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Millenial scale variations of the isotopic composition of atmospheric oxygen over Marine Isotopic Stage 4

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Abstract

During rapid events of the last glacial period (DO events), dramatic changes are recorded at high and low latitudes. Without a precise common timescale, links between changes in Greenland temperature and changes in biosphere productivity, hydrology regimes and sea level are difficult to establish. The composition of atmospheric oxygen ($\delta^{18}O_{atm}$) is influenced by global sea level changes, the global hydrologic cycle and the biosphere productivity. Since $\delta^{18}O_{atm}$ is measured in ice cores it gives the opportunity to investigate the underlying processes with no timescale uncertainty. Here, we present the first high resolution (50 yrs) record of the isotopic composition of atmospheric oxygen ($\delta^{18}O_{atm}$) measured in the air trapped in a Greenland ice core (NorthGRIP). Our record covers a sequence of DO events (18-19-20) corresponding to the Marine Isotopic Stage 4, ~75 to 60 ka ago. Our measurements reveal rapid changes of $\delta^{18}O_{atm}$ associated with the DO events. With a few additional measurements of the third isotope of oxygen (^{17}O) during the DO event 19, we exclude the hypothesis that sea level changes are responsible for the isotopic variations. They originate more likely from large changes in relative humidity and latitudinal repartition of the continental vegetation over the DO events.

Keywords: Dansgaard–Oeschger events; oxygen isotopes; biosphere; hydrological cycle; ice core; glacial

1. Introduction

Greenland ice cores have revealed the abrupt climate changes of the last glacial period [1]. Recent methods have been used to show that, during the so-called Dansgaard–Oeschger events (DO), the air temperature increases by up to 16±3 °C in less than 100 yrs in central Greenland [2,3] to reach a relatively warm period (interstadial) lasting several centuries. Then, the local temperature returns progressively to a cold period (stadial) lasting centuries to millennia. To address the latitudinal extent of the rapid events recorded with high resolution in these ice cores it is necessary to compare them to climate records representative of other latitudes.

The signatures of DO events have been described in different areas using various indicators [e.g. [4] for a

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review]. For example, marine cores evidence the rapid climatic variability through changes in the characteristics of the sea surface [e.g. [5]], pollen counting depicts the alternance of vegetation types [e.g. [6–11]] during the succession of the DO and speleothems record modifications of the local hydrological cycle [e.g. [12]]. However, a common timescale for the different local proxies is missing to describe on the global scale the sequence of changes during the DO events.

Recently, another important issue has been raised regarding the relationship between the occurrence of DO events and changes of the size of glacial ice sheets. Marine data obtained by benthic foraminiferal isotopic measurements ($\delta^{18}O_{benthic}$) and coral terraces suggest rapid variations of the sea level by 10 to 30 m in less than 500 yrs parallel to the DO events [13–17]. It is believed that such rapid sea level changes should be caused by instabilities of continental ice sheets. The resulting freshwater inputs in the North Atlantic ocean would have played a role in triggering millennial variations of the strength of the thermohaline circulation (THC) and thus of the North Atlantic temperature [18]. However, $\delta^{18}O_{benthic}$ can also be influenced by temperature and water mixing effects [19–21] and the temporal resolution of coral terraces is too coarse to describe continuously a rapid change. To validate or reject the hypothesis of abrupt sea level changes associated with the DO, further information on the past variations of ice sheet volume or equivalent sea level change over the DO is critical.

An indicator for changes in sea level, the global hydrological cycle, and the biosphere productivity is found in the air trapped in ice cores and thus should help to better constrain the sequence of changes within a DO event in a global manner. Indeed, the isotopic composition of atmospheric oxygen, $\delta^{18}O_{atm}$, is a composite of influences from the sea level changes imprinted to the mean sea water isotopic composition, $\delta^{18}O_{sw}$, and from oxygen fractionations in the hydrological and biological cycles. Long records of $\delta^{18}O_{atm}$ from air trapped in polar ice cores have been obtained over the last 8 climatic cycles with a low resolution (>1 kyr) [22–28]. They show low frequency variations reflecting past sea level changes, hence in $\delta^{18}O_{sw}$, as well as an additional periodic variability in the precession band. This difference between $\delta^{18}O_{atm}$ and $\delta^{18}O_{sw}$ is called the Dole effect and has been interpreted as a signal of low latitude hydrology and of terrestrial to oceanic biospheric productivity ratio [22,29,30]. It follows that the $\delta^{18}O_{atm}$ signal is complex and cannot be interpreted quantitatively in terms of past changes in the sea level, hydrological cycle or productivity alone. This is the reason why, up to now, $\delta^{18}O_{atm}$ was mainly used for the relative dating of polar ice cores and polar ice vs. marine cores taking advantage of the long residence time of oxygen in the atmosphere (1200–2000 yrs) [31,28].

Recently, Luz et al. [32] and Blunier et al. [33] suggested that the triple isotope composition of atmospheric oxygen offers the possibility to access the biological oxygen productivity unbiased by changes in sea level. Such a property results from the different relationships between $\delta^{17}O$ and $\delta^{18}O$ in the various processes involving oxygen. The fractionation induced by the hydrological and biological processes is mass-dependent so that $\delta^{17}O$ changes about half as much as $\delta^{18}O$. On the contrary, photochemical reactions in the stratosphere lead to mass-independent fractionation of the oxygen. The changes in the relationship between $\delta^{17}O$ and $\delta^{18}O$ in the lower atmosphere therefore reflect the relative proportions of two different oxygen fluxes: the exchange with the stratosphere and the biological productivity. Blunier et al. [33] obtained a low resolution (1 kyr) record of triple isotopic composition of oxygen over the last 60 kyrs on the GISP2 ice core and related it to the past changes in global biological productivity.

Here we discuss the sequence between high latitude temperature, low latitude biosphere, hydrological cycle and possible rapid sea level changes over the rapid climatic fluctuations of the last glacial period. We explore information obtained from the isotopic composition of oxygen trapped in the ice cores. We start with a summary of the current understanding of the origin of variations in the isotopic composition of atmospheric oxygen. Then, we present the first high resolution $\delta^{18}O_{atm}$ profile over a sequence of three DO events (18–20) over the period 80 to 60 ka, roughly corresponding to Marine Isotopic Stage 4 (MIS 4). This profile shows high frequency variability that parallels the evolution of Greenland temperature during the DO events. After examination of possible analytical biases on the $\delta^{18}O_{atm}$ record, we use a few additional measurements of $\delta^{17}O$ over the most prominent DO event 19 to propose the best scenario explaining the rapid variations of $\delta^{18}O_{atm}$ during this sequence.

2. $\delta^{18}O_{atm}$ and ^{17}O anomaly of atmospheric oxygen: a summary

2.1. Two isotopes of oxygen: $\delta^{18}O_{atm}$ and Dole effect

Fig. 1A summarizes the major contributions to $\delta^{18}O_{atm}$. $\delta^{18}O_{atm}$ is 23.8‰ heavier than ocean water $\delta^{18}O_{sw}$. This is called the Dole effect (for details, see the comprehensive review by Bender et al. [22]). The Dole effect is usually separated into terrestrial and oceanic contributions so that