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Assessing Shifts of Mediterranean and Arid Climates Under RCP4.5 and RCP8.5 Climate Projections in Europe

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Abstract—The Mediterranean basin is the richest biodiversity region in Europe and a global hotspot of biological diversity. In spite of that, anthropogenic climate change is one of the most serious concerns for nature conservation in this region. One of the climatic threats is represented by shifts of the Mediterranean climate and expansion of the arid climate. In this paper, we present an assessment of changes in the spatial range of the Mediterranean climate in Europe and the conversion into arid climate under different greenhouse gas forcings, namely RCP4.5 and RCP8.5. We used 11 simulations in two future 30-year periods of state-of-the-art regional climate models from EURO-CORDEX. Our results indicate that by the end of the century under RCP8.5 the present Mediterranean climate zone is projected to contract by 16%, i.e. an area ($\sim$ 157,000 km^2) equivalent to half the size of Italy. This compares with the less severe scenario RCP4.5 that projected only a 3% reduction. In addition, the Mediterranean climate zone is projected to expand to other zones by an area equivalent to 24 and 50% of its present extent under RCP4.5 and RCP8.5, respectively. Our study indicates that expansion of the arid zone is almost always the cause for contraction of the Mediterranean zone. Under RCP8.5 the arid zone is projected to increase by more than twice its present extent, equivalent to three times the size of Greece. Results of this study are useful for identifying (1) priority zones for biodiversity conservation, i.e. stable Mediterranean climate zones, (2) zones requiring assisted adaptation, such as establishment of new protected areas, implementation of buffer zones around protected areas and creating ecological corridors connecting stable Mediterranean zones.

Key words: Mediterranean climate, arid climate, regional climate model, biodiversity, climate change, adaptation.

1. Introduction

The Mediterranean basin is the richest biodiversity region in Europe and a global hotspot of biological diversity (Myers et al. 2000). Around half of plant and animal species and more than half of the habitats listed in the European Union's Habitats Directive (Council of the European Communities 1992) occur in the Mediterranean region. As the Intergovernmental Panel on Climate Change (IPCC 2014) pointed out, anthropogenic climate change is one of the most serious concerns for nature conservation in this rich biodiversity region. Additionally, the Mediterranean region is considered a climate change global hotspot (Giorgi 2006). Temperatures in the Mediterranean basin have increased by $\sim$ 1.3 °C relative to the 1880–1920 period, compared with an increase of $\sim$ 0.85 °C globally (Guiot and Cramer 2016) posing challenges to adaptation policies in the Mediterranean region. But Mediterranean ecosystems are also sensitive to changes in water availability, indeed the lower bound of precipitation of the Mediterranean climate type limits with the upper bound of the arid climate type (Hantel 1989; Kottek et al. 2006; Peel et al. 2007). Therefore, a relatively small decrease of precipitation could trigger a transition from Mediterranean to arid climate type. In turn, spatial shifts of the Mediterranean climate affect the availability and distribution of suitable habitats for wild species, contributing to reductions in endemic species range sizes (Benito Garzón et al. 2008; Keenan et al. 2011; Maiorano et al. 2013; Thuiller et al. 2005).

Previous studies have shown that climate-driven habitat loss is a major threat for Mediterranean biodiversity with projected spatial shifts of the present

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extent of the Mediterranean climate zone (Barredo et al. 2016; Klausmeyer and Shaw 2009). However, these studies have used either atmosphere–ocean general circulation models (AOGCMs) with a horizontal resolution in the order of hundreds of kilometres (Klausmeyer and Shaw 2009) or a limited number of regional climate model (RCM) simulations (Barredo et al. 2016), both using the previous SRES scenarios (Nakicenovic and Swart 2000) of the IPCC. In this paper, we present an assessment of changes in the spatial range of the Mediterranean climate domain (MCD) in Europe and the conversion into arid climate (hereafter arid climate domain—ACD) under two different Representative Concentration Pathways (RCPs) adopted by the IPCC in its Fifth Assessment Report, namely RCP4.5 and RCP8.5 (Moss et al. 2010; van Vuuren et al. 2011). In addition, we used the last generation of RCMs data from EURO-CORDEX (Jacob et al. 2014) at the unprecedented horizontal resolution of $\sim$ 12.5 km that represents a substantial improvement compared with previous attempts. Results of this study are useful for identifying areas projected to require focused conservation efforts, for instance, interventions such as Green Infrastructure (European Commission 2017a), as well as other adaptation measures oriented to facilitate animal and plant species migration to suitable habitats and conservation of the Mediterranean biodiversity.

2. Methods

In this study, we computed spatial shifts of MCD under two scenarios describing greenhouse gas concentration trajectories up to the year 2100 and named RCPs. These scenarios focus on anthropogenic emissions and do not include changes in natural drivers, e.g. solar or volcanic forcing or natural emissions (IPCC 2013). The first scenario, RCP4.5, is a trajectory describing radiative forcing of $\sim$ 4.5 Wm^{-2} ($\sim$ 650 ppm CO_2 eq.) with a stabilisation after 2100, corresponding to a projected change in global mean surface air temperature of + 1.8 °C (likely range 1.1–2.6 °C) relative to the reference period of 1986–2005 (Collins et al. 2013). The second scenario, RCP8.5, describes radiative forcing greater than 8.5 Wm^{-2} ($\sim$ 1370 ppm CO_2 eq.) in 2100. This latter pathway is seen as a high emission scenario (Moss et al. 2010; van Vuuren et al. 2011), corresponding to a + 3.7 °C (likely range 2.6–4.8 °C) world by the end of the century relative to 1986–2005 (Collins et al. 2013).

We used 11 RCM simulations in two 30-year periods covering 2021–2050 (hereafter 2021–50) and 2071–2100 (hereafter 2071–00) (Table 1). Changes in the MCD were computed for each simulation in relation to the reference period covering 1981–2010. Then, maps accounting for the three possible changes (i.e. stable, contraction and expansion) were produced for the 11 simulations, the two scenarios and the two periods. Additionally, shifts of the ACD were computed for assessing the effects on spatial changes of the MCD. The simulations and RCPs used were selected according to PESETA III Project (Dosio 2016, 2017; European Commission 2017c). This project aimed at deepening and further refining existing bottom-up analyses of climate change impacts in Europe. The project considered impacts on a series of sectors such as agriculture, energy, transport, river floods, coasts, droughts, habitat loss, forest fires, water, and human health. A common set of climate simulations and scenarios was used by all sectors with a focus on the biophysical dimension of impacts, extreme events and the exploration of various adaptation options.

High-resolution climate scenarios were sourced from the Coordinated Regional Downscaling Experiment (CORDEX) (Giorgi et al. 2009) of the World Climate Research Programme (WCRP). As part of the CORDEX project, the EURO-CORDEX (Jacob et al. 2014) initiative provides regional climate projections for Europe at $\sim$ 12.5 km horizontal resolution by downscaling the global climate projections of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al. 2012) and the RCPs (Moss et al. 2010; van Vuuren et al. 2011). In this study, we used simulations of daily air temperature and precipitation, which were previously corrected for bias by Dosio (2016), following Dosio and Paruolo (2011) and Dosio et al. (2012). Maps of mean monthly temperature and mean monthly precipitation were produced for the reference period and

Table 1

Regional climate model (RCM) simulations used in this study

Institute	Regional Climate Model (RCM)	Driving general circulation model (GCM)
CLM-Community	CCLM4-8-17	CNRM-CERFACS-CNRM-CM5
CLM-Community	CCLM4-8-17	ICHEC-EC-EARTH
CLM-Community	CCLM4-8-17	MPI-M-MPI-ESM-LR
DMI	HIRHAM5	ICHEC-EC-EARTH
IPSL-INERIS	WRF331F	IPSL-IPSL-CM5A-MR
KNMI	RACMO22E	ICHEC-EC-EARTH
SMHI	RCA4	CNRM-CERFACS-CNRM-CM5
SMHI	RCA4	ICHEC-EC-EARTH
SMHI	RCA4	IPSL–IPSL-CM5A-MR
SMHI	RCA4	MOHC-HadGEM2-ES
SMHI	RCA4	MPI-M-MPI-ESM-LR

Sourced from EURO-CORDEX (Jacob et al. 2014)

the two 30-year projections for each simulation/scenario.

The MCD and ACD were mapped using the Köppen–Geiger climate classification, which categorises world climates into five main groups and several subgroups on the basis of temperature and precipitation (Hantel 1989). The Mediterranean climate is often described using the Cs type of the Köppen–Geiger classification, defined as "warm temperate climate with dry summer" (Klausmeyer and Shaw 2009; Kottek et al. 2006), while the arid climate is represented by the B type, "arid climates" (Kottek et al. 2006; Peel et al. 2007). In this study, we used the criteria for Cs and B climate types according to Barredo et al. (2016), Garcia et al. (2014), and Peel et al. (2007), and followed Barredo et al. (2016), Garcia et al. (2014), Peel et al. (2007), and Russell (1931) using the temperature of the coldest month greater than 0 °C, instead of − 3 °C as used originally in the Köppen–Geiger classification in defining the temperate-cold climate boundary. Cs and B climate types are mutually exclusive, where the occurrence of one excludes the occurrence of the other. Unprojected latitude/longitude climate data were used for mapping the MCD and ACD, and equal-area projected maps were used for area change computation, taking the curvature of the earth into consideration.

Maps of the MCD were produced for each simulation, period and scenario. Therefore, 33 maps (11 simulations times three periods) were produced for each scenario. Change maps were then computed for each simulation between the reference period and the 2021–50 and 2071–00 periods. The change maps of each simulation and period were then summarised in one map for each scenario/period according to Table 2 and following the IPCC guidance (Mastrandrea et al. 2010). Thus, changes in regions in which more than 66% of the simulations agree are considered likely changes and confident changes where more than 90% of the simulations agree. Regions exhibiting agreement of less than 66% are considered uncertain changes. Therefore, the uncertain category represents cases when stable or contraction occurs in a range between one and six simulations. For example, if ten simulations suggest that a grid cell is within the MCD in the reference period and in the 2021–50, then that grid cell is confident stable for that period. Summary maps were created following two steps. First, the categories stable, contraction and expansion were included in a map. These categories are mutually exclusive; therefore, the presence of one excludes the other two. Second, the category uncertain was included in the map only in those grid cells that were not previously taken by one of the three categories of the first step. This is because the uncertain category is not mutually exclusive in relation to the three categories of the first step. The same approach was implemented for mapping changes in the ACD. Finally, ACD grid cells that are confident

Table 2

Categories of projected change of the Mediterranean climate domain (MCD) and arid climate domain (ACD) to 2021–50 and 2071–00

Projected change	Confidence	Number of simulations (out of 11)
Stable	Confident	10–11
	Likely	7–9
Stable/contraction	Uncertain	1–6
Contraction	Confident	10–11
	Likely	7–9
Expansion	Confident	10–11
	Likely	7–9

or likely stable were excluded from the uncertain MCD grid cells in the corresponding map.

In addition to assessing shifts of the MCD and the ACD, we computed projected changes in climate parameters over the current MCD. Changes of mean monthly temperature and mean monthly precipitation in the summer half of the year (from April to September), winter half of the year (from October to March) and annual were computed for both scenarios in the two periods. For computing the climate parameters a map representing the extent of the MCD in the reference period was implemented by overlaying MCD maps derived from the 11 simulations, and then selecting those grid cells where at least 7 simulations predicted MCD.

We performed a sensitivity analysis to assess the ability of the RCM simulations to reproduce a faithful delineation of the Mediterranean biome in Europe. The maps of the MCD produced using the reference period (1981–2010) of the 11 simulations were compared with three commonly used maps that represent the Mediterranean biome, the Myers et al. (2000)'s biodiversity hotspots (BDH) for conservation priorities, the global ecological zones (GEZ) for FAO forest reporting (FAO 2012), and the European Environment Agency's biogeographical regions (BGR) (EEA 2002). The three input maps of the Mediterranean biome were clipped to a common extent, equalling that of the simulations, and were then rasterised to the same grid size of the RCM simulations. We assessed only an area of interest covering the southern part of Europe to avoid large areas not considered Mediterranean that may bias the results towards agreement.

In the sensitivity analysis, we assessed agreement of the categorical maps using two metrics, the Cohen's Kappa coefficient (Cohen 1960; Hudson and Ramm 1987) and overall accuracy (Congalton 1991). The Kappa coefficient indicates the degree of agreement between categorical maps, with metric ranges from 0 (total disagreement) to 1 (perfect agreement). It reflects the difference between actual agreement and the agreement expected to occur by chance. Overall accuracy is one of the simplest descriptive techniques for map comparison, which is computed by dividing the total coincident number of grid cells in a comparison matrix.

3. Sensitivity Analysis

Results of the sensitivity analysis indicate that despite the differences between the climatic approach used in this study for delineating the MCD and the expert knowledge approach of the three maps of the Mediterranean biome, there is reasonable agreement between the maps of both approaches. Table 3 shows Kappa coefficient and overall accuracy obtained from the comparison between the maps of MCD resulting from the 11 simulations and the three maps of the Mediterranean biome (Fig. 1). The sensitivity analysis indicated that the MCD maps are closer to the delineation produced by the EEA's BGR map. Here, substantial agreement is indicated by the Kappa coefficient and overall accuracy is greater than 83% across the 11 simulations. Although minor than with the first map, there is also substantial agreement with the Myers et al.'s BDH. In this case, the Kappa

Table 3

Comparison of the Mediterranean climate domain (MCD) delineated using the Köppen–Geiger climate classification and 11 RCM simulations (reference period 1981–2010) versus Myers et al.'s (2000) biodiversity hotspots (BDH), the FAO's (2012) global ecological zones (GEZ) and the EEA's (2002) biogeographical regions (BGR), using Cohen's Kappa coefficient and overall accuracy

Simulations (RCM/GCM)	BDH		GEZ		BGR	
	Kappa	Overall accuracy (%)	Kappa	Overall accuracy (%)	Kappa	Overall accuracy (%)
CCLM4-8-17/CNRM-CERFACS-CNRM-CM5	0.63	85	0.50	81	0.66	86
CCLM4-8-17/ICHEC-EC-EARTH	0.60	83	0.48	80	0.64	85
CCLM4-8-17/MPI-M-MPI-ESM-LR	0.65	86	0.52	82	0.69	87
HIRHAM5/ICHEC-EC-EARTH	0.64	85	0.51	81	0.66	86
RACMO22E/ICHEC-EC-EARTH	0.66	86	0.53	82	0.69	87
RCA4/CNRM-CERFACS-CNRM-CM5	0.66	86	0.53	82	0.68	87
RCA4/ICHEC-EC-EARTH	0.63	85	0.52	81	0.65	85
RCA4/IPSL-IPSL-CM5A-MR	0.62	84	0.49	81	0.66	86
RCA4/MOHC-HadGEM2-ES	0.60	83	0.50	80	0.62	84
RCA4/MPI-M-MPI-ESM-LR	0.66	86	0.54	82	0.69	87
WRF331F/IPSL-IPSL-CM5A-MR	0.64	85	0.50	81	0.66	86

coefficient is marginally smaller than in the BGR and overall accuracy is greater than 82% across all simulations. Finally, the comparison with the FAO's GEZ exhibits only moderate agreement considering the Kappa coefficient and an overall accuracy above 79% across the simulations. Nevertheless, despite the resemblance between the maps of both approaches some differences emerged. For instance, in the southeast part of the Iberian Peninsula, there is an area considered Mediterranean in the three biome maps that in contrast falls outside the MCD of the 11 simulations. In fact, the RCM simulations consider this area already arid, i.e. within the ACD.

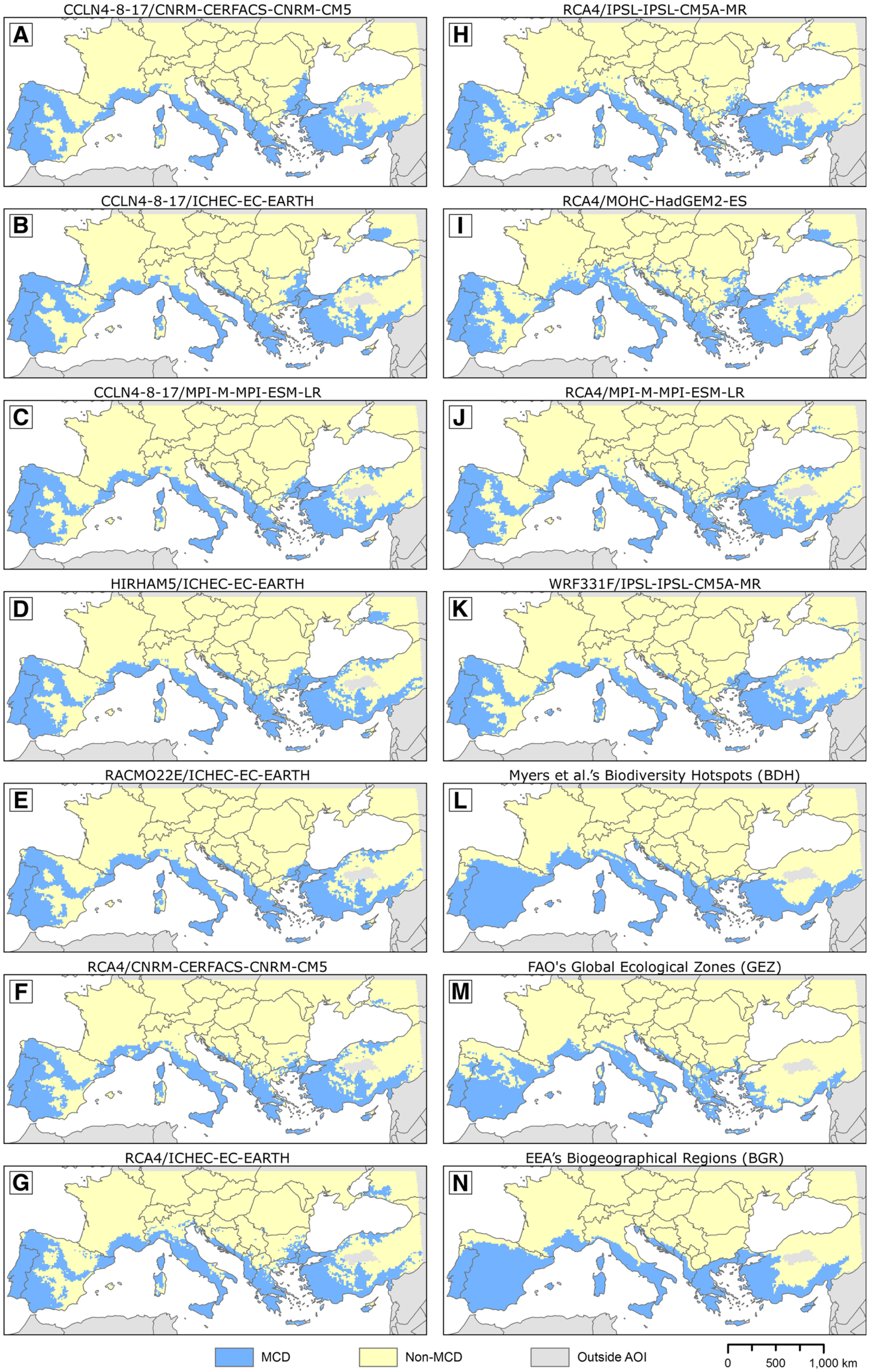
A point emerging from the sensitivity analysis is that the MCD maps computed using the climate simulations show comparable values of Kappa coefficient and overall accuracy in relation to each of the three maps of the Mediterranean biome. For instance, the difference between the largest and the smallest Kappa coefficient in relation to the BDH is only 0.06 and 3% regarding overall accuracy. This suggests that despite some differences in the simulations they resemble reasonably well the Mediterranean biome maps. In other words, they are spatially consistent and do not substantially differ from the maps of the Mediterranean biome. The similarity between the 11 MCD maps of the simulations is because the bias correction. For this reason, it is reasonable that the climatology of the reference period of the simulations is close to each other.

4. Results

The extent of the present MCD and ACD within the spatial domain of the RCM simulations is around 1,022,000 and 297,000 km^2, respectively. The extent was computed by selecting grid cells where seven or more RCM simulations predicted MCD or ACD in the reference period (1981–2010).

When assessing the simulations independently all of them projected a shrink of the present extent of the MCD under both RCP4.5 and RCP8.5 (Fig. 2a). By the 2021–50, both scenarios projected a comparable median loss of the present MCD of around 8–9%. However, by the 2071–00 the projected median shrink is more marked in RCP8.5, exhibiting 24%, in relation to RCP4.5, which projected 9%. Despite the fact that the present range of the MCD is projected to shrink, all the simulations projected shifts of the MCD in other climate domains. By the 2021–50 the projected median expansion (new areas) of MCD represent 32 and 23% of the present extent under RCP4.5 and RCP8.5, respectively (Fig. 2b). As consequence, all the simulations projected an increase of the overall extent of the MCD in relation to the present extent. Shifts of the MCD are projected to increase towards the end of the century, being more marked in RCP8.5, exhibiting a median expansion of 74%, than in RCP4.5, projecting 44%.

All the simulations projected large stable areas of the current ACD above 89% across periods and



CCLN4-8-17/CNRM-CERFACS-CNRM-CM5
A
RCA4/IPSL-IPSL-CM5A-MR
H
CCLN4-8-17/ICHEC-EC-EARTH
B
RCA4/MOHC-HadGEM2-ES
I
CCLN4-8-17/MPI-M-MPI-ESM-LR
C
RCA4/MPI-M-MPI-ESM-LR
J
HIRHAM5/ICHEC-EC-EARTH
D
WRF331F/IPSL-IPSL-CM5A-MR
K
RACMO22E/ICHEC-EC-EARTH
E
Myers et al.'s Biodiversity Hotspots (BDH)
L
RCA4/CNRM-CERFACS-CNRM-CM5
F
FAO's Global Ecological Zones (GEZ)
M
RCA4/ICHEC-EC-EARTH
G
EEA's Biogeographical Regions (BGR)
N
MCD
Non-MCD
Outside AOI
0
500
1,000 km

◀Figure 1
Mediterranean climate domain (MCD) delineated using the reference period (1981–2010) of 11 RCM simulations (**a**–**k**) and the Mediterranean biome according to: Myers et al.'s (2000) Biodiversity hotspots (BDH) for conservation priorities (**l**); the global ecological zones (GEZ) for FAO (2012) forest reporting (**m**); and the EEA's (2002) biogeographical regions (BGR) (**n**). Note that the maps **l**–**n** were clipped to a common extent equalling that of the climate simulations. Grey: outside the area of interest (AOI) of the sensitivity analysis

scenarios (Fig. 3a). The simulations also indicate projected expansion of the ACD in other climatic domains (Fig. 3b). This holds in all scenarios and periods with projected median expansions between 34 and 185% in relation to the current extent.

Summary maps of change show projected spatial shifts of the MCD using different levels of confidence (Fig. 4). In the 2021–50, a large proportion of the MCD is projected to be preserved in both scenarios. So it is at least likely (i.e. likely as well as confident) that 91% of the present MCD will be stable (Fig. 5). Similarly, projected expansion areas also show a comparable pattern in both scenarios. Finally, in this period, both scenarios projected a limited contraction of around 1%. Stable areas were projected in the Iberian Peninsula; southern areas of France including Corsica; western parts of Italy, Sardinia and Sicily; the Balkans; western, southern and north-west areas of Greece; Cyprus; and western zones of Turkey. Projected expansion areas are in north-western and southern parts of France, northern Spain, areas of northern Greece and central zones of Turkey.

Projected expansion of the MCD is more pronounced in the 2071–00 in both scenarios, but more marked in RCP8.5. In addition, by this period under RCP4.5 confident and likely contraction of the MCD totals 3% of the current extent. In contrast, under RCP8.5 it is at least likely that the MCD will contract by 16% (Fig. 4d), which is an area ($\sim$ 157,000 km^2) equivalent to half the size of Italy. As consequence, the present MCD is projected to contract to 70% (44% confident and 26% likely). Contraction areas are projected in central and southern zones of the Iberian Peninsula; southern Italy and Sicily; southern and north-eastern Greece and Crete; Cyprus; and parts of southern Turkey. In the 2071–00, projected expansion areas are more marked than in the previous period in either scenario (Fig. 5). Under RCP4.5, projected confident and likely expansion of the MCD

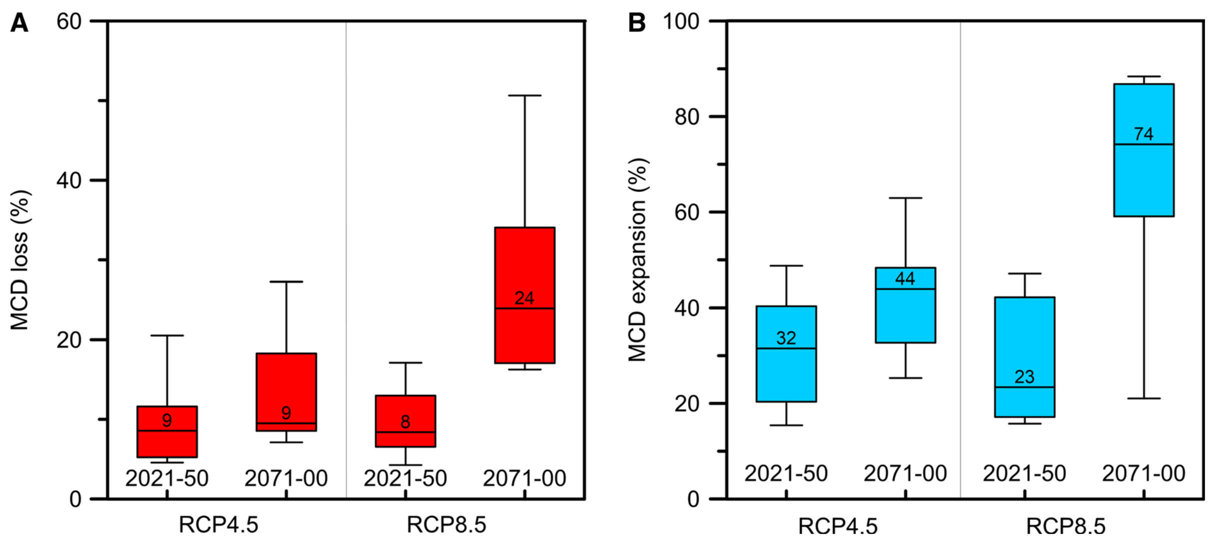


Figure 2
Projected relative changes of the Mediterranean climate domain (MCD) under scenario RCP4.5 and RCP8.5 in two future periods (2021–50 and 2071–00) in relation to the present MCD (1981–2010). The mean (horizontal line and number in boxes), 25–75% range (boxes), and minimum to maximum range (whiskers) across the 11 simulations are shown for each scenario and period. **a** MCD loss; **b** shifts of the MCD in other climatic domains

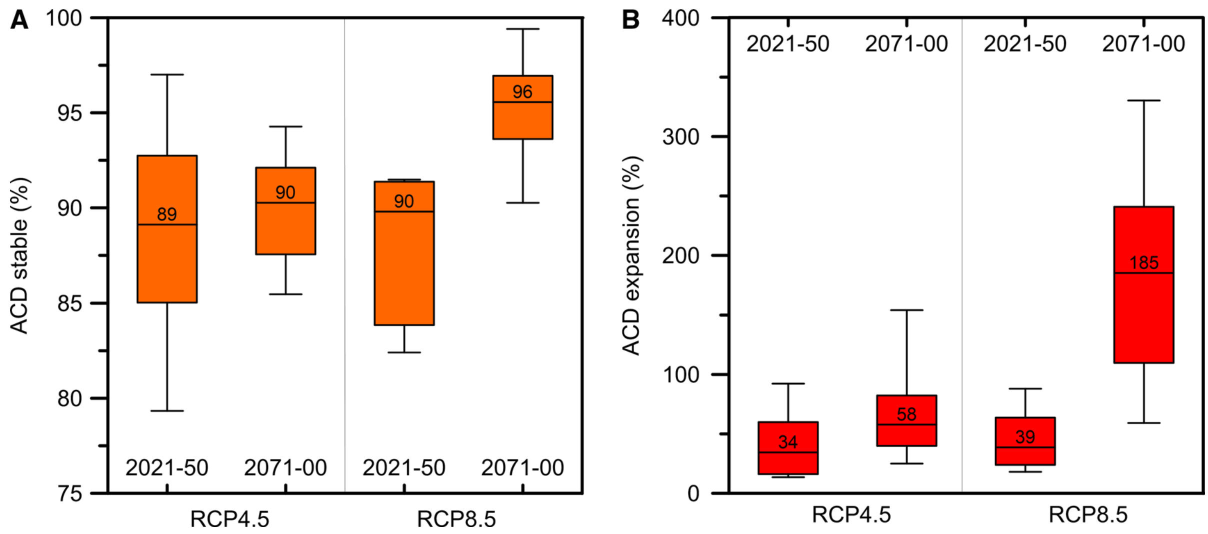


Figure 3
Projected relative changes of the arid climate domain (ACD) under scenario RCP4.5 and RCP8.5 in two future periods (2021–50 and 2071–00) in relation to the present ACD (1981–2010). The mean (horizontal line and number in boxes), 25–75% range (boxes), and minimum to maximum range (whiskers) across the 11 simulations are shown for each scenario and period. **a** ACD stable areas; **b** shifts of the ACD in other climatic domains

totals an area equivalent to 24% of the current extent. Under RCP8.5, the expansion in both categories is more pronounced, projected at 50%. The geographical distribution of expansion areas follows the pattern projected in the 2021–50, but with an evident increase in extent (Fig. 4b, d), e.g. in western and southern France.

Projected contraction of the present ACD is marginal ($< 1\%$) across scenarios and periods. By 2021–50 projected stable areas of the ACD under RCP4.5 and RCP8.5 are in the Iberian Peninsula; parts of Italy and Sardinia; eastern Greece and south-eastern Turkey (Fig. 6a, c). By this period both scenarios projected a likely expansion of 2 and 6%, respectively, while no confident expansion is projected in any scenario (Fig. 7).

The pattern of projected stable areas of ACD in 2071–00 follows that of the 2021–50. However, in the 2071–00 it is at least likely an expansion of 18% under RCP4.5. This compares to RCP8.5, where the likely expansion is projected at 111% and the confident expansion at 17% (Fig. 7), meaning that under this scenario the present ACD is projected to increase by more than twice its current extent, an increase equivalent to three times the size of Greece. The increase is projected in the Iberian Peninsula; southern Italy and Sicily; parts of Greece; parts of Turkey; eastern parts of Bulgaria and Romania; and eastern zones of the spatial domain of the climate simulations (Fig. 6d). Expansion of the ACD is almost always the cause for contraction of the MCD. For instance, under RCP8.5 in the 2071–00, 99% of the MCD loss is explained by expansion of the ACD.

Computed climate parameters indicate that the present MCD is projected to be hotter and drier in both scenarios. The annual mean temperature is projected to increase by 1.9 and 3.8 °C under RCP4.5 and RCP8.5, respectively by the 2071–00 (Fig. 8) from the 13.8 °C in the reference period. The increase is already evident in the 2021–50 in both scenarios. By the 2071–00 changes in temperature are expected to be more marked in the summer half of the year. Summer temperature is projected to increase by 2.1 °C under RPC4.5, in contrast with 4.2 °C under RPC8.5. This compares with winter temperature that is projected to increase less, i.e. 1.7 and 3.4 °C under RCP4.5 and RCP8.5, respectively.

In the present area of the MCD, annual precipitation is projected to decrease in both scenarios, but more markedly under RCP8.5 (Fig. 9). In the

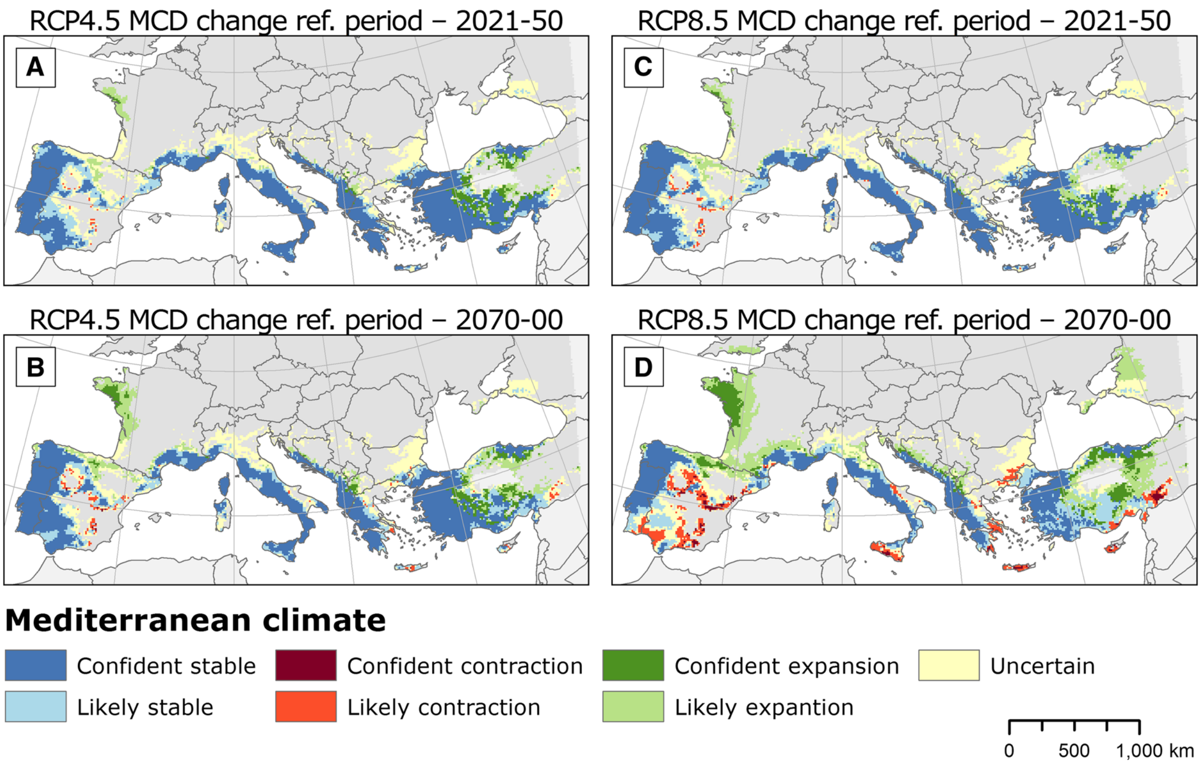


Figure 4

Projected changes of the Mediterranean climate domain (MCD) under scenario RCP4.5 and RCP8.5 in two future periods in relation to the reference period (1981–2010). **a**, **b** Changes under scenario RCP4.5 in the 2021–50 and 2071–00, respectively; **c**, **d** Changes under scenario RCP8.5 in the 2021–50 and 2071–00, respectively. White: outside the spatial domain of the RCM simulations

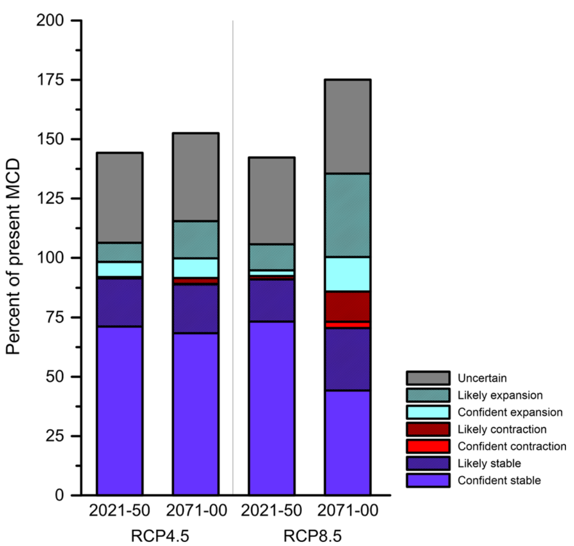


Figure 5

Projected relative changes of the Mediterranean climate domain (MCD) under scenario RCP4.5 and RCP8.5 in the 2021–50 and 2071–00 in relation to the reference period (1981–2010)

2021–50, a reduction of 2% is projected in both scenarios. Then, by the 2071–00, annual precipitation is projected to decrease by 3 and 12% under RCP4.5 and RCP8.5, respectively, from the 620 mm in the reference period. As for temperature increase, larger drops in precipitation are projected in the summer half of the year. By the end of the century summer precipitation is projected to decrease by 10 and 22% under RCP4.5 and RCP8.5, respectively. By this period winter precipitation is projected to remain stable under RCP4.5; in contrast a decrease of 8% is projected under RCP8.5.

5. Discussion

We assessed spatial shifts of the Mediterranean and arid climates using an approach that accounts for change in the area of analogous climates. Results of

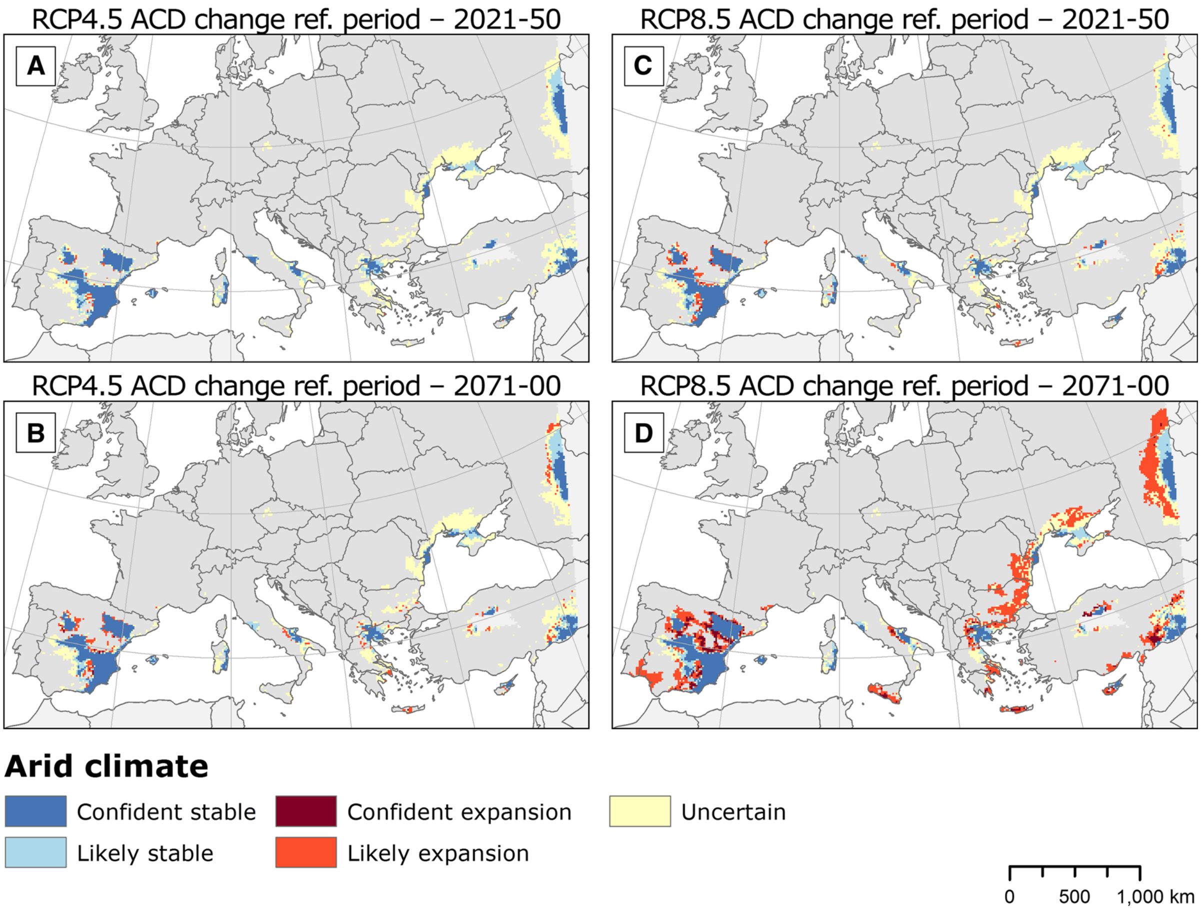


Figure 6
Projected changes of the arid climate domain (ACD) under scenario RCP4.5 and RCP8.5 in two future periods in relation to the reference period (1981–2010). **a**, **b** Changes under scenario RCP4.5 in the 2021–50 and 2071–00, respectively. **c**, **d** Changes under scenario RCP8.5 in the 2021–50 and 2071–00, respectively. White: outside the spatial domain of the RCM simulations

this study indicate projected contraction of the present area of the MCD under both RCP4.5 and RCP8.5 scenarios. The contraction process is evident in the 2021–50 and continues towards the end of the century. By this period, the contraction is notably more marked in the high emission scenario RCP8.5 than under the less severe scenario RCP4.5, where greater stability of the MCD is projected. The RCP4.5 scenario significantly reduces expansion of the ACD, this compares with the high emission scenario RCP8.5 where projected expansion is more than seven times larger.

Contraction of the present MCD supports the hypothesis of changes in species composition and interactions and may drive transient and new assemblages of plant and animal species (Blois et al. 2013). Nevertheless, there is high uncertainty regarding the impacts of climate change on biodiversity (Garcia et al. 2014; Moritz and Agudo 2013; Spangenberg et al. 2012; Urban et al. 2012). Contraction areas of MCD distant from stable or expansion areas will require adaptation measures, for instance ecological corridors oriented to facilitate the migration of plant and animal species. Results of this study also indicate a projected expansion of the MCD in other climate domains under both scenarios. These 'new' MCD areas could provide a suitable habitat for Mediterranean species if habitat quality and biotic interactions allow the establishment (Garcia et al. 2014).

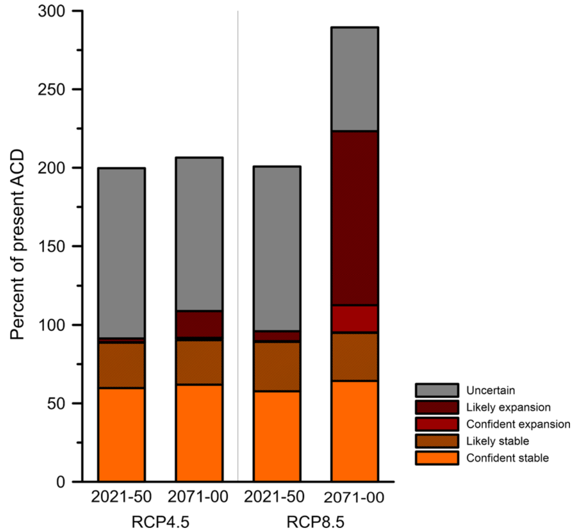


Figure 7
Projected relative changes of the arid climate domain (ACD) under scenario RCP4.5 and RCP8.5 in the 2021–50 and 2071–00 in relation to the reference period (1981–2010)

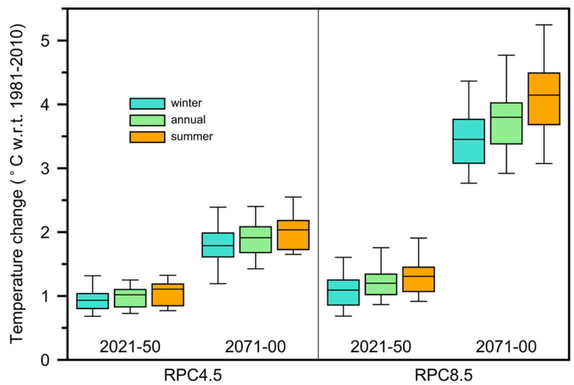


Figure 8
Projected temperature change (°C) in the Mediterranean climate domain (MCD) across scenarios relative to the reference period (1981–2010). Results are shown for the 11 RCM simulations for RCP4.5 and RCP8.5 in 2021–50 and 2071–00. Summer (orange): change in temperature of the summer half of the year; annual (green): change in annual temperature; winter (blue): change in temperature of the winter half of the year. The mean (horizontal line in boxes), 25–75% range (boxes), and minimum to maximum range (whiskers) across the 11 simulations are shown for each scenario, period and season

Expansion of the ACD is the main cause for loss of MCD. The conversion of MCD into ACD suggests a decrease of biodiversity due to migration or local extinction of Mediterranean species unable to cope with the magnitude of habitat change. Stable areas of the MCD that by the end of the century are projected

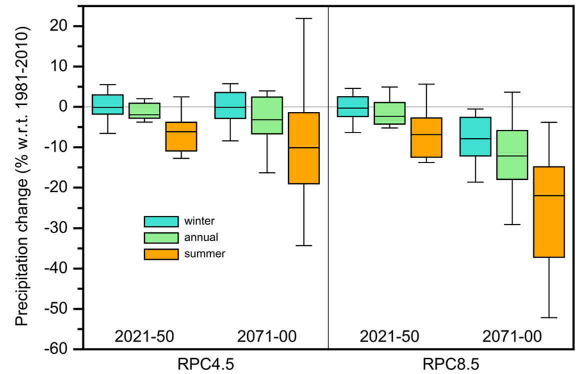


Figure 9
Projected precipitation change (%) in the Mediterranean climate domain (MCD) across scenarios relative to the reference period (1981–2010). Results are shown for the 11 RCM simulations for RCP4.5 and RCP8.5 in 2021–50 and 2071–00. Summer (orange): change in precipitation of the summer half of the year; annual (green): change in annual precipitation; winter (blue): change in precipitation of the winter half of the year. The mean (horizontal line in boxes), 25–75% range (boxes), and minimum to maximum range (whiskers) across the 11 simulations are shown for each scenario, period and season

to represent 88 and 70% of its present extent under RCP4.5 and RCP8.5, respectively, are of paramount importance for biodiversity conservation. These areas are fundamental for autonomous adaptation of vagile species serving as corridors and refugia. In fact, natural and semi-natural stable areas should be considered target zones for human-assisted adaptation, including Green Infrastructure (European Commission 2017a) and the expansion of the Natura 2000 protected area network (European Commission 2017b).

Projected changes in climate parameters indicate a transition towards hotter and drier conditions in the present MCD. This holds in both scenarios and both periods, but more severely under the high emission scenario RCP8.5. These projections support the hypothesis of an increase of other concomitant effects of climate change such as forest fires (Camia and Amatulli 2009; Migliavacca et al. 2013a, b; Moriondo et al. 2006), more frequent and longer drought (Allen et al. 2010; Hoerling et al. 2011; Lindner et al. 2010), the establishment and spread of invasive alien species (Hellmann et al. 2008) and changes in temporal and spatial patterns of forest pests and diseases (Barredo et al. 2015; Lindner et al. 2010; Netherer and Schopf 2010). The concomitant effects of these projected changes suggest decreasing levels of biodiversity.

Results of this study are in accordance with the previous studies assessing impacts of climate change in the Mediterranean region. Benito Garzón et al. (2008) indicated projected shrinks of suitable habitat of Mediterranean tree species in the Iberian Peninsula as consequence of anthropogenic climate change. They suggest likely local extinction of species with limited migration capabilities or in the absence of adaptation measures. These results are consistent with the projected loss of MCD and expansion of ACD in the Iberian Peninsula shown in this study. Results of Giorgi and Lionello (2008) using a suite of RCM describing IPCC SRES scenarios (Nakicenovic and Swart 2000) indicate a pronounced decrease of precipitation and warming, especially in the warm season, in the Mediterranean region by the end of the century. Under A1B (moderate emission scenario), precipitation was projected to decrease exceeding 25–30% and warming exceeding 4–5 °C. Despite differences in the spatial domain of both studies and the scenarios used, results of Giorgi and Lionello (2008) are consistent with our finding regarding changes in climate parameters and that the changes are projected to be worse in the summer half of the year.

The Köppen scheme relates vegetation types to characteristics of the interactive annual cycles of temperature and precipitation (Rohli et al. 2015b). Thus, this scheme is often used to predicting possible bioclimatic consequences of future climate change (Phillips and Bonfils 2015). Accordingly, several studies have used the Köppen–Geiger classification for assessing climate shifts at global level. Rubel and Kottek (2010) used global climate models and four SRES emissions scenarios. Their results suggest a global increase of 2.68% of the arid climate under the high emission scenario A1FI by the end of the century. Notably, the increase in arid climate is mostly due to shifts over the warm temperate climate that includes the Mediterranean climate type. In other study, Rohli et al. (2015a) assessed global climate shifts in both land and oceans under SRES scenario A1FI. Among other findings, their results suggest that the arid climate is projected to expand by 1% over land areas. Additionally, a decrease of 0.86% of the Mediterranean climate was also projected by the end of the century. Subsequently, Rajaud and Noblet-Ducoudré (2017) used 12 global climate models from the IPCC CMIP5 under RCP scenarios in an assessment of tropical and semi-arid expansion over temperate regions. Their results indicate, according to climate observations, a global expansion of 13% of warm semi-arid regions during the past century. Additionally, their results suggest that the expansion is projected to continue during the present century regardless of the scenario. For instance, under RCP8.5, the increase is projected at 38% by 2100 in relation to present conditions.

Elguindi et al. (2014) assessed projected climate change by the end of the century using a modified Thornthwaite climate classification. They used an ensemble of CMIP5 general circulation models projecting RCP scenarios. Their results suggest that the area coverage of torrid climate types expands by 11 and 19% at global level in RCP4.5 and RCP8.5, respectively. The expansion includes the Mediterranean region that was projected to shift to a drier climate. Despite differences between Köppen and Thornthwaite classifications, these results are in accordance with the previous global studies using the Köppen scheme.

Two studies assessed climate shifts in Europe using the Köppen classification. First, Gallardo et al. (2013) used the classification of Köppen–Trewartha with an ensemble of 15 RCMs under the SRES A1B scenario. They found that 22.3 and 48.1% of grid points in the domain are projected to change their climate by 2021–50 and 2061–2090, respectively, in relation to the present climate. Results of this study confirm the projected expansion of the arid climate in southeast Spain, Italy, Greece, Turkey and the coastal zones of northern Africa, and the shift of the Mediterranean climate towards north. Shifts of the arid climate over the Mediterranean climate were projected at 216,000 km^2 by the end of the century, a number that is reasonably in line with the 157,000 km^2 projected by our results under RCP8.5. The difference is mostly due to the use of different climate simulations, scenarios and approach. Second, Jylhä et al. (2010) found that between half and two-thirds of the study domain in Europe is projected to be affected by shifts towards a warmer or drier climate by the end of the century. They used median projections from a suite of 19 global climate models representing SRES scenarios. This study found observed shifts towards warmer and drier climates between 1950 and 1978 and 1979 and 2006 in 12.1% of the land area, and these shifts were projected to continue towards the end of the century, more notably under A1B and A2 scenarios. For example, expansion of the arid climate was projected in the Iberian and Italic Peninsulas, western and northern coasts of the Aegean Sea and in the Black Sea. Additionally, shifts of the Mediterranean climate were projected in western France. Despite the differences regarding methods and data, overall results of previous studies are consistent with the findings of this paper regarding expansion of the ACD and shifts of the MCD in Europe.

Regarding the decrease in precipitation and expansion of arid zones three studies are in accordance with our findings. First, Hoerling et al. (2011) identified a likely drop in wintertime precipitation over 1902–2010 in the Mediterranean region whose magnitude cannot be reconciled with internal variability alone. This is consistent with our projected drops in winter precipitation by the end of the century under RCP8.5, though not evidenced by the 2021–50 in this scenario, or in RCP4.5 in both periods. Additionally, they found increased drought frequency after about 1970. This finding appears to be consistent with the projected expansion of the ACD over MCD zones suggested in our study. Second, Gao and Giorgi (2008) using the Köppen classification, and other two measures of aridity, confirm the projected expansion of arid lands over central and southern zones of the Iberian, Italian, Hellenic and Turkish peninsulas and in areas of southeaster Europe (i.e. Romania and Bulgaria) by the end of the century. Changes are larger in high-end A2 scenario than in the low-end B2 scenario, although they are considerable in both of them. Third, in line with previous studies, results of Önol et al. (2014) support our findings regarding projected drops of precipitation and expansion of arid zones in the Eastern Mediterranean–Black Sea region by the end of the century. Using RCM simulations forced with three global circulation models under SRES scenarios, they found a projected "dramatic" precipitation fall in summer in the range of 30–90% under A2 and A1F1 scenarios. A range reasonably in-line with our results under RCP8.5 for the overall MCD that indicate a reduction in precipitation of 22% in the summer half of the year.

Two studies assessing changes in the area of Mediterranean climate under IPCC SRES scenarios were implemented at global (Klausmeyer and Shaw 2009) and European level (Barredo et al. 2016). Nevertheless, methodological, data and spatial domain differences of the studies make challenging any comparison with our study. First, Klausmeyer and Shaw (2009) used the Mediterranean climate definition of Aschmann (1973) that is more conservative than Köppen–Geiger used in the present study, although they also used Köppen–Geiger for sensitivity analysis. An important difference regarding the Köppen–Geiger definition is that we used the temperature of the coldest month greater than 0 °C, according to Peel et al. (2007) and Garcia et al. (2014), instead of − 3 °C. Using the temperature of the coldest month greater than 0 °C delineates a Mediterranean zone that is in agreement with areas traditionally considered part of the Mediterranean biome (e.g. Bohn et al. 2004; Médail and Quézel 1997, 1999; Olson et al. 2001). Another source of difference is that Klausmeyer and Shaw (2009) used simulations of future climate from AOGCMs with an horizontal resolution ranging from 125 to 550 km at the equator, disaggregated to a 5 km spatial resolution. AOGCMs are well suited for global assessments but lack detail in coastal zones or in areas of complex topography. Despite these differences, a comparison of the maps of both studies shows accordance in the overall pattern of the MCD, though the projected changes in the European region are more conservative in Klausmeyer and Shaw (2009). Second, Barredo et al. (2016) used four RCM simulations from ENSEMBLES (van der Linden and Mitchell 2009) at the 25 km horizontal resolution (scenario A1B) and 50 km (E1: stabilisation scenario), disaggregated to 1 km horizontal resolution. They indicate that by the end of the century under A1B and E1 scenarios the MCD is projected to shift to other climate domains by an area equivalent to 53–121% of its present extent, in addition the contraction was projected to 11–25%. Their results are in agreement with our study, where the expansion was projected at 50%, and the contraction at 16%, of the present extent under RCP8.5. Despite differences in the number of climate simulations assessed, horizontal resolution and scenarios used, results of Barredo et al. (2016) are in accordance with the present study.

Finally, using an ecosystem model, Guiot and Cramer (2016) suggested a series of climatic impacts in the Mediterranean region under RCP scenarios. Among the impacts with a likely effect on biodiversity they indicate regression of alpine forest, extension of Mediterranean sclerophyllous vegetation, expansion of the desert biome in the Iberian Peninsula and a general shift of the Mediterranean biome towards northern latitudes and higher elevations. These findings are in line with the projected shifts of the MCD and the expansion of the ACD over Mediterranean zones indicated in this study.

Our study presented a transparent methodology for mapping climate-driven Mediterranean habitat loss. However, despite known uncertainties in climate models, our results are subject to a few constraints. First, assessing impacts of climate change on biological response is a complex task that could be approached from different perspectives or by integrating predictive models representing biological mechanisms such as demography, species dispersal, evolution and species interactions (Urban et al. 2016). Additionally, different metrics may account for various dimensions of change, each with different implications for biodiversity conservation (Garcia et al. 2014). In this paper, we followed an approach using solely one type of metric that provides an assessment of changes of analogous climates. Despite it, this approach has been used previously providing valuable results regarding Mediterranean biodiversity conservation (Barredo et al. 2016; Klausmeyer and Shaw 2009).

Second, the spatial resolution of the RCM simulations used, although state-of-the-art (Jacob et al. 2014) is coarser than the optimal horizontal resolution required for assessing local-level landscape features such as small refugia, altitudinal gradients and effects of solar irradiation due to topography. This aspect can be alleviated using downscaling methods, e.g. change factor (Ekström et al. 2015). However, it is to be considered that downscaling methods would require increased computing resources. Third, the spatial domain of the bias-adjusted RCM simulations limits the study to the northern part of the Mediterranean biome. For instance, zones in North Africa, Middle East or the Canary Islands that are often considered Mediterranean, are outside the spatial domain of the simulations. Fourth, ideally the entire ensemble of CMIP5 simulations would provide a wider assessment of RCM uncertainty in future climate than the set of 11 RCM simulations used. However, Dosio (2016) suggests that the range of the 11 RCM simulation for a variety of climate change indices is in line, over Europe, with that of Sillmann et al. (2013) who analysed the entire CMIP5 ensemble.

Lastly, the sensitivity analysis was subject to two constraints. On the one hand, there is not a widely accepted definition of the Mediterranean biome. On the contrary, different definitions have been proposed for delineating the area considered Mediterranean (e.g. Aschmann 1973; Bohn et al. 2004; Médail and Quézel 1997, 1999; Olson et al. 2001). On the other hand, we used a purely climatic approach for the delineation of the MCD, which is in contrast with the method used for delineating the three maps of the Mediterranean biome. These aspects might pose some limitations for comparing the resulting maps of this study with the three biome maps. In summary, despite these constraints the sensitivity analysis provided relevant information about the ability of the RCM simulations and the Köppen–Geiger classification for delineating the MCD.

The Mediterranean region is projected to face shifts of its climatic domain and changes in climate parameters. Therefore, appropriate and timely climate adaptation in this region should be seen as a priority. Proactive adaptation and landscape management, facilitating a denser network of interconnected protected areas, are necessary instruments for protecting Mediterranean biodiversity from the threats of climate change. Additionally, mitigation (without adaptation) as represented by the RCP4.5 scenario significantly reduces projected expansion of the ACD and shifts of the MCD. Greater stability of the MCD under this scenario means in turn smaller impacts on biodiversity than under RCP8.5 and reasonably a minor incidence of the other concomitant effects of climate change in the Mediterranean zone.

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