# Persistent monsoonal forcing of Mediterranean Outflow Water dynamics during the late Pleistocene

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## ABSTRACT

**The mode and vigor of the global oceanic circulation critically depend on the salinity of (sub)surface water masses advected to the loci of deep-water formation. Within the Atlantic meridional overturning circulation (AMOC), an important supplier of high-salinity waters is the Mediterranean Outflow Water (MOW), discharging into the North Atlantic via the Strait of Gibraltar. Despite its importance for the North Atlantic salinity budget, the long-term dynamics of MOW production have remained poorly understood. Here we present high-resolution records of bottom-current velocity from three drill sites within the Gulf of Cádiz that document a persistent low-latitude forcing of MOW flow speed over the past ~150 k.y. We demonstrate that the African monsoon is the predominant driver of orbital-scale MOW variability via its influence on the freshwater budget of the eastern Mediterranean Sea. Consequently, MOW formation fluctuates in concert with orbital precession overprinted by centennial-scale oscillations of high-latitude origin. We further document that Northern Hemisphere summer insolation minima stimulate maximal injection of MOW-derived salt into the North Atlantic, likely strengthening the intermediate AMOC branch. The direct coupling of MOW dynamics to low-latitude climate forcing represents a hitherto neglected process for propagating (sub)tropical climate signals into the high northern latitudes.**

## INTRODUCTION

Recent studies have suggested a rather stable oceanic overturning circulation for most of the past 150 k.y. despite considerable variations in glacial versus interglacial boundary conditions (Guihou et al., 2011; Böhm et al., 2015). Hence, efficient negative feedbacks must help sustain a robust Atlantic meridional overturning circulation (AMOC), although the nature of these feedbacks still awaits clarification (Rahmstorf, 2002; Guihou et al., 2011; Böhm et al., 2015). Because the salinity budget of upper ocean waters in the North Atlantic preconditions the vigor of deep-water formation in the Nordic seas, much attention has been paid to processes that may enhance the salinity input into the high latitudes. The Mediterranean Outflow Water (MOW) is an important provider of high-salinity waters with a distinct impact on the intermediate-depth North Atlantic. The absence of MOW reduces AMOC intensity by as much as 15% compared to present-day conditions (Rogerson et al., 2012), whereas strong MOW outflow has the potential to invigorate deep-water formation and AMOC strength (Schmitz and McCartney, 1993; Potter and Lozier, 2004; Rogerson et al., 2012). However, the long-term dynamics of MOW dispersal into the North Atlantic have remained poorly understood, although abundant evidence exists for strong secular to millennial-scale oscillations (e.g., Llave et al., 2006; Voelker et al., 2006; Hernández-Molina et al., 2014). In light of these limitations, our study aims at constraining glacial-interglacial MOW variability and elucidating how this variability has impacted AMOC intensity on glacial-interglacial time scales.

## MOW FORMATION AND GULF OF CÀDIZ HYDROGRAPHY

The distinct salinity contrast between relatively fresh Atlantic surface water (~36.5 practical salinity units, PSU) and higher-salinity Mediterranean intermediate and deep water (~38.5 PSU) drives the exchange of water masses through the Strait of Gibraltar (Rogerson et al., 2012). Most of the water feeding the MOW is produced in the highly evaporative eastern Mediterranean Sea as Levantine Intermediate Water (LIW) (Millot, 2014). Further contributions to the MOW derive from the western Mediterranean as Western Mediterranean Deep Water, Tyrrhenian Dense Water, and Western Intermediate Water (Millot, 2014). However, the LIW represents the key driver of MOW production as it preconditions the deep- and intermediate-water formation in the western Mediterranean Sea (Rogerson et al., 2012; Toucanne et al., 2012; Millot, 2014). When the MOW enters the Gulf of Cádiz, its settling depth is determined by its buoyancy, while the divergence into an upper and a lower branch is controlled by the seafloor morphology (Rogerson et al., 2012; Fig. 1). Paleorecords indicate

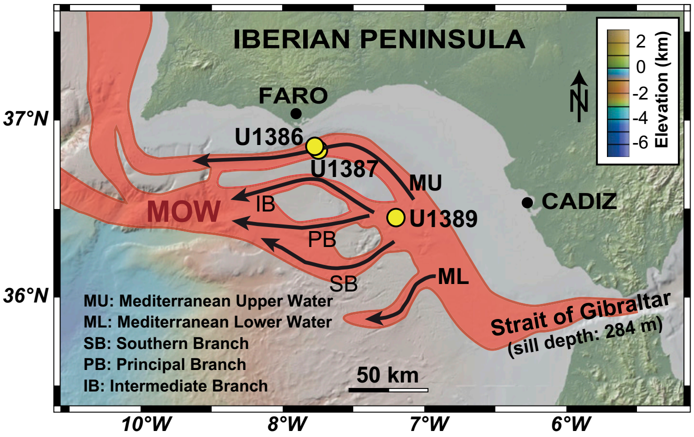

**Figure 1. Main flow paths of Mediterranean Outflow Water (MOW) within Gulf of Cádiz (Hernández-Molina et al., 2014), including position of investigated Integrated Ocean Drilling Program (IODP) Expedition 339 sites.**

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that the vertical position of the MOW within the Gulf of Cádiz varied considerably over time (Llave et al., 2006; Rogerson et al., 2012; Hernández-Molina et al., 2014), which must be considered for interpretations of past MOW fluctuations.

## MATERIAL AND METHODS

Our study is based on three sites drilled during Integrated Ocean Drilling Program (IODP) Expedition 339 (Stow et al., 2012) within the present-day flow paths of the MOW at the northern margin of the Gulf of Cádiz (Fig. 1; Table DR1 in the GSA Data Repository[1]). IODP Sites U1386 and U1387 were recovered from the Faro Drift situated within the upper MOW branch. Because Site U1386 is positioned closer to the moat generated by the MOW than Site U1387 (Fig. DR1 in the Data Repository), it is more sensitive to variations in bottom-current velocity. Site U1389 is located relatively proximal to the Strait of Gibraltar and hence is less affected by vertical shifts of the MOW path (Fig. 1). It is therefore a faithful recorder of the general MOW flow speed, whereas the other two sites provide information about potential vertical displacements of the upper MOW branch.

Split-core scanning of material from Sites U1387 and U1389 was performed with the Avaatech X-ray Fluorescence (XRF) Core Scanner II and III, respectively, at the Center for Marine Environmental Sciences (MARUM, University of Bremen) (Bahr et al., 2014). Measurements were carried out at 3 cm intervals, integrated over a 1.2 $cm^2$ area with a 10 mm down-core slit size, with separate runs performed using generator settings of 10, 30, and 50 kV and currents of 0.2, 1.0, and 1.0 mA, respectively. Sampling time was set to 20 s. Core scanning of Site U1386 was performed using the Avaatech XRF Core Scanner II at the Royal Netherlands Institute for Sea Research (NIOZ) at 1 cm resolution (1.2 $cm^2$ area, 10 mm down-core slit size), with separate runs of 10, 30, and 50 kV, using a current of 1.5 mA and sampling times of 10, 20, and 40 s, respectively. Relative standard deviations of selected element counts for Site U1386 are listed in Table DR2.

## CHRONOSTRATIGRAPHY

The chronostratigraphy of Site U1389 is well constrained by accelerator mass spectrometry (AMS) $^{14}C$ dating and by matching its planktonic $\delta^{18}O$ record to the North Greenland Ice Core Project (NGRIP; Seierstad et al., 2014) and the Iberian Margin core MD01-2444 (Hodell et al., 2013) (see also the Data Repository). The records from Sites U1386 and U1387 were tied to Site U1389 and its tuning targets by using normalized XRF-Br records (Bahr et al., 2014). High sedimentation rates, in places exceeding 100 cm/k.y. (Fig. DR2B), allow us to achieve centennial-scale resolution, hence providing unprecedented insights into MOW variability.

## MONSOONAL IMPACT ON MOW DYNAMICS

The Zr/Al ratio represents the accumulation of heavy minerals (e.g., zircon) over aluminosilicates under increasing bottom-current flow and accurately traces relative variations of MOW bottom-current velocity within the Gulf of Cádiz (Bahr et al., 2014). Our Zr/Al records, notably that from Site U1389, show a clear inverse correlation with records of African monsoonal strength and summer insolation (Fig. 2), with a dominant precessional component in the Site U1389 spectrum (Fig. DR3). The synchronicity of MOW fluctuations in all three Gulf of Cádiz records is remarkable and corroborates the perception that the MOW dynamics are a direct effect of a common forcing. Notably, even the relative amplitude of Zr/Al variations (reflecting differences in MOW flow speed) mirror the amplitude modulation of low-latitude summer insolation (Fig. 2F). We therefore propose that monsoon-driven alterations of the freshwater budget within the eastern Mediterranean Sea are the major driver of MOW variability on orbital time scales. A weak MOW flow within the Gulf of Cádiz is the direct consequence of enhanced runoff into the Mediterranean Sea during summer insolation maxima (Rossignol-Strick, 1983; Rohling et al., 2015) where it obstructs LIW formation (Rogerson et al., 2012; Rohling et al., 2015), and vice versa. This mechanism is consistent with the processes underlying sapropel formation in the eastern Mediterranean Sea during these times as a result of enhanced freshwater input and water-column stratification (Rossignol-Strick, 1983; Rohling et al., 2015; Fig. 2). The link between sapropel formation and a diminished MOW presence within the Gulf of Cádiz is consistent with studies of early Holocene sapropel S1 (Rogerson et al., 2012), and can now be extended back to Marine Isotope Stage (MIS) 5 (sapropels S3, S4, and S5, Fig. 2).

Insolation-forced LIW formation exerts a predominant control on the orbital-scale MOW dynamics, thereby marginalizing other factors such as eustatic sea-level variations. This is unexpected at first sight, because the salinity budget and overturning in the Mediterranean Sea are influenced by the sill depth (284 m) of the Strait of Gibraltar (Alhammoud et al., 2010; Rogerson et al., 2012). The blocking effect of a reduced sill depth promotes salinity accumulation in the Mediterranean Basin, but at the same time also constrains the outflow volume (Alhammoud et al., 2010; Rogerson et al., 2012). Our data are therefore in agreement with numerical simulations that imply a constant bottom-flow speed within the Strait of Gibraltar independent of the absolute glacial or interglacial sea level (Alhammoud et al., 2010). However, high rates of sea-level change could have modified the vertical and spatial position of the main branches of the MOW in the Gulf of Cádiz. This situation likely occurred during deglaciations (Rogerson et al., 2012), which are accompanied by a vigorous upper MOW branch as evidenced by the synchronous Zr/Al peaks during glacial terminations (Fig. 2). Freshening of Atlantic surface waters due to melting ice sheets increased the density contrast between Atlantic and Mediterranean water masses, and altered the vertical density structure within the Gulf of Cádiz causing an intensification and shoaling of the MOW plume (Rogerson et al., 2012).

## MILLENNIAL-SCALE VARIABILITY

Superimposed on the orbital-scale MOW variations, pulses of increased MOW speed occurred during Greenland stadials (Toucanne et al., 2007), coinciding with periods of enhanced LIW flow in the western Mediterranean Sea (Toucanne et al., 2012; Fig. 2C). Because the African monsoonal systems weakened during high-latitude cold events (e.g., Weldeab et al., 2007; Tjallingii et al., 2008; Fig. 2G), Nile River discharge was reduced during stadials (Revel et al., 2010; Fig. 2H), thereby enhancing LIW formation in the Levantine Basin and thus MOW production. The pronounced millennial-scale variability in our MOW records particularly during MIS 3 might have been amplified by pronounced winter cooling over the eastern Mediterranean due to a strong Siberian High (Kotthoff et al., 2008) as well as by an enhanced contribution of Western Mediterranean Deep Water promoted by intense winter cooling over the Gulf of Lion (Voelker et al., 2006).

## IMPACT OF MOW VARIABILITY ON AMOC INTENSITY

Enhanced MOW production likely contributed to the re-invigoration of the sluggish Atlantic thermohaline circulation at the end of Heinrich events (Rogerson et al., 2006; Voelker et al., 2006). Our data further suggest that an increased MOW production impacted the mode and intensity of the AMOC during MIS 5. Both the long-term increase and the MOW velocity peak during the insolation minima of MIS 5 correspond to an intensification of the intermediate-depth AMOC (Guihou et al., 2011; Fig. 3B). Notably, the strength of the deep AMOC declined slightly (Fig. 3C). Hence, a robust overturning circulation after the climatic optimum of MIS 5e was mainly supported by a strong intermediate-depth circulation

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[1] GSA Data Repository item 2015317, detailed methods, stratigraphy, spectral analysis, Figures DR1–DR4, and Tables DR1–DR4, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

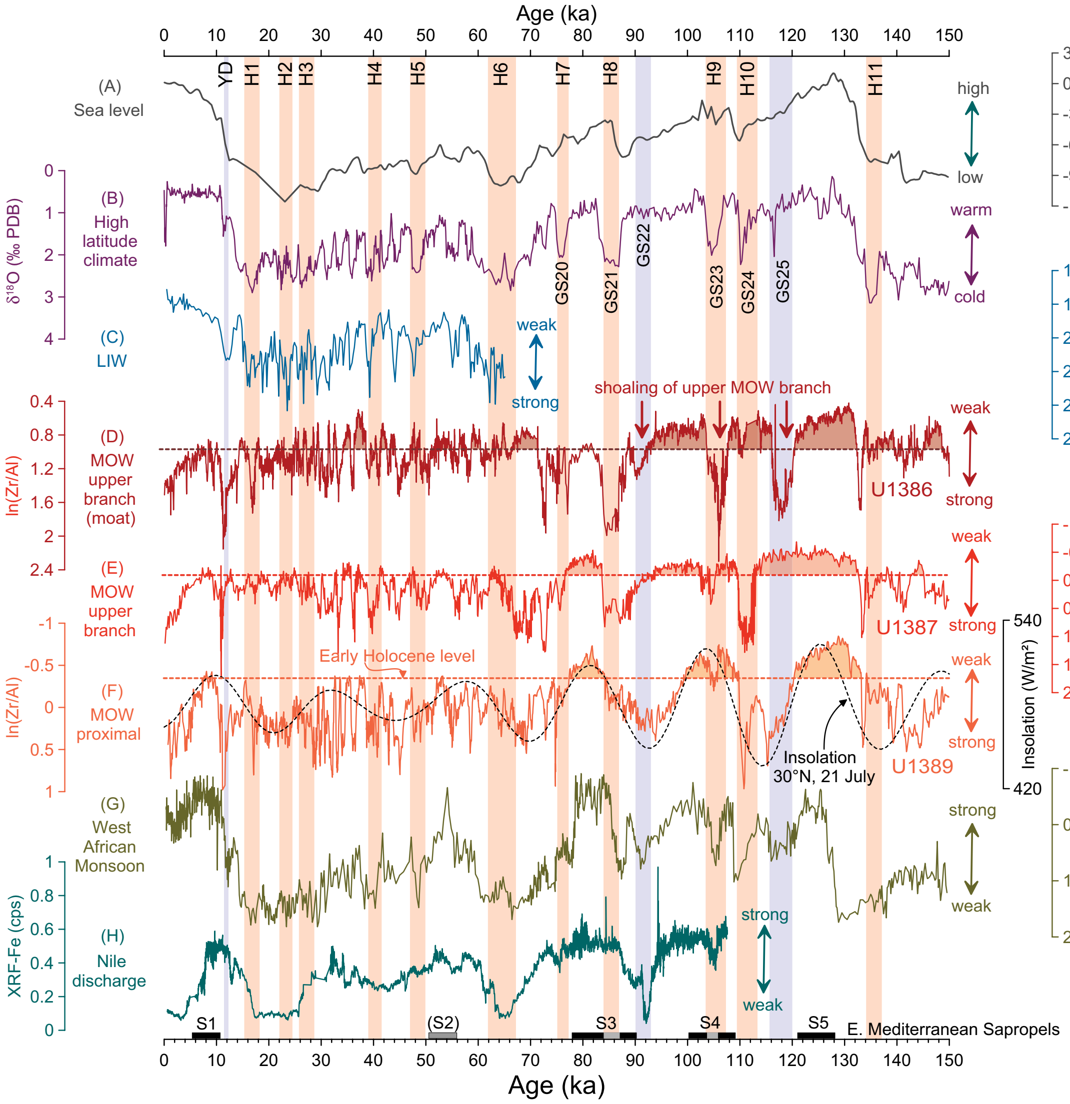

**Figure 2. Mediterranean Outflow Water (MOW) variability in paleoclimatic context. A: Eustatic sea level (Grant et al., 2012). B: Planktic $\delta^{18}O$ from Iberian Margin core MD01-2444 (Hodell et al., 2013) (PDB—Peedee belemnite). C: Sortable silt ($\overline{SS}$) of core MD01-2434, Corsica Trough, approximating Levantine Intermediate Water (LIW) flow speed (Toucanne et al., 2012). D–F: Zr/Al ratios reflecting MOW velocity at Integrated Ocean Drilling Program Sites U1386 (D), U1387 (E), and U1389 (F) (three-point running average; note inverted scales) with low-latitude summer insolation (Laskar et al., 2004). G: Niger River outflow, driven by West African monsoon (core MD03-2707; Weldeab et al., 2007) ($\delta^{18}O_{sw}$—$\delta^{18}O$ of seawater; SMOW—standard mean ocean water). H: Nile River discharge (core MS27-PT; Revel et al., 2010). YD—Younger Dryas; H—Heinrich stadials; GS—Greenland stadials of MIS 5; S—eastern Mediterranean sapropels (Rohling et al., 2015). All records are plotted on their original stratigraphy.**

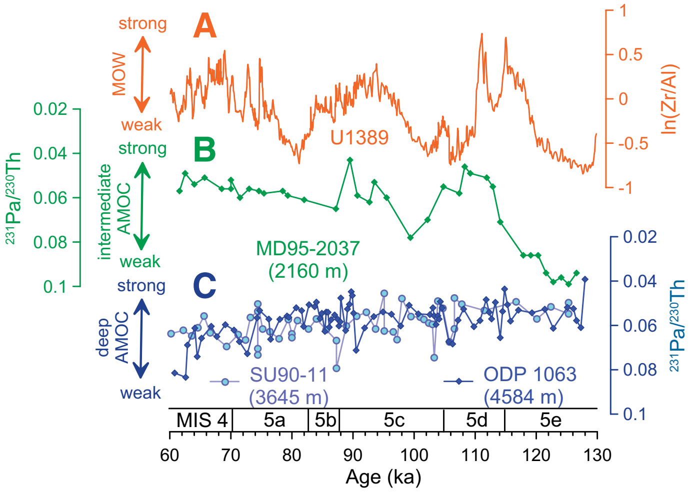

**Figure 3. Mediterranean Outflow Water (MOW) dynamics in relation to Atlantic meridional overturning circulation (AMOC) intensity during Marine Isotope Stage (MIS) 5. Peaks in Zr/Al ratios (three-point average) at Integrated Ocean Drilling Program Site U1389 (A), reflecting high MOW flow speed, coincide with enhanced overturning strength in intermediate Atlantic (core MD95-2037: Guihou et al., 2011) (B), opposed to slightly declining deep circulation (Ocean Drilling Program [ODP] Site 1063: Böhm et al., 2015; core SU90-11: Guihou et al., 2011) inferred from $^{231}Pa/^{230}Th$ ratios (C). MISs are given for reference. Stratigraphy of core MD95-2037 was adjusted to that of Site U1389 (Fig. DR4 [see footnote 1]); the other records are plotted on their original stratigraphy.**

(Guihou et al., 2011). A vigorous MOW production could have salinified the Atlantic at intermediate depth, thereby stimulating the shallow branch of the AMOC. Such a strong overturning circulation would not only have prolonged the prevalence of warm conditions at high latitudes (Potter and Lozier, 2004) but also contributed to initial ice-shield growth after MIS 5e (e.g., Grant et al., 2012) via sustaining moisture transport into the high latitudes. These findings would imply that increased outflow of MOW into the North Atlantic plays a role in stabilizing high- and mid-latitude climate, while at the same time promoting the demise into an ice age.

## SUMMARY

Our records of MOW variability over the past 150 k.y. document a close coupling between the low- and high-latitude components of the North Atlantic ocean-atmosphere system. Enhanced MOW production was fostered by a weak East African monsoon via a reduced freshwater input into the eastern Mediterranean Sea, and vice versa. Consequently, high amounts of saline MOW discharged into the intermediate-depth North Atlantic might have promoted deep-water formation and stabilized the meridional overturning circulation.

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