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Marine records of Holocene climatic variations

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Abstract

Holocene millennial climate variability is smaller than that of the last glaciation, due to the disappearance of large unstable ice sheets. Marine records show that the sea-surface temperature (SST) exhibited small variations, mainly in the high and low latitudes. They may be interpreted as a linear response to the mean annual insolation. Major changes in the hydrological cycle have been evidenced in the Asian and African monsoon area, resulting in enhanced precipitation and large river outflow in the Bay of Bengal and the Gulf of Niger. Enhanced rainfall over the Mediterranean Basin resulted in a weak circulation and sapropel formation below 800-m water depth in the eastern Mediterranean Sea. Finally small changes in the thermohaline circulation and the warm North Atlantic Drift have been detected in the Nordic Seas. The Holocene climatic variability is therefore similar to that of the Quaternary, but with small amplitude, while continents experienced large rainfall variations. ***To cite this article: J.-C. Duplessy et al., C. R. Geoscience 337 (2005).***

Résumé

Enregistrements marins des variations climatiques de l'Holocène. La variabilité climatique millénaire de l'Holocène est plus faible que celle de la dernière glaciation, en raison de l'absence de grosses calottes glaciaires instables. Les enregistrements marins mettent en évidence des variations modestes de la température de l'eau de mer, notamment dans les très hautes et très basses latitudes. Celles-ci peuvent être interprétées comme une réponse linéaire aux changements de l'insolation moyenne annuelle. En revanche, de grandes variations du cycle hydrologique ont affecté les moussons indiennes et africaines, au point de modifier la salinité de la baie du Bengale et du golfe du Niger. Une augmentation des pluies sur le bassin méditerranéen a perturbé le fonctionnement de la mer Méditerranée : sa circulation profonde a été ralentie et ses eaux sont devenues anoxiques pendant plusieurs millénaires dans le bassin oriental en dessous de 800 m. En milieu océanique ouvert, de petites fluctuations de la circulation thermohaline et de la dérive Nord-Atlantique sont surtout perceptibles dans les mers nordiques. La variabilité climatique de l'Holocène présente donc les mêmes caractéristiques que celles du Quaternaire, mais elle est fortement atténuée en milieu marin, alors que sur les continents, les variations du cycle hydrologique ont été considérables. ***Pour citer cet article : J.-C. Duplessy et al., C. R. Geoscience 337 (2005).***

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Mots-clés : Climat ; Paléoclimat ; Holocène ; Paléo-océanographie ; Changement climatique

1. Introduction

The Holocene, the current warm interglaciation, appears as a relatively stable climatic period when viewed in a long-term perspective. However, significant climatic variations have been evidenced over the continents. In Fennoscandia, it is generally accepted that climate became warmer shortly after the deglaciation and that a broad climatic optimum in mid-Holocene was followed by a declining climate [15]. Superimposed over this broad trend, glaciological, tree-ring and lake-sediment studies showed numerous climatic oscillations [20]. In the tropics, Holocene climatic variations result in abrupt hydrologic changes in regions influenced by the modern monsoon ([12] and references therein).

Recent years have seen the marine geological records of ocean and climate extended to higher and higher resolution. These studies demonstrated that century-scale changes are recorded in high-deposition-rate cores and that they correlate to high-resolution records from ice cores during the last glacial period [5]. However, the study of the present interglacial epoch in the ocean is made difficult because the upper centimetres of sediment are poorly compacted and are therefore badly preserved during coring. Consequently, high-resolution study of the Holocene requires both special coring techniques and selection of areas of fast and high sedimentary accumulation. In this paper, we shall review the major changes in sea-surface temperature (SST), thermohaline circulation and the hydrological cycle, which have been reconstructed using marine cores with accumulation rates high enough to preserve a detailed record of Holocene climatic variations and variability.

2. Sea-surface temperature variations

Long-term trends in North Atlantic SSTs have been explored recently [25,30]. However, the statistical error on SST estimates generated by faunal analysis is about 1–2 °C. As a consequence, only major SST trends can be detected by this method. By contrast, temperature reconstructions based on downcore variations in the concentration of alkenones indicate a small long-term cooling during the last 10 kyr north of 30°N opposed to a minor warming trend at low latitudes. This pattern of variability may be explained as a simple linear response of SST to the mean annual insolation, which decreases at high latitudes and increases at low latitude during the Holocene (Fig. 1). This interpretation is supported by a comparison with the SST trend observed during the previous interglacial (the

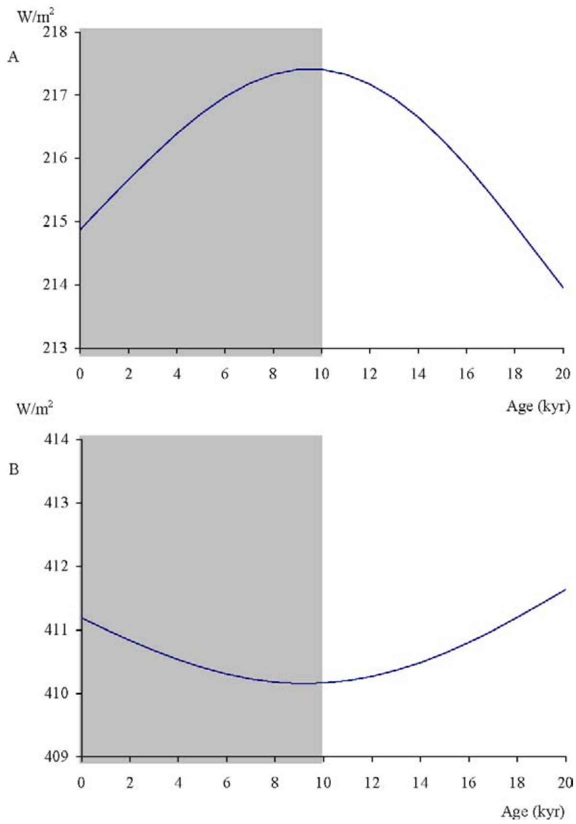

Fig. 1. Mean annual insolation at 65°N (**A**) and 10°N (**B**) from 0 to 20 kyr BP [2]. The dashed zone indicates the Holocene.

Fig. 1. Variations de l'insolation moyenne annuelle à 65°N (**A**) et à 10°N (**B**) entre 0 et 20 ka BP [2]. La zone hachurée indique l'Holocène.

Eemian, about 130–120 kyr ago), which shows a decreasing trend at high latitude and an increasing trend south of 40°N, in close correlation with the mean annual insolation variation pattern [8,9] as well as in model experiments [10]. Rimbu et al. [30] also showed that the western Mediterranean Sea exhibits a negative SST trend during the last 10 kyr, whereas the eastern Mediterranean Sea and the Red Sea show a positive trend, similar to that of the low-latitude North Atlantic Ocean. With reference to the analysis of modern observational and historical data, these authors interpret this behaviour as a continuous weakening of the North Atlantic Oscillation (NAO) pattern from the Early to the Late Holocene. Using atmospheric general circulation model simulations, which are solely forced by insolation and CO_2, they suggest that the weakening of the NAO may be attributed to tropical warming during winter due to the increase in solar radiation during the Holocene in response to the Earth's precession cycle. These results illustrate the major role of the insolation forcing to explain the small variability of SST during interglacial periods.

3. Hydrological-cycle variations

Amplification of the northern hemisphere seasonal cycle of insolation during the mid-Holocene caused a northward shift of the main regions of monsoon precipitation over India and Africa. Enhanced continental rainfall in these areas resulted in enhanced outflow of both the Himalayan rivers in the Bay of Bengal and the Niger River. The outflow of the rivers draining the Himalayan Mountains increased at the end of the deglaciation, about 11.5 kyr ago, and it was larger than today during the Lower and Mid-Holocene. Both the oxygen isotopic composition and salinity of surface water in the Bay of Bengal were

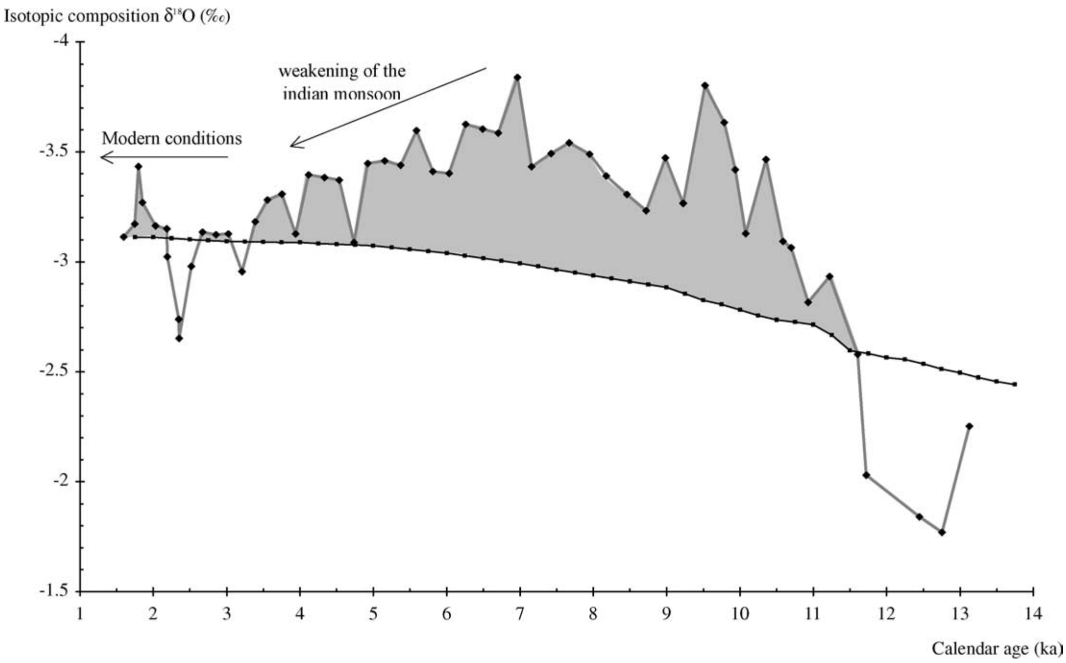

Fig. 2. Oxygen isotopic composition ($\delta^{18}O$) of *Globigerinoides ruber* (black diamonds) versus calendar age in core MD77-176 (14°31′N, 93°08′E, 2137 m) from the Bay of Bengal, and global $\delta^{18}O$ record (small black squares) normalized to the present value of the foraminiferal $\delta^{18}O$. The shaded area indicates river outflow larger than that of today.

Fig. 2. Variations de la composition isotopique de l'oxygène ($\delta^{18}O$) du foraminifère *Globigerinoides ruber* (losanges noirs) en fonction de l'âge calendaire dans la carotte MD77-176 (14°31′N, 93°08′E, 2137 m) prélevée en baie du Bengale. Les petits carrés noirs représentent les variations du $\delta^{18}O$ moyen de l'océan, normalisées à la valeur actuelle du $\delta^{18}O$ des foraminifères. La zone hachurée indique un débit des rivières himalayennes plus fort que celui d'aujourd'hui.

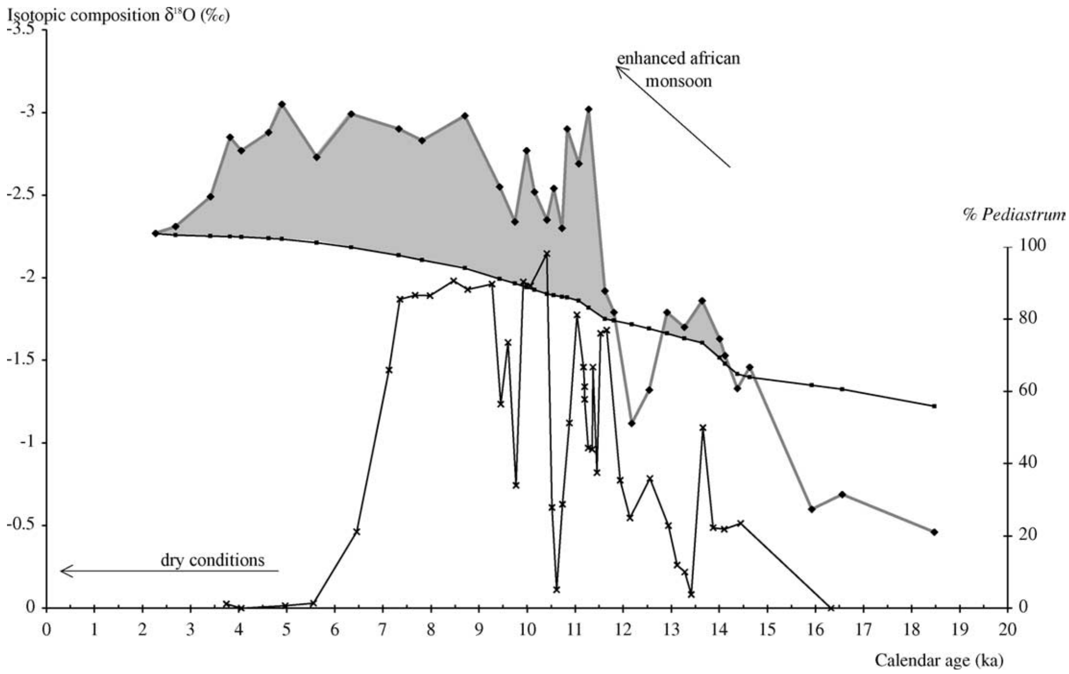

Fig. 3. δ^{18}O record of *G. ruber* (black diamonds), percentage of *Pediastrum* (crosses) in core KW31 (3°31′N, 5°34′E, 1181 m), and global δ^{18}O record (small black square) normalized to the present value of the foraminiferal δ^{18}O. The shaded area indicates river outflow larger than that of today.

Fig. 3. Variations de la composition isotopique de l'oxygène (δ^{18}O) du foraminifère *Globigerinoides ruber* (losanges noirs) en fonction de l'âge calendaire dans la carotte KW31 (3°31′N, 5°34′E, 1181 m), prélevée à l'embouchure du Niger. Les croix représentent les variations d'abondance d'une algue d'eau douce *Pediastrum* et les petits carrés noirs représentent les variations du δ^{18}O moyen de l'océan, normalisées à la valeur actuelle du δ^{18}O des foraminifères. La zone hachurée indique un débit du Niger plus fort que celui d'aujourd'hui.

lower than today. This resulted in a broad negative δ^{18}O peak in the isotopic record of the planktonic foraminifer *Globigerinoides ruber*, a species that lives mainly in surface waters (Fig. 2). Since about 6–7 kyr BP, the δ^{18}O record of *G. ruber* increases, reflecting a progressive weakening of the Indian monsoon, which became similar to that of today about 4 kyr ago. Superimposed over this long-term δ^{18}O record are short spells of weak monsoon, which became progressively stronger during the Upper Holocene (Fig. 2). The humid period over West Africa during the Lower and Mid-Holocene is recorded in the δ^{18}O and algae record of core KW31 recovered off the mouth of the Niger River (Fig. 3). Enhanced African monsoon began about 14.5 kyr ago, i.e. before the beginning of the Holocene. The increase of monsoon rainfall responsible for freshwater input to the Atlantic Ocean occurred gradually during the last glacial to interglacial transition [24]. By contrast with the Indian monsoon, which has decreased progressively during the last 6 kyr, the end of the African humid period is marked by several abrupt steps. The transport of freshwater algae by the Niger River stopped by 5.5 kyr BP, reflecting dry conditions taking place over West Africa. However, the outflow of the Niger River was still higher than today and it reached abruptly its present value by about 4 kyr BP [28]. Geomorphologic and biostratigraphic evidence indicates that northern Africa was considerably wetter than today and extensively vegetated in the Mid-Holocene. Lakes were present in now-dry basins as far north as 27°N and in the northwestern part of North Africa [16]. The northernmost extension of the West-African monsoon was therefore restricted to 27°N. However, dramatic changes of the freshwater budget also occurred over the Mediterranean Basin. These changes, centred around 8 kyr BP, resulted in the deposition of black organic-rich sediments, called sapropels. They testify to the establishment of bottom-water anoxia resulting from the lowering of the sea-surface salinity and the stratification of the eastern Mediterranean water column. The freshwater input was so large that the Mediterranean Sea was not a concentration basin and was unable to form deepwater by winter convection during this event [18]. Rossignol-Strick [31] suggested that the freshwater injection may originate from a giant teleconnection with the monsoon and that the Nile would have carried to the eastern Mediterranean Sea the heavy monsoon rain falling over eastern Africa. A reconstruction of sea surface salinity of the whole Mediterranean Sea at the time of the last sapropel showed that the outflow of the Nile River was indeed enhanced, but that it was too small to take account of the low salinity of the whole Mediterranean Sea surface water [18]. As a matter of fact, the surface water that entered the Mediterranean Sea through the Gibraltar Strait did not experience any salinity increase during its journey to the eastern basin [19]. The hydrological budget, which exhibits today a deficit of about 1 m of water over the whole Mediterranean Sea area, was nearly equilibrated at the time of the sapropel event. Such a dramatic change can only be explained by enhanced rainfall over the Mediterranean Sea and its drainage area. The Mid-Holocene period (6 kyr BP) was chosen by the Palaeoclimate Modelling Intercomparison Project (PMIP) to check the reliability of climate models in simulating climate change on the regional scale and to compare the response of different models to the insolation forcing without changing the vegetation cover and SST [6,17]. All the models produce increased precipitation over India and over northern Africa, in qualitative agreement with palaeoclimate reconstructions. However, none of the PMIP models produces a large-enough northward shift of the monsoon rainfall, consistent with the reconstructed changes in vegetation over northern Africa. None also simulates the heavy rainfall and the nearly equilibrated hydrological budget over the Mediterranean Basin. The magnitude of changes of the hydrological cycle and monsoon intensity during the Holocene is so large that it cannot be simply explained by simple model experiments and future work will be required to take into account synergistic interactions between the ocean, dynamical vegetation, and surface-water storage at the surface of the continents.

4. Oceanic-circulation variations

The role of the ocean as a regulator of the climate system is well known, but its potential role in destabilizing climate has only recently been discovered. The thermohaline circulation acts as a pump, which transfers heat (about 1.4×10^{15} W) from the South Atlantic to the North Atlantic. The conversion of surface water to deepwater in the North Atlantic Ocean results in the release of heat from the ocean to the atmosphere, which may have amplified millennial-scale climate variability during glacial times [7]. As a matter of fact, one of the most striking characteristics of millennial scale climate events during the Pleistocene is their association with changes in thermohaline circulation [22,26,33,35]. Recent attempts have therefore been made to document the thermohaline circulation variability during the Holocene, despite the difficulty of collecting undisturbed sediment cores with the most recent deposits recovered undisturbed. A deep-sea core raised from the Rockall Plateau exhibits small SST variations during the Holocene, but significant sea-surface salinity (SSS) and density variations (Fig. 4). The salinity record displays two broad minima separated by a maximum between 7 and 5 kyr BP. The first salinity minimum may be associated with the injection into the Labrador Sea of Laurentide meltwaters, about 8.2 kyr ago, although its duration seems to be longer than the meltwater event alone [1,14,29]. We still do not know whether this is a millennium-scale decrease of the salinity of the North Atlantic Drift water or an artificial expansion of the low salinity peak resulting from sediment bioturbation. The low salinity peak around 4 kyr BP is not associated with a meltwater event as the Laurentide ice sheet has already disappeared. It results from a change in the evaporation–precipitation budget of the North Atlantic surface water. Surprisingly, it roughly coincides with the final decrease of the Niger River outflow, suggesting a major change in atmospheric circulation and water cycle at this time. Further north, the Barents Sea is fed by the northernmost extension of the ocean conveyor belt. Its only source of warm ($\sim$1 °C) saline ($>$35‰) water is the Atlantic water flow. The Barents Sea hydrology is therefore strongly depending on the input of Atlantic water, which is present as an intermediate water mass separating the Arctic water at the surface from the extremely cold bottom water formed

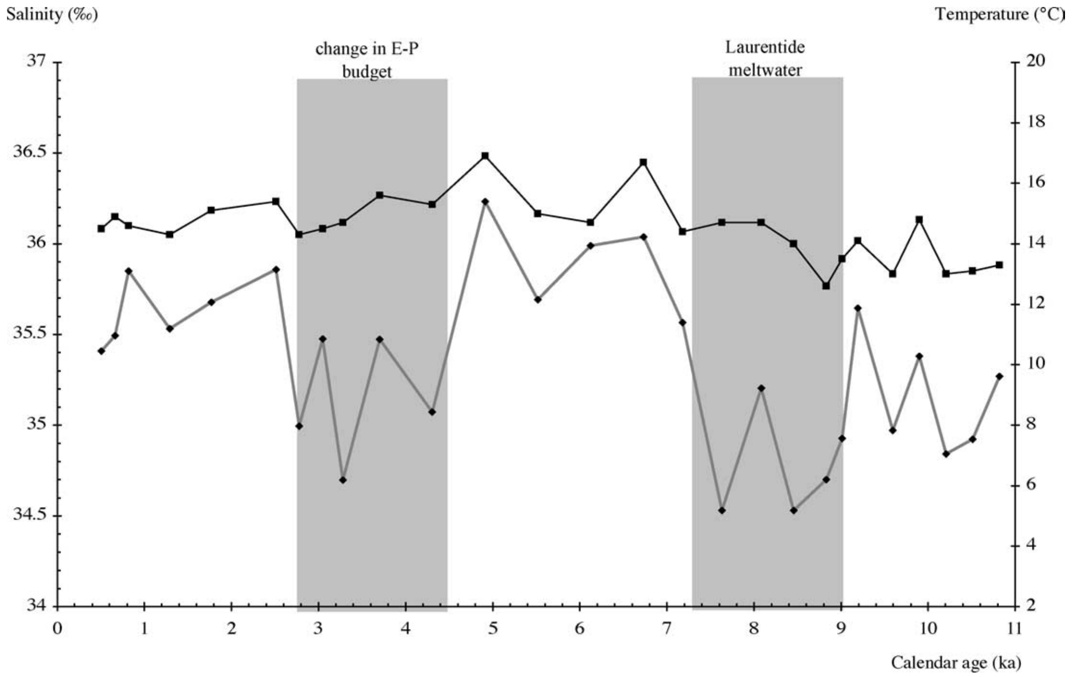

Fig. 4. Sea-surface temperature (black squares) and salinity (black diamonds) reconstructions from core NA87-22 (55°28′N, 14°47′W, 2161 m) from the Rockall Plateau.

Fig. 4. Reconstitution des variations de température (carrés noirs) et de salinité (losanges noirs) des eaux superficielles déduites de l'analyse de la carotte NA87-22 (55°28′N, 14°47′W, 2161 m) prélevée sur le plateau de Rockall.

through rejection of brine during freezing. The isotope records of core ASV 880 show that the Barents Sea experienced long-term and short-term climatic changes during the Holocene (Fig. 5). The warmer temperatures occurred between 7.8 and 6.9 kyr BP and this thermal optimum had a much shorter duration at 80°N than at lower latitudes, where its duration may exceeds three millennia [4,23]. Most local Holocene climatic changes appeared linked to changes in the flux of warm Atlantic waters entering the Barents Sea. During the temperature optimum, the Atlantic water occupied the whole water column of Franz Victoria Trough [11] and very little cold deepwater sank along the Barents Sea shelf. The strong cooling, which marked the end of the climatic optimum, was associated with a reduction of the flux of Atlantic water reaching the Arctic. The slowing thermohaline circulation resulted first in a temperature drop of the Atlantic waters penetrating the Arctic Ocean. These cold conditions allowed surface water freezing during winter, so that the bottom of the Barents Sea was progressively invaded by dense and cold water formed through rejection of brine during freezing, as it is observed today. The bottom water in Franz Victoria Trough became a mixture of Atlantic water and of dense brine water. The composition of this mixture varied during the Upper Holocene, following the intensity of the flux of Atlantic water carried by the North Atlantic Drift to the Arctic domain. The beginning of the temperature optimum in the Barents Sea, which closely follows the 8.2 kyr BP event, coincides with the increase in North Atlantic surface water salinity recorded in core NA 87-22. However, the more recent temperature variations in the Barents Sea do not correlate with the salinity record of core NA 87-22. As a matter of fact, all Atlantic water penetrating the Arctic domain does not enter the Barents Sea. The inflow of Atlantic water depends on the intensity of the westerlies. When the North Atlantic Oscillation (NAO) index is high, both westerlies and the northward-flowing Norwegian current are strong. The prevailing winds set up a wind stress that brings the Atlantic water toward Scandina-

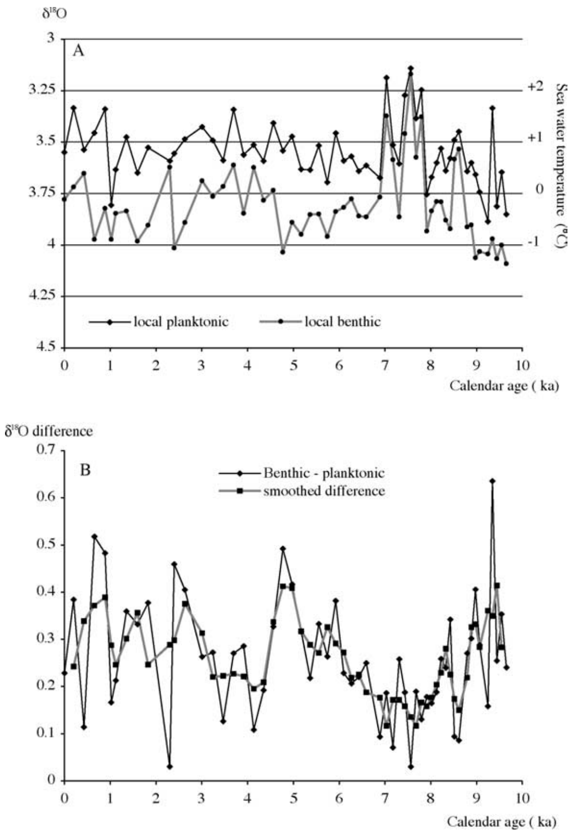

Fig. 5. (**A**) Planktonic (black diamonds) and benthic (black dots) δ^{18}O records corrected from global ice volume in core ASV 880 (79°55′N, 47°08′E, 388 m) raised from the Barents Sea during a cruise of the Shirshov Institute. These records are interpreted as seawater temperature records near 100 m (Atlantic water mass in which live planktonic foraminifera) and near the bottom (where benthic foraminifera live). (**B**) Benthic minus planktonic δ^{18}O difference in core ASV 880 (black diamonds) and smoothed record (black squares).

Fig. 5. (**A**) Variations de la composition isotopique de l'oxygène (δ^{18}O) des foraminifères planctoniques et benthiques, corrigées des variations du δ^{18}O moyen de l'océan dans la carotte ASV 880 (79°55′N, 47°08′E, 388 m) collectée en mer de Barents au cours d'une campagne océanographique du Shirshov Institute. Ces variations sont interprétées en termes de température de l'eau de mer dans l'eau atlantique (enregistrement des foraminifères planctoniques vivant vers 100 m de profondeur) et au voisinage du fond (enregistrement des foraminifères benthiques). (**B**) Différence de δ^{18}O entre les enregistrements planctoniques et benthiques dans la carotte ASV 880 (losanges noirs) et courbe lissée sur trois points (carrés noirs).

vian coasts and results in an active penetration of Atlantic waters into the Barents Sea [4]. Conversely, this penetration is reduced when the NAO index is low, so that the Barents Sea temperature does not depend only on the intensity of the global ocean thermohaline circulation. Other evidences of thermohaline circulation changes include grain-size variations in deep Atlantic Holocene deposits depending on the speed of bottom currents [3], carbonate content of Holocene sediments from the Bermuda Rise [21], changes in the export flux of coccoliths reflecting instabilities in surface circulation in the North Atlantic [13], and carbon-isotope variations in benthic foraminifera from the Feni Drift, interpreted as evidence for variations in the contribution of high-δ^{13}C North Atlantic deepwater relative to low-δ^{13}C southern Ocean water [27]. In addition, model experiments suggest that wind forcing plays a substantial role in maintaining large-scale thermohaline flow in the North Atlantic [32]. This whole set of studies demonstrate that the oceanic circulation has not been stable during the last 10 kyr, but further well-dated deepwater proxy records are needed to generate a fully consistent picture of thermohaline circulation variations and provide evidence for a climate–deepwater link during the Holocene.

5. Conclusion and discussion

Climate changes have been less severe during the present interglacial period than during the last glaciation. Small sea-surface temperature variations (<2 °C) have been evidenced in the North Atlantic Basin and may be interpreted as a linear response to mean annual insolation variations. The hydrological cycle experienced large changes, which are particularly strong over the continents in the tropics. A humid period at the beginning of the Holocene resulted in increased freshwater discharge of tropical rivers such as the Niger River in the Gulf of Guinea and the rivers that empty into the Bay of Bengal. Enhanced precipitation over the Mediterranean Basin also resulted in eastern Mediterranean Sea stagnation and sapropel formation. All these changes in the hydrological cycle may be related to variations of the monsoon intensity. The increase of both the latitudinal summer and mean annual insolation gradients resulted in more intense equator-to-pole atmospheric transport. This explains the increasing flux of freshwater from the tropical ocean to the continents, which has been detected up to Antarctica [34]. By contrast, due to the thermal inertia of the seawater, changes in the North Atlantic hydrology and circulation have been much weaker and the evidence for concurrent changes in climate and thermohaline circulation, well observed in the Barents Sea, is still ambiguous at low and middle latitudes.

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