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Response of the Mediterranean Sea Surface Circulation at Various Global Warming Levels: A Multi-Model Approach

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Key Points:

- A large regional climate ensemble to study the future evolution of the Mediterranean Sea has been built for various global warming levels
- Significant, linear and robust changes in surface circulation are projected for the northern Balearic and southern Adriatic regions
- Significant, linear and robust increase in the circulation variability is detected in open-sea regions

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Changes in Mediterranean circulation patterns due to global warming may have strong socio-economic and environmental impacts. We analyze the future evolution of the Mediterranean surface circulation under different levels of global warming by using 28 multi-decadal simulations from a set of fully coupled and high-resolution regional climate models of the Med-CORDEX multi-model initiative. There is no model agreement for a significant basin-scale modification of the surface circulation. However significant and robust local circulation changes are identified. In particular, the circulation is expected to shift from cyclonic to predominantly anticyclonic in the northern Balearic, while a strengthening of the cyclonic circulation is expected in the southern Adriatic. Furthermore, our results show an increase in the Mediterranean circulation variability primarily associated with a general increase of meso-scale activity. Generally, we find a linear increase of the identified changes with global warming levels.

Plain Language Summary Changes in the current flow of Mediterranean waters due to global warming could significantly impact the environment and local populations. This study analyzes the impact of climate change on the surface circulation of the Mediterranean Sea. For this purpose, we use a set of regional climate scenarios under different future greenhouse gas emissions, carried out by the Mediterranean modeling community. Under global warming, the models do not agree in predicting robust changes in surface circulation at the basin scale. However, we find significant circulation changes in specific regions. In particular, the circulation in the northern Balearic is expected to shift from counterclockwise to predominantly clockwise, while the counterclockwise circulation in the southern Adriatic is expected to strengthen. Finally, the variability associated with Mediterranean circulation is expected to increase, mainly as a consequence of an enhanced eddy activity. The response of the mean surface circulation and variability to global warming is stronger as the global warming level increases.

1. Introduction

Over the past two decades, the Mediterranean Sea has been identified as highly vulnerable to climate change (Cherif et al., 2020; Giorgi, 2006). In this context, global warming is expected to affect current atmospheric and oceanic conditions (Ali et al., 2022), which may have large socio-economic impacts in a region with a densely populated coastline. By the end of the 21st century, several studies based on the Intergovernmental Panel on Climate Change (IPCC) scenarios display significant trends in sea surface temperature (Soto-Navarro et al., 2020), marine heatwaves (Darmaraki et al., 2019; Rosselló et al., 2023), sea level rise (Sannino et al., 2022), deep water thermohaline characteristics and air-sea fluxes (Adloff et al., 2015; Parras-Berrocal et al., 2022, 2023; Somot et al., 2006). From the previous literature, only two studies (Darmaraki et al., 2019; Soto-Navarro et al., 2020) were based on a multi-model approach to assess the future impacts of climate change in the Mediterranean Sea within the Med-CORDEX initiative (Ruti et al., 2016; https://www.medcordex.eu/).

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At the ocean-atmosphere interface, the Mediterranean Sea surface circulation has been extensively studied for the present climate using in-situ observations, satellite, reanalysis, and model data (e.g., Escudier et al., 2021; Millot & Taupier-Letage, 2005; Morales-Márquez et al., 2021; Pascual et al., 2014; Poulain et al., 2012; Robinson et al., 1992; Vigo et al., 2018). Regional model representation of the Mediterranean surface circulation has improved (Adloff et al., 2018; Sevault et al., 2014) significantly since the first model intercomparison carried out for the Mediterranean Sea as part of the MEDMEX project (Beckers et al., 2002). However, as noted in the First Mediterranean Assessment Report (Cherif et al., 2020), future changes in the sea surface circulation have not been studied in detail. Despite its strong capacity to modulate regional climate, there are few studies concerning the future evolution of the Mediterranean surface currents and turbulence (Adloff et al., 2015; de la Vara et al., 2022; Macías et al., 2018; Ser-Giacomi et al., 2020). For the near future (horizon 2030), Macias et al. (2018) pointed to a strengthening of the northern current in the northwestern Mediterranean. Toward the end of the 21st century, Adloff et al. (2015) showed notable changes in the surface circulation of the Balearic and North Ionian Seas using different emission scenarios. Under a high-emission scenario, Ser-Giacomi et al. (2020) projected a significant increase in horizontal stirring associated with a rise in the kinetic energy of Mediterranean currents, primarily in its turbulent component. More recently, de la Vara et al. (2022) found a weakening of the cyclonic circulation around the Tyrrhenian Sea, while dynamical structures such as the Bonifacio Gyre and the recirculation area off Sardinia become more intense. However, all these works are based on a single-model approach, limiting the robustness of their conclusions as the model choice is known to be one of the main sources of uncertainty in future projections of the regional climate (Evin et al., 2021). Therefore, a multi-model analysis is needed to better characterize the model uncertainties and to provide more robust conclusions.

Knowledge of the interannual variability and future evolution of Mediterranean dynamics is essential for understanding changes in the distribution of energy fluxes, mass transports, biogeochemical processes, and ecosystem connectivity patterns (Rossi et al., 2014; Sciascia et al., 2022; Ser-Giacomi et al., 2021), among others. Therefore, this work aims to study, in a robust way, the response of the Mediterranean surface circulation at different levels of global warming (from +1 to +4°C relative to the pre-industrial period) using a multi-model approach. To this end, we analyze a large ensemble of multi-decadal simulations performed with high-resolution and fully coupled regional climate system models (RCSMs) from the Med-CORDEX initiative. For the first time to our knowledge, we use Global Warming Levels (GWLs; IPCC, 2021) to assess the impacts of climate change on the Mediterranean Sea. The use of GWLs allows us to characterize the contribution of changes in mean climate, extremes, and drivers of climate impacts, regardless of the specifics of the emission scenario leading to warming or the timing of the warming level occurrence (IPCC, 2021). GWLs also facilitate communication between climate scientists and socio-economic and policy decision-makers motivated by impacts and mitigation assessment. Here, we provide to the Mediterranean Sea community an application of this novel methodology for regional climate modeling studies.

The main features of the RCSMs, simulations, and GWLs used in this work are described in Section 2. The present Mediterranean surface circulation and the future evolution of the mean state and temporal variability are presented in Section 3. Finally, the main conclusions and perspectives are summarized in Section 4.

2. Methods

2.1. Regional Climate Scenarios

In this work, we perform a multi-model and ensemble analysis using a set of twenty-eight multi-decadal simulations from nine fully coupled RCSMs (AWI/GERICS-ROM, CMCC-COSMOMED, CNRM-RCSM4, CNRM-RCSM6, ENEA-REG, GUF-CCLM/NEMO-5, GUF-CCLM/NEMO-6, UBEL-EBUPOM, LMDz4-NEMOMED8v2) from seven research institutes of the Med-CORDEX initiative; this dataset represents the largest regional climate ensemble used so far to study the Mediterranean Sea. All models used in our analysis have previously been used, evaluated and compared in the Med-CORDEX framework (Anav et al., 2024; Sevault et al., 2014; Somot et al., 2018). A detailed description of model parameterizations and set-up as well as single-model evaluation papers can be found in Table S1 in Supporting Information S1.

The high resolution of the ocean (6–12 km; eddy-resolving) and atmospheric (12–50 km) models, as well as the high air-sea coupling frequency (at least 1 day) between the two components, provide a reasonably accurate representation of the air-sea fluxes, which is essential for the correct reproduction of the Mediterranean surface circulation. The domains cover the entire Mediterranean basin and a small portion of the North Atlantic.

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For data availability reasons, only monthly 2D dynamic sea level (DSL) and wind stress (Text S1 in Supporting Information S1) are considered. Indeed, as developed in Text S2 in Supporting Information S1, under the geostrophic and Ekman approximations, surface velocities can be retrieved from those variables. All the datasets were bilinearly interpolated onto a common regular 0.11° resolution grid (OMED-11i) provided by Med-CORDEX. Out of a total of 28 simulations, 11 are historical and 17 are 21st century projections (Table S1 in Supporting Information S1), driven by various CMIP5 (Taylor et al., 2012) and CMIP6 (Eyring et al., 2016) global circulation models (GCMs) and different families of IPCC emission scenarios (Representative Concentration Pathways (RCP2.6, RCP4.5 and RCP8.5, Taylor et al., 2012) and Shared Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, SSP5-8.5, O'Neill et al., 2016; Riahi et al., 2017)).

2.2. Global Warming Levels

One of the novelties of this work is that, for the first time, GWLs (IPCC, 2021) are used to assess the impact of climate change on the Mediterranean Sea, allowing us to pool different CMIP5 and CMIP6 scenarios and model generations. The GWLs are defined as the 20 year period over which the mean global surface air temperature reaches a given level of warming, between 1°C and 4°C, relative to the pre-industrial period 1850–1900 (Hauser et al., 2022). The GWLs used in this study (Table S2 in Supporting Information S1) are calculated from the GCMs driving the regional models following the AR6 IPCC report (IPCC, 2018; Nikulin et al., 2018) and provided by Hauser et al. (2022). However, application of the GWL approach to RCSMs has some limitations, as most regional coupled simulations start in the mid-twentieth century. In the GCMs, GWLs are calculated relative to 1850–1900, whereas we set the baseline period to 1981–2000, which is the earliest 20 year period common to all RCSMs. Thus, our reference period corresponds to a global warming of about +0.5°C (IPCC, 2021) instead of 0°C. However, as we show in the following section, we are confident that this limitation does not significantly affect our assessment of climate change. It should be noted that runs under different scenarios simulated by the same model have been pooled using the GWL framework.

3. Results

3.1. Present-Day Mediterranean Circulation

Before analyzing the future response, we first evaluate the ability of each RCSM to simulate the mean state and temporal variability of the surface circulation. We compare the simulated DSL with altimetric satellite observations (https://doi.org/10.48670/moi-00141) and reanalysis data provided by the Copernicus Marine Environment Monitoring Service (CMEMS, Escudier et al., 2020, https://marine.copernicus.eu/). The altimetric product provides multi-mission data over the Mediterranean Sea since 1993 with a nominal resolution of 1/8°, while the reanalysis provides monthly data since 1987 with a horizontal grid resolution of 1/24°. For our analysis, we use the period from 1993 to 2005, which is the longest available overlap with historical runs.

The mean DSL derived from satellite observations and CMEMS show a meridional gradient in the Mediterranean basin, with negative values on the northern coasts and positive values toward the south ranging from −0.16 to 0.23 m (Figures 1a and 1b). Although there is a high variability in the behavior between models, the spatial patterns are qualitatively well represented by the multi-model ensemble mean (MMEM, Figure 1c) and most of the RCSMs (Figure S11 in Supporting Information S1). Figure S12 in Supporting Information S1 (panels c–n) shows DSL differences between models and observations, suggesting that all models, except UBEL-EBUPOM, reproduce the negative sea level maxima enclosed by the cyclonic gyres in the main deep water formation areas (e.g., Gulf of Lions and southern Adriatic) and the positive maxima captured in the southern coasts associated with the anticyclonic mesoscale structures. The largest differences with respect to observations are found for GUF-CCLM/NEMO-6, GUF-CCLM/NEMO-5, LMDZ-CNRM, LMDZ-MPIESM and UBEL-EBUPOM, with spatial correlations (Pearson correlation coefficient, r) lower than 0.6 (Figure 1g). The models with lower RMSE and higher correlations ($r > 0.8$), such as CMCC-COSMOMED, ENEA-REG, and CNRM-RCSM6, fall within the uncertainty of the CMEMS reanalysis (Figures 1g–1i).

Results shown in Figures 1a–1c and Figure S11 in Supporting Information S1 indicate that the considered models reproduce the main features of the geostrophic circulation already shown by the observational reconstructions (Millot & Taupier-Letage, 2005; Rio et al., 2014) and other simulations (Bergamasco & Malanotte-Rizzoli, 2010;

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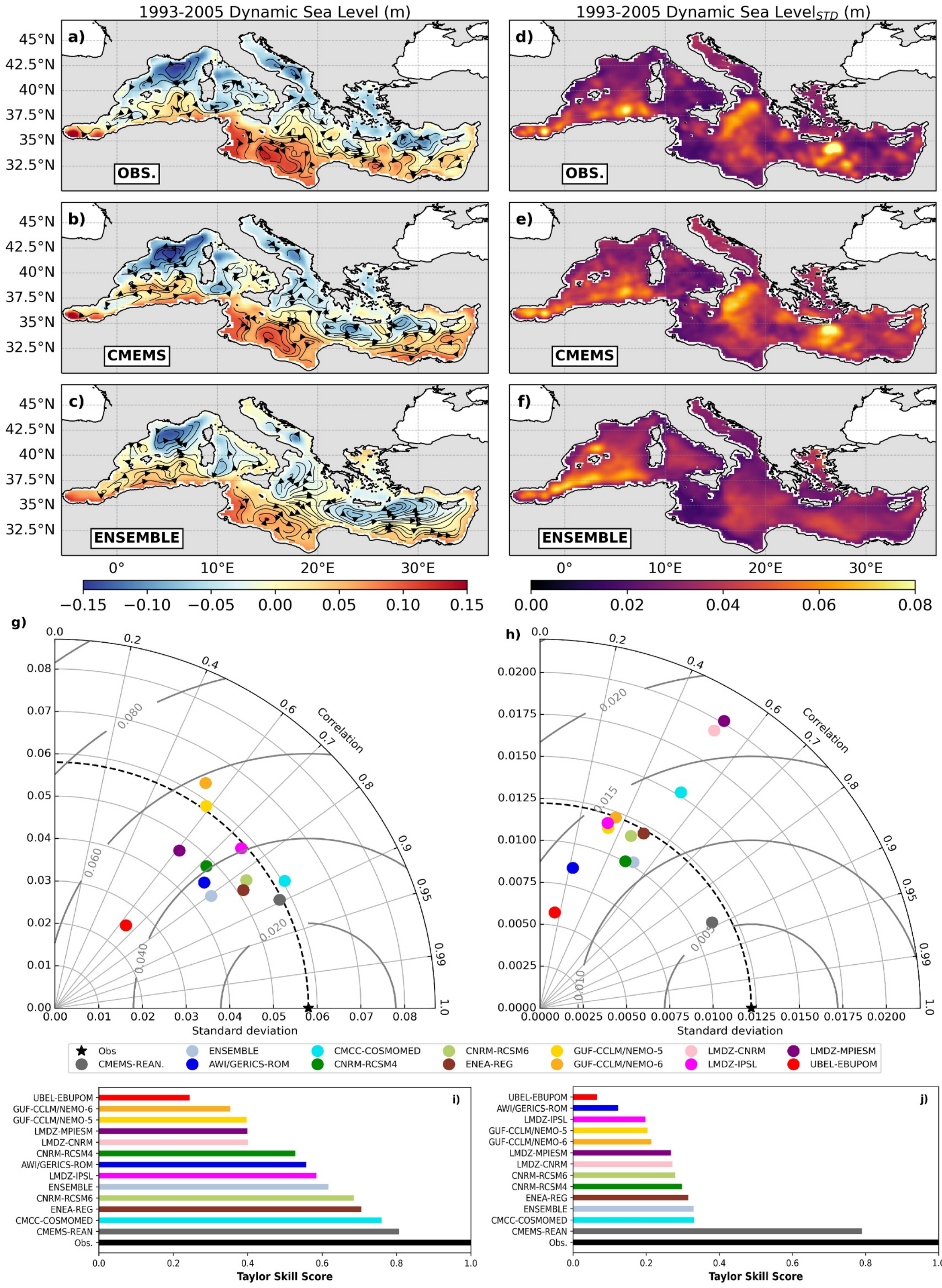

Figure 1. (a–c) 1993–2005 mean dynamic sea level (DSL, m) and geostrophic velocities (contours) from satellite measurements (OBS), the CMEMS reanalysis and ensemble mean. (d–f) 1993–2005 mean DSL (m) monthly variability from satellite measurements (OBS), the CMEMS reanalysis and ensemble mean. (g, h) Taylor diagram for Mediterranean (g) mean DSL and (h) DSL monthly variability during the 1993–2005 period. The diagram summarizes the relationship between standard deviation (m), spatial correlation (r) and RMSE (gray lines, m) for all datasets. (i, j) Taylor Skill Score (Taylor, 2001) of (i) DSL and (j) DSL monthly variability between satellite observations and each individual model.

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Pinardi et al., 2015). This circulation is characterized by the entry of Atlantic inflow through the Strait of Gibraltar, which flows eastwards off the African coast to form the Algerian Current. Once it reaches the Sardinia Channel, it splits into two main streams, one circulating counterclockwise throughout the western Mediterranean and the other flowing into the eastern Mediterranean through the Sicily Channel. The models with higher horizontal resolution in the oceanic component (CMCC-COSMOMED, CNRM-RCSM6, ENEA-REG) are able to resolve regional structures such as the Alboran, Northern Balearic, or Southern Adriatic gyres, among others. However, most of these gyres are missed in models with lower oceanic resolution (e.g., UBEL-EBUPOM). Despite the limitations of some models (Figures 1g–1i), none of them has been considered as not trustable to project the future evolution and all have therefore been selected for the rest of the study.

Regarding the temporal variability associated with the Mediterranean surface circulation, we analyze the standard deviation obtained from the monthly DSL (Figures 1d–1f and Figure S13 in Supporting Information S1) and geostrophic current (Figure S14 in Supporting Information S1). Satellite observations show values ranging between 0.01-0.12 m and 0.01–0.18 $m.s^{-1}$, with maxima located in areas corresponding to mesoscale structures such as the Alboran and Ierapetra gyres. While most models successfully capture the variability linked to the Alboran gyres and the Algerian current, they struggle to accurately simulate the variability associated with the Ierapetra gyre. Statistically, CMCC-COSMOMED and the MMEM have the highest correlation ($r > 0.5$, Figure 1h) and Taylor Skill Score (TSS, Figure 1j) with observations. Figure S15 in Supporting Information S1 suggests that the averaged DSL variability decreases with decreasing horizontal resolution. The minimum horizontal oceanic resolution required by the RCSMs to successfully reproduce the observed average variability in the Mediterranean is approximately 11 km. This is probably why AWI/GERICS-ROM and UBEL-EBUPOM underestimate the variability associated with the DSL as shown in Figure 1h.

To identify the processes involved in the total variability of the geostrophic current, we have decomposed the signal into different frequencies, that is, we compute the interannual, seasonal and intraseasonal variability (Table S3 in Supporting Information S1). Observations indicate that the main source of variability is associated with intraseasonal processes (possibly mesoscale dynamics), which is well represented by the MMEM. We also repeated this decomposition using the daily data available from CNRM-RCSM6. The total variability (computed from daily data) is dominated by the intraseasonal variability (Figure S16 in Supporting Information S1), as in the monthly decomposition.

For the wind-driven circulation, there is a great diversity in the model behavior and biases of the wind stress (Text S1 in Supporting Information S1). The Ekman component is much weaker than the geostrophic component, even at daily frequencies (Text S2 in Supporting Information S1), so we focus our study of scenario projections on the geostrophic circulation.

3.2. Future Evolution of Mediterranean Surface Circulation

The projected changes in mean DSL at GWL 2°C (GWL2) relative to the baseline period (1981–2000) for the MMEM are shown in Figure 2a. There are no changes at the basin scale, the changes in mean behavior are only local. As for the assessment period, the individual model responses exhibit a highly variable behavior in the future (Figure S17 in Supporting Information S1). All models project areas with significant changes at GWL2, with GUF-CCLM/NEMO-6 and ENEA-REG showing the stronger response, while UBEL-EBUPOM and LMDz-MPIESM show the weaker. Among the models, the higher increase (decrease) ranges from +0.02 to +0.17 m (−0.02 to −0.12 m), while DSL ranges from −0.16 to 0.23 m in the observations for the period 1993–2005. To identify areas of robust change, a multi-model agreement criterion was applied to Figures 2a and 2b. This criterion involves selecting locations where at least eight out of 11 models (over 70% agreement; following IPCC, 2021) agree on the sign of the total change (positive or negative) for a given GWL. Grid points that do not meet this threshold are discarded and masked in white. The ensemble projects robust changes in the Alboran, the Balearic (anticyclonic trend of up to +0.05 m) and the Adriatic (cyclonic trend of up to −0.03 m) seas.

Compared to GWL2, the magnitude of the changes increases at GWL4 (Figure S18a in Supporting Information S1), while the patterns remain almost constant. These results suggest that the magnitude of the response is proportional to the level of global warming, which is not always the case for ocean variables (e.g., heat content, sea level). In the Balearic and Adriatic seas, the DSL doubled the signal presented at GWL2, reaching values up to +0.1 m and −0.06 m respectively. In terms of the basin-averaged absolute change in mean DSL relative to the baseline period (Figure 2c), the magnitude of the change increases linearly with GWL. As denoted by the filled

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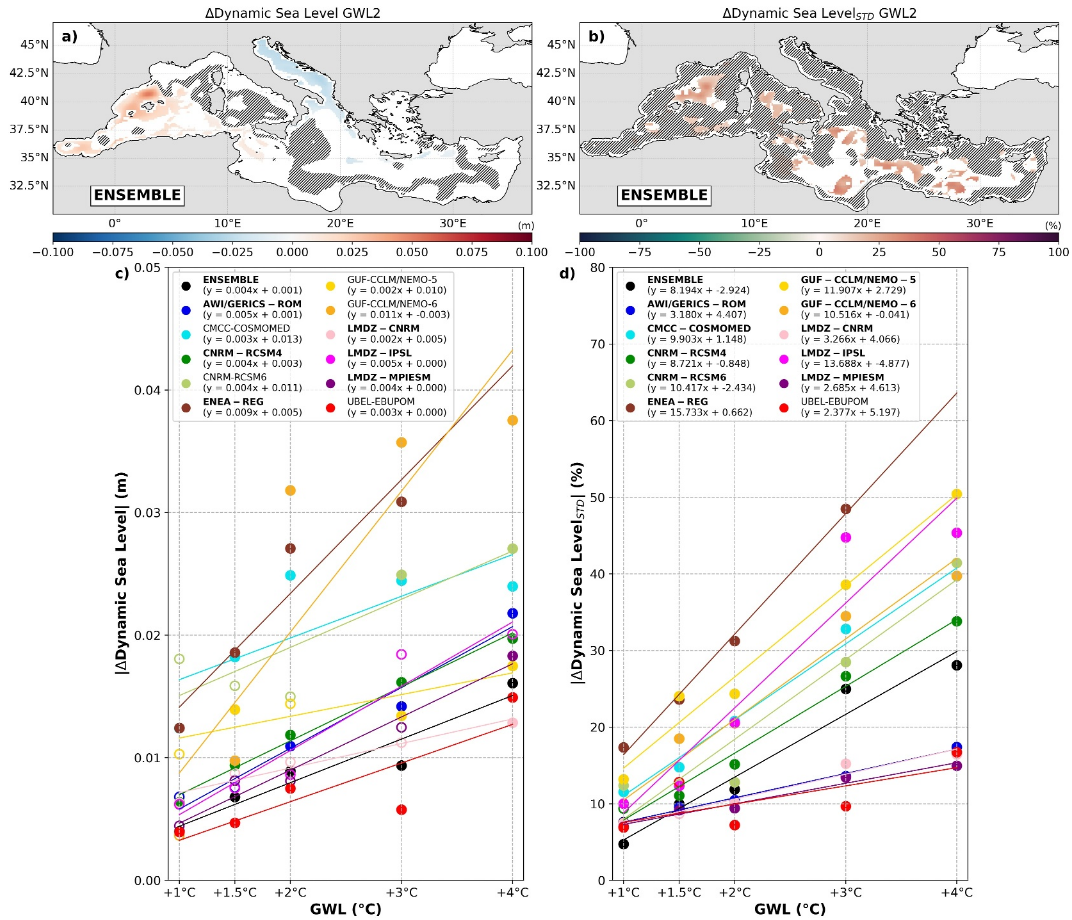

Figure 2. (a) Multi-model ensemble mean anomaly at GWL2 of mean dynamic sea level (DSL, m) with respect to the baseline period (1981–2000). (b) Multi-model ensemble mean ratio at GWL2 of DSL monthly variability (%) with respect to the baseline period. Hatched areas indicate insignificant changes at the 95% confidence level according to (a) the False Discovery Rate (FDR) procedure (multiple test $\alpha = 0.05$; Wilks, 2016) and (b) Fisher Test. Areas with less than 70% multi-model agreement are colored white. Basin-averaged absolute change of (c) DSL and (d) ratio of DSL monthly variability for global warming levels from 1°C to 4°C. Filled dots indicate statistically significant changes at the 95% confidence level according to (c) Student's *t*-test and (d) Levene's *t*-test. Bold model names in the legend indicate significant linear regression using p-values <0.05.

dots, the changes become statistically more significant with increasing warming, which is also shown in Figure S18a in Supporting Information S1. Six models out of 11 show significant linear regression (Figure 2c), the rate of change per GWL depending on the model. The MMEM projects a basin-average absolute DSL change of 0.4 cm/°C, while the faster response to the GWL is projected by GUF-CCLM/NEMO-6 and ENEA-REG with a change of ~1 cm/°C.

Changes in the DSL are associated with changes in the surface geostrophic circulation (Text S3 in Supporting Information S1). There is no model agreement for a significant modification of the surface geostrophic circulation at the basin-scale; the robust changes are found in the eastern Alboran Sea and the northwestern Mediterranean (Figure S7 in Supporting Information S1). The geostrophic velocity also increases linearly with warming.

3.3. Projected Changes in the Variability of the Mediterranean Surface Circulation

We now evaluate changes in the monthly mean variability associated with the Mediterranean surface circulation. These changes have been calculated as the ratio between the monthly standard deviation at a given GWL and that of the reference period.

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At GWL2, the MMEM projects a general increase in the DSL and geostrophic current variability (Figure 2b and Figure S19a in Supporting Information S1), at least in the areas where the change is statistically significant. This future increase in surface circulation variability has already been reported by Ser-Giacomi et al. (2020), using one of the simulations evaluated in this study (CNRM-RCSM4 under the RCP8.5 scenario). The robust changes are found in the open-sea and are mainly associated with an increase in intraseasonal variability (Table S4 in Supporting Information S1), which are likely driven by enhanced mesoscale (eddy) activity. In agreement with Ser-Giacomi et al. (2020), we interpret this increase in intraseasonal variability as related to the projected strengthening of horizontal density gradients (Figure S20 in Supporting Information S1), which feed baroclinic instabilities. The enhancement of baroclinic instabilities has also been identified as the main cause of increased eddy generation in other regions (Li et al., 2024). The highest increase of variability is located in the northwestern Mediterranean, the central Tyrrhenian Sea, the southern Ionian Sea, the Gulf of Sirte, and the Cretan Passage. Figures S21 and S22 in Supporting Information S1 show the future change in total variability (computed from monthly data) projected by each RCSM. Again, there is a large spread in the individual responses, but the spatial distribution of the anomalies is similar for DSL and geostrophic currents.

The magnitude of the response increases linearly with the GWL (Figure 2d and Figure S19 in Supporting Information S1). As shown in Figures S18b and S19b in Supporting Information S1, at GWL4, the variability of DSL increases by up to 130% while that of geostrophic velocity by up to 140% in regions such as the Gulf of Lions and the Cretan Passage. This suggests an enhanced surface mesoscale activity in the future. The basin-averaged absolute change shows that ENEA-REG has the highest variability increase for DSL, while UBEL-EBUPOM has the lowest. The rate of change for the MMEM is 8.2%/°C for DSL and 6.6%/°C for geostrophic velocity. Absolute changes also become more significant as warming increases.

3.4. Projected Changes in the Local Scale Circulation Modes

Having identified the strongest significant changes in the northern Balearic and southern Adriatic seas (Figure 2a), the evolution of local circulation modes in these regions is studied in detail. Additionally, other specific regions with smaller but visible changes, such as the Alboran Sea and the Ierapetra Gyre, as well as areas of interest to the Mediterranean community, such as the Bonifacio Gyre and the North Ionian Sea, are also assessed. Figure 3 shows the percentage occurrence of different circulation modes with increasing global warming for the target areas. This percentage has been calculated by pooling all available runs for each period. For each region, we define two/three different circulation modes by analyzing time-series of monthly mean vorticity. The limits of each mode have been determined subjectively, but based on the known physical behavior of these areas.

The most significant change is found in the northern Balearic Sea, which shows an increase in the frequency of the anticyclonic mode from 19% to 49%, suggesting that in this region the circulation shifts from cyclonic to predominantly anticyclonic at high GWLs (Figure 3a). The biased behavior of the MMEM compared to the observations suggests the need to apply observational constraints (Text S4 in Supporting Information S1). Considering only the RCSMs that fulfill the observational constraint (Figure S9 in Supporting Information S1), we obtain the same conclusions but with a higher increase (up to 37%) in the anticyclonic frequency (Figure S10 in Supporting Information S1). Furthermore, we find an emergent constraint on the northern Balearic surface circulation for different GWLs. Consistently with Adloff et al. (2015), changes in the surface circulation of the Balearic Sea are confirmed here in a multi-model framework. This reversal of the main circulation pattern may explain the strong surface warming and freshening projected for the Balearic Sea by the end of the 21st century (Adloff et al., 2015; Darmaraki et al., 2019; Soto-Navarro et al., 2020).

The cyclonic circulation in the southern Adriatic is projected to strengthen, with a 8% increase in the occurrence of the strong cyclonic mode at GWL4 compared to the baseline period. A similar trend can be observed at the Bonifacio Gyre, where the occurrence of the strong cyclonic mode is expected to become 11% more frequent. This result is consistent with the intensification of the Bonifacio Gyre reported in de la Vara et al. (2022).

In the North Ionian region, the circulation is mainly cyclonic in present climate and at all GWLs. However, the North Ionian Gyre reversal occurs approximately 15%–20% of the time in the considered periods. Therefore, global warming will not lead to an increase in the anticyclonic phase of BiOS (Gačić et al., 2010). By the end of the 21st century, Adloff et al. (2015) projected a substantial modification of the surface circulation mode in the

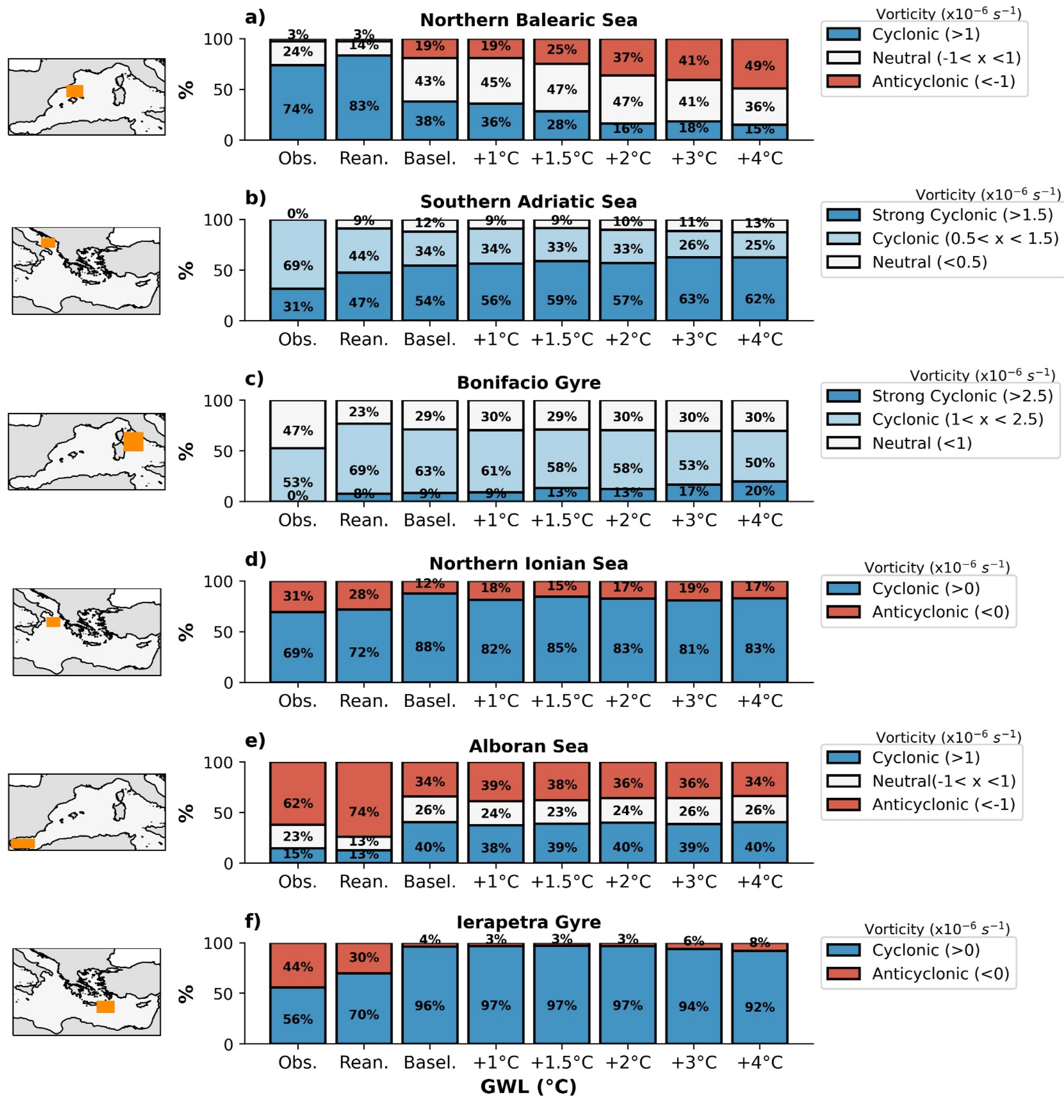

Figure 3. Percentage occurrence of different circulation modes derived from monthly vorticity (s^{-1}) for six target regions (yellow polygons). The limits of each circulation mode are defined in the legend of each region.

northern Ionian independently of the emission scenario considered. However, our results (considering all runs) indicate that no notable changes are projected in this region.

Although an increase in DSL is expected in the Alboran Sea (Figure 2a and Figure S18a in Supporting Information S1), there are no changes in the circulation modes. The anticyclonic mode associated with the Ierapetra Gyre is not well reproduced by the simulations during the baseline period. Nevertheless, the models project an increase in this anticyclonic mode with increasing warming, which may be related to an increase in Etesian wind (Figure S23 in Supporting Information S1).

4. Conclusions

This study addresses future changes in the Mediterranean Sea surface circulation. To date, previous works (Adloff et al., 2015; de la Vara et al., 2022; Ser-Giacomi et al., 2020) investigating the future change of surface circulation were based on single-model runs, which limits the generalization of results. A multi-model approach, like the one taken in this study, on the other hand, allows to identify features of the forced response common across different models, thus providing more robust conclusions. To this aim, we have assembled the largest ensemble of high-

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resolution and fully coupled regional climate system models ever used for a robust assessment of future changes in the Mediterranean Sea.

Furthermore, to our knowledge, this study is the first to apply the Global Warming Level (GWL) approach (IPCC, 2021) to a broad set of fully coupled regional climate models to assess the future climate evolution of the ocean at regional scale. Application of this novel methodology allows us to combine the CMIP5 (RCP2.6, RCP4.5, and RCP8.5) and CMIP6 (SSP1-2.6, SSP2-45, SSP5-8.5) scenarios as well as different regional climate model generations, for GWLs from 1°C to 4°C.

The historical simulations show a variable representation of the main features of present-day surface circulation. Geostrophic currents mainly drive the surface circulation, while Ekman currents are about one order of magnitude smaller than the mass-driven circulation. Regarding the 21st-century projections, we identify high model uncertainty in the future response of the basin-scale mean circulation and no large-scale circulation change in the multi-model ensemble mean. This result justifies a posteriori the need for large and diverse multi-model ensembles to study the plausible future evolution of oceanic regions or seas.

However, significant and robust changes are identified in specific regions, such as the northern Balearic Sea and the southern Adriatic Sea. One of the most surprising and significant results is probably that the local circulation is projected to shift from cyclonic to anticyclonic at high GWLs in the northern Balearic. This result is obtained with both the complete multi-model ensemble and a sub-sampled ensemble after applying an observational constraint. The observed frequency of the anticyclonic mode is 3% in the present climate, while it is projected to increase to 49% at GWL4. This shift is very likely the cause of the abnormal warming and freshening of this area obtained in the published literature. In contrast, strengthening of the cyclonic circulation is expected in the southern Adriatic region. We discard wind stress as the main driver of these changes due to inconsistencies between the model responses. Analysis of the mechanisms responsible for these changes requires a detailed dynamical study, which is beyond the scope of this work. Besides, the surface circulation variability is projected to increase, especially in open-sea areas, mainly due to an increase in intraseasonal variability, likely related to enhanced mesoscale activity. Finally, we highlight a linear increase in the basin-scale mean surface circulation response and in variability with respect to GWLs. Circulation and variability changes become statistically more significant with higher levels of warming.

From this study, we identify some perspectives to be addressed in future work.

- Develop a proper methodology (likely including sensitivity test and single-model deeper analyses) to unravel the physical mechanisms involved in the future evolution of surface circulation, especially in the northern Balearic Sea.
- Investigate the potential environmental and socio-economic impacts caused by changes in surface circulation.
- Assess the future evolution of Mediterranean circulation patterns throughout the entire water column.
- Develop coordinated multi-model ensembles of ocean or coupled regional climate models in other relevant areas of the world (e.g., regional seas, coastal zones) that are not well represented in global climate models to investigate regional impacts of climate change in the ocean.

Data Availability Statement

Model outputs used in this study are or will be freely available in the Med-CORDEX database (https://www.medcordex.eu/). The altimetric satellite observations (https://doi.org/10.48670/moi-00141) and the reanalysis data (Escudier et al., 2020) are publicly available at the Copernicus Marine Environment Monitoring Service (https://marine.copernicus.eu/). ERA5 reanalysis data (Hersbach et al., 2023) is accessible via https://doi.org/10.24381/cds.6860a573.

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References

Adloff, F., Jordà, G., Somot, S., Sevault, F., Meyssignac, B., Arsouze, T., et al. (2018). Improving sea level simulation in Mediterranean regional climate models. *Climate Dynamics*, *51*(3), 1167–1178. https://doi.org/10.1007/s00382-017-3842-3

Adloff, F., Somot, S., Sevault, F., Jordà, G., Aznar, R., Déqué, M., et al. (2015). Mediterranean Sea response to climate change in an ensemble of twenty first century scenarios. *Climate Dynamics*, *45*(9–10), 2775–2802. https://doi.org/10.1007/s00382-015-2507-3

Ali, E., Cramer, W., Carnicer, J., Georgopoulou, E., Hilmi, N. J. M., Le Cozannet, G., & Lionello, P. (2022). Cross-chapter paper 4: Mediterranean region. In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, et al. (Eds.), *Climate change 2022. Impacts, adaptation and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change* (pp. 2233–2272). Cambridge University Press.

19448007, 2024, 24, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2024GL111695 by E.N.E.A., Wiley Online Library on [22/01/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Anav, A., Antonelli, M., Calmanti, S., Carillo, A., Catalano, F., Dell'Aquilla, A., et al. (2024). Dynamical downscaling of CMIP6 scenarios with ENEA-REG: An impact-oriented application for the med-CORDEX region. *Climate Dynamics*, *62*(5), 3261–3287. https://doi.org/10.1007/s00382-023-07064-3

Beckers, J. M., Rixen, M., Brasseur, P., Brankart, J.-M., Elmoussaoui, A., Crépon, M., et al. (2002). Model intercomparison in the mediterranean: MEDMEX simulations of the seasonal cycle. *Journal of Marine Systems*, *33–34*, 215–225. https://doi.org/10.1016/S0924-7963(02)00060-X

Bergamasco, A., & Malanotte-Rizzoli, P. (2010). The circulation of the Mediterranean Sea: A historical review of experimental investigations. *Advances in Oceanography and Limnology*, *1*, 11–28. https://doi.org/10.1080/19475721.2010.491656

Cherif, S., Doblas-Miranda, E., Lionello, P., Borrego, C., Giorgi, F., Iglesias, A., et al. (2020). Drivers of change. In: Climate and environmental change in the Mediterranean basin – Current situation and risks for the future. In W. Cramer, J. Guiot, & K. Marini (Eds.), *First mediterranean assessment report*, *Union for the mediterranean, plan bleu* (pp. 59–180). UNEP/MAP. https://doi.org/10.5281/zenodo.7100601

Darmaraki, S., Somot, S., Sevault, F., Nabat, P., Cabos Narvaez, W. D., Cavicchia, L., et al. (2019). Future evolution of marine heatwaves in the Mediterranean Sea. *Climate Dynamics*, *53*(3–4), 1371–1392. https://doi.org/10.1007/s00382-019-04661-z

de la Vara, A., Parras-Berrocal, I. M., Izquierdo, A., Sein, D. V., & Cabos, W. (2022). Climate change signal in the ocean circulation of the Tyrrhenian Sea. *Earth System Dynamics*, *13*(1), 303–319. https://doi.org/10.5194/esd-13-303-2022

Escudier, R., Clementi, E., Cipollone, A., Pistoia, J., Drudi, M., Grandi, A., et al. (2021). A high resolution re-analysis for the Mediterranean Sea. *Frontiers in Earth Science*, *9*, 1–20. https://doi.org/10.3389/feart.2021.702285

Escudier, R., Clementi, E., Omar, M., Cipollone, A., Pistoia, J., Aydogdu, A., et al. (2020). Mediterranean Sea physical reanalysis (CMEMS MED-currents) (Version 1). *Copernicus Monitoring Environment Marine Service (CMEMS)*. [Dataset]. https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1

Evin, G., Somot, S., & Hingray, B. (2021). Balanced estimate and uncertainty assessment of European climate change using the large EURO-CORDEX regional climate model ensemble. *Earth System Dynamics*, *12*(4), 1543–1569. https://doi.org/10.5194/esd-12-1543-2021

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organizations. *Geoscientific Model Development*, *9*(5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

Gačić, M., Borzelli, G. L. E., Civitarese, G., Cardin, V., & Yari, S. (2010). Can internal processes sustain reversals of the ocean upper circulation? The Ionian Sea example. *Geophysical Research Letters*, *37*(9), L09608. https://doi.org/10.1029/2010GL043216

Giorgi, F. (2006). Climate change hot-spots. *Geophysical Research Letters*, *33*(8), L08707. https://doi.org/10.1029/2006GL025734

Hauser, M., Engelbrecht, F., & Fischer, E. M. (2022). Transient global warming levels for CMIP5 and CMIP6 (v0.3.0). *Zenodo*. https://doi.org/10.5281/zenodo.7390473

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., et al. (2023). ERA5 monthly averaged data on single levels from 1940 to present. *Copernicus Climate Change Service (C3S) Climate Data Store (CDS)*. [Dataset]. https://doi.org/10.24381/cds.f17050d7

IPCC. (2018). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. In V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, et al. (Eds.), *The context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Cambridge University Press. https://doi.org/10.1017/9781009157940.616.

IPCC. (2021). In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, et al. (Eds.), *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press. https://doi.org/10.1017/9781009157896.2391.

Li, X., Wang, Q., Danilov, S., Koldunov, N., Liu, C., Müler, V., et al. (2024). Eddy activity in the Arctic Ocean projected to surge in a warming world. *Nature Climate Change*, *14*(2), 156–162. https://doi.org/10.1038/s41558-023-01908-w

Macias, D., Garcia-Gorriz, E., & Stips, A. (2018). Deep winter convection and phytoplankton dynamics in the NW Mediterranean Sea under present climate and future (horizon 2030) scenarios. *Scientific Reports*, *8*(1), 1–15. https://doi.org/10.1038/s41598-018-24965-0

Millot, C., & Taupier-Letage, I. (2005). Circulation in the Mediterranean Sea. In A. Saliot (Ed.), *The Mediterranean Sea*, *Handbook of environmental chemistry* (Vol. 5K, pp. 29–66). Springer. https://doi.org/10.1007/b107143

Morales-Márquez, V., Hernández- Carrasco, I., Simarro, G., Rossi, V., & Orfila, A. (2021). Regionalizing the impacts of wind- and wave-induced currents on surface ocean dynamics: A long-term variability analysis in the Mediterranean Sea. *Journal of Geophysical Research: Oceans*, *126*(9), e2020JC017104. https://doi.org/10.1029/2020JC017104

Nikulin, G., Lennard, C., Dosio, A., Kjellström, E., Chen, Y., Hänsler, A., et al. (2018). The effects of 1.5 and 2 degrees of global warming on Africa in the CORDEX ensemble. *Environmental Research Letters*, *13*(6), 065003. https://doi.org/10.1088/1748-9326/aab1b1

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., et al. (2016). The scenario model intercomparison project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, *9*, 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Parras-Berrocal, I. M., Vazquez, R., Cabos, W., Sein, D., Álvarez, O., Bruno, M., & Izquierdo, A. (2022). Surface and intermediate water changes triggering the future collapse of deep water formation in the North western mediterranean. *Geophysical Research Letters*, *49*(4), e2021GL095404. https://doi.org/10.1029/2021GL095404

Parras-Berrocal, I. M., Vázquez, R., Cabos, W., Sein, D. V., Álvarez, O., Bruno, M., & Izquierdo, A. (2023). Dense water formation in the eastern Mediterranean under a global warming scenario. *Ocean Science*, *19*(3), 941–952. https://doi.org/10.5194/os-19-941-2023

Pascual, A., Vidal-Vijande, E., Ruiz, S., Somot, S., & Papadopoulos, V. (2014). Spatiotemporal variability of the surface circulation in thewestern mediterranean. In *The Mediterranean Sea* (pp. 5–23). American Geophysical Union. https://doi.org/10.1002/9781118847572.ch2. *Geophysical monograph series* (2).

Pinardi, N., Zavatarelli, M., Adani, M., Coppini, G., Fratianni, C., Oddo, P., et al. (2015). Mediterranean Sea large-scale low-frequency ocean variability and water mass formation rates from 1987 to 2007: A retrospective analysis. *Progress in Oceanography*, *132*, 318–332. https://doi.org/10.1016/j.pocean.2013.11.003

Poulain, P. M., Menna, M., & Mauri, E. (2012). Surface geostrophic circulation of the Mediterranean Sea derived from drifter and satellite altimeter data. *Journal of Physical Oceanography*, *42*(6), 973–990. https://doi.org/10.1175/JPO-D-11-0159.1

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., et al. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Rio, M.-H., Pascual, A., Poulain, P.-M., Menna, M., Barceló, B., & Tintoré, J. (2014). Computation of a new mean dynamic topography for the Mediterranean Sea from model outputs, altimeter measurements and oceanographic in situ data. *Ocean Science*, *10*(4), 731–744. https://doi.org/10.5194/os-10-731-2014

Robinson, A. R., Malanotte-Rizzoli, P., Hecht, A., Michelato, A., Roether, W., Theocharis, A., et al. (1992). General circulation of the eastern mediterranean. *Earth-Science Reviews*, *32*(4), 285–309. https://doi.org/10.1016/0012-8252(92)90002-b

Rosselló, P., Pascual, A., & Combes, V. (2023). Assessing marine heat waves in the Mediterranean Sea: A comparison of fixed and moving baseline methods. *Frontiers in Marine Science*, *10*, 1168368. https://doi.org/10.3389/fmars.2023.1168368

Rossi, V., Ser-Giacomi, E., López, C., & Hernández-García, E. (2014). Hydrodynamic provinces and oceanic connectivity from a transport network help designing marine reserves. *Geophysical Research Letters*, *41*(8), 2883–2891. https://doi.org/10.1002/2014GL059540

Ruti, P. M., Somot, S., Giorgi, F., Dubois, C., Flaounas, E., Obermann, A., et al. (2016). MED-CORDEX initiative for Mediterranean climate studies. *Bulletin of the American Meteorological Society*, *97*(7), 1187–1208. https://doi.org/10.1175/BAMS-D-14-00176.1

Sannino, G., Carillo, A., Iacono, R., Napolitano, E., Palma, M., Pisacane, G., & Struglia, M. (2022). Modelling present and future climate in the Mediterranean Sea: A focus on sea-level change. *Climate Dynamics*, *59*(1–2), 357–391. https://doi.org/10.1007/s00382-021-06132-w

Sciascia, R., Guizien, K., & Magaldi, M. G. (2022). Larval dispersal simulations and connectivity predictions for mediterranean gorgonian species: Sensitivity to flow representation and biological traits. *ICES Journal of Marine Science*, *79*(7), 2043–2054. https://doi.org/10.1093/icesjms/fsac135

Ser-Giacomi, E., Jordá-Sánchez, G., Soto-Navarro, J., Thomsen, S., Mignot, J., Sevault, F., & Rossi, V. (2020). Impact of climate change on surface stirring and transport in the Mediterranean Sea. *Geophysical Research Letters*, *47*(22), e2020GL089941. https://doi.org/10.1029/2020GL089941

Ser-Giacomi, E., Legrand, T., Hernández-Carrasco, I., & Rossi, V. (2021). Explicit and implicit network connectivity: Analytical formulation and application to transport processes. *Physical Review E: Statistical Physics, Plasmas, Fluids, and Related Interdisciplinary Topics*, *103*(4), 042309. https://doi.org/10.1103/PhysRevE.103.042309

Sevault, F., Somot, S., Alias, A., Dubois, C., Lebeaupin-Brossier, C., Nabat, P., et al. (2014). A fully coupled mediterranean regional climate system model: Design and evaluation of the ocean component for the 1980–2012 period. *Tellus A: Dynamic Meteorology and Oceanography*, *66*(1), 23967. https://doi.org/10.3402/tellusa.v66.23967

Somot, S., Ruti, P., Ahrens, B., Coppola, E., Jordà, G., Sannino, G., & Solmon, F. (2018). Editorial for the Med-CORDEX special issue. *Climate Dynamics*, *51*(3), 771–777. https://doi.org/10.1007/s00382-018-4325-x

Somot, S., Sevault, F., & Déqué, M. (2006). Transient climate change scenario simulation of the Mediterranean Sea for the 21st century using a high-resolution ocean circulation model. *Climate Dynamics*, *27*(7–8), 851–879. https://doi.org/10.1007/s00382-006-0167-z

Soto-Navarro, J., Jordá, G., Amores, A., Cabos, W., Somot, S., Sevault, F., et al. (2020). Evolution of Mediterranean Sea water properties under climate change scenarios in the Med-CORDEX ensemble. *Climate Dynamics*, *54*(3–4), 2135–2165. https://doi.org/10.1007/s00382-019-05105-4

Taylor, K. E. (2001). Summarizing multiple aspects of model performance in a single diagram. *Journal of Geophysical Research*, *106*(D7), 7183–7192. https://doi.org/10.1029/2000JD900719

Taylor, K. E., Stouffer, R., & Meehl, G. (2012). An overview of CMIP5 and the experiments design. *Bulletin of the American Meteorological Society*, *93*(4), 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1

Vigo, M. I., Sempere, M. D., Chao, B. F., & Trottini, M. (2018). Mediterranean surface geostrophic circulation from satellite gravity and altimetry observations. *Pure and Applied Geophysics*, *175*(11), 3989–4005. https://doi.org/10.1007/s00024-018-1911-0

Wilks, D. S. (2016). The stippling shows statistically significant grid points": How research results are routinely overstated and overinterpreted, and what to do about it. *Bulletin of the American Meteorological Society*, *97*(12), 2263–2273. https://doi.org/10.1175/BAMS-D-15-00267.1

References From the Supporting Information

Akhtar, N., Brauch, J., & Ahrens, B. (2018). Climate modeling over the Mediterranean Sea: Impact of resolution and ocean coupling. *Climate Dynamics*, *51*(3), 933–948. https://doi.org/10.1007/s00382-017-3570-8

Cavicchia, L., Gualdi, S., Sanna, A., & Oddo, P. (2015). The regional ocean atmosphere coupled model COSMONEMO_MFS. *CMCC Research Papers. Italy, Bologna*, 1–22. https://www.cmcc.it/wp-content/uploads/2015/04/rp0254-csp-04-2015.pdf

Conte, D., Gualdi, S., & Lionello, P. (2020). Effect of model resolution on intense and extreme precipitation in the Mediterranean region. *Atmosphere*, *11*(7), 699. https://doi.org/10.3390/atmos11070699

Cushman-Roisin, B. (1987). In P. Muller & D. Henderson (Eds.), *Dynamics of the oceanic surface mixed layer*. Hawaii Inst. of Geophys.

Darmaraki, S., Somot, S., Sevault, F., & Nabat, P. (2019b). Past variability of Mediterranean Sea marine heatwaves. *Geophysical Research Letters*, *46*(16), 9813–9823. https://doi.org/10.1029/2019GL082933

Djurdjevic, V., & Rajkovic, B. (2008). Verification of a coupled atmosphere-ocean model using satellite observations over the Adriatic Sea. *Annales Geophysicae*, *26*(7), 1935–1954. https://doi.org/10.5194/angeo-26-1935-2008

Hamouda, M. E., Czakay, C., & Ahrens, B. (2023). On convection during vb-cyclone events in present and warmer climate. *ESS Open Archive*. September 11. https://doi.org/10.22541/essoar.169447440.03083598/v1

Herrmann, M., Somot, S., Calmanti, S., Dubois, C., & Sevault, F. (2011). Representation of daily wind speed spatial and temporal variability and intense wind events over the Mediterranean Sea using dynamical downscaling: Impact of the regional climate model configuration. *Natural Hazards and Earth System Sciences*, *11*(7), 1983–2001. https://doi.org/10.5194/nhess-11-1983-2011

L'Hévéder, B., Li, L., Sevault, F., & Somot, S. (2013). Interannual variability of deep convection in the northwestern Mediterranean simulated with a coupled AORCM. *Climate Dynamics*, *41*(3–4), 937–960. https://doi.org/10.1007/s00382-012-1527-5

Molcard, A., Pinardi, N., Iskandarani, M., & Haidvogel, D. B. (2002). Wind driven general circulation of the Mediterranean Sea simulated with a spectral element ocean model. *Dynamics of Atmospheres and Oceans*, *35*(2), 97–130. https://doi.org/10.1016/s0377-0265(01)00080-x

Parras-Berrocal, I. M., Vazquez, R., Cabos, W., Sein, D., Mañanes, R., Perez-Sanz, J., & Izquierdo, A. (2020). The climate change signal in the Mediterranean Sea in a regionally coupled atmosphere–ocean model. *Ocean Science*, *16*(3), 743–765. https://doi.org/10.5194/os-16-743-2020

Primo, C., Kelemen, F. D., Feldmann, H., Akhtar, N., & Ahrens, B. (2019). A regional atmosphere–ocean climate system model (CCLMv5.0clm7-NEMOv3.3-NEMOv3.6) over europe including three marginal seas: On its stability and performance. *Geoscientific Model Development*, *12*, 5077–5095. https://doi.org/10.5194/gmd-12-5077-2019

Sein, D. V., Mikolajewicz, U., Gröger, M., Fast, I., Cabos, W., Pinto, J. G., et al. (2015). Regionally coupled atmosphere-ocean- sea ice-marine biogeochemistry model ROM: 1. Description and validation. *Journal of Advance in Modelling Earth Systems*, *7*(1), 268–304. https://doi.org/10.1002/2014MS000357

Sevault, F. (2024). *Atlas of the 1980-2018 ERA-Interim simulation with the coupled regional climate system model CNRM-RCSM6 (Versión v2)*. Zenodo. https://doi.org/10.5281/zenodo.11066601

Zavatarelli, M., & Mellor, G. L. (1995). A numerical study of the Mediterranean Sea circulation. *Journal of Physical Oceanography*, *46*, 8–688.

19448007, 2024, 24, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2024GL111695 by E.N.E.A., Wiley Online Library on [22/01/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License