EMI R&D PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Investigations of climate change in post-CMIP6 EC-Earth3 simulations over the Mediterranean climate regions
Computer Project Account:	spitcher
Start Year - End Year :	2023 - 2025
Principal Investigator(s)	Annalisa Cherchi
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The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The main objective of this special project is to investigate the climate change response over the Mediterranean Climate Regions (MCRs), which are particularly sensitive and vulnerable to processes of subtropical drying and expansion, using the post-CMIP6 version of EC-Earth3 and considering newly available climate scenarios reflecting the most recent climate policies. The analysis is further designed to assess the sensitivity of climate changes across progressively increasing global warming levels, providing a consistent framework to evaluate regional responses as a function of warming intensity.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

We have not encountered any technical issues from July 2023 to the present. However, anticipated changes in the availability of scenarios for future simulations have required an adjustment of the experimental design. In particular, these changes have led to the implementation of alternative experiments based on global warming levels (GWLs), as described below in the Results section, that influenced the overall plan for 2025 as anticipated.

Experience with the EMI R&D Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

Our experience with the administrative aspects has been overall positive. The few issues encountered during the course of the project were promptly addressed and efficiently resolved thanks to the technical support provided.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

Mediterranean Climate Regions (MCRs) comprise five geographically separated areas of the world: the Mediterranean Basin, the west coast of North America, central Chile, the Cape region of southern Africa, and southwestern Australia. Despite their geographical isolation, these regions share a distinctive climate characterized by cool, wet winters and warm to hot, dry summers. Located along the western margins of continents in the subtropics, MCRs represent transitional zones between humid temperate and arid climates. This intermediate climatic setting supports unique ecosystems with exceptionally high levels of biodiversity and endemism, while also sustaining densely populated areas, productive agricultural systems, and critical water resources. Consequently, MCRs are widely recognized as some of the world's most vulnerable regions to climate variability and anthropogenic climate change.

Climate model projections consistently indicate that Mediterranean Climate Regions will experience substantial changes during the twenty-first century. One of the most important expected responses is a geographical shift of the climatic conditions defining these regions. Using a probabilistic framework applied to CMIP5 projections, Alessandri et al. (2014) demonstrated an increased likelihood of a poleward displacement of Mediterranean climates, particularly over the Mediterranean Basin and western North America. At the same time, the equatorward margins are projected to undergo a transition toward more arid climate regimes, implying a contraction of the current Mediterranean climate envelope. Such shifts have profound implications for water availability, ecosystem resilience, agricultural productivity, and wildfire risk, as they alter both the spatial extent and the environmental conditions that characterize Mediterranean climates.

In addition to long-term shifts in their geographical distribution, MCRs are characterized by substantial climate variability on interannual to decadal timescales. Winter precipitation, which largely determines annual water availability, is strongly controlled by internal atmospheric variability across all Mediterranean Climate Regions. In the Mediterranean Basin, in particular, this variability is closely linked to large-scale atmospheric circulation modes, including the Northern Annular Mode and related teleconnection patterns. Superimposed on this natural variability, observational evidence indicates that nearly all Mediterranean Climate Regions—except western North America—have experienced significant drying over recent decades, with particularly pronounced trends emerging in the latest observational records (Senigalliesi et al., 2026). These observed changes are consistent with climate model projections, which robustly indicate a continued decline in precipitation and an intensification of hydroclimatic aridity throughout the twenty-first century (Seager et al., 2019; Seager et al., 2024). Understanding the interplay between natural variability, long-term trends, and potential nonlinear shifts in Mediterranean climate regimes is therefore essential for improving projections of future climate impacts and identifying critical thresholds beyond which abrupt regional changes may occur.

This report provides an overview of the current understanding of past and future changes in Mediterranean Climate Regions (MCRs), with particular emphasis on their response to increasing global warming. It first assesses the ability of the CMIP6 multi-model ensemble to reproduce the observed characteristics of MCRs (section 1) and considers evidence from the post-CMIP6 historical simulations performed (section 2). The report then examines available future climate scenarios and motivates the use of Global Warming Level (GWL) sensitivity experiments as a complementary framework for investigating climate responses (section 3). Building on this, it analyzes projected changes in Mediterranean Climate Regions across successive warming levels, with a focus on identifying emerging patterns, potential thresholds, and shifts in regional climate characteristics (section 4). Finally, the report concludes by summarizing the main findings and discussing their implications for future research (section 5).

1. *Evaluation of CMIP6 experiments (MME)*

This section evaluates the representation of Mediterranean Climate Regions (MCRs) in the CMIP6 multi-model ensemble (Eyring et al 2016) and examines their projected evolution under the CMIP6 future scenarios. MCRs are identified according to the updated Köppen–Geiger climate classification of Kottek et al. (2006), which provides an objective and widely adopted framework for defining Mediterranean climates based on long-term temperature and precipitation regimes (see Table 1 for the climate classification).

Type	Description	Criterion
A	Equatorial Climates	Tmin >= +18ºC
B	Arid climates	Pann < 10 Pth
C	Warm temperate climates	-3ºC < Tmin < +18ºC
Cs	Warm temperate climate with dry summer	Psmin<Pwmin, Pwmax > 3 Psmin & Psmin < 40 mm
D	Snow climates	Tmin < -3ºC
E	Polar climates	Tmax < +10ºC

Table 1: Climate-type classification based on climatology and monthly max/min of precipitation and temperature (from Kottek et al 2006). Pth is an (empirical) dryness threshold based on annual mean temperature and the ratio between summer and winter precipitation over the annual amount.

Figure 1 shows the global distribution of the selected climate-type classification in present-day (1979-2000) climatology, focusing on 4 types (Arid, warm temperate, Med and snow). As described in the caption some masking has been applied where the classification was not corresponding to the same evaluation based on observations. In this case, observations have been considered as ERA5 reanalysis (Hersbach et al 2020) for 2m temperature and GPCP (Adler et al 2018) for precipitation.

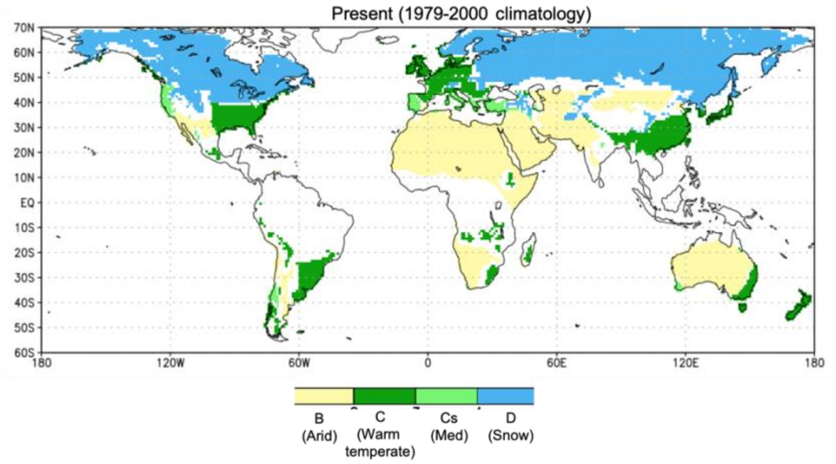

Figure 1: Climate-type classification for CMIP6 ensemble mean (historical experiments). Grid-points where the ensemble mean does not correspond to observations are not shown. The characteristics of the types of climate selected are described in Table 1.

Future changes are assessed using the CMIP6 Shared Socioeconomic Pathways (SSPs), a set of internally consistent scenarios combining alternative socioeconomic developments with different levels of greenhouse gas emissions and radiative forcing (O'Neill et al 2016). The SSPs selected (see Fig. 2) span a broad range of possible futures, from strong mitigation pathways associated with low forcing (e.g., SSP1-2.6) to intermediate scenarios reflecting current policy trends (e.g., SSP2-4.5), and high-emission pathways characterized by continued fossil-fuel dependence and high radiative forcing (e.g., SSP3-7.0 and SSP5-8.5). Together, these experiments provide the basis for assessing the robustness of projected changes in the spatial extent and climatic characteristics of MCRs under different anthropogenic climate forcing.

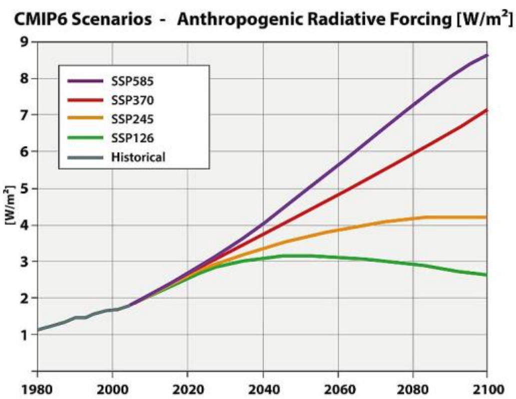

Figure 2: Schematic evolution of anthropogenic radiative forcing (W/m2) in the selected CMIP6 scenarios (colored lines) diverging from the historical distribution (black line). Adapted from O'Neill et al 2016

Future projections consistently indicate an increasing probability of a poleward expansion and an equatorward contraction of Mediterranean climate conditions as global warming intensifies (Figs. 3-5). Here, probability is defined as the fraction of models within the CMIP6 multi-model ensemble that classify a given grid point as belonging to the Mediterranean climate type. This probabilistic approach allows the robustness of the projected geographical shifts to be quantified, highlighting regions where there is strong inter-model agreement on future changes. Our analysis focuses on the Northern

Hemisphere Mediterranean regions (the Mediterranean Basin and western North America; Fig. 3 and Fig. 4) together with central Chile in South America (Fig 5). In contrast, the Mediterranean Climate Regions located in southern Africa and southwestern Australia are not shown here because the projected poleward displacement rapidly extends beyond the continental boundaries, limiting the possibility of meaningfully quantifying changes in the geographical extent of the climate type over land.

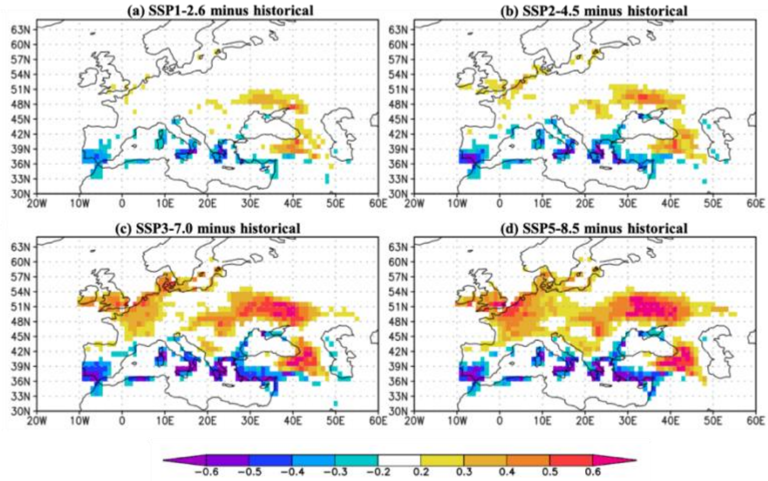

Figure 3: Change in probability to have a MED climate-type (SCENARIO minus historical) over the Mediterranean region

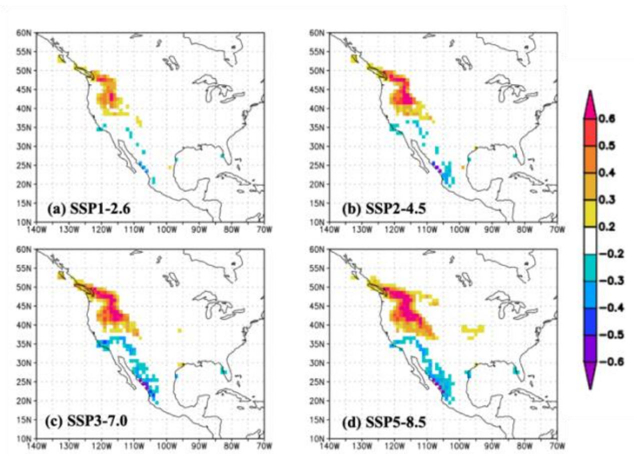

Figure 4: Same as Figure 3 but for North American MED region.

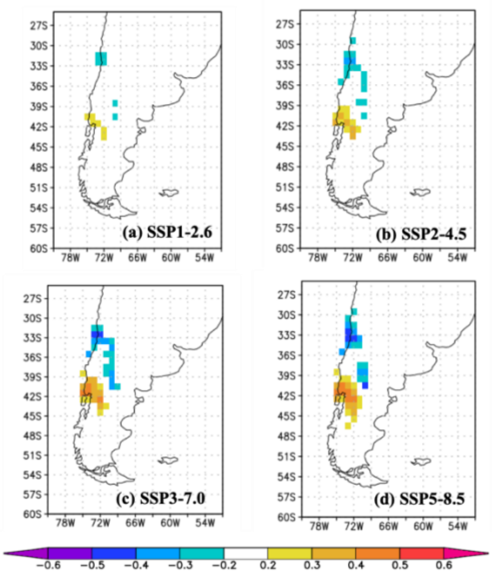

Figure 5: Same as Figure 3 but for South American MED region.

Our results show a systematic poleward migration of Mediterranean climates, while their equatorward margins are progressively replaced by more arid climate types, reflecting the expansion of subtropical dry zones under increasing radiative forcing, in line with known literature (Alessandri et al 2014; Seager et al 2024). The magnitude of these changes strongly depends on the emission scenario. Both the area experiencing a poleward expansion of Mediterranean climate conditions and the area undergoing retreat at the equatorward margins are approximately twice as large under the high-emission SSP5-8.5 scenario compared with the low-emission SSP1-2.6 scenario, with the spatial extent of these changes increasing almost linearly with radiative forcing.

2. ***Post-CMIP6 historical experiments***

Using EC-Earth3-ESM-1 post-CMIP6 model version we performed an historical simulation and while waiting for the availability of CMIP7 scenarios we evaluated the changes in MCR characteristics comparing the first part of the historical simulation with its end, i.e. comparing the 1860-1890 climatology with the 1984-2014 one. Figure 6 shows the distribution of three types of climate (SNOW, MED and WARM TEMPERATE) based on the classification described in section 1 to compare the climatology at the beginning of the historical simulation (upper panel) and in the most recent period (lower panel). From this analysis we cannot appreciate large differences.

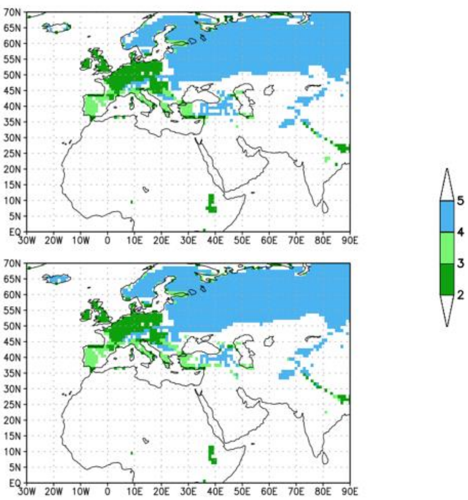

Figure 6: Climate-type classification in the EC-Earth3-ESM-1 historical simulation. Upper panel show the climatology of the period 1860-1890, while the lower panel show the climatology of the period 1984-2014. Grid-points where there is no correspondence with an observed climatology are not shown (as in Figure 1). Blue stands for point characterized by SNOW type of climate, light green stands for MED type of climate and dark green stands for WARM TEMPERATE type of climate.

3. ***CMIP7 Scenarios and GWL sensitivity experiments***

The original objective of this work was to exploit the forthcoming CMIP7 ScenarioMIP (van Vuuren et al 2026), which include a new generation of emission-driven scenarios specifically designed to investigate a wide range of future climate trajectories, including pathways with declining greenhouse gas concentrations and long-term climate evolution. However, these scenarios have been delayed in time and the framework to produce the projections with those scenarios have not been available in the timeframe of this project. To overcome this limitation while maintaining the scientific objectives, we propose to adopt an alternative strategy based on Global Warming Level (GWL) sensitivity experiments following the philosophy of the recently proposed TIPMIP protocol (Jones et al 2025). Rather than explicitly investigating overshoot pathways, these experiments provide a controlled framework to quantify the sensitivity of Mediterranean Climate Regions to progressively increasing warming levels and to identify potential thresholds, nonlinear responses, and abrupt transitions in their hydroclimatic characteristics. Analyses of this type of experiments allow to establish robust estimates of critical warming levels associated with shifts in Mediterranean climate regimes and can provide an essential benchmark for the interpretation of future projections and overshoot simulations once they become available. In this way, the proposed and performed GWL sensitivity experiments represent both a scientifically sound alternative to the unavailable scenarios and a complementary step towards understanding the thresholds governing abrupt changes and potential tipping behavior in worldwide MCRs. According to this, the resources planned for the projections have been used to produce 3 experiments at different GWL (2°, 3° and 4°C) with EC-Earth3-ESM-1 that are compared here with other companion simulations produced within OptimESM EU project and building on the pre-industrial simulation made available within the EC-Earth Consortium.

4. *MCRs changes in response to GWL increase*

Based on the explanation in Section 3, here we show an analysis of how MCRs change in response to GWL increase using a set of sensitivity experiments. As described above, the simulations performed here are combined with a companion set of experiments made available within the OptimESM EU project and the EC-Earth Consortium (see Table 2).

MODEL	piControl		GWL2		GWL3		GWL4	
	# of members	Length of exp. (yrs)	# of members	Length of exp. (yrs)	# of members	Length of exp. (yrs)	# of members	Length of exp. (yrs)
EC-EARTH	1	500	3 (*1*)	100	3(*1*)	100	3(*1*)	100
UKMO	1	500	1	100	1	100	1	100
CNRM	1	500	1	100			1	100
IPSL	1	500	1	100	1	100	1	100

Table 2: Description of the experiments used in this analysis. In Italic the simulations performed in this project.

In line with the analysis described in section 1, we have repeated here the evaluation of the distribution of the climate classification over the globe. Fig. 7 shows the worldwide distribution of the 6 types of climate listed in Table 1 comparing the piControl simulation with the three sensitivity experiments considered. Here the climatology is based on 50-years of stable simulation, and the values shown correspond to the multi-models and multi-members mean.

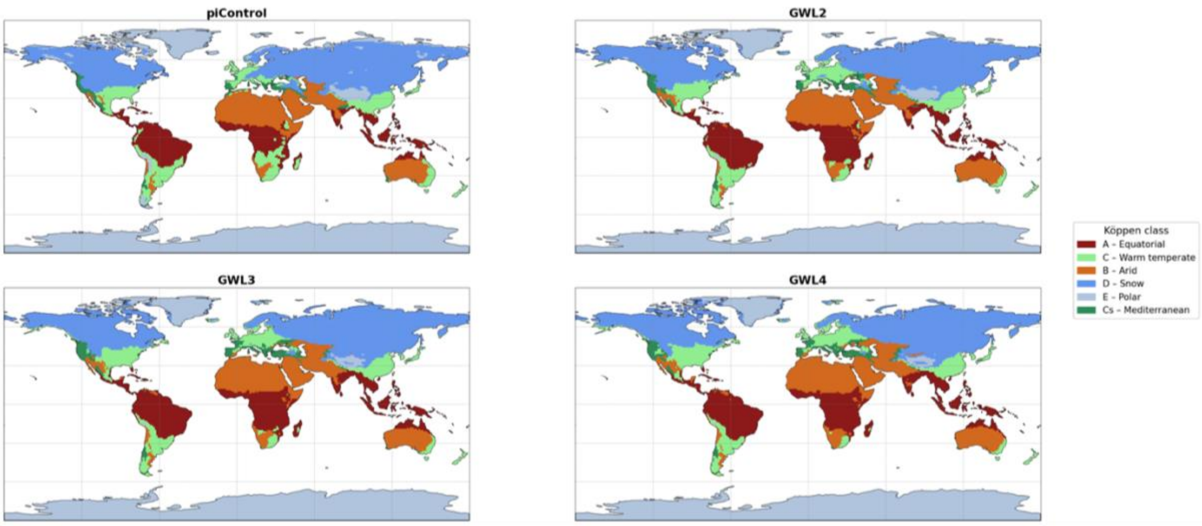

Figure 7: Climate-type classification for the sensitivity experiments described in Table 2. The characteristics of the types of climate selected are described in Table 1.

Defining the probability in terms of the fraction of members that classify a given grid point as belonging to the Mediterranean climate type, we have repeated the analysis described in section 1 to measure the change in different levels of global warming compared to the pre-industrial conditions. Consistently with the results shown for the CMIP6 simulations, an increased probability of a poleward expansion and an equatorward contraction of Mediterranean climate conditions are found as global warming intensifies (Figs. 8-10). As before, our analysis focuses on the Northern Hemisphere Mediterranean regions (the Mediterranean Basin and western North America; Fig. 8 and Fig. 9) together with central

Chile in South America (Fig 10), because of the limits associated with land distribution as described above.

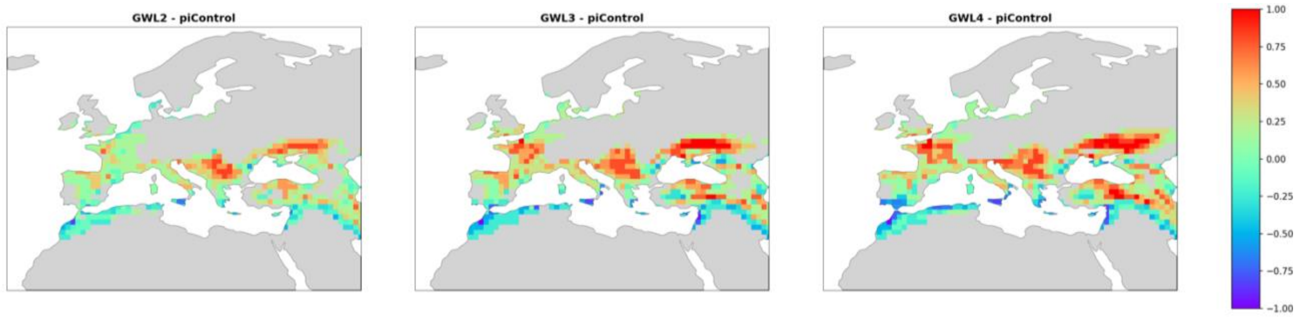

Figure 8: Change in probability (fraction) to have a MED climate-type (GWL minus pi-control) over the Mediterranean region

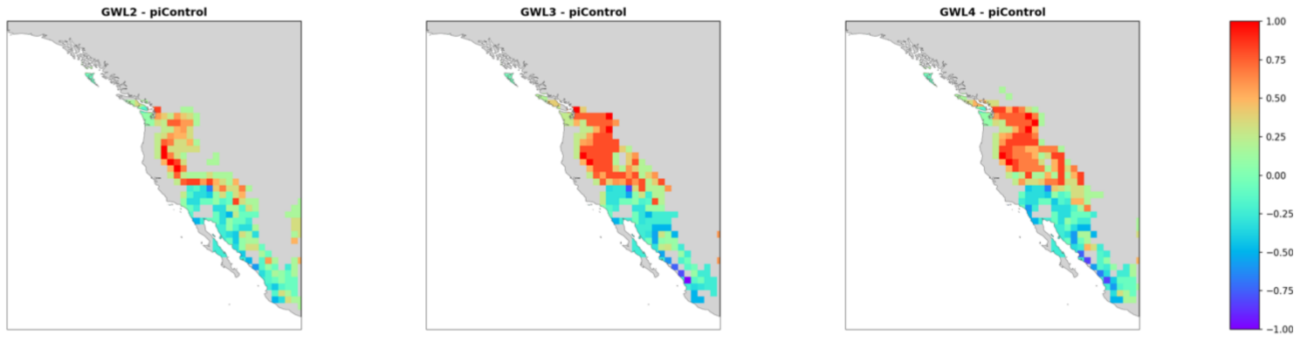

Figure 9: Same as Figure 8 but for Western North America region

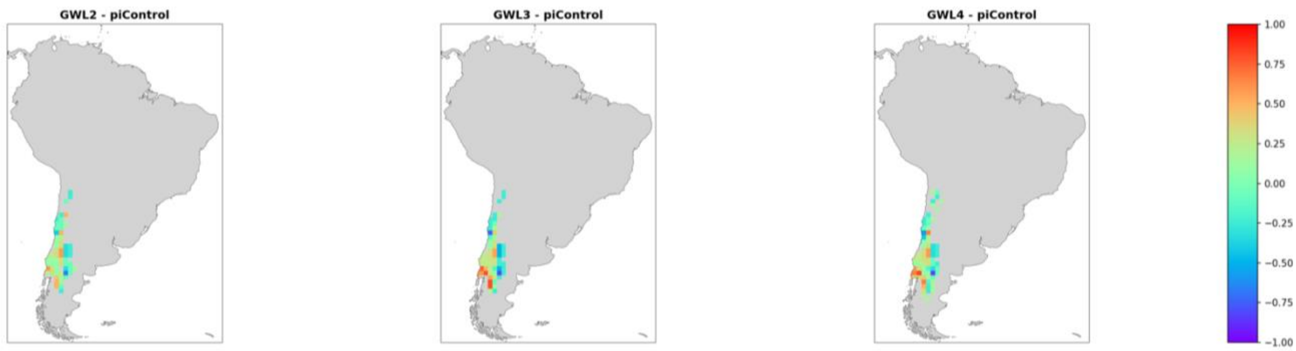

Figure 10: Same as Figure 8 but for South America region

Our results show a systematic poleward migration of Mediterranean climates, while their equatorward margins are progressively replaced by more arid climate types, reflecting the expansion of subtropical dry zones under increasing global warming. The magnitude of these changes strongly depends on the level of global warming reached.

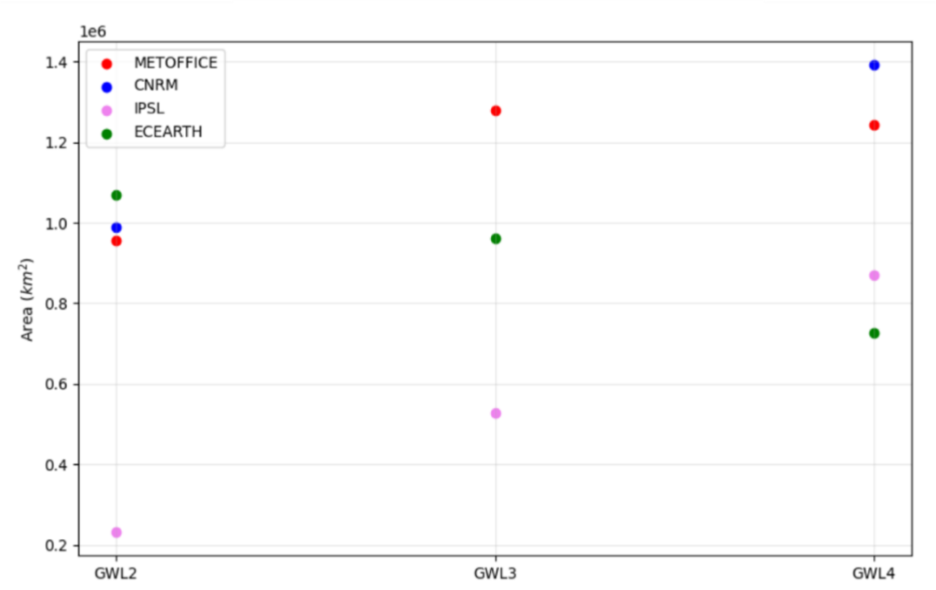

Figure 11: Scatter plot of area expansion (GWL experiment minus piControl) as function of GWL for the four models considered. Where more than one member is available the ensemble mean is computed and plotted.

To have an estimate of the expansion of the area with Mediterranean climate conditions characteristics, Fig. 11 shows its changes in km^2 in terms of reached GWL for each model. The sample of models selected evidence some diversities. Overall, the MED area tends to increase with increasing global warming level, suggesting a general expansion of this climate regime under warmer conditions. However, the response exhibits substantial inter-model variability. While some models show an approximately linear increase, others display a more irregular evolution, with changes that are non-linear or characterized by limited variation between successive warming levels. Furthermore, the magnitude of the increase differs considerably among models, indicating different sensitivities to global warming. These differences highlight the uncertainty associated with model-dependent representations of Mediterranean climate dynamics and suggest that the projected expansion of the Mediterranean climate is not only model-specific in magnitude but also in its progression across warming levels.

5. Conclusions and final remarks

This work has provided a comprehensive assessment of past and future changes in Mediterranean Climate Regions (MCRs), combining analyses of the CMIP6 multi-model ensemble with post-CMIP6 simulations performed using the latest version of EC-Earth3-ESM-1. The results confirm that Mediterranean climates are highly sensitive to anthropogenic warming and consistently project a poleward expansion of Mediterranean climate conditions together with a contraction of their equatorward margins, where progressively more arid climates emerge. The probabilistic framework adopted here demonstrates that these geographical shifts are robust across models and become increasingly pronounced under stronger radiative forcing. In particular, the CMIP6 analysis shows that both the expansion and contraction areas approximately double between the low-emission SSP1-2.6 and the high-emission SSP5-8.5 scenarios, highlighting an almost linear dependence of the spatial response on the level of climate forcing. In contrast, the comparison between the early and late periods of the historical EC-Earth3-ESM-1 simulation does not reveal substantial changes in the large-scale distribution of Mediterranean climate conditions, indicating that the most pronounced shifts are expected to occur during the coming decades under continued warming.

A key outcome of the project has been the successful adaptation of the original experimental strategy. Although the planned CMIP7 ScenarioMIP simulations were not yet available within the project timeframe, the implementation of Global Warming Level (GWL) sensitivity experiments, following the philosophy of the emerging TIPMIP framework, has provided an effective and scientifically robust alternative. These experiments reproduce the same large-scale patterns identified in the CMIP6 scenario ensemble, confirming that the poleward migration and equatorward retreat of Mediterranean climates intensify with increasing global warming. At the same time, the comparison across different Earth System Models reveals substantial inter-model differences in both the magnitude and the progression of the projected changes, emphasizing the importance of multi-model approaches for quantifying uncertainties associated with Mediterranean climate dynamics. Beyond providing an alternative to the delayed CMIP7 projections, the GWL framework establishes a valuable benchmark for identifying potential climatic thresholds and abrupt regional transitions. These results therefore lay the groundwork for future analyses based on the forthcoming CMIP7 ScenarioMIP simulations and overshoot experiments, which will enable a more comprehensive assessment of the reversibility, hysteresis, and long-term evolution of Mediterranean Climate Regions under different climate pathways.

References

Adler et al (2018) The global precipitation climatology project (GPCP) monthly analysis (new version 2.3) and a review of 2017 global precipitation. Atmosphere https://doi.org/10.3390/atmos9040138

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Seager R, Wu Y, Cherchi A, Simpson IR, Osborn TJ, Kushnir Y, Lukovic J, Liu H, Nakamura J (2024) Recent and near-term future changes in impacts-relevant seasonal hydroclimate in the world's Mediterranean climate regions. Int J Climatol 44(11) 3792-3820 https://doi.org/10.1002/joc.8551

Seager et al 2019 Climate variability and change of Mediterranean-type climates. J Clim https://doi.org/JCLI-D-18-0472.1

Senigalliesi V, Alessandri A, Cherchi A, Gelsinari S (2026) Drivers of water resource changes over the Mediterranean Climate Regions of the Northern Hemisphere. Earth's Future (Accepted)

Van Vuuren DP et al (2026) The scenario model intercomparison project for CMIP7 (ScenarioMIP-CMIP7). GMD https://doi.org/10.5194/gmd-19-2627-2026

List of publications/reports from the project with complete references

Cherchi A, Alessandri A, Lembo V, Gelsinari S, Renwick J (2024) Mediterranean Climate Regions in CMIP6 experiments: assessment of future changes and associated uncertainties. EGU24-16866 https://doi.org/10.5194/egusphere-egu24-16866

Cherchi A, Alessandri A, Renwick J, Senigalliesi V, Gelsinari S (2026) Assessment of future changes and associated uncertainties over Mediterranean Climate Regions in CMIP6 experiments. POS1.2: Advancing Climate Model Evaluation: Addressing Persistent Biases, Observational Uncertainties, and New Frameworks. CMIP Community Workshop 2026, Kyoto, Japan (https://cmip2026.org/)

Cherchi A, Alessandri A, Possega M, Senigalliesi V, Renwick J (2026) Future changes and associated uncertainties over the Mediterranean Climate Regions. EGU26-19239 https://doi.org/10.5194/egusphere-egu26-19239

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new EMI R&D Project.)

This specific analysis can be considered completed, with no further follow-up actions required. The related scientific report, intended for submission as peer-reviewed publications, is currently in preparation and will be finalized shortly. The experience gained from this special project has proven highly valuable and has already contributed to other ongoing activities, as well as to a new special project submitted by the same Principal Investigator, which commenced in January 2026.