGM) centered around 18,000 years ago (based on radiocarbon), and the beginning of the Holocene at about 10,000 years before present. At that time, the renowned CLIMAP group used the stratigraphy available to reconstruct the glacial world by averaging paleothermometric data over a wide time window, ranging between at least 14,000 and 24,000 yr BP, over which period climate was assumed to be rather stable. Even if northern European pollen records showed several phases of vegetation shift, the exact duration and spatial coverage of these shifts was unknown and their climatic significance was not well-enough understood to be separated from other biological effects, such as plant migration following ice-sheet demise.
Significant progress came from mass spectrometry developments applied to isotope geochronology in the mid- and late- 1980s. This allowed the precise analysis of radiocarbon on small samples such as foraminifera in marine sediments and enabled the measurement of U-Th ages for accurate dating of corals and speleothems. These technological improvements permitted meaningful comparisons between proxy records from the various archives originating from all latitudes and longitudes.
Today, it is clear that the old LGM time window corresponds to a period of more than ten millennia during which there was significant climate variability, including a prominent cooling event at the beginning of the deglaciation. This cooling event is known as the 'Oldest Dryas' by palynologists, as 'Heinrich Event #1' (H1) by paleoceanographers, and has even been dubbed the 'Mystery Interval' by prominent authors as they puzzled while attempting to synthesize and interpret its records.
The H1 drastic cooling, attributed to a pulse-like injection of ice and meltwater into the North Atlantic, was first evidenced in 1987 in sediments from the Iberian Margin. Three years later, significant improvements of the radiocarbon calibration demonstrated that about three millennia were missing from the deglaciation record. Accordingly, the LGM mean age was pushed from 18,000 to 21,000 yr BP, the midpoint of H1 was shifted from 13,500 to 16,000 yr BP, and the beginning of the Holocene was repositioned at about 11,500 yr BP. This new climate chronology was subsequently confirmed by counting 'cryovarves' within the GRIP and GISP2 Greenland ice cores. These studies have since been complemented by many other records from polar ice, marine and lacustrine sediments and cave speleothems.
In addition to extending the chronology by three additional millennia, improvement also arose from the quality of the new geological archives. These archives have allowed studies at much higher resolution than was previously achieved in the framework of CLIMAP, which included many records based on deep-sea cores characterized by low sedimentation rate, and thus very susceptible to smoothing processes such as bioturbation. In addition, analytical geochemistry has only recently provided techniques adapted to the production of high-resolution time series of various proxies based on elemental ratios, on organic compounds or on stable and radiogenic isotopes.
More than a dozen years after the H1 discovery, the same Iberian Margin sediments were used to show that H1 comprised at least two phases, H1a and H1b, based on ice rafted debris (IRD) and other proxies. It is now recognized that the entire H1 event (H1 sensu lato) is a three millennia-long period (ca. 17,500 to 14,500 yr BP).
To illustrate the progress in this research field, I will review the key records that can be used to document the complex nature of this episode. The H1 (s.l.) included several phases of intense cooling, of precipitation changes - notably at low latitudes and in the Asian monsoon area, of retreat and decay of glacial ice-sheets - as evidenced in sediments collected in river mouths, and of sea-level rise as recorded in corals from Tahiti and Barbados. Various isotopic proxies of deep-sea ventilation have been used to identify variations during the H1 sub-phases of the Meridional Overturning Circulation (MOC), indicating that ocean heat transport was involved in the observed climate fluctuations.
The various records documenting different climate parameters at many locations over the Earth can also be used in meaningful comparison with numerical model simulations performed in a transient mode. Collectively, these

works allow to estimate the phase relationships between the causes (insolation and the greenhouse effect) and the often abrupt responses of the various components of the climate system, such as the atmosphere, oceans and ice sheets.

Although these studies concern a naturally-occurring global warming that took place over a long time period, useful parallels will be drawn with the evolution of modern climate. In fact, the phase relationships between forcings (such as greenhouse gases and solar input) and changes in regional and global temperatures are also at the heart of modern global climate change. As for early deglaciation, the ocean can modulate warming regionally, thereby delaying, or even temporarily masking, long-term changes.

Climate changes over the last century have been smaller in magnitude than those of the last deglaciation. Fortunately for us, there has been no recent collapse of gigantic ice masses such as the Laurentian and Fennoscandian ice sheets. However, most climate models show a 20 to 40% reduction of the MOC during the 21st century. Even if this change exerts only a minor influence on the projected magnitude of global warming, such a slowdown in ocean circulation change is generally sufficient to reduce the simulated warming over the North Atlantic with a resulting impact on adjacent continents, including Europe.