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The CIRCE simulations: a new set of regional climate change projections performed with a realistic representation of the Mediterranean Sea

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Capsule: Climate change projections for the Mediterranean region performed improving the representation of the Mediterranean Sea into the climate system

Abstract

In this article we describe an innovative multi-model system developed within the CIRCE EU-FP6 Project and used to produce simulations of the Mediterranean Sea regional climate. The models include high-resolution Mediterranean Sea components, which allow to assess the role of the basin, and in particular of the air-sea feedbacks in the climate of the region.

The models have been integrated from 1951 to 2050, using observed radiative forcings during the first half of the simulation period and the IPCC SRES A1B scenario during the second half.

The projections show a substantial warming (about 1.5°-2°C) and a significant decrease of precipitation (about 5%) in the region for the scenario period. However, locally the changes might be even larger. In the same period, the projected surface net heat loss decreases, leading to a weaker cooling of the Mediterranean Sea by the atmosphere, whereas the water budget appears to increase, leading the basin to loose more water through its surface than in the past.

These results are overall consistent with the findings of previous scenario simulations, such as PRUDENCE, ENSEMBLES and CMIP3. The agreement suggests that these findings are robust to substantial changes in the configuration of the models used to make the simulations.

Finally, the models produce a 2021-2050 mean steric sea-level rise that ranges between +7 cm and +12 cm, with respect to the period of reference.

1. The problem of the Mediterranean Region Climate Simulations

The climate of the Mediterranean region, defined here as the area including the Mediterranean Sea and the surrounding areas, is determined by the interaction between mid-latitude and sub-tropical circulation regimes with 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, i.e. one of the most responsive areas to climate change (Giorgi 2006). The area is populated by over 500 million people, distributed in about 30 countries in Africa, Asia and Europe. Therefore, understanding climate variability here has also important social implications.

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 of the Mediterranean region. 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 such as PRUDENCE (Christensen and Christensen 2007) and ENSEMBLES (Christensen et al. 2009). At the same time, coordinated studies have been performed to investigate and to assess the climate change signal in the Mediterranean region projected by both regional and global models (Giorgi and Lionello 2008). Marcos and Tsimplis (2008), for example, used the CMIP3 data (Meehl et al. 2007) to assess the uncertainty range of the response of the Mediterranean Sea temperature, salinity and sea level change during the 21st century. According to their findings, the CMIP3 general circulation models (GCMs) reveal many difficulties in simulating a realistic Mediterranean Sea in present climate because of their low spatial resolution. Therefore, also the climate change signal produced by these models in the Mediterranean region should be considered with some caution. Using the same dataset, Mariotti et al. (2008) quantified the change in the regional water budget components. A

similar analysis has been done by Sanchez-Gomez et al. (2009), using the outputs of the ENSEMBLES atmosphere-only regional climate models (RCMs), with 25 km resolution over the Mediterranean Sea, for the A1B scenario. Their results show that both global and regional models produce climate scenarios characterized by a significant drying of the Mediterranean region, mainly after year 2050 of the emission scenarios.

Concerning the impact of the climate change on the Mediterranean Sea, so far very few studies have been specifically devoted to this basin. Furthermore, all of these studies were conducted with just one climate model, leaving largely unresolved the fundamental issue of the uncertainty associated with the choice of the model. A pioneering work was done by Thorpe and Bigg (2000) simulating a transient $2xCO_2$ scenario with a 1/4°-resolution ocean model forced by the air-sea fluxes of a low-resolution IPCC model (2.5°x3.5°). Later, Somot et al. (2006) performed a similar study using a higher-resolution ocean model (1/8°) forced by fluxes coming from a dynamical downscaling (50 km) of an A2 IPCC run. Both studies show an increase of the sea surface temperature (SST) and sea surface salinity (SSS), leading to a strong weakening of the Mediterranean thermohaline circulation (MTHC) and a change in the characteristics of the Mediterranean waters out-flowing at the Gibraltar Strait. The latter study took into account the climate change impact coming from all the various forcings of the Mediterranean Sea (air-sea fluxes, Atlantic characteristics, river runoff and Black Sea impact) concluding that all of them could be important contributors to the possible evolution of the sea characteristics.

Most of the above mentioned works are based either on global low-resolution ocean-atmosphere coupled climate models (AOGCMs) or stand alone (atmosphere-only or ocean-only) high-resolution regional models. Each of two approaches presents advantages and weaknesses. An important shortcoming common to the global coupled and regional atmosphere only models is their limited capability to include into the climate change

110 projections for this region a realistic representation of the processes associated with the
111 presence of the Mediterranean Sea. The global AOGCMs used so far have horizontal
112 resolutions generally not sufficient to represent the complexity of the geomorphology of the
113 region. In Figure 1, panels a and b show the Mediterranean Sea and the surrounding mountain
114 chains (Atlas, Alps and Caucasus Mountains) as they are represented in a global model with a
115 horizontal resolution of about 300 km in the atmosphere and about 100 km in the ocean. This
116 is the order of resolution employed, for example, in several models used to perform the
117 CMIP3 simulations (Meehl et al, 2007). It appears evident that a number of important
118 features, such as, for example, the complex topography, the islands, the straits and the
119 coastlines of the Mediterranean Sea itself are only barely resolved. Therefore, these models
120 reproduce the small-scale physical processes that characterize the climate behaviour of the
121 region very poorly.

122 On the other hand, the atmosphere-only regional models used so far to downscale the
123 global simulations, such as those, for example, employed in the PRUDENCE or
124 ENSEMBLES EU-Projects, are usually implemented with horizontal resolutions ranging
125 from 50 km to 20 km, which according to Gibelin and Déqué (2010) and Gao et al. (2006)
126 should be sufficient to simulate a realistic circulation over the Mediterranean Sea and the
127 European continent. These models, however, are forced with prescribed lower boundary
128 conditions (SSTs) and thus they do not take into account any air-sea feedbacks. The lack of
129 these feedbacks reduces the consistency between SST, air-sea fluxes and vertical structure of
130 the atmosphere (air-sea coupling), diminishing the confidence in the modelling results over
131 the Euro-Mediterranean area (Somot et al. 2008). Furthermore, the Mediterranean SST used
132 to force the models over the basin are produced with low-resolution AOGCMs, which are
133 inadequate to reproduce the small scale features that distinguish the behaviour of this sea

(e.g., Marcos and Tsimplis 2008). Similar arguments hold for regional ocean-only model simulations, where air-sea feedbacks are not fully considered.

The deficiencies in including a realistic modelling 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 Mediterranean area and the European continent. A first attempt to remedy these deficiencies has been made by Somot et al. (2008) 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 for additional details). According to their results, the coupled model appears 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) 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.

In the framework of the CIRCE (Climate Change and Impact Research: the Mediterranean Environment) EU project, a set of coupled models has been developed with the aim of producing climate change projections for the Mediterranean region. Following Somot et al. (2008), all of the models include a high-resolution numerical model of the Mediterranean Sea and thus they can simulate the small-scale features of the basin. They have been integrated to produce multi-model ensemble simulations of the present climate and future change projections. The multi-model ensemble approach adopted in CIRCE is one of the techniques most frequently used to assess the uncertainties that can arise from different types of model errors (Deque et al. 2007). This approach provides an estimate of the uncertainty due to

structural variations among a range of models by combining them, with the main assumption of a quasi-independent development of the considered models and excluding any systematic analysis of individual sources of errors. In general, the multi-model ensemble experiments are not specifically designed to provide formal error estimates. They are in essence "ensembles of opportunity" and the ensemble spread can be seen as a tool to characterize the model uncertainty. The CIRCE experiments, thus, will allow the quantification of the Mediterranean Sea response to climate change, providing also an estimate of the uncertainty associated with the choice of models, though the relatively small size of the multi-model ensemble (five members) will not allow a comprehensive and statistically robust uncertainty assessment.

In the following we will discuss the basic characteristics of the CIRCE models, their ability to simulate the major features of the observed climate in the Mediterranean region and how these features might be possibly affected by the global warming in the next few decades.

2. The CIRCE models

The major novelty featured by the CIRCE models compared with the climate models commonly used to produce scenario simulations is the inclusion of a realistic representation of the Mediterranean Sea into the climate system. To achieve the aim, the CIRCE models include high-resolution atmospheric components fully coupled with high-resolution models of the Mediterranean Sea able to resolve those small-scale features that characterize the physiography of the basin, as it is shown in Figure 1 (panels c and d).

Figure 2 provides a schematic representation of the implementation of the CIRCE models. All of the models have a relatively high-resolution atmospheric component over the Mediterranean region (ranging from 80 to 25 km) that can be either stretched/global or limited-area over this region. These atmospheric components are coupled with a high-resolution model of the Mediterranean Sea, exchanging local air-sea fluxes. When the

183 atmospheric model is global (Figure 2, left panel), the rest of the global ocean is represented
184 by a global low-resolution ocean model coupled with the Mediterranean Sea in the vicinity of
185 the Strait of Gibraltar. When the atmospheric component is regional (Figure 2, right panel),
186 the lateral boundary conditions for both the limited-area atmosphere and the Mediterranean
187 Sea models are provided by global simulations.

188 Table 1 summarizes the main characteristics of the CIRCE models along with references
189 where more detailed descriptions of the models' features and in depth discussions of the
190 technical aspects are made. Here, for the sake of brevity, we provide only a general overview
191 of the modelling strategy, in order to illustrate the basic characteristics of the CIRCE
192 approach. In three cases (CMCC, CNRM and LMD), the Mediterranean Sea component is
193 coupled with a global atmosphere and, in a region near Gibraltar, with a global ocean. In these
194 models, every atmosphere-ocean coupling time step (~3 hours for CMCC and daily for
195 CNRM and LMD), heat (radiative and turbolent fluxes), mass (evaporation, precipitation and
196 runoff) and momentum fluxes are provided to the ocean models (both global and
197 Mediterranean) by the atmospheric model. At the same time, the atmosphere receives the
198 global SST and the sea-ice distribution values from the global ocean and the SST in the
199 Mediterranean Sea from the Mediterranean model. The communications between the oceanic
200 and atmospheric components are carried out with the coupler OASIS3 (Valcke 2006).

201 The global and Mediterranean ocean components, on the other hand, exchange the
202 coupling fields in a so-called "Atlantic box" (a relatively large area located to the west of
203 Gibraltar) via oceanic open boundaries, where the exchanged quantities (profiles of
204 temperature, salinity, zonal and meridional velocity and sea surface elevation) are suitably
205 interpolated. The coupling occurs every 8 hours in the CMCC model and on daily basis in the
206 CNRM and LMD models. The Atlantic characteristics in these modes evolved interactively in

the global refined models as the Mediterranean Sea component is fully coupled to the global ocean.

The climate simulations produced with these models (CMCC, CNRM and LMD), thus, account for the regional-scale processes that characterize the Mediterranean basin and provide, for the first time, the possibility to accurately assess the role and feedbacks of the Mediterranean Sea in the global climate system.

In the remaining two models (ENEA and MPI), the Mediterranean Sea is coupled with a high-resolution atmospheric limited area component. The coupling, done through OASIS3, is similar to the one implemented for the global models: heat, moisture and momentum fluxes are passed from the limited area atmosphere to the Mediterranean Sea component, and the latter returns SSTs to the atmospheric model with a coupling frequency of 6 hours. In this case, however, the coupled simulations are conducted prescribing lateral boundary conditions both for the atmosphere and for the ocean (in the Atlantic box). Specifically, the lateral boundary conditions for the MPI model are obtained from the CMCC model simulation (Scoccimarro et al, 2011), whereas the ENEA model uses data from the ECHAM5/MPI-OM CMIP3 simulations (Giorgetta et al. 2006). Therefore, in contrast with the CMCC, CNRM and LMD models, where the Mediterranean component is fully coupled to the global ones, in these regional coupled models (ENEA and MPI) the Mediterranean Sea does not provide feedbacks to the global climate system. However, the coupling between the high-resolution atmospheric and Mediterranean Sea components are expected to improve the consistency between SSTs, air-sea fluxes and vertical structure of the atmosphere (air-sea coupling) with respect to the coarse resolution global driver (Dell'Aquila et al. 2012) and thus to better simulate ocean–atmosphere feedbacks thereby providing more confidence in present and future climate changes over the Mediterranean region (Somot et al. 2008).

Rivers are interactively coupled to the atmosphere and ocean models for ENEA, CMCC and MPI and are, thus, impacted by the climate change signals. In the CNRM and LMD models, on the other hand, river discharges are kept constant at the observed monthly climatological values, as they are not provided of a suitable river routing scheme. In the scenario simulations, the climatological values of river discharge used in these two models, thus, are not consistent with the possible changes in land precipitation. A discussion of the implications of this choice has been done in Dubois et al. (2012). However, the river discharge is the smaller component of the water budget in the Mediterranean Sea and the error we make using climatological values is smaller than other approximations we make. For example, in reality in many Mediterranean rivers the actual discharge is strongly modulated by human activities, such as water demand for agriculture purposes (e.g., Lopez-Moreno, 2008). These land use changes are only marginally considered in the CIRCE models.

The Black Sea contribution to Mediterranean water budget (B) is treated differently in the different models. In the MPI case, where the Black Sea is explicitly represented, B is the net water transport computed at the Dardanelles Strait. In the CMCC and in the ENEA models, the B contribution is defined as the residual of the E-P-R (Evaporation-Precipitation-Runoff) budget for this basin in the atmospheric model. Then, following Somot et al. (2006), the budget is used as a freshwater input in the Aegean Sea. However, in the ENEA case, the computed values have been rescaled using monthly coefficients derived from a previous run forced by reanalysis in order to match observations (Dell'Aquila et al. 2011). The LMD and CNRM models, on the other hand, used monthly climatological values (Beuvier et al. 2010).

The water and heat budget of the Mediterranean Sea are controlled also by the water exchanges with the Atlantic Ocean, through the Strait of Gibraltar. Such exchanges are highly variable, with strong fluctuations ranging from semidiurnal to seasonal and interannual time-scales. Provision of a realistic reproduction of the physical processes that regulate the water

exchange between Mediterranean Sea and Atlantic Ocean at the Strait of Gibraltar is not straightforward. Recent works indicate that in order to make realistic simulations of the water exchanges at Gibraltar, a model should have very high resolution (both in horizontal, about 500 m, and in vertical, about 10 m, directions), it should include explicit tidal forcing, and it should be implemented with physical parameterizations taking into account diapycnal mixing and entrainment (e.g. Sannino et al 2009b and references therein). A model that has these characteristics would be able to properly reproduce the small-scale mechanisms that govern the water flow through Gibraltar and its hydraulic criticality (Sannino et al. 2009). However, the explicit representation of such small-scale processes in numerical models of the Mediterranean Sea designed for climate studies, and therefore running over several decades, is extremely demanding on computing resources and, at the present, beyond the available resources at many research centres. Thus, also in the CIRCE models the Strait of Gibraltar is modelled using only few grid points and vertical levels, and, in some cases, using relatively simple parameterizations for entrainment and mixing processes. Specifically, for the physical parameterization for entrainment and mixing processes applied at the strait, CMCC uses an up-stream advection scheme for active tracers, whilst in the rest of the basin a MUSCL (Monotonic Upwind Scheme for Conservation Laws, Van Leer 1979) scheme is adopted. The vertical diffusivity in this area, between 30 and 150 m depth, is increased in order to parameterise unresolved processes induced by vertical mixing. In the same geographical area the bottom friction drag coefficient is linear and five times larger than in the other parts of the model. ENEA increases the vertical diffusion 10 times with respect to the rest of the model in the Strait area, and replaces the horizontal bi-Laplacian viscosity with a Laplacian viscosity. MPI, CNRM, and LMD do not apply any specific parameterization (Dubois et al. 2012 and Elizalde et al. 2010).

The simulations

The models described above have been used to make climate simulations of the second part of the 20th Century (1951-2000) and the first part of the 21st Century (2001-2050). During the 20th Century period of the simulations, the distribution and concentration of the atmospheric greenhouse gases (GHGs) and aerosol (anthropogenic sulfate only) have been specified from observations, as it has been done for the CMIP3 20th Century integrations (hereafter referred to as 20C3M, Meehl et al. 2007). During the 21st Century period, on the other hand, the GHGs and anthropogenic aerosol have been specified according to the A1B IPCC-SRES scenario (Nakicenovic et al. 2000).

The model simulations have been initialized with the Levitus (Levitus 1982) or MedAtlas-II (MEDAR-Group 2022) climatology as initial conditions for the ocean and either atmospheric re-analyses or AMIP-type simulations (i.e. simulations where the atmospheric-only model has been integrated using observed SST as boundary conditions) for the atmosphere. A spin-up of several decades of the coupled system has then been performed by integrating the model with the 1950's permanent conditions (radiative forcing). For example, in the case of the CMCC model, the global coupled system (global atmosphere and global ocean) has been integrated for about 200 years and then the Mediterranean Sea model has been added to the system and another 50-year spin-up integration has been done. A similar spin-up procedure has been used with the other models (for additional details, please see the references reported in Table 1) and, in most of the cases it has allowed the models to reach a reasonably stable state (i.e. no significant long-term temperature drift was found for the upper ocean). Only in one case, the LMD model, there is some evidence that, despite the spin-up, the bottom water of the Mediterranean Sea (deeper than 1000 m) is still affected by a cooling trend at the beginning of the CIRCE integration that will affect the behaviour of the whole water column for the earlier decades of the simulation, as we will see in the computation of the steric effect in Section 3.

306 Once the model spin-up has been completed, the GHGs and aerosols have been changed
307 according to the 20C3M radiative forcing up to year 2000 and afterwards, from year 2001 to
308 2050, following the A1B scenario. As shown in Table 1, the ENEA and MPI models have
309 been integrated using boundary conditions from the 20C3M and A1B simulations performed
310 with ECHAM5MPI-OM (Giorgetta et al. 2006) and with the CMCC CIRCE simulation
311 respectively.

312 More detailed descriptions and in depth discussions of the models' features and how the
313 simulations have been conducted can be found in Dubois et al. (2012), Gualdi et al. (2012)
314 and in the documentation papers and reports listed in Table 1.

315 ## 3. Some results from the CIRCE projections

316 Here we illustrate some basic findings obtained from the CIRCE simulations, with the aim
317 of providing a quick overview and summary of the results of the CIRCE models and their
318 potential, especially for climate change impact studies in the Mediterranean region. A more
319 extended and detailed discussion of the results obtained from the CIRCE models can be found
320 in Artale et al. (2010), Gualdi et al. (2012), Dubois et al. (2012), Elizalde (2011) and
321 Dell'Aquila et al. (2011).

322 Overall, the CIRCE models appear to reproduce reasonably well many of the observed
323 features related to the orographic forcing. Compared to the CMIP3 models, the simulation, for
324 example, of the seasonal mean precipitation over the north-west of the Iberian Peninsula,
325 Alpine region, western coast of the Balkans and south-west Anatolian Peninsula seems to be
326 locally improved. Despite these local improvements, the overall model systematic errors over
327 the region remain substantial, both in terms of T2m and precipitation (Gualdi et al. 2012).
328 During both winter (DJF) and summer (JJA), the models are generally colder than
329 observations by about 2°C over most of the Mediterranean area.

Over land, larger errors, though confined to very small areas, are found locally in the northern foothills of the Alps (about -6°C), whereas a warm bias (about +4°C) covers the south-eastern part of the Alpine region. The models tend also to overestimate the precipitation over central Europe in both seasons, whereas rainfall tends to be underestimated in the Alpine region, Middle East and, in JJA, in the area of the Black Sea. A more detailed description of the CIRCE models' errors can be found in Gualdi et al. (2012).

Over the sea, the SST error appears to be rather uniform across the basin and can be explained by either too cold air-sea fluxes during the spin-up integration coming from the atmospheric model or by the advection of too cold waters through the Gibraltar Strait (Dubois et al. 2012, Dell'Aquila et al. 2011).

Despite the systematic error, however, most of the CIRCE models reproduce reasonably realistic patterns of near surface temperature and precipitation and a realistic structure of the Mediterranean SST, especially, of the observed SST gradients.

In order to provide an overall estimation of the capability of the CIRCE models in reproducing the main features of the observed Mediterranean climate, we computed the Taylor diagrams (Taylor 2001) of the T2m, precipitation and SST seasonal means (Figure 3). In this application, the simulated means are compared to the observed ones, with the spatial standard deviation and its associated root mean square difference (RMSD) plotted in relation to the pattern correlation. Specifically, Figure 3 shows the Taylor diagrams of the simulated Mediterranean SST averaged over the basin, and T2m and precipitation over land averaged over the Mediterranean area (28°-48°N, 9.5°W-38.5°E). The observations used in the analysis are T2m and precipitation obtained for the period 1971-2000 from the gridded observations (CRU-TS.3, Mitchell and Jones, 2005) and the high-resolution SST re-analysis for the Mediterranean Sea (Adani et al. 2011) for the period 1985-2000. A similar analysis has been done using the Mediterranean SST from the HadISST data set (Rayner et al. 2003) for the

period 1971-2000 and the results obtained are fully consistent with those shown in Figure 3 panels a and b.

Furthermore, to provide also a comparison between the CIRCE and the CMIP3 models' performance, we included in the diagrams the results obtained from a set of CMIP3 simulations. Importantly, the purpose of this work is neither to provide an exhaustive assessment of the differences between the CIRCE and the CMIP3 models nor to study all of the simulations available in the CMIP3 database. Thus, the set of CMIP3 models and simulations that we consider here is not comprehensive. With the ten CMIP3 models presented in Table 2 and considered in the analysis, we expect to have a representative sample of the performance of state-of-the-art coupled models in simulating the Mediterranean region climate and its possible projected changes. More information about the CMIP3 models can be found on the CMIP3 website at PCMDI: http://wwwpcmdi.llnl.gov/ipcc/model documentation/ipcc_model_documentation.php.

Overall, the majority of CMIP3 models (indicated with a + in the pictures of Figure 3) underestimate the spatial standard deviation. In several cases, the CIRCE models (coloured dots) appear to be closer to observations (black dot), though the spatial standard deviation of precipitation in DJF and T2m and SST in JJA tend to be slightly overestimated. Moreover, the majority of the CIRCE models have larger pattern correlations and smaller RMSDs than the CMIP3 ones. The Taylor diagrams of the multi-model ensemble means (indicated with ◇ for the CMIP3 case and with □ for the CIRCE case) give further evidence of the slight improvement of the CIRCE Mediterranean SST, land T2m and land precipitation compared to the CMIP3 models.

Noteworthy, both in the CIRCE and CMIP3 ensembles, the multi-model means appear to be in better agreement with observations than any of the individual models. This result is consistent with previous findings (e.g., Glecker et al. 2007), where much wider ranges of

physical variables were considered and analyzed. Pincus et al. (2008) suggested that the improvement associated with the multi-model means is generally due to both the spatial smoothing and the model systematic errors compensation performed by the multi-model averaging.

Finally, also the amplitude of the multiannual (interannual and decadal) variability (not shown) appears to be reasonably well captured by the CIRCE models both in terms of spatial distribution and amplitude, with maximum values of about 1°C.

Near-surface temperature and precipitation

The evolution of the simulated near-surface temperature averaged over the Mediterranean land during the recent past is in substantial agreement with the observations, showing that the region surrounding the Mediterranean Sea has been warming during most of the 20th Century. During the period 1951-2000 the ensemble mean warming trend is about 0.1±0.04°C/decade (statistically significant at the 95% level, according to Mann-Kendall trend test). The increase of the low-level temperature is found to have a remarkable spatial and seasonal modulation. During northern summer, the trend over western and central Europe appears to be larger than in the winter season. The largest trend (up to 0.2°C/decade) is found in JJA over the Iberian Peninsula and western part of North Africa. Importantly, the simulated trends found for the second half of the 20th Century are consistent with the results obtained from the observations for the instrumental period (1951-2005, Ulbrich et al. 2012).

A more in depth discussion of the trends of T2m and precipitation observed in the Mediterranean region and a comparison between the observed values and the CIRCE simulations can be found in Ulbrich et al. (2012) and Gualdi et al. (2012).

The CIRCE projections for the 21st Century suggest that remarkable changes in the climate of the Mediterranean region might occur already in the next few decades of the scenario, showing a rather steadily increase of the near-surface temperature that leads the

Mediterranean lands (i.e., the land comprised within the area 28°-47°N, 10°W-40°E) to be substantially warmer at the end of the integration period with respect to the 1961-1990 mean. The increment of the mean temperature is particularly pronounced in southern Europe and Northern Africa in summer (JJA) and over the Alps, where during both winter and summer season the projected 2021-2050 mean warming appears to be as large as 2°C.

The evolution of the simulated Mediterranean SST (Figure 4) shows no clearly discernable trends during the early period of the integration (1951-1980), then a positive trend appears to emerge, starting from the second half of the 1980s. The mean SST warming found for the period 2021-2050 compared to the reference period 1961-1990 ranges between +0.8 °C and 1.8°C.

The regional characteristics of the projected changes in different sub-regions of the Mediterranean area are shown in Figure 5, where the changes in mean T2m (right panels) and precipitation (left panels) are plotted. In particular, the pictures show the changes over seven sub-regions obtained as the differences between the mean for the period 2021-2050 and the reference period 1961-1990. The sub-regions are defined according to Giorgi and Lionello (2008) as: whole Mediterranean (Med) 28°-48°N, 9.5°W-38.5°E; Northern Mediterranean (NMed) 41°-48°N, 9.5°W-38.5°E; Southern Mediterranean (SMed) 28°-41°N, 9.5°W-38.5°E; Western Mediterranean (WMed) 28°-44°N, 9.5°W-10.5°E; Central Mediterranean (CMed) 28°-46°N, 10.5°E-20.5°E; Eastern Mediterranean (EMed) 28°-44°N, 20.5°W-38.5°E; Alpine region (ALPS) 44°-48°N, 5.5°E-15.5°E).

Figure 5 offers also the opportunity to compare the CIRCE projected change with the signal obtained from the considered CMIP3 models. Furthermore, it provides a first assessment of the differences (spread) between the results obtained from the different CIRCE models (+ symbols), which are an important component of the uncertainties that affect the CIRCE projections.

The results shown in Figure 5 left panels indicate that the projected warming appears to be relatively uniform across the considered sub-regions during JJA. In this season, all of the areas appear to be affected by a mean increase of T2m which ranges between about 1.75°C and 2°C in the CIRCE models and between 1.5 and 1.75°C in the CMIP3 ones. During winter (DJF, Figure 5, upper left panel), there are more pronounced differences between the responses of the sub-regions to the radiative forcing. The Alpine region, for example, appears to be more sensitive, showing a larger warming, particularly pronounced in the CIRCE projections. Also the spread of the results obtained from the different CIRCE models exhibits some substantial spatial and seasonal dependency. The difference between the model projections in the Northern Mediterranean (NMed) and in the Alps is significantly larger than the model spread found for the Southern or Eastern Mediterranean (SMed or EMed), especially during northern winter. Importantly, during both seasons, there is a remarkable agreement between the CIRCE and CMIP3 T2m projected changes, at least in terms of their multi-model ensemble means.

The changes in precipitation (Figure 5, right panes) show a clear tendency towards dryer conditions for the whole Mediterranean area, which is visible in both seasons, but more pronounced during summer. Overall, the change in precipitation between the 2021-2050 seasonal means and the seasonal means for the reference period is of about -5%. The model results show reduced rainfall over most of the sub-regions, even if the uncertainty due to the CIRCE model spread appears to be higher than for the T2m case. During summer (right lower panel), the reduction of precipitation appears to characterize all of the sub-regions, whereas in winter (upper left panel) the precipitation response appears to be different in the northern part of the Mediterranean area compared to the rest of the domain. Here, no substantial change (NMed) or even some rainfall increase (ALPS) is found, in agreement with the findings of Giorgi and Lionello (2008). Finally, also for the projected precipitation changes the results

obtained from the CIRCE models appear to be remarkably consistent with the CMIP3 simulations, especially for the DJF season.

The tendency towards a warmer and dryer climate for the Mediterranean region in the next decades is consistent with the change in surface circulation suggested by the change found in the projected mean sea-level pressure (MSLP, not shown). In DJF, a large area of increased MSLP covers the entire Mediterranean region, which, thus, appears to be characterized by increased anti-cyclonic circulation and enhanced stability. Furthermore, the increased anti-cyclonic circulation associated with the enhanced Mediterranean surface pressure is, in turn, associated with a northward shift of the Atlantic storm track. Both the increased stability and the northward displacement of the storm track have the effect of reducing the cyclonic activity in the Mediterranean basin, which is consistent with the decreased winter precipitation found in the projections. These results are in agreement with previous results based on the CMIP3 climate projections (Giorgi and Lionello 2008), with the trends in MSLP found in the observations during the instrumental period (Ulbrich et al. 2011) and with the PRUDENCE climate change projections (Christensen and Christensen 2007). The consensus that we see between the CIRCE projections and the results obtained from previous investigations leads to think that these findings are considerably robust to substantial changes in the configuration of the climate models used to produce the scenario simulations.

Changes in the Mediterranean Water Budget

The trends in temperature and precipitation found in the CIRCE projections are also associated with a more vast change, involving the Mediterranean basin and its hydrologic cycle in particular. Over the land surrounding the Mediterranean basin, projected evaporation shows very little change in winter and a clear tendency to decrease in summer, whereas over the sea it appears to increase both in winter and in summer. Noteworthy, these findings are fully consistent with Held and Soden (2006). The projected value of the budget evaporation-

480 precipitation (E-P) shows a marked positive trend, both over the sea and over the surrounding
481 lands, due to the combined effect of increased evaporation and reduced precipitation, in
482 agreement with results of Mariotti et al. (2008) and Sanchez-Gomez et al. (2009) obtained
483 using the CMIP3 and the ENSEMBLES simulations respectively.

484 The analysis of the simulated water budget (WB) of the Mediterranean Sea and its various
485 components (E-P-R-B, where R is the river runoff and B the net freshwater flux coming from
486 the Black Sea) shows that, in agreement with the observations, the Mediterranean Sea is an
487 evaporative basin, with a net loss of water through the surface, compensated by a net water
488 mass inflow from the Atlantic through the Strait of Gibraltar. Also the values of the simulated
489 water budget appear to be generally consistent with the observational data (~1.7 mm/day,
490 Sanchez-Gomez et al. 2011). Figure 6 shows the evolution of the simulated WB of the
491 Mediterranean basin for all of the CIRCE integrations. In the second half of the 20th Century,
492 the simulated WB is characterized by some large variability, but no clear long-term trends. In
493 the second part of the integration period (2000-2050), on the other hand, all of the models
494 exhibit a WB significant positive trend, with an ensemble mean value of approximately
495 0.07±0.02 mm/day per decade. The WB increase for the projected period 2021-2050
496 compared to the 1961-1990 mean ranges between 0.15 mm/day (for the ENEA model) and
497 0.35 mm/day (for the CMCC model). In all of the simulations, these changes are mostly due
498 to the decrease found in P, R and B and the increase in E. Specifically, the model projections
499 suggest that the increase in sea-surface evaporation might be as large as +3% (close to the
500 +2.9% found in Mariotti et al. 2008), whereas the reduction in rainfall is of about –9% (larger
501 than the -7.8% found in Mariotti et al. 2008). Therefore, according to the CIRCE projections
502 in the next decades the Mediterranean Sea might loose more water through its surface than in
503 the recent past. Also in this case the CIRCE simulations appear to be in overall agreement

with observations and the modelled tendencies are consistent in sign with those observed in the 1960-2000 period (Mariotti et al. 2008).

Changes in the Mediterranean Heat Budget

An analysis of the Mediterranean Sea surface heat budget (HB=SW+LW+LH+SH, where SW is the net surface short wave radiation, LW is the net surface long-wave radiation, LH is the latent heat flux and SH is the sensible heat flux) shows that, for all of the CIRCE models, the net budget is negative at the Mediterranean Sea surface, meaning that there is a net heat loss from the sea surface. The simulated HB for the reference period ranges between -1.7 W/m2 (ENEA model) and -6.4 W/m2 (LMD model), whereas the ensemble-mean is of -3.8 W/m2. These values compare well with the observations (e.g., -7.0 W/m2 from Pettenuzzo et al. 2010 and -3.0 from Sanchez-Gomez et al. 2011), though individually the components of the model HB can differ from the observed ones. Noteworthy, the fact that all of the CIRCE models produce a negative heat budget in the Mediterranean basin and in reasonably good agreement with the observations is an important result. This feature, which is a well-known characteristic of the Mediterranean Sea, in fact, is generally not reproduced by atmospheric only regional models (e.g., Sanchez-Gomez et al. 2011).

The simulated negative heat loss at the surface of the Mediterranean is compensated by a gain of heat from the Atlantic through the Strait of Gibraltar. During the control period, all of the CIRCE models show a net positive heat flux entering, through Gibraltar, into the Mediterranean Sea. The simulated values range between 2.3 and 6.3 W/m2, well consistent with the estimates obtained from the observations (Sanchez-Gomez 2011 and Pettenuzzo et al. 2010).

The projected response for the next decades shows, in all of the models, an increase in SW heat gain (reduced cloud cover), a decrease in the LW heat loss (the increased incoming LW radiation due to the atmospheric greenhouse effect prevails on the increased outgoing LW

radiation due to the higher SSTs), a decrease in the SH loss (the air-sea temperature gradient decreases as the atmosphere warms faster that the ocean) and an increase in the LH heat loss (increased evaporation). In all of the CIRCE simulations, the surface net heat loss decreases during the 21st century projections and the projected response in the different heat flux components appear to be consistent among all models. The mean simulated HB for the period 2021-2050 is of about -0.8 W/m2, leading to a weaker cooling of the ocean by the atmosphere.

An extensive analysis of the Mediterranean water budget and heat budget as simulated by the CIRCE models, including a detailed comparison with the observations and a discussion of the projected changes is provided in Dubois et al. (2012).

Changes in the Mediterranean Sea-Level

The CIRCE projections provide also an estimate of the possible sea-level change in the Mediterranean Sea due to the steric effect, which for this basin has been shown to be quite substantial (Marcos and Tsimplis 2008). Combining tide-gauge observations and satellite products, Calafat et al (2009) suggest that the steric effect in the Mediterranean Sea might produce a trend of sea-level change of 0.3 cm/yr for the 1993-2000 period and 0.1 cm/yr for the 1961-2000 time interval. Figure 7 shows the evolution of the simulated steric sea-level change in the CIRCE integrations from 1951 to 2050. During the reference period (1961-1990), the ensemble mean tendency is of -0.07±0.2 cm/yr. The models produce a rather broad range of trends, varying from the positive values of the ENEA and CNRM models (+0.16 and +0.17 cm/yr, respectively) to the relatively small negative values of the CMCC and MPI simulations (-0.16 and -0.13 cm/yr, respectively) to the large negative value found for the LMD case (-0.57 cm/yr). The large negative steric trend found in the reference period of the LMD simulation, is most likely due to a remarkable negative temperature drift still present in the Mediterranean Sea water during the early decades of the integration. The cooling is

554 particularly pronounced during the 1951-1970 period (e.g., about -0.03°C/year in the upper
555 1000 m) and it is probably due to an incomplete spin-up of the model.

556 Throughout the projected period, all of the CIRCE models show significant positive trends
557 of the steric sea-level change (0.29±0.13 cm/yr). The 2021-2050 mean steric sea-level rise
558 ranges between +7 cm and +12 cm, with respect to the reference period. Marcos and Tsimplis
559 (2008), using the A1B CMIP3 simulations, found that the steric effect for the Mediterranean
560 Sea at the end of the 21st Century might account for an average sea-level change ranging
561 between -22 and +18 cm. In the CIRCE projections, therefore, the range of sea-level change
562 appears to be significantly reduced compared to the results of Marcos and Tsimplis (2008).
563 However, the relatively small number of models that form the CIRCE ensemble does not
564 allow performing a robust uncertainty assessment. Therefore, with the present results, we
565 cannot attribute the smaller spread to an actual reduction of the uncertainty produced, in turn,
566 by the improved representation of the Mediterranean Sea in the models.

567 Finally, it is noteworthy that the CIRCE range of steric change is consistent also with
568 Tsimplis et al. (2008), where at the end of a 21st Century SRES A2 projection performed with
569 a coupled atmosphere-ocean regional climate model (Somot et al. 2008) the basin-averaged
570 sea-level rise is of about 13 cm.

571 ## 4. Concluding remarks

572 The CIRCE project has made substantial efforts to improve the simulations of the climate
573 of the Mediterranean region, with the aim of providing more reliable climate change
574 projections for this area. In particular, we enhanced the representation of the Mediterranean
575 Sea in the climate system by including ocean components permitting mesoscale circulation
576 features in the Mediterranean basin. For the first time, the evolution of some key sea variable
577 (such as, for example, SST, SSS, sea-level, water and heat fluxes) can be obtained at high

resolution over the Mediterranean Sea and with a high degree of physical consistency due to coherent air-sea flux modelling by dedicated coupled atmosphere-ocean models.

When compared with the CMIP3 simulations, the CIRCE models show some improvement in reproducing the seasonal means of T2m, precipitation and SST. However, the CIRCE simulations, which include high-resolution air-sea coupling in the Mediterranean region, show significant systematic errors in near-surface temperature and precipitation. Such errors are locally larger than those obtained with regional high-resolution atmospheric only models (e.g. the ENSEMBLES models).

The CIRCE models provide a reasonably good estimate of the Mediterranean water budget and, especially, of the surface heat budget. In contrast with most of the ENSEMBLES models, the total heat budget in all of the CIRCE simulations is negative for the present period, with values in good agreement with observations, satisfying the heat closure budget controlled by the heat transport through Gibraltar, also consistent with the observational results.

The CIRCE projections indicate that remarkable changes in the Mediterranean region climate might occur already in the early few decades of the scenario. A substantial warming (almost 1.5°C in winter and almost 2°C in summer) and a significant decrease of precipitation (about 5%) might affect the region in the 2021-2050 period compared to the reference period (1961-1990), in an A1B emission scenario. However, locally the changes might be even larger. The projected surface net heat loss decreases in the projected period, leading to a weaker cooling of the Mediterranean Sea by the atmosphere. On the other hand, the water budget appears to increase in the next decades, leading the Mediterranean Sea to loose more water through its surface than in the past. Furthermore, according to the CIRCE projections, the climate change might induce a 2021-2050 mean steric sea-level rise that ranges between +7 cm and +12 cm, with respect to the period of reference.

The climate change projections obtained from the CIRCE models are overall consistent with the findings obtained in previous scenario simulations, such as PRUDENCE, ENSEMBLES and CMIP3. The agreement leads to think that these findings are robust to substantial changes in the configuration of the climate models used to produce the scenario simulations. The consensus between the CIRCE projections and the previous findings, especially those obtained from PRUDENCE and ENSEMBLES, shows also that, in general terms, the regional air-sea coupling does not impact strongly the response to anthropogenic climate change.

The CIRCE results show also a non-negligible spread, which is, most likely due to differences in the models physics and in the experimental set up, such as the use of global and limited area model configurations, the latter integrated with boundary conditions coming from different global simulations. Also, it is likely that the introduction of the air-sea coupling in the CIRCE simulations contributes to the spread of the responses, although a size of five ensemble members does not allow testing it in a statistical sense. An increase in spread, however, does not necessarily imply an increase in uncertainty in the CIRCE simulations with respect to the results obtained with uncoupled models. The use of uncoupled regional models, as, for example in ENSEMBLES or PRUDENCE, introduces an underestimated uncertainty because the models neglect the physical processes associated with the two-way interaction between atmosphere and ocean, which might be important, as shown in Somot et al. (2008) and Artale et al. (2010).

Finally, it is important to keep in mind that despite some improvements, the CIRCE models still have large systematic errors. Therefore, to increase the reliability of the climate change projections, further efforts are required to reduce the biases introduced by the regional air-sea coupling.

The most evident and pronounced systematic error in the CIRCE simulations is the cold bias that appears to affect the entire region. As it has been discussed in Dubois et al. (2012), this bias might arise from different sources such as too cold Atlantic water entering at Gibraltar and atmospheric air temperature boundary conditions. However, also problems in the model physical parametrizations (e.g., the surface albedo, especially over the Mediterranean Sea) might contribute to the error.

The models discussed here can be improved in many ways, either trying to reduce the systematic errors and improving the representation of important processes. As a first step, for example, the parameterisation of the surface albedo over the Mediterranean Sea could be improved by introducing a dependency on the zenith angle. The change in the albedo representation might have an impact of more than 15 W/m2 on the net shortwave radiation (Dubois et al. 2012), affecting thus the surface temperature. Also the representation of the fresh water input, both from the river discharge and the Black Sea, should be enhanced, improving further the water balance of the basin. Moreover, in order to provide more accurate estimates of the possible Mediterranean Sea level rise, the local and remote effects of the atmospheric pressure should be included in the ocean model equations.

The regional climate simulations performed within CIRCE represent the first attempt to address the possible climate change in the Mediterranean area using a set of coupled numerical models able to represent the basic physical properties of the Mediterranean Sea, with a multi-model approach. They have represented a seminal effort that will be continued and improved in new international programmes and initiatives such as, for example, HyMeX (Hydrological cycle in the Mediterranean Experiment, Drobinski and Ducrocq 2008) and Med-CORDEX (Mediterranean Coordinated Regional Climate Downscaling Experiment, Ruti et al. 2011).

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796 **Tables**

Model	Atmosphere component	Global Ocean component	Mediterranean Sea component	Gibraltar and Lateral Boundary Conditions	Rivers and Black sea
CMCC (INGV) (Scoccimarro et al. 2011)	**ECHAM5** 80km, L31	**OPA8.2 - ORCA2 grid** ~ 2°x2° (0.5° equator), L31	**NEMO-MFS** 1/16° (~ 7km), L71 (Oddo et al. 2009)	Fluxes exchanged between global ocean and Mediterranean Sea. Mediterranean outflow distributed over the upper 300m in the global ocean grid point near Gibraltar.	TRIP river scheme (Nile runoff corrected to the observations after 1968). Black sea input from the E-P-R flux (Oki and Sud, 1998).
LMD (IPSL) (Hourdin et al. 2006, Zou et al. 2010)	**LMDZ global + LMDZ regional** 300 km, L19 + 30 km, L19	**OPA9 - ORCA2** ~ 2°x2° (0.5° equator), L31	**NEMO-MED8** 1/8° (9-12 km), L43 (Beuvier et al. 2010)	Tracer profile and fluxes exchanged using Cross-Land Advection parameterisation and buffer zone .	Climatological river discharge (Ludwig et al. 2009).
CNRM (Météo France/ CNRM) (Somot et al., 2008)	**ARPEGE-Climate TL159c2.5**, stretched model: 50x50 km over Euro-Mediterranean-North Africa) L31	**OPA9 - ORCA2** ~ 2°x2° (0.5° equator), L31	**NEMO-MED8** 1/8° (9-12 km), L43 (Beuvier et al. 2010)	Tracer profile and fluxes exchanged using Cross-Land Advection parameterisation and buffer zone.	Climatological river discharge (Ludwig et al. 2009).
PROTHEUS (ENEA) (Artale et al., 2010)	**REG-CM3** 30 km, L19	-	**MIT-gcm** 1/8° (9-12 km), L42 (Sannino et al. 2009a)	Atlantic buffer zone. Lateral Boundaries from ECHAM5/MPI-OM (Giorgetta et al. 2006).	IRIS rivers scheme. Instantaneous runoff to the river mouth. Black sea input from E-P-R budget bias corrected.
MPI (MPI-HH) (Elizalde 2011)	**REMO** 25 km, L31	-	**MPI-OM** 9 km, L29 (Elizalde et al. 2010)	Atlantic buffer zone. Lateral Boundaries from CMCC. (Scoccimarro et al, 2011).	Interactive hydrological model and Black sea model (Hagemann and Jacob 2007).

797

798 **Table 1:** summary of the basic features of the CIRCE models and their implementation. References indicate where a more detailed description of

799 the models, their features and performances are described and discussed.

Acronym	CMIP3 model name	Centre	Atmospheric resolution	Oceanic resolution
BCCR	BCCR-BCM2.0	Bjerknes Centre for Climate Research (Norway)	2.81° x 2.81° L31	1.5°x(1.5° - 0.5°) L35
CNRM	CNRM-CM3	Météo-France / Centre National de Recherches Météorologiques (France)	2.81° x 2.81° L45	2°x(1.5° - 0.5°) L31
CSIRO	CSIRO-Mk3.5	CSIRO Atmospheric Research (Australia)	1.88° x 1.88° L18	1.88° x 0.84° L31
GFDL	GFDL-CM2.1	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory (USA)	2.5° x 2° L24	1°x(1° - 0.33°) L50
IAP	FGOALS-g1.0	LASG / Institute of Atmospheric Physics (China)	2.81° x 2.81° L26	1°x(1° - 0.33°) L30
IPSL	IPSL-CM4	Institut Pierre Simon Laplace (France)	3.75° x 2.5° L19	2°x(1.5° - 0.5°) L31
MIROC	MIROC3.2(hires),	CCSR/NIES/FRCGC (Japan)	1.1° x 1.1° L56	0.28° x 0.19° L47
MPI	ECHAM5/MPI-OM	Max Planck Institute for Meteorology (Germany)	1.88° x 1.88° L31	1.5° x 1.5° L40
NCAR	CCSM3	National Center for Atmospheric Research (USA)	1.4° x 1.4° L26	1°x(1.1° - 0.27°) L40
UKMO	HADCM3	Hadley Centre for Climate Prediction and Research / Met Office (UK)	3.75° x 2.5° L38	1.25° x 1.25°

Table 2: List of models and relative resolution (atmosphere and ocean). The grid interval is approximate, as it may vary across latitudes and may be different in the longitude and latitude directions. The reader is referred to the PCMDI web site http:// www-pcmdi.llnl.gov for more information on models and experiments.

FIGURE CAPTIONS

Figure 1: orography of the Euro-Mediterranean region and bathymetry of the Mediterranean Sea as represented in a state-of-the-art global coupled ocean-atmosphere model with horizontal resolution of about 300 Km in the atmosphere and 1º in the ocean (panels a and b), and in the CIRCE models where in most of the models the resolution is higher than 50 Km in the atmosphere and 1/8º in the ocean.

Figure 2: scheme of the basic characteristics of the CIRCE models. Left: set up of the models with a high-resolution Mediterranean Sea component coupled with a global ocean and a global atmosphere (INGV, IPSL and METEOFrance models). Right: set up of the models where the high-resolution Mediterranean Sea component is coupled with a high-resolution limited area atmospheric model (ENEA and MPI models).

Figure 3: Taylor diagrams of SST (panel a, DJF mean, panel b JJA mean), T2m over land (panel c, DJF mean, panel d JJA mean) and precipitation over land (panel e, DJF mean, panel f JJA mean). The plot summarizes the pattern correlation, root mean square difference, and spatial standard deviation of each of the CMIP3 and CIRCE models with respect to observations (SST Mediterranean re-analysis, Adani et al. 2011 and CRU TS 3, Mitchell and Jones, 2005) over the Mediterranean area (28°-48°N, 9.5°W-38.5°E).

Figure 4: evolution of the sea-surface temperature (SST) anomalies from 1951 to 2050 as simulated with the CIRCE models (thin black lines) and with the CMIP3 models (red dashed line). The anomalies are expressed in °C and have been computed with respect to the 1961-1990 mean. The thick, black curve is the CIRCE multi-model mean, whereas the shading is the CIRCE multi-model standard deviation with respect to the multi-model mean. In order to

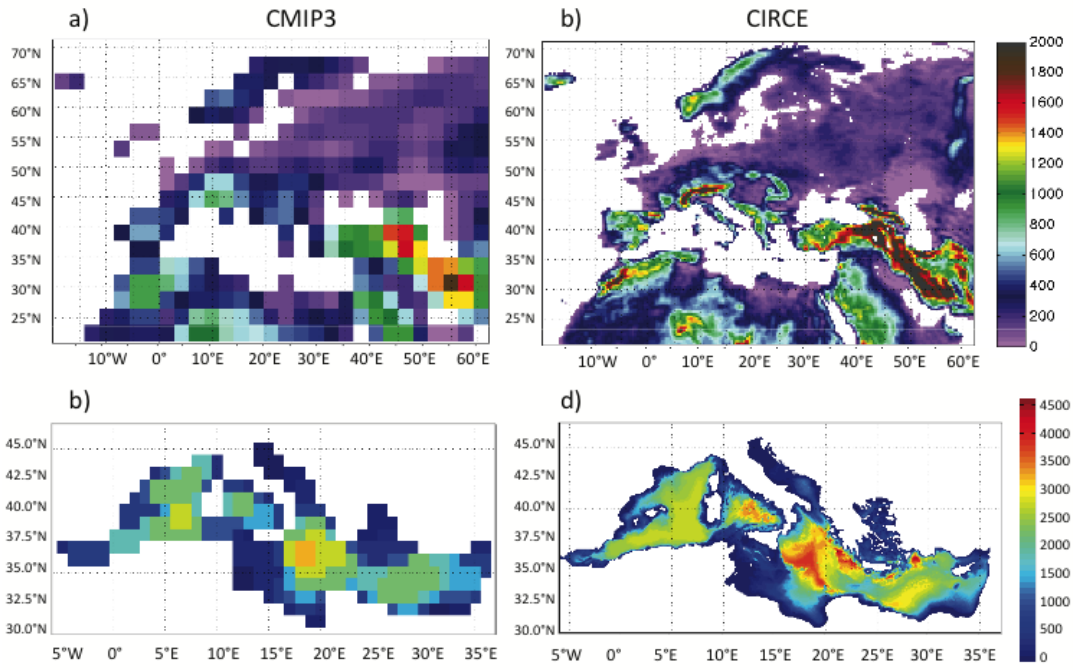
highlight the long-term trends, the interannual variability has been filtered by applying 5-year running mean.

Figure 5: change in seasonal mean 2-meter land temperature (T2m, left panels) and mean precipitation (right panels) obtained from the CIRCE and the CMIP3 simulations for the 2021-2050 period compared to the reference (1961-1990) period. The CIRCE models are indicated with the + symbol, whereas the filled black circles represent the CIRCE multimodel ensemble means and the filled red squares represent the CMIP3 multimodel ensemble means. Upper panels show the changes for the winter (DJF); lower panels show the changes for the summer (JJA). The differences have been computed for seven areas of the Mediterranean region defined according to Giorgi and Lionello (2008). Units are °C for T2m and % of the reference period value for precipitation.

Figure 6: as in Figure 3, but for the water budget of the Mediterranean basin expressed in mm/day. The budget is computed as the difference between Evaporation, Precipitation and Runoff averaged over the Mediterranean Sea and the contribution from the Black Sea (E-P-R-B).

Figure 7: as in Figure 4, but for the steric component of the sea level change. The plotted values (cm) show the evolution of the simulated sea-level change due to the steric effect. Steric anomalies are computed with respect to the reference period (1961-1990).

FIGURES



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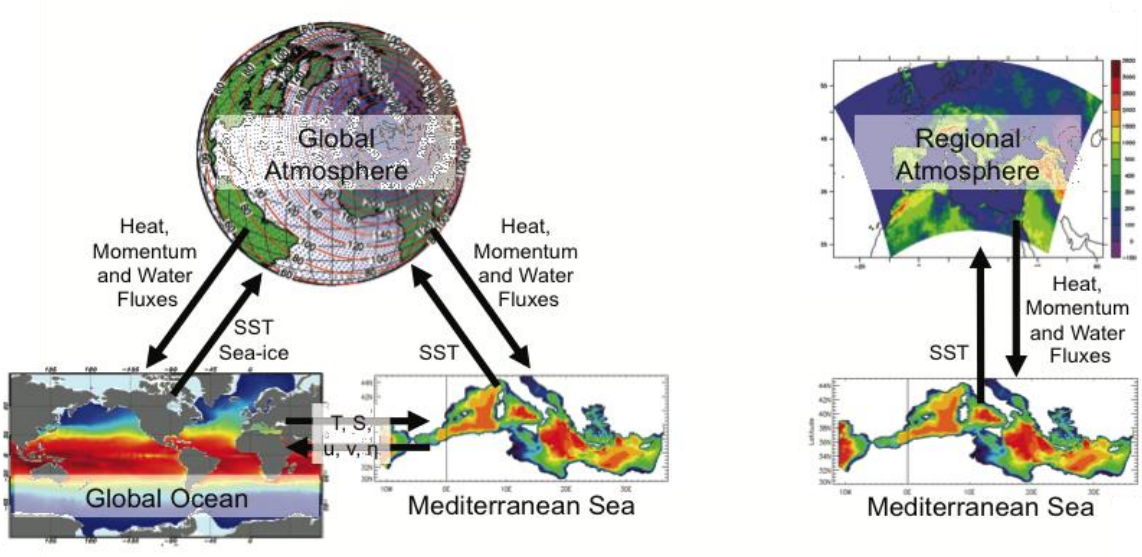

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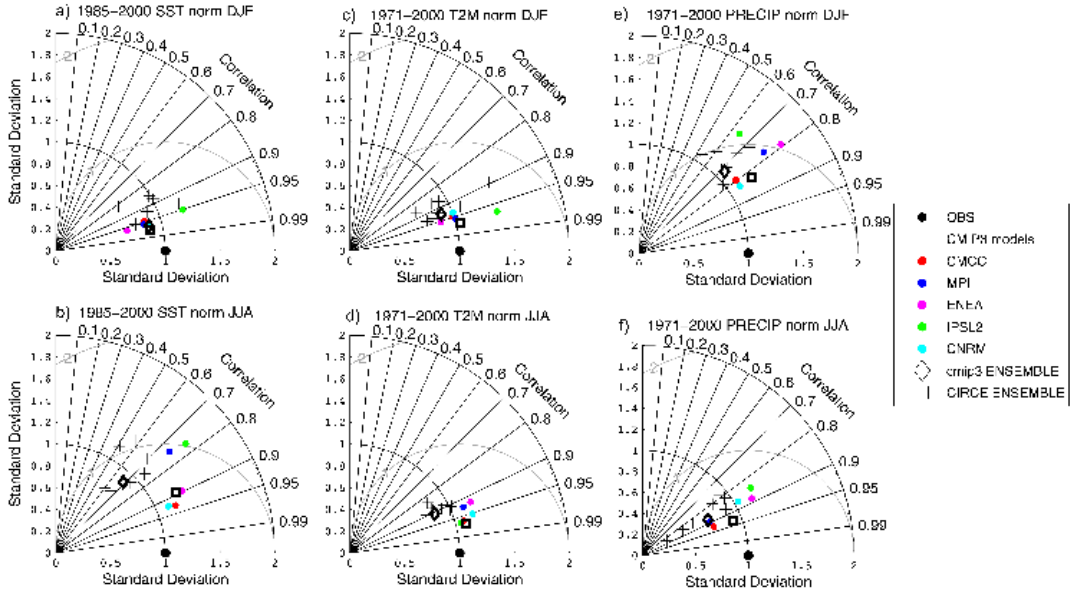

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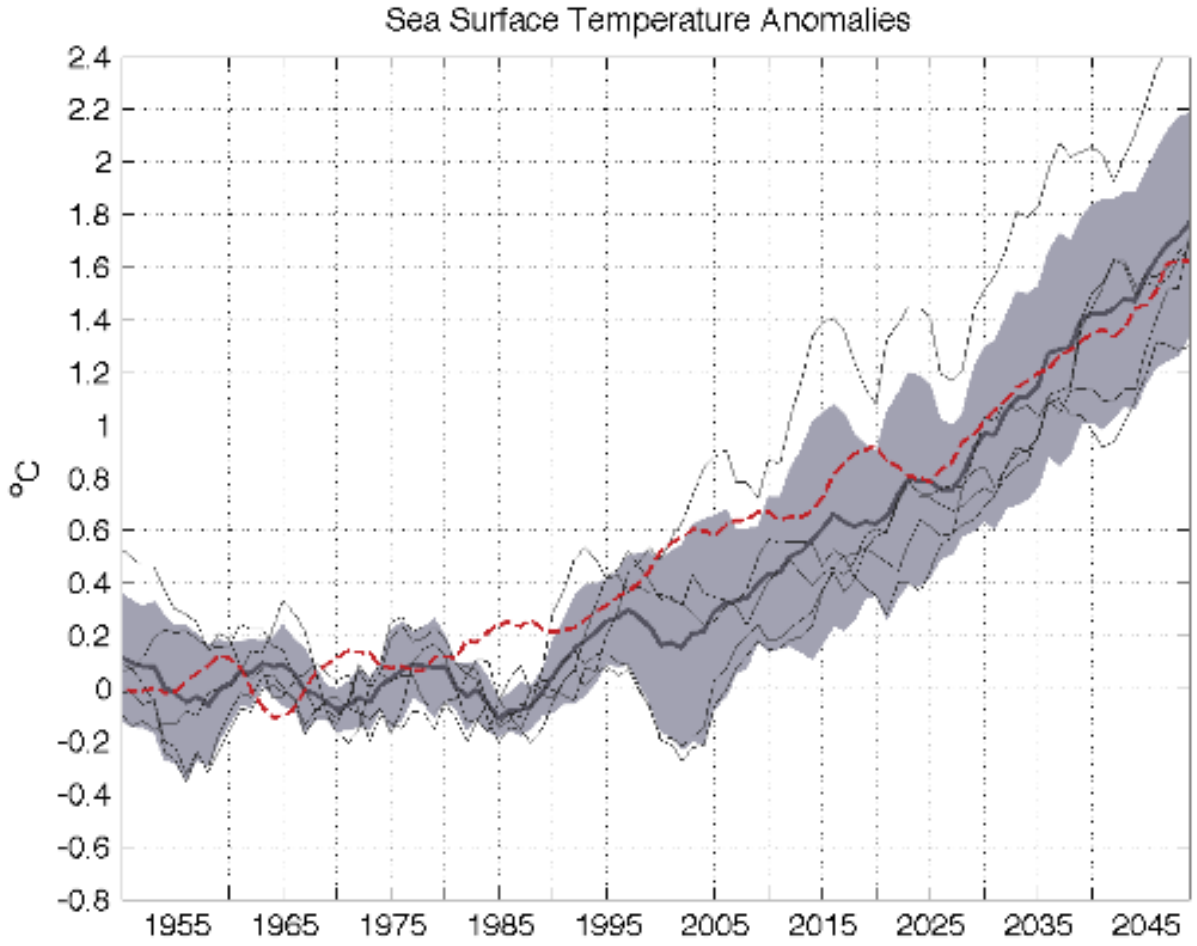

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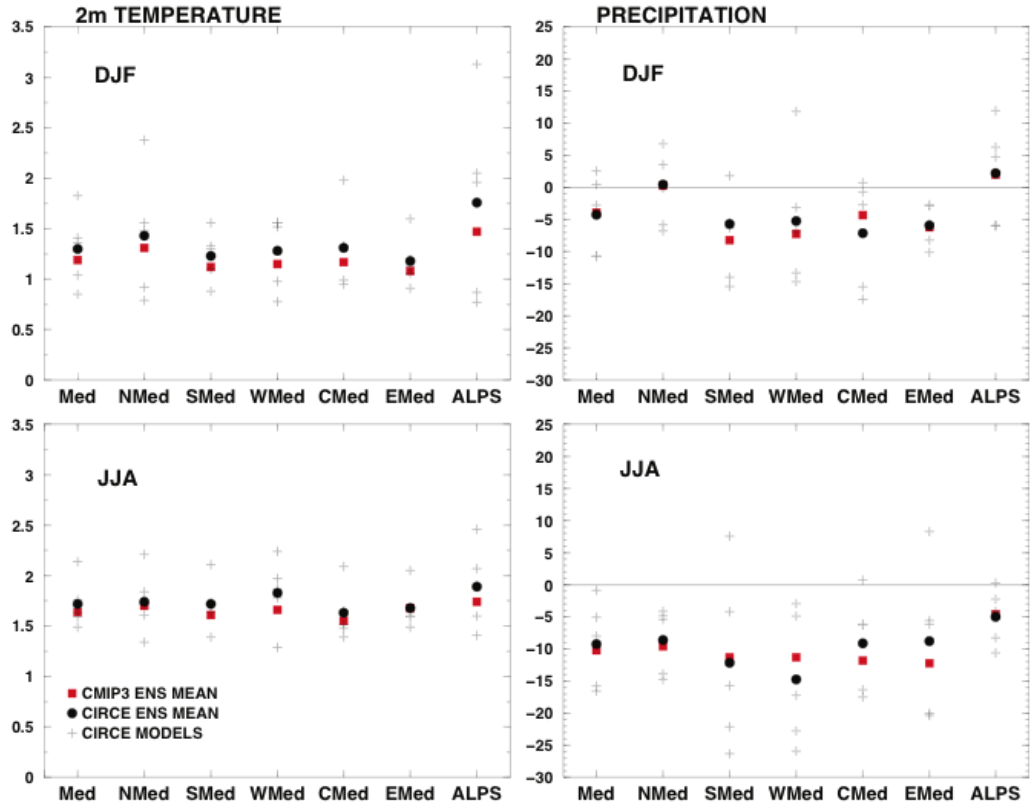

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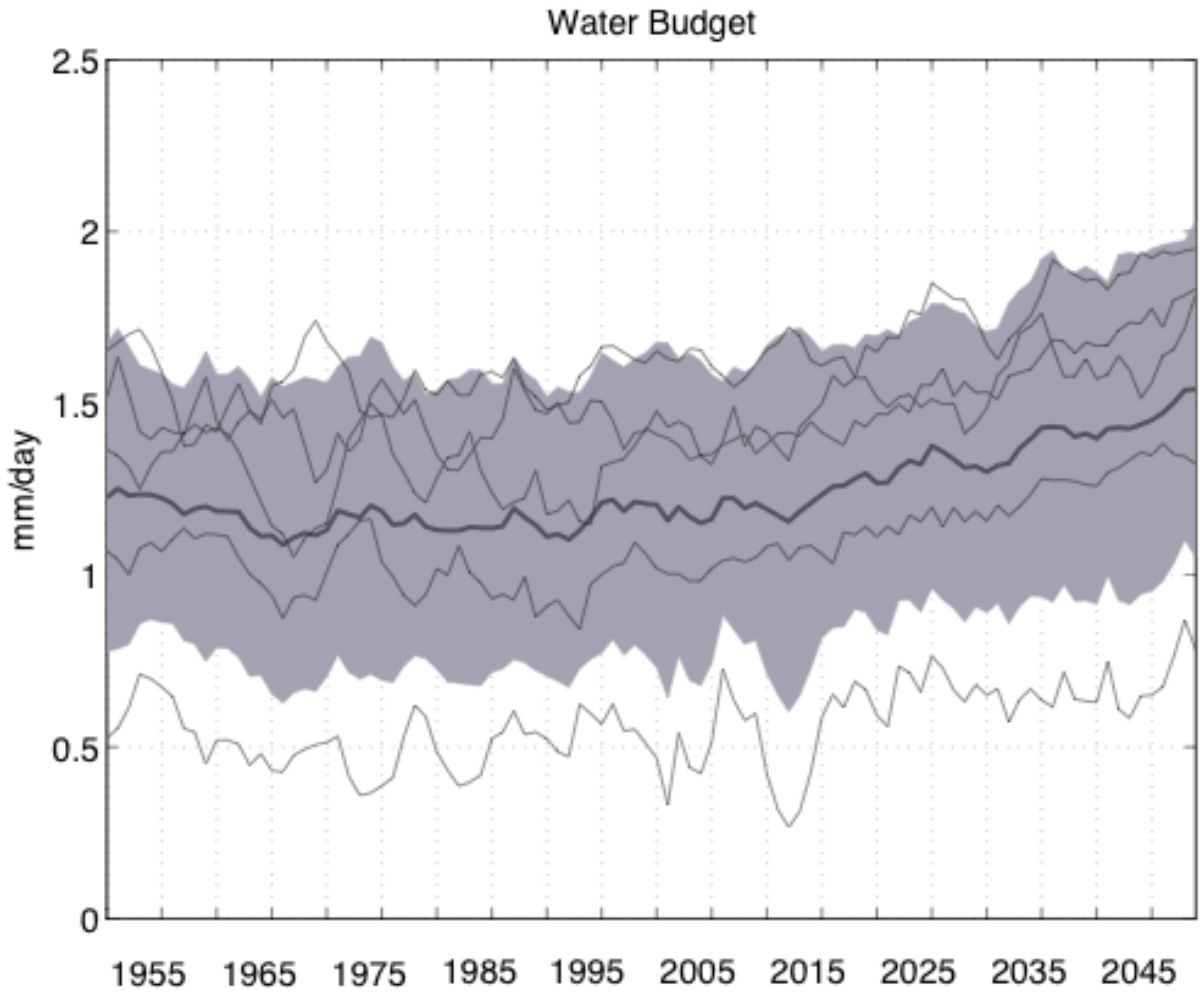

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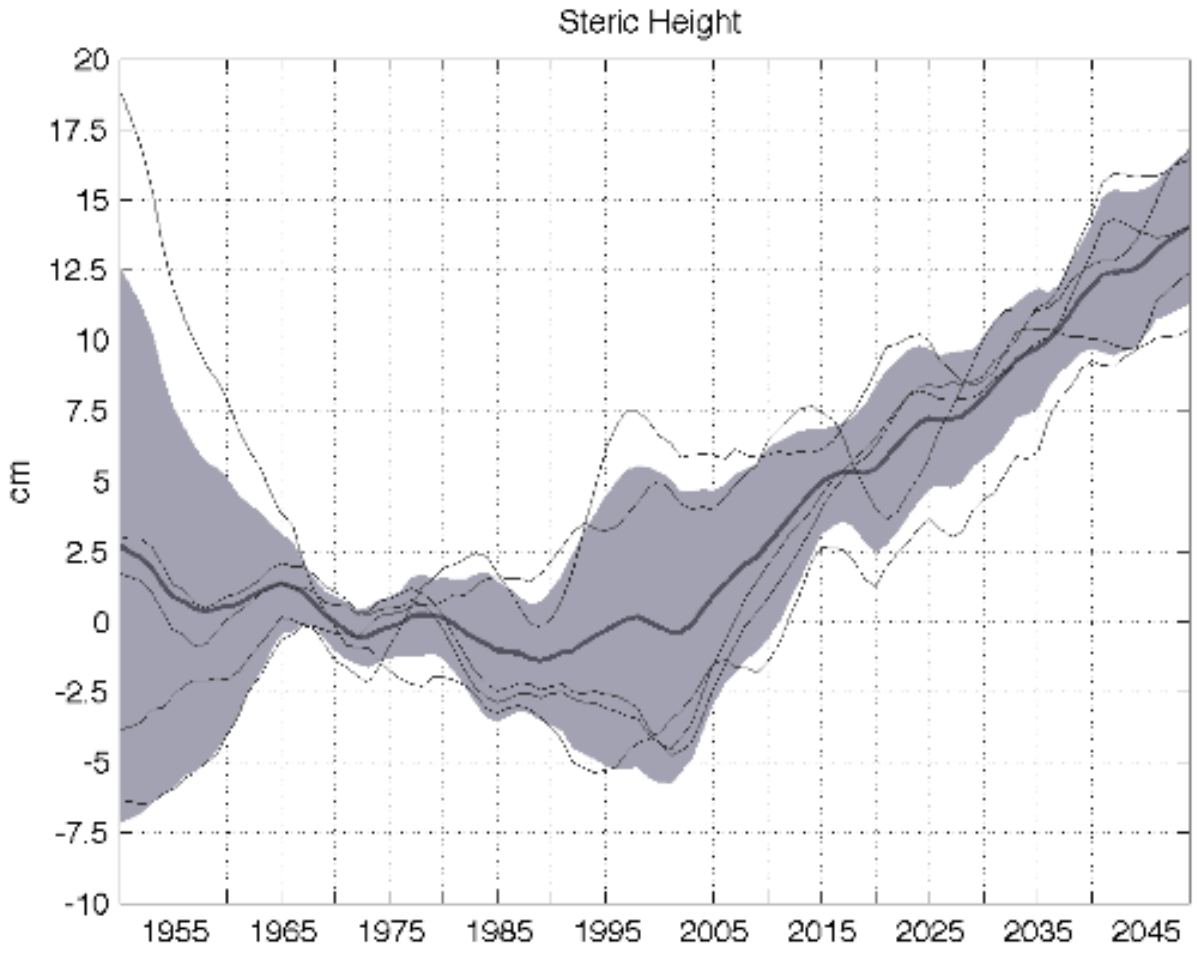

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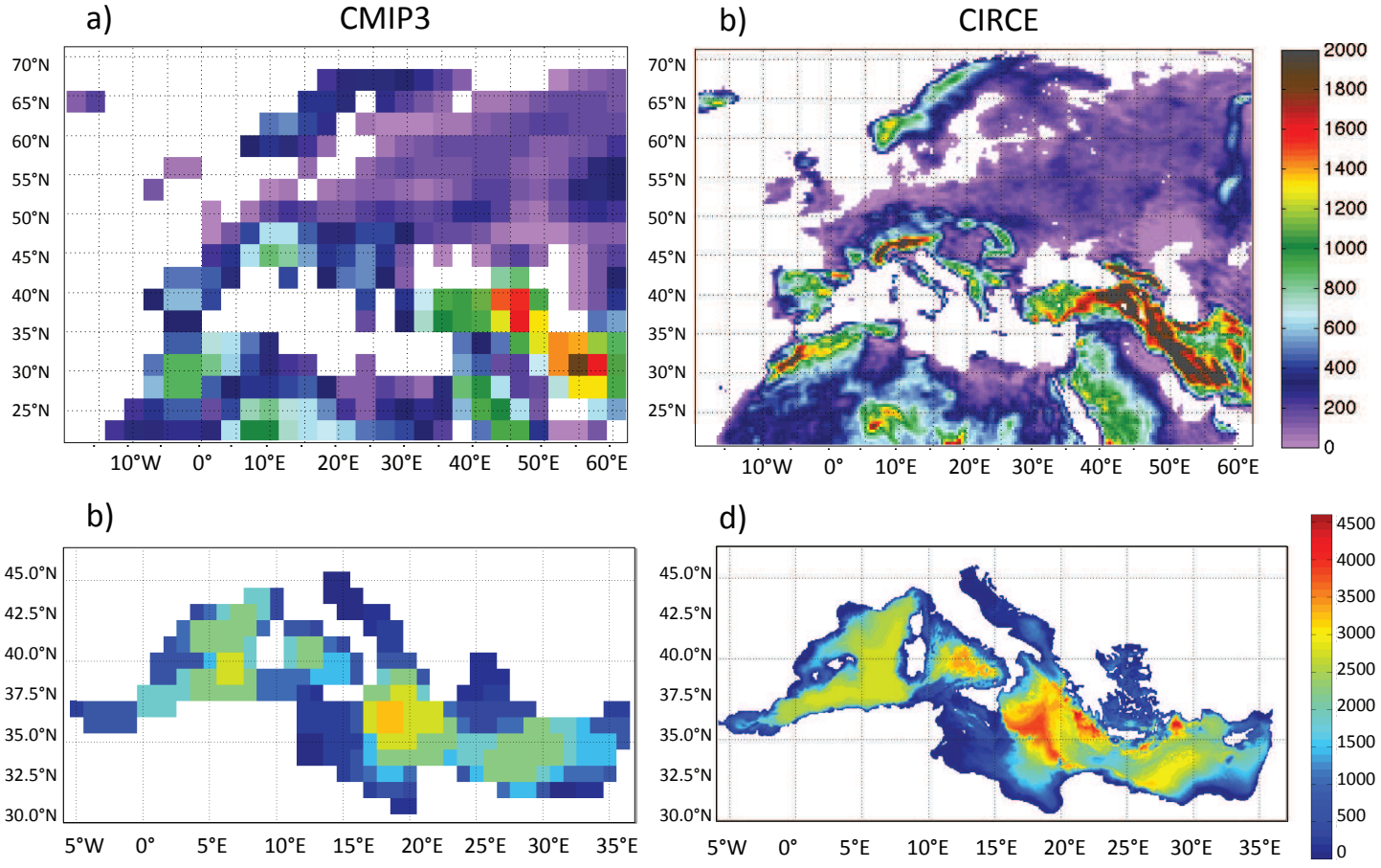

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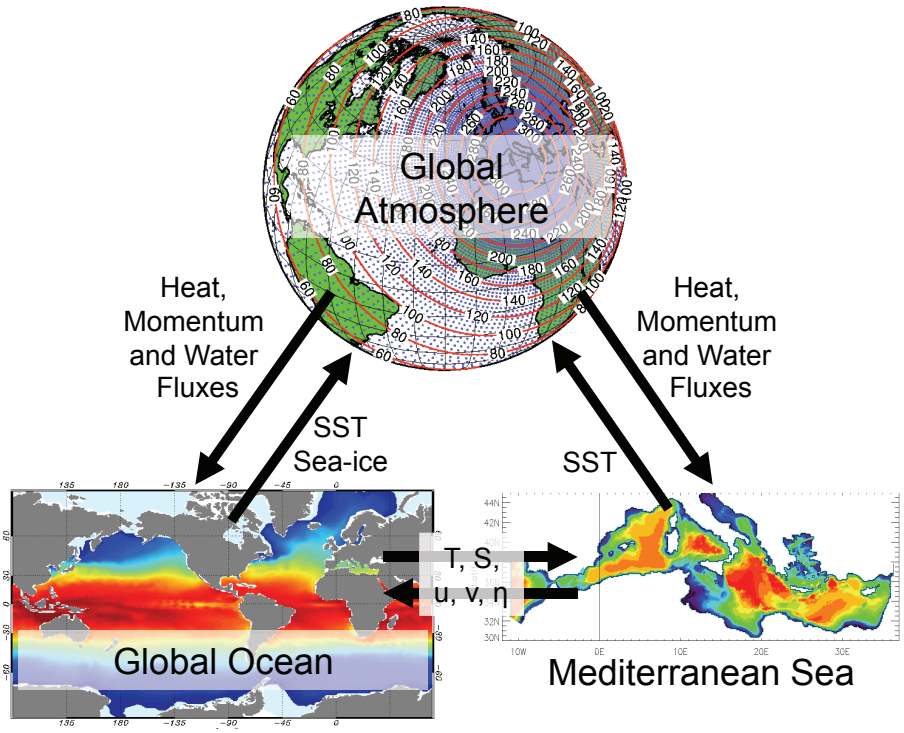

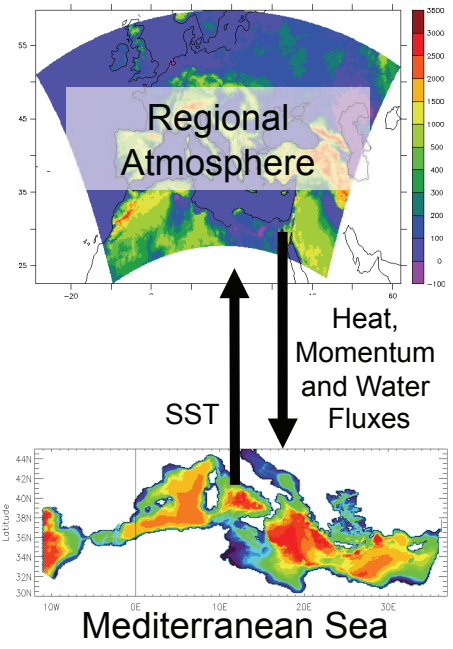

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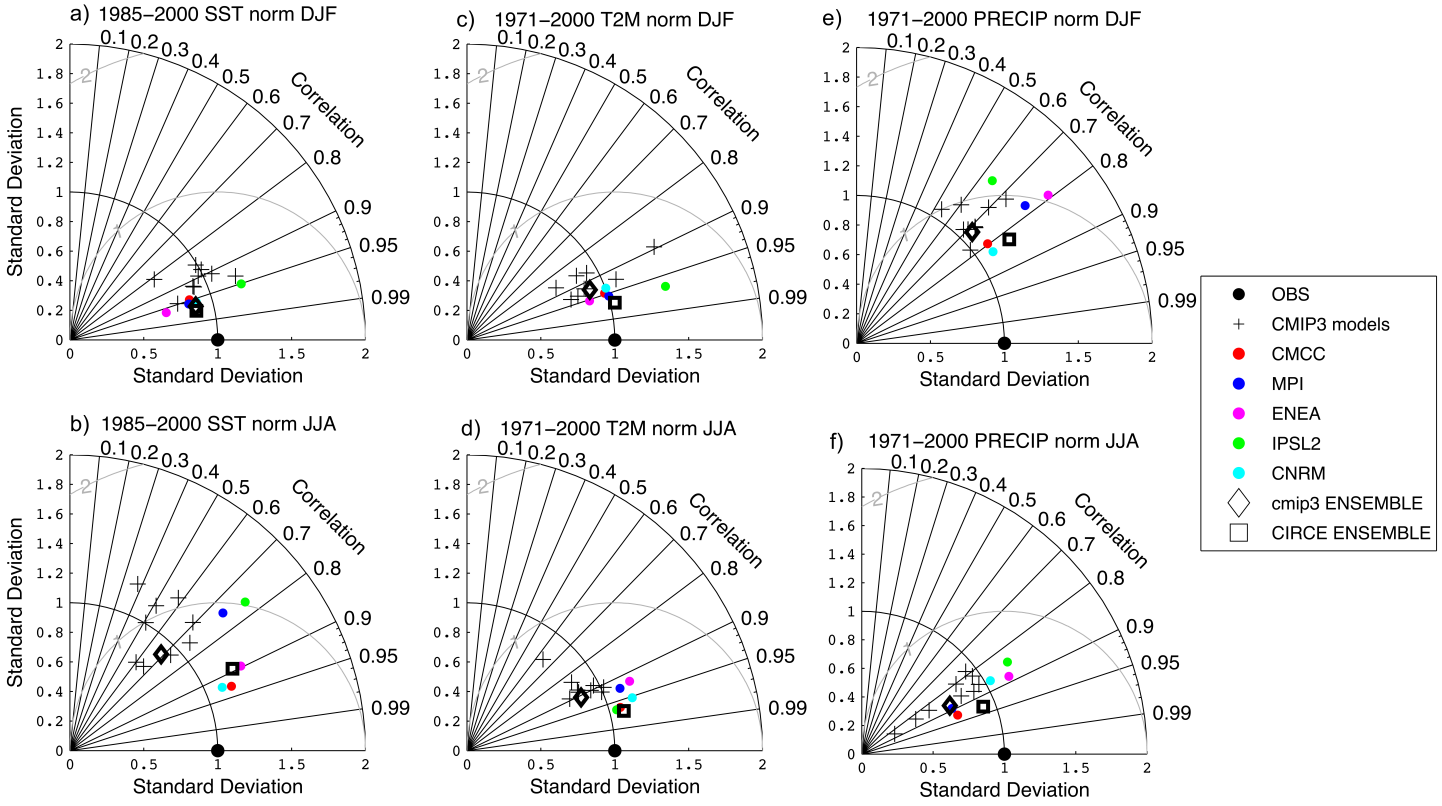

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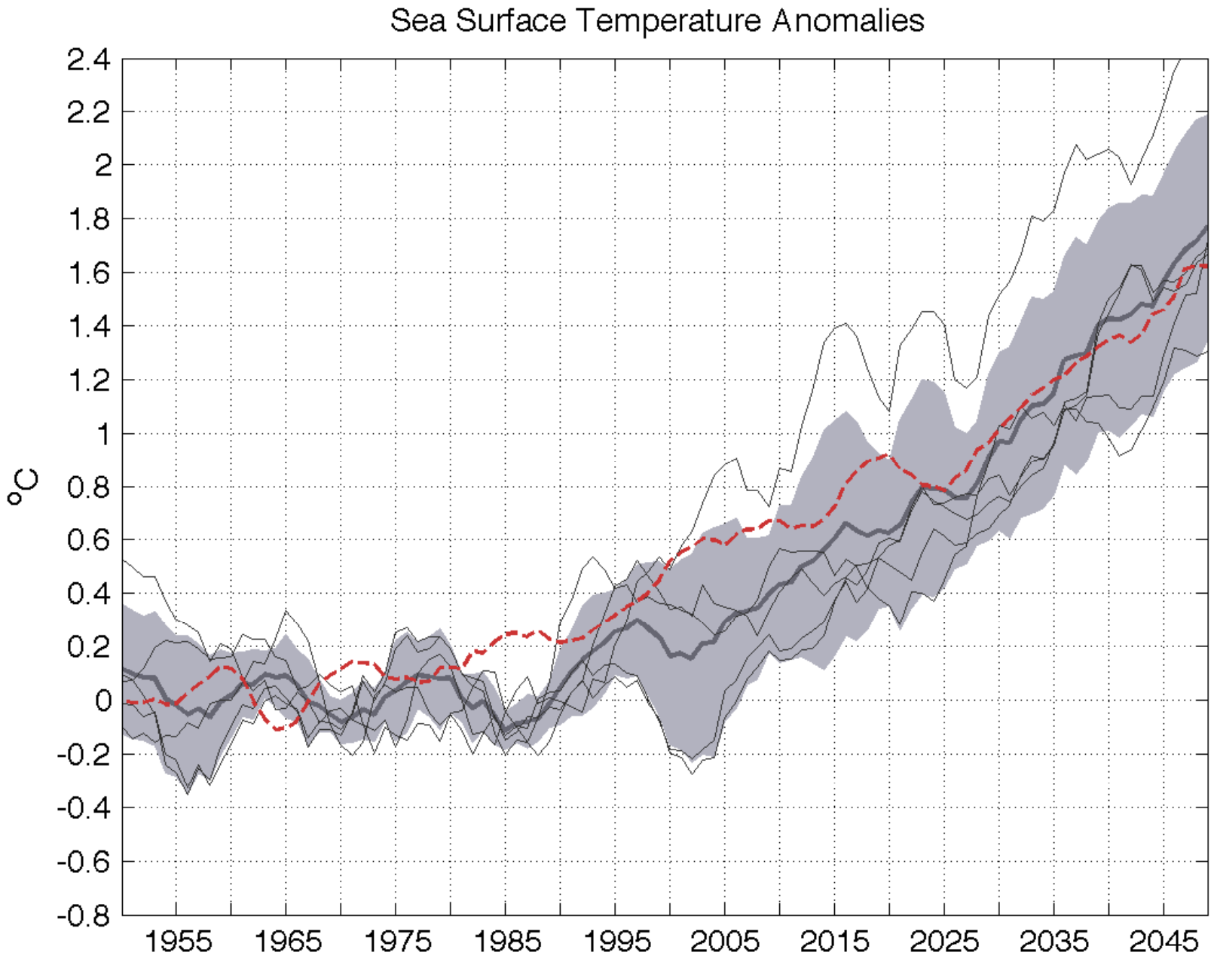

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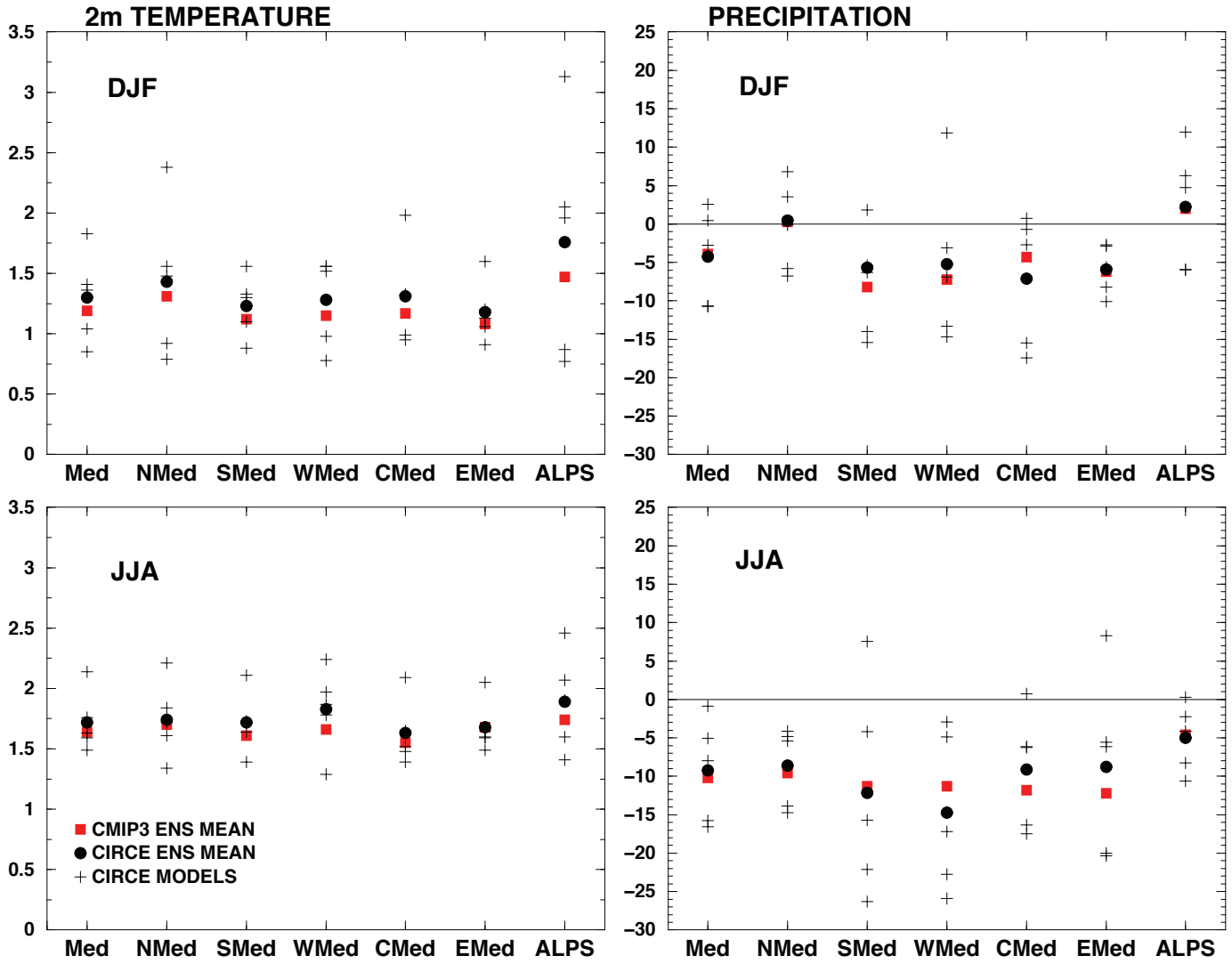

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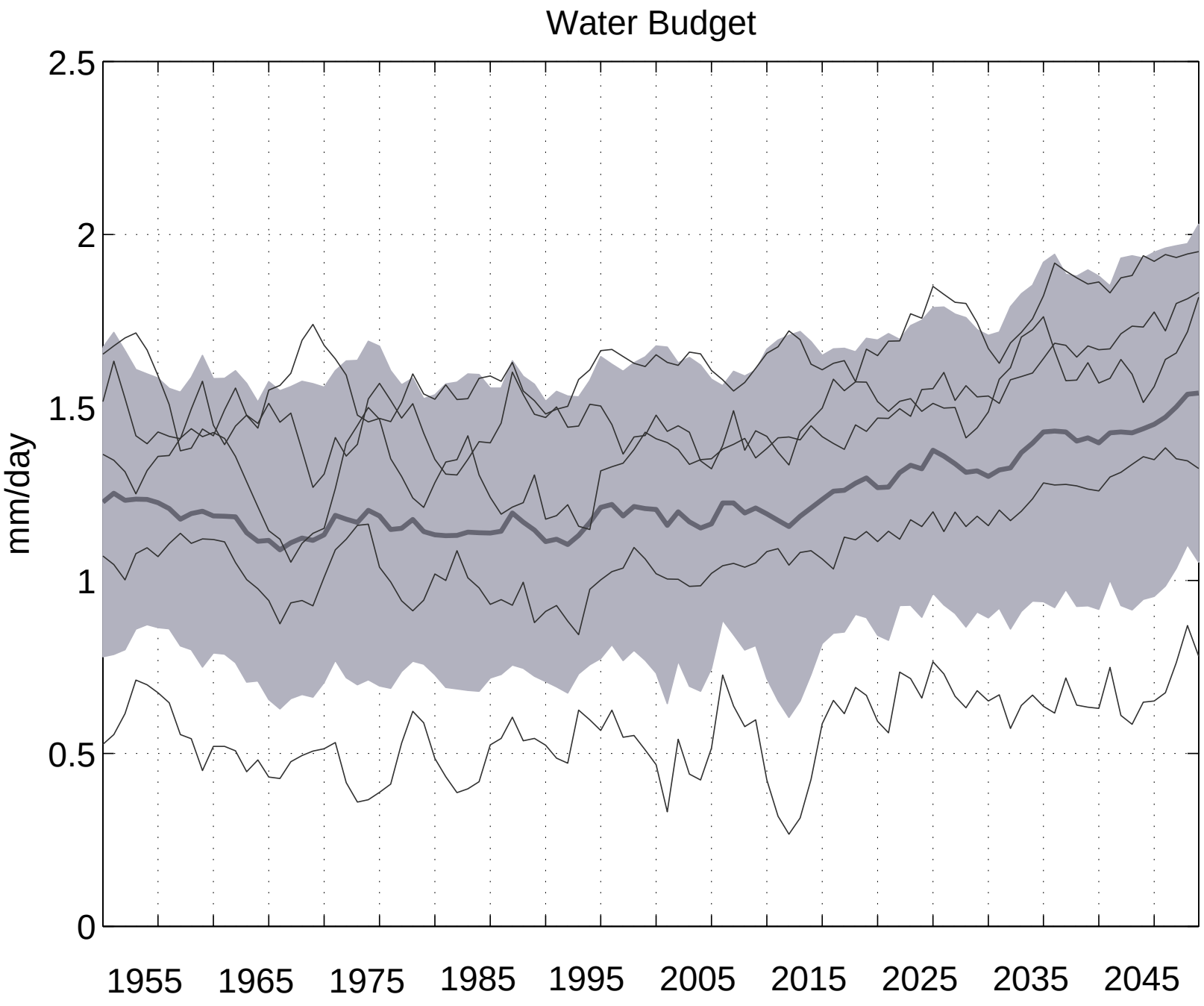

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