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Key Points:
- The Mediterranean Sea freshwater budget is highly variable through a precession cycle
- The African summer monsoon drives eastern Mediterranean hydrology
- The Atlantic margin and western Mediterranean are influenced by the winter Atlantic storm tracks

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Precessional Drivers of Late Miocene Mediterranean Sedimentary Sequences: African Summer Monsoon and Atlantic Winter Storm Tracks

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Abstract Cyclic sedimentary patterns in the marine record of the Mediterranean Sea have been consistently correlated with orbitally-driven shifts in climate. Freshwater input driven by the African summer monsoon is thought to be the main control of such hydrological changes, where the runoff signal is transferred from the eastern to the western Mediterranean. The geological record from the Atlantic margin also contains precession-driven dilution cycles that have been correlated with the sedimentary sequences in the western and eastern Mediterranean despite the lack of a direct connection with the basin. In these regions, Atlantic winter storms have also been invoked to explain the wet phases. In the absence of seasonally-resolved proxy data, climate simulations at high temporal resolution can be used to investigate the drivers of Mediterranean hydrologic changes both on precessional and seasonal timescales. Here, we use the results of 22 ocean-atmosphere-vegetation simulations through an entire late Miocene precession cycle. These show that the African summer monsoon drives the hydrologic budget in the Eastern Mediterranean during precession minima, while the western marginal basins are generally dominated by local net evaporative loss. During precession minima, the western Mediterranean and the Atlantic margin are also influenced by enhanced winter precipitation from the Atlantic storm tracks. We can, therefore, identify two different moisture sources affecting the circum-Mediterranean area, characterized by the same phasing with respect to precession, but with opposite seasonality. This supports the interregional correlation of geological sections in these areas, as we show for the Messinian and speculate for other time periods.

1. Introduction

The geological record of the Mediterranean Sea for most of the Neogene period (~23–2.6 Ma) is characterized by regular alternations of open marine marls and organic-rich, sapropelic layers (e.g. Bethoux, 1993; Hilgen, 1991). These cyclic alternations have been linked to precession-controlled dry-wet oscillations in circum-Mediterranean climate and consequent changes in the hydrologic budget of the basin (Hilgen, 1991; Rohling et al., 2015, and references therein). Sapropelic layers in the Mediterranean Sea are thought to be a product of the basin's biogeochemical response to enhanced runoff and to have been deposited during times of minimum climatic precession (hereafter, referred to simply as minimum precession and corresponding to maximum summer insolation at 65°N). At this time, intensified runoff would also lead to high nutrient supply, resulting in increased primary productivity, water column stratification, and consequent deep anoxia, favoring the preservation of organic-rich sediments (e.g. Rossignol-Strick, 1985).

The increased runoff into the Mediterranean Sea at precession minima has generally been associated with enhanced summer monsoonal rainfall of North African origin, flowing into the Mediterranean Sea via the Nile river (Rossignol-Strick, 1983), ephemeral wadi systems and other extinct rivers (Coulthard et al., 2013; Paillou et al., 2009), and the Chad-Eosahabi catchment during the late Miocene (e.g. Griffin, 2002, 2006). Late Miocene offshore sediment cores record low dust fluxes from North Africa at several locations (Colin et al., 2014; de Menocal & Bloemendal, 1995), confirming the presence of humid conditions. Typically, it is assumed that the deposition of sapropelic layers in both the western and eastern Mediterranean are driven by the same mechanism (monsoonal runoff) and are, therefore, in phase with respect to precession minima (Rohling et al., 2015, and references therein). As a consequence, the characteristic cyclicity found in marine

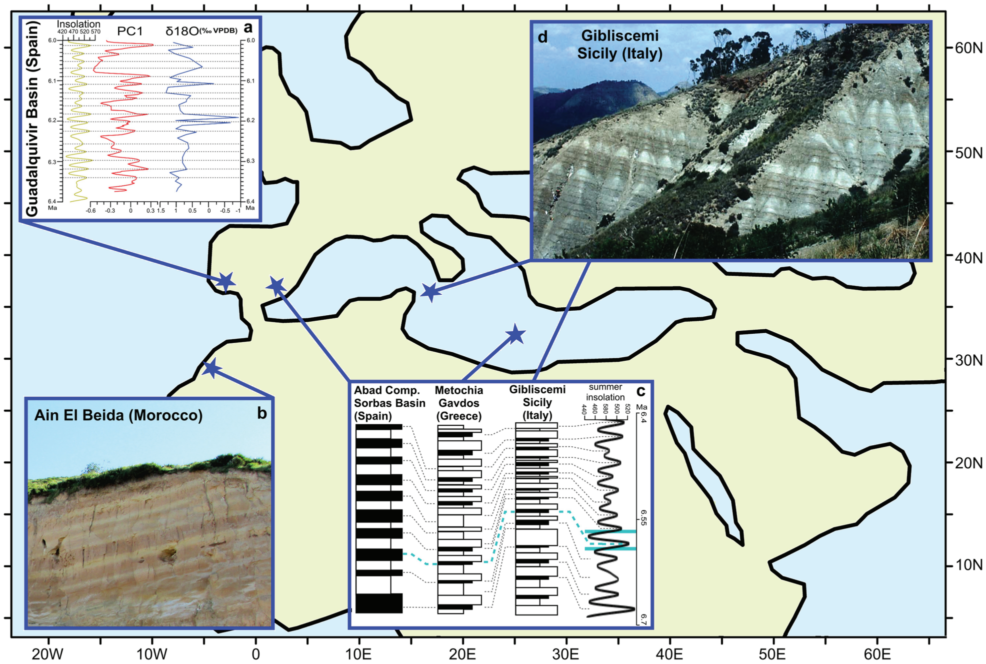

Figure 1. Location of the main late Miocene geological sections discussed in the text plotted on the modelÕs late Miocene paleogeography. (a) Dilution cycles visible in the elemental composition of the Montemayor Core in the Guadalquivir Basin (Spain); plotted are the first principal component (PC1) from the analysis of van den Berg et al. (2015), mainly consisting of biogenic carbonate, and the δ^{18}O from Pérez-Asensio et al. (2013), correlated with the insolation curve; see Figure 6 in van den Berg et al. (2015) for the complete record. (b) Late Miocene dilution cycles as shown by the color alternations in the sediments from the Ain el Beida section (Morocco). (c) Schematic log of the Abad Composite section in the Sorbas Basin (Spain) with sapropel-marl-diatomite alternations, correlated with the Metochia section in Gavdos (Greece) and the Gibliscemi-Falconara section (also in panel d) in Sicily (Italy), all showing equivalent orbitally driven patterns and correlated with the 65°N summer insolation curve (modified from Sierro et al., 2001); the interval simulated by Marzocchi et al. (2015) is indicated by the turquoise lines on the insolation curve. (d) Late Miocene sapropel-marl alternations in the Gibliscemi section in Sicily (Italy).

sediments from both Mediterranean cores and those exposed on land around its margins is used for the stratigraphic correlation of geological successions in the western and eastern subbasins (e.g. Perez-Folgado et al., 2003; Sierro et al., 2001) and for the astronomical tuning of the age models of these sequences, based on the Northern Hemisphere summer insolation curve (e.g. Hilgen, 1991; Lourens et al., 1996).

The paleoclimate record also indicates the presence of humid conditions during precession minima at locations beyond the geographic reach of the monsoon systems, such as the Mediterranean Atlantic margin, the Middle East, and central Asia (Arz et al., 2003; Cheng et al., 2012; Tzedakis, 2007). The source of of the additional freshwater input to these regions is still debated, and moisture sources other than the African summer monsoon have been invoked (e.g. Rohling and Hilgen, 1991; van der Laan et al., 2012) and linked to winter rather than summer precipitation (e.g. Meijer and Tuenter, 2007; Toucanne et al., 2015). Late Miocene geological sections on the Atlantic margin, not connected to the Mediterranean Sea (e.g., western Morocco and western Spain; see Figure 1) and sediment cores from the Iberian Margin, have also been correlated to the Mediterranean sedimentary successions (e.g. Sierro et al., 2000; van den Berg et al., 2015; van der Laan et al., 2012), as they exhibit analogous precession-driven dilution cycles. Nonetheless, the different depositional environments suggest that orbitally-driven sedimentary patterns at these locations may have been generated by different drivers of increased precipitation and runoff and could reflect either local (Bosmans, Drijfhout, Tuenter, Hilgen, & Lourens, 2015) or regional Atlantic (Brayshaw et al., 2011; Kutzbach et al., 2013) processes or both (Rogerson et al., 2019). Sections on the Atlantic margin and in the marginal basins of the western Mediterranean may be affected by the activity of winter Atlantic storms, but the available reconstructions fail to directly capture the seasonal component and discriminate between the possible different origins of the moisture source (Kutzbach et al., 2013). As a result, the origin of the precession-driven precipitation is generally extrapolated based on data location and dominant present-day moisture sources active in those areas (e.g., for western Mediterranean records, see Toucanne et al., 2015) or simply assumed to be related to the more traditionally-established precessional driver, the African summer monsoon (e.g. Bahr et al., 2015).

Most of the hypotheses about the phasing between cyclical variations in orbital forcing, changes in the hydrology, and the resulting sedimentary sequences (e.g., the sapropel record) in the Mediterranean Sea, are however still largely untested, because of the lack of unequivocal seasonal signals in the data. Numerical modeling represents a valuable tool to interpret and integrate the available geological record, which makes it possible to explore the climatic response at precessional, centennial, and seasonal timescales. Two modeling studies have previously addressed the seasonal component of the precipitation signal into the Mediterranean Sea (Bosmans, Drijfhout, Tuenter, Hilgen, & Lourens, 2015; Kutzbach et al., 2013) but only by considering orbital extremes and using idealized simulations. By contrast, we analyze the seasonal evolution of the Mediterranean Sea's freshwater budget using the results of 22 numerical simulations (Marzocchi et al., 2015) that span a complete late Miocene precession-driven insolation cycle with varying obliquity (from now on referred to simply as precession cycle). This not only means that no assumptions are made about which phase of the precession cycle will result in a more (or less) extreme climatic response, but it also allows us to investigate how seasonality (e.g., of the runoff into the Mediterranean Sea) varies across a full precession cycle.

In this study, we investigate the hypothesized different origin of the moisture sources both in the eastern Mediterranean and marginal western marginal basins, as well as outside the Mediterranean on the Atlantic margin, in order to explore their phasing with respect to precession, and consider the implications for the interpretation of the sedimentary record.

2. Data and Methods

Using the available subprecessional orbital ensemble of climate simulations from Marzocchi et al. (2015), we calculate the hydrologic fluxes (precipitation, P; evaporation, E; runoff, R) for the Mediterranean Sea and analyze the seasonal evolution of the freshwater budget (P-E+R) across the simulated precession cycle. This allows us to explore the links between changes in the hydrology and the cyclical sedimentation patterns observed in the geological record of the Mediterranean region.

The two seasonality extremes correspond to the two precession extreme simulations. PH (Precession-driven High seasonality), which corresponds to a precession minimum and is characterized by the warmest summers (Earth in perihelion) and the coldest winters (Earth in aphelion) in the Northern Hemisphere (NH); hence, the enhanced seasonality. PL (Precession-driven Low seasonality), which is characterized by reduced seasonal differences in the NH and corresponds to a precession maximum.

Note that the results in this study are presented using a fixed-angular calendar, with the original model data being corrected using the method by (Pollard and Reusch, 2002). See Marzocchi et al. (2015) (Supplementary Material) for further details on the effects of applying this correction.

2.1. Model Description and Experimental Design

The numerical simulations were carried out using a version of the UK Hadley Centre Coupled Model (HadCM3L, version 4.5), a global general circulation model (GCM) with a horizontal resolution of 3.75° longitude by 2.5° latitude for both the atmosphere and ocean components, 19 vertical levels in the atmosphere and 20 in the ocean, and coupled to the dynamic vegetation model TRIFFID (HadCM3BL-M2.1; Valdes et al., 2017). Including land surface processes and interactive vegetation improves the simulation of late Miocene warm climatic conditions, in particular when using relatively low CO_2 concentrations (e.g. Bradshaw et al., 2012); examples of vegetation changes between experiments PH and PL can be found in Marzocchi et al. (2015) (see their Figure 12). Here, we only consider simulations with 280 ppm CO_2 concentrations, given the little difference found by Marzocchi et al. (2015) in the amount of monsoonal rainfall in the African region between 280 and 400 ppm. This is also in agreement with the suggested CO_2 concentrations below 300 ppm for the late Miocene (Bolton and Stoll, 2013; Mejia et al., 2017) and with the observed global cooling trends that have been associated with an ongoing decline in CO_2 concentrations during this time period (Herbert et al., 2016). A late Miocene paleogeography (Markwick, 2007) is used in the simulations, including an open Panama Gateway and a closed Bering Strait; see Marzocchi et al. (2015) for further details and a full description of the model in its late Miocene setup and an assessment of its performance can also be found in (Bradshaw et al., 2012).

The experimental design consists of 22 equally spaced snapshot simulations (one every 1,000 years) spanning a full late Miocene precession cycle, between 6.568 and 6.589 Ma (within the Messinian period). This specific time slice was chosen because model results can be compared with astronomically tuned sedimentary and faunal data from the Mediterranean region available on precessional timescales for the same time period (e.g. Mayser et al., 2017; Modestou et al., 2017; Perez-Folgado et al., 2003; Sierro et al., 2001). This cycle is also characterized by relatively high eccentricity values, which act to enhance the precession-induced climatic signal. Further details of the modelÕs description and of the experimental design for the Messinian orbital simulations can be found in (Marzocchi et al., 2015), including an assessment of the differences between simulated precipitation, surface air temperature, and the available Messinian terrestrial proxy data at a global scale.

2.2. Astrochronology of Mediterranean and Atlantic Reference Sections

The records from the Mediterranean and Atlantic margin have all been astronomically tuned. The resultant astronomical age models or astrochronologies are either partly or completely independent from assumptions about the phase relationship between the sedimentary cycles of interest and precession. On the Atlantic margin, high-resolution age models were constructed for the Ain el Beida and Loulja reference sections (see Figure 1) of the latest Miocene to the earliest Pliocene age, using the sedimentary cycle pattern and associated geochemical records for tuning (Krijgsman et al., 2004; Van der Laan et al., 2006). More recently, a similar methodology was used also for the Guadalquivir Basin (van den Berg et al., 2015), covering essentially the same time interval. However, these chronologies are not completely independent as the underlying tuning is built on assumptions about the phase relation with astronomical parameters. These inferred phase relations are in turn based on clear similarities in the climate proxy response of specific geochemical tracers, such as stable isotopes and elemental ratio records, between the Atlantic margin and Mediterranean sections/sites. Nevertheless, these age models have been independently confirmed by planktonic foraminiferal biostratigraphy (Hilgen et al., 2000) and by the detailed correlation of the oxygen isotope records of the Moroccan sections to the benthic isotope record of Ocean Drilling Program (ODP) Site 982 in the North Atlantic (Hodell et al., 2001; Van der Laan et al., 2006); the latter reveal the marked influence of glacial cycles in addition to the precession-dominated sedimentary cycles and associated geochemical proxies of interest for our target climate simulations.

By contrast, the tuned age models developed for the upper Pleistocene deep-sea cores of the Atlantic margin are fully independent from tuned age models developed for sapropel-bearing sections and cores in the Mediterranean. The age models of Moreno et al. (2001) and (Bozzano et al., 2002) have been developed by tuning benthic isotope records to the standard SPECMAP isotope chronology and are thus independent from any assumption about the phasing of the precession-dominated sedimentary cycles, which reveal an in-phase relationship with precession. The same holds in principle for the Shackleton Site of the Iberian margin, although in this case the tuned age model is more complicated and includes the use of millennial scale variability and ^{230}Th-dated speleothem isotope records (for details, see Hodell et al., 2013).

The phase relations used for the tuning of the Mediterranean upper Miocene successions that our climate simulations are targeting are again based on similarities observed in climate proxy response of the sedimentary cycles compared with much younger counterparts. For these younger cycles of late Pleistocene age, independent age constraints are available based on the same ^{230}Th-dated speleothem records, and hence, they can be dated much more precisely (e.g. Grant et al., 2016). This is necessary to independently determine the phase relationship between Pleistocene sapropels and summer insolation, which was previously only known for the youngest Holocene sapropel. These sapropels show an in-phase relationship, with the exception of some sapropels such as S1 and S5, which reveal a lag of 3-kyr as a consequence of major deglaciations that they are associated with (Grant et al., 2016; Ziegler et al., 2010).

2.3. Drainage Basins Definition and Hydrologic Fluxes Calculations

The study area is subdivided into 11 fluvial catchments and the Mediterranean Sea is split into eastern and western basins (Figure 2). We calculate precipitation and evaporation values over each of the 13 drainage areas for each of the 22 simulations from the orbital ensemble, to obtain the net hydrologic fluxes. To do so, we use the same methodology and the same drainage basins definition as (Gladstone et al., 2007), where evaporation from the surface of rivers is not directly taken into account and runoff is transported

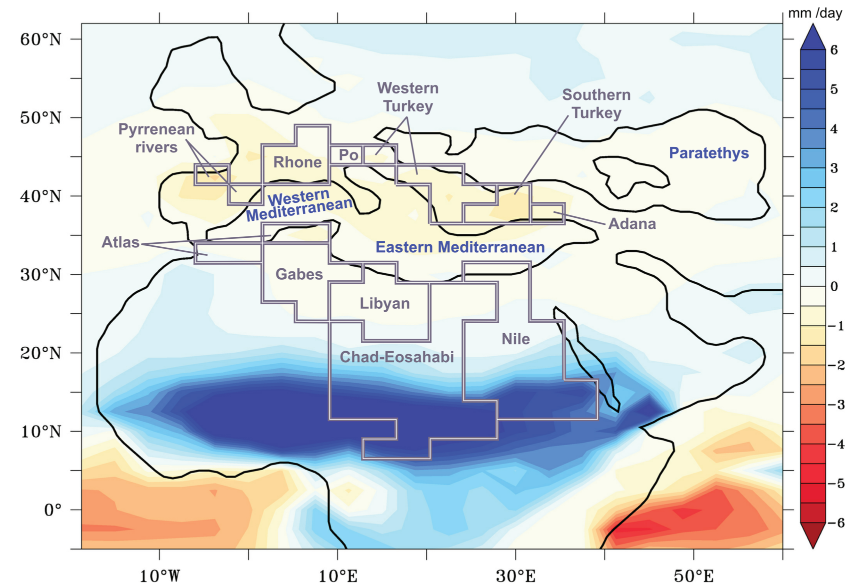

Figure 2. Late Miocene catchments draining into the western and eastern Mediterranean as defined in Gladstone et al. (2007). Background colors show the summer precipitation difference (JJAS) between precession minimum and precession maximum simulations, highlighting the increased precipitation over the main North African catchments during precession minimum (as shown in Marzocchi et al., 2015).

instantaneously to the Mediterranean Sea. This may explain some of the discrepancies between the simulated preindustrial river discharge and modern observational data (Gladstone et al., 2007; see their Table 2). However, because the river extent and surface area are constant throughout the precessional cycle, the evaporation from its surface will vary minimally with the changing orbit and will therefore not have a substantial impact on the difference between precession minimum and maximum. As such, while the modeled absolute discharge rates should be treated with caution, the modeled orbital cyclicity in discharge rates are likely robust.

The difference between the preindustrial and late Miocene values (as also shown in Gladstone et al., 2007) and between the two precessional extremes (PH and PL) analyzed here, is substantially larger than the error. Nonetheless, we only discuss our results as differences between orbital extremes or between the western and eastern Mediterranean, rather than in terms of absolute values.

Simulated precipitation and evaporation for the Mediterranean Sea, compared to paleo-reconstructions and modern observations, are shown in Figures S1 and S2 (Supplementary Material), both for the preindustrial and late Miocene simulations. Note that the model's resolution does not allow an accurate representation of ocean circulation in the Mediterranean basin, which is therefore not discussed in detail in this manuscript. A poor representation of ocean circulation could result in erroneous distribution of physical properties (i.e., temperature and salinity) with depth; however, we expect this to have a relatively small effect on the hydrologic budget calculations of the basin as a whole. This is supported by the close match between present-day observations (i.e., precipitation and evaporation) and the preindustrial control simulation (Figure S2a).

The model's representation of African monsoon precipitation is assessed in Marzocchi et al. (2015).

2.4. Moisture Budget Calculations

The moisture budget analysis methodology and notation follow Seager and Henderson (2013) and Seager et al. (2014), so they are only be briefly described here. The purpose of this diagnostic is to partition the modelled *P-E* moisture convergence into two components that represent convergence due to the time-mean flow (*CMF*) and convergence due to eddies (*CTE*). The steady-state moisture budget in pressure coordinates is defined as:

$$\overline{\overline{P}} - \overline{\overline{E}} \approx - \frac{1}{\rho_w} \nabla \cdot \sum_{k=1}^{K} (\overline{\overline{u_k}\,\overline{q_k}} + \overline{\overline{u'_k q'_k}}) \overline{dp_k} \quad (1)$$

Where: P is precipitation, E is evaporation, ρ_w is the density of water, q is specific humidity, and u is the vector horizontal velocity; in the sum over pressure levels (k), K is the total number of vertical levels, and dp_k is the pressure thickness of each level. All quantities are divided into monthly means (over-bars), climatological monthly means (double over-bars), and departures from monthly means (indicated by the primes), in order to obtain the climatological budget. See Seager and Henderson (2013) and Seager et al. (2014) for further details.

The first term on the right-hand-side of equation (1) represents the moisture convergence by the mean flow (spatial departures from the mean, *CMF*), while the second term indicates the moisture convergence by the submonthly transient eddies (time departures from the mean, *CTE*). Given that the output of the orbital climate simulations is only stored as monthly means, we cannot directly calculate the term related to the transient eddies; this is, therefore, obtained as a residual (difference between P-E and the mean flow). This holds to a good approximation (Li and Ting, 2017), as shown in Figure S3 (Supplementary Material) when compared to the results of Seager et al. (2014), where daily data were used to calculate the transient eddies contribution in historical simulations from the 5^{th} Climate modeling Intercomparison Project (CMIP5).

3. Simulated Messinian Hydrologic Fluxes

Hydrologic fluxes in the western and eastern Mediterranean are analyzed both seasonally and across the simulated Messinian precession cycle. Values for precipitation (P), runoff (R), and freshwater budget (P + E + R) in each of the simulations from the precessional ensemble and for both the western and eastern subbasins are given in Table S1 (Supplementary Material).

Note that the freshwater budget presented in Figure 3 does not include the effect of direct oceanic exchange between the western and eastern subbasins. As such, our calculations are not representative of the western Mediterranean as a whole, which is also influenced by transport with the eastern Mediterranean, but instead represent the late Miocene western marginal basins (e.g., Sorbas, Guadalquivir; see Figure 1) where ocean transport was likely to have been limited by a narrow gateway and the hydrologic budget dominated by the local runoff (e.g. Flecker et al., 2015; Mayser et al., 2017; Modestou et al., 2017; van den Berg et al., 2015). The Messinian geological data is almost entirely drawn from these marginal environments.

3.1. Precessional Changes in the Runoff to the Mediterranean Sea

In the climate simulations analyzed in this study, North Africa is characterized by intensified rainfall during NH summer for simulations close to experiment PH, leading to a greening of the area south of the Sahel region (Marzocchi et al., 2015), in agreement with the late Miocene geological record (e.g. Colin et al., 2014; de Menocal & Bloemendal, 1995). The link between orbital forcing (i.e., mainly precession) and the African monsoon has previously been shown in both modeling (e.g. Marzocchi et al., 2015; Bosmans, Drijfhout, Tuenter, Hilgen, Lourens, & Rohling, 2015) and observational studies (e.g. Rossignol-Strick, 1983; Larrasoaña et al., 2003). The enhanced monsoonal freshwater input from the North African watershed reaches the eastern Mediterranean as runoff. This contribution would have been particularly relevant during insolation maxima, because there is evidence that the Chad-Eosahabi catchment has drained into the Mediterranean Sea at times (Griffin, 2006, 2002), and this captures a substantial proportion of North African summer monsoon precipitation when the Intertropical Convergence Zone (ITCZ) is positioned further north (Figure 2). Including or excluding the runoff from this catchment will, therefore, significantly modify the resulting Mediterranean Sea freshwater budget (Figure 3l). The importance of evaluating the contribution of the Chad-Eosahabi catchment on the Mediterranean freshwater budget for the late Miocene period has previously been highlighted in other modeling studies (Simon et al., 2017; Bosmans, Drijfhout, Tuenter, Hilgen, & Lourens, 2015; Gladstone et al., 2007). In particular, Simon et al. (2017) showed that without a substantially increased freshwater capture from the North African catchments, the timing of deposition of a few of the sapropelic layers in two key Messinian geological sections would be offset from precession minima. However, no offset in phasing was found by Simon et al. (2017) within the precession cycle considered in this study.

The impact of the enhanced monsoonal freshwater input from the North African watershed is especially evident in the eastern subbasin, into which all the major North African catchments drain. As a consequence, the highest runoff to the eastern Mediterranean occurs during the summer-autumn months around experiment PH (Figure 3e). By contrast, the runoff into the western Mediterranean originates from smaller rivers on the European continent. Runoff into the western Mediterranean is also highest around PH (Figure 3a,b), but unlike the eastern subbasin, it is at its strongest during the winter and spring months (Figure 3a). Precipitation over the western Mediterranean catchments is highest during the winter months (not shown), but due to the soil response, the highest runoff into the basin occurs in spring (Figure 3a), as a consequence of snow melt.

The magnitude of the runoff into the eastern Mediterranean is considerably higher than into the western subbasin (up to 6 times greater; see Figure 3d). As a result, the monsoonal freshwater contribution into the eastern subbasin dominates the total runoff into the Mediterranean Sea, and a strongly seasonal precession-driven signal can also be observed basin-wide in the freshwater budget (Figures 3c–3f). The considerable differences in seasonality and magnitude of the runoff signal in the western and eastern Mediterranean, and consequently the freshwater budget, suggests the existence of two distinct moisture sources driving the freshwater input into the two subbasins.

The mean annual runoff into the Mediterranean Sea peaks around experiment PH; when the Chad catchment is included, maximum runoff is about twice the magnitude compared to when it is excluded (Figure 3f). Runoff differences around experiment PL are much less significant. Inclusion of the Chad catchment impacts only the magnitude of the signal and not the timing or nature of the relationship between the freshwater budget and precessional forcing. For simplicity, all the subsequent discussion of results will only consider those including runoff from the Chad-Eosahabi catchment. For additional discussions and sensitivity experiments, see also Simon et al. (2017).

3.2. Seasonal and Orbital Forcing of the Mediterranean Sea Freshwater Budget

The magnitude of the summer monsoonal freshwater input into the eastern Mediterranean from the North African watershed explains the strongly seasonal nature of this precessional signal in the freshwater budget of this subbasin (Figure 3i). Our results suggest that a switch to positive values for the eastern Mediterranean freshwater budget may occur during the summer months around PH. The freshwater budget is otherwise negative throughout the rest of the cycle and annually (Figures 3i,3j), as a result of net evaporative loss over the Mediterranean Sea due to its latitudinal position (e.g. Peixoto and Kettani, 1973). Despite the precession control observed in the runoff into the western Mediterranean (Figure 3a), the reduced magnitude (compared to the eastern Mediterranean) of this freshwater input does not significantly influence the freshwater budget of the western marginal basins (Figure 3g), which is dominated by evaporative loss and remains consistently negative (Figure 3h). While the eastern Mediterranean's freshwater budget is dominated by the runoff component, especially during the summer months, in the western marginal basins local precipitation and evaporation drive the freshwater budget, particularly in the winter months. Evaporation in the Mediterranean Sea is at its lowest during the spring-summer months (see Figure S2, Supplementary Material), and, as a result, the freshwater budget in the West is much more negative in winter than in spring. The seasonal pattern is not significantly altered by the orbital control on the runoff.

The total freshwater budget for the Mediterranean Sea is dominated by the contribution from the eastern subbasin (Figure 3k) and is, therefore, in phase with the precessional forcing. As a consequence, the total freshwater budget is also driven by the monsoonal runoff from the North African catchments. Influenced by the contribution from the eastern subbasin, positive values may be reached for the total Mediterranean Sea freshwater budget during the summer-autumn at times of PH.

4. Implications for the Interpretation of the Sedimentary Record

For the first time, we have simulated and analyzed the response of the western and eastern Mediterranean freshwater budgets to orbital forcing through a full late Miocene precession cycle. Despite the strong variability between PH and PL, the mean annual hydrologic fluxes averaged through a full precession cycle do not appear to be substantially different from those of the present day Mediterranean Sea, leading to a similar freshwater deficit over the basin (see also Marzocchi et al., 2016). This is consistent with the hypothesis that the structure of the atmospheric circulation over the Mediterranean remained largely unchanged during precession cycles despite changes in the sources and amount of moisture advection (Rogerson et al., 2019) and with the establishment of basin-wide ocean circulation and environmental conditions similar to today after the closure of the Indian Gateway (e.g. de la Vara and Meijer, 2016) in the early to middle Miocene (14 to 14.5 Ma) (e.g. Rögl, 1999) . This would also explain the consistent cyclic sedimentary patterns containing sapropels that have been observed in the Mediterranean Sea over the last 14 Ma (Hilgen et al.,

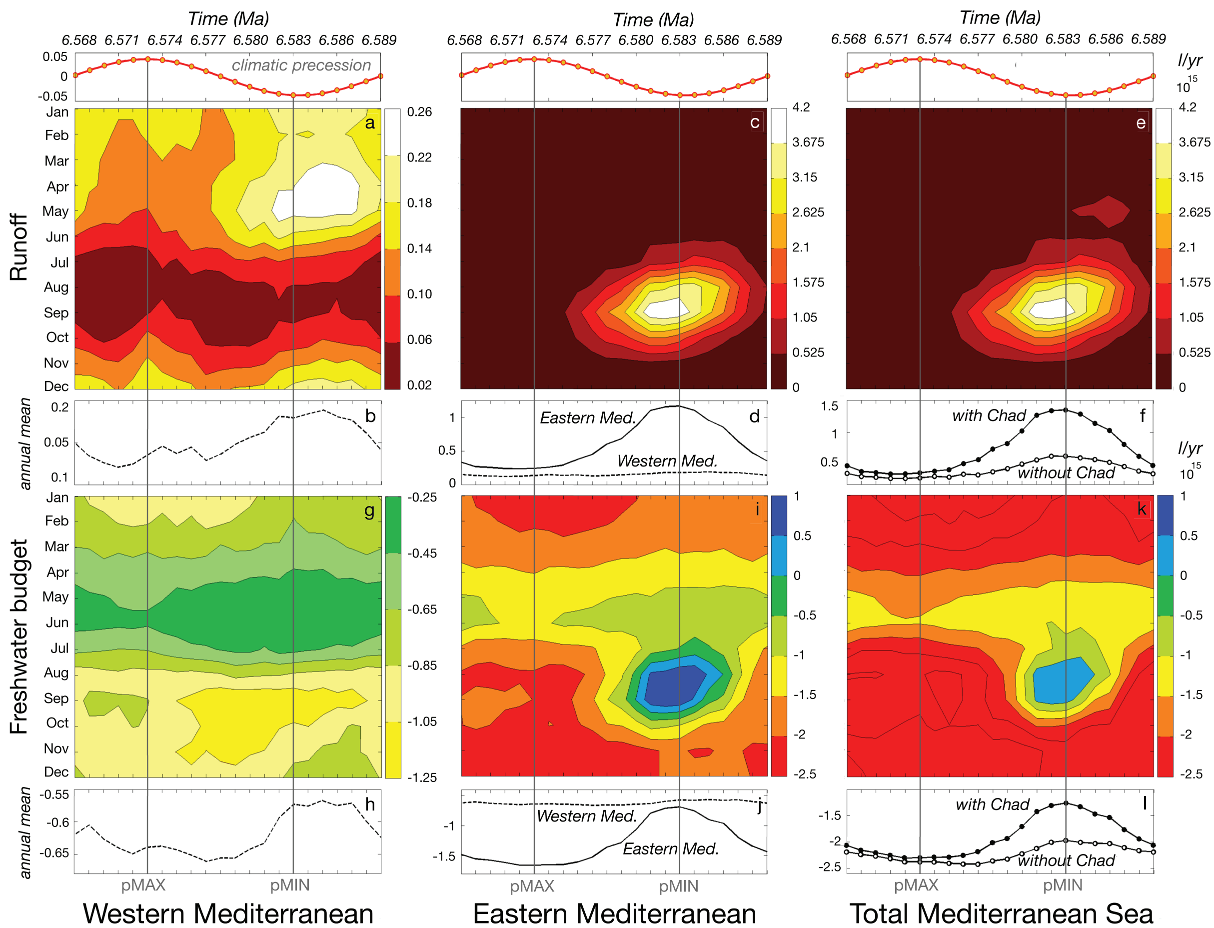

Figure 3. The time axis indicating the full precession cycle and the 22 simulations (dots) is at the top of the figure. Top panels: seasonal runoff into the (a) western, (b) eastern, and (c) total Mediterranean Sea across the full precession cycle. Bottom panels: seasonal freshwater budget in the (d) western (e), eastern, and (f) total Mediterranean. The line plots (b, d, f, h, j, and l) are annual means with respect to the panels directly above them (on different scales); dashed lines represent the western Mediterranean, the solid lines the eastern Mediterranean, and the lines with markers the total Mediterranean Sea (filled markers when the Chad basin is included, empty markers when it is excluded). All values are in units of liters per year (l/yr). Note the different scales in the western Mediterranean plots (panels a and g) due to the substantially smaller values.

1999; Mourik et al., 2010). Such results differ from those of Gladstone et al. (2007), who obtained a more positive Miocene Mediterranean hydrologic budget using present-day orbital forcing (e.g., closer to our PL simulation). However, their simulations were carried out using an atmosphere-only GCM forced with highly-idealized and potentially overestimated sea surface temperatures (see Figures S4 and S5, Supplementary Material), making the comparison to our simulations problematic.

Using the results of our hydrologic calculations, we can now revisit some of the outstanding questions relating hydrological changes in the Mediterranean Sea to the deposition of cyclical sedimentary sequences in the late Miocene and the correlation of western and eastern Mediterranean sequences, as well as those along the Atlantic margin. Our discussion focuses on the late Miocene, but some of these implications can likely be extended to all times of Mediterranean sapropel deposition (e.g., last 14 million years).

4.1. Existence of Two Distinct Precessional Moisture Sources

The differences in the magnitude and timing of the runoff reaching the two Mediterranean subbasins, and driving their freshwater budgets, suggests the presence of two distinct precession-driven moisture sources. There is a clear southward shift of winter precipitation patterns between experiments PL and PH (Figure 4; for summer and annual means, see Figure S6 in the Supplementary Material), indicating that the western Mediterranean is affected by the winter storm tracks crossing the Atlantic Ocean during PH (see also Kutzbach et al., 2013). This would explain the different timing of the runoff with respect to the eastern Mediterranean, which is instead driven by the African summer monsoon (Figure 2).

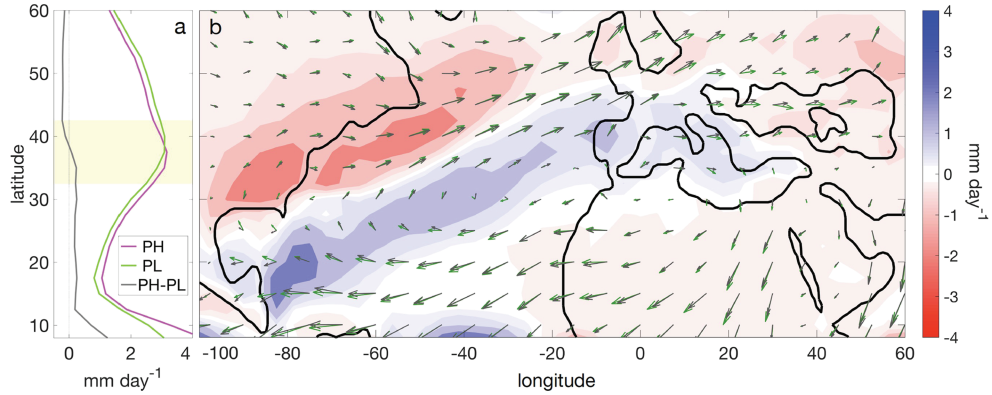

Figure 4. a) Zonally averaged DJF precipitation for experiments PH (magenta), PL (green) and their difference (PH-PL, grey). The zonal average is taken globally (for comparison with Figure 6b in Kutzbach et al. (2013) and the yellow shading highlights the latitudes of our regions of interest. b) PH-PL precipitation anomaly (shading) and low level (925 hPa) winds (PH = grey, PL = green).

The importance of enhanced (with respect to the annual mean) winter precipitation in the Mediterranean region is often neglected, in favor of the more established summer monsoonal input, as highlighted in a few other studies (e.g. Brayshaw et al., 2011; Kutzbach et al., 2013; Meijer and Tuenter, 2007). Moreover, the origin of the winter signal has not yet fully been demonstrated, and both local (Bosmans, Drijfhout, Tuenter, Hilgen, & Lourens, 2015) and extra-Mediterranean (Brayshaw et al., 2011; Kutzbach et al., 2013) moisture sources have been invoked. In our late Miocene simulations, the Atlantic storm tracks represent an effective additional moisture source that influences the Mediterranean Sea and the Atlantic margin with the same phasing with respect to precession as the African monsoon, but with opposite seasonality. Winter/spring, rather than summer/autumn, runoff may be more relevant in the western marginal basins for the regional freshwater budget. In fact, during the winter months, there is an equatorward shift in precipitation (also consistent for P-E, not shown) between experiments PH and PL, which crosses the Atlantic Ocean and directly hits the Mediterranean regions (Figure 4). An analogous response to orbital forcing in the circum-Mediterranean regions has also been shown by Kutzbach et al. (2013) in idealized simulations (e.g., see their Figure 6) and Brayshaw et al. (2011) for the Holocene. This is accompanied by relatively small changes in the zonal wind patterns (Figure 4 and Kutzbach et al., 2013) and relatively small, but statistically significant zonally-averaged winter precipitation anomalies (see Figure 4d in Marzocchi et al., 2015 and Kutzbach et al., 2013).

Traditionally, even at locations that appear well beyond the reach of the African summer monsoon, there has been a more prominent focus on this driver, likely due to the lack of extensive model-based evidence for a mechanism associated with winter precipitation (Kutzbach et al., 2013). To clearly determine whether the southward shift in winter precipitation observed in our simulations can ultimately be attributed to changes in the Atlantic storm tracks, we calculate a moisture budget (as described in section 2.2; see equation [1]) for experiments PH and PL and separate the different contributions into three components: *P-E*, moisture convergence by the mean flow (*CMF*), and convergence by transient eddies (*CTE*; i.e. storm systems), where the last component is obtained as a residual, *CTE = (P-E) - CMF* (Li and Ting, 2017). Changes in *CTE* dominate P-E differences between PH and PL in the regions of interest (Figure 5) and wetter conditions (see changes in *P-E*, Figure 6a) in the western Mediterranean can largely be explained by the higher-frequency *CTE* component of the circulation (Figure 6c). These patterns can, therefore, be linked to the winter Atlantic storm tracks (Seager et al., 2014) rather than to local changes in convective precipitation. In the eastern Mediterranean, wetter conditions are instead driven by the *CMF* component of the circulation (6b).

The magnitude of the runoff signal originating from the winter storm tracks is much smaller than the contribution from the monsoonal rainfall in summer. However, storm track precipitation directly hits the Iberian Peninsula in winter, as well as northern Morocco, which would generate enhanced local runoff with substantially reduced time lags in delivery from the catchments, compared to the North African ones. This might have an enhanced effect in marginal basins such as Guadalquivir or Sorbas (Spain, see Figure 1), which may have had a hydrologic budget of opposite sign compared to the Mediterranean Sea (Modestou et al., 2017). In contrast, not all of the monsoonal precipitation will reach the eastern Mediterranean Sea, given the ephemeral nature of some of the North African rivers and the resulting time lags (see section 4.3). The existence of two distinct precession-driven moisture sources provides new possible interpretations for past humid climate periods (Kutzbach et al., 2013), where the two precipitation systems, one in winter, the other summer, could act in tandem at some locations, providing year-round increased humidity (Toucanne et al., 2015), or explain wetter conditions in regions beyond the reach of the African summer monsoon (Hoffmann et al., 2016). For the latest Marine Isotope Stages (MIS 4 and 3), speleothem fluid inclusions confirm that the amount of atmospheric moisture advection over the circum-Mediterranean regions changes during orbital cycles, indicating that westerly rainfall was advected through the Atlantic storm track during humid periods, even though the largest part of it was sourced from the Mediterranean Sea itself (Rogerson et al., 2019). The composition of these fluid inclusions reflects both western and eastern Mediterranean sources; the Atlantic end member is only recorded during phases forced by precession, while during intervals dominated by obliquity the only moisture source is of Mediterranean origin (Rogerson et al., 2019).

For the late Miocene, these two moisture sources would explain the correlation between geological successions in the Mediterranean Sea (e.g., Spain, Greece, Italy) and those outside the Mediterranean along the Atlantic margin (Figure 1), such as in northern Morocco (e.g., Ain El Beida and Oued Akrech) and western Spain (e.g., in the Guadalquivir Basin). The sedimentary sequences outside the Mediterranean Sea do not contain sapropelic layers, but do show precession-controlled carbonate dilution cycles in their major element ratios (e.g. van der Laan et al., 2012; van den Berg et al., 2015). The sequences on the Iberian Peninsula are clearly not influenced by the monsoonal runoff from the Chad or Nile catchments, but increased summer monsoonal rainfall could directly reach northern Morocco at precession minima, as it extends northward along the Atlantic coast (between ∼20–30°N, see Figure 2 and Bosmans, Drijfhout, Tuenter, Hilgen, and Lourens, 2015 and Brayshaw et al., 2011). Another possibility, is that Mediterranean Outflow could have transported the Mediterranean's precessional signal northward along the Iberian coast, as hypothesized for the Pleistocene (Bahr et al., 2015). However, it has been shown that the Messinian dilution cycles found in the Guadalquivir Basin are not influenced by Mediterranean Outflow (van den Berg et al., 2015), indicating Atlantic winter storms as the most likely moisture source for these regions, at least in the late Miocene.

In the Pliocene, carbonate dilution cycles have also been found both in the western Mediterranean and the Gulf of Cadiz (Ochoa et al., 2018; Sierro et al., 2000), while peaks in hematite and iron found at times of precession minima in sediment cores from the Iberian (Hodell et al., 2013) and Moroccan (Bozzano et al., 2002; Moreno et al., 2001) margins of late Pleistocene age could be of fluvial rather than eolian origin (i.e., related to increased dust fluxes from the African continent). Similarly, the older Miocene cycles in the Ain el Beida section near Rabat (see Figure 1) have been interpreted as dilution cycles, with dilution being caused by enhanced precipitation and fluvial input. However, the upper Pleistocene carbonate cycles from the Atlantic margin of Morocco (Bozzano et al., 2002; Moreno et al., 2001) and the associated color (redness) cycles at the Iberian margin (Hodell et al., 2013) all show essentially an in-phase relation with precession or minor lags, meaning that there is no clear geological evidence for a lagged response of the winter signal in the western Mediterranean or Atlantic margin, like the modelled runoff could suggest for the western marginal basins (Figure 3a). This might result from the additional influence of obliquity in the simulated insolation cycle, but additional data from the Atlantic margin and western Mediterranean would be necessary to provide a clearer comparison and explanation. Another aspect that we cannot fully address here is the contribution of winter runoff from the northern Mediterranean borderlands (mainly via the Rhone catchment) into the western Mediterranean, which may have been much more important at other times, as suggested for interglacial periods (e.g. Toucanne et al., 2015; Rohling et al., 2015).

4.2. What Drives Precessional Circum-Mediterranean Sedimentary Patterns?

The driving mechanism behind meridional shifts of the Atlantic winter storm tracks and the role played by the land-ocean temperature contrast is still highly debated for present-day climate, despite the available instrumental record (Shaw et al., 2016). Therefore, it is challenging to pinpoint which mechanism may be driving past changes detected in both the African monsoon and Atlantic storm tracks that we identified on precessional time scales for our Messinian simulations (e.g., see Figures 4 and 5).

Kutzbach et al. (2013) hypothesize the existence of a dynamic link between the tropical and extratropical atmospheric circulation, suggesting that the southward shift in the storm tracks could be a response to a hemispheric East-West change in tropical heating. The decreased DJF insolation forcing would cause both a large-scale reduction in tropical precipitation over the continents and a large-scale cooling of the tropical and

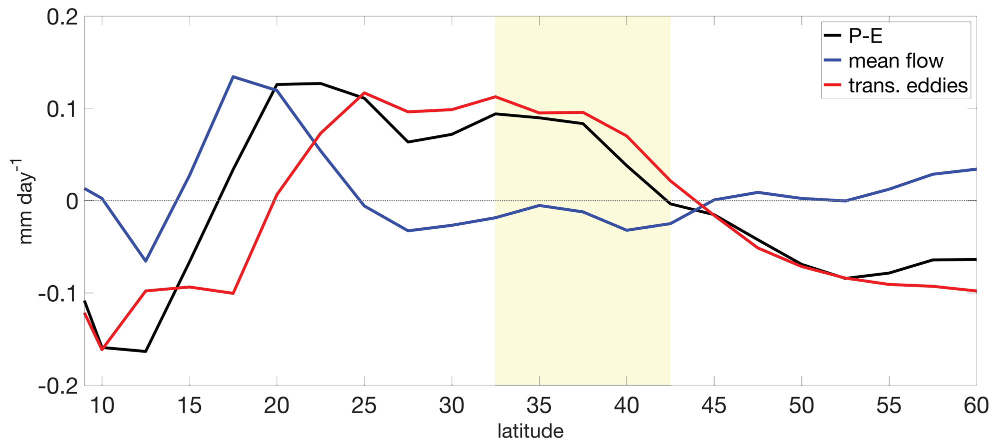

Figure 5. Zonal average in DJF between 100°W and 40°E of the contribution to the moisture budget from P-E (black), moisture flux convergence by the mean flow (blue) and by the transient eddies (red). Shown is the anomaly between the PH and PL experiments for each of the three components. The yellow shading highlights the regions of interest.

subtropical atmosphere, which is likely to be linked to the southward shift of the Mediterranean storm track system. This appears to be supported by other studies that highlighted the connections between tropical and extratropical responses to reduced winter insolation and the southward shift of circulation features, including those in the Mediterranean regions (Kutzbach et al., 2013, and references therein).

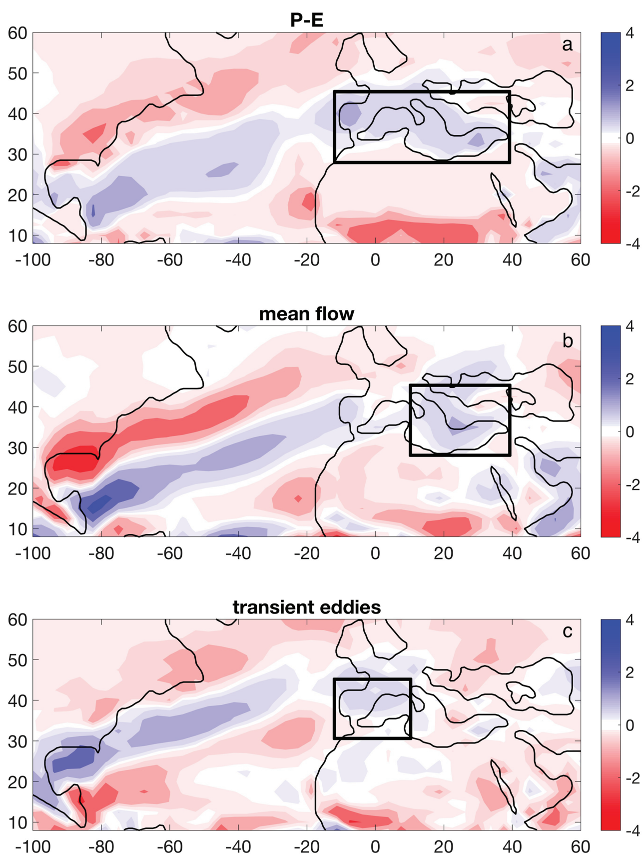

Figure 6. PH-PL anomaly in DJF for the different components of the moisture budget: P-E (top), moisture flux convergence by the mean flow (middle), transient eddies (bottom). Black boxes highlight the Mediterranean regions of interest and the differences between patterns in the western and eastern parts of the basin.

Storm tracks, jet stream, and Intertropical Convergence Zone (ITCZ) meridional shifts may also be linked to sea surface temperature/surface air temperature changes in the North Atlantic (e.g. Beghin et al., 2015; Brayshaw et al., 2011; Park et al., 2015), but evidence for this mechanism in our simulations is inconclusive. A set of specific sensitivity studies using a hierarchy of models (including higher spatial resolution and idealized simulations) would be needed, in order to analyze quantitatively the potential mechanism linking both monsoons and storm track dynamics on precessional time scales. This is beyond the scope of this study and of the capabilities of the climate model that was used.

Regardless of the driving mechanism, the matching phase relationship between the African summer monsoon and the Atlantic winter storm tracks with respect to precession (e.g., see Figures 2–4), even though each have a different seasonality, supports the bed-to-bed interregional stratigraphic correlations between Mediterranean sections and those on the Atlantic margin, such as those applied by Hilgen et al. (2000) and Krijgsman et al. (2004). However, the existence of different climate drivers may trigger distinct sedimentary responses in the western marginal basins and on the Atlantic margins, which should be taken into account for stratigraphic correlations based on the assumption of synchronous deposition of specific lithologies (Modestou et al., 2017). Recognising that enhanced freshwater supply to the eastern and western Mediterranean occurs at different times of the year, challenges the simplistic expectation that the biogeochemical responses seen across the Mediterranean Sea represent synchronous depositional events. In fact, it has already been suggested that tying the midpoint of the sapropelic layers to precession minima may be incorrect for the tuning of some Messinian sections (e.g. Krijgsman et al., 2001; Perez-Folgado et al., 2003), particularly in the well-exposed marginal basin sections where different lithologies may be time-equivalent to sapropels formed in the main basin (Modestou et al., 2017). Although these phase lags do not significantly change Messinian chronology, they do affect our interpretation of the marginal and open-marine Mediterranean environments. For instance, in marginal basins such as Sorbas, the local hydrologic budget may be out of phase with that of the wider western Mediterranean both in time and sign, which may account for the occurrence of specific local lithologies (Modestou et al., 2017).

4.3. Basin-wide Hydrologic Response and Regional Time Lags

The results of our subprecessional analysis of the Miocene Mediterranean hydrologic budget agrees with reconstructions from the eastern Mediterranean, where organic biomarkers show the dominant terrestrial input into the basin during precession minima, associated with enhanced runoff of monsoonal origin from the North African catchments (Mayser et al., 2017). The monsoonal freshwater input, which is dominant both basin-wide and in the eastern Mediterranean, is linked to late-summer precipitation (Figures 3e,k). However, there may be a delay of several months between peak monsoonal precipitation (August-September) over the North African catchments and its transport to, and impact on, the Mediterranean Sea via runoff. Many of the paleo-rivers crossing North Africa and reaching the Mediterranean Sea were likely to have been ephemeral and would have only existed at times of intensified monsoons (Coulthard et al., 2013). In addition, the Chad-Eosahabi palaeo-lake infilling would have required time before the ephemeral rivers could start outflowing. On the other hand, these could have kept reaching the Mediterranean for up to 3 months after the seasonal monsoon peak (Coulthard et al., 2013). This means that the increased freshwater and nutrients input carried by the North African rivers would have reached the eastern Mediterranean during the late-autumn and winter. An enhanced freshwater input, even if relatively small in magnitude, reaching the basin at this time of the year, when deep water is formed (e.g. Pinardi and Masetti, 2000), may affect conditions at the surface more effectively and lead to water column stratification and bottom water stagnation. This would then create a favorable environment for the deposition of organic-rich layers, especially when combined with the increased input of nutrients (Meijer and Tuenter, 2007).

In the western Mediterranean marginal basins, the localized precipitation and runoff signals are likely to have been a relatively large component of the freshwater budget (Mayser et al., 2017) and it is from these marginal settings that the Miocene geological record is derived. However, these local precipitation and runoff signals are a much smaller component of the hydrologic budget for the western Mediterranean subbasin as a whole; therefore, it is not clear that these alone could generate the water column stratification and biogeochemical response required to produce the sapropel-marl sedimentary cyclicity observed in the Quaternary record. This cyclicity is likely to have been a function of Mediterranean-wide circulation and primary productivity, driven by the eastern subbasin, with an additional minor contribution from local winter runoff (e.g. Rohling et al., 2015; Toucanne et al., 2015). If the western Mediterranean's precessional cyclicity results from an eastern Mediterranean driver, this requires exchange between the two basins (in the late Miocene, the Strait of Sicily was deeper than today Roveri et al., 2008) and the transfer of Levantine Intermediate Water (or of an equivalent water mass distributed basin-wide) from the East to the West. This hypothesis cannot be verified fully in the Messinian geological record, as sapropelic sediments are found in western and eastern Mediterranean marine sections that are now exposed on land, but there are no available sediment cores from the central part of the basin for this time period. On the other hand, the Pliocene carbonate dilution cycles in the western Mediterranean, point to a direct influence of enhanced winter precipitation (Ochoa et al., 2018), and sediment cores containing sapropel successions from the Quaternary have been recovered in the West (Rohling et al., 2015, and references therein), even though these are less prominent than their counterparts in the eastern Mediterranean. Rogerson et al. (2008) also quantified that an appropriately-timed freshwater pulse would have played a key role in the formation of Holocene organic rich layers in the western Mediterranean; with favorable conditions, a similar mechanism could also apply for older sapropelic layers, but with the caveat that exchange at the Mediterranean-Atlantic gateway would have been different.

By using a global GCM we are able to simulate large-scale features that influence the circum-Mediterranean regions, such as the movements of the ITCZ and shifts in the storm tracks, which require an extended model domain. However, this means that the spatial resolution of our model is not adequate to analyze the details of Mediterranean ocean circulation, even less at a subbasin scale. This could be achieved with the combination of idealized experiments (e.g. Modestou et al., 2017) and regional models (e.g. Meijer and Tuenter, 2007) informed by global climate simulations such as those used in this study.

5. Summary and Conclusions

Our results highlight the strong variability of the Mediterranean hydrologic fluxes throughout a full precession cycle, which should be taken into account when sampling and interpreting geological data. This variability is likely to have been even more significant in precession cycles with higher amplitude than the one simulated here (6.568 and 6.589 Ma).

Most studies, both model and data-based, generally emphasize annual or summer precipitation changes between orbital extremes, rather than focusing on winter moisture sources. The African summer monsoon is often considered as the sole driver, even at locations that are outside the areas of influence of the monsoonal system, likely due to the lack of evidence for winter precipitation in the observational record. The potential for a significant role of the Atlantic winter storm tracks on the Mediterranean regions has been suggested by some other modeling (Brayshaw et al., 2011; Kutzbach et al., 2013) and observational studies (Hoffmann et al., 2016; Toucanne et al., 2015). Here, we have provided further support for this hypothesis, based on nonidealized fully-coupled climate simulations, which confirm the link between winter precipitation changes in the Mediterranean and large-scale atmospheric circulation. While our analysis is specific for the late Miocene, the consistency with results from other studies for the Quaternary (Brayshaw et al., 2011) and with idealized simulations (Kutzbach et al., 2013), suggests that the southward shift of winter precipitation of Atlantic origin is driven by orbital forcing rather than paleogeography.

Runoff into the western and eastern Mediterranean shows an in-phase precession-driven control, but a different seasonality and magnitude, due to the two distinct moisture sources influencing the two subbasins. This supports the temporal (precessional) stratigraphic correlation of sedimentary sequences basin-wide in the Mediterranean Sea and on the Atlantic margin. However, proxies from these regions are likely to be out-of-phase seasonally; this offset would not affect the correlation between sections in the eastern and western subbasins, given that this is achieved on precessional time scale (e.g. Perez-Folgado et al., 2003; Sierro et al., 2001), but it should be taken into account in the collection and interpretation of paleoclimate proxies at subprecessional timescales (see also Hoffmann et al., 2016; Kutzbach et al., 2013).

Our study provides potential alternative interpretations of the paleoclimatic record. We focus on a specific late Miocene example, supporting the precessional correlation of Mediterranean and Atlantic successions, which traditionally has been hard to justify through a monsoon-related mechanism, given the location of some of these sections. The combination of the two seasonally-distinct moisture sources could have led to year-round wetter conditions during times of precession minima from North Africa to the Mediterranean and the Middle East. This may not only be relevant for the late Miocene, but also during the more recent African humid periods, with potentially important implications for human migrations (Hoffmann et al., 2016; Kutzbach et al., 2013; Toucanne et al., 2015).

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