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Abstract For now, the question about future sea level change in the Mediterranean remains a challenge. Previous climate modelling attempts to estimate future sea level change in the Mediterranean did not meet a consensus. The low resolution of CMIP-type models prevents an accurate representation of important small scales processes acting over the Mediterranean region. For this reason among others, the use of high resolution regional ocean modelling has been recommended in literature to address the question of ongoing and future Mediterranean sea level change in response to climate change or greenhouse gases emissions. Also, it has been shown that east Atlantic sea level variability is the dominant driver of the Mediterranean variability at interannual and interdecadal scales. However, up to now, long-term regional simulations of the Mediterranean Sea do not integrate the full sea level information from the Atlantic, which is a substantial shortcoming when analysing Mediterranean sea level response. In the present study we analyse different approaches followed by state-of-the-art regional climate models to simulate Mediterranean sea level variability. Additionally we present a new simulation which incorporates improved information of Atlantic sea level forcing at the lateral boundary. We evaluate the skills of the different simulations in the frame of long-term hindcast simulations spanning from 1980 to 2012 analysing sea level variability from seasonal to multidecadal scales. Results from the new simulation show a substantial improvement in the modelled Mediterranean sea level signal. This confirms that Mediterranean mean sea level is strongly influenced by the Atlantic conditions, and thus suggests that the quality of the information in the lateral boundary conditions (LBCs) is crucial for the good modelling of Mediterranean sea level. We also found that the regional differences inside the basin, that are induced by circulation changes, are model-dependent and thus not affected by the LBCs. Finally, we argue that a correct configuration of LBCs in the Atlantic should be used for future Mediterranean simulations, which cover hindcast period, but also for scenarios.

Keywords Mediterranean · Sea level · Regional climate model · Lateral boundary conditions · Atlantic forcing

This paper is a contribution to the special issue on Med-CORDEX, an international coordinated initiative dedicated to the multi-component regional climate modelling (atmosphere, ocean, land surface, river) of the Mediterranean under the umbrella of HyMeX, CORDEX, and Med-CLIVAR and coordinated by Samuel Somot, Paolo Ruti, Erika Coppola, Gianmaria Sannino, Bodo Ahrens, and Gabriel Jordà.

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1 Introduction

According to the last IPCC Assessment Report [AR5, IPCC 2013], the expected change in the global temperature during the next decades will lead to sea level rise through thermal expansion of the ocean and melting of ice sheets and

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glaciers. Atmosphere-Ocean General Circulation Models (AOGCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) project a global sea level rise between 26 and 97 cm by the end of this century, depending on the socio-economic scenario. Nevertheless, the spread in the sea level projections is large at both regional and global scales. In the frame of the AR5, future Mediterranean sea level change has not been clearly addressed. However, the basin is particularly exposed to risks inherent to rising sea level (e.g. coastal erosion, flooding). It is thus crucial to characterize how regional sea level mean and extremes will respond to climate change, in order to make decision on development of adaptation strategies to face risks related to the changing climate.

Variations of Mediterranean sea level are driven by (a) mass redistribution inside the basin due to changes in the circulation and/or the atmospheric mechanical forcing, (b) thermal expansion, which can induce local and/or basin average changes, and (c) changes in the nearby Atlantic sea level , which propagate as a barotropic signal into the Mediterranean as a basin-wide signal. Changes in the freshwater flux inside the Mediterranean (evaporation, precipitation or rivers runoff) do not modify the sea level as far as they are quickly compensated by changes in the transports at the Strait of Gibraltar. In other words, when the sea level gradient along the strait is modified, the net transport through the Strait is also modified in such a way that the gradient is kept constant. Additionally, it has to be noted that the hydraulically controled dynamics of the water exchange at the Strait of Gibraltar is what defines the along strait sea level gradient. However, the variations in time of that gradient are relatively small when compared to the other mechanisms.

AOGCMs are the natural choice to simulate the influence of Atlantic sea level variations in the Mediterranean, but their coarse resolution prevents from a reasonable simulation of thermal expansion and mass redistribution (Calafat et al. 2010). Conversely ocean regional climate models (ORCMs) are much better suited to model the local processes but the lack of Atlantic infomation in RCMs can hamper their ability to model interannual to multidecadal variations (Calafat et al. 2010, 2012).

The goal of this paper is to compare different approaches adopted by ORCMs to model Mediterranean sea level variability and to recommend the most suitable approach for an adequate representation of sea level in regional ocean model set up for the Mediterranean Sea. To do so we compare the sea level variability reproduced by an ensemble of ORCMs, most of them available from the Med-CORDEX database (Ruti et al. 2015, http://www.medcordex.eu), with several observational products in order to elucidate the best approach to configure Mediterranean ORCMs. We focus on the treatment of the Atlantic boundary conditions which has been suggested to be of paramount importance for Mediterranean sea level modelling (Calafat et al. 2012). We analyse the seasonal and interannual variability of mean sea level as well as the regional differences.

The paper is organized as follows: a review of the approaches followed to model Mediterranean sea level variability in ORCMs is presented in Sect. 2. The datasets and the models used in the comparison are described in Sect. 3. Sect. 4 discusses the results from the multi-ORCMs intercomparison and the adequacy of the different methods. We conclude with Sect. 5.

2 Approaches to estimate Mediterranean sea level from ORCMs

Almost all ORCMs use the Boussinesq approximation and preserve volume, rather than mass. Thus they are not able to produce global thermal expansion and only the spatial gradients of sea level are correctly reproduced (Greatbatch 1994; Griffies and Greatbatch 2012). To overcome this limitation, Greatbatch (1994) proposed to add a spatially constant but time variable correction $\Delta\eta_B$ that accounts for the expansion/contraction integrated over the whole model domain A, and which is to be added to the outputs of global ocean models. This correction $\Delta\eta_B$ is computed as follows:

$$\Delta\eta_B = -\frac{1}{\rho_s A}\int_A \int_{z=-H}^{z=0} \Delta\rho \, \mathrm{d}z \, \mathrm{d}A \tag{1}$$

where η is the surface elevation, ρ_s the surface density, A the model domain, ρ the density and H the depth. Note that this is equivalent to the steric height.

This constant is computed for each time step and added a posteriori to the sea surface height maps provided by the model. This approach has also been often applied to Mediterranean ORCMs. However, the problem is that Eq. (1) assumes that the mass in the domain remains constant, which is not necessarily the case in regional domains. In particular, for the Mediterranean, salt changes are non-negligible and the application of Eq. (1) can lead to wrong conclusions, specially for the representation of multidecadal variations (see Jordà and Gomis (2013) for an in-depth discussion on this issue). Therefore, Jordà and Gomis (2013) proposed that a more suitable choice for the Mediterranean would be to use a modified version of Eq. (1), adding the mass component related to the addition of salt in the basin:

$$\Delta\eta_B = \underbrace{-\frac{1}{\rho_s A}\int_A \int_{z=-H}^{z=0} \Delta\rho \, \mathrm{d}z \, \mathrm{d}A}_{\text{STERIC COMPONENT}} + \underbrace{\frac{1}{\rho_s A}\int_A \int_{z=-H}^{z=0} \Delta S \, \mathrm{d}z \, \mathrm{d}A}_{\text{SALT MASS COMPONENT}} \tag{2}$$

where S is the salinity.

This approach is useful to estimate the effects of thermal expansion while considering that the mass can change in the basin due to variations in the salt content. However, it does not take into account the relation with sea level variations in the Atlantic. Changes in the nearby Atlantic are propagated into the basin as a basin-wide barotropic signal, so the Mediterranean follows the Atlantic changes. Conversely, changes in the Mediterranean sea level (e.g. a decrease due to increased evaporation) are propagated towards the Atlantic but do not modify significantly the Atlantic sea level due to its much larger surface. The implications of this are diverse and the clearest example is the sea level response to freshwater fluxes inside the basin. The water deficit in the Mediterranean would imply a sea level drop of 0.7 m year^{-1}. However this is quickly compensated by an increase in the water transport at the Strait of Gibraltar, so the basin average level is kept equal to the nearby Atlantic level.

From a modelling point of view, some ORCMs simulate the Atlantic reservoir by imposing an extra surface water flux in the nearby Atlantic of the same magnitude of the freshwater flux integrated over the Mediterranean (e.g Beuvier et al. 2010). The drawback of this approach is that it does not consider the effects of Atlantic variations. A more suitable approach is then to impose variable lateral boundary conditions (LBCs) in the Atlantic side of Mediterranean ORCMs. Then, the model dynamics in the external mode (the 2D mode) will propagate that information into the Mediterranean. Note that most models use a mode splitting approximation with a 2D and a 3D modes. The limitations of the Boussinesq approximation act on the 3D mode, while nothing prevents the 2D mode to reproduce non-zero mean sea level variations. The information required at the LBCs could be provided by AOGCMs, global reanalyses or observational datasets (e.g. altimetry or sea level reconstructions). It has to be noted that if the Atlantic information is imposed, then no further correction for the Mediterranean thermal expansion is required. The ORCMs naturally simulate the differences in the thermal expansion between the Atlantic and the Mediterranean. Thus, if the Atlantic signal is realistic enough, the model will be able to simulate the effects of thermal expansion inside the basin.

3 Data sets

3.1 Altimetry data

We use the dataset from the climate change initiative (CCI) which aims to improve satellite-derived dataset on climatic time scales, for some variables considered as essential in the context of changing climate (essential climate variable, ECV). An exhaustive evaluation of the sea level product is presented in Ablain et al. (2015). This dataset is a multi-satellite merged product that consists of time series of gridded Sea Level Anomalies (SLA, doi:10.5270/esa-sea_level_cci-MSLA-1993_2013-v_1.1-201412): the SLA data are calculated after merging all the altimetry mission measurements together into monthly grids with a spatial resolution of 1/4 of degree. The data include a dynamical atmospheric correction. We call this dataset CCI-ECV.

3.2 Sea level reconstructions

Two regional sea level reconstructions for the Mediterranean region are used for comparison before the altimetric period, Calafat and Jordà (2011) and Meyssignac et al. (2011). Both reconstructions base on the same technique (reduced order optimal interpolation) where data from coastal tide gauges are combined to obtain sea level fields in the whole basin. This method requires the definition of spatial covariances that link the coastal ocean with the open sea. The main difference between both reconstructions is that Calafat and Jordà (2011) define the spatial covariances from satellite altimetry and Meyssignac et al. (2011) use the outputs of a numerical model. Also they use a slightly different set of tide gauges to perform the reconstruction. Meyssignac et al. (2011) cover the 1970–2005 period while Calafat and Jordà (2011) span from 1950 to 2008. The latter also provides an estimate of the uncertainty associated to the reconstruction.

3.3 Regional model data

An ensemble of four ORCMs is compared. All are hindcast simulations, coupled or forced with a regional atmosphere model driven by the ERA-Interim reanalysis (Dee et al. 2011), thus following the observed interannual variability. All models are state-of-the-art models and provide the same information (temperature, salinity, circulation and, in particular, sea level). They differ in the atmospheric forcing or coupling, and in resolution but especially in the treatment of the lateral boundary conditions in the Atlantic buffer zone. They are listed hereafter in order of increasing complexity of their treatment of the Atlantic sea level signal.

3.3.1 LMDZ-MED—fixed Atlantic

This fully coupled regional climate model is detailed in an exhaustive way in L'Hévéder et al. (2013). It is composed of LMDz4-regional as atmospheric component (Li et al. 2012) and of NEMOMED8 (Beuvier et al. 2010; Adloff et al. 2015) as oceanic component. NEMOMED8 is a regional configuration of the NEMO ocean model (Madec 2008), setup for the Mediterranean Sea. It has an horizontal resolution ranging from 9 to 12 km and 43 vertical levels. In this simulation, the net "evaporation–precipitation–river" (E–P–R) flux computed over the basin is added in the Atlantic buffer zone, in a way that the volume of the basin is kept constant to a fixed prescribed Atlantic level (Beuvier et al. 2010). This model configuration implicitly imposes that basin averaged sea level variations will be very small. In order to overcome this limitation and to consider the thermal expansion effects, the steric constant (in space, not in time) proposed by Jordà and Gomis (2013) (Eq. (2) in this paper) will be added off-line to the Mediterranean output. Concerning the water exchange through the Bosphorus, as Black Sea is not interactive in the NEMOMED8 model, it is treated as an additional river runoff in the Aegean. This simulation covers the 19802008 period.

3.3.2 CNRM-RCSM4—variable Atlantic from reanalysis not assimilating altimetry

CNRM-RCSM4 is a regional climate system model (RCSM) built from to the ocean model NEMOMED8, regional version of NEMO v2.3, 9–12 km resolution, 43 levels; coupled to the regional atmosphere model ALADIN-Climate (Colin et al. 2010; Herrmann et al. 2011) and to the TRIP river routing model. An exhaustive evaluation of the model can be found in Sevault et al. (2014). Compared with LMDZ-MED, a relaxation of the sea surface height (SSH) in the Atlantic buffer zone, has been added to this model. This method was first implemented in NEMOMED12 (Beuvier et al., 2012). It was similarly added to NEMOMED8 (Soto-Navarro et al. 2014), with the following formula:

$$ssh\_new(x,y,t) = ssh(x,y,t) + relax(x,y) \times (ssh\_ref(x,y,t) - ssh(x,y,t), \quad (3)$$

where *ssh_new* is the SSH of the model after relaxation, *ssh* is the SSH of the model prior the relaxation, *ssh_ref* is the monthly value of the reference at the boundary condition, and *relax* is the relaxation term which spatially varies along the longitudes. *relax* is maximum at the western boundary and decreases linearly until 7.5°W, then it is equal to zero for the rest of the domain. In practice this means that *ssh_ref* is imposed at the Atlantic boundary and *ssh_new* from the model is relaxed to the boundary values in a 3.5° band.

The NEMOVAR–COMBINE ocean reanalysis (Balmaseda et al. 2010) is used at the Atlantic western boundary of the domain in the CNRM-RCSM4 simulation. This reanalysis does not include any SSH assimilation. It provides monthly temperature, salinity and dynamic SSH information for the period 1980–2008. Then, from 2009 to 2012, the year 2008 is maintained, as NEMOVAR–COMBINE is not available beyond 2008. This simulation covers the 1980–2012 period.

As the Black Sea is not included in the ocean model component, one ocean grid point receives the freshwater flux corresponding to the water budget of the Black Sea. This simulation covers the 1980–2012 period.

3.3.3 MORCE-MED—variable Atlantic from reanalysis assimilating altimetry

MORCE-MED (Drobinski et al. 2012; Lebeaupin-Brossier et al. 2013) is a regional coupled model composed of the ocean model NEMOMED12 (Beuvier et al. 2012), regional version of NEMO V3.2, coupled to the atmospheric model WRF (Skamarock et al. 2008). NEMOMED12 has an horizontal resolution ranging from 6.5 to 8 km and 50 vertical levels. As for CNRM-RCSM4, the model SSH is relaxed toward a reference dataset in the buffer zone. For the period 2002–2008, the reference is GLORYS-1 (Ferry et al. 2010), a reanalysis of the global ocean circulation at a 1/4° horizontal resolution available for this period, which assimilates SLA from satellite data. For the period 1989–2001, data come from the SSH monthly seasonal cycle of the previous simulation with a time shift of 5 months in the seasonal cycle to follow the cycle of GLORYS-1 in the near Atlantic domain, there is thus no interannual variability before 2002. An exhaustive description of this methodology can be found in Beuvier et al. (2012). GLORYS-1 anomalies in the Atlantic buffer zone (11°W–7.5°W) have an amplitude of about 14 cm, in agreement with AVISO products, which were assimilated in the GLORYS-1 reanalysis. In MORCE-MED, the Black Sea net inflow into the Mediterranean is prescribed as a river, similarly to LMDZ-MED. This simulation covers the 1989–2008 period.

3.3.4 MED12—improved dataset for the Atlantic

Here, the ocean model NEMOMED12, regional version of NEMO V3.2, same as in Sect. 3.3.4 but on 75 levels, is used in a forced mode. As atmospheric conditions, we use ALDERA (Hamon et al. 2016), a new atmospheric forcing resulting from the dynamical downscaling of ERA-Interim with the regional atmospheric model ALADIN. The relaxation method of the SSH in the buffer Atlantic zone is the same as for CNRM-RCSM4 and MORCE-MED. In this simulation, we choose to prescribe a complete signal of Atlantic sea level to consider both local and global changes, at seasonal and interannual time scales. To achieve this, we use data from the ORAS4 global ocean reanalysis (Balmaseda et al. 2013) which includes sea level contributions from ice sheet mass loss, glaciers ice melt, changes in land water storage, as well as global thermal expansion. ORAS4 provides Atlantic boundary conditions for SSH, temperature and salinity to the regional ocean model for the period 1980–2012. Because ORAS4 underestimates the regional seasonal cycle in the near Atlantic region compared to satellite-derived gridded data (Fig. 1), we decided to add a

12-month correction, calculated from the difference between CCI-ECV and ORAS4, in the buffer zone, considering a 12-month climatology for the 1993–2010 period for both datasets. We add this 12-month correction to each year of ORAS4 near-Atlantic sea level data prescribed in the buffer zone of the Mediterranean model. In MED12, the Black Sea net inflow is also treated as a river. This simulation covers the 1980–2012 period.

In summary, the differences between the four ORCMs are in the model resolution and forcing, and in the information imposed in the Atlantic. The first will mainly affect the representation of regional differences inside the Mediterranean while the latter will mainly affect the basin average response of the Mediterranean. In particular LMDZ-MED does not incorporate Atlantic variability and only considers local thermal expansion, CNRM-RCSM4 uses information from a global reanalysis that does not assimilate altimetry, MORCE-MED uses information from a global reanalysis that does assimilate altimetry but only after 2001, and MED12 uses a corrected version of the global ocean reanalysis ORAS4.

4 Multimodel intercomparison results

In this section, the four regional simulations are compared to satellite-derived data covering the period 1993–2010. For the pre-altimetric period, only in the Mediterranean diagnostics (Sect. 4.2), we refer to the two reconstructions of Mediterranean sea level, represented by the grey shaded envelop in figures. The sea level signal prescribed in the Atlantic buffer zone is first analysed in terms of seasonal cycle and interannual variability. Then, we focus on the Mediterranean basin, looking at the seasonal cycle, the interannual

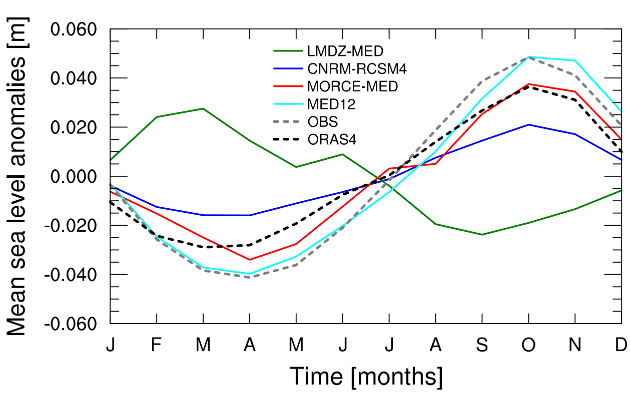

Fig. 1 Mean seasonal cycle of sea level averaged over the Atlantic box of the models for the 1993–2008 period. Values are centered on the mean. Model simulations are compared to observations (CCI-ECV) and to the global ocean reanalysis ORAS4

variability, the spatial patterns and trends. For all the simulations we use monthly fields as done with the altimetry. To analyse the interannual variations yearly values are obtained by simple averaging. Trends are computed through a linear regression.

4.1 Near-Atlantic sea level variability

4.1.1 Seasonal cycle

The seasonal cycle of sea level averaged over the Atlantic buffer zone (from the western limit to Gibraltar) differs a lot in the different simulations, depending on the information prescribed. With the E–P–R water report method, LMDZ-MED shows an inverse seasonal cycle in the buffer zone simply because the net E–P–R water budget is larger in the Mediterranean during the winter season. This method had been designed to prevent the Mediterranean from emptying as there is a net freshwater loss over the basin. However, the downside of this approach is that the seasonal cycle modelled in the Atlantic box is wrong, as shown in Fig. 1. In the case of CNRM-RCSM4, the seasonal cycle is underestimated compared to the altimetry-derived dataset CCI-ECV because the COMBINE global ocean reanalysis does not assimilate altimeter-derived SLA. The MORCE-MED model prescribes, from 2002 on, sea level information from a global ocean reanalysis which assimilates SLA from satellite. MORCE-MED is therefore closer to the seasonal cycle of the reference CCI-ECV than the two previous simulations. However, MED12 is obviously the closest, since the seasonal cycle prescribed at the boundary corresponds to CCI-ECV, due to the correction applied to the data derived from ORAS4 in the MED12 simulation. However one can notice from the differences between the CCI-ECV and MED12 curves that the relaxation only happens on a small band of the Atlantic box of the model domain. After 6°W, the model evolves freely.

4.1.2 Interannual variability

Figure 2 represents interannual sea level variations averaged over the Atlantic zone of the models. The absence of trend is noted for LMDZ-MED, which does not have Atlantic variable sea level conditions, as well as for CNRM-RCSM4 and MORCE-MED (before 2002) whose prescribed Atlantic conditions do not integrate SLA from satellites. Considering CCI-ECV as the reference, MED12 represents best the interannual variations and trend with a correlation of 0.91 with the CCI-ECV dataset (Table 1). Among the other three simulations, CNRM-RCSM4 performs best until 2003, because MORCE-MED uses the relaxation towards GLORYS-1 only from 2002 onward. The interannual variability of MORCE-MED before 2002 is thus very poor due to the

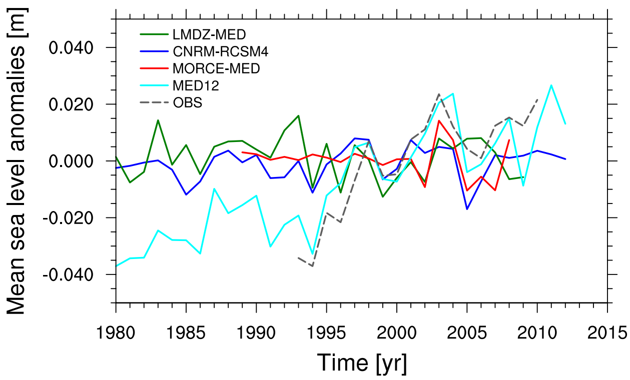

Fig. 2 Interannual time series of sea level averaged over the Atlantic box of the models. Values are centered on the 1993–2008 period. Model simulations are compared to observations (CCI-ECV)

experimental setup which does not take into account the Atlantic interannual variability before that year. By construction, the interannual variability displayed by LMDZ-MED follows the interannual variability of Mediterranean E–P–R, which is not correlated with the actual sea level variations in the North-East Atlantic. Therefore, the LMDZ-MED variations in the Atlantic box do not match CCI-ECV variability. The new simulation MED12, interanually driven by ORAS4 in terms of SSH, follows well the interannual variability of CCI-ECV with a very high correlation, but also performs best for the pre-altimetric period (before 1993), reflecting the quality of the ocean reanalysis used at the Atlantic boundary.

4.2 Mediterranean sea level variability

In order to assess to which extent the sea level signal prescribed west of the Strait of Gibraltar drives the sea level signal in the Mediterranean Sea, we analyse our four simulations over the basin, in terms of spatial average, spatial patterns and trends.

4.2.1 Seasonal cycle

Figure 3 represents the seasonal cycle of the models and the reference. The "EPR water report" method used in LMDZ-MED leads to a flat seasonal cycle. For the three other models, the simulated seasonal cycle is highly dependent on the quality of the Atlantic dataset. The prescription of data from a reanalysis with no assimilation from satellite sea level information, as in CNRM-RCSM4, leads to a Mediterranean sea level which has an underestimated seasonal cycle. MORCE-MED and MED12 both use Atlantic data including satellites information: MED12 has a correction of the seasonal cycle toward CCI-ECV in the prescribed Atlantic dataset, and MORCE-MED prescribes data from the GLORYS-1 reanalysis which assimilates satellite data for the simulated period 2002–2008, and applies a correction to follow the seasonal cycle of GLORYS-1 for the simulated period 1989–2001. For these reasons, MED12 and MORCE-MED both have a Mediterranean seasonal cycle which is consistent with the reference. This is clearly depicted by the root mean squared deviation (RMSD) with the value of 1 cm for both MORCE-MED and MED12, 2.5 cm for CNRM-RCSM4 and 5 cm for LMDZ-MED (Table 2). MED12 presents a 1-month forward lag of the max, whereas MORCE-MED and CNRM-RCSM4 have no lag. Concerning the amplitude of the seasonal cycle, MED12 (13 cm) and MORCE-MED (12.5 cm) are both in good agreement with the

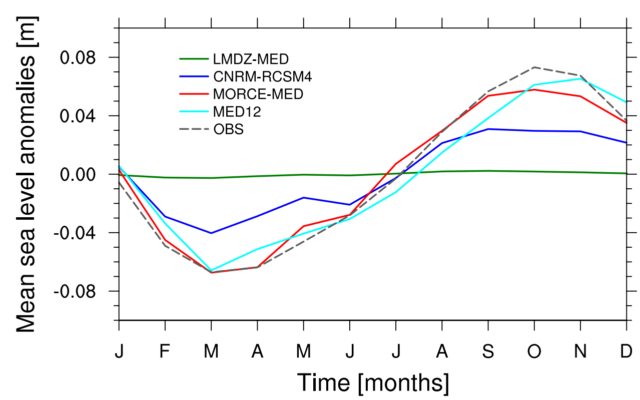

Fig. 3 Mean seasonal cycle of Mediterranean sea level for the 1993–2008 period. Values are centered on the mean. Model simulations are compared to observations (CCI-ECV)

Table 1 Correlation coefficient and root mean square deviation (RMSD) with respect to CCI-ECV for the common period 1993–2008, for the interannual sea level variability in the Atlantic box

Model	Correlation non-detrended	Correlation detrended	RMSD (cm) non-detrended	RMSD (cm) detrended
LMDZ-MED	0.06	0.03	1.6	1.3
CNRM-RCSM4	0.34	0.68	1.2	0.7
MORCE-MED	0.08	0.39	1.4	0.9
MED12	0.91	0.83	0.2	0.6

Calculations are made for both non-detrended and detrended timeseries

Table 2 Amplitude, lag and root mean squared deviation (RMSD) of the Mediterranean cycle of each simulation

Data	RMSD (cm)	Lag (months)	Amplitude (cm)
CCI-ECV	–	–	14
LMDZ-MED	5	−1	0.5
CNRM-RCSM4	2.5	0	7
MORCE-MED	1	0	12.5
MED12	1	+1	13

Lag and RMSD are calculated toward CCI-ECV as reference (1993–2010)

reference (14 cm). CNRM-RCSM4 only simulates half of the amplitude displayed in satellite-derived data (Table 2).

4.2.2 *Interannual variability*

Figure 4a represents the interannual variations of sea level averaged over the Mediterranean basin for the different simulations, for reconstructions before the altimetric period, and for satellite-derived product from 1993 on. Figure 4b displays the impact of the different corrections applied to the LMDZ-MED time series. Table 3 summarizes the correlation of the detrended interannual timeseries of the simulations with CCI-ECV, and Table 4 compares the trends. Both tables refer to the common period 1993–2008. When comparing the SSH provided by the different models (Fig. 4a), it can be seen that LMDZ-MED is not producing any significant variability. Even if the correlation with altimetry is relatively high (Table 3), the range of variations is much smaller. Also the trends are negligible (Table 4). This was expected as by construction LMDZ-MED simulates an almost constant Mediterranean sea level. For CNRM-RCSM4 and MORCE-MED, the interannual variability is provided by the LBCs. Both simulations provide similar results in terms of variability and trends. The interannual variability is correlated to the observed variability (0.5 and 0.56 respectively) but the long-term trends are clearly wrong (Table 4). For MED12, which includes the improved signal from the Atlantic in its LBCs, the results are clearly better. The interannual variability shows the right magnitude and is highly correlated with the observations (0.80). Also, in MED12, the simulated trend for the common period is 1.62 mm year^{-1}, close to the observational estimate (1.78 mm year^{-1}).

As mentioned previously, the SSH in the LMDZ-MED model is almost constant. In order to compensate this limitation of the modelling system, the typical solution is to add the Greatbach constant (Eq. (1)) to the model SSH. For the LMDZ-MED model (see Fig. 4b), the addition of the total steric component provides interannual variablity and a negative trend (−0.89 mm year^{-1}). This variability is

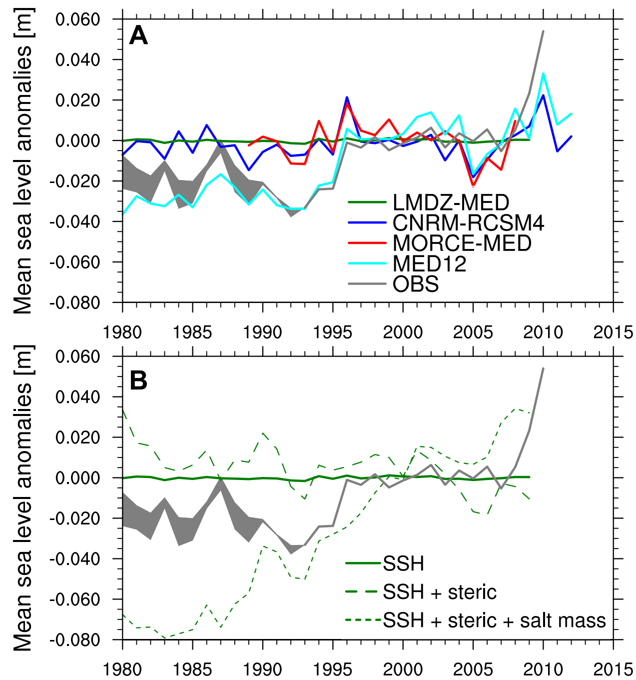

Fig. 4 Interannual time series of sea level averaged over the Mediterranean basin. Model simulations are compared to observations (reconstructions prior 1993, CCI-ECV afterwards). **A** displays the SSH as provided by the different models. **B** displays the LMDZ-MED solution without any correction, applying the steric correction (Eq. 1) and applying the steric + salt mass corrections (Eq. 2)

induced by changes in the basin averaged temperature and salinity. When the mass changes due to salinity changes are included (Eq. (2)), and thus only the actual expansion is represented, the interannual variability is similar but a stong positive trend appears (4.48 mm year^{-1}). This is due to the warming trend present in LMDZ-MED and already identified by Llasses et al. (2016). This trend was driven by the warming of the deepest layers in the Levantine basin and attributed to a too short spin-up, thus being unrealistic. The conclusion of this comparison is twofold: (a) in cases where the models have fixed Atlantic conditions, the a-posteriori correction suggested by Jordà and Gomis (2013) improves the interannual variability but caution is required with the trends as model drifts can contaminate them; (b) in order to get an accurate simulation of Mediterranean sea level the mass transfer between the Atlantic and the Mediterranean has to be properly simulated as it is the driving mechanism of interannual to multidecadal Mediterranean variations.

4.2.3 *Spatial patterns*

Figure 5 compares the mean dynamic topography (MDT) patterns from Rio et al. (2014) (RIO 2014) as reference with the different simulations. The new MDT RIO 2014

Table 3 Correlation with CCI-ECV for the common period 1993–2008, for the interannual sea level variability in the Mediterranean

Data	Non-detrended	Detrended
LMDZ-MED – Dynamic SSH	0.33	0.57
LMDZ-MED – Dynamic SSH + steric	0.02	0.54
LMDZ-MED – Dynamic SSH + steric + salt mass	0.79	0.48
CNRM-RCSM4	0.16	0.50
MORCE-MED	0.15	0.56
MED12	0.86	0.80

Calculations are made for both non-detrended and detrended timeserie

Table 4 Trend for the common period 1993–2008

Data	Trend [mm $year^{-1}$]
LMDZ-MED – Dynamic SSH	−0.01
LMDZ-MED – Dynamic SSH + steric	−0.89
LMDZ-MED – Dynamic SSH + steric + salt mass	4.48
CNRM-RCSM4	−0.42
MORCE-MED	−0.66
MED12	1.62
CCI-ECV	1.78

was computed especially for the Mediterranean Sea from model outputs, altimeter measurements and oceanographic in situ data, and benefits from improvements made possible by the use of extended data sets and refined processing. It covers the 1993–2012 altimetric period. MDT patterns can be considered as proxies for the mean surface circulation. From this figure, we see that SSH spatial patterns are not necessarily improved with the revised near-Atlantic signal in MED12, but seem rather model-dependent. It is difficult to determine a "best" spatial representation among these four simulations; this shows that ORCSMs have difficulties to represent

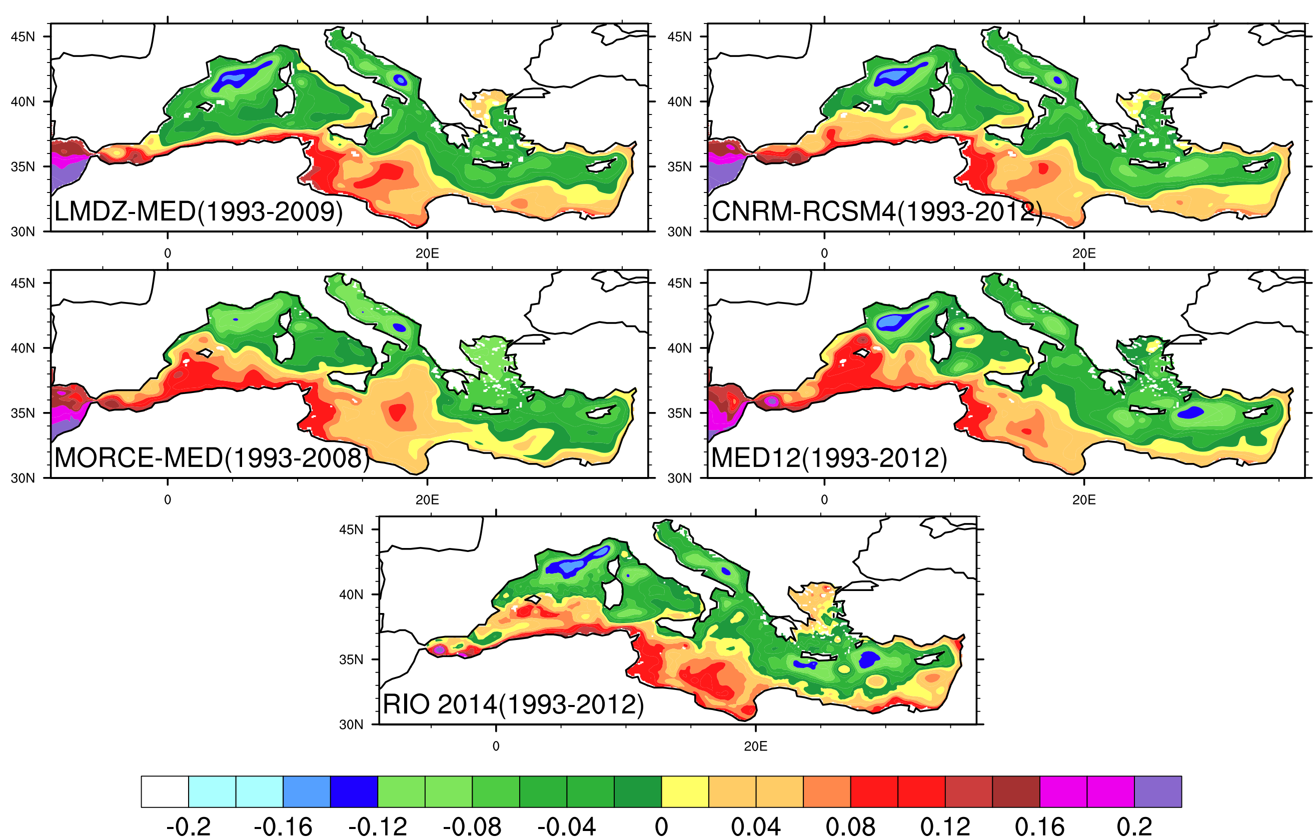

Fig. 5 Spatial view of sea surface height averaged from 1993 to the end of each simulation. Models are compared to the climatology of Rio et al. (2014)

accurately sub-basin circulation variability (L'Hévéder et al. 2013; Sevault et al. 2014). One of the most distinct feature among the models occurs in the Alboran Sea. MORCE-MED and MED12 both have a sub-surface circulation with Atlantic waters flowing northward toward the Balearic Islands after entering through the strait of Gibraltar, which is likely unrealistic according to observations (Millot and Taupier-Letage 2005). However, a recent study by Pinardi et al. (2013) shows results from a retrospective reanalysis which displays a northward flowing segment. In LMDZ-MED, Atlantic waters entering at Gibraltar are trapped into gyres in the Alboran Sea and then stick to the North-African coast. Rio et al. (2014) propose a feature in between, quite close to the patterns displayed in CNRM-RCSM4 in the Alboran region. Concerning the North-Western Mediterranean, the low sea level feature associated to the large gyre in the convection area of the Gulf of Lions is well-represented in most of the models, but for MORCE-MED, where it remains weak.

In the eastern basin, MED12 shows the most consistent circulation compared to Rio et al. (2014). For example, in the other simulations, the Algerian current crosses the Sicily Channel but then circulates too far north in the Ionian, especially in MORCE-MED. MED12 displays the most realistic pattern for this feature. In the Levantine basin, the Rhodes cyclonic gyre, where winter convection occurs, is only accurately represented in MED12. The anticyclonic Ierapetra gyre (South-East of Crete) is nicely displayed in the reference dataset but this feature is absent in all the model simulations. The differences between the simulations and the altimetric data are mainly seen on spatial mesoscale patterns, the very large scale patterns being in agreement between both products. This is probably because the model spatial resolution ranges from 6 to 12 km and is not enough to properly simulate all the mesoscale and sub-mesoscale processes that play a role in the Mediterranean. Moreover, it has to be noted that the resolution of the models is not enough to properly model the hydraulic control and the water exchanges at the Strait of Gibraltar (Sannino et al. 2014). This would have a negative impact on the quality of the circulation around the Strait of Gibraltar as far as the transfer of momentum would not be accurate. However, in terms of Mediterranean sea level this is not a problem because the transport adjustments are set up at low frequency and thus unaffected by the details of the exchange [see for instance the quality of the results obtained with a 15 km model by Gomis et al. (2006)]. An in-depth anaysis of the causes for the differences and discrepancies of sub-surface circulation features among Mediterranean regional ocean models would be interesting but it remains beyond the scope of the present study.

4.2.4 *Spatial trends*

The basin-wide averaged trends have been presented in Table 4 and it has been shown that MED12 (1.62 mm year^{-1}) better agrees with CCI-ECV (1.78 mm year^{-1}). Spatial trend anomalies with respect to basin average are represented in Fig. 6. CCI-ECV displays spatial trend anomalies which are negative around the Balearic Islands, in the Ionian, and in the south-west Levantine meaning that the local sea level rise in these regions is slower than the basin average trend, with even negative trends in the north-west Ionian (absolute values not shown). Positive trend anomalies are displayed around Crete. The trend patterns in the Ionian show the recovery after the Eastern Mediterranean Transient, which ends when the altimetric period begins. The changes in North Aegean trend patterns could reflect circulation changes related to changes in the Bosphorus fluxes. The positive/negative dipole south-east of Crete could be attributed to a shift of the Ierapetra gyre. In the western basin, the interpretation of the changes is more delicate.

Concerning models' capability to represent spatial trends, we found that, except in MORCE-MED, local negative trend anomaly patterns of the western basin are in correct agreement with those displayed by the satellite-derived data despite the models' difficulties to represent an adequate circulation in the Alboran region (see Sect. 4.2.3). For the eastern basin, the negative trend anomaly pattern of the north-west Ionian, attributed to the post-EMT recovery, is present in all models, although it is shifted southward in MORCE-MED. Concerning the absence of trend anomaly patterns in North Aegean in all models, the representation of the Bosphorus is too crude to be able to show the impact of changes in the Black Sea outflow on the circulation.

Local structures of sea level trend are driven by processes such as water mass changes, which are not necessarily influenced by the boundary conditions. The major improvement at Mediterranean global scale (see Sects. 4.2.1 and 4.2.2) is thus not clearly present at local scale. This might be a problem when analysing the spatial variability of the Mediterranean for the present climate, since the regional differences are up to ≈20 cm, thus larger than the basin scale temporal changes (≈7 cm over the last 3 decades).

However, in future scenarios it is the opposite: sea level rise will be expressed as a basin-wide signal of 50–80 cm, while regional variability will change much less. In particular, Adloff et al. (2015) have shown that global warming could modify the circulation patterns. This would induce local differences in sea surface height of up to +10 cm. The gain from prescribing adequate sea level conditions at the Atlantic boundary is thus evident, even more for future longer time scales.

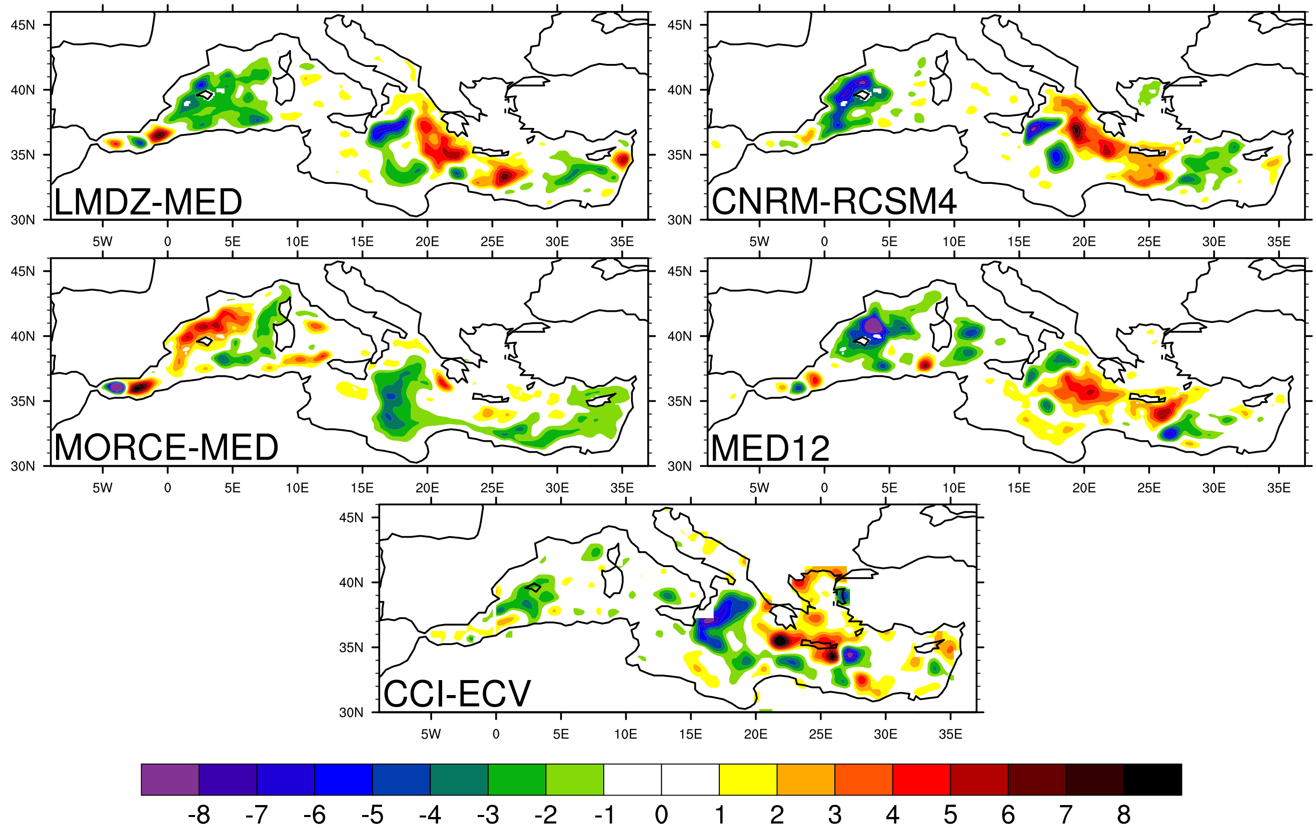

Fig. 6 Spatial anomalies of sea level trend with respect to basin average, in mm year^{-1}, for the common period 1993–2008. Model results are compared with the trends from the satellite-derived dataset CCI-ECV

5 Conclusions

This study aimed at evaluating different approaches to simulate Mediterranean sea level variability and change with regional Mediterranean climate models. In particular, several choices commonly used for the Atlantic lateral boundary conditions (LBCs) were analysed and the resulting simulated Mediterranean sea level was compared with observational datasets. Results show that Mediterranean mean sea level is strongly influenced by the Atlantic conditions and thus the quality of the information in the LBCs is crucial for the good modelling of Mediterranean sea level. This allows to account for global sea level change (including global steric and mass addition), since the Atlantic is known to drive the Mediterranean variability at interannual and interdecadal time scales. With improved Atlantic LBCs, the MED12 simulation accounts for both local and large-scale sea level changes from the near-Atlantic. These new LBCs allow a major improvement of the representation of mean Mediterranean sea level, as it was proposed by both Calafat et al. (2012) and Tsimplis et al. (2013). This result also suggests that previous regional projection of Mediterranean sea level should be considered with caution as none of them considered variable Atlantic sea level conditions. Concerning the regional differences inside the basin that are induced by circulation changes, we find that these are model dependent and not affected by the LBCs. In models, local SSH patterns and local trends still present discrepancies compared to satellite-derived data, and are not clearly improved with correct Atlantic boundary forcing. The reason is that sub-surface circulation patterns are influenced by other processes which are not affected by Atlantic sea level variability (i.e. local dynamics). However, correct Atlantic conditions with full global signal should be used for future Mediterranean simulations. This includes both hindcast simulations and also future scenarios, where part of the signal from the global ocean could be obtained from global circulation models. The improved Atlantic sea level forcing dataset is available on demand.

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