Monsoonal Forcing of European Ice-Sheet Dynamics During the Late Quaternary

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AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL078751

Key Points:
- Mediterranean climate variability paced European Ice Sheet advances
- Glacial warm-water pooling along the continental margin of western Europe was caused by monsoonally paced enhanced Mediterranean Outflow Water entrainment into the midlatitude North Atlantic
- Yet unrecognized marine-terrestrial pathway that allows low-latitude forcing to shape midlatitude glaciations

Supporting Information:
- Supporting Information S1

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Citation:
Kaboth-Bahr, S., Bahr, A., Zeeden, C., Toucanne, S., Eynaud, F., Jiménez-Espejo, F., et al. (2018). Monsoonal forcing of European ice-sheet dynamics during the Late Quaternary. *Geophysical Research Letters*, *45*, 7066–7074. https://doi.org/10.1029/2018GL078751

Received 13 MAY 2018
Accepted 30 JUN 2018
Accepted article online 11 JUL 2018
Published online 25 JUL 2018

Monsoonal Forcing of European Ice-Sheet Dynamics During the Late Quaternary

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Abstract The dynamics of Northern Hemisphere ice sheets during Late Quaternary glacials have yet been dominantly examined from a Laurentide Ice Sheet perspective, which helped shaping the idea of moisture-starved glacials and small-scale ice volume variability. However, the waxing and waning of the European Ice Sheet (EIS) casts doubt on this perception. Understanding EIS dynamics under glacial boundary conditions is crucial because its meltwater pulses influence global climate by weakening deepwater formation in the North Atlantic Ocean. Here we show that the advection of subtropical water toward the continental margin of western Europe lead to enhanced moisture availability on the continent and fueled the growth of EIS lobes during glacials. This warm-water pooling was caused by monsoonally paced enhanced Mediterranean Outflow Water (MOW) entrainment that dragged subtropical surface waters toward the European margin. This mechanism presents a yet unrecognized marine-terrestrial pathway that allows low-latitude forcing to shape high-latitude glaciations.

Plain Language Summary The build-up of glacial ice shields required large amounts of atmospheric precipitating as snow. However, under full glacial conditions, cold surface oceans reduce the amount of evaporation, which counteracts the growth of large continental ice shields. Our study aims to unravel the source and transport pathways of moisture that helped to rapidly form the European Ice Shield during the past two glacials. We propose the novel concept that the outflow of dense Mediterranean water into the North Atlantic played a decisive role as it helped to “drag” warm surface waters toward the European Margin by strengthening the Azores Current. This warm, subtropical water current supplied vast amounts of moisture, which then was transported northward into continental Europe and fueled ice sheet growth. The strength of Mediterranean Outflow Water discharge into the Atlantic strongly depends on monsoonal activity in its source region in the Eastern Mediterranean Sea. Thus, warm water advection toward western Europe and associated glacier growth of the European Ice Shield are intimately linked to low-latitude climate changes, closely following the ~21 kyr beat of orbital precession.

1. Introduction

Continental ice sheets are traditionally thought to be rather stable once the Earth’s climate state has descended into full glacial conditions; in that state, low sea surface temperatures and extended sea-ice cover in the high northern latitudes effectively counteract the advection of moisture as it is required for further ice-sheet growth (McClymont et al., 2013; Ruddiman & Mcintyre, 1979). However, frequent meltwater intrusions from the western part of the European Ice Sheet (EIS; Figure 1) into the Bay of Biscay have challenged this view (Toucanne et al., 2009, 2015). They testify to repeated waning of the EIS during full glacial conditions, which by extension implies rapid regrowth of the EIS. Importantly, oscillations as they are documented for the EIS have not yet been reported for the Laurentide Ice Sheet (see supporting information S1 for details on Laurentide Ice Sheet variability), which may suggest a possible decoupling of EIS dynamics from that of other ice sheets in the Northern Hemisphere (Bahr et al., 2018; de Boer et al., 2014; Lisiecki & Raymo, 2005). Notwithstanding its limited size, the EIS plays a critical role for global climate due to its vicinity to the centers of deepwater formation in the subpolar North Atlantic. Here its meltwaters have the potential to disrupt

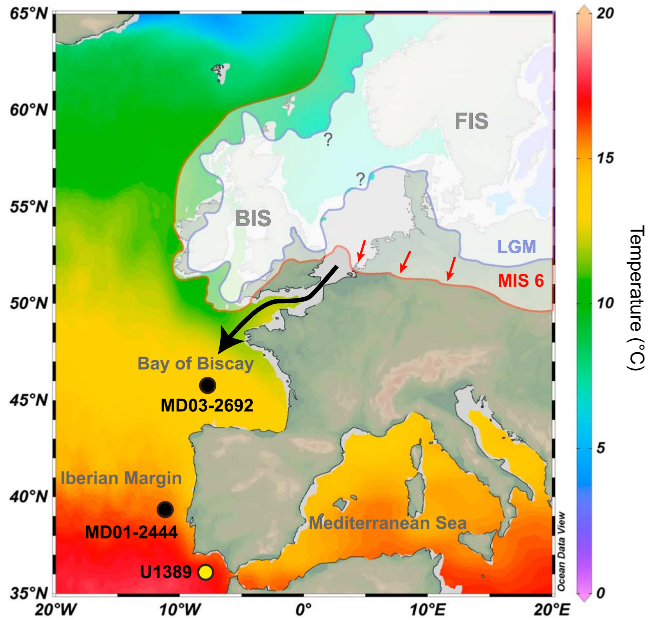

Figure 1. Map showing positions of Site U1389 and other locations along the European continental margin mentioned in the text, present-day mean annual sea-surface temperatures (50 m water depth), and maximum extent of European ice sheets during the Last Glacial Maximum and MIS 6 (Ehlers et al., 2011; Toucanne et al., 2015). FIS = Fennoscandian Ice sheet; BIS = British Ice sheet; dotted arrow = Fleuve Manche paleoriver. Sea surface temperatures are derived from the World Ocean Atlas 2013.

deepwater formation, thereby causing a weakening of the meridional overturning circulation (Hodell et al., 2017; Toucanne et al., 2015). The rapid regrowth of the Late Quaternary glacial EIS after intermittent phases of destabilization during times of increasing summer insolation required an enhanced moisture supply (Sánchez Goñi et al., 2018). However, the mechanism fuelling moisture advection to the EIS during full glacial conditions has remained largely elusive. Here we present proxy records from the southwestern European margin that for the first time document a persistent coupling between subtropical water-mass advection and growth of the southwestern EIS lobes on precession time scales during the past 250 kyr (Figure 1). Based on these data, we demonstrate a yet unrecognized low-latitude forcing of EIS build-up via marine-terrestrial feedback in the Mediterranean realm that is superimposed on midlatitude ice-sheet modulation.

2. Data and Methods

2.1. Azores Current Variability

Today, warm, subtropical surface waters (14–16 °C; ~36.2 practical salinity unit, PSU) reach the western European Margin through the Azores Current (AzC; flow core between 32 and 37°N), which represents the northeastern delineation of the North Atlantic subtropical gyre system (Peliz et al., 2009). Numerical models show that the existence of the AzC and hence the presence of subtropical surface waters east of 20°W depends solely on the buoyancy-driven entrainment of Mediterranean Outflow Water (MOW) into the North Atlantic (Jia, 2000; Volkov & Fu, 2010). The highly saline (>36 PSU) MOW is directly fed by intermediate-water masses exiting the Mediterranean Sea through the Strait of Gibraltar where it cascades down the water column due its high density (Millot, 2014; see supporting information S2 and Figure S1). The sinking of the MOW drags warm subtropical surface waters to the east, thereby creating the AzC that transports warm waters toward the Iberian Margin (Jia, 2000; Volkov & Fu, 2010). Particularly during winter and spring, the Iberian Poleward Current, a branch of the AzC, becomes a prominent feature off western Iberia concurrent with the northward shift of the thermal Subtropical Front (Voelker & de Abreu, 2011). Along with this shift, warm and salt-rich waters of subtropical origin waters tend to recirculate from the Gulf of Cadiz northward along the Iberian Margin (i.e., Site MD95-2040; see Figure 1) and can be traced as far north as the Bay of Biscay (Voelker & de Abreu, 2011).

2.2. MOW Flow Reconstruction

Integrated Ocean Drilling Program (IODP) Site U1389, which has provided the material for our study, is situated off SW Iberia within the main branch of the MOW at a water depth of 630 m (Figure 1). Because it is unaffected by vertical slope movements of the MOW plume, it represents a faithful recorder of MOW flow vigor on glacial-interglacial timescales throughout the Pleistocene (Bahr et al., 2015; Kaboth et al., 2017). To reconstruct the variability of MOW entrainment as the ultimate driver of AzC strength, we utilized the well-established Zr/Al proxy (Bahr et al., 2014, 2015). The Zr/Al ratio documents the accumulation of heavy minerals (e.g., zircon) over aluminosilicates under the increasing bottom-current flow of the MOW (Figure 2c). For the following discussion we assume that MOW flow speed as recorded by the Zr/Al ratio at Site U1389 is positively related to the volume flux Q_{MOW} of MOW after NACW entrainment (Jia, 2000; Volkov & Fu, 2010) and hence AzC formation. This is based on recent model studies showing that an increased density contrast between MOW and NACW significantly increases the amount of NACW entrainment (Xu et al., 2007). The entrainment is fostered by the higher velocity of the MOW compared to that of the surrounding NACW, which results in the generation of small-scale eddies (Baringer & Price, 1997; see supporting information S3). These eddies draw less dense ambient NACW water into the MOW plume, which in turn increases its volume flux Q_{MOW}. Due to its position downstream of the Strait of Gibraltar, Site U1389 is ideally suited to estimate Q_{MOW} as a driver of AzC formation. However, we are aware that the MOW flow velocity

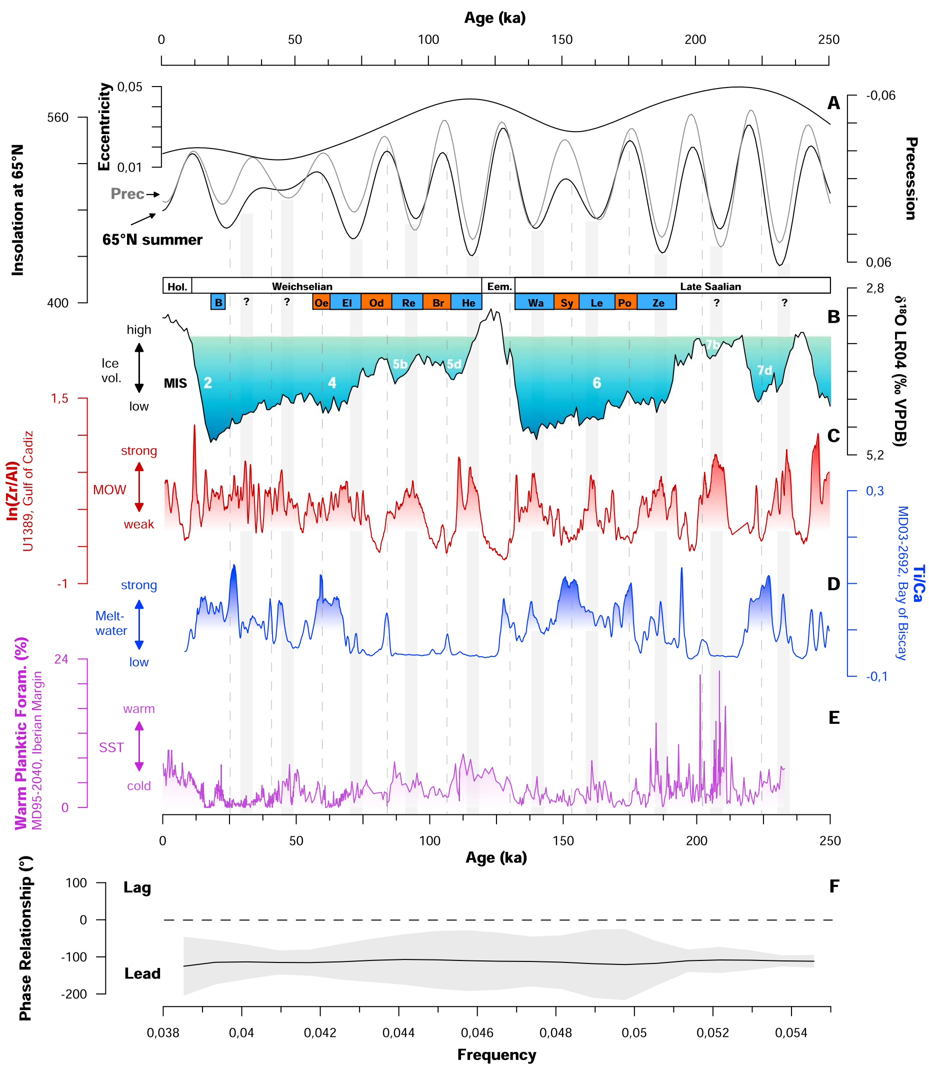

Figure 2. Terrestrial and marine proxy records for the Late Quaternary (0–250 kyr). (a) Eccentricity, precession, and summer (21 June) insolation curve for 65°N (Laskar et al., 2004). (b) Global benthic $\delta^{18}O$ stack LR04 (Lisiecki & Raymo, 2005) as a measure of global ice volume. Marine Isotope Stages (MIS) follow Lisiecki and Raymo (2005). Corresponding continental glaciations and known ice advance and retreat phases are presented on top of panel b following the terminology for western and central Europe (Litt et al., 2007). Ze = Zeitz phase; Po = Pomßen interval; Le = Leipzig phase; Sy = Seyda interval; Wa = Warthe phase; He = Herning stadial; Br = Brörup interstadial; Re = Rederstall stadial; Od = Odderade interstadial; El = Ellund phase; Oe = Oerel stadial. (c) Zr/Al record from Site U1389 in the Gulf of Cadiz. Strong MOW phases are marked by grey bands. (d) Ti/Ca record from Site MD03-2692 in the Bay of Biscay (Toucanne et al., 2009). Peak Ti/Ca values are marked by black dashed lines. (e) Relative abundances of warm-water planktic foraminifera at Site MD95-2040 (see supporting information S5). (f) Phase relationship between the Zr/Al record from Site U1389 (reflecting MOW variability) and the Ti/Ca record from Site MD03-2692 (reflecting Fleuve Manche variability) for the precession band (frequency range = 0.039–0.053; 26–18 kyr). Mean phase value is indicated by black line; upper and lower 95% uncertainty levels are indicated by grey shaded area.

(u_{MOW}) inferred from the Zr/Al record at Site U1389 does not directly record Q_{MOW}. This is due to the fact that changes in Q_{MOW} result from variations in the transported volume (V_{MOW}) per time (t) as $Q_{MOW} = V_{MOW} * t^{-1}$. An increase in Q_{MOW} may therefore result from a higher V_{MOW} although u_{MOW} actually decreased or remained constant. To constrain the relation of Q_{MOW} and u_{MOW} at Site U1389, we utilize the well-documented changes in MOW volume flux at Gibraltar ($Q_{MOW\text{-}Gib}$) and u_{MOW} during the late and early Holocene. During the deposition of sapropel S1, the eastern Mediterranean Sea—the source region of MOW—was freshened substantially by increased terrestrial runoff in concert with an intensified Northeast African monsoon (Rohling et al., 2015). As a consequence, the Atlantic-Mediterranean density gradient decreased and fostered a strong reduction of $Q_{MOW\text{-}GIB}$ (Rogerson et al., 2012). Following Xu et al. (2007), this led to reduced entrainment of NACW and thus a lower Q_{MOW}. In line with a lowered Q_{MOW}, reduced Zr/Al ratios at Site U1389 suggest a reduction of bottom-current velocity (reflecting u_{MOW}) during the time interval corresponding to S1 formation (Bahr et al., 2015). In contrast, the higher density difference between the Mediterranean Sea and the North Atlantic during the late Holocene, associated with a reduction of monsoonal run-off, went along with higher MOW flow speed at Site U1389 (Bahr et al., 2015). Based on our comparison, we find that u_{MOW} at Site U1389 correlates positively with Q_{MOW}; hence, our Zr/Al-based bottom-current velocity record allows to infer changes in Q_{MOW} and, by extension, AzC formation.

The positive correlation between recorded u_{MOW} at Site U1389, Q_{MOW}, and Mediterranean-Atlantic density gradients could also hold true under glacial boundary conditions. However, this depends on whether the shoaling of the Strait of Gibraltar due to glacial sea level drop did impact not only Mediterranean-Atlantic water-mass exchange but also the physical properties of MOW. Recent simulations of the Mediterranean-Atlantic water-mass exchange under Last Glacial Maximum (LGM) conditions indicate that even a sea level drop of 150 m would have decreased $Q_{MOW\text{-}Gib}$ by only 20% (Simon & Meijer, 2015). For context, the measured modern interannual transport variability off Gibraltar is 10% (García Lafuente et al., 2007). While $Q_{MOW\text{-}Gib}$ was therefore slightly reduced during the LGM, the salinity of the Mediterranean Sea increased by ~5 PSU (Rohling et al., 2015). This lead to a doubling in the salinity gradient between the Atlantic and the Mediterranean Sea ($\Delta S_{MedSea\text{-}Atlantic}$), and subsequently almost doubled the velocity of the MOW exiting Gibraltar (Rohling et al., 2015). Following Xu et al. (2007), the effect of an increased glacial salinity gradient across the Strait of Gibraltar and its higher outflow velocity should have led to increased NACW entrainment and enhanced Q_{MOW} after entrainment. Although more detailed modeling studies are required to quantify Q_{MOW} under glacial boundary conditions, our first-order estimates indicate that (i) the eastward pull on the AzC was likely increased relative to today and (ii) the bottom-flow velocity at Site U1389 should also have been elevated. The latter assumption is confirmed by the elevated Zr/Al ratios at Site U1389 during Marine Isotope Stage (MIS) 6 when compared to interglacial values of MIS 1 and 5e (Figure 2e).

Based on reconstructions of MOW vigor variability across the last 130 kyr, it becomes clear that on orbital time scales MOW behavior follows a persistent precession beat (Bahr et al., 2015; Kaboth et al., 2016). This reflects the sensitivity of MOW to monsoonally controlled freshwater discharge into its eastern Mediterranean source region (Bahr et al., 2015; Kaboth et al., 2016). There, surface water freshening disrupts intermediate convection—and thus the formation of MOW source waters—when monsoonal runoff enters the eastern Mediterranean Sea via the River Nile (Bahr et al., 2015; Kaboth et al., 2016; Rodrigo-Gámiz et al., 2014). This situation occurs during precession minima. In contrast, during precession maxima (i.e., low NH insolation) the North East African monsoonal system is positioned further to the south, which reduces Nile River runoff and by extension fosters MOW formation (Rohling et al., 2015; Rossignol-Strick, 1983). High-latitude climate variability, on the other hand, influences MOW production only on millennial to submillennial time scales (e.g., during Heinrich Stadials).

For this study, we extended the Zr/Al data set from Site U1389 of Bahr et al. (2015) to ~250 kyr in order to cover MOW flow variability during MIS 6 and 7, which are characterized by particularly prominent EIS fluctuations (Toucanne et al., 2009).

2.3. Establishment of Age Models for Sites U1389 and MD03-2692

The age model of Site U1389 for the last ~150 kyr is based on AMS ^{14}C dates (until 16.3 kyr) and matching its planktic $\delta^{18}O$ record to core MD01-2444 from the Iberian Margin (Hodell et al., 2013; see supporting information S4). Age control for Site MD03-2692 is based on the correlation of its benthic $\delta^{18}O$ record to the LR04 global benthic $\delta^{18}O$ stack (Mojtahid et al., 2005; Toucanne et al., 2009). In addition, we used a novel optimization algorithm based on the "astrochron" R software package (see supporting information S4) to constrain potential age-model ambiguities in our comparison of proxy records from Sites U1389 and MD03-2692.

3. Results and Discussion

High Zr/Al ratios documenting pronounced intensifications of MOW flow occurred at Site U1389 during MIS 7d, 7b, 6, 5d, 5b, 4, and 2 (Figure 2c). Due to its proposed impact on the AzC, a strong admixture of MOW into the North Atlantic would result in the propagation of warm, subtropical surface waters toward the western European Margin. The presence of such waters during phases of strong MOW is in fact documented by increased abundances of warm-water-dwelling planktonic foraminifera off Iberia (Figure 2e; see supporting information S5). This relationship is particularly strong during MIS 6 and early-to-mid MIS 5 but is markedly weaker during subsequent MIS 4 to MIS 2. We further infer that this intrusion of subtropical waters was not forced by frontal shifts induced by changes in Atlantic Meridional Overturning (AMOC) strength as the surface hydrography at the Iberian Margin is only sensitive to phases of extreme AMOC slowdown (i.e., during the most pronounced Heinrich Events) when subarctic water reaches as far south as the Gulf of Cadiz (Voelker et al., 2009; Voelker & de Abreu, 2011).

Notably, episodes of enhanced MOW flow coincide with west-southwest trending advances of the EIS in northern Germany and the Netherlands during full glacial conditions as documented by glaciogenic sediments (Ehlers et al., 2011; Figure 2a). We argue that this temporal coincidence is a direct consequence of warm-water advection toward southwest Europe caused by the enhanced entrainment of MOW into the North Atlantic during precession maximum (insolation minimum) conditions. The accumulation of warm surface waters in the eastern North Atlantic led to enhanced formation of atmospheric moisture (Sánchez Goñi et al., 2018; Figure 3a) that was advected northeastward into the continent as documented by central European paleosol records (Schirmer, 2016; Zeeden et al., 2016). The atmospheric moisture transport was further enhanced by the reorganization of the North Atlantic jet stream during glacial periods (Luetscher et al., 2015), with a southward displaced and intensified jet stream as a response to the growth of the Laurentide and European Ice Sheets (Löfverström & Lora, 2017). At the same time, the formation of a permanent high-pressure system above the Fennoscandian Ice Sheet caused frequent Rossby-wave breaking over western Europe (Luetscher et al., 2015; Figure 3a). These atmospheric conditions enhanced the meridional advection of moist and warm subtropical air masses toward central Europe, providing the humidity required for EIS regrowth (Luetscher et al., 2015).

The repeated EIS advances, in turn, fed the paleoriver discharge of the Fleuve Manche (Figure 1) under increasing summer insolation (precession minimum) during full glacial conditions. The intensified supply of terrigenous material from dissociating EIS has been traced within the Bay of Biscay by high Ti/Ca ratios in Core MD03-2692 (Figure 2d; Toucanne et al., 2009); it is persistently preceded by strong MOW production (Figure 2c). Importantly, this is consistent with the proposed MOW-driven ice-sheet build-up. The anticorrelation between MOW flow strength and continental meltwater discharge clearly reflects the waxing and waning of the EIS. The same temporal succession of MOW-related ice-sheet build-up and subsequent insolation-forced disintegration occurs during cold phases within interglacials. This holds particularly true for MIS 7d, but to a lesser degree also for MIS 7b, 5d, and 5b. In all cases, MOW intensifies at the onset of the respective cold phase (Figure 2c), fostering the build-up of EIS lobes via a strong AzC. Fleuve Manche activity occurs subsequently during the termination of the cold phases when insolation increases and ice sheets dissociate (Figure 2d). The reduced amplitude of the Ti/Ca ratio during MIS 7b, 5d, and 5b most likely results from smaller ice EIS during these periods. Nonetheless, we conclude that the pattern of MOW-driven warm-water advection to the eastern North Atlantic leading to continental ice-sheet advances is a robust and persistent feature of EIS dynamics on glacial-interglacial time scales during at least the past ~250 ka (Figure 3). However, there is no clear evidence for cold phases in the glacial-interglacial records of continental Europe parallel to AzC strengthening as it would be a consequence of the proposed scenario (Ehlers et al., 2011). This apparent mismatch can be resolved considering that a substantial portion of the glaciogenic and periglacial evidence in terrestrial settings is obliterated by subsequent glacial advances (Litt et al., 2007). In light of the incompleteness of terrestrial records, our approach may therefore be instrumental for improving the chronology of terrestrial glaciations in central Europe. It should also be noted that the Fleuve Manche represents only one of the major meltwater routes of the EIS, capturing predominately signals from the central EIS. Uncertainties remain with regard to the waning and waxing cycles of the more northern and eastern parts of the EIS. Hence, our proposed mechanism should primarily affect the SW part of the EIS. Nonetheless, based on the notion that moisture from the Iberian Margin is transported as far north as the Arctic (Sánchez Goñi et al. (2018), MOW-driven moisture accumulation may also have played a role beyond central Europe.

The outlined mechanism can also provide new insight into circulation patterns in the greater North Atlantic region (i.e., beyond the waters off Iberia) during the past 250 kyr. According to model studies, a weak AzC,

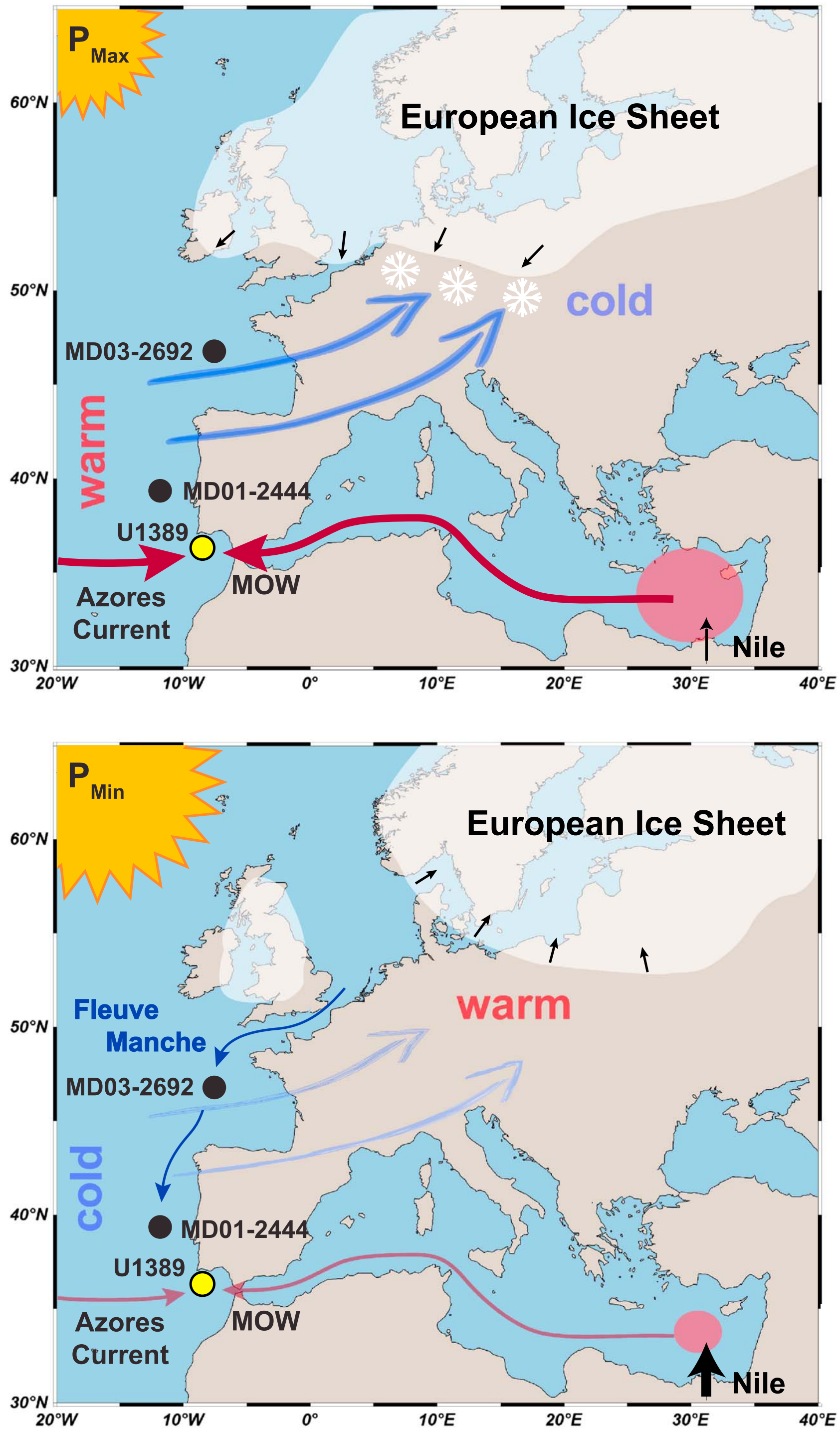

Figure 3. Schematic illustration of the insolation-driven modulation of European ice sheets. (a) During precession maxima (i.e., low insolation), aridity in NE Africa promotes MOW production, which enhances the strength of the Azores Current. Surface water warming off Iberia provides a source for moisture that is transported inland by deflected westerlies. Growth trajectories of the subsequent ice advances in continental Europe are directed toward the moisture source. (b) During precession minima (i.e., high insolation), the meltwater derived from the disintegration of the European ice-sheets feeds into the Fleuve Manche paleoriver and travels further south along the western European Margin. High summer insolation simultaneously strengthens the North African monsoon. This results in intensified freshwater discharge into the eastern Mediterranean Sea where it disrupts intermediate-water overturning and thereby reduces MOW production.

aligning with reduced MOW pull, facilitates a stronger circulation of the subtropical gyre; this, in turn, causes an enhanced northward transport of warm waters from the subtropical gyre and leads to an intensification of the AMOC (New et al., 2001). Considering that weaker MOW entrainment occurs during precession minima, an increased AMOC can contribute further heat for the warming of Europe, in addition to that provided by orbitally controlled insolation. This effect will further enhance EIS disintegration.

Such an effect may have been particularly relevant under the warm background conditions of interglacial periods. However, during glacials a weakening of the AzC would allow for meltwater exiting the Bay of Biscay to travel along the Iberian Margin as far south as ~37°N (Margari et al., 2014). This is supported by the synchronous increases in Ti/Ca ratios in the Bay of Biscay and in the relative portion of tetra-unsaturated alkenones (indicating a surface water freshening) at the southern tip of Iberia during periods of Fleuve Manche activity (Margari et al., 2014). In contrast, a strong AzC, caused by enhanced MOW pull, would be associated with reduced northward heat transport from the subtropical gyre and a pooling of warm water masses. This may have further aided the formation of a strong marine-continental gradient at midlatitudes, and hence, EIS formation.

In general, our results indicate that low-latitude pacing on precessional time scales played a decisive role in the accumulation of continental ice sheets in Europe. This low-latitude control derives from the eccentricity-modulated precession pacing of MOW production (represented by Zr/Al ratios at Site U1389), which precedes meltwater discharge by the Fleuve Manche river (Ti/Ca variability at Site MD03-2692) by a half to a third of a precession cycle (Figure 2f, see supporting information S4). As a consequence of the monsoonal influence on Mediterranean density structure, MOW variability effectively transmits a low-latitude orbital pacing to the East Atlantic off Iberia and via atmospheric moisture transport ultimately to the region of ice formation on the European continent (Figure 3). The fact that moisture availability is increased during precession maxima is crucial for the build-up of ice sheets because low insolation results in cooling over the continent, which is a prerequisite for the precipitation of moisture as snow. At the same time, the low insolation also limits the summertime melting along the southern margins of the ice sheet. Our findings of a monsoonally driven mechanism that influences the moisture supply into continental Europe and thus modulates its ice volume strongly support the hypothesis that the low latitudes were instrumental in shaping high-latitude glaciations throughout the Pleistocene (Beck et al., 2018).

The impact of precessional forcing on EIS build-up and its modulation by eccentricity may also explain the variability in EIS extent throughout the last 250 kyr. Paleosol records from northern Germany and the Netherlands document that ice advances during MIS 6 (Late Saalian) resulted in a substantially larger and thicker EIS than during the LGM (Ehlers et al., 2011; Lambeck et al., 2006; Figure 1). Based on the here proposed mechanism, the absence of major ice lobes from central Europe during the LGM would be due to relatively low moisture supply. Such a scenario is supported by the muted fluctuations of the Zr/Al ratio at Site U1389 during MIS 2; they indicate a reduced MOW strength during the LGM compared to MIS 6 (Figure 2c). As a consequence, warm-water advection toward the western European Margin via the AzC was weaker during the LGM than during MIS 6, leaving the EIS moisture-starved. This is also in line with our findings of reduced sea surface temperatures at the northern Iberian margin that indicate a reduced northward propagation of subtropical waters due to diminished MOW pull on the AzC. This pattern has also been captured in climate models suggesting a wet southern Iberia and dry conditions across northern Iberia and continental Europe (Laîné et al., 2009). The relatively modest MOW entrainment during the LGM in contrast to MIS 6 was likely caused by the ~400 kyr eccentricity minimum that reduced precession amplitudes during MIS 2 (Figure 2a). Low precession amplitudes lead to less severe dry phases in North Africa and thus less prominent peaks in MOW strength. In contrast, the glacial advances within MIS 6 occurred during an ~400 kyr eccentricity maximum, when particularly pronounced aridity phases lead to exceptionally high MOW production (Trauth et al., 2009; Figures 2a and 2c).

4. Conclusions

The link between MOW production, AzC strength, and EIS growth as shown by our data reveals a yet unrecognized, persistent monsoonal forcing on high-latitude ice-sheet dynamics for the past 250 kyr (Figure 3). As the MOW has been an integral feature of North Atlantic oceanography since at least the Late Pliocene (Hernandez-Molina et al., 2014), we propose that glacial EIS dynamics in SW continental Europe may have been modulated by the same monsoonally driven mechanism during the past ~3 Myr. Because the magnitude of ice-sheet growth and decay determines the potential amount of meltwater release into the North Atlantic, this low-latitude forcing should be incorporated into conceptual and numerical ice-sheet models to better constrain the impact of the European ice sheets on global climate variability.

Acknowledgments
We would like to thank M. Rogerson and M. F. Sanchez-Goni for their constructive reviews of an earlier version of our manuscript. The Integrated Ocean Drilling Program (IODP) is acknowledged for providing samples. Funding was received through the German Research Foundation (DFG; grant BA 3809/4 to Ba6 to R/6 to Röhl) and NWO-ALW grant (project number 865.10.001) to Lucas J. Lourens. All data used in this study are available on www.pangaea.de.

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