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Response to the referee 1

We would like to thank the referees for their constructive feedbacks and insightful comments. We appreciate the time and effort the referee dedicated to review our manuscript, which helped us to improve our presentation. We have incorporated the suggestions made by them, and below you find our responses to the referees' comments (in blue).

Major comments:

Abstract

1. The abstract is brief and concise and summarizes the main conclusions of the study – maybe the authors can add some additional sentences on the uncertainties and limitations of the model-only study and include some basic statements on the suitability of the CCSM model to be used for drought studies over the Mediterranean realm.

Thanks for the comment. We will include the points the referee mentions regarding the limitations of a single-model study and the suitability of the CESM model for drought analysis over the Mediterranean region in the abstract of revised manuscript.

Introduction

2. The authors should include a chapter on a more detailed description of the mean climatic characteristics of the Mediterranean area, especially during the winter half year when most of hydroclimatic variability plays a role. Moreover, it would be illustrative to elaborate in greater detail the spatial differences in hydroclimatic variability between the western and eastern Mediterranean area concerning the annual cycle (cf. references at the end of review by Dünkeloh and Jacobeit (2003), Luterbacher et al. (2006), Trigo et al. (1999), Peyron et al., (2017)).

We agree with the referee's point. We did not elucidate the climate in the eastern area, as our focus is more on the western-central area. We will provide more details on the hydrodynamic variability over the Mediterranean region including the spatial difference between the western and eastern Mediterranean in the introduction of the revised version.

3. A second point that might be also motivated in the introduction is why only a single model simulation with PMIP3-like forcings is investigated. Admittedly, the spatial resolution is one of the biggest advantages of the simulation, but also other simulations could have been addressed, especially when large-scale areal averages are analyzed. Authors should try to motivate why CCSM4 in this version is outstanding and suited for drought investigations over the Mediterranean area. (cf. also Coats et al. (2015) for a model-only studies over North American droughts).

We agree with the referee that we should provide more explanation on why we use a single CESM simulation.

First, as you mention, the spatial resolution of this long simulation is a great advantage for our study in a small constrained area. Though we used the regionally averaged indices, we think that the spatial resolution allows a better representation of regional processes relevant for precipitation, therefore, for droughts. For example, the rainfall over the region is strongly influenced by extratropical storm tracks and cyclones. The precipitation and atmospheric dynamics associated with these climatic features depend on the model spatial resolution and better represented in GCMs with higher resolutions (Champion et al., 2011; Watterson, 2006). Hence, we think using a model with finer resolution is appropriate for this region.

Second, we want to study the physical mechanisms of continuous Mediterranean droughts during the last millennium. One of our main focus is to identify the roles of the internal variability and external forcings in the past Mediterranean droughts, and we believe that we were able to answer partially to this question using this CESM simulation. However, we are aware that more analysis is needed to support this result, for example, to assess more clearly the role of volcanic forcing on droughts. For that, we plan to apply some more methods, such as a wavelet coherence analysis, in a similar way as Coats et al. (2013), between drought indices and volcanic eruptions.

We will include the new analysis and an explanation on the benefit of using this model. To be balanced, we will also discuss potential drawbacks and limitations of a single model study.

Description of the model and simulations

4. The CCSM model has a very high spatial resolution, but I was wondering why the vertical resolution is quite low, consisting of only 26 levels. A number of PMIP3 models use a lower spatial resolution but with a considerably higher vertical resolution. I mention this issue because it might have important implications for the atmospheric dynamics, controlling precipitation variability, both spatially and temporally, over the Mediterranean area. Hence, a realistic simulation of those processes is pivotal for a realistic simulation of drought (or non-drought) dynamics.

We agree that the vertical resolution of a model has implications on the atmospheric dynamics. We use the physically tested version provided by NCAR. It is not a straightforward task to increase the vertical resolution of the model, as a rigorous testing and tuning of the model would be needed, therefore, an assessment of the impacts of different vertical resolutions specifically on drought dynamics is not easily possible. We also checked the literature and did not find a study focusing on this issue.
One hint that the vertical resolution is sufficient is given by the comparison of the simulation with the reanalysis data. We found that the correlations between geopotential heights (at 850 and 500 hPa) and the scPDSI in the model during droughts for the period of 1901-2000 seem to be in range with the correlation fields of the reanalysis data (NOAA 21th Century Reanalysis V3; Compo et al., 2011), which you can see the figure 1 below. Thus, the

model mimics reasonably well the atmospheric dynamics associated with droughts. We plan to include these plots in the supplementary of the revised manuscript.

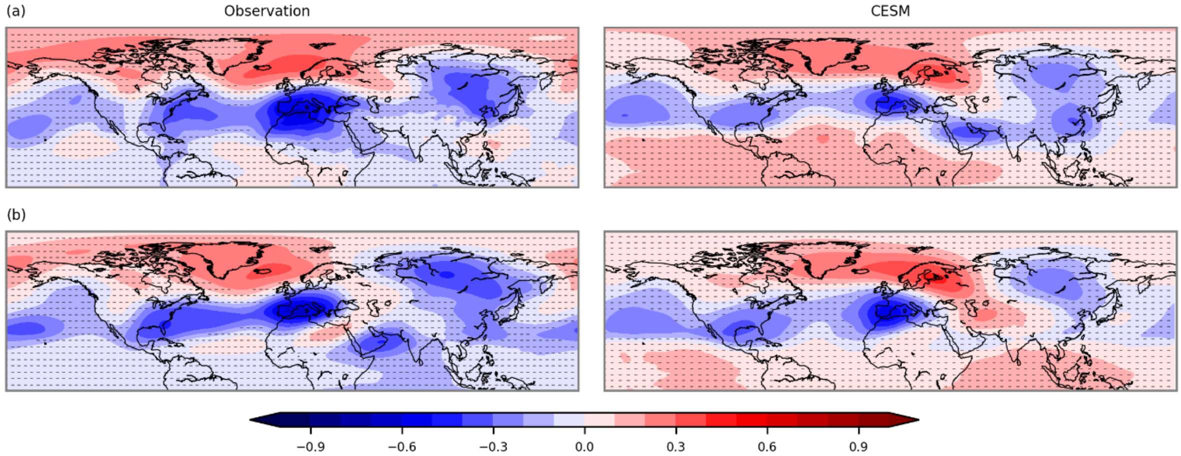

Figure 1. Fields of correlation between the monthly scPDSI and geopential height at (a-above) 850 hPa and (b-below) 500 hPa for the period of 1901-2000 in (left) the NOAA 21th century reanalysis V3 data and (right) CESM. Regions where the correlations are not statistically significant at 5% level by Mann-Whitney U test are dashed.

5. The authors mention the orbital forcing is set to 1990 AD conditions for the control simulation – I guess this also applies for the transient simulation. Which effects could this have when the orbital parameters are not varying concerning the radiation changes, especially during the summertime in the course of the last millennium?

Certainly, the change in orbital parameters from 850CE led to a progressive change in insolation in the Northern Hemisphere, such as the increase in summer insolation and a shift of the maximum month of insolation at high latitudes (Schmidt, 2011). However, the impact of these changes on the climate during the last millennium is rather small compared to the other forcings, such as the total solar irradiance and volcanic eruptions (PAGES Hydro2k Consortium, 2017). Clearly on longer time scales such as the last 6000 years, the orbital forcing has a stronger effect and cannot be ignored.

6. Also, as the Mediterranean area in the northern region has a very vulnerable vegetation cover that is also important for hydrological dynamics, some words on the reconstruction and potential changes in land cover over the area would be informative for the readership. Likewise, the authors mention the soil model consisting of 15 layers, which is quite extensive for a global Earth System model. As soil dynamics also play a central role in the investigations carried out at a later stage, authors should add some more information on the soil model and highlight its importance, especially over the Mediterranean area.

We will elucidate the relationship among vegetation, soil and hydrological dynamics, and the benefits of using the soil moisture as a drought metric in the results and discussion section of the revised version.

The referee 2 commented that we can shorten the model description just by citing Lehner et al. (2015), as more details are already explained in that literature. Therefore, we will keep the paragraph on the model description as it is now (section 2.1) and not add more description on each component model, including the soil model, as the readers can directly refer to Lehner et al. (2015) for more information.

Drought definitions

7. As I mentioned previously, I like the approach addressing several drought-related and quantifying indices, as results might be dependent on the respective metric used. I missed however a comparison of the general hydrological cycle for present-day climate in comparison with observational and/or re-analysis data sets. I suggest to at least perform a validation for i) the winter season for precipitation spatially resolved over the Mediterranean area and ii) the annual cycle separated over the western and eastern and northern and southern Mediterranean (cf. links for data sources at the end of this review) in the 2nd half of the 20th century. This is important to test whether the model is capable to reproduce the main climatic features in important on investigations in the context of drought (cf. López-Moreno et al., (2009) for present-day situation).

We agree with the referee that the validation of CESM against observational data is missing in our manuscript. We plan to add a new section about the validation among the observation-model-proxy in the revised version.

You can see some of the related figures below. We compared the summer and winter mean precipitation fields, and the mean annual cycles over the western and central Mediterranean region between the observational (U. Delaware gridded station data; Willmott and Matsuura, 2001) and CESM data for the period of 1901-2000. We applied the Mann-Whitney U test to see the significant grids at 5% of confidence level. In general, the observation and model show a similar pattern, except for few grids in the summer and different grids in the winter (Figure 2). For the annual cycles, it seems that the model shows overall less intense precipitation than the observation, but the maximum and minimum months of precipitation are coherent (Figure 3).

We also performed the correlations between the scPDSI and SST (ERSST v5; Huang et al. ,2017), and the scPDSI and geopotential height at 850 hPa during droughts using the observational and CESM data for the same period (Figure 4). They share similar statistically significant regions with same signals, over the central Equatorial Pacific in SST, and over the mid-to-high latitudes in geopotential height.

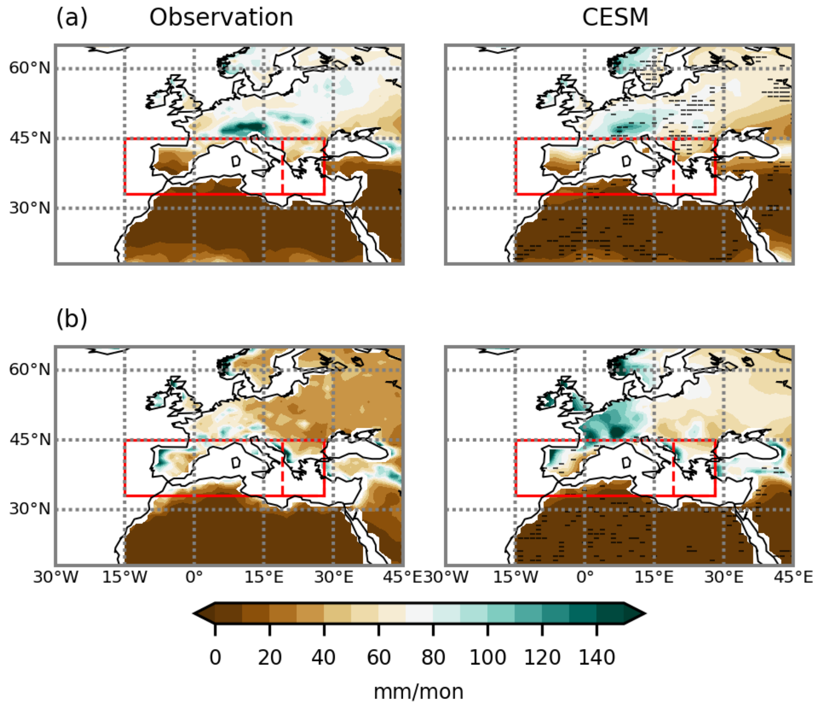

Figure 2. Mean seasonal precipitation during the (a-above) summer and (b-below) winter for the (left) observational data and (right) CESM. In the CESM, Regions where the means are not statistically significant compared to the observation are dashed.

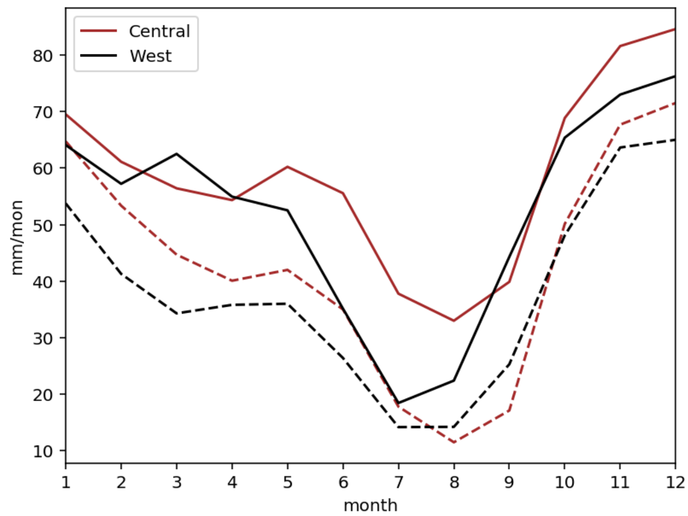

Figure 3. Mean annual cycles of precipitation over the regions in the boxes on figure 2, for the observation (continuous line) and CESM (dashed).

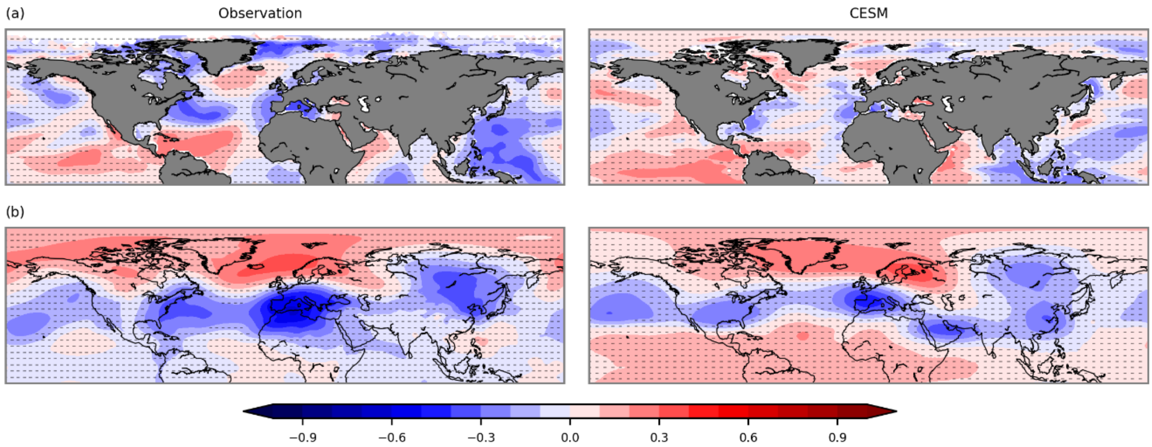

Figure 4. Fields of correlation between the monthly scPDSI and (a-above) SST and (b-below) 850 hPa for the period of 1901-2000 in the (left) observational data and (right) CESM. Regions where the correlations not statistically significant at 5% level are dashed.

8. A second issue here is the question why the authors do not present a spatially resolved analysis for their study region. The areal extent of their region is quite large and planetary wave train structures might affect the area at the same time with different impacts. For instance, a ridge structure over the western Mediterranean can be accompanied by a trough structure at the same time over the Eastern Mediterranean with profound differences related to the hydrological impacts. A consequence might be that in situations with non pan-Mediterranean droughts, those dipole structures between east/west and north/south are cancelled out and the respective areal averages only contain a residual component that is not related to atmospheric circulation dynamics. Maybe the authors could at least mention how the usage of areal average might affect their conclusions.

We agree with the referee that we need to clarify our choice of the region. We did not mention in our manuscript that we want to study droughts with more pan-Mediterranean characteristics, as the region shows an overall drying trend in the modern period and future projection (see the figure 5 below, also some citations in the introduction of our manuscript, for example, Naumann et al., 2018). Additionally, recently some devastating drought events with pan-European characteristic, covering large parts of the southern Europe, including our region of study, have been reported (Garcia-Herrera et al.,2019; Spinoni et al., 2017). Thus, understanding the mechanisms associated to these types of events in the past would be useful to understand their present dynamics and future changes.

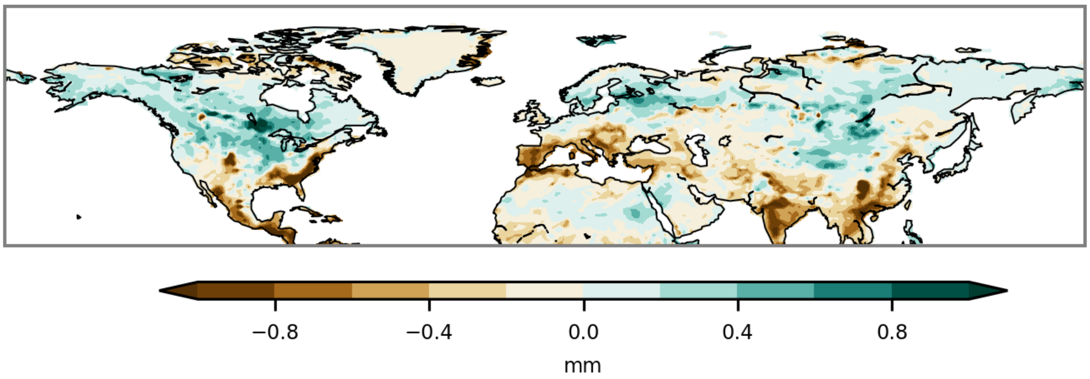

Figure 5. Mean soil moisture anomaly with respect to 1000-1849 AD for the period 1901 - 2000 AD in the CESM.

We found that when droughts occur over the region of study in the past (850 - 1849 AD) in the model, the percentage of area with the soil moisture anomaly below 0 mm over our region of study is more than 50%, in average 75.06%, covering a large part of the Mediterranean region. Thus, the droughts in our analysis can be clearly seen as pan-Mediterranean droughts (Figure 6).

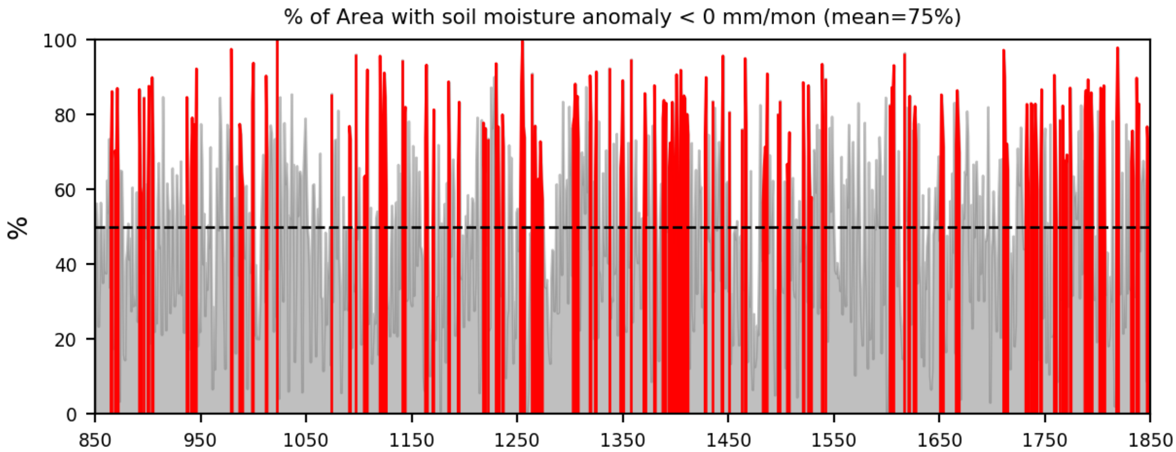

Figure 6. Percentage of area in the Mediterranean region (rectangle in the figure 2) with the soil moisture anomaly below 0 mm from 850 – 1849 AD. Drought periods are shaded in red. The mean coverage of the region with negative soil moisture anomaly during droughts is 75.06%.

In addition, the Empirical Orthogonal Function analysis on the monthly precipitation indicates that, the chosen region shares a similar variability in the first EOF (13.28%) and second EOF (11.01%) in the observation (Figure 7). Also, this region shares the overall similar influence of NAO, which is an important driver for precipitation over the region (Martin et al. 2004).

We will elaborate better our motivation and choice of the region as we did here in the revised manuscript.

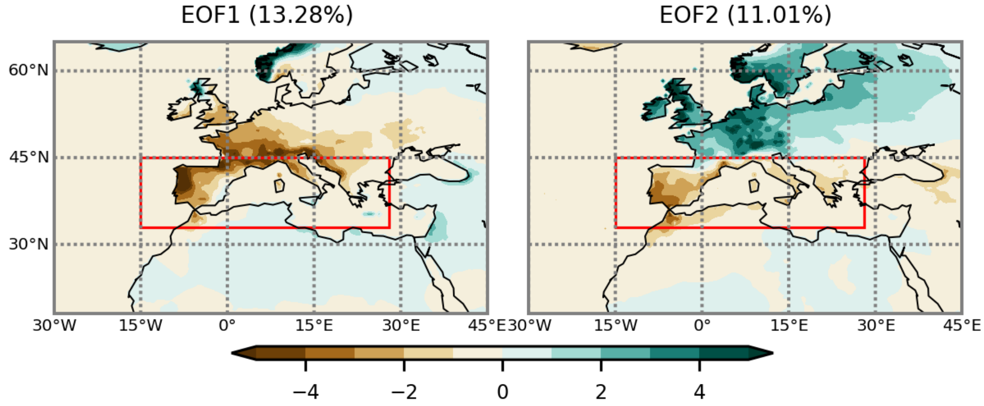

Figure 7. Variance explained by the first two EOF in the observational precipitation.

Quantification of droughts events over the Mediterranean: Selection of a drought index.

9. A general issue investigating droughts over semi-arid regions like the European Mediterranean area with a pronounced annual cycle relates to the high (mulit-annual) temporal and spatial variability of the availability of water resources. Therefore, drought or periods with scarcity of water are an intrinsic part of the climatic conditions over those regions. Likewise, this also applies for the opposite case with strong torrential rains leading to flooding and disastrous destructions over the respective areas. I think those points should be mentioned here or earlier in the introduction to put the drought terminology into context, underpinning that dry conditions are an integral part of the climate over those areas. Other, non climatic factors, for instance related to geology in terms of limestone with a high potential to effectively store water during winter and release it during summer could be mentioned. In addition, human impacts with steadily increasing demand for water resources play an important role interfering with the direct climatic driven changes in drought dynamics.

We will add some sentences about the complexity of studying droughts over a dry region with pronounced hydrological cycles with strong variability, and the steadily increasing human impacts on the drought in the last century in the introduction of the revised manuscript.

Dynamics of multi-year droughts

10. I liked this part because it links the (regional) drought dynamics over the Mediterranean area with large scale modes of atmospheric (NAO) and atmosphere-ocean (ENSO) variability. However, especially in terms of ENSO I suggest to use a more objective test metric, because in my opinion the numbers are not really convincing for a robust inference which state of the ENSO precedes Mediterranean droughts. The authors should motivate their definition of a positive NAO / ENSO state that should considerable deviate from mean or neutral conditions. For instance, the threshold values of the SST anomaly over the tropical Pacific is set to ±0.5 K. Authors might use a metric based on percentiles of the according index-PDFs and investigate *the situation separated into full period and drought prone years to test the robustness of the according conclusion. This could eventually also allow a quantitative differentiation in moderate/strong events for NAO and ENSO and their impacts on Euro-Mediterranean droughts.*

We agree with the referee that we should use more objective metric to discern different phase of ENSO and NAO. Thus, we changed our method to discern negative and positive phase of ENSO and NAO: instead of using the absolute values of -0.5 and 0.5, we set the threshold based on the percentiles of the distribution during the non-drought periods: 25 percentile for negative phase and 75 percentile for positive phase, both for ENSO and NAO. You can see the modified plot in the figure 8 below. From this analysis, we found that there is a clear preference to negative/positive ENSO/NAO during Mediterranean droughts. However, no connection between the frequency of droughts and intensities of ENSO and NAO are found, as you can also observe in the figure 8. We will update the text in the result section of the revised manuscript according to this analysis. Still, our conclusion that the roles of ENSO and NAO vary at different stages of droughts remain unchanged.

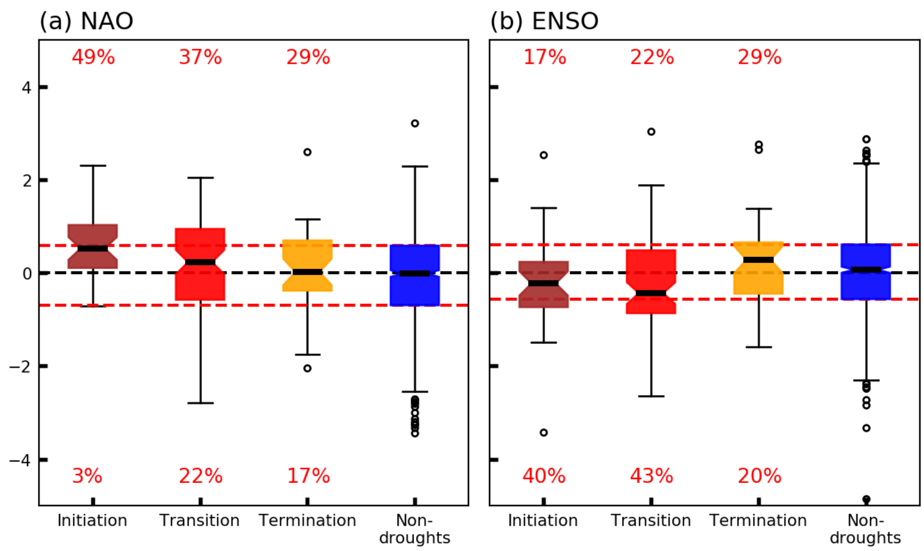

Figure 8. Distribution of (left) NAO and (right) ENSO during the initiation, transition and termination stages of multi-year Mediterranean droughts and during the non-drought period. Dashed red lines indicate the 25 and 75 percentiles of the distribution during the non-drought periods, and the numbers on the plot show the percentages of events that are under or over these thresholds in each stage of droughts.

Historical and Future conditions on droughts: 1850 to 2099 AD

11. The authors use a very strong GHG scenario – I wonder how results change in simulations with less pronounced increase in GHG. Moreover, how can changes in vegetation cover and/or human water consumption play into drought dynamics purely based on climatic considerations?

We chose the RCP8.5 scenario as we could see more pronounced changes in the climate compared to the past condition. Additionally, this scenario is a part of the continuous run of this CESM simulation from 850 to 2099 AD (Lehner et al., 2015). Regarding the impacts of different GHG scenarios on the Mediterranean climate and droughts, among many others, Lehner et al. (2017) performed analysis to assess drought risks using the same model. They show that the drought risk over the Mediterranean increases in all GHG scenarios. We cited this paper in our introduction.
The roles of vegetations and vegetation cover, and anthropogenic influences on droughts are highly discussed topics in drought studies. We will elaborate some discussion on this in our revised manuscript.

12. In this context it is again important to ask about the consequences if the main controlling factors (e.g. atmospheric circulation, Trigo et al., (1999)) are not realistically simulated. Are the models really able to realistically mimic the (change) of atmospheric circulation over the past and the following years? This is especially important, given the fact that Mediterranean precipitation is characterized by very short-lived and very intense precipitation events initiated by meso-scale circulation patterns (e.g. Genoa low) that might not be represented well enough in those models.

We performed some observation-model comparison and we plan to add a new section on validation in the revised manuscript. Refer to our responses #4 and #7.
Here, we used the monthly resolved variables, thus, the short-lived meso- and/or synoptic scale events are only included as averages in our analysis. In another study in our research group, we use this simulation to investigate so-called Vb cyclones, which move from the area of Genoa towards Central Europe. This study shows that the model is able to simulate the cyclones that lead to heavy precipitation, though it is necessary to dynamically downscale these features to assess their impact in Mountain regions like the Alps (Messmer et al. 2020). We will mention this study in the revised manuscript.

Conclusions

13. The conclusions are a good summary – what I think is important to add one or two chapters with more critical comments and insights on the limitations and uncertainties involved in the study (e.g. only single model used, validation of atmospheric circulation dynamics, importance of non-climatic events for drought dynamics), and also the implications in the context of model-proxy comparisons.

Thanks for your suggestion. We will include more discussion on the limitations and uncertainties involved in our study, implications and possible future studies.

Minor comments:

14. Figure caption: If possible, please add below the technical description of the Figure a short sentence what are the main contents of the Figures for a better overview for the reader on the main conclusion of the respective plot(s).

We will update the figure captions accordingly.

15. Figure 1: Please include latitudes and longitudes in the figure – why is the eastern Mediterranean region not completely included into the analysis?

We will update the figure with the latitude and longitude. For the choice of the region, please refer to our response #8.

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