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The Regional Ocean-Atmosphere Coupled Model COSMO-NEMO_MFS

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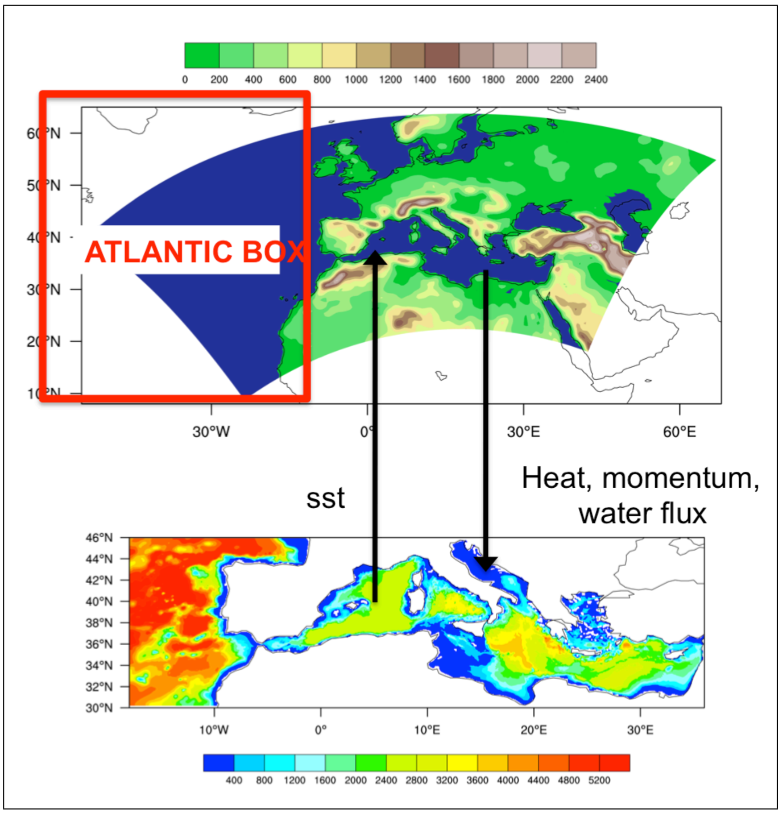
SUMMARY The main features of the regional ocean-atmosphere coupled model system COSMO-NEMO_MFS have been described. The sensitivity of the model on a number of physical parameterizations is investigated, by performing four different integrations forced by the same lateral boundary conditions derived by ERA-Interim. Model evaluation is performed, focusing on air-sea feedbacks through the analysis of heat fluxes at the surface. Evaluation of a number of features related to ocean and atmosphere circulation is also performed, and the model skill in reproducing extreme precipitation events is explored.



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1 INTRODUCTION

The climate of the Mediterranean region, understood here as the region including the Mediterranean Sea and the surrounding areas, is determined by the interaction between mid-latitude and sub-tropical regimes and the complex morphology (mountain chains and land-sea contrasts) that characterizes this part of the Earth. The region has been identified as one of the main climate change hot-spots (Giorgi 2006 [8]), i.e. one of the most responsive areas to climate change. Moreover, this area is populated by over 500 million people, distributed over approximately 30 countries in Africa, Asia and Europe, making it one of the most interesting case studies from the scientific point of view and important from a social perspective. In the recent past, a number of scientific initiatives and projects have been undertaken to assess the possible changes that anthropogenic global warming might induce in the climate of the European continent and in the Mediterranean area. Specifically, scenario simulations aimed at quantifying the possible future climate change in the European and Mediterranean region have been designed and performed in the framework of EU Projects PRUDENCE (Christensen and Christensen 2007 [3]), ENSEMBLES (Christensen et al. 2009 [4]) or CIRCE (Gualdi et al. 2013a [11]). At the same time, coordinated studies have investigated and discussed the climate change signal in the Mediterranean region projected by both regional and global models (Giorgi and Lionello 2008 [10]; Hertig and Jacobeit 2008a [16]; Hertig and Jacobeit 2008b [16]; Hertig and Jacobeit 2011a [14]; Hertig and Jacobeit 2011b [17]; Hertig et al. 2010 [15]). On the same line, Marcos and Tsimplis (2008) [23] used data from the CMIP3 (Coupled Model Inter-comparison Project 3, Meehl et al. 2007a [25]) GCMs to assess the uncertainty range of the response of the Mediterranean temperature, salinity and sea level change along the twenty- first century. They mainly demonstrated that, because of their low spatial resolution, the CMIP3 GCMs were not able to simulate a realistic Mediterranean Sea in present climate and that their climate change results were consequently doubtful. Mariotti et al. (2008) [24] used the same low-resolution database to assess the uncertainty in the change of the water budget components. Similarly, Sanchez-Gomez et al. (2009) [28] used the outputs of the ENSEMBLES Atmosphere-only RCMs (25 km resolution over the Mediterranean Sea) to evaluate the change of the water budget components. They concluded that the various models used (GCMs and RCMs) agreed on the drying of the Mediterranean basin mainly after 2050. Scoccimarro et al. (2014) [29] used the CMIP5 climate change projections (Taylor et al. 2012 [33]) to investigate how climate change might influence the characteristics of extreme events in the region. Their results show that extreme precipitation events might increase in terms of intensity as a response to global warming. Concerning the impact of climate change on the Mediterranean basin, very few studies were specifically dedicated to the Mediterranean Sea case and its possible evolution along the twenty- first century before the CIRCE project and none of them were a coordinated effort to tackle the uncertainty issue (see Gualdi et al. 2013a [11] and Gualdi et al. 2013b [12] and references therein). Furthermore, most of these works are based either on global ocean-atmosphere coupled climate models (AOGCMs) or on atmosphere or ocean-only regional models, each of which presents advantages and weaknesses. An important shortcoming common to the global coupled and regional atmosphere only models is their limited capability to include a realistic representation of the processes associated with the presence of the Mediterranean Sea into the climate change projections for this region. The global AOGCMs used so far, in fact, have spatial resolutions generally not sufficient to resolve the small-scale features and processes that characterize the Mediterranean basin and its climate. The atmosphere only regional models are usually implemented with horizontal resolutions ranging from 50 to 20 km and higher. According to Li (2006) [21] this would be sufficiently fine to simulate a realistic circulation over the Mediterranean Sea and the European continent. These models, however, are forced with prescribed lower boundary conditions (sea-surface temperatures, SSTs) and thus they do not take into account any air-sea feedbacks. Furthermore, the Mediterranean SST used to force the models over the basin are produced with low-resolution AOGCMs, which are inadequate to reproduce the small scale features that distinguish the behavior of this sea (e.g., Marcos and Tsimplis 2008 [23]). Similar arguments hold for regional ocean-only model simulations, where air-sea feedbacks are not considered and the surface fluxes are generally obtained from low resolution models. The deficiencies in including a realistic modeling of the Mediterranean Sea into the climate system might have considerable consequences on the quality and reliability of the climate change projections that state-of-the-art models (both global and regional) provide for the European and Mediterranean regions. A first attempt to remedy these deficiencies has been made by Somot et al. (2008) [30] who developed an atmosphere-ocean regional climate model (AORCM) coupling a variable resolution version of a global atmospheric model with a high-resolution oceanic model of the Mediterranean Sea (see Somot et al. 2008 [30] for more details). According to their results, the coupled model seems to be in good agreement with the observations over the Mediterranean region for the reference period 1961-1990. Moreover, it appears to perform as well as or even better than most of the PRUDENCE state-of-the-art uncoupled regional models forced with observed SSTs in the Mediterranean basin. Importantly, Somot et al. (2008) [30] found also substantial differences between the regional coupled and uncoupled climate change projections, which can be ascribed to the inclusion of the Mediterranean Sea model.

Following the spirit of Somot et al. (2008) [30] and the multi-model approach taken in the framework of the CIRCE project (e.g., Gualdi et al. 2013a [11]), a new multi-model climate simulation programme, named Med-CORDEX (www.medcordex.eu), specifically thought for the Mediterranean region, has been launched. The Med-CORDEX initiative, as part of the CORDEX (Coordinated Regional Downscaling EXperiment) international effort (Giorgi et al., 2009 [9]), is a unique framework in which the research community will make use of coupled regional atmospheric, land surface, river and ocean climate models and singular components at very high-resolution to increase the reliability of past and future regional climate information and better understand the processes that are responsible for the climate of the region. CMCC will contribute to the Med-CORDEX simulations with a set of regional models implemented in the Mediterranean region. Specifically, the COSMO-CLM, limited area atmospheric model will be employed in stand-alone mode and it will also be used in coupled mode with the oceanic model NEMO implemented in the Mediterranean basin.

In this report, we describe the coupling between the COSMO atmosphere and the NEMO_MFS ocean components of the CMCC regional coupled model for high-resolution climate simulations in the Euro-Mediterranean region. Specifically, the report will summarize the characteris-

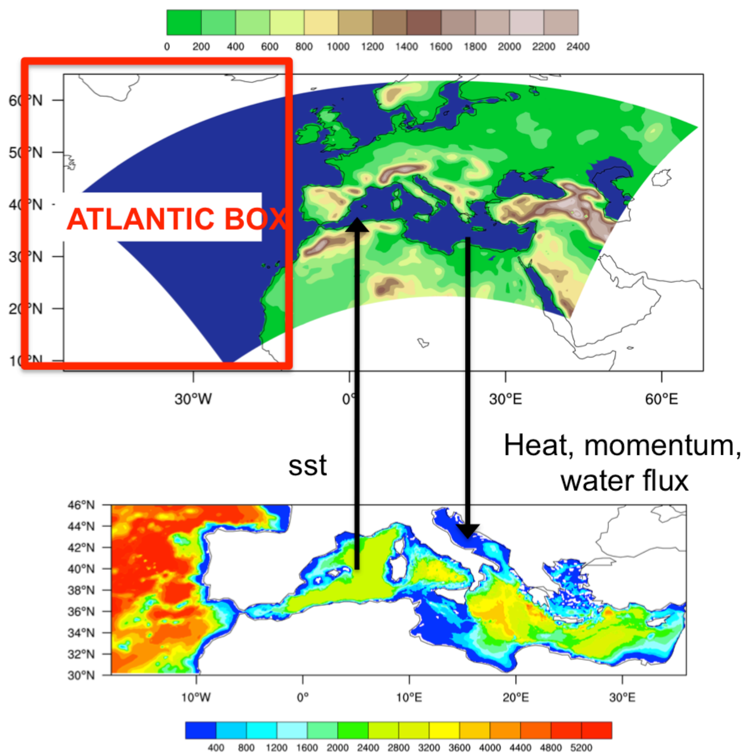

Figure 1:
Domains of the atmospheric model (with topography) and of the ocean model (with bathymetry).

tics of the physical coupling between the model components (Section 2), and the results of the tests performed in order to optimize its performance on the domain of interest (Section 3). A summary in Section 4 will conclude the report.

2 MODEL COMPONENTS AND COUPLING

2.1 THE ATMOSPHERIC COMPONENT: COSMO-CLM

COSMO-CLM (Rockel et al. 2008 [20]) is the climate version of the COSMO model (Steppeler et al. 2003 [31]), the operational non-hydrostatic mesoscale weather forecast model developed at the German Weather Service (DWD). Successively, the model has been modified by the CLM-Community, in order to develop also climatic applications. The updates of its dynamical and physical packages allow its application in cloud resolving scales (Doms and Forstner 2004 [6]). It can be used with a spatial resolution between 1 and 50 km. For more details on the formulation of the model and on the parameterization settings, the reader is addressed to (Holton 2004 [18]; Kessler 1969 [19]; Tiedtke 1989 [35]). In the present version of the coupled AORCM, the atmospheric component COSMO-CLM is implemented with a spatial resolution of about 0.44° (about 44 km) and 40 vertical levels. The spatial domain covers the Mediterranean region, including an Atlantic box, ranging from 54W-67E and 8.75N-63.75N (Figure 1). The choice of the domain is justified by the need to cover the Mediterranean basin region, including an area over the eastern part of the Atlantic Ocean (Atlantic box), which is necessary to the coupling with the Mediterranean Sea model.

2.2 THE OCEANIC COMPONENT: NEMO-MFS

The ocean component of the AORCM is NEMO-MFS, a regional configuration of Nucleus for European Modelling of the Ocean (NEMO; Madec 2008 [22]) implemented at very high resolution in the Mediterranean basin. As it has been shown in Oddo et al. (2009) [26], NEMO-MFS is an eddy-permitting marine model able to represent the dynamical processes that characterize the Mediterranean Sea. In the present configuration of the coupled AORCM, NEMO-MFS has a 1/16° (about 6.7 km) horizontal resolution and 71 levels along the vertical. More information about the performances of NEMO-MFS in reproducing the main features of the Mediterranean Sea dynamics can be found in Oddo et al. (2009) [26]. Gualdi et al. (2013a) [11], Gualdi et al. (2013b) [12] and Dubois (2012) [7], on the other hand, provide an extended discussion of the capability of NEMO-MFS to reproduce the observed features of the air-sea surface fluxes, when coupled to an atmospheric model.

2.3 THE COUPLER OASIS

The communication between the atmospheric model and the ocean models is carried out with the Ocean Atmosphere Sea Ice Soil version 3 (OASIS3) coupler (Valcke 2013 [36]). Every 120 min (coupling frequency), heat, mass, and momentum fluxes are computed and provided to the ocean model by the atmospheric model. At the same time, the atmosphere receives the Mediterranean SST from the ocean model. It is worth noticing that the high-resolution information produced by NEMO-MFS is partly deteriorated in the coupling procedure, by interpolating the field to the coarse atmospheric model. On the other hand, Dubois et al. (2012) [7], examining the performances of CIRCE models in terms of surface heat and water budgets over Mediterranean Sea, showed that the presence of an underlying marine model, which realistically simulates the small-scale spatial structures over the Mediterranean, is still beneficial in terms of the air-sea interactions.

3 RESULTS

3.1 MODEL CONFIGURATION AND PARAMETERIZATIONS

Different model configurations have been tested, in order to explore the model sensitivity on some of the crucial physical parameterizations employed, and to identify the optimal configuration to reproduce the features of Mediterranean climate. The focus of such sensitivity analysis has been the correct representation of ocean-atmosphere heat fluxes. Air-sea interactions and feedbacks play a crucial role in the Mediterranean; such aspect is of foremost importance as far as coupled models are concerned: it is well known that the correct closure of heat budget represents one of the main challenges when the modelisation of the Mediterranean is tackled. Four different integrations have been performed for the period 1979-2011. Such simulations (referred to as V1-V4 hereafter) differ in the parameterizations of the atmospheric model, while the coupling setup is the same. All the simulations are forced by the same lateral boundary conditions, derived by the ERA-Interim fields, at 6-hourly frequency. The main features of the model configuration are the following:

1 Model version V1 features the default configurations of COSMO. In particular:

- The parameterization of atmospheric aerosols is the one of Tanré (1984) [32]: constant concentrations are prescribed.
- The convective parameterization employs the Tiedtke (1969) [35] convective scheme.
- Sea surface albedo has a constant value (0.07).

2 Model version V2 features a different aerosol parameterization with respect to V1:

- The parameterization of atmospheric aerosols is the one of Tegen (1997) [34]: a seasonal cycle for the different aerosol species is introduced.
- The convective parameterization employs the Tiedtke (1969) [35] convective scheme.
- Sea surface albedo has a constant value (0.07).

3 Model version V3 features a different convective parameterization with respect to V:

- The parameterization of atmospheric aerosols is the one of Tanré (1984) [32]: constant concentrations are prescribed.
- The convective parameterization employs convective scheme used in the ECMWF Integrated Forecast System (IFS) cycle 33r1 (Betchold et al. 2008 [2]).
- Sea surface albedo has a constant value (0.07).

4 Model version V4 features both the modified aerosol and convective parameterizations. In addition the sea surface albedo has been modified to introduce a seasonal cycle:

- The parameterization of atmospheric aerosols is the one of Tegen (1997) [34]: a seasonal cycle for the different aerosol species is introduced.

- The convective parameterization employs convective scheme used in the ECMWF Integrated Forecast System (IFS) cycle 33r1 (Betchold et al. 2008 [2]).
- The seasonal cycle of sea surface albedo is introduced, using the values from Cogley (1979) [5].
- A 25-year spin-up of the coupled system is performed before starting the integration.

In the rest of this section, the evaluation of the different model versions is presented. In Section 3.2 air-sea fluxes are discussed, Section 3.3 deals with the ocean evaluation, Section 3.3 with the atmosphere evaluation, and in Section 3.4 selected results on extreme events are presented.

3.2 AIR-SEA INTERACTIONS

In Figures 2-5 are shown the basin averages of the four components of the atmosphere-ocean heat flux. Both the seasonal cycle, and interannual variability are presented. The yearly time series is compared with the range derived from observational estimates (Sanchez-Gomez et al 2011 [27]). Solar radiation (Fig. 2) appears to be underestimated by 20÷30 W/m^2 in simulations V1 and V3. In simulation V2 the underestimation is reduced to less than 5 W/m^2, while the value found in V4 is in the observational range. The larger contribution to the discrepancy between the yearly average in different model versions appears to come from the summer season. The amplitude of the emitted thermal radiation (Fig. 3) is underestimated of approximately 5 W/m^2 in model versions V1, V2, and V3, while it is within the observational range in model version V4. The yearly time series of V1 and V2 are strongly correlated with each other, as are V3 and V4, while the correlation between the two pairs is much lower. Coherently, V1 and V2 exhibit similar seasonal cycle, as V3 and V4 do. The latent heat emitted by the ocean (Fig. 4) appears to be underestimated by approximately 15 W/m^2 in simulations V1 and V3. In simulation V2 the underestimation is reduced to less than 5 W/m^2, while the value found in V4 is in the observational range. The seasonal cycle in the four simulations is similar, with a shift reflecting the overall bias. The sensible heat emitted by the ocean (Fig. 5) appears to be underestimated by approximately 3 W/m^2 in simulations V1 and V3. In simulation V2 the flux is slightly overestimated, while the value found in V4 is in the observational range. The seasonal cycle in the four simulations is similar, with a shift reflecting the overall bias. Figure 6 shows the net surface heat flux (the sum of the four components). The difference between the different simulations is quite modest. It has to be stressed, however, that while versions V1, V2, and V3 produce a value that is not far from the observed one due to compensation of errors, V4 does so by representing correctly the four different components. Moreover, the mean net surface heat flux of V2 has a positive sign, opposite to the one estimated from observations. Finally, Figure 7 shows the heat flux through the Gibraltar Strait. Such value is related to the above discussion, as it is expected to compensate the heat loss at the surface. The Gibraltar heat flux in simulations V1, V2 and V3 exhibits a negative trend of approximately 2 °C/30 y. In model simulation V4 the trend is reduced to less than 2 °C/30 y. The origin of such trend is further discussed in Section 3.3.

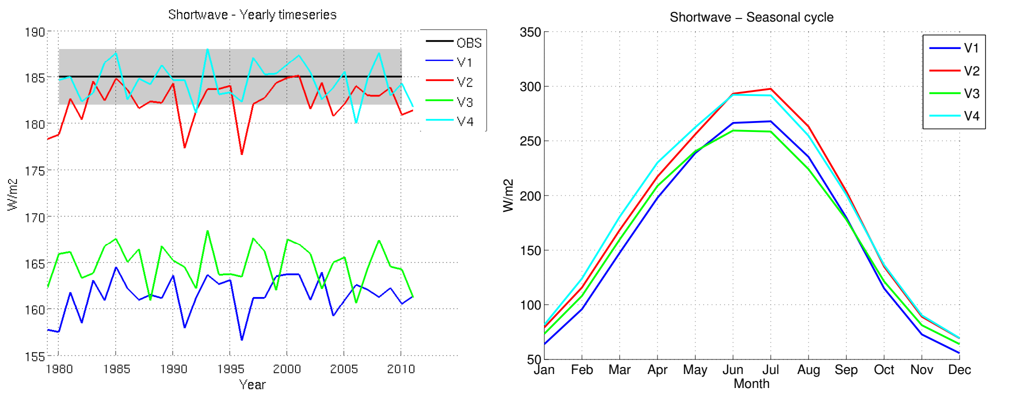

Figure 2:
Basin average of surface net shortwave radiation flux: inter-annual variability (left panel) and seasonal cycle (right panels) in model V1 (blue), V2 (red), V3 (green), and V4 (cyan). The black line and shading represent the observational estimate and range.

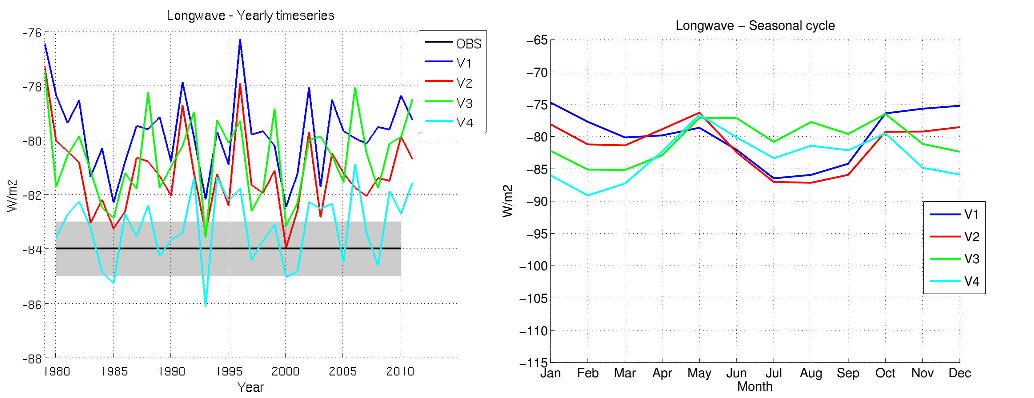

Figure 3:
Basin average of surface net longwave radiation flux: inter-annual variability (left panel) and seasonal cycle (right panels) in model V1 (blue), V2 (red), V3 (green), and V4 (cyan). The black line and shading represent the observational estimate and range.

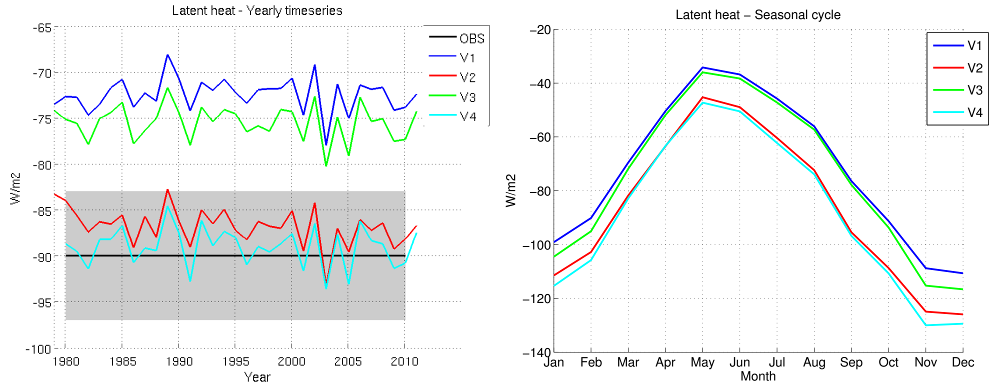

Figure 4:
Basin average of surface latent heat flux: inter-annual variability (left panel) and seasonal cycle (right panels) in model V1 (blue), V2 (red), V3 (green), and V4 (cyan). The black line and shading represent the observational estimate and range.

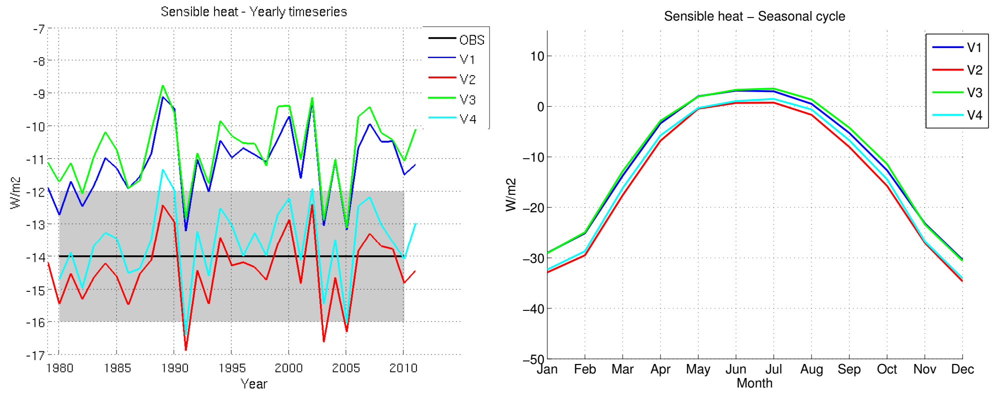

Figure 5:
Basin average of surface sensible heat flux: inter-annual variability (left panel) and seasonal cycle (right panels) in model V1 (blue), V2 (red), V3 (green), and V4 (cyan). The black line and shading represent the observational estimate and range.

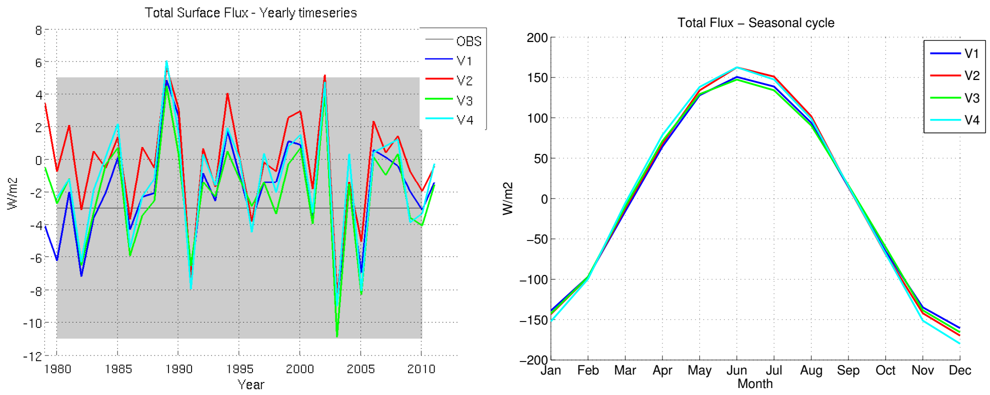

Figure 6:
Basin average of surface net heat flux: inter-annual variability (left panel) and seasonal cycle (right panels) in model V1 (blue), V2 (red), V3 (green), and V4 (cyan). The black line and shading represent the observational estimate and range.

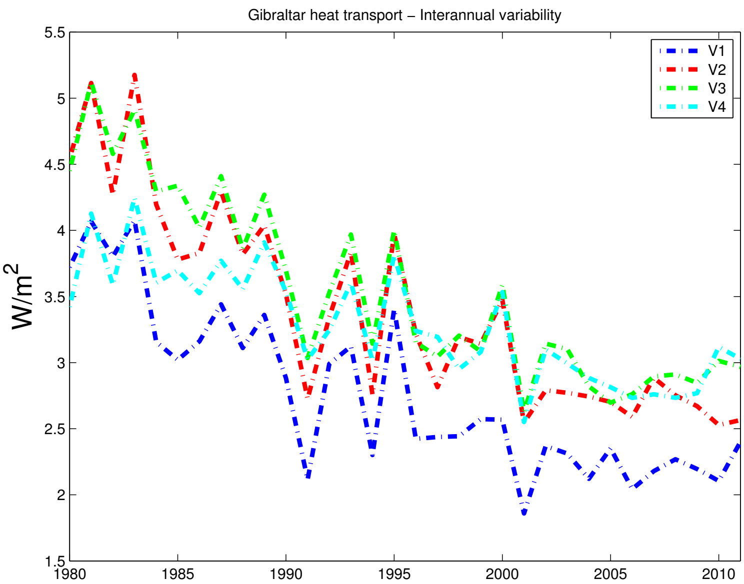

Figure 7:
Heat flux at the Gibraltar Strait: inter-annual variability in model V1 (blue), V2 (red), V3 (green), and V4 (cyan).

3.3 EVALUATION: OCEAN

Figure 8 shows the time series of yearly mean and the seasonal cycle of basin averaged sea surface temperature (SST) in the four different model simulation, compared with satellite observations. Model V1 and V3 show a bias of the yearly SST of respectively 1 °C and 0.5 °C. Simulation V2 agrees with observation during the first decade, while it shows an underestimation of approximately 0.5 °C during the last decade. Simulation V4 agrees with observation during the last decade, while it shows an overestimation of approximately 0.5 °C during the last decade. All the simulations show a smaller trend with respect to the one found in observations. All the simulations underestimate the SST in summer (with the smaller distance from observations found in V4). During winter, on the other hand, an underestimation is observed in V1, an overestimation in V2 and V4, while V3 reproduces the correct value. As Figure 9 shows, the winter overestimation in V2 and V4 receives the larger contribution from the eastern part of the basin, while V3 shows a positive bias in the eastern Mediterranean and a negative bias in the western Mediterranean. The summer negative bias of SST in V1, V2 and V3 is basin-wide. V4 on the other hand shows a positive bias of JJA SST in the eastern Mediterranean and a negative bias in the western Mediterranean. In Figure 10 are shown the time series of yearly mean and the seasonal cycle of basin averaged sea surface salinity in the four different model simulation. V2 and V4 produce results very close to each other, as do V1 and V3. The two pairs of simulations show a discrepancy of about 1.5 PSU, with the pair V2-V4 exhibiting a small positive bias (0.1 PSU/30 y). Fig 11 shows the time series of yearly mean Mediterranean Sea volume-averaged temperature, in the four model simulations and reanalysis (Adani et al. 2011 [1]). The simulation V1 shows a good agreement with reanalysis. V2 has a trend of that (0.4 °C/30 years) much larger than the one present in reanalysis. V3 has also a trend larger than reanalysis (0.2 °C/30 years). V4, on the other hand, shows a bias of approximately 0.4 °C with respect to reanalysis, but has a comparable trend.

In the rest of the section, results related to the dynamics at the Gibraltar Strait are presented. The ingoing and outgoing mass transports (Fig. 12) show a good agreement between the different simulations during the second and third decade of the integration. During the first decade, V1 V2 and V3 show large trends until an equilibrium value is reached, while this effect is not present due to the spin-up. The net mass flow (Fig. 13) has a similar value in all simulations (about 0.4 Sv). Such value is in good agreement with observational estimates. The inflow temperature (Fig. 14) has values constant over the integration. The difference in the values found in the different simulations reflects the different sea surface temperature in the Atlantic box (see Fig. 9). The outflow temperature, on the other hand, shows different trends, due to the trend of outflowing Mediterranean waters (see Fig. 11). This feature explains, for a large part, the behavior of Gibraltar heat transport discussed in Section 3.2 (Fig. 7).

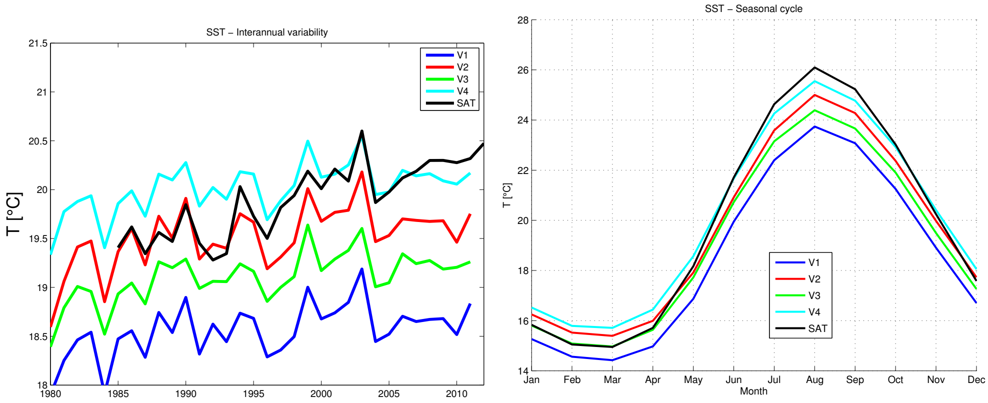

Figure 8:
Basin average of sea surface temperature: inter-annual variability (left panel) and seasonal cycle (right panels) in model V1 (blue), V2 (red), V3 (green), and V4 (cyan). The black line indicates satellite measurements.

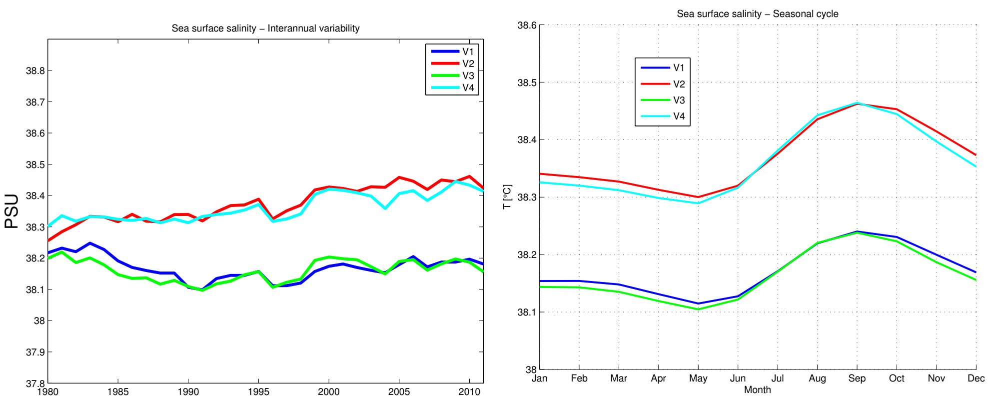

Figure 9:
Basin average of sea surface salinity: inter-annual variability (left panel) and seasonal cycle (right panels) in model V1 (blue), V2 (red), V3 (green), and V4 (cyan).

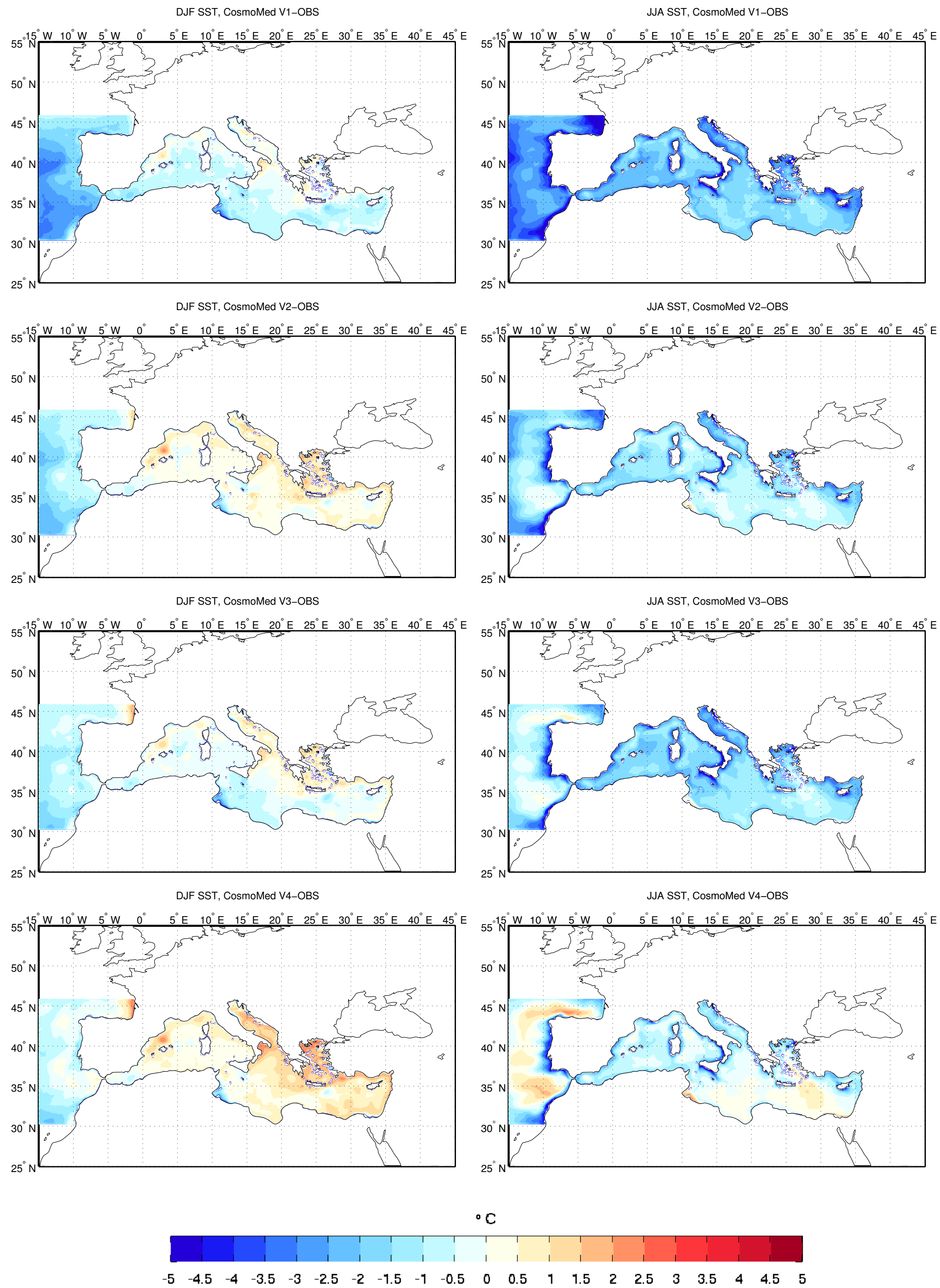

Figure 10:
Bias, with respect to E-OBS, of sea surface temperature in DJF (left column) and JJA (right column) in model simulations: V1 (first row), V2 (second row), V3 (third row) and V4 (fourth row).

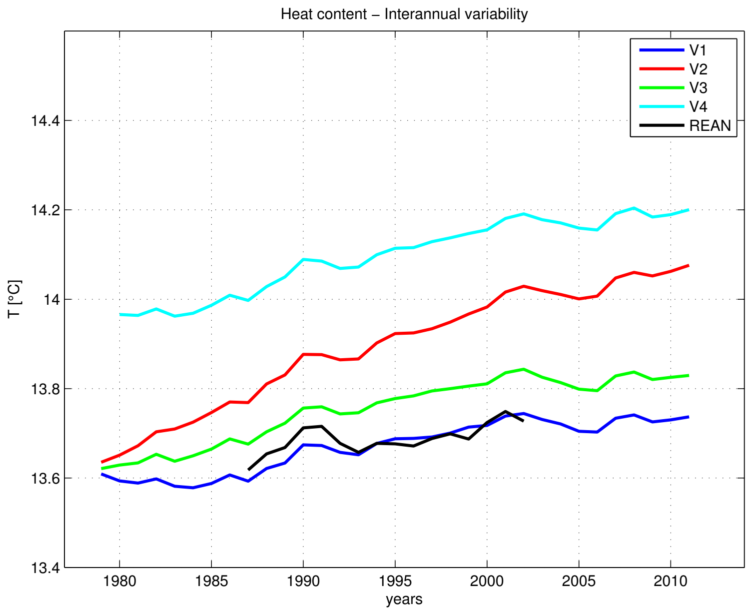

Figure 11:
Volume average of Mediterranean Sea temperature: inter-annual variability in model V1 (blue), V2 (red), V3 (green), and V4 (cyan). The black line indicates values from reanalysis.

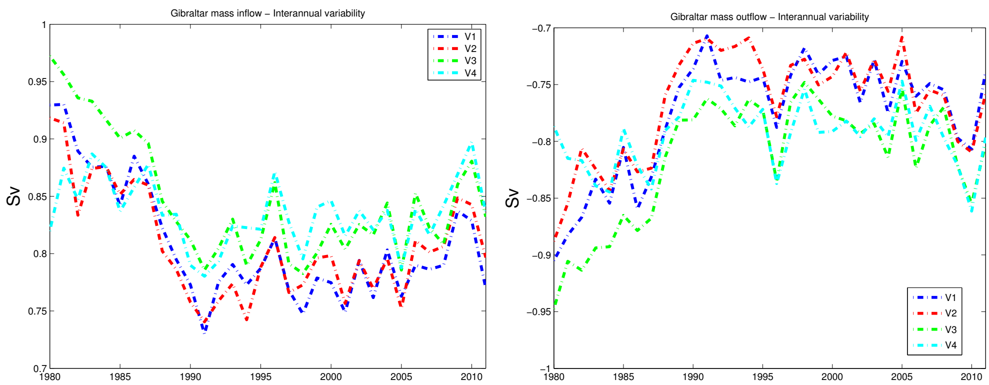

Figure 12:
Inter-annual variability of Gibraltar Strait mass inflow (left panel) and outflow (right panel) in model V1 (blue), V2 (red), V3 (green), and V4 (cyan).

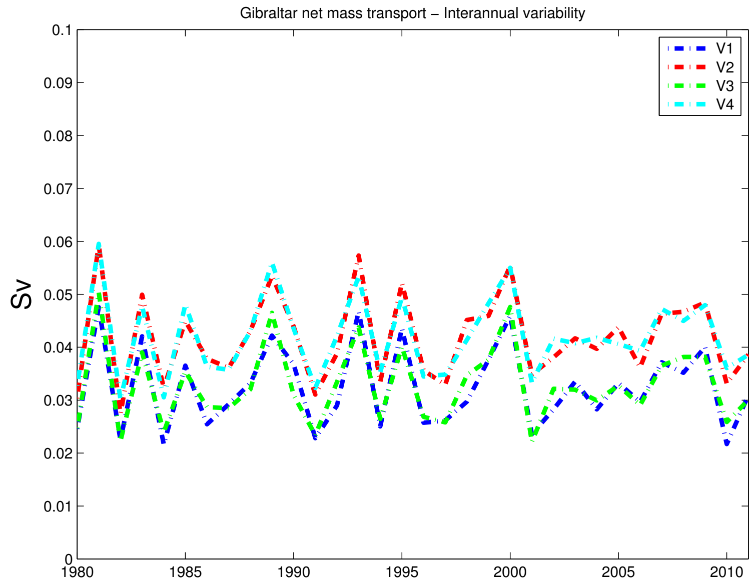

Figure 13:
Inter-annual variability of Gibraltar Strait net mass transport in model V1 (blue), V2 (red), V3 (green), and V4 (cyan).

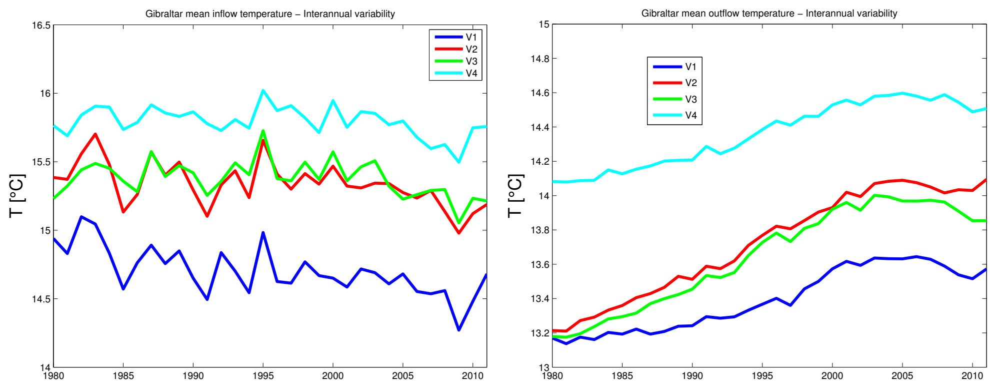

Figure 14:
Inter-annual variability of Gibraltar Strait mean inflow (left panel) and outflow (right panel) temperatures, in model V1 (blue), V2 (red), V3 (green), and V4 (cyan).

3.4 EVALUATION: ATMOSPHERE

Figure 15 shows the bias of seasonal (DJF and JJA) mean precipitation, with respect to the E-OBS dataset reference (Haylock et al. 2008 [13]), in the four model simulations. The patterns of bias are similar in all the simulations. Winter precipitation is overestimated in central Europe and the Balkans, while it is underestimated in the western part of Iberia, and on the southeastern part of the domain (north-west Africa, Anatolia and Middle-East). Summer precipitation, on the other hand, is overestimated in the Balkans and Eastern Europe, while it is correctly reproduced in the rest of the domain. The magnitude of the summer bias is smaller in V2 and V4, with respect to V1 and V3. No further relevant differences between the model versions emerge. Figure 16 shows the bias of seasonal (DJF and JJA) mean temperature, with respect to the E-OBS dataset reference, in the four model simulations. The patterns of winter temperature are similar in all the simulations. Winter temperature is overestimated in Eastern Europe while it is moderately underestimated in the western part of the domain. The pattern of summer precipitation in model simulations V1 and V2 shows a negative bias over most of the domain (with the exception of north-west Africa and Middle-East). V3 and V4 show on the other hand a different pattern, with a warm bias in the Balkans.

3.5 EVALUATION: EXTREME EVENTS

Figure 17 shows the skill of the different model versions in reproducing extreme precipitation events. The 99-th percentile of daily precipitation has been computed for every grid point, removing from the time series dry days ($P<1$ mm/day), and compared with the same quantity for the reference observational E-OBS dataset. Model simulations V1 and V2 show an underestimation of the precipitation percentile over the entire domain. V3 and V4, on the other hand show a mixture of areas with positive and negative biases. The overall distance from observations, however, is largely reduced.

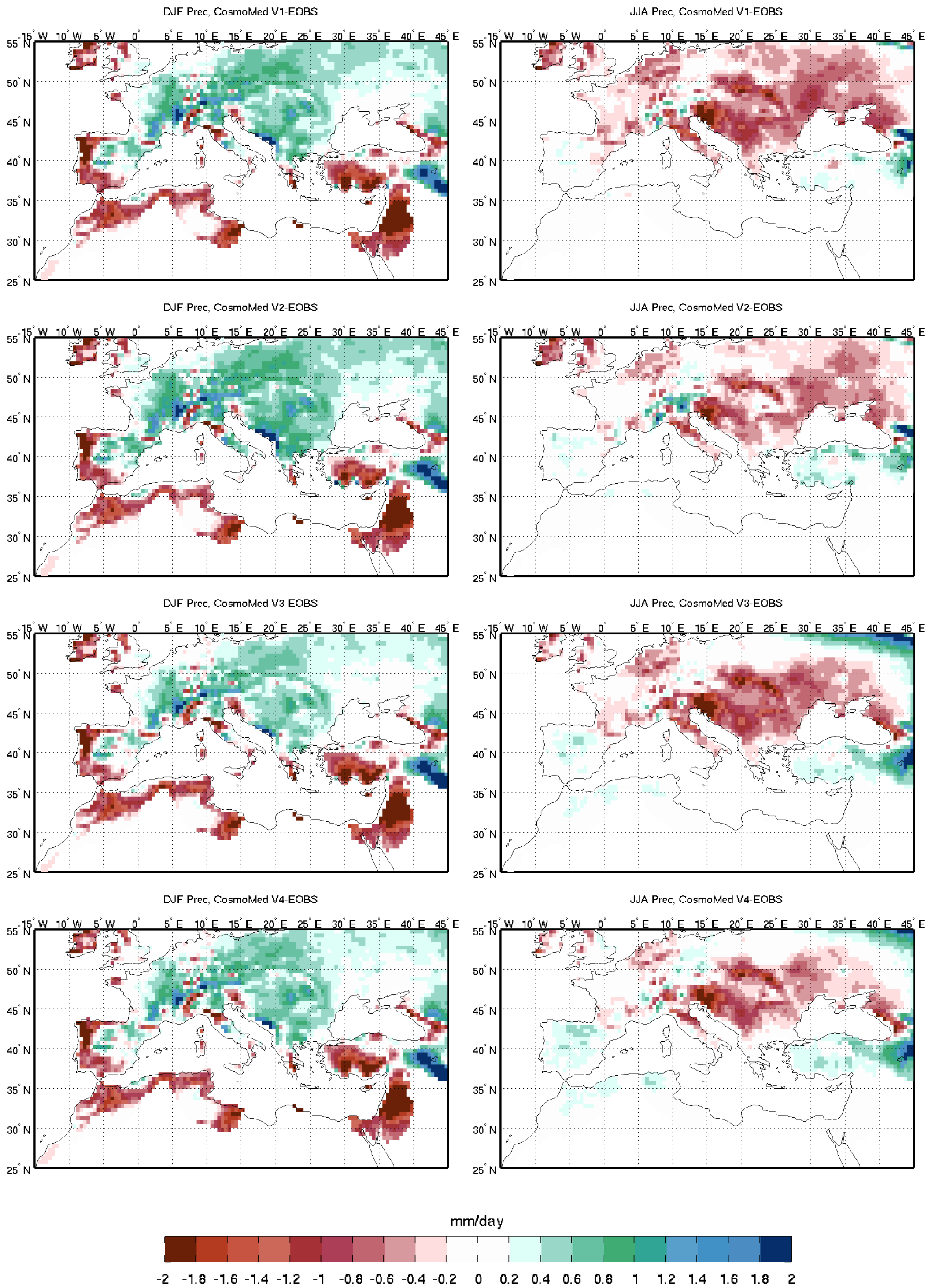

Figure 15:
Bias, with respect to E-OBS, of seasonal precipitation in DJF (left column) and JJA (right column) in model simulations: V1 (first row), V2 (second row), V3 (third row) and V4 (fourth row).

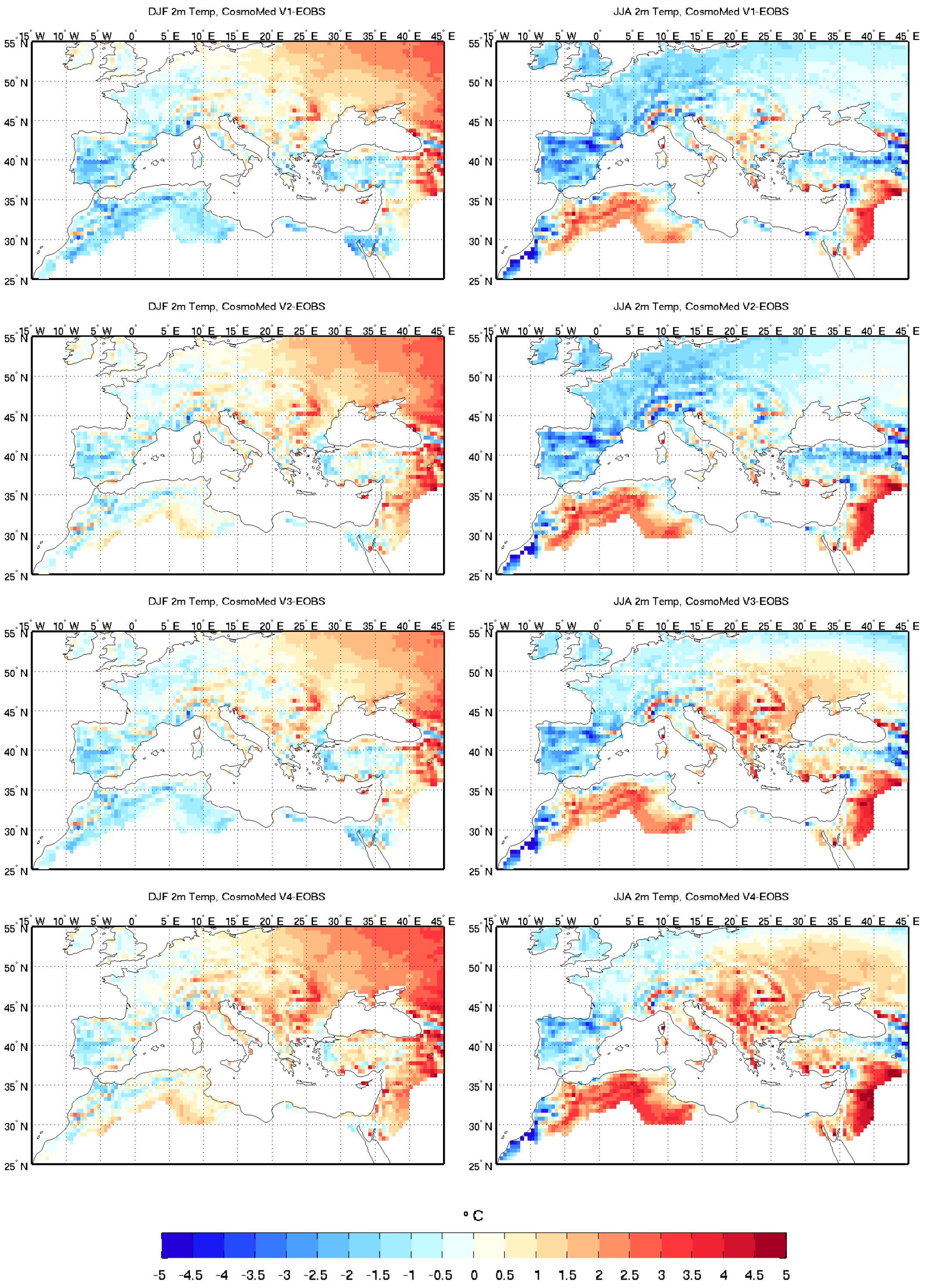

Figure 16:
Bias, with respect to E-OBS, of seasonal 2 m temperature in DJF (left column) and JJA (right column) in model simulations: V1 (first row), V2 (second row), V3 (third row) and V4 (fourth row).

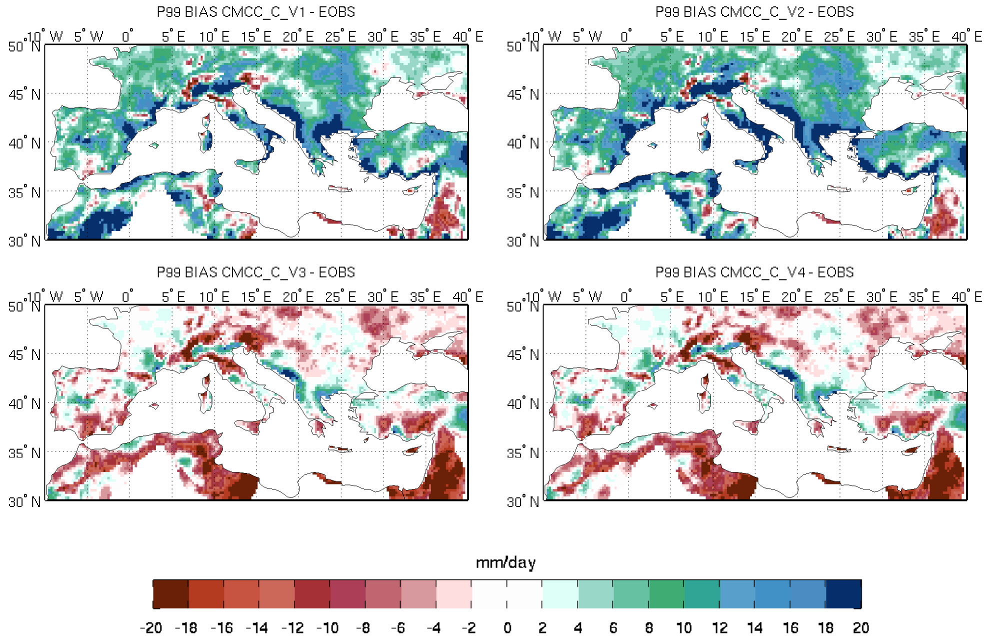

Figure 17:
Bias of 99th percentile of daily precipitation, with respect to E-OBS, in model simulations: V1 (top left), V2 (top right), V3 (bottom left) and V4 (bottom right).

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