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# Precession and obliquity forcing of the freshwater budget over the Mediterranean

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ABSTRACT

There is strong proxy and model evidence of precession- and obliquity-induced changes in the freshwater budget over the Mediterranean Sea and its borderlands, yet explanations for these changes vary greatly. We investigate the separate precession and obliquity forcing of the freshwater budget over the Mediterranean using a high-resolution coupled climate model, EC-Earth. At times of enhanced insolation seasonality, i.e. minimum precession and maximum obliquity, the area was wetter and the Mediterranean Sea surface was less saline. The latter has been attributed to increased runoff from the south as a consequence of a strengthened North African monsoon, as well as to increased precipitation over the Mediterranean Sea itself. Our results show that both mechanisms play a role in changing the freshwater budget. Increased monsoon runoff occurs in summer during times of enhanced insolation seasonality, especially minimum precession, while increased precipitation is important in winter for both precession and obliquity. We relate changes in winter precipitation to changes in the air-sea temperature difference and subsequently, convective precipitation. The freshening in the minimum precession and maximum obliquity experiments has a strong effect on Mediterranean sea surface salinity and mixed layer depth, thereby likely influencing deep sea circulation and sedimentation at the ocean bottom.


## 1. Introduction

The response of Mediterranean climate to orbital forcing is a heavily debated topic in paleoclimatology. A large body of data has shown that at times of enhanced insolation seasonality, i.e. minimum precession and maximum obliquity, the Mediterranean area was wetter and the Mediterranean Sea surface freshwater budget (evaporation minus precipitation and runoff) was reduced. As a consequence of reduced surface buoyancy loss, deep water ventilation was weakened and dark, organic-rich layers formed on the sea floor. Rossignol-Strick (1985) proposed a physical link between the occurrence of these so-called sapropels and orbitally forced increases in North African monsoon strength, which consequently strengthens Nile river runoff. Although the sapropels are mainly paced by precession, an obliquity pattern is present as well (e.g. Lourens et al., 1996).

The strengthening of the North African monsoon during times of increased insolation seasonality, such as minimum precession and maximum obliquity, has been confirmed by many studies (Kutzbach et al., 2013; Bosmans et al., 2015; Larrasoaña et al., 2013, and references therein). The subsequent increase in runoff towards the Mediterranean holds as the most widely adopted hypothesis for the formation of sapropels, appearing in handbooks on paleoclimatology (Ruddiman, 2007). However, other components of the Mediterranean climate may have played a role as well. Increased precipitation over the basin itself at times of increased summer insolation has been related to increased summer precipitation (Rossignol-Strick, 1987; Rohling and Hilgen, 1991; Rohling, 1994). This idea has however largely been abandoned; recent

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palynological, lake isotopic and lake-level studies point to summer aridity (e.g. Tzedakis, 2007, 2009). Hence wetter conditions over the Mediterranean basin must be related to increased winter precipitation, often attributed to increased Mediterranean storm track activity (e.g. Tzedakis, 2007; Brayshaw et al., 2011; Kutzbach et al., 2013). Furthermore, strong similarities between the sapropel record in the Mediterranean and sedimentary sequences in western Spain and Morocco suggests that both respond to orbital forcing in similar ways (van der Laan et al., 2012). Atlantic storm tracks affect both western Spain and Morocco and can induce increased storm activity over the Mediterranean, hence increased storm track activity could explain wetter conditions at times of increased insolation seasonality in both regions. Increased (net) precipitation over the Mediterranean basin and increased river runoff from the northern borderlands of the Mediterranean may be of equal or greater importance than increased Nile river runoff in changing the freshwater budget, as the former two freshwater sources are situated more favourably in terms of location and timing of the deep water ventilation (Meijer and Tuenter, 2007).

To summarise, orbitally forced changes in the Mediterranean freshwater budget, and therefore sapropel formation, have been attributed to various sources (e.g. Tzedakis, 2007, 2009; Rohling et al., 2009; Kutzbach et al., 2013). The model study by Kutzbach et al. (2013) states that not only monsoon runoff but also winter precipitation over the Mediterranean at times of a precession minimum could explain humid periods in paleoclimatic records, but give no comparison of precipitation and runoff amounts. Meijer and Tuenter (2007) showed the relative roles of (net) precipitation and runoff from both north and south, but based their result on a low resolution intermediate complexity model. Both studies focus on precession forcing, while obliquity leaves an imprint on the sapropel record as well (Lourens et al., 1996). In this study, we use for the first time a high-resolution general circulation model, EC-Earth, to investigate changes in the Mediterranean freshwater budget due to changes in both precession and obliquity. Specifically, we aim to determine the relative roles of precipitation, evaporation and runoff over/into the basin. Also, we examine the causes behind changes in these freshwater budget terms, in order to determine whether changes in the Mediterranean freshwater budget are mainly driven by the North African monsoon, (Atlantic) storm tracks or local changes.

This paper starts with an overview of the model, EC-Earth, and a description of the experimental design (Section 2). We then briefly discuss the freshwater budget in a pre-industrial control experiment in Section 3.1, as an evaluation of EC-Earth's capability of modelling Mediterranean climate. The main results are shown in Sections 3.2, 3.3 and 3.4, where we examine changes in (net) precipitation and runoff as well as possible causes. We also briefly touch upon the possible effects of the freshwater budget changes on deep water formation in Section 3.5. Section 4 provides a discussion in which we compare our results to both proxy data and model studies. A conclusion is given in Section 5.

## 2. Model and experiment set-up

### 2.1. EC-earth

EC-Earth is a fully coupled ocean-atmosphere GCM (general circulation model). Here we use version 2.2, based on the Integrated Forecasting System (IFS), cycle 31R1 of the European Centre for Medium-range Weather Forecast (ECMWF), running at a resolution of roughly $1.125° \times 1.125°$ (T159) with 62 vertical levels. For more details see Hazeleger et al. (2010, 2011). Dynamic vegetation is not included. The ocean component consists of NEMO (Nucleus for European Modelling of the Ocean), version 2, running at a horizontal resolution of nominally 1° with 42 vertical levels (Madec 2008; Sterl et al., 2011). For the vertical levels a z-coordinate is used with thickness increasing from 10 m at the surface to 100–300 m at depth. The Mediterranean consists of 363 surface gridboxes in the horizontal on a curvilinear C-grid. NEMO incorporates the sea-ice model LIM2. The ocean, sea-ice, land and atmosphere modules are coupled through the OASIS3 coupler (Valcke and Morel, 2006).

The same version of EC-Earth was shown to reproduce Mid-Holocene monsoon precipitation well compared to PMIP2 model studies (Bosmans et al., 2012). Furthermore, in the precession and obliquity experiments that are also used in this study, the North African monsoon was shown to respond strongly to the insolation forcing, being mainly driven by enhanced moisture transport from the Atlantic (Bosmans et al., 2015). This is in line with recent GCM studies (e.g. Herold and Lohmann, 2009) but in contrast to previous intermediate complexity model studies such as that of Tuenter et al. (2003), which showed a distinctively different source of moisture. Hence the state-of-the-art model EC-Earth has already provided new paleoclimatological insights.

### 2.2. Experiments

In this study we use four idealized experiments in which the precession and obliquity effects can be studied separately. These experiments were also used in Bosmans et al. (2015). The orbital configuration used in each experiment is summarised in Table 1.

During minimum precession (Pmin), when the precession parameter $e\ \sin(\pi + \tilde{\omega})$ is at its minimum value, Northern Hemisphere summer solstice occurs at perihelion (the point closest to the Sun). Seasonality of insolation is enhanced on the Northern Hemisphere and decreased on the Southern Hemisphere. During maximum precession (Pmax), Southern Hemisphere summer occurs at perihelion. Insolation differences at ~ 40° N are on the order of 100 $Wm^{-2}$ for precession and 15 $Wm^{-2}$ for obliquity with opposite anomalies in summer and winter (see Fig. 1 in Tuenter et al. (2003) or Bosmans et al. (2015)). Only orbital parameters, and thus insolation, vary amongst the experiments; all other boundary conditions (e.g. greenhouse gasses, ice caps) are kept at pre-industrial values, as is the calendar. More details can be found in Bosmans et al. (2015). Furthermore, we briefly discuss a pre-industrial control experiment using boundary conditions as prescribed by the Paleoclimate Modelling Intercomparision Project (see http://pmip3.lsce.ipsl.fr). This pre-industrial experiment is described in Bosmans et al. (2012).

In this study we compare Pmin with Pmax, and Tmax with Tmin, i.e. we investigate the effect of increased summer and decreased winter insolation. These experiments were initiated from a pre-industrial control experiment. Each experiment is run for 100 years, of which the last 50 years are used to create the climatologies shown in this study. This is long enough for atmospheric and surface variables that are of interest to equilibrate to the forcing (see Bosmans et al. (2015)). The globally averaged tendency term of

**Table 1**
Overview of the orbital configuration in each experiment. Obl is the obliquity (tilt), $\tilde{\omega}$ is the longitude of perihelion, defined as the angle from the vernal equinox and perihelion, measured counterclockwise. $e$ is eccentricity. $e\ \sin(\pi + \tilde{\omega})$ is the precession parameter. Note that for Tmax and Tmin there is no precession because of the circular orbit ($e = 0$).

| Experiment | Obl (°) | $\tilde{\omega}$ (°) | $e$ | $e\ \sin(\pi + \tilde{\omega})$ |
|---|---|---|---|---|
| Pmin | 22.08 | 95.96 | 0.056 | −0.055 |
| Pmax | 22.08 | 273.5 | 0.058 | 0.058 |
| Tmax | 24.45 | – | 0 | 0 |
| Tmin | 22.08 | – | 0 | 0 |