The paper tackles the problem of climate change in the Mediterranean, exploring the role of teleconnections and local feedbacks in modulating future projections. To this aim, climate simulations are designed and run using a state-of-the-art climate model. The authors find climate change in agreement with previous literature (warming and drying), however their findings suggest reduced amplitudes in change. They explain these differences with the improved ability of the model in simulating SNAO teleconnections and land surface feedbacks.

We thank the reviewer for a very through revision comments and feedback regarding our manuscript. We have addressed all of the major comments when revising the manuscript. This includes either applying the reviewer's suggestion or a thorough justification for not doing that. We have also made an effort to address the minor comments. Overall, we've reworked the text of the manuscript to improve its conciseness and clarity.

Major comments 1. I acknowledge the huge work the authors did in carefully revising and discussing the literature, and in performing and discussing many analysis, but this makes the paper very long. My first general recommendation is to somehow shorten the manuscript, to facilitate the reader to be focused on the key messages delivered by the paper. For instance, discussions of previous findings is sometimes too detailed and redundant: accepted knowledge on summer climate in the Mediterranean region should be described in detail in the Introduction (or in a dedicated Background section) and briefly recalled when necessary in the text.

AU: Thank you for the comment. Following the reviewer's suggestion we've reworked the manuscript to make it more comprehensible. Particularly, we have summarized the discussion of the previous studies in a more concise way (section 3.2.1 and 3.2.2, pp 9: lines 1-46, pp 10: lines 7-21). The relevant information on the Mediterranean climate moved from sections 3.2 and 3.3 (pp 8: lines 15-27) to the Introduction (pp2: lines 10-22).

2. The main finding of the paper is the different amplitude of future projection of the Mediterranean climate simulated by the CM2.5 model in comparison with CMIP3 and CMIP5 simulations. To illustrate this crucial aspect, the authors refer to the existing literature on the topic. However, when quantitative differences are discussed, comparison with a Figure would be helpful. I suggest the authors to add some figures (in the supplement) showing projections of the future Mediterranean climate (precipitation and temperature) in the CMIP5 ensemble or, if downloading CMIP5 data is too time consuming, at least the CM2.1 model output, to show differences with the same model at lower resolution and not including the improved land model LM3.

AU: Thank you for the suggestion. In order to facilitate the comparison between the CM2.5 future projections and other models we have updated references and also included a supplementary figure. Figure R1 depicts changes estimated based on the RCP8.5 CSIRO-Mk3-6-0 model 10-member projections ensemble. Unfortunately, there are no RCP scenarios for GFDL CM2.1. Instead, we use the CSIRO-Mk3-6-0 model, which includes the ocean component based on the GFDL ocean model. We refer also to the very comprehensive analysis in Jacob et al. 2014 and Fussel et al. 2017 (Map 3.4, pp. 76), employing many GCM-RCM combined simulations from the EURO-CORDEX project. Discussion of these results is included in the text (section 4.1, pp 15: lines 10-27).

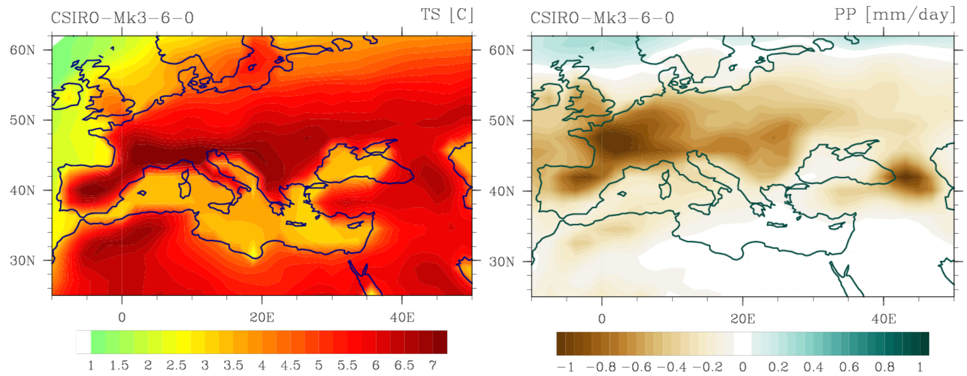

Figure R1. Projected future changes for the summer (JJA) surface temperature (left,°C), and precipitation (mm/day, right) based on the 10-member ensemble simulations of the CSIRO-Mk3-6-0 model, for the forcing scenario RCP8.5.

3. Data: why NCEP reanalysis are selected for comparison? On the same period, ERAI data are available at higher resolution. ECMWF datasets are also available for the 20th century. Same question about precipitation data: why University of Delaware? Testing other temperature/precipitation datasets (CRU, EOBS) would change your results? In general, comparing your results with different datasets would improve the robustness of your conclusions.

AU: Yes, we agree that a verification of the results with different datasets would improve the robustness of the conclusions. Following reviewer's suggestion we have incorporated EOBS dataset in the analysis of the regional precipitation (Figure 4). We agree that EOBS provides high quality data and serves as a good reference for the regional precipitation. Given the same spatial resolution as CM2.5, EOBS allows for comparing very fine features over the complex orography of the Mediterranean.

However, incorporating datasets with higher resolution wouldn't necessarily serve the purpose of the analysis of the large-scale circulation features. We have included below an additional figure (Figure R2), depicting sea level pressure and wind vector at 850hPa both in ERA-I and ERA 20CR, showing very good agreement between the suggested observational datasets.

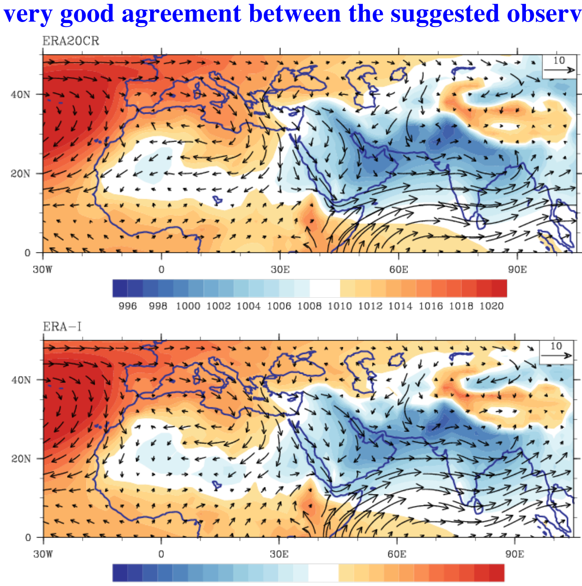

Figure R2. Seasonal (JJA) sea level pressure (hPa) and wind vector at 850hPa (m/s) in (top) ERA-20C, (bottom) ERA-I; for the 1979-2017 period.

In the analysis of the mid-level and upper level atmospheric dynamics, we would refrain from using the 20th century data sets such as ECMWF's ERA-20C or NOAA-CIRES 20th Century Reanalysis. Both of these data sets are based on the assimilation of the surface pressure values, which makes them a less plausible reference in the analysis of the upper level atmospheric dynamics. For example, the comparison of the vertical velocity at 500 hPa in Figure R3 reveals a strong positive bias in ERA-I, compared to the rest of the analyzed datasets (note the difference in the scalebar).

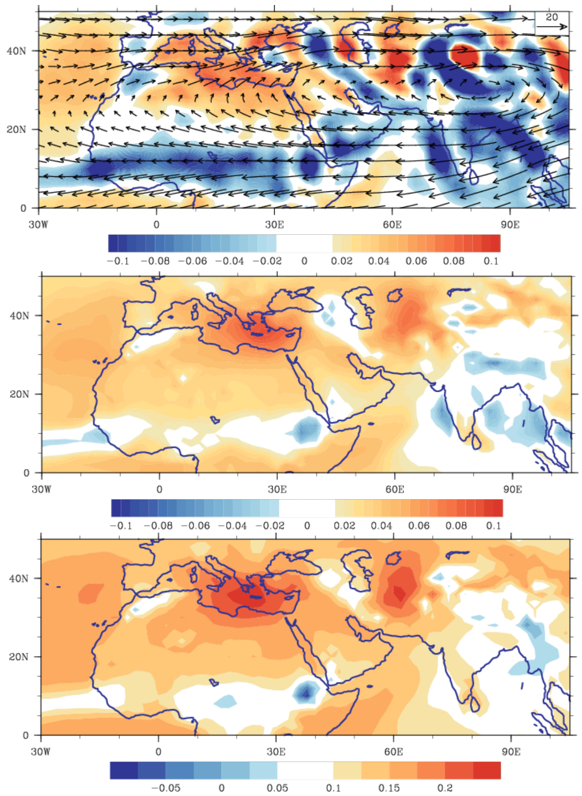

Figure R3. Seasonal (July) time-mean vertical velocities at 500hPa (Pa/s), estimated for (top) NOAA-CIRES 20th Century Reanalysis, (middle) as ECMWF's ERA-20C, (bottom) ERA-Interim for 1979-2017.

4. One main issue of the paper is the choice of the time window to be analysed. The aim of the paper is to study summer Mediterranean climate, so that you select JJA. However, through the paper, different periods are selected for different analysis: JA or just July. I recommend to homogenize the period to be analyzed (preferably JJA), for better comparison of the results. If there are specific reasons to analyze different period, these reasons should be highlighted.

AU: The choice of the time window is dictated by the method being most adequate to the analyzed climate component.. The teleconnection of SNAO with the climate over the Mediterranean region is manifest mostly during the peak summer, i.e. July-August. On the other hand the analysis in section 3.3. "Summer climate regime over the eastern Mediterranean" focuses on the month of July. "The choice is driven by the fact that the magnitude of subsidence and the Etesians is at its maximum in July while the response of the Rossby waves to monsoon rainfall is also the strongest (Tyrlis et al. 2012, Lin et al. 2007, Lin et al. 2009). The justifications of all the time window choices are included in the manuscript, but we have highlighted this information both in Methods (pp 5, lines: 22-23; pp 6, lines: 25-27; pp 7, lines: 5-8) and in the text (pp 12, lines: 10-14).

5. Methods section is rather long and sometimes confused: EOF analysis is described twice, the description of correlation/regression analysis is not really necessary here, as well as the reference to figures discussed later in the paper. I recommend to focus the section on the description of more sophisticated methods, such as EOF and stormtrack definition, and leave the description of correlation/regression analysis to the Results section. The section should be then shortened and optimised.

AU: We have clarified and rewritten the Method section in a more concise way (pp 6, lines: 12-27, 29-38; pp 7, lines: 1-21). Additionally, we have updated the description of storm track definition (p5, 40-46).

6. Model validation: in Figures 1-4 you compare the CTRL simulation to the NCEP data, and I see some important biases in terms of intensity (SLP in monsoonal regions) and location of some features (axes of the anticyclonic circulations at 500 hPa). This is due to the fact that in NCEP reanalysis there is GHG forcing, which is not included in the CTRL simulation (as you also highlight in the text, P21, L34-37). It would not be more consistent to compare the CTRL simulation to a different period, i.e. a period of 20C reanalysis/precipitation less affected by GHG forcing?

AU: We would refrain from the suggestion offered by the reviewer. Comparing CTRL simulation with a different or longer period of observations than the recent three decades would be a more appropriate solution, from the perspective of contributing forcing components. However, the quality of the observations-based precipitation datasets is much lower before the satellite era (~1979). For the analysis of atmospheric circulation we prefer to use a shorter period of NCEP/NCAR2 (DOE) data set rather than the longer Twentieth Century Reanalysis. We justify this choice with the findings in Krueger et al. 2013. This study has shown that the early part of the SLP record (first half of the 20th century) in the Twentieth Century Reanalysis suffers substantial inhomogeneities, most likely associated with the increasing number of observations and improved measurement techniques. Moreover, taking into account that both the NOAA's 20CR Reanalysis as well as ECMWF's ERA-20C datasets assimilate only surface pressure reports, sea ice, and sea surface temperature distributions, the expression of the high level atmospheric variables is highly uncertain in these datasets, as shown for example in the Figure 2 (omega at 500hPa) in the response to the question #3.

7. SNAO simulation: the analysis of SNAO impact in Figure 5 is not compared with any reanalysis product. The SNAO impact on climate in Europe is explained with variations in the stormtrack (Figure 7): why reanalysis data are shown and not model simulation?

AU: The representation of the SNAO in observations, using the SLP in different time periods, is shown in Figure 6. However the observed impact of SNAO has been shown in detail in Folland et al. 2009 and Blade et al. 2012. We prefer to make a reference to the existing literature rather than to repeat an existing analysis, especially to maintain brevity given major comment 1 requesting that we shorten the manuscript length.

Yes, the SNAO teleconnection with hydroclimate in northwestern Europe can be directly explained with variations in large-scale circulation over the North Atlantic and associated variations in storm tracks (as shown in observations and simulations in Folland et al. 2009). In this manuscript we intend to emphasize the sensitivity of the relationship between the SNAO and the storm tracks to the chosen period. For example, the relationship is stronger for the period starting in mid-century (i.e. 1950-1990, dominated with the dipole SNAO pattern (Figure 6e) than for the later period (1970-2011, dominated with the monopole over the British Isles (Figure 6g), suggesting that the representation of SNAO derived from the recent decades is likely being obscured by other climate components. We don't intend to investigate the simulated in CM2.5 impacts of SNAO on the North-Atlantic storm tracks. This is of course an interesting topic, but beyond the scope of this manuscript. We will clarify this point in the manuscript (pp 10: lines 33- 45; pp 11: 1-3). To maintain brevity, given major comment 1 requesting that we shorten the manuscript length, we will also move Figure 7 to the supplementary material.

8. Figure 11: the caption of the figure and discussion at P17 should be improved. You first state that you compute EOFs for the CNTR simulation, than you project the HIST-PROJ fields onto the CTRL EOF to get the 1860-2100 time series. Than you state that you also compute EOFs separately for HIST and PROJ. Then you discuss the 1860-2100 time series in Fig. 11c, then you go to HIST and PROJ EOFs in Fig. 11ab, and finally you discuss the contribution of the 1860-2100 SNAO to the end-of century projection of precipitation (Fig. 11de). I find this discussion confusing. This is a crucial point of the paper and should be presented clearly. I recommend the authors to improve the readability of this section. Moreover, the discussion of the SNAO impact on temperature projection should be significantly expanded.

AU: Following the reviewer's suggestion, we will clarify this part of the discussion, as well as the caption of Figure 11 and the corresponding methods. Yes, we agree. In this section we address three problems, which requires three different analysis approaches. We consider important to justify each of them. We have made a substantial effort to optimize the length of the discussion, clarified the discussion and improved the relevant caption (pp 15, 16).

We also would like to remind, that the manuscript focuses on the impact of SNAO on the Mediterranean hydroclimate, and its future changes (section 3.2.2 and 4.2). There is a very limited knowledge on the impacts of SNAO on temperature (basically two papers: Blade et al. 2012, Folland et al. 2009), and these results are far from unequivocal. The results shown in these two articles differ depending on chosen length of dataset and method of analysis (e.g. whether the correlations are based on interannual variations or including multidecadal signal). Our analysis seems more consistent with Folland et al. 2009, who applied rigorous statistics to avoid effects of autocorrelation caused by low-frequency components in a relatively short data set. We have now included the relevant information and highlighted the existing ambiguity to the section 3.2.1 (pp 11). However, we would prefer to abstain from further discussion, to avoid speculation. If reviewer has certain opinion on this issue, it might be helpful to receive a more elaborate suggestion.

9. Results: the differences between CM2.5 and CMIP5 models in projecting the paper Mediterranean climate are explained with a) better representation of the SNAO teleconnection and b) improved representation of the land-atmosphere interaction by the LM3 model (see also the Abstract). However, the improvements of the LM3 model are not presented in the paper, nor how these new features actually improve the representation of the land-atmosphere interactions (*e.g. representation of soil moisture, evapotranspiration, albedo*). A brief presentation of the LM3 model as well as a discussion of how it improves climate simulation in the Mediterranean is needed.

AU: Thank you for bringing up this gap in our writing. We have clarified the Abstract, added references to the data section (pp 5, lines 1-4), and added text to the results and summary section (pp 15, lines 4-13; pp 21, lines 10-24) relating to land model improvements and some research highlighting LM3 performance. We agree that more analysis is required to further support this claim, which would add significant text and figures to the paper. We have included references of studies beginning to look into this problem, but have left the exploration of land-atmosphere interactions of the SNAO using LM3 for future research.

Added references:

Berg, A., B.R. Lintner, K. Findell, S.I. Seneviratne, B. van den Hurk, A. Ducharne, F. Chéruy, S. Hagemann, D.M. Lawrence, S. Malyshev, A. Meier, and P. Gentine, 2015: Interannual Coupling between Summertime Surface Temperature and Precipitation over Land: Processes and Implications for Climate Change. J. Climate, 28, 1308–1328, https://doi.org/10.1175/JCLI-D-14-00324.1

Berg, A., Findell, K., Lintner, B., Giannini, A., Seneviratne, S. I., Van den Hurk, B., Ruth Lorenz, Andy Pitman, Stefan Hagemann, Arndt Meier, Frédérique Cheruy, Agnès Ducharne, Sergey Malyshev & P. C. D.

Milly, 2016: Land–atmosphere feedbacks amplify aridity increase over land under global warming. Nature Climate Change, 6(9), 869.

Milly, P.C., S.L. Malyshev, E. Shevliakova, K.A. Dunne, K.L. Findell, T. Gleeson, Z. Liang, P. Phillipps, R.J. Stouffer, and S. Swenson, 2014: An Enhanced Model of Land Water and Energy for Global Hydrologic and Earth-System Studies. J. Hydrometeor., 15, 1739–1761, https://doi.org/10.1175/JHM-D-13-0162.1

10. Conclusions: most of the paper is devoted to the analysis of the SNAO teleconnection and its impact on future climate change in the Mediterranean, which show a significant (P17, Figure 11) impact on precipitation in southern Europe. And in the abstract you indicate this as one of the main results of the paper. Conversely, in the Conclusions you somehow reduce the importance of the SNAO impact (P22, L38-40), explaining the differences with the CMIP5 simulations as a consequence of the improved land model. This point needs to be clarified.

AU: Following the reviewer's suggestion, we have clarified the main message of the manuscript. We agree that the analysis of the impacts of the SNAO teleconnection consumes a significant part of the manuscript. This part shows a significant contribution of the SNAO to precipitation over southern Europe. However, the comparison of the SNAO impacts between CM2.5 model and CMIP3/CMIP5 models suggests that the SNAO can not explain the difference in the future projections between these models. The apparent stark contrast between the CMIP3/CMIP5 and CM2.5 regional projections could more likely originate from the enhancements in the LM3 land model incorporated to CM2.5 at high spatial resolution, rather than the impacts of the SNAO. Future work should focus on understanding differences in land surface responses in this region to the SNAO and projected climate change.

Minor comments:
P2, L15: the connection between the Mediterranean and the African monsoon has been robustly described as Mediterranean → Africa (see papers by Raicich et al. 2003 and Rowell 2003 [https://doi.org/10.1175/1520- 0442(2003)0162.0.CO;2]).

The influence of the African monsoon on the Mediterranean is less clear: Ziv et al. 2004, but also Fontaine et al. 2011 [https://doi.org/10.1002/joc.2108], actually find a link between convection in Africa and subsidence in the Mediterranean, however the mechanism is still not clear (see Gaetani et al. 2011 [https://doi.org/10.1029/2011GL047150]). Indeed, the Asian monsoon could be dominant in modulating the Mediterranean-Africa connection. Please modify the sentence to account for this aspect.

Thank you for the comment. We found and included all the missing references, and modified the sentence (Raicich et al. 2003 and Rowell 2003, Fontaine et al. 2011) (pp 2, lines: 22-24).

P2, L26-29: please add a reference.
P3, L18-20: please add a reference.
Thank you, we add the references.

P3, L43: "fixed levels of radiative forcing", do you mean 'radiative forcing from fixed levels of emission/concentration'?
We have corrected the sentence (pp:4, line 14)

P4, Methods: is the model fully coupled? How many vertical levels are in the ocean model?
We have added the information (pp 4).

P6, L15-16: this sentence should be moved to the Results section. **Thank you, we have applied the suggestion.**

P6, L18-19: what do you mean with "vector time series"? The time series of the vector containing spatial data? **Correct.**
P7, L39: from Figure 4, precipitation magnitude is actually, not "apparently", larger than observations.
We have corrected the sentence. (pp 8, line 19)
P7, L45: "none of the CMIP5. . ." **Yes, we applied the correction (pp 8, line 24).**

P8, L1: do you mean that the CM2.5 runs in the CMIP5 archive are better than other models in the archive? Or do you refer to the runs you analyse in this paper? If this is the case, you should provide a figure to support this statement.
Thank you. We referred to the CMIP5 analysis shown in Kelley et al. (2012). We will clarify this and add the reference where appropriate.

P8, L10-13: when discussing the impact of NAO and SNAO on European climate, add references.
We have added the references throughout the paper.
P8, L17: "and rather wet conditions".
Thank you, we applied the correction (pp 2, line 11).
P8, L18-19: add references on future projections of SNAO.
This paragraph is now rewritten and moved to Introduction (pp2)

Section 3.2: the objective is to test the capability of the model in simulating the SNAO as an independent internally-generated mode of climate variability. However, the long introduction at P8-9 does not actually help in understanding why this is necessary. Is the internal variability modulated at multidecadal time scales? Is this modulation externally forced? Please try to clarify motivations and objectives of the section.

As stated in the introduction of section 3.2, the purpose is to analyze the capability of the CM2.5 model to simulate the SNAO as an independent, internally generated climate component, which would prove the physical validity of the statistically-derived component. The "internally-generated" means that that the modulation is generated by the internal climate variations and it is not externally forced. However "the origin of the multi-decadal signal of SNAO has been linked (Knight et al. 2006, Folland et al 2009, Linderholm and Folland 2017) to the Atlantic Multidecadal Oscillation, which originates from internal variations in thermohaline circulation (Knight et al. 2005, 2006, Delworth and Mann 2000; Enfield et al. 2001), but for the recent decades also from anthropogenic sources (Rotstayn and Lohman 2002; Mann and Emanuel 2006)." Yes, we agree that the introduction of section 3.2 is too long. We have moved part of the information to section 1 and clarified the main purpose of section 3.2 (pp 8, lines: 30-44).

P8, L20-26: this paragraph is confusing: on the one hand, it is true that different approaches/datasets may lead to uncertainty in the observed SNAO-Mediterranean teleconnection; on the other hand, uncertainties in model simulations originate from model shortcomings. Therefore uncertainty in the real and model worlds could originate from both intrinsic non-linear nature of the phenomenon and inadequate statistical/modelling tools. Please rephrase.
We have substantially shortened and clarified the paragraph (pp 8, lines 30-44).

P9, L8-9: I cannot understand why and how anthropogenic forcing should intensify SNAO contribution (to the summer atmospheric circulation over North Atlantic). Please explain.
We have substantially rewritten this section and this sentence is not included.

P9, L34: add the figures for July and August to the Supplement.
We won't add this figure to the Supplementary Information, which already contains 10 supplementary figures, but have included the information that the figure is not attached (pp 9, line: 15),
P9, L35: what is the interest of comparing with the HadCM3 model?
This section analyzes the capability of CM2.5 in simulating SNAO and compares it with the available results of other models, in this case HadCM3 and HadGEM1 in Folland et al. 2009.
P9, L42: is it HadGEM1 or HadCM3?

The statement is correct.

P13, L6-7: why an East Mediterranean index is used to compute correlation in Figure 8d, instead of the first EOF for NCEP omega? **Figure 8d shows the correlations computed based on three-decade time series of NCEP omega at the mid-atmospheric level. Taking into account the relatively short length of the data set (compared to 1000 years CTRL run) and a relatively smaller plausibility of the data at the middle and higher atmospheric levels, we refrain from applying an EOF analysis to the NCEP dataset. In our consideration, applying an EOF analysis to such a short time series could lead to degeneracy of the derived eigenvalues. In other words, the EOF mode derived from the NCEP dataset could be easily a spurious combination of several modes, rater than a realistic representation of the SNAO mode.**

P14, L25-26: what do you mean with "estimated at the original model resolution"? Do you mean "computed"? **Yes, Thank you for the correction (pp 13, line 8)**

P14, L32: east. **Correction applied (pp 13, line 15)**

P17, L1-3: I don't understand why you refer to Fig. 10a (showing end-of-century projections) to discuss changes in SNAO. You could maybe use this figure to support your analysis of future SNAO.

The figure shows the projected future changes (please note that in the current version this is Figure 9) and indeed we are using this figure to support the analysis of future SNAO (although it supports also the interpretation of the analysis of the already observed SNAO changes). The fingerprint of the future changes, derived from the sea level pressure projections, is consistent with the observed evolution of SNAO and thus it may constitute a possible contribution of the anthropogenic component already observed in the 20th century. We have tried to clarify this issue in the manuscript (pp 15, lines: 11-30).

P17, L14-16: it would be preferable to present the regression method to estimate the SNAO impact here rather than in the Method section. **Yes, we moved this line to the Methods.**

P17, L43: "warming is lower over . . . than . . ."

Thank you, we have substantially rewritten and improved this section.

P18, L7-12: it is not clear to me whether you are discussing you results (in Figure 10) or previous findings. If you discuss your results, please add more references to Figure 10, otherwise add a reference to a paper.

Yes, we have clarified the paragraph (pp 16, 17-25).

P20, L39-41 and 42-45: please add references.

Thank you, we have updated references in the section.

P21, L20: "preindustrial value". **We have substantially shortened and clarified whole section.**

P22, L9-10: please add a citation to CMIP5 results.

Thank you, we have applied the correction.

Figures: for better comparison, figures presenting climate change in the Mediterranean should share the same geographical boundaries. Same recommendation for figures presenting SNAO and Asian monsoon teleconnections, respectively.

Unfortunately this idea is not feasible and doesn't serve the purpose of the analysis. Each figure is presented in different context. For example, projected future changes for SLP are discussed in the context of the Euro-Atlantic climate. In contrast, regarding precipitation and temperature we want to focus on the Mediterranean region, but also discuss it form the perspective of climate in Europe. We have thoroughly reconsidered the way each figure is presented.

Figure 6: what do contours represent? The sign looks reversed with respect to the standard SNAO pattern. Could you please fix this, not to mislead the reader?

We have improved the figure and presented the SNAO at its positive phase. We have included the clarifying information in the caption. However, we strongly disagree with the reviewer in saying that the "positive phase" is a "standard pattern".

Figure 7: does it make sense to project the SNAO index derived from 20CR onto NCEP data? Why not just analyse one dataset?

We agree with the reviewer that it is usually easier to use just one data set. However for the sake of consistency with an earlier part of the analysis, we used the 20CR dataset instead of the NCEP dataset. In the earlier part of the analysis we used the 20CR dataset, because the alternative ones, such as NCEP-NCAR1 or NCEP –DOE, would be too short for the analysis of the evolution of SNAO during the 20th century.

Figure 8: Do you perform EOF on omega 500 and 300 together? Or is EOF analysis performed separately on omega 500 and 300? If this is the case, which time series do you use for correlations?
Yes, the EOF analysis is performed separately for each level. The method is described in the manuscript but we will clarify and highlight this information also in the caption (pp7, lines 1-8).

Figure 10: wind is displayed at which level? Is not model resolution 0.5?
Thank you, we have included the missing information and applied the correction.
Figure 11: in panels d and e you show regressions, while in Fig. 9c you show correlations.
Figure d and e doesn't show regressions, but the projected changes. The impact of the SNAO in figure e is removed using linear regression. We have clarified the figure the caption.
Figure 12: is omega at 200 or 500? **The information is included.**

See P18, L23. Supplement: please follow the logical order of the paper to number the figures. Also please write complete captions, avoiding to refer to captions in the main text.
Thank you for all the comments and advice regarding the figures.

Dear editor,
I have read this paper and think it fits the scope of ESD. Moreover, I think the material presented in the paper is an welcome addition to the knowledge on climatic changes in the Mediterranean. My main issues with the current manuscript are in the presentation. I think it is quite long and should be more focused, possibly with a reduction in the number of figures.
Kind regards,

AU: We thank the reviewer for a very through revision comments and feedback regarding our manuscript. We have addressed all of the major comments when revising the manuscript. This includes either applying the reviewer's suggestion or a thorough justification for not doing that. We have also made an effort to address the minor comments. Overall, we've reworked the text of the manuscript to improve its conciseness and clarity.

Specific comments:
1. The paper is quite long and elaborate, maybe wise to focus a bit more and reduce the number of figures?

AU: Thank you for the comment. Following the reviewer's suggestion we will work on the manuscript to make it more comprehensible. We've reworked the manuscript to make it more comprehensible. Particularly, we have summarized the discussion of the previous studies in a more concise way (section 3.2.1 and 3.2.2, pp 9: lines 1-46, pp 10: lines 7-21). The relevant information on the Mediterranean climate moved from sections 3.2 and 3.3 (pp 8: lines 15-27) to the Introduction (pp2: lines 10-22). We also moved one figure with storm tracks to the Supplementary Material (Figure SI 2).

2. There are many long sentences throughout the paper, which make it hard to follow the reasoning sometimes. I suggest to have a good look at opportunities to shorten them.

AU: Thank you. We have improved the readability of the Introduction, Methods, Results and Summary.

3. In many places in the manuscript, geographic names (Levant, Asia Minor, Balkans, Sahara, North Africa, EMED, and many more) are used to describe the model results. This assumes that the reader knows the location of all these places, which is probably not true. I suggest to indicate the relevant places in a figure and to be more specific in the geography when mentioning other places.

AU: Thank you. We described the necessary regions in the Methods section, and provided the specific locations (particularly pp 6, lines: 12-17).

4. You compare the high resolution model output to NCEP/DOE reanalysis of 2.5 degree resolution. Why not compare it to higher resolution products, such as ERA5?

AU: Thank you for the comment. Incorporating datasets with higher resolution wouldn't necessarily serve the purpose of the analysis of the large-scale circulation features. We have included below an additional figure (Figure R2), depicting sea level pressure and wind vector at 850hPa both in ERA-I and ERA 20CR, showing very good agreement between the suggested observational datasets.

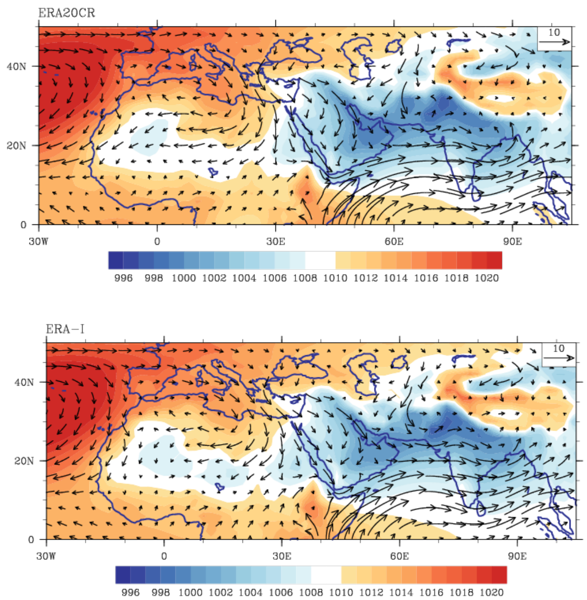

Figure R2. Seasonal (JJA) sea level pressure (hPa) and wind vector at 850hPa (m/s) in (top) ERA-20C, (bottom) ERA-I; for the 1979-2017 period.

However a verification of the precipitation results with higher resolution datasets would improve the robustness of the conclusions. Following reviewer's suggestion we have incorporated EOBS dataset in the analysis of the regional precipitation (Figure 4). EOBS provides high quality data and serves as a good reference for the regional precipitation. Given the same spatial resolution as CM2.5, EOBS allows for comparing very fine features over the complex orography of the Mediterranean.

5. Is there a significant difference between the top and bottom panels in Fig 7? It is not clear to me, maybe use a different color scale?

AU: Please note that the figure is now in the Supplementary Material. Yes there is a significant difference between the top and bottom correlations (but not the storm track patterns), computed between the stormtrack proxy and the SNAO index. For example, negative correlations over northwest Europe in the 1970-2011 (bottom) are weaker than -0.5, while the correlations in 1950-1990 (top) are stronger than -0.65. The difference in the computed correlations questions the robustness of the SNAO (not the storm tracks), derived from the recent three-to –four decades. Please find more discussion on this in pp 10, lines 30-40.

6. Indicate different data sources (HIST, PROJ runs) in Fig 11c? Maybe by a vertical line in the plot?

AU: Thank you, we have included the vertical line in the figure.

7. P21L35, "This may stem from...". I agree that the anthropogenic forcing is not included in the control run and may contribute to this discrepancy. But what about other explanations?

AU: Please note tht we substantially rewritten and clarified the Summary and Discussion section (18 and 19). We also included more information in Introduction (pp2, lines 11-16), and section 3.2.1 (pp 8, 32-36):
"The origin of the multi-decadal signal of SNAO has been linked (Knight et al. 2006, Folland et al 2009, Linderholm and Folland 2017) to the Atlantic Multidecadal Oscillation, which originates from internal variations in thermohaline circulation (Knight et al. 2005, 2006, Delworth and Mann 2000; Enfield et al. 2001), but for the recent decades also from anthropogenic sources (Rotstayn and Lohman 2002; Mann and Emanuel 2006)."

We would like to provide a more thorough explanation for the apparent better agreement between the observed and simulated SNAO before 1980s than for the later period:

This may stem from the fact that the SNAO component derived for the simulated and observed recent decades (1980s-2010s) could be to a large extent conditioned by a coincidence of the multidecadal scale internal (unforced) variability and multidecadal anthropogenic forcing. Taking into account the random nature of the unforced climate variations, their temporal evolution in the simulated 1980's-2010's period may look very different from the observed one. In a presence of an additional long-term component, such as anthropogenic forcing, the EOF analysis (which is set to extract a signal explaining a maximum variance) is likely to choose a combination of a random representation of the unforced variability and the anthropogenic forcing. This combination (regarded as the SNAO component) may have a very different form in the observations and simulations.

Changes in the future summer Mediterranean climate: contribution of teleconnections and local factors.

Monika J. Barcikowska[1], Sarah B. Kapnick[2], Lakshmi Krishnamurty[3], Simone Russo[4], Annalisa Cherchi[5], Chris K. Folland[6,7,8]

[1]Environmental Defense Fund, New York City
[2]Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, 201 Forrestal Road, Princeton, NJ 08540, USA
[3]Princeton University, GFDL Princeton University Forrestal Campus, 201, Forrestal Road, Princeton, NJ 08542, USA
[4]European Commission, Joint Research Centre, Via Enrico Fermi, Ispra, Italy
[5]Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici, and Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy
[6]School of Environmental Sciences, University of East Anglia, Norwich, UK
[7]Department of Earth Sciences, University of Gothenburg, Sweden
[8]International Centre for Applied Climate Sciences, University of Southern Queensland, Australia

Abstract

The simulated regional future changes for the Mediterranean region in summer with a high resolution coupled model (CM2.5) suggest pronounced warming and drying over most parts of the region. However, the changes are distinctively less radical when compared with the CMIP5 multi-model ensemble. In addition, changes over the Southeast (off the coast area of the Balkans) and Central Europe indicate not only a very modest warming, compared to the CMIP5 projections, but also wetting tendencies. Our analysis highlights importance of a correctly projected magnitude of changes of the summer North Atlantic Oscillation and its regional impacts, which have the capacity to partly offset the anthropogenic warming and drying over the western and central Mediterranean. However, the difference of CM2.5 projections of future changes over previous-generation models indicates a possible role of other factors such as land surface-atmospheric interactions, which are a governing factor for thermal- and hydro-climate over Central and Southeastern Europe. De facto, CM2.5 incorporates a new and improved land model (LM3). The CM2.5 projections also indicate a maximum of warming (eastern Mediterranean land region) and drying (Asia Minor) over the eastern Mediterranean. In this specific region, the projected changes indicate a decreasing influence of atmospheric dynamics in maintaining the regional temperature and precipitation balance and instead an increasing influence of local surface temperature on the local surface atmospheric circulation.

1. Introduction

The climate of the Mediterranean region is primarily characterized by mild, wet winters and hot, dry summers. This climate zone is located between 30°-45°N, hence it is affected by the variability of the atmospheric circulation both in mid-latitudes and in the tropics. Moreover, the geomorphological characteristics of the

Mediterranean Sea region, including gulfs, peninsulas, islands, as well as the mountain ridges surrounding the basin, make the climate of this region distinctively complex.

The North Atlantic Oscillation and the East Atlantic pattern (e.g. Hurrell, 1995, Krichak et al. 2002, Barcikowska et al. 2017b) are the main manifestation of mid-latitudes influence for winter precipitation in the northern parts of the region. The summer expression of the NAO (SNAO, Folland et al. 2009, Linderholm et al., 2009, Blade et al. 2012), due to its northeastward-shifted location, affects the Mediterranean region, as well. The observations-based SNAO shows a northern lobe centered over southern Greenland and a southern lobe located close to the British Isles (Folland et al. 2009 and Blade et al. 2012). The positive SNAO phase yields a stronger meridional SLP gradient over the North Atlantic, an enhanced anticyclonic southern lobe with dry conditions over northwest Europe and rather wet conditions over the central Mediterranean. Several studies indicated an exisiting linkage between SNAO phases and the Atlantic Meridional Oscillation (Knight et al. 2006, Folland et al 2009, Linderholm and Folland 2017), which originates from both internal ocean variations (Knight et al. 2005, 2006, Delworth and Mann 2000; Enfield et al. 2001), and anthropogenic sources (Rotstayn and Lohman 2002; Mann and Emanuel 2006).However, current literature has not yet reached a full consensus on the spatial definition (fingerprint), origin and impacts of the SNAO. The results of observational analysis vary, depending on the observational dataset, the chosen period, the chosen summer months, and the analysis method (Barnston and Livezey, Hurrell and van Loon 1997, Hurrell and Folland 2002; Hurrell et al. 2003, 2009, Cassou et al. 2005, Folland 2009, Blade 2012). In fact, there is a strong sensitivity of the derived SNAO fingerprint to the chosen period (i.e., for shorter periods of about 30 years-length) with marked variations in the percentage of SLP variance explained over the selected domain (Blade et al 2012). These sensitivities support the notion that the derived component may stem from the combined effects of interannual to multi-decadal components, as highlighted by Folland et al. 2009 and Linderholm and Folland, 2017.

In summer, the northward shift of the Hadley cell reveals a connection between the hot and arid eastern part of the region and the Asian and African monsoons, as well as a possible connection between these two monsoons (Rodwell and Hoskins 1996, Ziv et al. 2004, Fontaine et al. 2011, Raicich et al. 2003, Rowell 2003). The regional summer climate features a seasonal minimum of the rainfall, persistent mid-level and upper–level subsidence and low-level northerlies (Raicich et al. 2003, Mariotti et al. 2002, Tyrlis et al. 2013) centered over the central-eastern part of the Mediterranean. The low-level northerlies are called Etesian winds (HMSO 1962; Metaxas 1977; Maheras 1980; Prezerakos 1984; Reddaway and Bigg 1996; Zecchetto and de Biasio 2007; Chronis et al. 2011) and they result from the zonal pressure gradient forged by the Atlantic subtropical anticyclone and the western flanks of the Asian monsoon heat low (Bitan and Saaroni 1992; Saaroni and Ziv 2000; Alpert et al. 2004; Saaroni et al. 2010). The cool air advection of the Etesian winds counterbalances the adiabatic warming of the mid- and upper level subsidence, maintaining in this way a thermal balance over the eastern Mediterranean. Moreover, Ziv et al. 2004 have identified a significant correlation between these factors, which likely stems from the Asian Summer Monsoon teleconnection exerting an influence on both the Mediterranean surface and mid- and upper-troposphere dynamics. Rodwell and Hoskins, 1996 demonstrated this linkge, showing that diabatic heating released by the Asian monsoon convection and precipitation triggers a Rossby wave pattern response, which propagates westward, interacts with the mid-level westerlies, and finally induces subsidence and hot and dry conditions over the eastern Mediterranean and the Sahara. This mechanism has been corroborated in several observational and modeling studies (Tyrlis et al. 2013, Rizou et al. 2015, Cherchi et al. 2014, Cherchi et al. 2016). On the other hand, the impact of the monsoon on the Etesian winds has been shown (Rodwell and Hoskins 2001) to be a direct result of changes in the subsidence over EMED, which via Sverdrup's equation trigger changes in the low-level northerly flow (i.e. the Etesians).

This agrees with Ziv et al. 2004 who pointed that changes in the low-level monsoon heat low, which expands westward across Arabian Peninsula, could modulate the zonal pressure gradient and the concomitant Etesians.

The geographic location and socio-economic state of the Mediterranean makes the population in this region particularly vulnerable to climate change. The southern part of the Mediterranean, which is dominated by agricultural activities, is especially sensitive to prolonged water shortages and their consequences, such as drought and wildfires. Giorgi (2006) found this region to be particularly responsive to projected climate change and identified it as a climate hot spot. In fact, both CMIP3 (Giorgi and Lionello 2008, Hanf et al. 2012) and CMIP5 future projections region (Diffenbaugh and Giorgi 2012, Alessandri et al. 2014, Mariotti et al. 2015, Feng et al. 2014) indicate a very strong warming and reductions in precipitation during the summer season. These changes can severely impact water and food security.

At the same time, observational studies have yet to find unambiguous evidence of decreasing precipitation in the recent decades (Blade et al. 2012b, Giorgi and Lionello 2008). Blade et al. (2012) argued that impacts of the summer NAO teleconnection on the European hydroclimate are underrepresented in CMIP3 models, thus questioning the credibility of future summer climate projections for the region. The underrepresentation of the simulated impacts of SNAO could spuriously amplify projected Mediterranean warming and drying. Kelley et al. (2012) indicated that CMIP5 models show a rather modest improvement in the simulated regional hydroclimate, most likely due to increased horizontal resolution. Historical simulations of CMIP5 models still differ from the observations, for example by showing a strong wetting over the northwestern parts of Europe and drying over the southwestern parts of the Mediterranean (e.g. Kelley et al. 2012), though some earlier lower resolution models do show strong drying over many, though not all, parts of north west Europe as well (e.g. Rowell and Jones, 2006). These inconsistencies do not add to the credibility of the current future projections for the Mediterranean and suggest that the severe simulated regional warming and drying requires further investigation, likely using higher resolution models. A further caution is evidenced by the fact that particularly over the last half century the SNAO and the summer European atmospheric circulation as a whole have shown strong multi-decadal variability (Linderholm and Folland, 2017), just as the winter NAO (Scaife et al. 2008). There is also paleoclimate data evidence of related multi-decadal to century timescale variations in the SNAO and Mediterranean climate since 1441 (Linderholm et al, 2009).

The interpretation of the projected future severe warming over the eastern Mediterranean region remains debatable. Cherchi et al. (2016) attempted to interpret the projected summer changes in the region from the perspective of the monsoon –desert mechanism (Hoskins 1996, Rodwell and Hoskins 1996), which links the hot and arid climate of the eastern Mediterranean to the South Asian monsoon rainfall. This mechanism, as shown in the idealized simulations of Rodwell and Hoskins (1996), can be enforced by the diabatic heating of the monsoon convection, which triggers westward propagating Rossby waves and a subsidence and warming localized over the eastern Mediterranean. Given the fact that most CMIP5 models project an increase in the future Asian Monsoon precipitation, one would also expect a strengthening of a subsidence in the eastern Mediterranean. However projected changes indicate rather opposite tendencies of the subsidence in this region, despite a strong severe drying and warming. Cherchi et al. (2016) could not unambiguously resolve this inconsistency, suggesting an explanation associated with either changing representation/impacts of the "desert-monsoon" mechanisms or the emerging presence of non-linear processes in the regional surface circulation.

On the other hand, Seneviratne et al. (2006) identified soil moisture-temperature feedbacks as a dominant factor controlling summer temperature variability in the Mediterranean and Central Europe in a changing climate. Soil moisture-climate feedbacks were also linked to a non-linear warming of hot extremes in climate change projections for the Mediterranean (Diffenbaugh et al. 2007). Hirschi et al. (2011) confirmed the effect of soil moisture availability for hot extremes in observations in Southeastern Europe and found also that the soil moisture-temperature feedbacks in RCMs are often overestimated over Central Europe. Some studies argued that the deficiencies in the atmosphere - land surfaces feedbacks are a primary cause of a strong summertime warm bias in most of the CMIP3 and CMIP5 models, which spuriously amplifies the projected future temperatures (Christensen and Boberg, 2012, Mueller and Seneviratne, 2014).

Accordingly, in this study, we,: a) analyze future summer climate changes over the Mediterranean region and b) investigate the possibility of emerging new regional climate regimes, describing them, and quantifying their contribution to the projected future changes over Europe. Identifying a regional signal attributed to a particular mechanism or climate regime is not an easy task, given the complexity of the climate in the region. This complexity stems not only from the complex morphology of the region, but also from the teleconnections acting on yearly-to-multi-decadal timescales (e.g. SNAO), and multi-decadal changes caused by anthropogenic gases and aerosols. Addressing these issues requires integrations at high spatial resolution, control runs with greenhouse gas and aerosol compositions being held at the fixed levels and well represented land-atmospheric feedbacks between soil moisture and precipitation. Hence, here we use control, historical and future simulations of the GFDL CM2.5 model (Delworth et al., 2012), that incorporates higher spatial resolution and improved land model (LM3), likely improving the simulated hydroclimate over many continental regions including Europe.

In addition, we create an analysis of the Mediterranean summer climate and interpret the results through the prism of large-scale circulations, teleconnections and the regional factors. Section 2 describes the model and experiments used, the dataset for comparison and the methodology. Section 3 focuses on the summer time-mean climatology of the region, as well as its teleconnections. It evaluates the performance of the model in terms of the simulated regional precipitation, as well as large-scale circulation features, which shape the summer regime of the Mediterranean climate. It also examines the main components of internal variability dominating atmospheric circulation over the Euro-Atlantic region, such as the summer NAO, and their impact on Mediterranean climate. The last part of this section focuses on a representation of key dynamical features shaping the climate regime over the eastern Mediterranean, i.e. including the linkage between the mid- and upper-level subsidence and the low-level pressure gradient (and the associated Etesian winds) together with its coupling with the Indian Monsoon. Section 4 investigates future climate changes over the Mediterranean derived from the model projections. It examines the regional changes from the perspective of large-scale circulation over the Euro-Atlantic and associated summer NAO teleconnections. The derived regional changes are also interpreted in the context of the changing relationships between the dynamical factors governing the eastern Mediterranean. Again, the long control run is used to verify whether the derived changes in the eastern Mediterranean climate regime can be attributed to the local effects of the warming Mediterranean and how these effects will impact the whole Mediterranean and European climate. Section 5 discusses and summarizes the main results.

2. Data and Methods

2.1 Coupled model and experiments

The coupled model use in this study is the Geophysical Fluid Dynamics Laboratory (GFDL) CM2.5. It has an atmospheric and land surface horizontal grid scale of approximately 50 km with 32 levels in the vertical. The horizontal grid scale of the ocean increases from 28 km in the tropics to 8-11 km in high latitudes. CM2.5 incorporates a new land model (LM3), with an enhanced representation of soil moisture and land-atmospheric feedbacks between soil moisture and precipitation (Milly et al. 2014, Berg et al. 2016). Details of the CM2.5 model features can be found in Delworth et al. (2012). The representation of the summer precipitation climatology in CM2.5 is also compared using a 4000-years control run of GFDL CM2.1, that is the CM2.5's predecessor. CM2.1 incorporates a grid scale of 2° latitude x 2.5° longitude for the atmosphere. The ocean resolution is variable being approximately 1° latitude x 1° longitude, with a finer meridional resolution in the tropics. The CM2.1 atmospheric model has 24 vertical levels (Delworth et al. 2006). The ocean component CM2.1 and CM2.5 consists of 50 levels in the vertical. Future changes projected with CM2.5 are compared with that derived with the CSIRO-Mk3-6-0 model (1.9° x 1.9° horizontal resolution for the atmosphere), which includes the ocean component based on the GFDL ocean model. This choice was determined by the fact that future projections of CSIRO-Mk3-6-0 model, unlike CM2.1, follow the same protocol of forcing scenario, i.e. the IPCC RCP8.5 scenario (Meinshausen et al. 2011, Riahi et al. 2011), as those of CM2.5.

The set of experiments performed using CM2.5 are listed in Table 1 and it consists of control simulations (hereafter CTRL) and 5-members ensembles of historical simulations (hereafter HIST), and of future projections (hereafter PROJ) performed with CM2.5. The CTRL simulation consists of a 1000-year integration, where greenhouse gas and aerosol compositions are held fixed at the levels of the year 1860. In HIST and PROJ ensembles, the forcing follow the protocols of the Coupled Model Intercomparison Project Phase 5 (http://cmip-pcmdi.llnl.gov/cmip5/forcing.html). For the historical period (1861-2005), the radiative forcings are based on observational estimates of concentrations of well-mixed greenhouse gases (GHG), ozone, volcanoes, aerosols, solar irradiance changes and land-use distribution. While for the future (2006-2100) the radiative forcing follow an estimate of projected changes defined in the IPCC RCP8.5 scenario. This scenario assumes high population growth, slow technological change and energy intensity improvements, and a lack of developed climate change policies, resulting in large energy demand and GHG emissions.

2.2 Datasets used for comparison

The simulated features of large-scale circulation are compared with reanalysis data of monthly pressure at mean sea-level (hereafter SLP), wind vectors at the 850hPa and 200hPa levels, and vertical velocity at 200hPa for the period 1979-2017. Reanalysis data is provided by the NCEP-DOE AMIP-II Reanalysis 2 with 2.5° x 2.5° horizontal resolution and 17 vertical levels (Kanamitsu et al., 2002; https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html).

The simulated precipitation is compared with the seasonal time-averaged precipitation provided by the University of Delaware (V4.01), Legates and Willmott 1990; http://climate.geog.udel.edu/~climate/html_pages/README.ghcn_ts2.html (last access: July 2018). This is a global gridded land data set with 0.5° x 0.5° horizontal resolution for the period 1980-2015. For the same period we use also EOBS precipitation data set provided E-OBS dataset from the EU-FP6 project UERRA (http://www.uerra.eu) and the Copernicus Climate Change Service (Cornes et al. 2018, version 17), provided at 0.25° x 0.25° horizontal resolution.

The observational analysis of the summer North Atlantic Oscillation (section 3.2) is carried out using July-August mean sea level pressure (SLP), provided by NOAA/ESRL PSD 20th Century Reanalysis version 2c (Compo et al. 2006, https://www.esrl.noaa.gov/psd/data/20thC_Rean/). The spatial patterns of the dominant component of the SLP variations are computed with Empirical Orthogonal Function (EOF) analysis, over the domain [25°-70°N, 70°W-50E°], following Folland et al. 2009. The robustness of the pattern is tested against chosen periods of different length.

The relationship between the SNAO and the North Atlantic storm track is derived by computing correlations between the SNAO index and the proxy of storm track in July-August. The storm tracks are represented with the standard deviation of the daily geopotential height at 300 hPa, following Folland et al. 2009. The data is a priori filtered using a Butterworth filter with a bandwidth of 2-8 days. The storm tracks are derived for the 1950-1990 and 1970-2011 periods, using NCEP/NCAR 1 data (Kalnay et al. 1996), provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at https://www.esrl.noaa.gov/psd/.

2.3 Analysis methods

The representation of the simulated large-scale atmospheric circulation over the Mediterranean is analyzed using CTRL runs' monthly mean fields of the lower, mid- and upper- level dynamics over the region covering southern Europe, North Africa and South Asia [30°N–50°N, 30°W–110°E]. The analysis of the simulated SNAO teleconnection focuses on the Euro-Atlantic region. In the analysis of the eastern Mediterranean climate, we define region of focus as EMED [30°-36°N, 36°-42°E]. We will also refer to the eastern Mediterranean land region, which includes: Syria, Lebanon, Israel, Jordan, as the Levant region.

The time-mean large-scale circulation features are analyzed based on the monthly means of hydro-meteorological variables for the summer (June, July and August, hereafter JJA) season. Future changes are estimated by comparing the climatology at the end of the twenty-first century (i.e. 2061–2099, hereinafter future) of the RCP8.5 scenario with that at the end of the twentieth century (i.e. 1961– 1999, hereinafter present) of the historical simulation using monthly mean fields for the summer season.

The teleconnection of the Mediterranean climate with SNAO is analyzed using the full (1000 year) CTRL run (section 3.2), as well as the historical and future runs. The SNAO is defined as a lead component of SLP vector time series over the Euro-Atlantic region [25°N–75°N, 70°W–50°E] in "core summer" (July-August), following Folland et al. 2009. The choice of the time window is determined by the fact that the temporal behavior of the SNAO in significantly correlated only within these two months. The impact of this teleconnection on Mediterranean climate is estimated using correlations between SNAO PC time series and the regional temperature and precipitation, using the long CTRL experiments and the historical and future ensembles. The evolution of the SNAO fingerprint in the 20th and 21st century is analyzed by projecting the vector time series of HIST and PROJ experiments (240 yrs, 1861-2100) on the SNAO eigenvector derived from the CTRL run. To analyze potential changes in the spatial pattern of SNAO and associated impacts, the EOF analysis is applied independently to each of the HIST and PROJ ensembles, in the period 1950-2010 and 2040-2100, respectively, detrending the timeseries before computing the EOF. In both epochs, the analysis has been also tested for shorter periods (i.e. 50 and 30 years), which did not change the results in qualitative terms. Each of the five SNAO time series for the 1950-2010 and 2040-2100 periods were correlated with the respective detrended precipitation fields.

The summer climate regime of the eastern Mediterranean (hereafter EMED) is examined from the perspective of the regional mid- and upper-tropospheric subsidence and its physical linkage with the surface circulation (section 3.3). The seasonal variability of the subsidence over the eastern Mediterranean is derived from EOF analysis applied to vertical velocity (omega) fields at 500 hPa, and also at 300 hPa over the region covering the Mediterranean, North Africa and Middle East in July season. The physical linkage between the subsidence and surface circulation is estimated using correlations between the time series of the first EOF component (PC1) and the regional sea level pressure, geopotential height and wind vectors at 850 hPa. The relationship between the EMED region dynamics and the Indian Summer Monsoon is estimated by computing additional correlations with precipitation, outgoing long wave radiation, and the vertically integrated water column. The analysis shows the correlations computed using time series of EOF omega at 500 hPa, but the correlations using EOF omega 300 hPa were almost the same. The results of the analysis are shown for July, when the magnitude of subsidence and the Etesians is at its maximum and the response of the Rossby waves to monsoon rainfall is also strongest (Tyrlis et al. 2012, Lin et al. 2007, Lin et al. 2009). The results derived for June and August are shown in the Supplementary Information.

Future changes in the dynamical linkages governing the summer climate regime over the eastern Mediterranean were analyzed by comparing the five-decade long samples for July, i.e. 1960-2010 and 2050-2100. The linkage was calculated in a similar manner to that of the control run using correlations between the time series of the EOF over the EMED region subsidence and the atmospheric surface circulation fields. All EOF time series were computed by projecting the respective run on the eigenvector derived from the control run. The correlations were derived for each run (historical and future, respectively), using a priori detrended timeseries. The final result shows the ensemble mean for the five-member historical and future correlations.

An additional analysis investigates the potential influence of the local temperature (i.e. in the EMED region) on the derived local dynamical relationships (section 4.3 and Supplemenary Material). Therefore, the derived correlations were differentiated between samples with the 300 warmest and the 300 coldest summers (July) over the Mediterranean, chosen from the control run time series. Their selection is based on surface temperature in the EMED region. Additionally, a diagnosis of temperature impacts on the regional atmospheric circulation was performed using composite differences between the two temperature samples and the associated relative humidity, sea level pressure, wind components, geopotential height, vertical velocity and precipitation. The results were corroborated by testing their sensitivity to the precise choice of the region.

3 Summer mean present climate and teleconnections over the Mediterranean region

3.1 Simulated summer mean Mediterranean climate

Figure 1 demonstrates that the model captures the subtropical low-tropospheric circulation with high fidelity when compared with the reanalysis (NCEP-DOE). It reproduces accurately the zonal pressure gradient over the Mediterranean, both in terms of pattern and magnitude, forged by the difference between the subtropical anticyclone over the North Atlantic and the massive Asian monsoon heat low. The latter extends westward, through the Arabian Peninsula towards the Levant region and southern Asia Minor. Concomitant to the zonal pressure gradient and adjustments to the regional orography is a persistent west-northerly flow over the central and eastern Mediterranean (i.e. the Etesian winds). The model reliably captures its local-scale features, created by adjustments to the regional topography. This includes a local wind maximum centered over the Aegean Sea and its southern extension reaching the Sahel region. These northerlies are also channeled through the Red Sea Straits and the Persian Gulf, reaching the Indian Ocean.

Figure 2 shows that the model reproduces the location and magnitude of the summer subtropical mid-troposphere anticyclone, which spreads from the eastern Mediterranean across the South Asia. The simulated mid-troposphere also captures the location and a realistic magnitude of the persistent mid-troposphere (500 hPa) subsidence (positive omega) which creates the exceptionally hot and arid climate of the eastern Mediterranean. This subsidence gradually decreases towards the Iranian Plateau, which together with ascending motion over the South Asian monsoon region, creates a large-scale time-mean zonal gradient. The simulated zonal gradient is well shown (Fig 3a) by a vertical cross-section of vertical velocity (omega) averaged over 20°-34°N between the east Mediterranean region (positive omega means strong subsidence) and the South Asia (negative omega means ascending air). This characteristic gradient agrees well with its observational counterpart (Fig 3b) both in terms of magnitude and pattern. Importantly, the model captures the observed local maximum of the eastern Mediterranean subsidence located at middle-tropospheric levels (300-700 hPa), the region most sensitive to the impact of the Indian monsoon.

Figure 4 shows climatologies of the Mediterranean precipitation provided by the observations, the CM2.5 control run, and also its low-resolution (CMIP3) predecessor, i.e. CM2.1 at their original horizontal resolutions. Although both CM2.1 and CM2.5 depict the general spatial features of the climatology (i.e. large values in the northern Mediterranean, particularly over the Alps and the Balkans), the former introduces large biases (up to 50%) in regions with sharp spatial gradients. CM2.5 resolves much better the spatial features of precipitation, clearly indicating the advantages of higher horizontal model resolution for regions with complex orography. However, precipitation magnitude in most mountainous areas, e.g. the northern Iberian Peninsula, the Alps and over Asia Minor, is larger than in both observational data sets, i.e. U. Delaware.and EOBS. The climatology in CM2.5, in terms of pattern and magnitude, seem to be much more consistent with the EOBS data set. However, due to a relatively large observational uncertainty in many mountainous areas, it is difficult to validate the model rainfall climatology in these regions. Kelley et al. (2012) underlined the importance of higher horizontal resolution in simulating precipitation over the Mediterranean. They compared the climatologies of CMIP3 and CMIP5, suggested a modest improvement in CMIP5 models compared to CMIP3 in representing precipitation over the Mediterranean region, most likely associated with increased horizontal resolution. However, none of the CMIP precipitation climatologies could realistically capture the complexity of regional features (e.g. local maxima over the northern Asia Minor and the Balkan coast) to such a high degree as in CM2.5. Overall, our analysis indicates that the high-resolution CM2.5 control run provides a realistic mean representation of the surface- and upper-tropospheric circulation over the Mediterranean. The model skillfully simulates sharp gradients of precipitation over the morphologically complex terrain and its climatology is considerably better than its low-resolution predecessor, the CM2.1 model.

3.2 The impact of the summer North Atlantic teleconnections on the Mediterranean region

The origin of the multi-decadal signal of SNAO has been linked (Knight et al. 2006, Folland et al 2009, Linderholm and Folland 2017) to the Atlantic Multidecadal Oscillation, which originates from internal variations in thermohaline circulation (Knight et al. 2005, 2006, Delworth and Mann 2000; Enfield et al. 2001), but for the recent decades also from anthropogenic sources (Rotstayn and Lohman 2002; Mann and Emanuel 2006). The imperative of the following section is to test the capability of the model to simulate the SNAO as an independent, internally generated climate component, which would prove the physical validity of the statistically-derived component. The SNAO is defined as a leading eigenvector of the atmospheric circulation over the North Atlantic region [25°-70°N, 70°W-50N°]. For this purpose we use the monthly SLP output (July-August) of the full period (1000 years) of the CTRL experiment (Table 1). The analysis is also repeated for the HIST and PROJ runs. The results are compared with the observational analysis, using SLP provided by the 20CR dataset in the period 1870-2010. However, allowing for the fact that a) circulation over the SNAO region is influenced by different key factors at different times, giving rise to time-varying dominant modes of apparent internal variability; and b) each simulation represents a different, non-deterministic state of internal climate variations, one should not expect to obtain from each run a replica of the observed SNAO component.

The North Atlantic Oscillation (NAO) is the most prominent pattern of winter atmospheric variability in this region and numerous studies have demonstrated its impact on European hydroclimate. Similar influences of its summer counterpart (the SNAO) have also been discussed but with considerable differences of detail, which stem from a distinct northward shift of the SNAO pattern compared to the winter NAO. However, the results on the origin and impacts of SNAO are not equivocal, depending largely on the definition of the SNAO, in terms of chosen spatio-temporal domain; and on the chosen observational dataset and methodology.

The imperative of the following section is to test the capability of the model to simulate the SNAO as an independent, internally generated climate component, which would prove the physical validity of the statistically-derived component. The SNAO is defined as a leading eigenvector of the atmospheric circulation over the North Atlantic region [25°-70°N, 70°W-50N°]. For this purpose we use the monthly SLP output (July-August) of the full period (1000 years) of the CTRL experiment (Table 1). The analysis is also repeated for the HIST and PROJ runs. The results are compared with the observational analysis, using SLP provided by the 20CR dataset in the period 1870-2010. However, allowing for the fact that a) circulation over the SNAO region is influenced by different key factors at different times, giving rise to time-varying dominant modes of apparent internal variability; and b) each simulation represents a different, non-deterministic state of internal climate variations, one should not expect to obtain from each run a replica of the observed SNAO component.

3.2.1 Spatial pattern of SNAO

Considering the first two EOFs in the CTRL SLP averaged in summer, EOF1, representing the SNAO, clearly dominate the summer SLP variations, explaining twice as much total variance as EOF2. Moreover, the percentages of explained variance (34% and 15%) resemble those of the observations-based EOF1 and EOF2 in Folland et al. 2009, i.e. ~28% and ~14% respectively. In the following we focus on the leading pattern (hereafter called CTRL EOF1).

Figure 5a depicts spatial pattern of CTRL EOF1. The derived dipole resembles the observed SNAO signature (e.g. Folland et al. 2009), including a distinct northward shift when compared to the winter counterpart (shown e.g. in Barcikowska et al. 2017). The dipole pattern has a northern lobe over the south-western flank of Greenland and a southern lobe centered north of the Azores in the vicinity of ~45°N, 30°E. At its positive phase SNAO is manifest with negative anomalies in the former and positive anomalies in the latter region, thereby strengthening the meridional SLP gradient over the North Atlantic. The pattern is similar also when analyzed for the single months July and August (not shown). The simulated SNAO pattern is almost identical to the one derived from the HadCM3 model control run, as shown in Folland et al. 2009.

Further analysis indicates also that the signature of the simulated SNAO is much more consistent with the observed one before 1950s, rather than in the recent six decades. Figure 6 depicts patterns of EOF1's derived from four 50-yr periods of the 20CR reanalysis (i.e. a. 1870-1920, b. 1900-1950, c. 1940-1990, d. 1960-2010), indicating clearly their evolution in time. Similar results were obtained for the independent 40-yr periods (1851-1890, 1891-1930, 1931-1970, 1971-2010 in Figure SI1). The EOF derived for periods before 1950s (shown here for 1870-1920 and 1900-1950) closely resembles the SNAO simulated in the model (Fig 5a), i.e. including the northern centers of action at southern Greenland and with the southern lobe situated north of the

Azores (~45°N, 35°E). In contrast, the EOF derived for 1960-2010 or 1971-2010 exhibits a weak northern lobe and a much stronger southern lobe, with the latter being also shifted north-east, towards the British Isles. These differences are consistent with other observational analysis of the recent six decades (i.e. Blade et al. 2012 and Syed et al. 2012).

Analysis of the HIST runs shows that the pattern of the leading EOF also evolves in a similar way to the observations-based SNAO pattern (Figure 6). For the early observational period (1870-1920), all the derived SNAO signatures, i.e. EOF derived from all HIST runs (Figure 6b, Figure SI2 left column), observations, and CTRL (Figure 5a) resemble the SLP dipole with the northern lobe over Greenland and the southern lobe located north of the Azores around 40-45ºN. In contrast, for the most recent period (1960-2010, Figure 6g, h) both observations and HIST runs depict SNAO with the weaker northern lobe and southern lobe being shifted north-eastward, towards the British Isles. These changes are found in 4 out of the 5 HIST members available, when comparing the periods 1870-1920 and 1960-2010 (Figure SI2). This tendency slightly intensifies when the more recent period is extended towards the future using PROJ members (e.g. 1970-2030, 1970-2060 Figure SI3). Considering the nature of HIST experiments, this analysis suggests that the anthropogenic forcing, which is the only deterministic factor for them, is likely an important contributor in shaping the SNAO, and hence explaining to some degree the temporal evolution of its spatial signature in the 20th century.

3.2.2 Impact of SNAO on the Mediterranean hydroclimate

Figure 5 indicates that the simulated SNAO yields a large-scale fingerprint in the precipitation, geopotential height and temperature over the North Atlantic and Europe, which largely resembles the observed one (e.g. Folland et al. 2009, Blade et a. 2012). This includes a distinct tripolar pattern of precipitation anomalies with the lobe over the southern Greenland, over northern Europe and its vicinity over the North Atlantic, and over southern Europe and most of the Mediterranean region (Fig 5c). The derived SNAO teleconnection at its positive (negative) phase, manifested in the positive (negative) SLP anomalies over its southern lobe (Fig 5a), is linked with an anomalous drying (wetting) over northwestern Europe, but with anomalous wetting (drying) over the Mediterranean (Fig 5c).

The simulated location of the southern SLP node is located southwest of the British Isles, and so its largest impact is in this region with negative correlations reaching a value of about -0.7 (Fig 5a). The maximum impact of the observed teleconnection, as shown in Folland et al. 2009, is of similar magnitude and exceeds ~0.6, though its location is centered over the British Isles. This difference directly relates to the difference in the center of the observed southern node of SNAO, when compared from that in CRTL runs, discussed in the previous section. For Mediterranean hydroclimate, the consequences of a positive SNAO phase are the inverse of those in northwest Europe and also of smaller magnitudes (i.e. ~0.2-0.35). Corresponding wet anomalies are centered over Italy, the central and southeastern Iberian Peninsula, and Asia Minor.

The pattern and magnitude of SNAO teleconnection presented here is largely consistent with the one derived from the GFDL CM2.1 model, the low-resolution predecessor of CM2.5 (Blade et al. 2012). The CM2.5 correlation coefficients over the Mediterranean are also quite similar to those of the observations-based SNAO in Folland et al. 2009, exceeding locally 0.3 (1900-1998). In contrast, Blade et al. 2012, using a shorter data set (EOBS, 1950-2010), found much larger correlations, locally exceeding 0.6. This disparity may likely stem from the difference in the length of the analyzed data sets and differences in contributing factors. For example, the SNAO time series, as defined by Blade et al. 2012, are largely shaped by a multi-decadal signal of both the natural and anthropogenic origin. By contrast, anthropogenic climate components are not included in the

CM2.5 control run and the simulated SNAO teleconnection stems predominantly from the internal climate variations on interannual time scales.

The impact of the SNAO on the northern Europe and southern Europe hydroclimate has been explained through different mechanisms. The teleconnection between SNAO and the northwestern Europe hydroclimate has been straightforwardly explained with impact of the North Atlantic storm tracks, which are controlled by the large-scale circulation in this region. Folland et al. 2009 have shown, using NCEP data, that a positive (negative) SNAO index relates to the North Atlantic storm tracks being shifted northward (southward) towards the northwestern (southwestern) Europe. Our analysis, using the SNAO index derived from 20CR, and the storm tracks proxy derived from NCEP, confirms this relationship (Figure SI4). More importantly, the strength of the derived relationship depends on the chosen period. For example, the derived correlations are distinctively stronger in the earlier period, i.e. 1950-1990, when SNAO resembles a dipole pattern (Figure 6e), than for the latter period (1970-2011), when the SNAO better resembles a monopole-type pattern located over the British Isles (Figure 6g). These results are consistent with the notion that the monopole-like version of the SNAO, derived from the most recent decades of observations, is contaminated by other climate components. Hence it is not necessarily the most plausible representation of the SNAO. However, addressing this issue as well as verifying the simulated linkage between the SNAO and the North Atlantic storm tracks are beyond the scope of this study and it could be eventually subject for future research.

The impact of the SNAO on the Mediterranean hydroclimate (shown by in observations by Linderholm et al. 2009) can be better explained through associated changes in a mid- and upper-tropospheric geopotential height, consistent with Blade et al 2012. Correlations derived between the SNAO time series and 500hPa geopotential height (Fig 5b), show the strongest influence over the western and central Mediterranean, i.e. the Iberian Peninsula, Italy and to a smaller extent the Balkan coast. Well collocated with this pattern are correlations with precipitation and surface temperature, although for the latter the impact of the SNAO seems much smaller. Hence, anomalous precipitation in these regions during the positive SNAO phase likely stem from an anomalous mid- and upper tropospheric trough, associated cooling, and intensified potential instability over the central Mediterranean.

Overall, the results presented in this section demonstrate that CM2.5 is capable of simulating SNAO teleconnections and their contribution to Mediterranean hydroclimate. The associated physical mechanisms are consistent with observational findings and other modeling studies employing older generations of models.

On the other hand, the impact of SNAO on surface temperature in the Mediterranean shows discernible differences, compared to the observational studies (Blade et al. 2012, Folland et al. 2009). For example, the maximum of the derived correlations in CM2.5 is located over the Iberian Peninsula (exceeding locally ~0.35). In contrast, both studies show the maximum of the correlations shifted towards central and eastern Mediterranean, although with a significant disparity in the derived magnitudes. While the former study suggests the maximum magnitude of correlations reaching 0.7-0.8, the latter study suggests correlations twice as smaller when using a longer data set and low-frequency component removed. Hence the impact of SNAO on the European temperatures remains a debatable issue and requires further investigation in the future.

3.3 Summer climate regime over the eastern Mediterranean

In this section we investigate the ability of the CM2.5 control experiment to reproduce the summer climate regime over the eastern Mediterranean (EMED, as defined ins Sect. 2), including the relationship between the surface dynamics and the mid- and upper-tropospheric circulation over the region and its teleconnection with the Indian Summer Monsoon (hereafter ISM). Here we show results for July alone but those for June and August are shown as Supplementary Information. This choice is driven by the fact that the magnitude of subsidence and the Etesians is at its maximum in July while the response of the Rossby waves to monsoon rainfall is also strongest (Tyrlis et al. 2012, Lin et al. 2007, Lin et al. 2009).

Figure 7d, (see also Ziv et al. 2004, Tyrlis 2012) shows that the model captures skillfully the observed features of the regional relationship between the mid- and upper-tropospheric subsidence and surface circulation. The relationship is depicted in Figure 7 as correlations computed between time series of EOF1 (Figure 7a) of the mid and upper- tropospheric vertical velocity (omega) over the Mediterranean and those of geopotential height at 850hPa, wind vector, outgoing longwave radiation and precipitation. EOF1 derived either for omega at 500 hPa or 300 hPa, explains the dominant amount of variance (~33% and 35%, respectively). Its spatial pattern closely resembles the simulated and the observed (Tyrlis et al 2012, Ziv et al. 2004) key feature of the mid- and upper omega summer climatology, i.e. with a maximum located near Crete. The correlations (Figure 7b,c), derived between the EOF1 500hPa and the regional surface circulation, depict a physically consistent linkage (Figure 9d, Ziv et al. 2004, Tyrlis 2012) between strengthening of the subsidence over the EMED and strengthening of the zonal pressure gradient over the Mediterranean and thus the Etesians over the EMED.

The Etesians spread southward from the Aegean Sea, through Egypt and towards the Sahel which is consistent with observational findings underlining the role of the Etesians in regulating the moisture transport over Africa and hence for regulating the African monsoon (Raicich et al. 2003, Ziv et al 2004, Lelieveld et al. 2002; Rowell 2003). The northerlies intensify also over the Arabian Peninsula as north westerlies, with wind anomalies spreading towards the Gulf of Persia and the Indian Ocean. The simulated pattern agrees well with its observational counterpart, derived by correlating the regional anomalies of omega 500hPa and meridional wind using the detrended NCEP–DOE data set. Note that due to a relatively short data set (1979-2015), the correlations are not significant at the 10% level for some regions and thus not shown, even if they agree well with those simulated, for example the positive correlations in northwest Africa.

This relationship between mid-level subsidence and the low-level circulation is manifested to some extent in the regional summer precipitation and outgoing longwave radiation. Figure 8 shows that correlations derived between the same EOF of omega at 500hPa and precipitation are negative and centered over southern Italy and the Balkans. This implies that the stronger subsidence over EMED may contribute to precipitation reductions in these regions, consistent with the intensified zonal pressure gradient and the associated intensification of the anticyclonic circulation over the western and central parts of the Mediterranean. However, the summer precipitation in the Mediterranean is in general very low and correlations do not exceed 0.3, implying a rather small effect. On the other hand, the EMED subsidence variations show much stronger correlations (up to 0.8) with the outgoing long-wave radiation (OLR) over the region (Figure 8). This is consistent with the impact of the adiabatic descent and associated radiative cooling in dry regions under clear sky conditions.

The simulated relationship between the interannual timescale variations in EMED region and the northwestern parts of India (Fig 8) is consistent with the features of the observed teleconnection with the Indian summer Monsoon (ISM) (Hoskins et al. 1996, Hoskins et al. 2001, Tyrlis et al. 2012, Ziv 2004, Cherchi et al. 2014). The variations of the EOF of omega at 500hPa show significant and relatively high correlations with the three monsoon indices, i.e. subsidence over EMED is negatively correlated with OLR (up to -0.45), and positively correlated with vertically integrated water vapor (up to 0.6, not shown) and precipitation over the northwestern parts of India (up to 0.3). This implies a connection between anomalously stronger subsidence over the EMED region and the intensified Indian summer monsoon. Consistent with this linkage are intensified southerly winds over the Arabian Sea, which feed the ISM with moisture (Figure 6b, c), and a deeper heat low spreading west from India towards the Arabian Peninsula and the Sahel. The latter intensifies the zonal pressure gradient over the Mediterranean, which illustrates how the ISM impacts the low-level circulation in Mediterranean as suggested in Ziv et al. 2004.

These results suggest that CM2.5 is capable of capturing the most prominent features of the summer climate regime over the EMED: the mid- and upper tropospheric subsidence over the EMED and the low-level Etesian winds. Moreover, these results also show that the model reproduces their links with the ISM. Changes in these interactions over the EMED and their teleconnections may give rise to pronounced effects on local Mediterranean summer temperature regime. Accordingly, the next section investigates the projected future Mediterranean climate, interpreting this through changes in large-scale circulation as well as through local relationships and teleconnections.

4. Climate changes in the 21st century

4.1 Comparison of future and present summer climate

In CM2.5, the projected changes in large-scale circulation features over the Euro-Atlantic region and west Asia correspond to a large extent to those seen in the CMIP3 and CMIP5 projections. Figure 9 depicts changes in the summer surface atmospheric circulation, as shown by SLP in JJA and wind vectors computed at the original model horizontal resolution (~0.5°). The most prominent feature over the Euro-Atlantic region, a northward shift and strengthening of the meridional SLP gradient, and hence the meridional circulation cells, is a typical fingerprint of anthropogenic climate change (Collins et al. 2013). The associated anomalous bipolar SLP pattern shows negative (cyclonic) SLP anomalies centered over Greenland and positive (anticyclonic) SLP anomalies centered southwest of the British Isles. This pattern closely resembles the fingerprint of the CTRL-based SNAO. The projected positive SLP anomaly is however shifted slightly north east of the CRTL SNAO, so it is likely that the anthropogenic fingerprint will project on the positive SNAO phase, quite like as found by Folland et al. 2009 for HadCM3 and HadGEM1.

CM2.5 projections also indicate negative SLP anomalies over North Africa, the eastern Mediterranean and the Arabian Peninsula, which are accompanied by a very strong warming exceeding 6°C. These changes, together with an anomalous convergent flow and pronounced anomalies of ascending air at low-and mid-tropospheric levels (Figure 3c, Figure SI5) over the Arabian Peninsula, contribute to the intensification of the Persian trough. Although the Persian trough constitutes an extension of the southwest Asian Monsoon heat low, the future SLP over the monsoon region shows positive anomalies. This indicates a weakening of the monsoon heat low and, correspondingly, of the northerly flow over the Persian Gulf. It is also worth noting that the anomalies of ascending motion over the Levant region and the Arabian Peninsula, together with an anomalous subsidence over the center, north-eastern Mediterranean, and Asia Minor, create a distinct gradient in the vertical velocity changes. This gradient is particularly evident in July (Figure SI5), due to a magnified intensification of the heat low and anomalous ascending motion over the Levant region.

The projections also show clear differences, both quantitatively and qualitatively, when compared with the CMIP5 multi-model ensemble of RCP8.5 projections (Collins et al. 2013) and the CMIP3 ensemble of the A1B scenario (Giorgi and Lionello 2008). The intensity of the changes over the Euro-Atlantic region shown by CM2.5 is much larger (Figure 9) than in the CMIP5 ensemble average (Collins et al. 2013, Fig 12.18), even when the analysis is conducted at the CMIP resolution. For example, one of the most robust features of the anthropogenic fingerprint, i.e. anomalous positive SLP anomaly in the vicinity of British Isles, is almost twice as intense (~up to 3hPa), when analyzed at 2° horizontal resolution. Moreover, in contrast to the CMIP5 ensemble, the projected CM2.5 positive SLP anomalies over the British Isles expands through northwestern Europe to the southeastern regions: this intensifies the anticyclonic circulation over the western and central Mediterranean. The CMIP3 ensemble (Giorgi and Lionello et al. 2008) show similar tendencies but with a much smaller magnitude confined just to northwestern Europe. On the other hand, the CMIP5 ensemble shows negative SLP anomalies spread over the whole Europe, North Africa and Arabian Peninsula. These differences between the CM2.5 and the CMIP ensembles yield opposite effects on the Mediterranean surface circulation. In CM2.5, positive SLP tendencies to the west of the Mediterranean and the strengthening of the heat low in the eastern Mediterranean, Arabian Peninsula and North Africa foster the strengthening of the climatological zonal pressure gradient, and the associated northerly winds over the Aegean Sea. In contrast, the strengthening of the heat low, which expands over the whole Mediterranean, gives rise to a weakening effect on the regional zonal pressure gradient and the northerly flow in the central and eastern Mediterranean (Collins et al. 2013, Fig 12.18).

Analysis of future changes in mean surface temperature and precipitation indicates (Fig 9b,c) a less radical warming and a weaker and less spatially extensive drying over central and southern Europe, when compared to the CMIP3 (Dubrowski et al. 2014), CMIP5 (Collins et al. 2013) ensembles and a high resolution EURO-CORDEX GCM-RCM RCP8.5 multi-model ensemble (Fussel et al. 2017, Jacob et al. 2014, Figure SI6). For regions like the Iberian Peninsula and Asia Minor warming is on average ~2°C lower. The largest difference (more than 3°C) occurs over the southeastern Europe and northern parts of the Balkans, which feature a local minimum of warming ~1°C and wetting tendencies. The latter has not been captured in the CMIP models. For example, the 10-member RCP8.5 ensemble of the CSIRO-Mk3-6-0 model projects (Figure SI6) a strong warming, which over southern Europe exceeds locally ~7°C (e.g. the southern France and Iberian Peninsula), while in the southeastern Europe and northern Balkans it exceeds ~6°C. The multi-model ensemble average of combined GCM–RCM simulations from the EURO-CORDEX initiative (Fussel et al. 2017, Map 3.4, pp. 76) indicates a comparable magnitude of warming, although with local maximum of warming (exceeding 6°C) shifted towards the Iberian Peninsula, while warming over the southeastern Europe and northern Balkans varying between 3.5 and 5.5°C. In both CMIP ensembles the projected very intense warming and drying over the whole European region has been often questioned and linked with a warm summertime bias, caused likely by the deficient representations of moisture-temperature feedbacks. However, some CMIP3 and CMIP5 models, which incorporate a relatively high resolutions (CNRM-CM5 and EC-Earth-DMI, ~1-1.5°, Christensen and Boberg, 2012), although much lower than the CM2.5, feature both relatively low temperature bias and also relatively milder anthropogenic changes.

Furthermore, the gradient of warming between the southwestern and northeastern parts of Europe in CM2.5 is much sharper and shifted southward when compared with these ensembles (see Fussel et al. 2017, Map3.4; Figure SI6). For example, the minimum of warming (1.5-2°C) in the EURO-CORDEX ensemble is located over the southeastern Baltic countries, while in the CM2.5 the minimum expands across the central Europe and southeastward, towards the northern coast of the Black Sea. Hence the latter contributes in CM2.5 to a stark contrast in the warming between the Mediterranean coast including coastal region of Balkans (4-6°), and the inland Balkans together with southeastern Europe (1°C). This temperature gradient (Fig 9b) marks also a clear transition zone between the drying of southwestern Europe and the wetting of northeastern Europe (Fig 9c). This transition zone, analogously to the warming gradient, is much sharper and shifted southward in the CM2.5 projections when compared with the CMIP3 and CMIP5 models (Fussel et al. 2017, Map 3.8). For example, future changes derived from the CSIRO-Mk3-6-0 model ensemble (Figure SI6) feature drying over whole Europe, except Scandinavia. However, the location of the precipitation transition zone among CMIP5 models features large inter-model spread, which makes the magnitude and sign of the changes over large parts of central Europe uncertain (Fussel et al. 2017, Map 3.2).

Owing to its relatively high resolution, CM2.5 also provides more spatially refined information, which includes for example sharper gradients along the coasts or in the mountainous regions. All coastal regions experience reductions in precipitation, expected from the strengthening temperature contrast between the fast warming land and slower warming sea. These reductions are especially pronounced along the northwestern coasts of the Iberian Peninsula, where rainfall is typically larger due to incoming North Atlantic storms. The advantages of the increased horizontal resolution also become apparent for the Levant and the Arabian Peninsula. This is because the low-resolution CMIP models have difficulties with realistically resolving the projected zonal gradient between oppositely signed rainfall tendencies (i.e. drying over the eastern Mediterranean and wetting on the western flanks of the monsoon). This results in a much smaller changes and statistical insignificance.

Finally, the projected magnitude of the strong warming and drying in the Mediterranean shown by CMIP3 and CMIP5 has often been questioned, due to the deficiencies in representing land-atmosphere feedbacks and a weak sensitivity to atmospheric teleconnections such as the SNAO. For example, Blade et al. 2012 argued that the drying projected in most CMIP3 and CMIP5 models is overestimated due to a deficiency in capturing the SNAO teleconnection and its cooling and wetting effects over the Mediterranean associated with a future more positive SNAO. However, our analysis has shown that the regional impacts of the SNAO in CM2.5 (section 3) are almost the same as those indicated by the low-resolution CM2.1 model. This suggests that the difference in the projected future changes between the CM2.5 and previous generation models may stem rather from the other factors such as representation of soil moisture and land-atmospheric feedbacks between soil moisture and precipitation in the LM3 model used in CM2.5 (Berg et al. 2016; Milly et al. 2014).

4.2 Future changes in SNAO- Mediterranean teleconnections

Temporal evolution of the SNAO depicted (Figure 10c) by the ensemble average of the HIST+PROJ runs reveals relatively weak positive SNAO tendencies in the latter half of the 20^{th} century and a much stronger positive trend during the 21^{st} century. However, for the former period each realization features strong internal variations. This is consistent with recent observations of SNAO featuring a rich interannual to multi-decadal variability and a weak positive trend described in section 3.2.1. For the latter period (particularly 2040-2100) the trend becomes strong enough to be discernible in every realization.

Further analysis suggests also subtle changes in the future spatial pattern of the SNAO. Comparison of SNAO signatures in the 1960-2010 and 2050-2100 periods indicates a northeastward movement of the SLP dipole. This feature is also consistent with the projected changes in large-scale circulation over the North Atlantic (Figure 9a) featuring an intensification and northeastward shift of the meridional SLP gradient. Figure 10a,b, shows that the derived northeastward intensification of the SNAO is manifest in the future European hydroclimate. The correlations, derived between the time series of the SNAO principal component and precipitation anomalies, indicate a shift of the southern SNAO lobe towards the British Isles. This corresponds with a stronger influence of the SNAO on the Euro-Atlantic precipitation, i.e. enhanced drying during the positive SNAO phase. The opposite-sign correlations over southern Europe show also a slight increase, particularly for the Iberian Peninsula, southern Balkans and Asia Minor, indicating an increase in the wetting impact of the SNAO on the Mediterranean.

It is important to mention that the intensified future impact of the SNAO over the Mediterranean, i.e. wetting, is not reflected in the overall mean hydrological changes in this region (Figure 9b,c), with the latter indicating rather a strong warming and drying. Hence the key implication of these results is that without the SNAO the future climate drying in the Mediterranean would be even more severe. The inferred contribution of the SNAO that offsets the regional drying is depicted in the following analysis. Figure 10d,e compares the overall regional future changes, derived between 1961-1999 and 2061-2099, with the changes excluding the impact of the SNAO. The comparison shows that without the SNAO contribution the average drying over the southeast and central Iberian Peninsula would intensify from ~-0.4 to -0.65 mm/day, and for the Balkan coast from ~-0.3 to -0.55mm/day, and for parts of Asia Minor from ~-0.6 to -0.8 mm/day. The location of the largest differences is consistent with the location of the intensified impact of the SNAO (Figure 10a,b). It is worth to highlighting that for regions like the Iberian Peninsula, the estimated contribution of the SNAO (wetting) is comparable with the magnitude of the projected overall drying. This confirms an important role of SNAO and its future changes by offsetting the future drying in the southern Europe.

These results are also consistent with Blade et al. 2012, who emphasized the role of the SNAO in shaping the future Mediterranean climate. On the other hand, our results do not support the theory proposed by Blade et al. 2012, that the regional impact of the SNAO simulated in the CMIP5 models is too weak, thereby causing an excessive warming and drying in the future projections for the Mediterranean. The estimated impact of the SNAO (in terms of pattern and magnitude) in CM2.5 is almost the same as that shown for the CM2.1 (Blade et al. 2012) and yet the CM2.5 projections indicate a substantially less intense warming and drying over southern Europe, compared to CM2.1 (Blade et al. 2012), CMIP3 and CMIP5 ensembles (Collins et al. 2013). For regions like northern Balkans and central Europe CM2.5 indicates even wetting tendencies, in contrast to drying in the CM2.1 runs and CMIP3/CMIP5 ensembles. For these regions CM2.5 even indicates also strikingly weaker warming, compared to the CMIP5 ensemble (Collins et al. 2013; compare for example ~1 to 2°C warming in CM2.5 with ~6-7°C warming in CSIRO-Mk3-6-0 over southeastern Europe). Additionally, the fact that both GFDL models (i.e. CM2.1 and CM2.5) show very small or no SNAO impact in these regions, suggests the influence of other factors than the SNAO are responsible for these discrepancies.

4.3 Future changes in other aspects of the summer climate in the EMED region

This section investigates other projected CM2.5 climate changes in the EMED region, including low-tropospheric circulation and mid- and upper tropospheric subsidence, the main factors that maintain the regional temperature balance. The projected future intensification of the Etesians as well as the weakening subsidence should yield a cooling and wetting effect on that region. Nevertheless, future projections indicate a very strong warming and drying in this region (e.g. Figure 9; Cherchi et al 2016, Collins et al. 2013). This suggests a decreasing influence of the atmospheric dynamics on the temperature balance of this region and an increasing impact of surface warming on surface circulation. The latter is manifested in the intensification of the heat low over Sahara, EMED and Arabian Peninsula, accompanied by anomalous surface convergence and ascending air centered over the maximum warming—the Levant and the Arabian Peninsula.

In the following, we investigate future changes in these factors governing the summer EMED regime by analyzing the stationarity of the local linkages and teleconnections by comparing their representation in the HIST and PROJ experiments. We also compare coupling of the EMED regime with the Indian summer Monsoon and explore the impact of the local surface warming on the regional surface circulation.

4.3.1 Changes in the local and remote relationships with the EMED climate regime

Figure 11 compares the HIST and PROJ five-member ensemble mean correlations, showing substantial qualitative and quantitative differences between the historical and the future periods. The linkage between the EMED subsidence and surface circulation, in terms of pressure, northerly winds over the Aegean Sea (Etesians), as well as their extension towards North Africa and Persian Gulf, is much weaker for 2050-2100. For example, correlations between the EMED subsidence and the northerlies decrease locally (e.g. Persian Gulf) by more than a factor of two (from ~0.7 to ~0.3) between 1960-2010 and 2050-2100. This is consistent with radically decreased correlations with water vapor and precipitation (from ~0.4-0.5 to ~0) over the African monsoon region, which is largely fed by moisture transported by the Etesians.

At the same time, correlations between the EMED subsidence and ISM indices (July), i.e. precipitation and column integrated water vapor (Fig 11e, f), does not change much. In both cases correlations reach 0.5 for precipitation, and 0.6 for the water vapor. For the latter, the maximum correlations only decrease from 0.7 to 0.6. Both patterns are slightly shifted toward the southern parts of India in the future period, consistent with a southward shift of the southerlies over the Arabian Sea that act as a moisture supply for the ISM monsoon.

These results imply generally insignificant changes in the future mid- or upper-tropospheric teleconnection between the EMED and ISM regions. However they do suggest a pronounced weakening of the local linkage between the mid- and upper-tropospheric subsidence and surface circulation over the EMED. Moreover, given that the local linkage serves as a "medium path" for the teleconnection between the ISM and surface circulation over EMED, future weakening of the local linkage will most likely diminish the impact of this teleconnection on the EMED surface circulation. On the other hand, the projected intensification of the heat low over North Africa, EMED and Middle East suggests a growing contribution of surface temperature to the summer climate regime in those regions. Thus in the following section we explore apparent nonlinearities in the summer climate regime of the eastern Mediterranean associated with the local surface temperature.

4.3.2 Nonlinear dependency of the local interrelations between the low-tropospheric and the mid-tropospheric dynamics and their contributions to the thermal balance over EMED.

The nonlinear dynamical influences over EMED can be explored using the CTRL in order to differentiate impacts of the local (EMED) temperature on the local linkage between the mid- and upper tropospheric subsidence and surface circulation. Removing the time-varying climate forcing impacts from the HIST runs allows us to focus on the natural variability of the system and nonlinear interactions that may be difficult to statistically calculate in shorter HIST runs. As described in section 2, we construct two samples from the CTRL run with 300 July months with the lowest temperature and 300 with the highest one with respect to the mean surface temperature for the EMED region. We carry out a correlation analysis for these two periods, much as done in the previous section comparing recent historical and future periods. Figure SI7 shows a radical drop in derived correlations between the mid-level subsidence and the Mediterranean pressure, Etesian winds and their extension over the North Africa and Persian Gulf, and water vapor over the Sahel. These results are similar to those comparing present and future climate for these variables (Fig 11).

Figure 12 shows a direct response of the summer Mediterranean climate to the surface warming over EMED, estimated with composite differences between the two samples, in terms of temperature, relative humidity, pressure and wind vector, geopotential height at 500hPa and 800hPa, omega at 500hPa and precipitation. Interestingly, Figure 12a shows maximum of warming over Asia Minor and not the Levant, suggesting a potential feedback between these regions. Fig 12c shows bipolar SLP anomalies, with low pressure coincident with intensified heat low anomalies over North Africa, EMED and Middle East, and an anomalous anticyclonic circulation between northeast and northwest of this region. The latter is centered over the Black Sea and spreads towards the central Mediterranean, creating a stronger zonal pressure gradient over the Mediterranean and intensified Etesian winds. The intensified heat low over the EMED and Arabian Peninsula (Fig 12c) agree well with the enhanced local convergence and reduced subsidence at the low- and mid-tropospheric levels at 500hPa (Figure 12e) and 700hPa (not shown). At the same time, the positive SLP anomalies (Figure 12c) and increased subsidence over Asia Minor and Black Sea are physically consistent with increased adiabatic warming and stability, manifested in the local maximum warming, reduced relative humidity and precipitation. An analysis for the JJA season yields similar results, although with a reduced magnitude due to a smaller contribution of June and August months (Figure SI8).

Analysis of the effects of local warming over larger domains, i.e. including southern parts of the central and western Mediterranean (Figure SI9) yields similar results, i.e. opposite SLP anomalies for the southern Mediterranean (North Africa and the EMED) and northern central and eastern Mediterranean. However, the magnitude of the response over southwestern regions becomes equally strong to that over the EMED. Interestingly, analyses for regions which include the northeastern parts of the Mediterranean (30°-50°E, 30°-45°N), yields a reduced response (a weaker intensifying anticyclone) over these northern regions. Thus the derived anomalous anticyclone over Balkans and Black Sea is much stronger when the warming is confined to the southeastern parts (i.e. Levant and Arabian Peninsula). This emphasizes the role of the warming surface temperature over arid regions of North Africa and Arabian Peninsula in shaping the climate of the surrounding regions.

The composite response to anomalous warming over EMED can be readily associated with changes in the local circulation, i.e. an intensified zonal pressure gradient and Etesians over Mediterranean, as well as an intensified heat low, anomalous convergence and weakening low- and mid-tropospheric subsidence over the EMED and the Arabian Peninsula. All these changes are also seen in the future projections obtained for JJA (Figure 9a,b,c, Figure SI5a,c,e), and particularly in the month of July (Figure SI5b,d,f). Moreover, the response of positive SLP, increased subsidence and drying over central Mediterranean (i.e. Italy), the Balkan coast and Asia Minor are also consistent with the future changes (Figure 9), suggesting a potential contribution of the warming over Levant and the Arabian Peninsula to projected warming and drying over Asia Minor.

This analysis indicates that the dynamical regime over the EMED has a nonlinear influence on local temperature. During relatively cool years the dynamical relationship between the low-level circulation and mid-level subsidence, which balances the temperature over EMED, seems to be much stronger. By contrast, warming over EMED region can trigger a local response in the surface atmospheric circulation, which weakens the local dynamical linkages and hence their contribution in maintaining the local temperature balance. Hence it is possible that surface temperature-driven atmospheric responses will become a more prominent factor shaping future Mediterranean climate. This idea is supported by the consistency of this response (i.e. strong warming, intensifying heat low, anomalous convergence and very pronounced ascending motion at the low and mid-levels of the EMED and Arabian Peninsula, intensified zonal pressure gradient and Etesians, drying over Asia Minor and southern Balkans) with projected anthropogenic changes over the EMED region. Similar results are obtained for June and August, although with different intensity and location of the SLP and precipitation anomalies.

The analysis however does not explain the processes involved in the dipole-like response in the circulation, which includes SLP, winds and omega anomalies north from the EMED region (particularly Asia Minor and Black Sea). One might suspect that, in response to warming over the EMED, the anomalous convergence and ascending motion over the EMED triggers a seesaw connection with northward-located regions. This link could stem from the interactions of the anomalous warming and upward velocity anomalies with the seasonally varying descending branch of the Hadley cell over EMED, in result expanding it towards Asia Minor. Testing this hypothesis needs more elaborate analysis and could be objective of coming research.

5. Summary and Discussion

Based on the state of the art future projections (CMIP3 and CMIP5-generation) the Mediterranean has been identified as a climate change hot spot (Giorgi and Lionello 2008), not only due to the sensitivity of its climate to the anthropogenic forcing but also due to the socio-economic vulnerability of the local societies. Yet the projected changes are not fully reflected in the observations for the second half of the 20th century. While the derived anthropogenic fingerprint clearly suggests strong warming and drying during the summer, the observations indicate opposite wetting tendencies for some regions—in the vicinity of Black Sea and off the Balkan coast. This discrepancy may stem from the fact that the Mediterranean climate features abundant cross-scale variations, which at present dominate the anthropogenic signal. But there can be other reasons for this inconsistency, i.e. the deficiencies in models' representation of land-atmospheric feedbacks (as mentioned above) or the deficiencies in capturing impacts of certain teleconnections. The former has been shown to cause an overestimation of the projected future summer warming and drying in most of CMIP3 and CMIP5 models (Christensen and Boberg, 2012, Christensen and Boberg, 2012, Mueller and Seneviratne, 2014), particularly in the Mediterranean, Central and Southeast Europe (Diffenbaugh et al. 2007, Hirschi et al. 2011, Seneviratne et al., 2006). The latter has been suggested to incapacitate CMIP3/CMIP5 models in offsetting projected future regional drying, and hence spuriously exaggerate the regional warming and drying (Blade et al. 2012). The Mediterranean is a region of the confluence of the mid-latitude and subtropical teleconnections, which translated through the complex regional orography, makes simulating its climate extremely challenging. Obtaining realistic future projections for this region require not only refined spatial scales, but also a realistic balance between the contributing impacts of local land-atmosphere feedbacks, large-scale circulation, and teleconnections.

In this study, we use the high-resolution CM2.5 climate model integrations to analyze the projected regional future changes and interpret them through the prism of simulated SNAO teleconnections, the local dynamical regime, and the impact of warming land surface.

The analysis of the CM2.5 control run demonstrates the high capability of the model to simulate realistic summer climatology of the Mediterranean. The model very accurately reproduces key regional features of the associated large –scale atmospheric circulation, both in terms of the location and magnitude. This includes, for example, the subtropical mid-tropospheric anticyclone between the Levant and South Asia, and the low-tropospheric zonal pressure gradient between the subtropical North Atlantic anticyclone and the massive Asian monsoon heat low. The high spatial resolution of the integrations allows for capturing the sensitivity of the low-level atmospheric flow to the local orography, which is manifest in two branches of Etesian winds: over the Aegean Sea and its southward extension toward the Sahel region, as well as over the Persian Gulf. Also the mean precipitation, which features an exceptional spatial complexity in the Mediterranean, is represented with a much higher degree of realism when compared with the low-resolution CM2.1,for example.

Our analysis shows also that CM2.5 simulates teleconnection of the Mediterranean with the atmospheric circulation over the North Atlantic with high fidelity. The model plausibly reproduces the fingerprint of the summer North Atlantic oscillation (SNAO), and its influence on the Mediterranean hydroclimate, when compared with 20th century observations (Folland et al. 2009). Remarkably, the simulated (from the CTRL experiment_ SNAO fingerprint is in better agreement with the observed SNAO before the 1970s/1980s, rather than for the later decades. This is likely related to the strong multi-decadal signal of the SNAO in the most recent decades (as highlighted by Linderholm and Folland 2017) that may have partly originated from anthropogenic forcing, which is not included in the CM2.5 control run, though this is by no means certain. The impacts of the SNAO on the Mediterranean hydroclimate are comparable, in terms of pattern and magnitude, with the CMIP3/CMIP5 simulations, e.g. as manifested in the increased precipitation over southern Europe during the positive SNAO phase. Overall, the analysis of the control run confirms the capability of CM2.5 to simulate key components of the regional climate, i.e. SNAO teleconnections and the local linkage between the surface and upper-level dynamics in the Mediterranean summer regime. The further analysis investigates the regional the future changes through the prism of future evolution of these two factors.

For the eastern Mediterranean, the most prominent features of its summer climate regime, i.e. the low-level northerly flow and the mid- and upper -tropospheric subsidence, are skillfully reproduced by the model. The strong linkage between these two factors demonstrates their counterbalancing effects on the regional temperature. Additionally, the significant correlations between the mid- and upper tropospheric subsidence over the Mediterranean and the indices of the Indian summer monsoon are consistent with the monsoon-desert mechanism (Rodwell and Hoskins, 1996, and Tyrlis et al., 2013).

The analysis of the CM2.5 projected future climate changes over the Euro-Atlantic region is to a large extent congruent with the CMIP5 ensemble. For example, changes in large-scale circulation over the North Atlantic, such as an expansion of the Hadley cell, an intensification and a northward shift of the atmospheric meridional cells, manifested by an anomalous anticyclone southwest of British Isles, constitute a typical fingerprint of the future summer anthropogenic change. In CM2.5, the general drying of the subtropics (southern Mediterranean) and wetting of the mid-latitudes (northern Europe) is consistent with the CMIP3/CMIP5 ensembles, and explained with the “wet-get-wetter and dry-get-drier” mechanism (Held and Soden, 2006; Seager et al., 2007). Consistent with previous CMIP studies, CM2.5 projects a much stronger warming in southwestern Europe and weaker warming in northeastern Europe.

However, CM2.5 projections reveal features, which are discernibly different from the CMIP3 and CMIP5 ensembles.For example, the magnitude of the CM2.5 projected warming over Europe and hence also the Mediterranean is much less radical. The derived future changes in precipitation over the Mediterranean are also smaller and feature a more complex pattern. This pattern consists of drying over large parts but also wetting tendencies over the Alps and northern parts of the Balkans. The CM2.5 projected wetting intensifies further towards central and northeastern Europe, which in contrast to CMIP3 and CMIP5 ensembles projecting rather drying over most of Europe, and wetting over Scandinavia. This difference is reflected in the projected in CM2.5 drying – wetting contrast over Europe, which is much sharper and with the transition zone being shifted southward, compared with the CMIP5 ensemble.

The CM2.5 projected future circulation over southern Europe also differs from the CMIP ensembles. CM2.5 projections indicate a strengthening of the zonal pressure gradient over the Mediterranean and the associated northerly flow/Etesian winds, contrary to a rather small weakening of the flow projected in CMIP5. This is a direct consequence of a) the strengthening anticyclonic circulation over the North Atlantic and higher sea level pressure over northwestern and central parts of Europe, and b) the intensification of the heat low over Sahara, the Persian trough and Asia Minor. In contrast, the intensified heat low in the CMIP5 ensemble covers not only arid subtropical regions but spreads over most of Eurasia (except the southern part of the monsoon region), suggestive of dominating contributions of land-atmosphere feedbacks.

Further analysis has shown also that the CM2.5 projected strengthening anticyclonic circulation over the North Atlantic is reflected in the strengthening of the SNAO towards its positive phase, which is also consistent with the CMIP3 and CMIP5 projections (e.g. Collins et al. 2013, Folland 2009). These changes of SNAO have been shown to be manifest in the positive anomalies of precipitation (wetting) over large parts of the Mediterranean. For example, without the impact of SNAO, the projected in CM2.5 drying over the Iberian Peninsula, Italy, and the Balkan coast would be much stronger (locally up to ~30-40%). This confirms an important role of SNAO in counterbalancing the thermodynamic effects of the projected drying over the Mediterranean in both the CM2.5 and CMIP projections. Nevertheless, it is important to note that a) the representation of the regional SNAO impacts, and b) projected future changes in SNAO, is comparable between the CM2.5 and with some older generations models such as CM2.1, both in terms of pattern and magnitude. Thus SNAO does not seem to be a strong candidate explaining the differences in the future projections for the summer European climate between CM2.5 and CMIP3/CMIP5 ensembles.

Many studies have suggested rather that soil moisture-climate feedbacks are of dominant importance for summer climate in these regions (Seneviratne et al. 2006, Diffenbaugh 2007, Hirschi et al 2011). At the same time, most of CMIP3 and CMIP5 models are deficient in capturing soil moisture-atmosphere feedbacks (Christensen and Boberg, 2012; Mueller and Seneviratne, 2014, Boberg and Christensen, 2012). This causes a temperature dependent bias and spuriously amplifies the projected regional warming and drying, manifested ultimately in the CMIP5 ensemble mean as a very strong overall warming and drying over Europe. In contrast, Berg et al. 2016; Milly et al. 2014 demonstrated an improved representation of soil moisture and land-atmospheric feedbacks between soil moisture and precipitation in the LM3 model used in CM2.5. The enhanced feedbacks in this region are shown in Berg et al. (2015) with a lower resolution earth system model using LM3. Hence the apparent stark contrast between the CMIP3/CMIP5 and CM2.5 (mild warming and wetting) regional projections could more likely originate from the enhancements in the land model incorporated in CM2.5 at its high spatial resolution, rather than the impacts of the SNAO. These feedbacks should be explored in future work using targeted experiments like the Global Land–Atmosphere Coupling Experiment (Seneviratne et al. 2013) but lie outside the scope of this paper.

Additionally, the changes in climate regime projected in CM2.5 also suggest a weakening role of atmospheric dynamics in maintaining the regional hydroclimate and temperature balance over the eastern Mediterranean. For example, the projected changes over Asia Minor show very strong drying and warming, despite the increasing influence (i.e. wetting and cooling) of the SNAO teleconnection. Also, the warming over the Asia Minor and Levant regions constitutes a local maximum for the changes in the Mediterranean region, despite the cooling effect of strongly intensifying Etesians and the weakening mid- and upper-tropospheric subsidence in EMED.

The derived weakening linkage between the low-level circulation (e.g. northerly flow) and the mid-and upper-level subsidence over the EMED, which balances the regional temperature, is indicative of the nonlinearity in the summer EMED regime introduced by the local surface temperature. Additionally, the comparison of warmer and cooler EMED seasons in the control run indicates an increasing influence of local surface temperature on the local low-level atmospheric circulation in a warmer climate. This response stems likely from a sensitivity of this desert-like land to radiative forcing. It is manifest in an anomalous intensification of the heat low over the EMED, Sahara and the Persian trough, but also in positive SLP anomalies, increasing subsidence, maximum warming, reduced relative humidity, and reduced precipitation in the regions located north from Levant, in particular Asia Minor. All of these features are consistent with future climate changes projected by CM2.5. This supports the overall notion of an increasing impact of the interactions between land surface and atmosphere, as well as a decreasing influence of atmospheric dynamics, and hence of teleconnections, on the future summer regime in this region.

"The authors declare that they have no conflict of interest."

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Table1 Abbreviation names for the CM2.5 experiments

NAME of the experiment	Ensemble size	Number of years total	Historical period [yrs]
CTRL	1	1000 yrs	-
HIST	5	145	1861-2005
PROJ	5	95	2006-2100

FIGURES

Figure 1. Seasonal (JJA) sea level pressure (hPa) and wind vector at 850hPa (m/s) in a) NCEP-DOE2, b) CM2.5. Time-mean of seasonal data from years 101–1000 of the control simulations are used, and years 1979-2017 of the observed data.

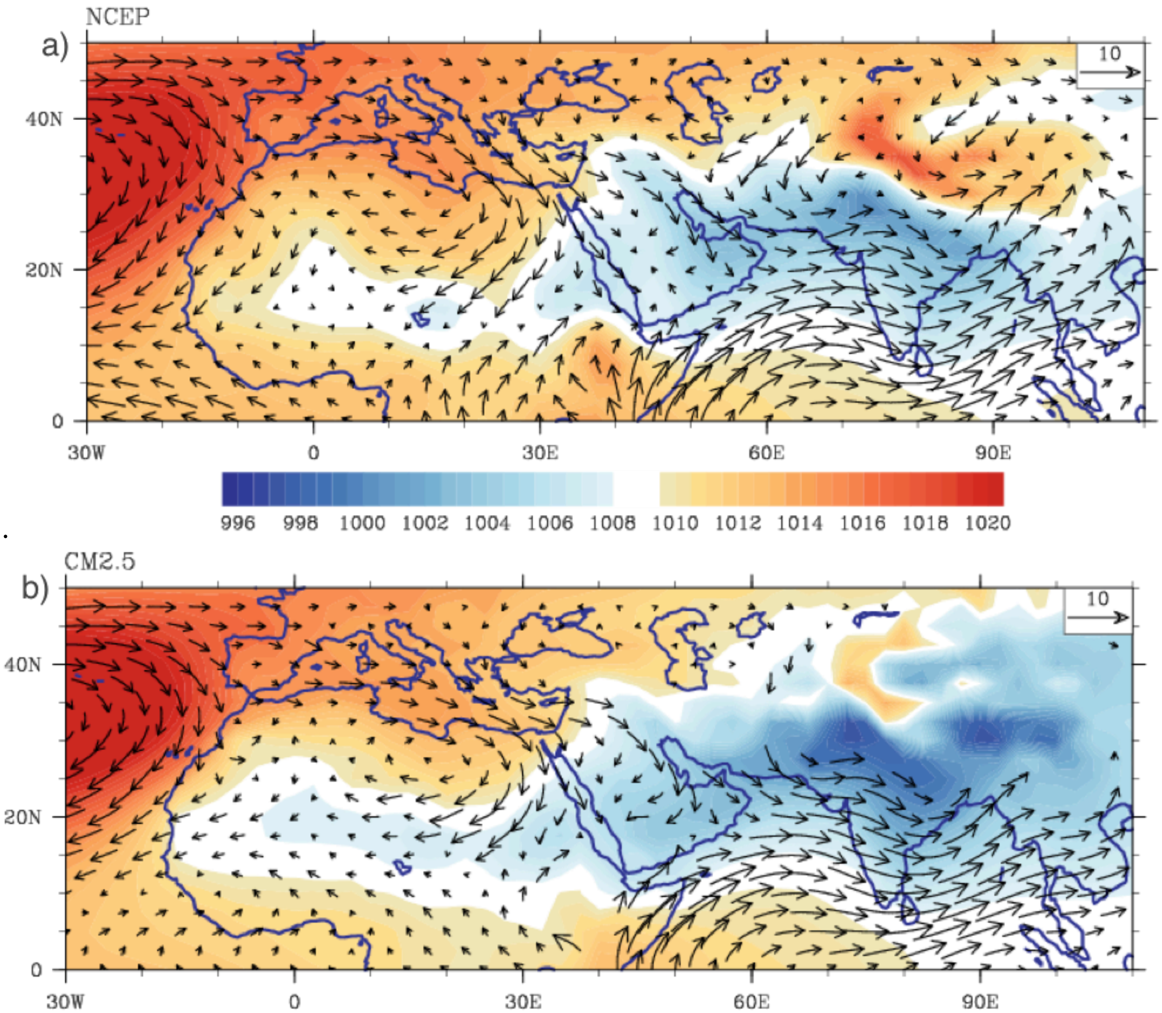


Figure 2. Seasonal (July) time-mean vertical velocities at 500hPa (Pa/s) and wind vectors at 200hPa (Pa/s), estimated for a) NCEP-DOE2 in the period 1979-2017, and b) CM2.5 CTRL run in years 101-1000. Both data sets are interpolated to the 2.5° horizontal grid.

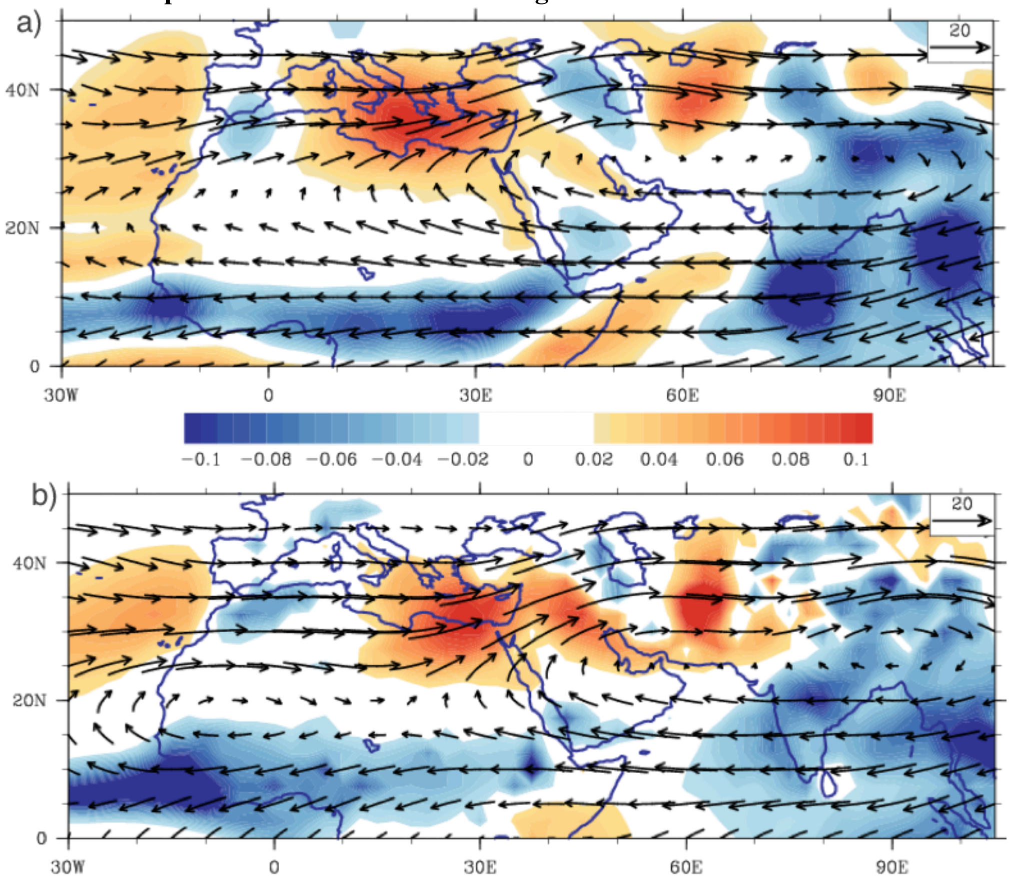


Figure 3. Height (pressure)-longitude cross-section of vertical velocity (Pa/s, shaded contours, downward motion denoted with positive values) and vector of zonal wind (m/s) and vertical velocity (converted to m/s and scaled with a factor of 1000) in July. Figure shows time-mean values in July a) derived for the period 1979-2017 in NCEP-DOE2, b) derived from 101-1000 years of CNTL run in CM2.5; and c) projected future changes in the period 2061-2099 in PROJ ensemble mean, compared with the baseline period 1961-1999 in the HIST ensemble mean. All fields are shown on the 2.5°x2.5° horizontal grid and at the original vertical levels, common for CM2.5 and NCEP-DOE2.

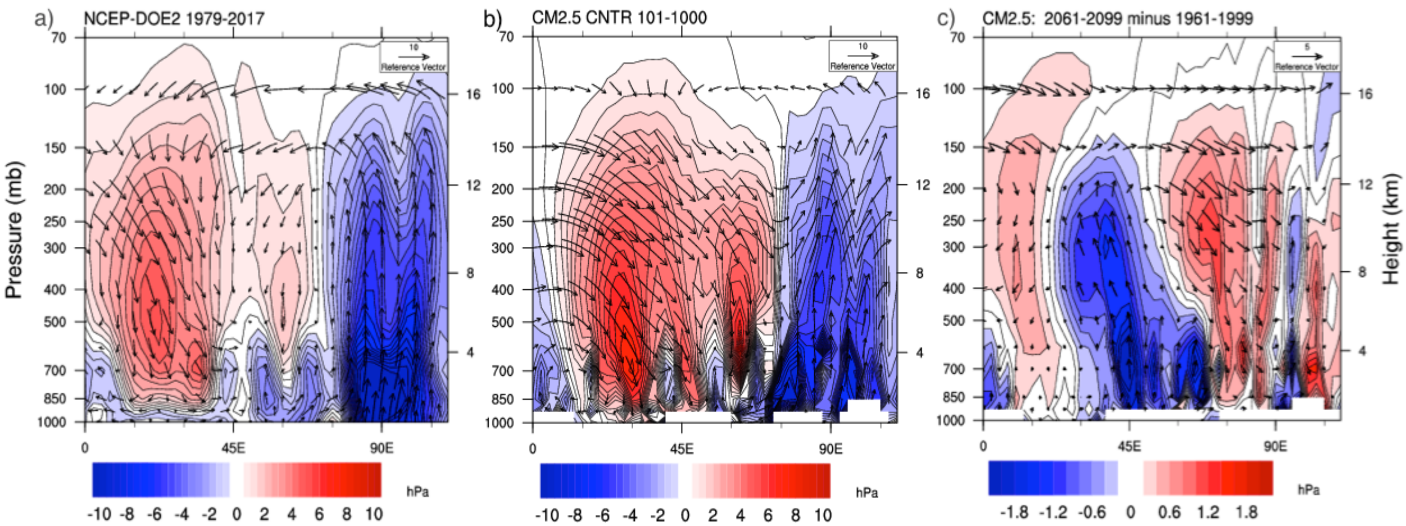


Figure 4. Seasonal (JJA) mean precipitation (mm/day) for a) EOBS observations, b) University of Delaware Climatology, b) CM2.1, c) CM2.5. The time-mean of seasonal data from years 101–1000 of the control simulations are used, and years 1980-2015 of the observed data sets. Both observational data sets are shown at 0.5° lat x lon resolution. Regions with missing data are left blank.

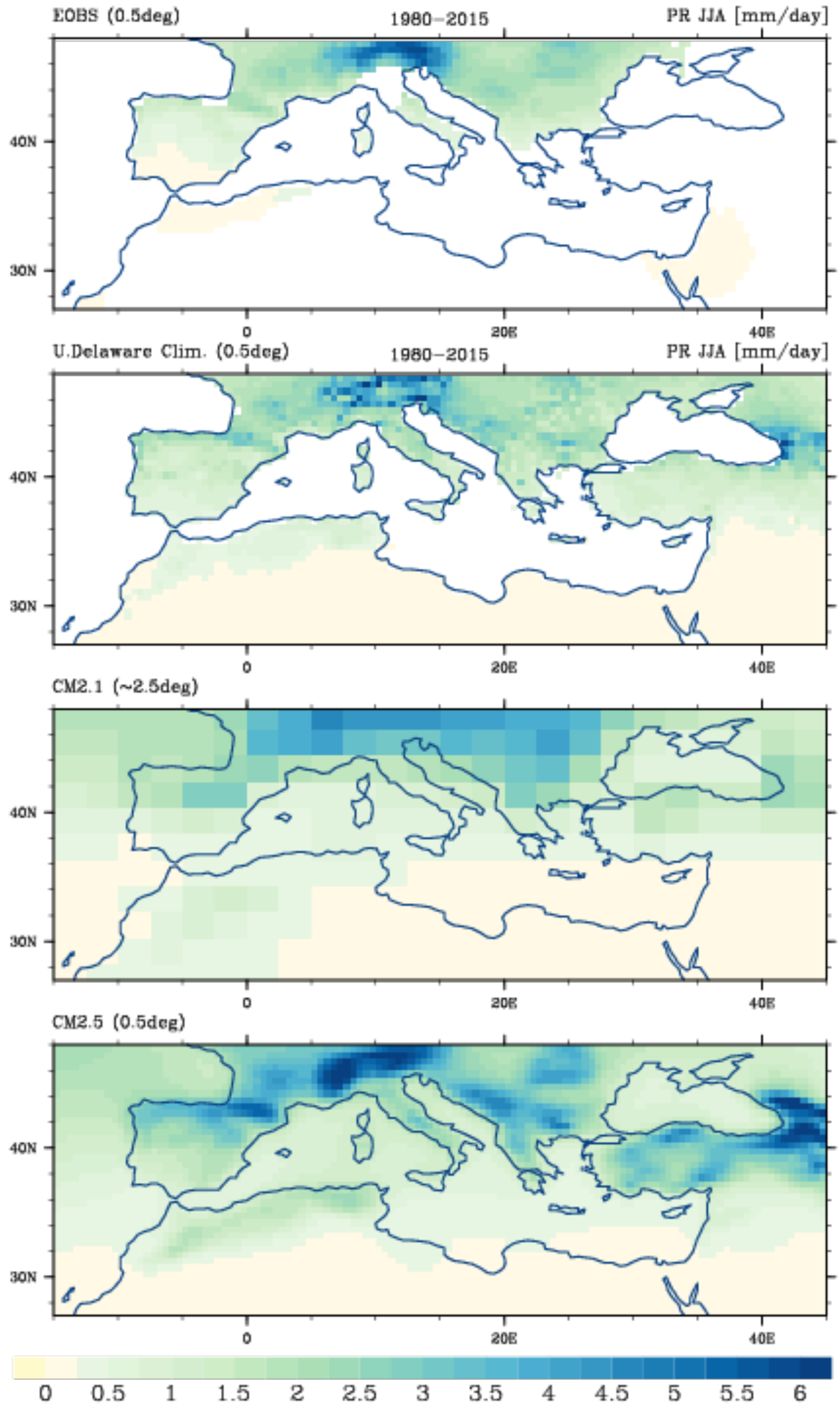


Figure 5. Correlation between principal component time series of the SNAO SLP in JA and a) sea level pressure b) temperature at 2m (shaded) and geopotential height at 850hPa (contours), c) precipitation. All derived from the CTRL run. Contours in a) and c) are shown for 0.25 and 0.5 correlations. Correlations are shown only when significant at 1% level.

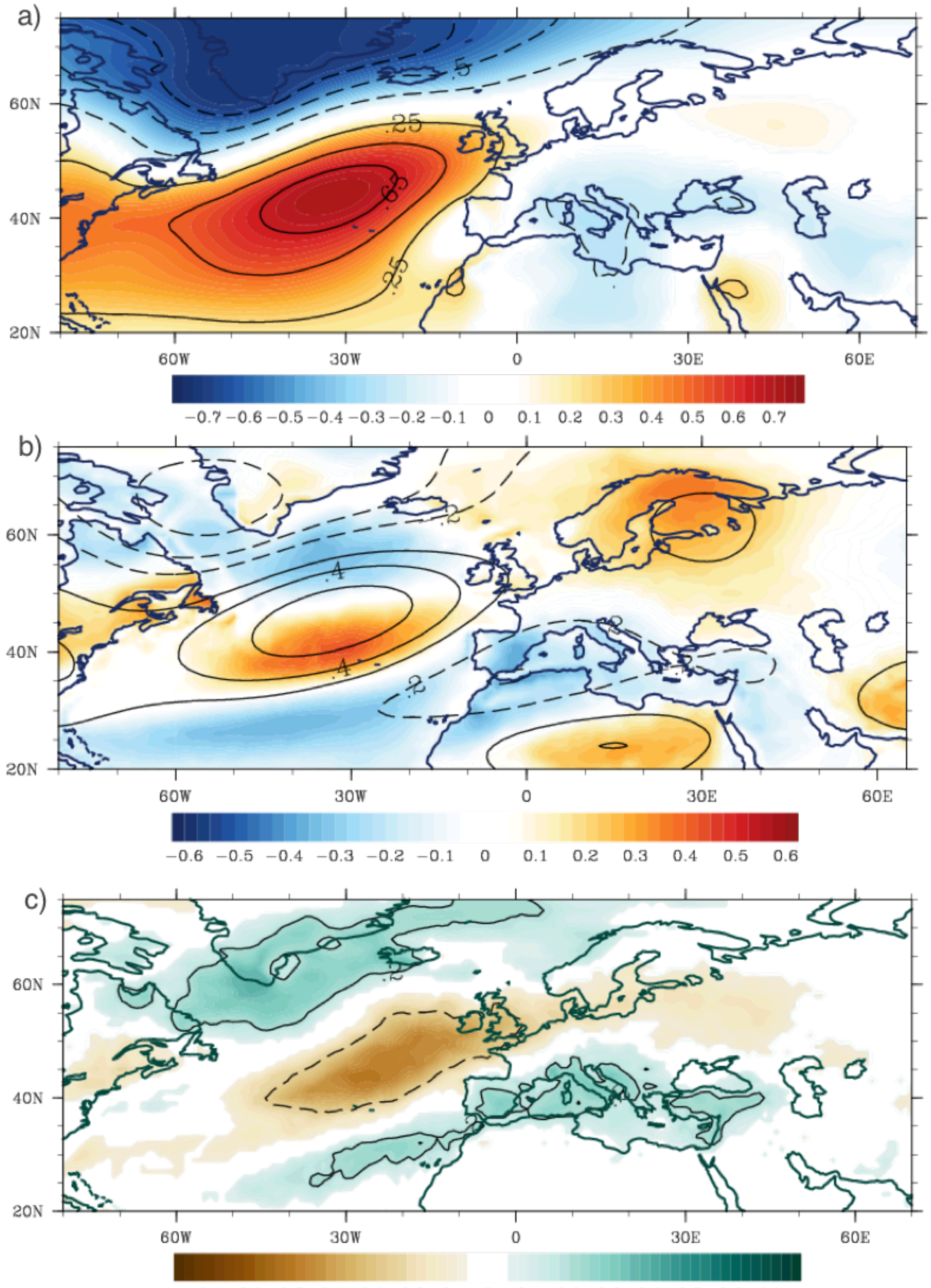


Figure 6. Spatial pattern of the SNAO (EOF), derived from the 20CR reanalysis (left), and from the first CM2.5 HIST run (right), shown as correlations between the first principal component time series and SLP in July-August. The pattern is derived from periods a)-b) 1870-1920, c)-d) 1900-1950, e)-f) 1940-1990, g)-h) 1960-2010. Please note that the sign of each derived EOF is arbitrary. The analysis took into account that fact and unified the sign, showing the SNAO at its positive phase.

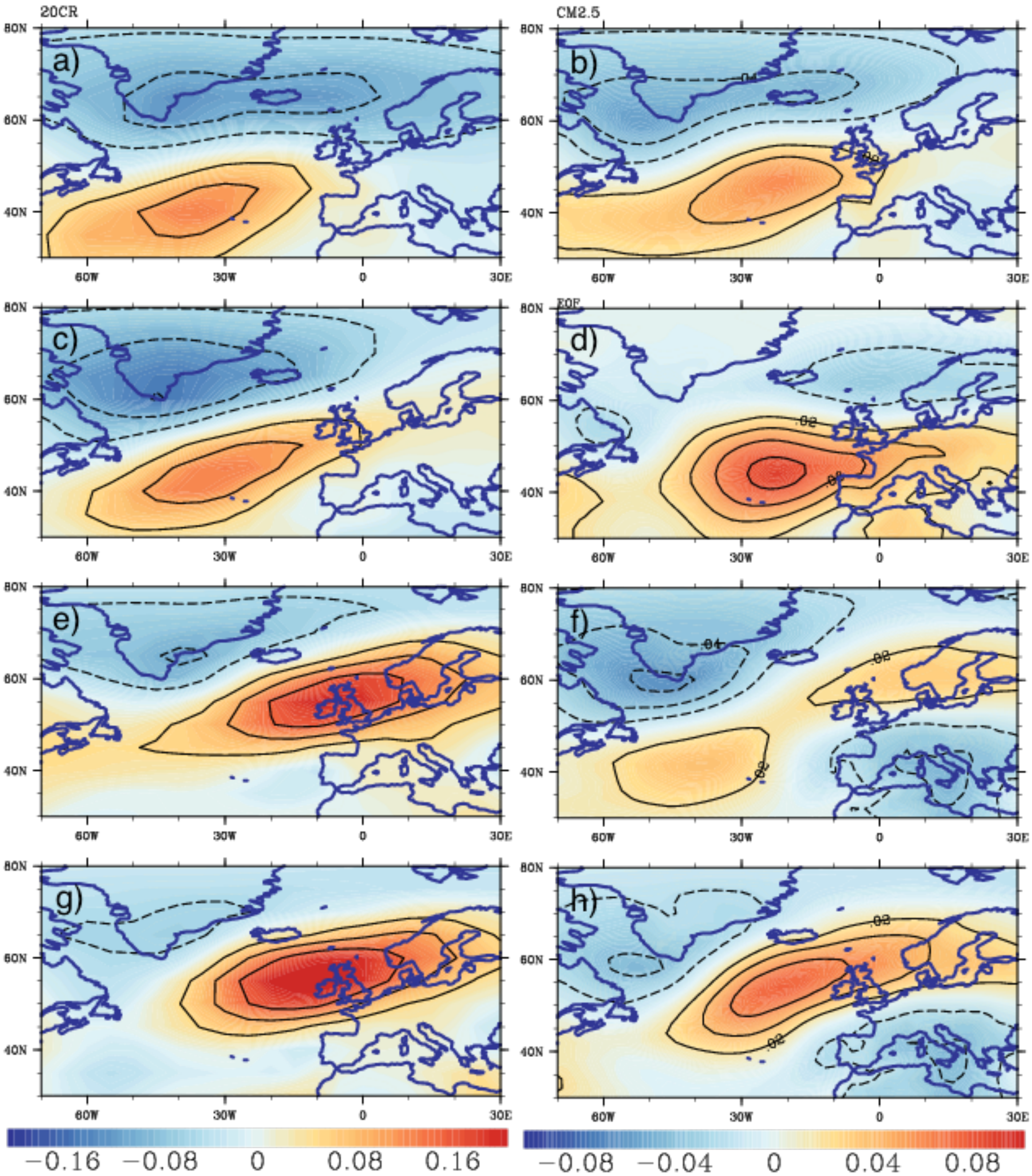


Figure 7. a) First EOF of CM2.5 vertical velocities at 500 hPa (EOF1 omega, shaded) and 300hPa (contours), derived from the monthly mean of July in the CTRL run. The time series of EOF1 omega at 500 hpa are correlated with b) geopotential height (shaded), u, v components (shown as vector) at 850hPa and c) meridional wind at 850hPa. d) Correlations derived between the observed (NCEP) omega 500hPa over the eastern Mediterranean region (32°-34°N, 25°-30°E) and the meridional wind at 850hPa. Correlations shown are at b)-c) the 1%, and d) the 10% significance level.

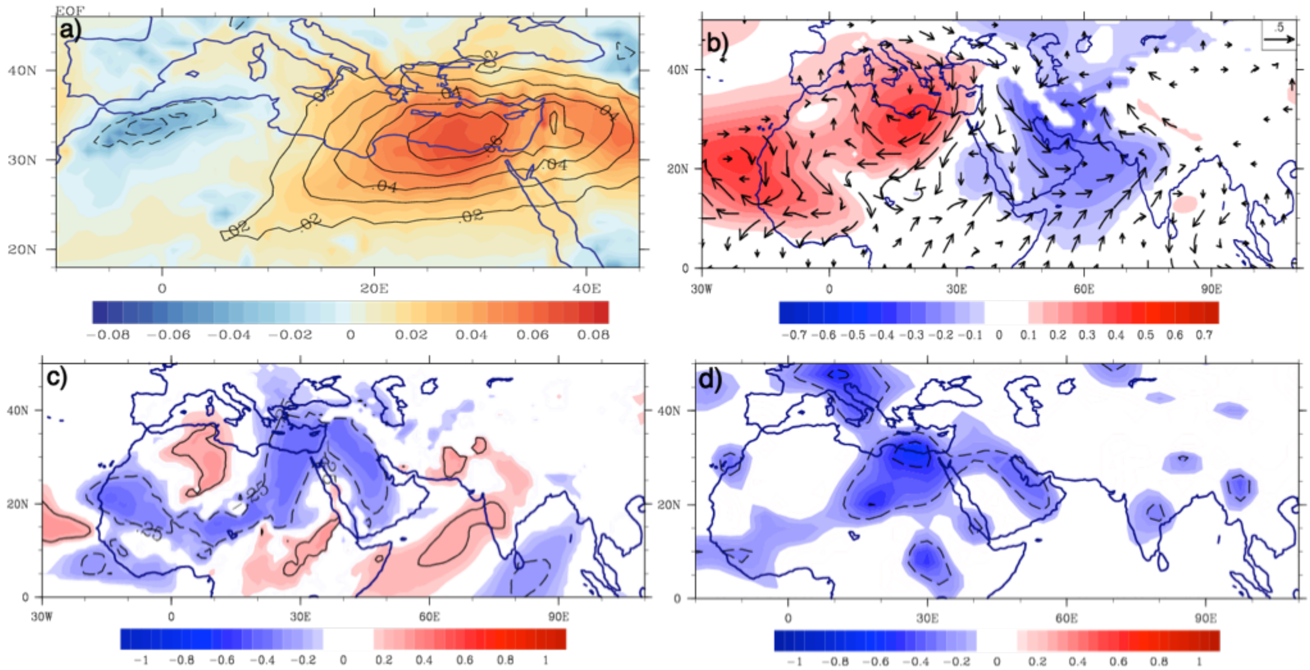


Figure 8. Correlations between the time series of the EOF1 omega (derived for omega 500hPa, see Figure 7a) and a) outgoing long wave radiation (shaded), omega at 500 hPa (contours: -0.2, 0.2, 0.4), b) precipitation; derived from the monthly means of July in CTRL run. Correlations shown are at the 1% significance level.

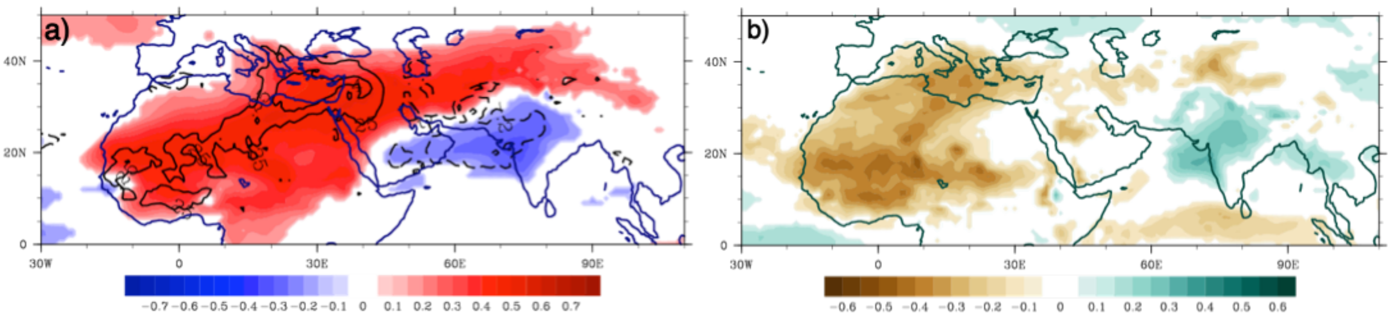


Figure 9. Projected future changes for the summer (JJA) a) sea level pressure (hPa, shaded) and u,v wind components at 850hPa (m/s, vector), b) surface temperature (°C), c) total precipitation rate [mm/day], over the period 2061-2099 compared with the baseline period 1961-1999. Changes are derived at the original horizontal resolution.

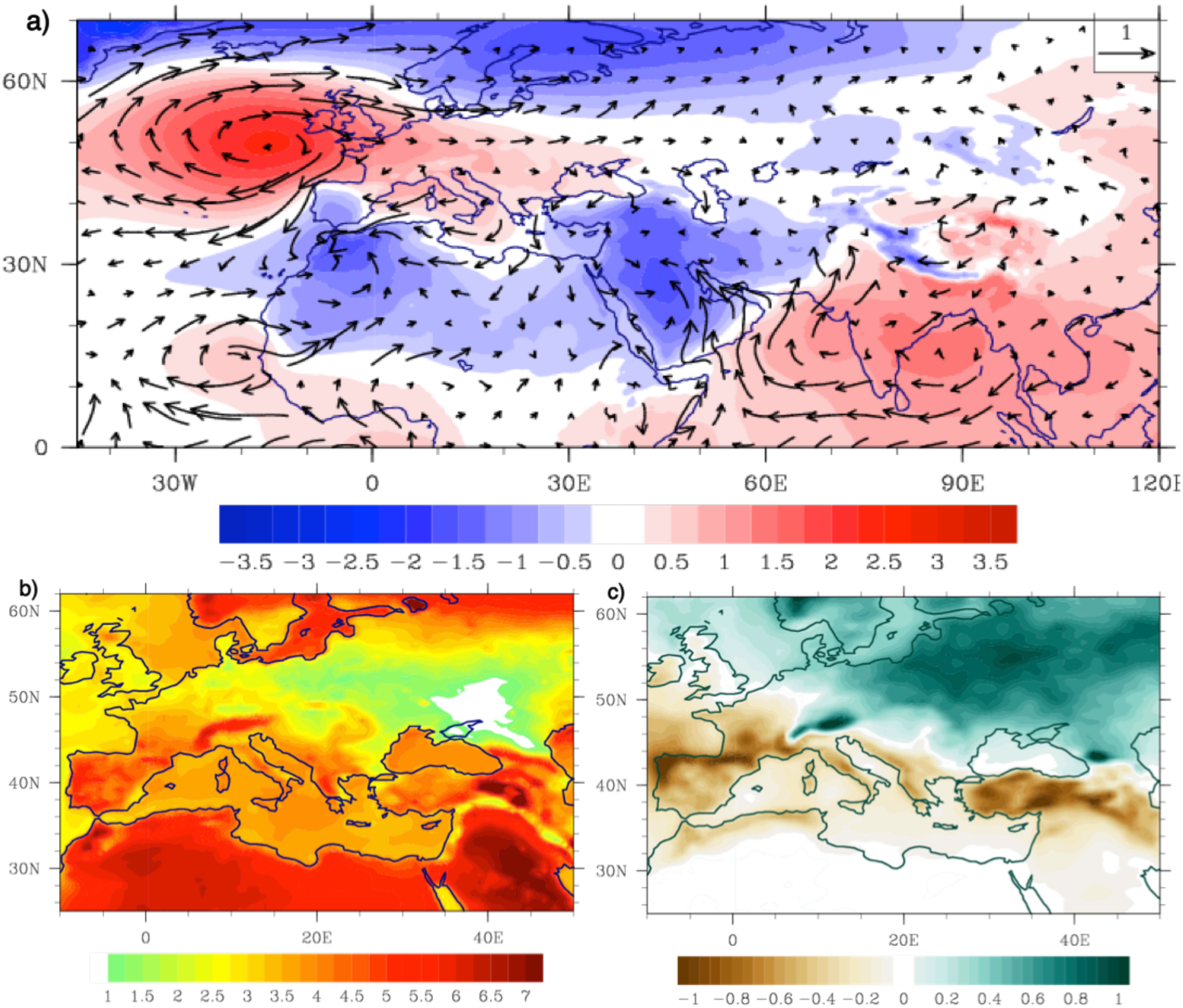


Figure 10. (a, b) Correlations (shaded) between the SNAO time series and precipitation in1900-1950 (a) HIST runs), and 2050-2100 (b) PROJ runs). Contours denote 0.25 and 0.5. c) Evolution of SNAO SLP time series in 1850-2100 period for each run (blue) and the ensemble mean (red). The vertical line divides the HIST and PROJ time series. (d, e) Projected future changes in the summer precipitation (mm/day) (as in Fig 8c, except that estimated at 1° horizontal resolution), d) including SNAO impact and e) with the impact of the future SNAO removed (shaded). The impact of SNAO is estimated based on the linear regression between the detrended time series of SNAO and precipitation.

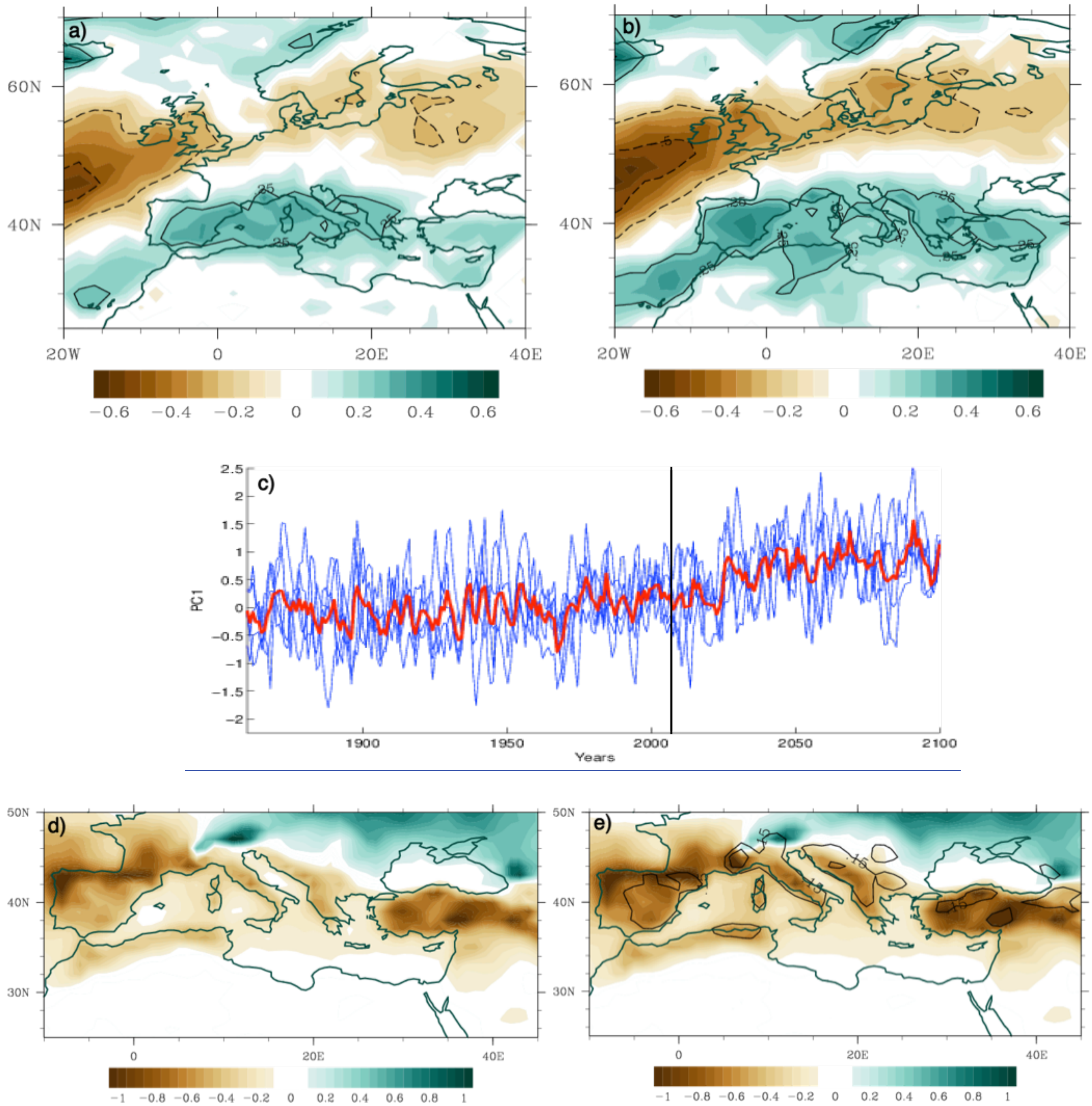


Figure 11. Correlations between the PC1 time series of omega at 500hPa in July and surface atmospheric circulation in the periods (a,c,e) 1960-2010 and (b,d,f) 2050-2100. Correlation values are estimated for a)-b) SLP (shaded and contours), c)-d) meridional wind (shaded and contours), e)-f) precipitation (shaded and contours) and vertically integrated water vapor (contours for the values -0.5, 0.3, 0.5). For a)-d) contours are shown for 0.25 and 0.5 correlation values.

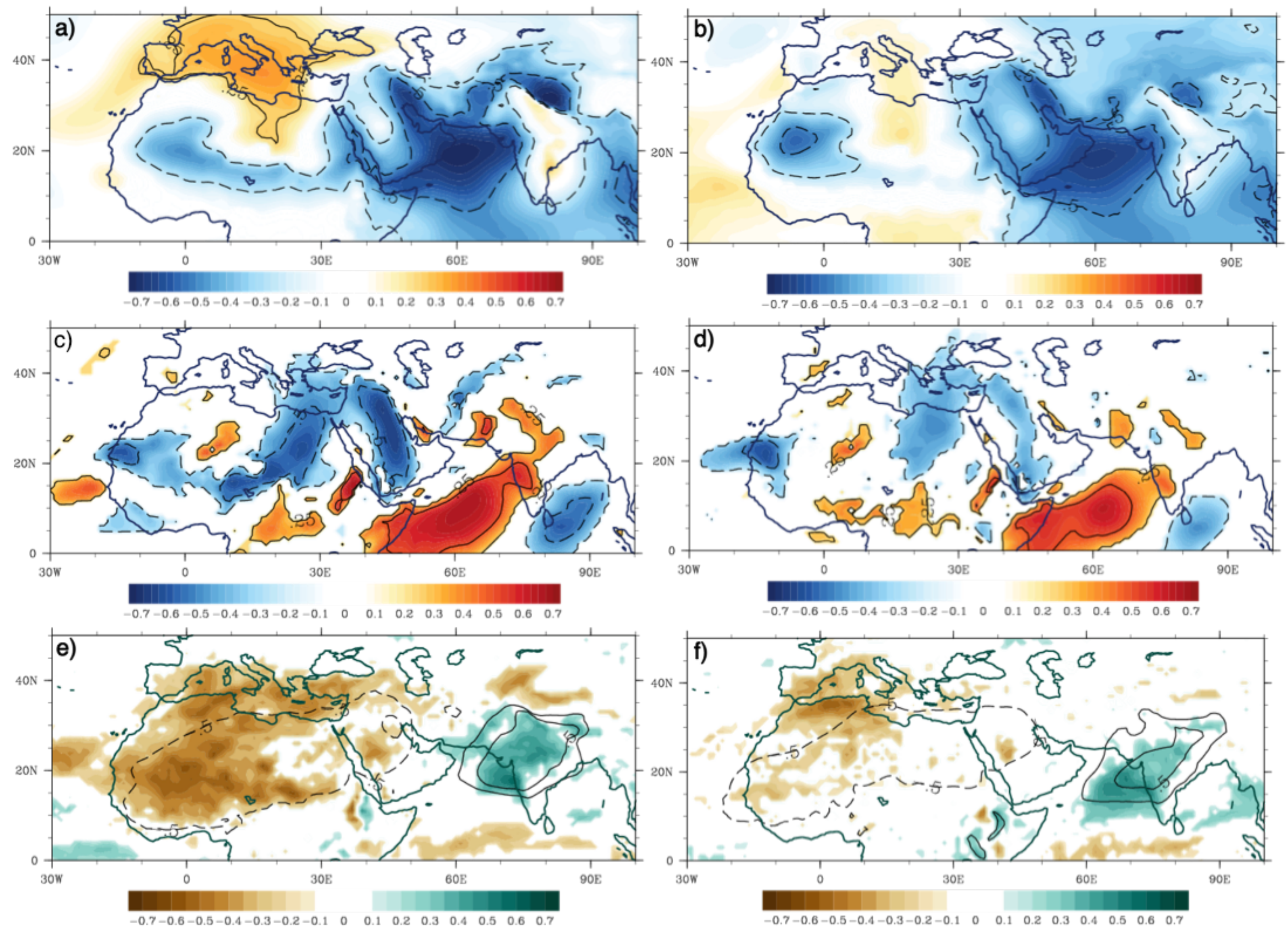
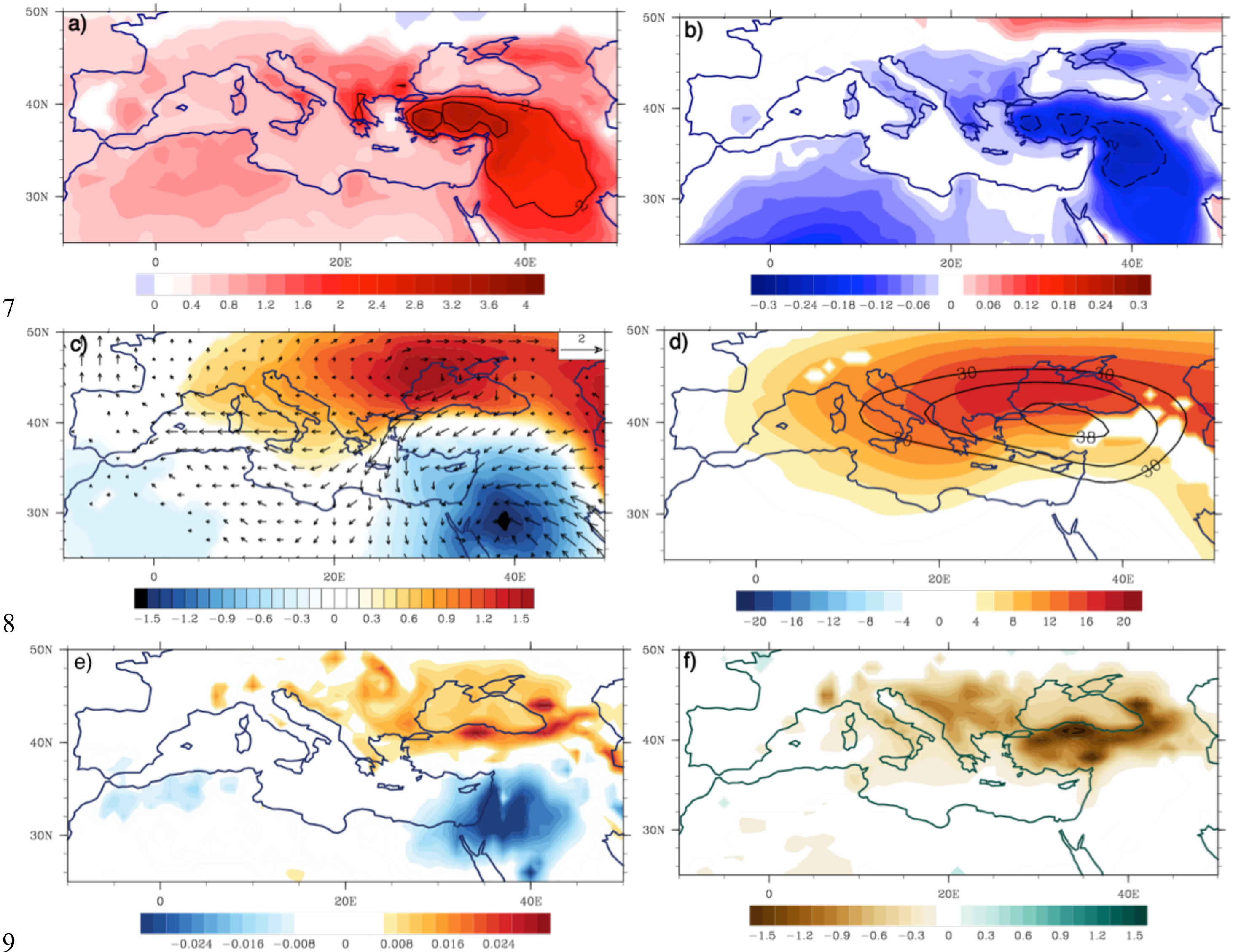


Figure 12. a) Composite differences between the sample with the 300 warmest and 300 coolest seasons over the eastern Mediterranean (30°-36°N, 36°-42°E), for July in the CTRL run, derived from a) surface temperature (°C), and associated differences in b) relative humidity, c) SLP (hPa) and vector wind at 850hpa (m/s), d) height at 850hPa (shaded) and 500hPa (contours), e) omega at 500 hPa, f) precipitation (mm/day).



Supplementary Material

Fig SI1. Spatial pattern of SNAO, derived from the 20CR reanalysis, derived from periods: 1851-1890, 1891-1930, 1931-1970, 1971-2010.

Fig SI2. Spatial patterns of the SNAO using SLP, derived from five HIST runs in 1870-1920 (left column), and 1960-2010 (right column). The pattern is shown as correlations between time series of the first PC of SLP and SLP fields in July-August. The sign of each derived EOF is arbitrary, but here the signs were converted to match the SNAO at its negative phase.

Fig SI3. Spatial pattern of SNAO using SLP derived from the period 1970-2030 in the five HIST+PROJ runs. The pattern is shown as correlations between the principal component time series of the first EOF of SLP and SLP fields in July-August.

Figure SI4. (left) Mean storm track patterns for 1950–1990 (top) and 1970-2011 (bottom), represented by the standard deviation of daily 300 hPa geopotential height (m) in July–August. The data was bandpass-filtered on time scales of 2–8 days. (right) Correlations derived between the standard deviation of the filtered seasonal (July-August) values of 300-hPa height (derived from NCEP/NCAR 1 data) and the SNAO index (derived from 20CR data).

Fig SI5. Future changes projected for vertical velocities at a) 500 hPa, c) 600 hPa, e) 700 hPa in JJA and in July in b), d), f) respectively. The changes are derived in the period 2061-2099 and compared with the baseline period 1961-1999, derived at the original horizontal resolution (~0.25°). The vertical axis is oriented downward, i.e. negative tendencies (in blue) indicate upward motion while positive tendencies (red, stronger subsidence) indicate downward motion.

Figure SI6. Projected future changes for the summer (JJA) surface temperature (left,°C), and precipitation (right, mm/day) based on the 10-member ensemble simulations of the CSIRO-Mk3-6-0 model, for the forcing scenario RCP8.5.

Fig SI7. As in Fig 11, except that correlations are derived, based on the sample with the 300 coldest (a,b) and 300 warmest (c,d) complete seasons over the eastern Mediterranean in the CTRL run. Correlations are shown for a)-b) meridional wind, c)-d) precipitation.

Fig SI8. As in Figure 12c, except that for a) June, b) August, and for a larger domain.

Fig SI9. As in Figure 12c, except that the regions used for differentiation between warmest and coolest seasons are larger: a) 0°-40°E, 30°-36°N, b) 20°-40°E, 30°-36°N, c) 30°-50°E, 30°-36°N, d) 30°-50°E, 30°-40°N, e) 30°-50°E, 30°-45°N.

Fig SI10. Correlations between the principal component time series of EOF1 omega over EMED and precipitation in (a) June, (b) July (as in Figure 8c), (c) August. Solid lines denote positive correlations, and stippled denote negative correlations, both for the absolute values larger, than 0.25.