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Development of a sequential tool, LMDZ-NEMO-med-V1, to conduct global to regional past climate simulation for the Mediterranean basin: An Early Holocene case study

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Abstract

Recently, major progress has been made in the simulation of the ocean dynamics of the Mediterranean using atmospheric and oceanic models with high spatial resolution. High resolution is essential to accurately capture the synoptic variability required to initiate intermediate and deep-water formation, the engine of the MTC (Mediterranean Thermohaline Circulation). In paleoclimate studies, one major problem with the simulation of regional climate changes is that boundary conditions are not available from observations or data reconstruction to drive high-resolution regional models. One consistent way to advance paleoclimate modelling is to use a comprehensive global to regional approach. However, this approach needs long-term integration to reach equilibrium (hundreds of years), implying enormous computational resources. To tackle this issue, a sequential architecture of a global-regional modelling platform has been developed and is described in detail in this paper. First of all, the platform is validated for the historical period. It is then used to investigate the climate and in particular, the oceanic circulation, during the Early Holocene. This period was characterised by a large reorganisation of the MTC that strongly affected oxygen supply to the intermediate and deep waters, which ultimately led to an anoxic crisis (called sapropel). Beyond the case study shown here, this platform may be applied to a large number of paleoclimate contexts from the Quaternary to the Pliocene, as long as regional tectonics remain mostly unchanged. For example, the climate responses of the Mediterranean basin during the last interglacial (LIG), the last glacial maximum (LGM) and the Late Pliocene, all present interesting scientific challenges which may be addressed using this numerical platform.

1 Framework of the study

1.1. Introduction

The Mediterranean basin is a key region for the global climate system and is considered to be a climate "hotspot" (Giorgi, 2006), due to its high sensitivity to global warming. In the past, it has been the seat of important human civilisations, and it continues to play a very important role in international geopolitics with a dense population along its coasts. There is great diversity in the Mediterranean

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ecosystems, both marine and terrestrial. The Mediterranean region is also rich in paleoclimate records with a variety of proxies. Indeed, this area experienced major changes during the glacial-interglacial cycles (Jost et al., 2005; Ludwig et al., 2018; Ramstein et al., 2007). Another long-term cycle of changes due to high-frequency precession which drastically modified the hydrological patterns of this area (monsoon, sapropels) is also superimposed.

Due to the peculiarities of both the atmospheric and oceanic circulation in the region, high-quality climate modelling of the Mediterranean region needs to have high spatial resolution. Indeed, the presence of strong gusts of wind in winter are essential to trigger oceanic convection and these can only be correctly represented in high-resolution models. Limited area models (LAM), or regional climate models (RCM), present some advantages in this regard, since they generally demand less computing resources, allowing them to be run at high spatial resolution for a given region. However, their usefulness for paleoclimate purposes is limited because of the lack of adequate lateral boundary conditions to drive the RCMs. The main reason why few comprehensive modelling exercises to explain paleoclimate changes around the Mediterranean have been performed is that the level of computing resources required for high resolution and long simulations is inaccessible. This is especially true in the case of the Mediterranean Thermohaline Circulation (MTC), which has significantly changed in the past, at both centennial and millennial scales.

In this paper, we developed a modelling suite to define high-resolution atmospheric conditions over the Mediterranean basin from global ESM (Earth System Model) paleoclimate simulations. In a second step, we used this atmospheric forcing to run a highly resolved ocean model (NEMOMED8 1/8°) to accurately simulate ocean dynamics. This tool allows us to achieve a high spatial resolution and equilibrated simulations with a run time of 100 years. The objective of this study is to develop a modelling platform sufficiently comprehensive to conduct paleoclimate studies of the Mediterranean basin. The potential of this platform is illustrated by investigating climate situations from the present period and from the Early Holocene that generated sapropel events.

The sapropel events provide excellent case studies on the impact of global changes on the Mediterranean basin. These periodic events are related to a long period of anoxia of the deep and bottom waters triggered by an enhancement of the African monsoon caused by periodicities of the orbital precession. However, the localisation of the forcing source caused by orbital variability is still a subject of debate. This is especially true for the last sapropel, denoted S1, which occurred during the early Holocene (between 10500 and 6800 ka BP) (De Lange et al., 2008). Reproducing past climate variations over the Mediterranean basin, including the sapropel events, is therefore a challenge for the modelling community.

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The paper is organised as follows: In the first part, we briefly review the different approaches used to simulate the Mediterranean climate and sea conditions, and we present the concept of the sequential procedure that we propose. In a second part, we present in detail the model architecture we developed. Finally, we present applications with simulations of the historical period (1970-1999) and the Early Holocene (around 9.5 ka).

1.2. Overview of current Mediterranean Sea modelling

The Mediterranean Sea, due to its limited size and its semi-enclosed configuration, has a faster equilibrium response (100 year) than the global ocean (1000 year). Because of this semi-enclosed configuration, there are a few requirements that modelling of the Mediterranean Sea needs to satisfy so that its evolution can be properly represented. High resolution in both the atmospheric forcing and the oceanic configuration is necessary to correctly simulate the convection areas and the associated thermohaline circulation (Lebeaupin Brossier, et al., 2011). Depending on the mechanism studied, the resolution of the ocean model used by the research community ranges from ¼° (e.g. for paleo-climatic simulation), to 1/75° (for hourly description of the mixed layer, tide-based investigation). The results for oceanic convection are highly dependent on the flux of heat and water and the wind stress at the air-sea interface, especially the seasonal variability and intensity. There are many modelling configurations in the scientific literature making it impossible to provide an exhaustive review of all of them. We can summarise them by presenting the different approaches used to drive the Mediterranean oceanic model, along with their advantages and drawbacks. We underline our new, coherent method, which captures the changes in ocean dynamics in the Mediterranean basin derived from global paleoclimate simulations.

Observations and reanalysis

The most common way to simulate the general circulation of the Mediterranean Sea is to run a regional oceanic general circulation model forced by surface fluxes and wind stresses derived from observations and reanalyses. In this way, an oceanic model can be driven by realistic fluxes. In most cases, it implies a spatial atmospheric resolution of less than 50 km and a daily temporal resolution, at a minimum, in order to simulate the formation of dense water (Artale, 2002). This approach is adapted to simulate the present-day Mediterranean Sea and to explore the complexity of its sub-basin circulation and water mass formation (Millot and Taupier-Letage, 2005). However, this method is not well adapted to the study of past and future climate.

Atmospheric model

A second method consists of forcing a regional oceanic model with simulations from an atmospheric model, AGCM (Atmospheric Global Climate Model) or ARCM (Atmospheric Regional Climate Model). Since the AGCM resolution (typically 100 to 300 km horizontally) is coarse, statistical and/or

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dynamical downscaling is usually needed, especially for wind-stress so that the ORCM (Ocean Regional Circulation Model) can be correctly forced (Béranger et al., 2010). Currently, dynamical downscaling with ARCM is the preferred option because it generally improves simulations of the climate in the Mediterranean region and especially of the hydrological cycle (Li et al., 2012).

This configuration is broadly used to assess anthropogenic climate changes (Adloff et al., 2015; Macias et al., 2015; Somot et al., 2006). In these studies, the Mediterranean Sea simulations are generally driven by the outputs of an ARCM, which is, in turn, driven by the GCM or observations. It should be noted that biases in oceanic variables can be reduced through constant flux correction (Somot et al., 2006). This configuration is suitable for high-resolution simulation of the past Mediterranean Sea (Mikolajewicz, 2011 for the LGM; Adloff et al., 2011 for the Early Holocene among others).

Regional coupled model

Although the majority of the Mediterranean Sea models are ocean-alone models, some of them use a coupled configuration between the Mediterranean Sea and the atmosphere. Such a coupled configuration generally improves the simulation of the air-sea fluxes, including their annual cycle (de Zolt et al., 2003), but may show climate drifts in key parameters such as the SST. Regional coupled models are now emerging as a tool in Mediterranean climate modelling (Artale et al., 2010; Dell'Aquila et al., 2012; Drobinski et al., 2012; Sevault et al., 2014; Somot et al., 2008). However, this full-coupling configuration is currently not possible for high-resolution paleoclimate issues requiring long simulation.

Importance of boundary conditions

The boundary conditions applied to the Mediterranean Sea domain, in particular, the exchanges of water, salt and heat with the Atlantic Ocean through the Strait of Gibraltar modulate significantly the Mediterranean circulation (Adloff et al., 2015). This is especially true at the millennial scale where deglaciation episodes and fluctuations of the AMOC (Atlantic Meridional Overturning Circulation) and the Mediterranean Sea affect each other (Swingedouw et al., 2018). The level of discharge from the main rivers is also crucial as is illustrated by the sapropel episodes, where an increase in freshwater input drastically slowed down the MTC. Most of current models impose prescribed (observed when possible) conditions in the near Atlantic zone, including temperature and salinity. The same methodology can be used to prescribe river discharges. However, it must be acknowledged that determining inputs from rivers into the Mediterranean Sea, either of water or other materials, still presents serious challenges for modelling.

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1.3. Concepts for a sequential procedure to perform global-to-regional modelling

In this paper, we propose a new architecture for high-resolution modelling of the climate of the Mediterranean basin for past, present and future climates. This architecture is based on a method as much consistency between the models as possible and high congruency with data.

Step 1: Global climate

Our goal is to simulate different climate conditions for the Mediterranean basin. The first step of any relevant procedure should be to simulate the global climate conditions from which we drive the simulation of the regional climate. These may be already available in simulations from previous PMIP exercises for various periods (e.g. mid-Holocene, Last Glacial Maximum, Last Interglacial and mid-Pliocene) as well as for different sapropel events and interglacials (e.g. MIS11, MIS13 and MIS19). However, this is not always possible due to the large volume of high-frequency 3-D atmospheric circulation variables involved. An alternative approach, used in some regional climate simulations (Chen et al, 2011; Goubanova & Li, 2007; Krinner et al, 2014), consists of using an AGCM (either an independent one or the same one used for the global climate simulation) run with appropriate values for global Sea Surface Temperature (SST) and Sea Ice cover (SIC). SST is crucial to determine atmospheric features and responses, while SIC plays a key role in determining the global albedo. Monthly SST and SIC are necessary and sufficient to drive an AGCM. They can be acquired from global climate simulations or through a bias-correction procedure.

Step 2: Regional climate

After running an AGCM, regional climate can be now reproduced with an ARCM nested into the high-frequency outputs from the AGCM. Of course, the ARCM can be run in parallel to the AGCM, or with a small time delay. Thus, we avoid a large accumulation of intermediate information between the AGCM and the ARCM. In our study, we assume that there would be no feedback from the regional scale to the global scale, so only a "one-way" transfer of information (from global to regional) is considered. In our case, the ARCM is a strongly zoomed-in version of the AGCM and is also driven by monthly SST and SIC values. The higher resolution of the ARCM allows the synoptic variability and seasonality of the Mediterranean region to be depicted so that a realistic wind pattern and hydrological cycle may be reproduced. This approach provides a general framework for use in many different paleoclimate periods from the Pliocene to the Pleistocene, as long as the basin tectonics remain unchanged.

Step 3: Mediterranean Sea Circulation

Daily air-sea fluxes and wind stress provided by the ARCM are used as surface boundary conditions to drive the ORCM to investigate the oceanic dynamics of the Mediterranean. It is reasonable to assume that the boundary conditions of these air-sea fluxes represent the long-term trends of the oceanic dynamics. Rivers may be considered interactive or not depending on the investigative objectives: runoff can be prescribed from climatology or obtained from the hydrological component of the surface model. Again, we highlight that our architecture does not include any feedback, between either the regional ocean and the regional atmosphere, or the regional ocean and the global ocean. This configuration means that we can avoid dealing with certain issues, for example, the influence of the Mediterranean Outflow Water on the North Atlantic Ocean but is well adapted to provide consistent river runoff associated with changes in continental precipitation.

2 Model architecture

We used an ensemble of modelling tools that includes two atmospheric models and a regional oceanic model. Figure 1 summarises the configuration and shows the experimental flowchart.

2.1. The atmospheric models (AGCM and ARCM)

LMDZ4 (Hourdin et al., 2006; Li, 1999) is the atmospheric general circulation model developed and maintained by IPSL (Institut Pierre Simon Laplace). It has been widely used in previous phases of CMIP and PMIP projects. The resolution of the model is variable. Its global version used here (referred to as LMDZ4-global) is 1.875° in longitude and 1.25° in latitude with 19 layers in the vertical. It provides the boundary conditions to drive LMDZ4-regional. LMDZ4-regional (Li et al., 2012) is a regionally-oriented version of LMDZ4 with the same physics and same vertical discretisation, dedicated to the Mediterranean region. The zoomed-in model covers an effective domain of 13°W to 43°E and 24°N to 56°N with a horizontal resolution of about 30 km inside the zoom. The rest of the globe outside this domain is considered to be the buffer-zone for LMDZ4-regional where a relaxation operation is performed to nudge the model with variables from the AGCM. The resolution of LMDZ4-regional decreases rapidly outside its effective domain. In both LMDZ4-global and LMDZ4-regional, land-surface processes, including the hydrological cycle, are taken into account through a full coupling with the surface model, ORCHIDEE.

2.2 The regional oceanic model (ORCM)

NEMOMED8 (Beuvier et al., 2010; Herrmann et al., 2010) is the regional Mediterranean configuration of the NEMO oceanic modelling platform (Madec, 2008). The horizontal domain includes the Mediterranean Sea and the nearby Atlantic Ocean which serves as a buffer zone (from 11°W to 7.5°W). The horizontal resolution is 1/8° in longitude and 1/8°cosφ in latitude, i.e. 9km to 12km from the north to the south. The model has 43 layers of inhomogeneous thickness (from 7m at the surface to 200m in the depths) in the vertical. River discharges are accounted for as freshwater fluxes in the grids corresponding to the river mouths. A first dataset of river discharges represents 33 river mouths throughout the Mediterranean region. It contains monthly mean climatological values of runoff.

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Interactive calculations of freshwater discharges from rivers by the land-surface model, ORCHIDEE, include 192 river mouths for the Mediterranean. The Black Sea, not included in NEMOMED8, counts as a river dumping freshwater into the Aegean. The deposit rate is calculated based on total runoff into the Black Sea, plus the net budget of precipitation (P) minus evaporation (E) over the Black Sea.

2.3 Modelling Sequence

As shown in Fig. 1, the first step in our modelling chain is to obtain SST and SIC values from an Earth System Model simulation able to reproduce global climate (for the past, present or future). We can reasonably hypothesise that major global climate information can transit from global SST and SIC. This hypothesis was deemed legitimate for climate downscaling purposes for Antarctic and Africa, in Krinner et al. (2014) and Hernández-Díaz et al. (2017) respectively. In the present work we use IPSL-CM5A (Dufresne et al., 2013) to extract relevant SST and SIC values to drive the AGCM (LMDZ4-global) and the ARCM (LMDZ4-regional). The next step is to run the two atmospheric models, LMDZ4-global and LMDZ4-regional, in the usual way as proposed by the AMIP community. This is the most expensive step, as atmospheric models are the most demanding in terms of computing resources. Fortunately, it is not necessary to run them for a long time as the atmosphere reaches equilibrium quickly. We applied 30 years of simulation to both models. We consider this duration to be long enough to depict climate variability for the simulation of past events. The AGCM nudges the ARCM in the conventional way of one-way nesting for temperature, humidity, meridional and zonal wind every two hours. The nudging is done using an exponential relaxation procedure with a timescale of half an hour outside the zoom and 10 days inside the zoom. Table S1 in the SOM summarises the forcings used, especially the orbital forcing and atmospheric CO_2.

The necessary variables (surface air temperature, wind stress, P-E over the sea, heat fluxes) are provided by ARCM to NEMOMED8. The salinity and temperature conditions are provided in three dimensions in the buffer zone. River runoff depends on the configuration used. Table S2 in SOM details these boundary conditions.

2.4 Bias correction

The sequential modelling chain, despite the lack of interactivity and feedback at interfaces, allows for error removal and bias correction at each step of the methodology. This adjustment is sometimes crucial, especially when model outputs need to be of very high quality to be incorporated into impact studies. This concept was further described in Krinner et al. (2019), as illustrated in Fig. 16 of their paper. Therefore, to enhance our confidence in the realism of the simulation results, bias-correction may be introduced when necessary. The correction method used in the present work generally follows the conventional procedure, which is based on the difference between the model outputs for present day simulations and actual observations. Biases corrected in this way, theoretically only valid for the

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historical simulation (named HIST hereafter), are assumed to remain unchanged for past and future simulation scenarios. However, the transferability between past and future periods is questionable. There is no guarantee that the model error for a period is the same for other periods, even though the model physics may be the same. In addition, paleodata are often rare and incomplete, and so, are unsuitable for evaluation and correction of model errors. The most reliable basis is that established for the present day. The reader can find a full description of the bias corrections in the supplementary online material, "Text S2: Bias correction".

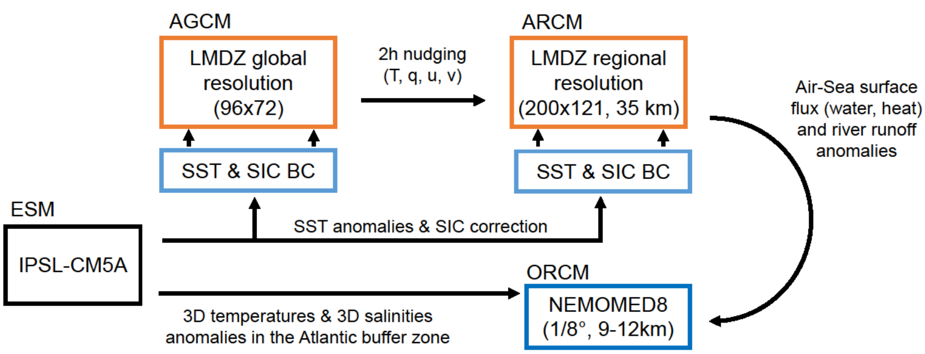

Figure 1: Flowchart of the modelling chain including the four main components: ESM, AGCM, ARCM and ORCM. BC: boundary condition, u: meridional wind, v: zonal wind, q: specific humidity, T: temperature, S: salinity, SST: sea surface temperature, SSS: sea surface salinities.

3 Validation of the modelling chain for present-day climate 1970-1999

In this section, we evaluate the capacity of the model to reproduce the climate of the recent past, in particular, its ability to simulate sea surface characteristics as well as the Mixed Layer Depth (MLD) and oceanic convection patterns as these are key elements to reproduce the evolution of the Mediterranean Sea in past climate conditions.

3. 1 Experimental design

For the HIST experiment, we used SST and SIC observations (source: ERA-Interim) to force the AGCM. River runoff is from the climatology of Ludwig et al., (2009). Monthly mean climatological sea temperatures and salinities (from WOA) are used for the Atlantic boundary zone. HIST atmospheric simulations for both global and regional simulations have a duration of 30 years. The length of the HIST oceanic simulation is also 30 years, but obtained after a 150-year spin-up. The forcings for each

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experiment are detailed in "Table S1" and Table S2" in the supplementary online material. Spin-up phases for each simulation are also shown from "Figure S4" to "Figure S7" for the overturning stream function and the index of stratification.

3.2 Evolution of temperatures

Figure 2 depicts the temporal evolution, between 1970 and 1999, of annual mean surface air temperatures at two metres in the atmospheric simulations (global and regional) compared to observations for the whole globe and over the Mediterranean region. The two models reproduce a range of temperatures similar to the observations, with the Mediterranean temperatures warmer than the global temperatures. The regional model reproduces the warming trend and aspects of the interannual variability which are quite close to observations.

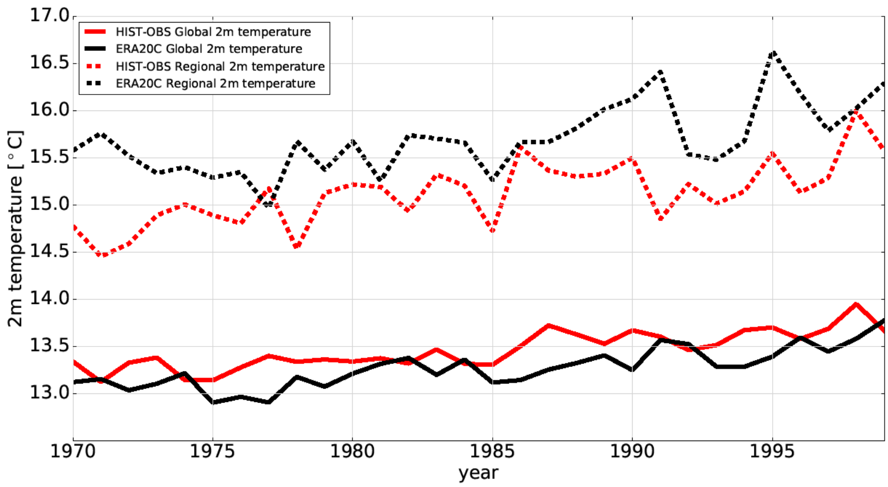

Figure 2: Time series of annual mean surface air temperatures at 2 m in HIST (red) and ERA20C (black) for global average (solid lines) and Mediterranean-only average (dashed lines).

3.3 Precipitation and freshwater budget

Figure 3 shows the average annual precipitation for 1970-1999 in HIST over the Mediterranean region and the differences with observations. The main features of the distribution of precipitation over the Mediterranean region are simulated, in particular the distinct contrast between the very low precipitation in the southern region and higher precipitation in the north. However, the regional model tends to overestimate precipitation over most of Europe, especially over the Alps, the Pyrenees, the Balkans and other mountainous regions. The freshwater budget over the Mediterranean Sea from observations and

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the various simulations conducted in this study are summed up in table 3. (from a synthesis study by Sanchez-Gomez et al., 2011). The simulated continental precipitation is overestimated, but both the precipitation and evaporation over the Mediterranean Sea in HIST is very close to the observations.

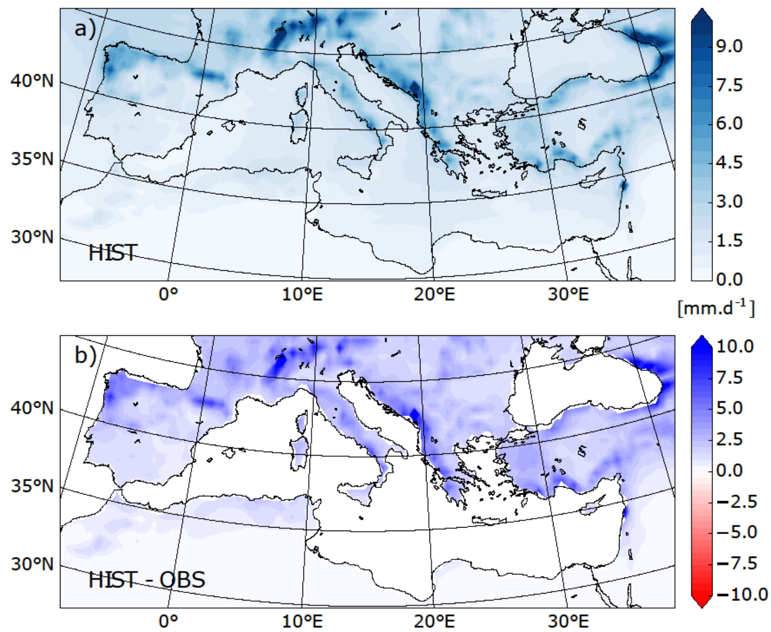

Figure 3: Annual mean precipitation (mm/day) in HIST (panel a). Deviation of HIST simulation from observation-based CRU data (HIST-CRU, panel b, over land only, averaged over the entire simulation).

3.4 Mediterranean Sea surface characteristics

Figure 4 displays the temperatures and salinities of the Mediterranean Sea simulated in HIST and the deviations from observations. The model is able to capture the main characteristics of the pronounced west-east gradient of SSS in the Mediterranean Sea (Figure 4 a). Values are within the range of observations (mean bias = -0.32 PSU, error = 0.37 PSU, table 4). In the simulation, the Aegean Sea is not salty enough (about -1.5 PSU) and the Adriatic/Ionian Sea is too salty (+1 PSU).
The model reproduced the northwest to southeast temperature gradient, as shown in Figure 4b. However, the model shows a general cold bias (from -0.5 to -1.5 °C) over the entire Mediterranean (Figure 4e), due to the cold bias already observed for the air temperature at 2m in the regional atmospheric forcing (cf Figure 2).

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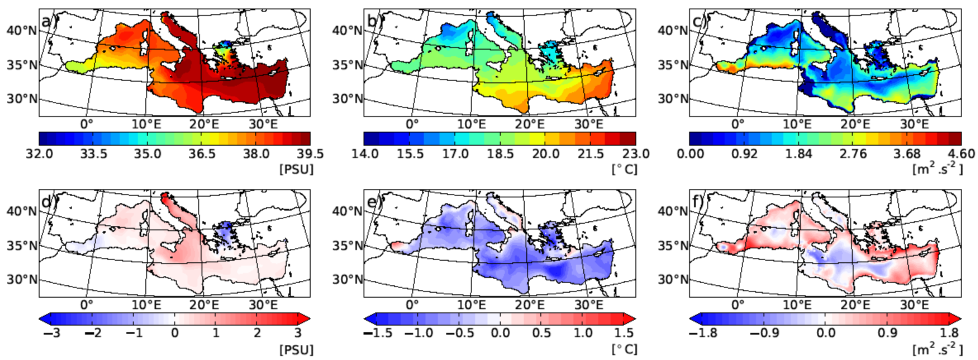

Figure 4: Annual mean sea-surface salinity (left panels, SSS in PSU), sea-surface temperature (middle panels, SST in °C) and index of water column stratification (right panels, winter IS in m^2/s^2) simulated in HIST (top panels) and the HIST deviation from the observation-based MEDATLAS data (averaged over the entire simulation).

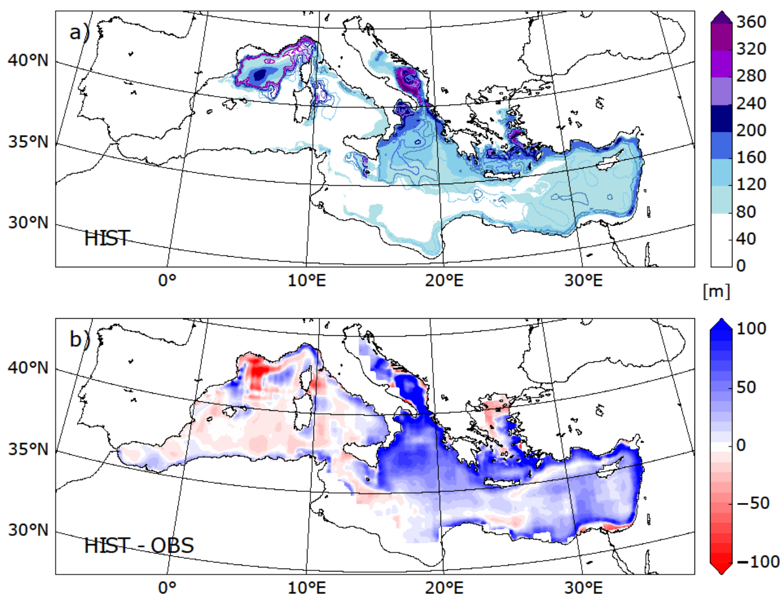

Figure 5: a) Mixed layer depth simulated in HIST (panel a, in m) and as deviation of HIST from observations of Houpert et al., (2015) averaged over the entire simulation**.**

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	SST	SSS	IS
Mean bias	**0.64**	**-0.32**	**-0.91**
RMS error	**0.45**	**0.37**	**0.29**

Table 1: Mean bias of the HIST simulation expressed as the deviation from observations (MEDATLAS-II), and root mean square errors.

3.4 Mediterranean Thermohaline circulation

Here, we evaluate the general characteristics of the simulated thermohaline circulation in regions where deep and intermediate water formation occurs. Figure 4c displays the stratification index (IS[1]) for HIST. IS is a vertical integration of the Brunt-Vaisala frequency. A lower IS implies that convection is more likely. The range of IS biases (Figure 4f), is from -1 to 1 m2.s-2 (mean bias = -0.91 m2.s-2, error = 0.29 m2.s-2). The model satisfactorily reproduces the convection in known intermediate and deep-water formation areas, namely the Gulf of Lions, the Adriatic Sea, the Ionian Sea, the Aegean Sea and the North Levantine.

Comparison with observations of the mixed-layer depth (Houpert et al., 2015) confirms that the model reproduces realistic intermediate and deep-water formation patterns (figure 5a), with a thicker MLD in the eastern basin and a shallower MLD in the Gulf of Lions (figure 5a).

We then analyse the simulated Mediterranean overturning circulation (figure 6). The Zonal Overturning stream Function (ZOF[2]) in figure 7a depicts the surface and intermediate circulation and the intermediate/deep circulation. The surface current from the Strait of Gibraltar flows up to 30°E and back to the Atlantic Ocean in the intermediate layers, through the Levantine Intermediate Water (LIW)

[1] $IS(x,y,h) = \int_0^h N^2(x,y)zdz$. N^2 is the Brunt-Väisälä frequency. IS is calculated at each model grid (x,y) for a given depth h (set as the bottom of the sea, or as 1000 m when the depth is greater than 1000 m).

[2] $ZOF(x,z) = \int_h^z \int_{ys}^{yn} u(x,y,z)dydz$. u is the zonal currents, h is the depth of the bottom, yn and ys are the north and south coordinates respectively.

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outflow. Figure 6 c e and g represents the Meridional Overturning stream Function (MOF[3]) in the Gulf of Lions, the Adriatic Sea and the Aegean Sea, respectively. The surface cell in the longitude-depth plan is comparable to previous studies done with the same regional oceanic model, but with different forcings (Adloff et al., 2015; Somot et al., 2006): the mean strength of the surface cell ranges from 0.8 to 1.0 Sv, and the longitudinal extension is from 5°W to 30°E. The simulated intermediate and deep cells are recognized in existing studies as having different characteristics. Our simulated pattern is very close to a similar historical run in Adloff et al., (2015), but is weaker than a historical run in Somot et al., (2006) and a second historical configuration (with refined air-sea flux) in Adloff et al., (2015). A large spread between the models for this pattern indicates that there is still a lack of modelling capacity to simulate the deep circulation of the Mediterranean Sea.

[3] $MOF(y,z) = \int_h^z \int_{xe}^{xw} v(x,y,z)dxdz$. v is the meridional currents, h is the depth of the bottom, xw and xe are the west and east coordinates respectively.

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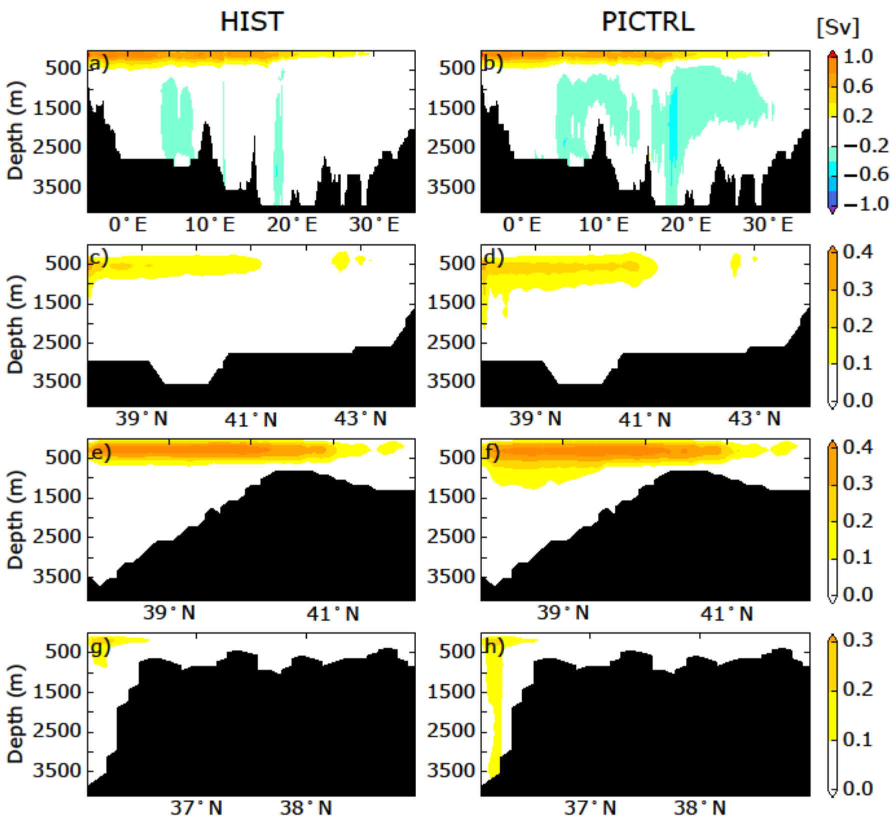

Figure 6: Zonal Overturning stream-Function (ZOF, first column from left, panels a, and b) integrated from north to south and shown as a longitude-depth section for the whole Mediterranean Sea, for HIST, and PICTRL simulations (from top to bottom), respectively. Other panels show Meridional Overturning stream-Function (MOF) shown as a latitude-depth section, integrated west/east for the Gulf of Lion (second column from left), the Adriatic/Ionian Sea (third column from left), and the Aegean Sea (averaged over the entire simulation for HIST and over the last 30 years of simulation for PICTRL).

3.5 Summary of Validation

Validation of our platform was based on the historical period, 1970 to 1999. The atmospheric simulation is consistent with observations for the air temperature at 2m at both global and regional scales. There is significant overestimation of precipitation over the land surrounding the Mediterranean Sea. However, the freshwater budget over the sea is close to observations for both evaporation and precipitation. When

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freshwater river discharges into the Mediterranean Sea are bias-corrected against the observed climatology, the areas of intermediate and deep convection produced by the model are realistic. The thermohaline circulation is well captured by the oceanic model (compared to the simulations of Adloff et al., 2015 and Somot et al., 2006 for instance), which inspires confidence in our modelling platform for the investigations of past climate.

4 Application of the modelling chain to the Early Holocene

In this section, we present results obtained when our sequential modelling chain is applied in a paleoclimate context, which was our initial motivation for developing this modelling tool. We chose to test the performance of our tool on the Early Holocene, a period marked by significant changes in climate and ocean dynamics over the Mediterranean basin, when the last sapropel event, S1, occurred in the Mediterranean Sea. Our experimental design relies on the comparison of two simulations: the Early Holocene (EHOL) with PICTRL based on pre-industrial conditions, the latter acting as a reference.

4.1 Experimental design

As indicated in the general flowchart of our modelling platform, global SST and SIC are required to initiate our sequential modelling. The basic assumption is that the climate change signal can be reconstructed from global SST and SIC, an accepted practice within the climate modelling community. In this study, we use two existing long-term coupled simulations from IPSL-CM5A, one covering the pre-industrial period and the other covering the Early Holocene (around 9.5 ka) . Taking the last 100 years of each simulation, we construct a climatological SST and SIC. After conducting bias-correction, these outputs are then used to drive LMDZ-global and LMDZ-regional in a further step. The duration of the PICTRL and EHOL atmospheric simulations is 30 years (both global and regional models).

Oceanic temperature and salinity in the Atlantic buffer-zone, as well as freshwater discharges from Mediterranean rivers, are all bias-corrected for NEMOMED8, as described in the general methodology. However, it needs to be pointed out that the reference point for the Nile river discharge is not modern observations but is set at pre-industrial values (2930 m3/s for annual mean, Vorosmarty, et al., 1998) corresponding to a period before construction of the Aswan dam. The oceanic simulation is 90 years for EHOL and 30 years for PICTRL, performed after a 200-year spin-up of PICTRL.

4.2 Climate features depicted in LMDZ-global

Because Early Holocene simulations are mainly driven by insolation forcing, an important feature is the model response to seasonal temperatures. Figure 7 shows the difference between EHOL and PICTRL, as reproduced in LMDZ-global, for the summer/winter temperature, JJAS precipitation and JAS surface runoff. The atmospheric model imprints a stronger seasonality due to the increased Early Holocene insolation. Warmer summer temperatures over Europe and North Africa (+ 6 °C) and lower winter temperatures over Africa (-2 °C) reflect this feature. Variations of the precession also trigger an enhancement of the African Monsoon (+ 10 mm/day over the Ethiopian region). The main consequence of this increase in precipitation is an enhanced surface runoff over the Ethiopian region. This hydrological state is similar to the African Humid Period caused by the enhanced African Monsoon and the resultant increase in surface runoff, as shown in Rossignol-Strick et al. (1982).

Our results are similar to those of previous modelling exercises for the Early- and Mid-Holocene (e.g. Adloff et al., 2011; Bosmans et al., 2012; Braconnot et al., 2007; Marzin & Braconnot, 2009). They are also consistent with various reconstructions of Mid-Holocene precipitation (Harrison et al., 2014). A detailed comparison can be made with the Early Holocene simulation reported in Marzin and Braconnot (2009) which used the same orbital parameters and the same atmospheric model as we did. However, their model was coupled to an oceanic model, while we used an atmospheric model and prescribed SST and SIC as boundary conditions. Generally speaking, our results for both surface air temperature and precipitation are very similar to those of Marzin and Braconnot (2009), attesting to the validity of our approach using a simple atmospheric model constrained by boundary conditions. In the ensemble of PMIP simulations, available for the Early Holocene and mid-Holocene, there are some robust outputs for the climate response to orbital forcing but there are also some weaknesses common to most of the models (Braconnot et al., 2007; Kageyama et al., 2013). One of these weaknesses is the underestimation of the spread of the African monsoon towards North Africa. However, the increased discharge from the Nile river, induced by the enhanced monsoon is well supported by data (Adamson et al., 1980; Revel et al., 2014; Williams et al., 2000).

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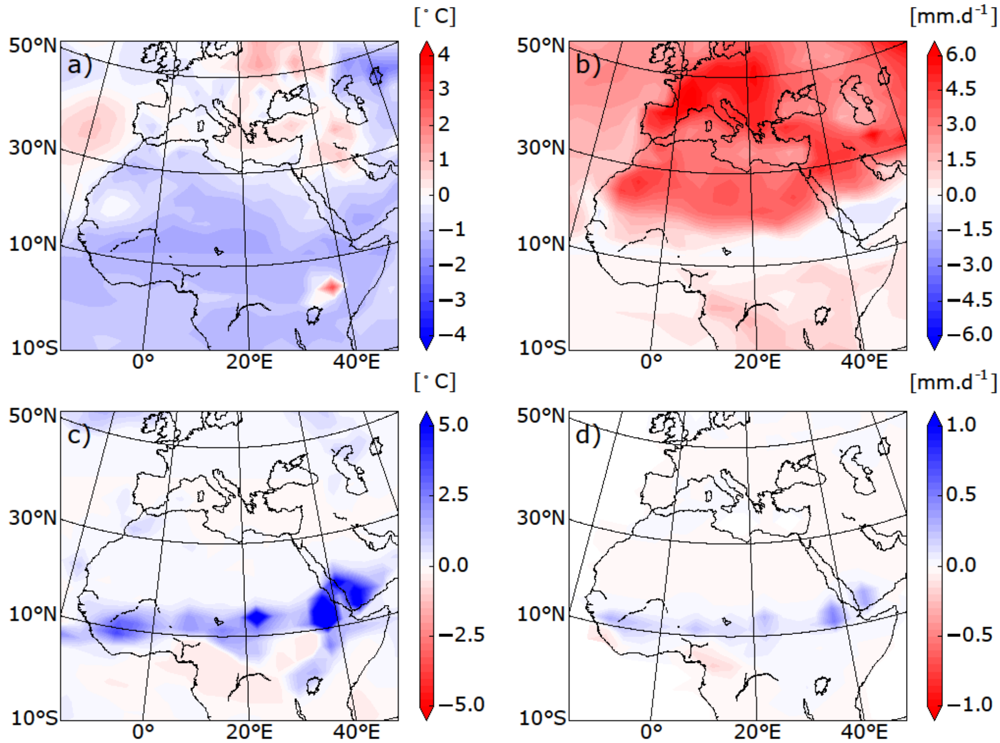

Figure 7: Deviations between EHOL and PICTRL in LMDZ-GLOBAL for a) winter temperatures at 2m, b) summer temperatures a, c) June to September precipitation, and d) July to September surface runoff (averaged over the entire simulation).

4.3 Mediterranean climate features with dynamical downscaling refinement

Figures 8, 9 and 10 show the results from the regional atmospheric model (LMDZ-regional, compared to those from LMDZ-global) for PICTRL and EHOL over the Mediterranean region. In both the global and regional simulations, an increased seasonality with warmer summers (+2 to +6 °C) and colder winters, especially over land (-3 to -1 °C, Figure 8), is depicted. Downscaling with LMDZ-regional slightly reduces the amplitude of the summer warming and shows a more homogenous signal in winter over land. The general circulation of the surface wind in PICTRL is west to east (Figure 9b), in line with the dominant winter regime of westerlies in the region. This important feature is almost missed in the global model (Figure 9a) which reproduces a lower intensity than the ARCM. In the regional model, the EHOL-PICTRL difference (figure 9d) shows a northward shift in position, with maximum changes occurring in the Levantine basin. The global model depicts a different response, with a dipole of change in wind intensity (figure 9c). The winter precipitation in EHOL, for ARCM (LMDZ-regional), increases over land in the Balkans and Italy and over the Adriatic, Ionian and Aegean Seas (figure 10b). These

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changes are also present in the AGCM (LMDZ-global) that, furthermore, shows an increase in Spain and Portugal (figure 10a). It is in summer that the two models show the largest differences. In ARCM (LMDZ-regional), the Mediterranean basin experiences drier conditions, except in Italy and the North of the Balkans. Over the sea, precipitations slightly increase in EHOL (figure 10). However, the AGCM (LMDZ-global) shows drier conditions in the northern two thirds of the Mediterranean domain, with more humid conditions in the southern third (figure 10c). Changes in precipitation lead to unavoidable modifications in the runoff and river discharge into the Mediterranean Sea.

Although it is not straightforward to compare our "snapshot" simulations against environmental records (often used to reconstruct a timeline), our results compare well with the available data for this area (see supplementary online material, "Text S3: Comparison of model simulation outputs and reconstructed data for the Mediterranean basin"). Numerous proxies provide information on lake levels, paleo fires, pollen, isotopic signals recovered from speleothems which together describe the Mediterranean climate in the past. All of these proxies need to be brought together to provide a clear impression of the Mediterranean climate for this period (Magny et al., 2013; Peyron et al., 2011). Magny et al., (2007), based on records from Lake Acessa (Italy), suggested that aridification took place around 9200–7700 cal BP. Zanchetta et al., (2007), based on data recovered from speleothems in Italy, conclude that the Western Mediterranean basin experienced enhanced rainfall during the S1 (10000-7000 cal BP). Jalut et al., (2009), using pollen data, suggest that the summers were short and dry and that there was abundant rainfall in winter (autumn and spring as well) and remarked that these wetter conditions favoured broad-leaf tree vegetation. Different proxies seem to provide contradictory information and therefore, seasonality must be introduced to reconcile them. Peyron et al., (2011) mentioned wet winters and dry summers during the 'Holocene optimum'. Magny et al., (2013) support the hypothesis of seasonal contrast based on the analysis of multi-proxies.

Our EHOL simulation successfully depicts this temperature contrast between winter and summer. Precipitation is enhanced in winter. In summer, the Mediterranean region is globally drier, except over Northern Italy and the northern Balkans. As explained above, there is no precipitation signal over Northern Africa, although evidence of paleo-lakes has been found in Algeria (Callot & Fontugne, 1992; Petit-Maire et al., 1991), Tunisia (Fontes & Gasse, 1991) and Libya (Gaven et al., 1981; Lezine & Casanova, 1991) during the early Holocene indicating increased rainfall in this area. In the supplementary material, we provide a comparison between simulated continental precipitation outputs and pollen reconstruction data. This comparison shows that the winter precipitation anomalies are consistent in both cases but that there is a distinct difference in summer values due to the more contrasted summer in the EHOL simulation (supplementary material 1).

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Peyron et al., (2017) simulated precipitation changes over the Mediterranean region for Mid and Late Holocene using an atmospheric regional model. Their simulations and those presented in this study are quite difficult to compare because of the period simulated (mid and late Holocene/ Early Holocene) and the reference period used to compare them (Present-day/Pre-industrial).

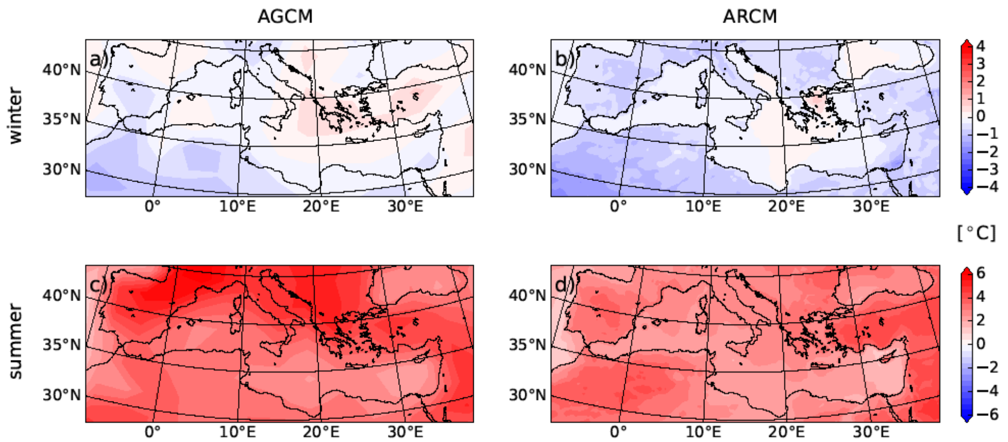

Figure 8: Deviations between EHOL and PICTRL for winter temperatures at 2m (first row) and in summer temperature at 2m (second row), for the AGCM (first column) and the ARCM (second column), averaged over the entire simulation.

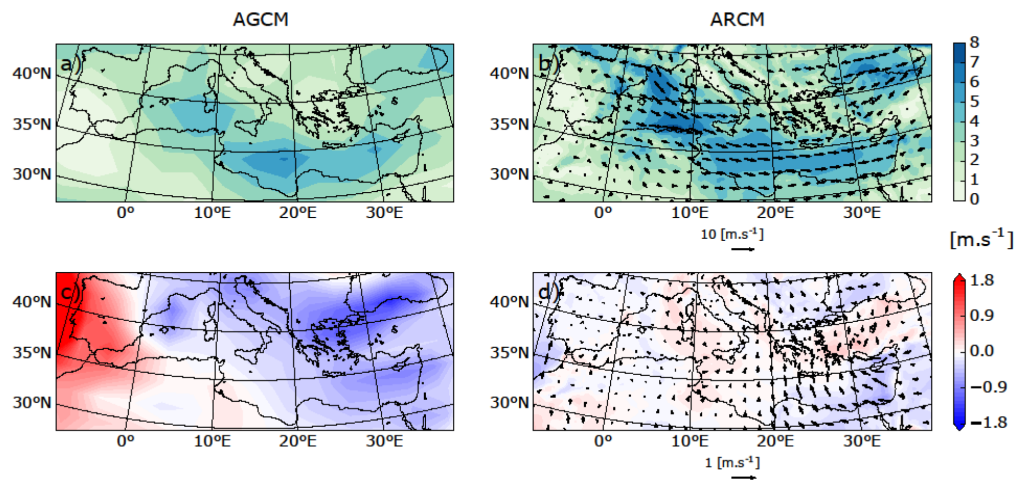

Figure 9: Winter wind-speed in PICTRL (first row) for a) the AGCM and b) the ARCM. Deviations (EHOL-PICTRL, second row) for c) the AGCM and d) the ARCM, averaged over the entire simulation.

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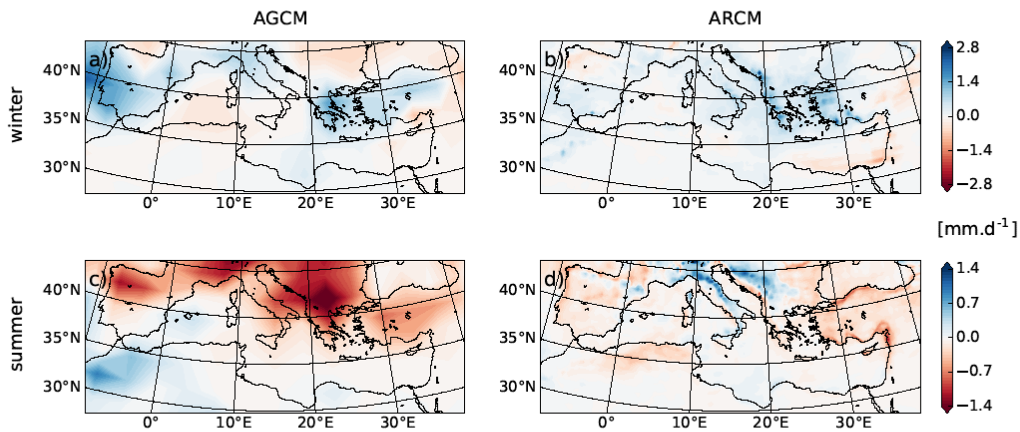

Figure 10: Deviations between EHOL and PICTRL for winter precipitation (first row) and in summer precipitation (second row), for AGCM (first column) and ARCM (second column), averaged over the entire simulation.

4.4 Hydrological changes

Figure 11 shows the runoff simulated by the atmospheric model. The Nile River is shown in Figure 11a. Figures 11b and 11c plot the anomalies in river discharge between EHOL and PICTRL. The signal for the simulated Nile runoff in PICTRL shows an increase due to an overestimation of precipitation compared to pre-damming values. Both observations and simulations reach their maxima in summer.

Figure 11 b and c show that the anomaly in freshwater supply into the Eastern Mediterranean basin in summer and autumn is mainly due to the Nile River. However, in winter, the Albanian rivers (Drini, Mat, Dures, Shkumbin and Vjosa) as well as the Vardar and the Buyukmenderes, produce positive anomalies in EHOL, due to enhanced winter continental precipitation in this simulation (figure 10 b and e). In EHOL, the supplementary winter freshwater input is less pronounced for the western basin than for the eastern basin. However, the North African rivers have not been represented because precipitation has not changed much in their catchment area (figure 10 b and e).

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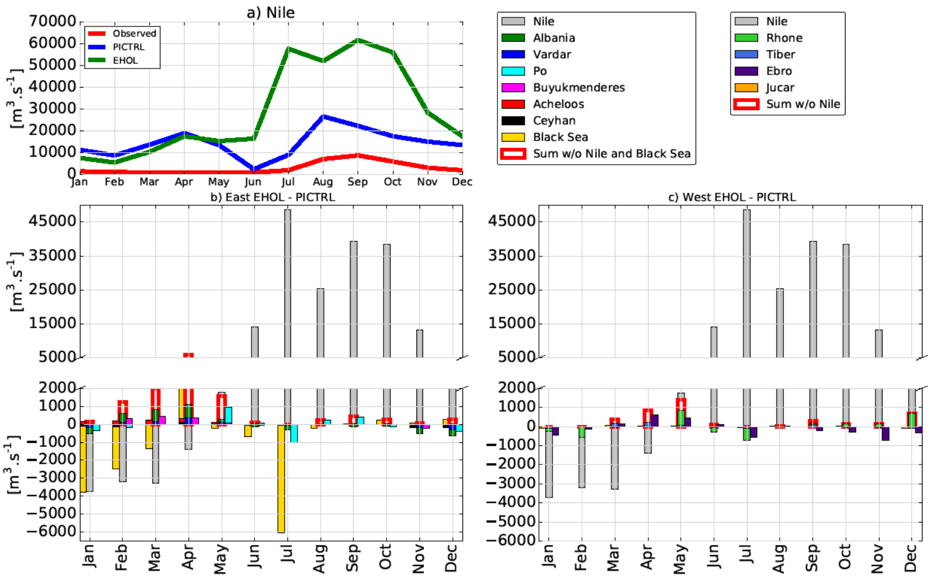

Figure 11: a) climatological runoff of the Nile River: observed pre-damming values (red), PICTRL (blue), EHOL (green), EHOL – PICTRL anomalies applied to observations. Absolute monthly anomalies between EHOL and PICTRL in the simulated river runoff for b) rivers flowing into the eastern basin, c) rivers flowing into the western basin including the Nile River (the scale is different between the upper and lower b) and c) sub figures).

Experiments/variables (mm/yr)	Evaporation	Precipitation	River runoff
OBS	1129	426	102-142
HIST	1106	443	74
PICTRL	1031	451	98
EHOL	1094	460	225

Table 2: The Mediterranean Sea freshwater budget. OBS is a summary of Sanchez-Gomez et al, 2011 (for the period 1958-2008). River discharges in HIST are taken from the climatology of Ludwig et al., 2009. The same applies to PICTRL with the Nile set at its pre-industrial (pre-damming) value, 2930 m3/s, annually (Rivdis). River discharges in EHOL are based on changes in continental runoff between EHOL and PICTRL.

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4.5 Changes in water properties of the Mediterranean Sea

At the end of our modelling chain, we can examine changes in the properties of the Mediterranean seawater produced by NEMOMED8 for PICTRL and EHOL. It is important to mention at this stage, that for the correction of the river runoff the reference is the pre-industrial state, and not the historical simulation (as is the case for SST and SIC). Our aim was to keep river runoff anomalies free of anthropogenic influence. In addition, the fact that the "pre-industrial" Nile river runoff (in other words before damming) is well known influenced this choice. Figure 12 shows changes (EHOL minus PICTR) for sea surface salinities, stratification index and MLD. The freshwater inputs from the Nile and the north-eastern margin imply a lower salinity in the eastern basin. This decrease in salinity enhances stratification throughout the Mediterranean Sea (with the exception of the Sicily Sea) and affects the convection areas by decreasing the MLD. This global stratification in EHOL is followed by a general reduction in the thermohaline circulation compared to PICTRL (ZOF and MOF, figure 13 a, b, c, d).

Numerous studies have documented the sapropel event, S1 and the state of the Mediterranean Sea that caused it. Emeis et al., (2000), mentioned a decreased SSS during this period in both the eastern and western basins (As did Kallel et al., (1997) in the Tyrrhenian basin). In the subsection "*Sea Surface Temperatures*" and "*Sea Surface Salinity*" of the section "Text S3"in the supplementary online material, we compared the simulated SST and SSS to reconstructions. Although simulated SST is in good agreement with the reconstructed data, there is a gap between the simulated SSS and reconstructions. This discrepancy is not surprising. Indeed, there are many explanations for the underestimation in our model of the salinity. One of them is a common weakness in Early to Mid-Holocene simulations, namely, the underestimation of the northward spread of the African monsoon and therefore, the underestimation of the freshwater flow from North Africa. Adloff (2011), already pointed to a shortfall in freshwater input to reconcile the simulated and observed SSS during the Early Holocene. Our oceanic simulation depicts these behaviours well and is similar to previous modelling studies with lower resolution (Adloff et al., 2011; Bosmans et al., 2015; Myers et al., 1998).

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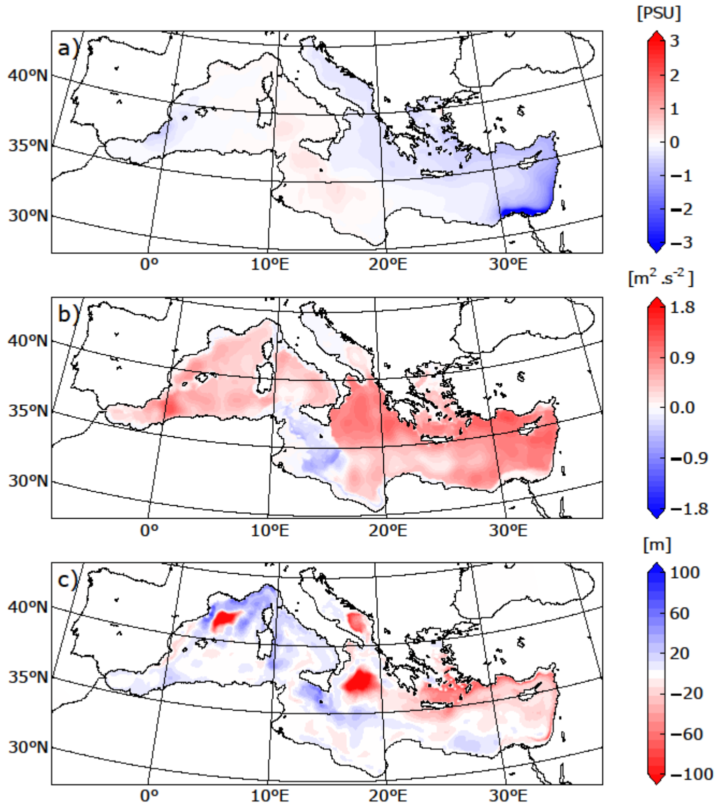

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549 **Figure 12: Deviations between EHOL and PICTRL in a) sea surface salinity, b) stratification**
550 **index, c) mixed-layer depth, averaged over the last 30 years of simulation**

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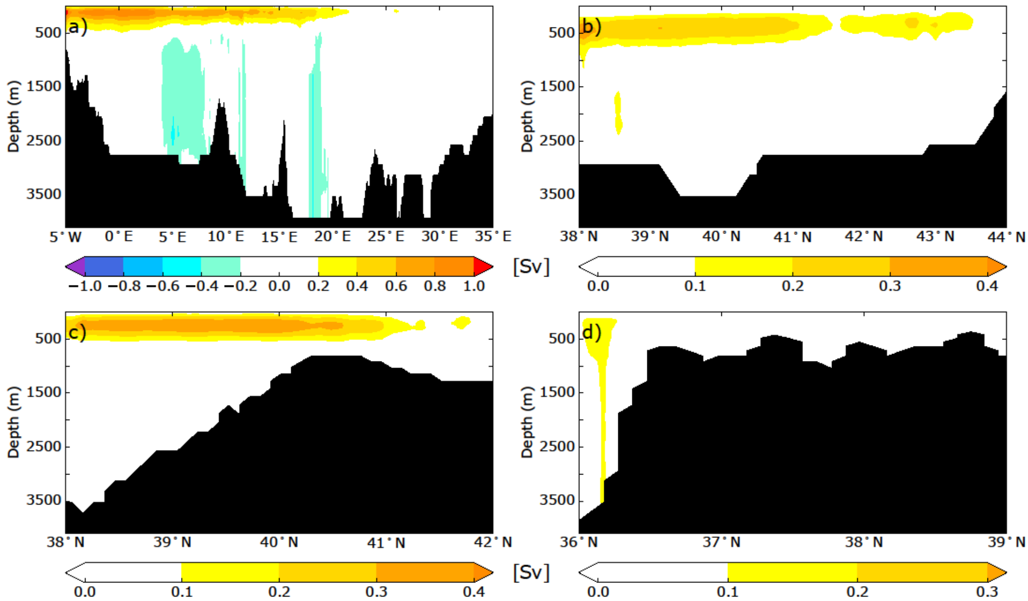

Figure 13: ZOF (a) and MOF (b, Gulf of Lion, c, Adriatic/Ionian Sea, d, Ionian Sea) for EHOL experiment, averaged over the last 30 years of simulation.

5 Conclusion and perspectives for the modelling platform

This study aimed to develop a modelling platform to simulate different climatic conditions of the Mediterranean basin. We developed a useful regional climate investigation platform with high spatial resolution over the Mediterranean region. This is particularly relevant for the study of impacts on the circulation of the Mediterranean Sea. The model chain has been evaluated for the historical period. We have presented Early Holocene simulations as an example of the potential of this platform to simulate past climate. For the Early Holocene, our model reproduced satisfactorily the global and regional climate features, compared to the observed data. Our platform allowed, for the first time, the generation of a high-resolution freshwater budget for this period, with a particular focus on continental precipitation, a key factor for the Mediterranean Sea in the assessment of its impact on circulation during the onset of the sapropel event, S1. An important limitation of our sequential approach is the fact that it does not take account of feedback of ocean changes on atmospheric circulation. However, this architecture allows bias correction, conducted at different levels of the platform. One way to overcome this problem would be to consider an “asynchronous mode”, namely, to take account of feedback from the ocean component to the atmosphere at a yearly or decadal frequency.

Two other issues need to be discussed for the Early Holocene. The first one is sea level, which was 20 metres lower than the present day (Peltier et al., 2015). For the sake of simplicity, we did not take into account this difference of sea level in the EHOL simulation. The second issue is the timing of the (re)connection between the Black Sea and the Aegean Sea. This topic is still being debated. Sperling et al., (2003) suggested this reconnection occurred around 8.4 ka BP, while by the calculations of Soulet et al., (2011) it happened around 9 ka BP. Other studies found that an overflow from the Black Sea likely occurred before this reconnection due to Fennoscandian ice-sheet melting during the deglaciation (Chepalyga, 2007; Majoret al., 2002; Soulet et al., 2011). For the purposes of this work, we decided to maintain the Bosphorus open in our simulation, with the water exchange set at its modern value.

The modelling sequence, moving from global simulation at low resolution to high-resolution regional ocean modelling, avoids the problem of boundary conditions, and provides a fully consistent platform that may be used for many paleoclimate studies. We focused here on the Early Holocene period but this architecture could be used to study other periods investigated in MIPs, such as the Last Glacial Maximum or the deposition of older sapropels, from the Pliocene to the Quaternary, as long as the tectonics remain mainly unchanged (PMIP, PlioMIP).

Code and data availability. The current version of LMDZ and NEMO are available from the project website: https://forge.ipsl.jussieu.fr/igcmg_doc/wiki/DocImodelBlmdz and http://forge.ipsl.jussieu.fr/nemo/wiki/Users under the terms of the CeCill license for LMDZ and NEMO both. The exact version of the model used to produce the results used in this paper is archived on Zenodo (Vadsaria et al., 2019), as are input data and scripts to run the model and produce the plots for all the simulations presented in this paper.

Author's contribution. This study was co-designed and approved by all co-authors. The simulation protocol was constructed by TV and LL from a modelling architecture provided by LL. TV conducted the numerical simulations and drafted the first version of the manuscript. All co-authors are largely involved in the writing and revision of the manuscript.

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