Dr. Hugues Goosse, editor
Climate of the Past

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25th November

Dear editor Dr. Hugues Goosse,

We would like to thank you for the opportunity to resubmit our revised manuscript. We would also like to thank again the reviewers for their constructive feedbacks and insightful comments that helped us to improve our presentation. We have addressed the reviewers' comments and you can find our point-to-point responses to each of the reviewers below in order (Response to the referee 1 and 2) and the mark-up revised manuscript at the end of this file.

Sincerely,

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<u>Response to the referee 1</u>

We would like to thank again 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. As the model related limitations and uncertainties are quite ample in topics (the modes of variability, mid-latitude dynamics and precipitation, comparison to proxies and uncertainties in future scenario), we provided more extensive discussion on these issues in the conclusion (Sect. 4) and added a new section that validates the model (Sect. 3.1.) in the 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, thus, we included a more detailed description on the mean climate of the Mediterranean in the introduction (Sect. 1. lines 37 – 56) mentioning about the spatial differences between west and east side during the winter and influence of large scale circulation patterns in different regions of Mediterranean:

Sect. 1, lines 37 – 46) "Overall, the region shows mild and wet winters, and hot and dry summers (Lionello et al., 2006). The variability of precipitation is not uniform across the entire Mediterranean area. The western and eastern regions show different precipitation regimes during the winter. A regional mode of circulation that explains a large percentage of the variability in winter is characterized by opposite pressure and precipitation patterns between the west-central and eastern Mediterranean regions, known as Mediterranean Oscillation (Dunkeloh and Jacobeit, 2003). Besides, the regional precipitation is strongly influenced by the mid-latitude storm tracks and cyclones, which become stronger during

the winter (Lionello et al., 2016, Raible et al., 2007; Raible et al., 2010; Ulbrich et al., 2006), regional cyclones (Alpert et al., 1990), and large-scale modes of variability, such as the North Atlantic Oscillation (NAO), East Atlantic - West Russian pattern (EA - WR) and El Niño-Southern Oscillation (ENSO) (Lionello et al., 2006; Raible, 2007).”

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).

As we said in the first response phase, we provided more explanations on the reason and benefit of using this single model in the introduction (Sect. 1.) and conclusion (Sect. 4.).

Sect. 1. lines 123 – 129) “The spatial resolution of the model is a clear advantage for our study on a relatively small confined area. The precipitation of the region is strongly influenced by extratropical cyclones and in general, GCMs have difficulties in reproducing in full degree the dynamics and precipitation associated with these meso-scale phenomena (Raible et al. 2007; Watterson et al., 2006). Nevertheless, these atmospheric dynamics and precipitation are better represented in GCMs with finer spatial resolution (Champion et al., 2011; Watterson et al., 2006). Hence, using a model that provides a seamless simulation for period 850 – 2099 AD guarantees an improved representation of precipitation related processes, thus, drought associated mechanisms over the region.”

Sect. 4. lines 561 – 568) “Fifthly, it is important to mention that our analysis is based on a single model output and this raises questions related to single model studies, such as boundary condition problems and model-dependent biases and physics (PAGES Hydro2kConsortium, 2017). Nevertheless, for a small confined area that surrounds a large body of water mass, the Mediterranean Sea, and the land coverage is limited, we found the necessity to use a simulation with a finer resolution to represent the regional climate better. In the end, our study provides a useful understanding on the long-term variability and mechanisms of Mediterranean droughts by analyzing the entire last millennium. We addressed the influences of external and internal variability on Mediterranean droughts and distinctly different roles of the large-scale modes of variability and regional circulation during the different stages of multi-year droughts.”

Additionally, in order to assess more clearly the role of volcanic forcing on droughts, the wavelength coherence analysis is included in the result section (Sect. 3.2) in lines 333 - 341 and figure 6 in the revised manuscript.

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 provide here the same response as the first response phase: 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-a below. Thus, the model mimics reasonably well the atmospheric dynamics associated with droughts.

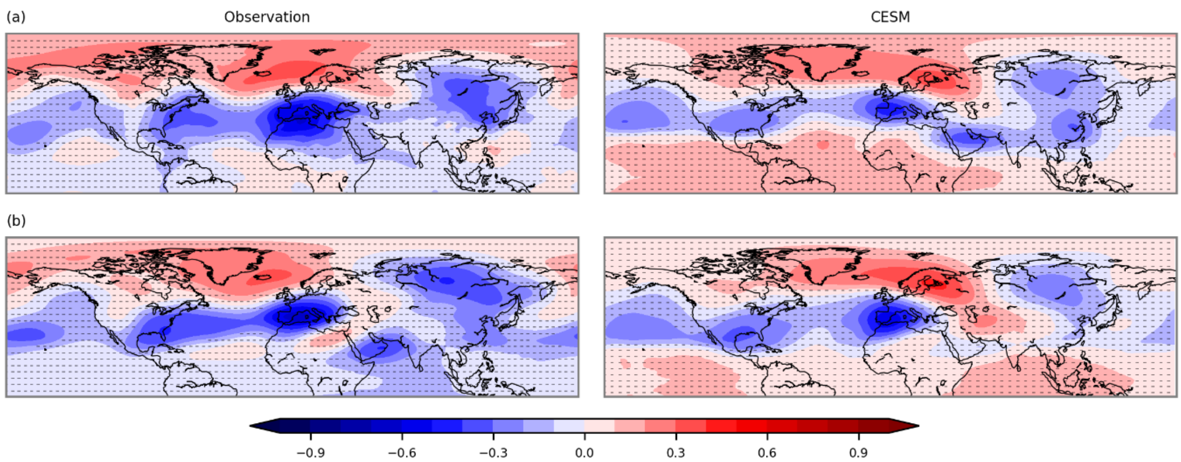

Figure-a. Fields of correlation between the monthly scPDSI and geopential height at (a-above) 850 hPa and (b-below) 500 hPa for the period of 1901-2000 in (left) the NOAA 21th century reanalysis V3 data and (right) CESM. Regions where the correlations are not statistically significant at 5% level by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

In the revised manuscript, we only included the correlation at 850 hPa (figure 4 and Sect. 3.1. in lines 269 - 278 in the revised manuscript), as the statement derived from these maps of different heights are the same.
Note also that changing the vertical resolution is not an easy task, as then the model parameterizations need to be partly retuned. So, we follow the NCAR suggestions and used a version which was officially released by the NCAR (i.e. a version which is rigorously tested).

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?

We provide here the same response as the first response phase: 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 included in the conclusion (Sect. 4.) a paragraph discussing on complex interaction among vegetation, soil and atmosphere. Instead of focusing only on Mediterranean vegetations, we elaborated this part more in general way, as the roles of plants and their interaction with climate in extreme hydrological conditions are still not fully understood.

Sect. 4. lines 569 – 579) "Lastly, we emphasize again the importance of assessing different drought indices in the paleoclimate context, also in the present and future warming scenario. Assessing different drought metrics is important for drought studies, as the most commonly used drought indices are based on water balance only from the atmospheric moisture supply and demand, and they tend to magnify drought risks in the future warming scenario (Berg and Sheffield, 2018; Mukherjee et al., 2018; Swann et al., 2016). For a more comprehensive picture, droughts need be quantified with indices that can also reflect water stress on plants and ecosystem, and complex interactions among soil, atmosphere and vegetation. We used the upper 10 cm soil moisture anomaly to partially tackle this issue and derived spatial patterns associated with Mediterranean droughts based on this index. Still, the upper 10 cm soil moisture do not fully involve a complex interaction in the soil and atmosphere occurring during droughts. As vegetation is known to have more complex responses to the changing climate and droughts (Swann 2018; Swann et al., 2016), the role of vegetation in extreme hydrological events can provide a more comprehensive view on drought mechanisms."

Regarding the description on the soil model, 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 did not mention more in detail about each components model, including the soil model, and the readers can directly refer to Lehner et al. (2015), and related literature.

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).*

As we said in the first response phase, we included a new section that compare the observation, OWDA and model: "Sect 3.1. Validation of CESM: comparison among observation, proxy and model (1901 – 2000 AD).". In the section, we performed the comparison of mean seasonal spatial and annual cycle of precipitation between the observation and model over the region of study in the validation section.

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.

As we said in the first response phase, we elaborated better our motivation to focus on this specific averaged region in the introduction (Sect. 1.), and the reason for selecting the extent of the region in the model description and methods section (Sect. 2.)

Sect. 1. lines 116 - 121) "We choose this specific area, as this region has been affected by recent large scale droughts (Garcia et al., 2019; Spinoni et al., 2017), which can be seen as pan-west-central Mediterranean droughts. Moreover, the region shows coherent desiccation in the future scenario (Dubrovsky et al., 2014). From now on, for simplicity, we refer to the west-central Mediterranean region in our study simply as the Mediterranean region. We focus on understanding the dynamics that induce past persistent pan-regional multi-year droughts, and whether the dynamics that induce droughts in the past will change in the historical and future periods with the anthropogenic increase in GHG."

Sect. 2.2. lines. 153 – 157) "The focus area of the study is the western and central Mediterranean region confined to 15°- 28°E and 33°- 45°N (Fig. 01). The extent of the region is selected based on Empirical Orthogonal Function analysis on the monthly precipitation from the observation (gridded station precipitation from U.Delaware v5.01; Willmott and Matsuura, 2001). The region shares overall a similar variability in the first EOF (13.28%) and second EOF (11.01%) (Fig. 1), in which this similarity also can be attributed to the influence of North Atlantic Oscillation in precipitation over the region (Dunkeloh and Jacobeit, 2003)"

Sect 2.3. lines 217 – 221) "Lastly, in order to define droughts with pan-west-central Mediterranean characteristic, we select only drought events where more than 70% of the region of study is occupied by negative indices (Fig. 1). Though, for multi-year droughts, we allow that this condition does not need to be fulfilled for the initiation and termination years but only for the transition years: a drought can start weak and with a more local characteristic, then expand to a larger proportion of the Mediterranean, and weaken again in the termination years."

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 (multi-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 agree with the referee that droughts are intrinsic part of the climate over the regions. The tree-ring-based reconstruction support this fact too, by showing a drought variability of multidecadal frequency over the western Mediterranean region during the last millennium (Cook et al. 2016a). We included this point and the corresponding literature in the introduction (Sect. 1. lines 73 - 78). Regarding torrential rainfall and flooding, as our focus is more on droughts with longer time scales (year to multiyear), we assume that short-lived events are already included as averages in drought calculations. Instead, the importance of small spatial scale (meso-scale) events associated to mid-latitude storm tracks on droughts was mentioned in introduction (Sect. 1, lines 124 – 127). The non-climatic factor, for example, related to anthropogenic influences was added in the conclusion (Sect. 4. lines 580 – 581).

Sect. 1. lines 73 - 78) "Using the summer self-calibrated Palmer Drought Severity Index (scPDSI) based on tree ring reconstructions (also known as the Old World Drought Atlas; OWDA; Cook et al., 2015), Cook et al. (2016) showed that there have been several dry periods during the last 900 years over the region, some with persistent pan-Mediterranean characteristics. The region has experienced drought variability with frequencies of not only interannual, but multidecadal timescales."

Sect. 1. lines 124 – 127) "The precipitation of the region is strongly influenced by extratropical cyclones and in general, GCMs have difficulties in reproducing in full degree the dynamics and precipitation associated with these meso-scale phenomena (Raible et al, 2007; Watterson, 2006). Nevertheless, these atmospheric dynamics and precipitation are

better represented in GCMs with finer spatial resolution (Champion et al., 2011; Watterson, 2006)."

Sect. 4. lines. 580 – 581) "[…] human impacts can modify the natural mechanisms and propagation of droughts (van Loon et al., 2016) increasing droughts risks and water shortage issues over the region."

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, thus, this part is updated because of the modified thresholds to discern positive/negative NAO and ENSO: The phases of NAO and ENSO are defined with respect to the non-drought periods: the values below 25 (above 75) percentile of NAO and ENSO during the non-droughts periods are considered as negative (positive) phases of NAO and ENSO respectively. We updated the texts (Sect. 3.4. lines 407 - 433) and respective plot (figure 9 in the manuscript or at the end of the responses) according to the modified values. As the text is long, we do not include here the modified paragraph.

We set the extreme positive NAO as the 95 percentiles and extreme negative ENSO as the 5 percentiles. We found that strong extreme positive NAO are more frequent during droughts, mainly during the initiation years. However, for extreme negative ENSO, the changes in frequencies in different stages of droughts are not observed (Sect. 3.4. lines 417 – 421).

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 mentioned briefly a complex interaction between plants and atmosphere (same as the response #6) and also the anthropogenic influences on droughts with the respective paper in the conclusion (Sect. 4. lines. 580 - 581, same as the response #9).

Regarding the different GHG scenarios, we provide the same response as the first response phase: 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 the introduction (Sect. 1.).

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 addressed this issue regarding the atmospheric circulation associated with Mediterranean droughts in the response #7.
We observed that some differences exist between the observation and model, mainly in terms of mean scPDSI, and we attribute this difference to the model ability to perform dynamics and precipitation associated with meso-scale phenomena. We introduced this issue in the introduction (Sect. 1. lines 123 – 129, also see our response #3) and discussed in detail in the result section (Sect. 3.1. lines 259 – 261).

Sect. 3.1. lines 259 - 261) "One of the reason for the difference in the overall scPDSI between the model and observation is potentially related to the model performance on meso-scale phenomena, which play an important role for the regional precipitation during the wet season (Alpert et al., 1990; Ulbrich et al., 2009; Champion et al, 2007; Watterson, 2006)."

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.

We included these points that the referee mentions in the conclusion (Sect. 4.):

- Limitations of the single model (lines 561 – 564): "[…] it is important to mention that our analysis is based on a single model output and this raises questions related to single model

studies, such as boundary condition problems and model-dependent biases and physics (PAGES Hydro2k Consortium, 2017). Nevertheless, for a small confined area that surrounds a large body of water mass, the Mediterranean Sea, and the land coverage is limited, we found the necessity to use a simulation with a finer resolution to represent the regional climate better."

- Limitations of the model performance (lines 545 – 552): "The model inherent biases in representing ENSO and NAO (Bellenger et al., 2014; Fasullo et al., 2020) can have some implications in our results on the frequencies of ENSO and NAO at different stages of droughts. The model may produce too frequent and strong La Niña conditions and positive NAO during droughts due to its amplified, decadal for ENSO and seasonal for NAO, variability. Moreover, due to the uncertainty associated with the changes in these modes in the future scenario, caution is required when interpreting the connection between droughts and modes of variability in the future warming scenario. Nonetheless, this problem does not affect our conclusion: the roles of ENSO and NAO become weaker with the longevity of droughts, while the regional circulation and feedback become more dominant at maintaining the persistence of droughts, which is also found in the future warming scenario."

- Anthropogenic influence on droughts (lines 580 – 581): "[…] human impacts can modify the natural mechanisms and propagation of droughts (van Loon et al., 2016) increasing droughts risks and water shortage issues over the region."

The validation, thus, the comparison among observation, proxy and model is also extensively discussed in the newly added validation section (Sect. 3.1).

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 updated the captions.

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

The respective figure is updated. Concerning the choice of the region, we addressed this issue in the response #8.

Figures

For the comment #10:

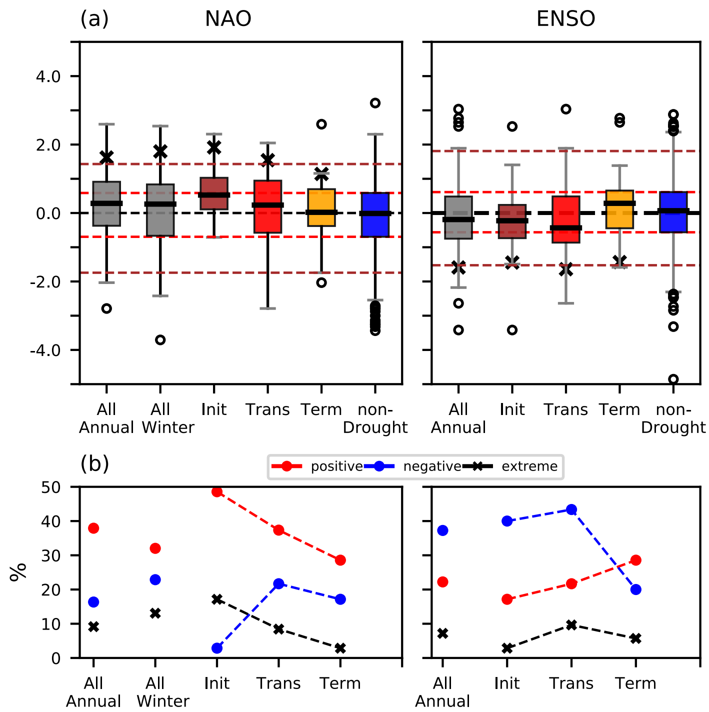

Fig 9. (a) Box plots of NAO and ENSO during multi-year Mediterranean droughts. The black crosses indicate 95 percentile value for NAO, and 5 percentile value for ENSO. Dashed red lines indicate the 25 and 75 percentiles of non-drought periods, which are the thresholds to discern negative/positive states of NAO and ENSO. Dashed brown lines indicate 5 and 95 percentile of non-drought periods. (b) Frequencies of occurrences of positive and negative states of NAO (left) and ENSO (right) for annual and winter total, and each stage of droughts. Black crosses indicate the frequencies of occurrence of extreme positive NAO and extreme negative ENSO.

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Response to the referee 2

We would like to thank again 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:

This is interesting work with valuable implications. However, in my opinion the authors have based their analysis and conclusions on the ability of the CESM to simulate pre-instrumental drought occurrence/frequency (and do not sufficiently prove that the CESM can do this) and draw several conclusions that appear to be based on visual comparisons of data in figures that I found hard to believe (and in some cases appeared simply incorrect) without further quantitative support.

We updated the figures in order to represent better our result and added the statistical tests where are necessary. We also included more details on the ability of CESM to simulate the present and past climates, and the limitations associated with the model.

Main concerns:

1. CESM simulation data are not easily accessible without contacting the researcher who ran the simulations. (As noted below, I wanted to try replicating the authors' analysis by comparing the CESM data to the OWDA data, but the CESM data are not publicly available.)

We provide some of the data used for our analysis (precipitation, temperature, geopotential heights) on anonymous FTP server:
https://fileserver.climate.unibe.ch/public/woonkim/

2. I wonder if perhaps some parts of the Mediterranean region experience drought at different times/magnitudes in the instrumental data (also in the CESM data)? Why did the authors choose this region?
Please provide more evidence that drought/precipitation in the region varies coherently (e.g., suggest showing more information in Figure 1 other than a map and a box).

As we said in the first response phase, we elaborated better our motivation to focus on this specific averaged region in the introduction (Sect. 1.), and the reason for selecting the extent of the region in the model description and methods section (Sect. 2.)

Sect. 1. lines 116 - 121) "We choose this specific area, as this region has been affected by recent large scale droughts (Garcia et al., 2019; Spinoni et al., 2017), which can be seen as pan-west-central Mediterranean droughts. Moreover, the region shows coherent desiccation in the future scenario (Dubrovsky et al., 2014). From now on, for simplicity, we refer to the west-central Mediterranean region in our study simply as the Mediterranean

region. We focus on understanding the dynamics that induce past persistent pan-regional multi-year droughts, and whether the dynamics that induce droughts in the past will change in the historical and future periods with the anthropogenic increase in GHG."

Sect. 2.2. lines. 153 – 157) "The focus area of the study is the western and central Mediterranean region confined to 15°- 28°E and 33°- 45°N (Fig. 01). The extent of the region is selected based on Empirical Orthogonal Function analysis on the monthly precipitation from the observation (gridded station precipitation from U.Delaware v5.01; Willmott and Matsuura, 2001). The region shares overall a similar variability in the first EOF (13.28%) and second EOF (11.01%) (Fig. 1), in which this similarity also can be attributed to the influence of North Atlantic Oscillation in precipitation over the region (Dunkeloh and Jacobeit, 2003)"

Sect 2.3. lines 217 – 221) "Lastly, in order to define droughts with pan-west-central Mediterranean characteristic, we select only drought events where more than 70% of the region of study is occupied by negative indices (Fig. 1). Though, for multi-year droughts, we allow that this condition does not need to be fulfilled for the initiation and termination years but only for the transition years: a drought can start weak and with a more local characteristic, then expand to a larger proportion of the Mediterranean, and weaken again in the termination years."

3. The authors gloss over a critical comparison of the paleo to the model data (lines 179-182) - they conclude the background drought statistics (occurrence/frequency) in the CESM are similar to the OWDA. Yet, an examination of figure 1c suggests to me that the drought occurrence in the model and paleo data are quite dissimilar- the bulk of droughts in the CESM are centered around 6-10 years in length, and in the OWDA the distribution is centered around 1-4 year drought lengths. This discrepancy is quite striking to me, and I was surprised when the authors claim these distributions are comparable.

As we responded in the first response phase, we agree with the referee that the absolute numbers of drought occurrence are dissimilar. We modified the respective texts and updated the plots in order to visualize better our results on the Sect. 3.2.

Sect 3.2. lines 299 - 306) "[…] the discrepancy between CESM and OWDA is clear, with OWDA presenting the mean duration of 5.38 years and CESM with 7.89 years. These means are statistically different to each other (p-value from Mann-Whitney U test of 0.003). This seems to be consistent with the result in the previous section (Sect. 3.1.) that shows that OWDA has droughts with shorter durations compared to the present-day observation and CESM over the Mediterranean region. Thus, this characteristic is still present during the entire last millennium. The variability of droughts over time in OWDA and CESM is also different to each other (Fig. 5.c), without a specific common period of increase in droughts. This gives us a first hint that the occurrence of droughts over the region are not mainly driven by the external natural forcings. Both time series present a common period of decrease in droughts around 1600 AD."

4. If the authors want to make this claim, I suggest using some sort of metric (e.g., something like a Mann-Whitney or Wilcoxon rank-sum test or some sort of distribution comparison metric) to show these two drought occurrence distributions are statistically similar. Even a *report of the median, mean, and range would be more helpful than the visual comparison. I also suggest the authors use other metrics such as showing average drought occurrence per century (e.g., see Figure 3 in Parsons et al., 2018, J. Clim.).*

We provided a new representation of the duration of droughts through a box plot that visualizes duration, number of droughts, means and medians of duration (see Figure 5 in the revised manuscript or at the end of the responses). We also performed Mann-Whitney U test between the summer CESM scPDSI and OWDA, which shows a p-value of 0.003. Also refer to our response #3.

5. Other suggestions include comparing the power spectra (PSD) of the OWDA and CESM PDSI. For example, I made Southern Mediterranean regional mean time series of PDSI from the OWDA and from the CESM1 LME run2 (this is an admittedly lower resolution version of CESM1; Otto-Bliesner et al., 2015; but the background drought statistics in the CESM LME and higher resolution versions of CESM are quite similar, at least in SW North America -e.g., Parsons and Coats, 2019, JGRA) over the 850- 1849 CE time period. I found the power spectra show quite dissimilar behavior for the CESM and OWDA PDSI variables, with varying discrepancies as varying frequencies depending on how I standardize them.

Refer to our response #3 and #4. We performed Mann Whitney U test and found a statistical dissimilarity between both time series and discussed about this point in the Sect. 3.2. in lines 299 - 306.

6. Comparison of CESM with instrumental/reanalysis data: the authors missed an opportunity to validate the performance of the CESM in the historical/instrumental era against instrumental/reanalysis data. The authors show (e.g., Figures 3,4,6,7) background geopotential height, SST, etc. anomaly patterns associated with drought, but they have not used instrumental-based data to show the model can accurately simulate the observed climate, and I remain unconvinced the background drought statistics are similar to the OWDA (see Main Concern (3) above).

As we said in the first response phase, we included a new section that compare the observation, OWDA and model: "Sect 3.1. Validation of CESM: comparison among observation, proxy and model (1901 – 2000 AD)."

7. Authors could compare patterns associated with drought (using a metric such as 2D pattern correlation) in the model to observed/reanalysis geopotential height (ERA5 or 20th Century Reanalysis) and SST (NOAA ERSSTv5, HadSST, etc.), as well as drought occurrence in the model to instrumental data (GPCCv2018 precipitation, Dai PDSI, CRU precipitation).Example of how other authors have made these comparisons among model and instrumental/ reanalysis data: Figure 2 in Parsons et al., 2018, J Clim., Figure 2 in Coats et al. 2013, GRL, Figure 2 in Stevenson et al., 2015, J Clim.)

The pattern correlation between the scPDSI and SST, and the scPDSI and geopotential height at 850 hPa in the CESM and reanalysis - observational data for the period of 1901-2000 are added in the validation section (Sect. 3.1.) in lines 269 – 278. As the text is long,

we do not include the paragraph here. You can find the corresponding correlation maps in the figure 4 in the revised manuscript or at the end of the responses.

8. The authors do not address several of the known shortcomings in the CESM model (e.g., frequency/strength of ENSO events; Parsons et al., 2017, J. Clim, Figure 6; Bellenger et al., Clim. Dyn, 2015 for a comparison of ENSO characteristics among models and instrumental data) and what the implications of these shortcomings could be for their study, especially because the authors make claims about likelihood of ENSO events before/during/after droughts. I suggest the authors consider the findings of Ault et al. (2014, J Clim), who show that the background power spectra/statistical characteristics of drought/precipitation (e.g., white noise, power law, etc.) are critical for drought magnitude and duration, and many CMIP5-class models do not show the same background variability as instrumental/ paleo data in many regions.

We included a discussion about the limitation of model regarding ENSO and NAO and possible implications of it in our result in the result section (Sect. 3.1.) and conclusion (Sect. 4).

Sect 3.1. lines 279 – 284) "It is known that the variability of ENSO is too strongly represented in CESM (Parsons et al., 2017; Stevenson et al., 2018). Nevertheless, the model is able to capture relatively well the hydroclimate condition associated with the ENSO teleconnection (Stevenson et al., 2018). In case of NAO, the seasonal variability of NAO seems to be amplified in many CMIP models (Fasullo et al., 2020). The CESM, however, resembles the present-day NAO pattern well and the spatial precipitation and temperature associated with this mode of variability in Europe (Deser et al., 2017). These inherent biases with respect to modes of variability (in particular for ENSO) can partially explain the differences we observe here between the model and observation."

Sect. 4. lines 545 – 552) "The model inherent biases in representing ENSO and NAO (Bellenger et al., 2014; Fasullo et al., 2020) can have some implications in our results on the frequencies of ENSO and NAO at different stages of droughts. The model may produce too frequent and strong La Niña conditions and positive NAO during droughts due to its amplified, decadal for ENSO and seasonal for NAO, variability. Moreover, due to the uncertainty associated with the changes in these modes in the future scenario, caution is required when interpreting the connection between droughts and modes of variability in the future warming scenario. Nonetheless, this problem does not affect our conclusion: the roles of ENSO and NAO become weaker with the longevity of droughts, while the regional circulation and feedback become more dominant at maintaining the persistence of droughts, which is also found in the future warming scenario."

9. Especially when future warming is considered, it is important to focus on metrics of drought that don't just focus on 'atmospheric centric' supply and demand, especially if ecosystem/water resource drought impacts are important. See Swann et al., 2016, PNAS, and Swann (2018) who note that drought severity/impacts in a warming climate can be grossly overestimated by use of variables/metrics such as PDSI.

We included a paragraph discussing about the problems associated with atmospheric centric drought indices in the result section (Sect. 3.2.) and conclusion (Sect. 4).

Sect. 3. lines 347 – 352) "Moreover, using the SOIL helps us to avoid the overestimation of drought risk and severity that occurs with many offline drought indices. The offline estimation of droughts by some common drought metrics, such as scPDSI, tends to magnify the impact of increase in temperature, therefore in potential evapotranspiration, on drought-associated atmosphere - surface feedback (Seneviratne et al., 2010). Hence, in the warming scenario, the indices that are constructed based on atmospheric supply and demand of moisture, such as scPDSI and SPEI, strongly overestimate future drought risks (Berg and Sheffield, 2018; Cook et al., 2018; Swann et al., 2016)."

Sect. 4. lines 573 – 579) "For a more comprehensive picture, droughts need be quantified with indices that can also reflect water stress on plants and ecosystem, and complex interactions among soil, atmosphere and vegetation. We used the upper 10 cm soil moisture anomaly to partially tackle this issue and derived spatial patterns associated with Mediterranean droughts based on this index. Still, the upper 10 cm soil moisture do not fully involve a complex interaction in the soil and atmosphere occurring during droughts. As vegetation is known to have more complex responses to the changing climate and droughts (Swann et al., 2016), the role of vegetation in extreme hydrological events can provide a more comprehensive view on drought mechanisms."

10. I appreciate that the authors included 10cm soil moisture, but given that surface soil water content can basically just follow precipitation variability in many regions, and thus, not really reflect full depth soil moisture trends (e.g., Berg et al., 2016), I think it would be helpful for the authors to show that they are analyzing variables actually relevant for plants/ecosystems/water resources in a warming climate, and not just supply/ demand from the atmosphere. At least a discussion of some of these points could really strengthen the paper.

We included a discussion about the drought index related issues and possible role of vegetation (and its interaction with soil and atmosphere) in the conclusion (Sect. 4) in lines 569 – 579. Also refer to our response #9.

"Lastly, we emphasize again the importance of assessing different drought indices in the paleoclimate context, also in the present and future warming scenario. Assessing different drought metrics is important for drought studies, as the most commonly used drought indices are based on water balance only from the atmospheric moisture supply and demand, and they tend to magnify drought risks in the future warming scenario (Berg and Sheffield, 2018; Mukherjee et al., 2018; Swann et al., 2016). For a more comprehensive picture, droughts need be quantified with indices that can also reflect water stress on plants and ecosystem, and complex interactions among soil, atmosphere and vegetation. We used the upper 10 cm soil moisture anomaly to partially tackle this issue and derived spatial patterns associated with Mediterranean droughts based on this index. Still, the upper 10 cm soil moisture do not fully involve a complex interaction in the soil and atmosphere occurring during droughts. As vegetation is known to have more complex responses to the changing climate and droughts (Swann, 2018; Swann et al., 2016), the role of vegetation in extreme hydrological events can provide a more comprehensive view on drought mechanisms."

Specific comments:

11. Lines 13-14: the authors just list one or two types of drought (meteorological), but what about hydrological, agricultural/ecosystem, socioeconomic types of drought?

As we responded in the first phase, here, we mostly used the drought metrics that reflect the meteorological (SPI), and agricultural (scPSDI, SPEI, SOIL) droughts. Though, it is important to mention that when the time scales of droughts become longer (like 1 year as our study), the differentiation among types of droughts becomes more difficult. We included more explanation on different types of droughts in the introduction of the revised manuscript.

Sect. 1. lines 18 – 24) "[…] it can be classified in four types: meteorological drought, associated with the decrease in precipitation; agricultural drought, associated with the depletion of soil moisture and impacts on crops and plants; hydrological drought, characterized by the depletion of streamflow and water reservoirs, and lastly socio-economic drought, that occurs when the other types of droughts cause impacts on society, in a way that the water supply cannot meet the demand from society (Mishra and Singh, 2010). If a drought lasts for a longer time period, meteorological drought is transformed to other kind of droughts, agricultural and/or hydrological, and different types of droughts become interconnected to each other (Wang et al., 2016; Zhu et al., 2019)."

12. Line 22: 'climate hot-spot'- please cite a paper that shows this
Line 23: 'increase in drought episodes' – again, please cite a paper supporting this
Lines 45-46: 'attributed to the increase in the atmospheric greenhouse gases (GHG) concentration, which causes . . . decrease in precipitation over the region' - citation?
Line 52: 'unprecedent intense drought projections' – citation?

We updated and corrected the citations.

13. Lines 63-64: The separation of ocean-atmosphere conditions during various drought stages has been done before- nice to acknowledge previous work (e.g., Parsons and Coats, 2019; Namias, 1960).

We included Parsons and Coats (2019) and Namias (1960) in the introduction (Sect. 1.), lines 85 – 91.

14. Lines 76-77: 'warm-dry temperature-hydroclimate co-variability at multidecadal timescales' confusing wording.

We reformulated the paragraph that includes the sentence to make the content of the paragraph clearer.

Lines 98 – 104) "[…] Ljungqvist et al. (2019) examined a long-term covariability between the summer temperature and hydroclimate during the Common Era. By comparing the instrumental records, tree ring-based reconstructions, and model simulations, they found

that a warm-dry relationship with multi-decadal variability is more dominant in the southern Europe. Though, all datasets share some common leading modes of covariability across different time frequencies, there are some discrepancies among instrumental records, proxies, and model. The proxies present a stronger positive temperature-hydroclimate relationship, while the model exhibits a stronger negative relationship than the instrumental records."

15. Line 92: 'high horizontal resolution' is subjective (and now closer to 'average resolution') in many CMIP6 models).

We removed "high" and replaced it by the resolution of the model (1.25° x 0.9°).

16. Line 102: Why not use the CESM LME (Otto-Bliesner et al., 2015)? There are more iterations, with several RCP8.5 extensions (and a much longer 1000 yr piControl run that is easier to compare w the last millennium runs given the similar length of simulations), allowing for a more complete analysis of internal variability. Is the background climate state that much better in the 1 degree vs the 2 degree version of the model? I ask because the authors explicitly state on lines 119-120 that they are interested in studying internal vs externally forced variability, and multi-model ensembles provide an ideal experimental framework for doing this.

As we said in the first response phase, we provided more explanations on the reason and benefit of using this single model in the introduction (Sect. 1.) and conclusion (Sect. 4.).

Sect. 1. lines 123 – 129) "The spatial resolution of the model is a clear advantage for our study on a relatively small confined area. The precipitation of the region is strongly influenced by extratropical cyclones and in general, GCMs have difficulties in reproducing in full degree the dynamics and precipitation associated with these meso-scale phenomena (Raible et al. 2007; Watterson, 2006). Nevertheless, these atmospheric dynamics and precipitation are better represented in GCMs with finer spatial resolution (Champion et al., 2011; Watterson, 2006). Hence, using a model that provides a seamless simulation for period 850 – 2099 AD guarantees an improved representation of precipitation related processes, thus, drought associated mechanisms over the region."

Sect. 4. lines 561 – 568) "Fifthly, it is important to mention that our analysis is based on a single model output and this raises questions related to single model studies, such as boundary condition problems and model-dependent biases and physics (PAGES Hydro2kConsortium, 2017). Nevertheless, for a small confined area that surrounds a large body of water mass, the Mediterranean Sea, and the land coverage is limited, we found the necessity to use a simulation with a finer resolution to represent the regional climate better. In the end, our study provides a useful understanding on the long-term variability and mechanisms of Mediterranean droughts by analyzing the entire last millennium. We addressed the influences of external and internal variability on Mediterranean droughts and distinctly different roles of the large-scale modes of variability and regional circulation during the different stages of multi-year droughts."

Additionally, as we mentioned in the first response phase, in order to assess more clearly the role of volcanic forcing on droughts, the wavelength coherence analysis is included in the result section (Sect. 3.2) in lines 331 - 339 and figure 6.

17. Line 107: the years 2001-2020 AD/CE are not the future

We modified the sentence as : "We use the Community Earth System model version 1.0.1 and its continuous transient simulation of 1250 years (850 - 2099 AD) where the 2005 – 2099 AD is run with the RCP 8.5 scenario, and control simulation of 400 years at perpetual 850 AD conditions (Lehner et al., 2015)" , lines 140 – 142.

18. Lines 103-112: Suggest just citing Lehner et al. for the model description

We removed the sentences about each component model, and just cited Lehner et al. (2015), in line 142.

19. Line 127: As in Main Concern (2), please show the region varies coherently in instrumental/paleo and the version of CESM used here

We addressed this issue in the response #6.

20. Lines 131-132: removing a linear trend over the 1850-2099 time period looks quite problematic to me (e.g., Figure 9)- removing a linear trend over this time period will add in non-climatic variability artifacts from the trend removal. It looks to my eye like there is a trend 1900-2000, then a separate trend 2000-2099.

We applied the detrending method to two time periods separately: the 1850-2000 and the 2001-2099. We mentioned these steps in the model description and method section (Sect 2.2), but we reformulated the respective paragraph (lines 170 – 174) to clarify the procedure.

Sect. 2.2, lines 170 – 174) "For the second period (1850 - 2099 AD), the anomalies are linearly detrended in order to examine the background mechanisms associated with dryness during this period without the anthropogenic influence on climate. This is performed by splitting the time period into two and applying the least squares method to the each of the period separately: from 1850 to 2000 and from 2001 to 2099 AD. Then, the detrended anomalies are compared against the non-detrended anomalies for the same period and also for the first period."

21. Line 149-150: linear temperature trend is removed, but then authors study the impacts of warming using this drought metric, which includes temperature. . .so have the authors removed temperature changes, then try to study the impacts of warming on drought? This reasoning doesn't make sense to me. Perhaps a more clear explanation. of trend removal would help (?).

Here, we aim to see whether during this period, there is a natural change in the mechanisms of droughts or the changes in droughts are due to the anthropogenic influences.

We reformulated the paragraph about the detrending procedure in the Sect. 2.2. (refer to our response #20) and also rearranged the sentences about this result in Sect. 3.5. in order to clarify our observation.

Sect. 3. 5. lines 505 – 509) "This result shows that the natural mechanisms associated with droughts remain the same as it is in the past period, thus, no natural changes on drought mechanisms occur for the period of 1850 – 2099 AD. This means that the intensification of Mediterranean droughts is clearly due to the anthropogenic influences: in the future scenario, the intensity of atmosphere - soil feedback is magnified, due to the increase in GP and TS, and this mechanism becomes the dominant one at controlling the desiccation over the region."

22. Lines 140-155: As in Main Concern (6): I think all of these drought metrics/variables, with the exception of upper 10cm soil moisture, do NOT reflect actual impact on plants/ecosystems in a warming climate. Also, upper soil water content can diverge from deeper soil water – authors should show that this is a useful metric here that is distinct from precipitation alone if they want to argue that their study has relevance for ecosystem impacts.

We addressed this issue in the responses #9 and #10.

23. Lines 161-164: This drought counting method appears similar to Herweijer et al. 2007; Coats et al. 2013b- did the authors come up with this metric, or can they use a similar metric to previously published work (if so, please cite) to maintain consistency across the literature?

Here, we provided same response as the first response phase: the drought counting method we used differs from the counting methods from the literature mentioned here including the one by Herweijer et al (2007). In our work, one drought cluster has to have only negative or zero anomalies with at least one year that the drought index falls below its 10 percentiles of distribution, and any wet year would stop the continuity of drought. By defining a drought cluster in this way, we make sure we only take strong events, also, assuring that a dry condition persists throughout the entire year. We explained our counting method in the 2.3 section of our manuscript.
We have already checked that the other counting methods (for example, the method by Coats et al. (2013) that a drought starts with two continuous years of negative anomalies and stops with two continuous positive anomalies) are not appropriate for our region of study, where slight dry conditions are more frequent.

24. Lines 168-170: see above note about similar methods in Parsons and Coats as well as Namias.

Refer to our response #13.

25. Lines 179-183: As in Main Concern (3): Please be more quantitative. To my eye, these distributions do not appear similar- the OWDA shows droughts that are mostly 1-4 yrs, and the CESM shows droughts centered around 8 yrs. Please use a more quantitative method to compare drought time series power spectrum and/or drought frequency in paleo and model data.

We modified the plots and performed some statistical tests. Refer to our response #3 and #4.

26. Lines 187-188: difficult to visually compare these different drought metrics in lower panels in Figure 2 because the x axis limits are different.

We modified the respective plot and texts. Refer to our response #3.

27. Lines 204-205: 'no noticeable changes in occurrence of droughts' - is this to the eye? Can you use a more quantitative method to show this (e.g., running counts of droughts in 50 yr windows or something like that)?

We agree with the referee that the text is misleading. We changed the text as "at first glance, similarly to the summertime OWDA and CESM, no noticeable coherent changes among all indices, such as a common period of increase in the occurrence of droughts over time, is noticed." in lines 329 – 331.

Also, as we said in the first response phase, we changed the plot to show the occurrence and duration of droughts to 100-yr running mean of duration of Mediterranean droughts (figure 5 in the manuscript or at the end of the responses), which can better show the point we mention.

28. Lines 205-206: 'not driven by external forcing': again, this conclusion appears to be drawn based on a visual comparison, which seems insufficient to me. Lehner et al. (2015, ESD, Figure 5) use running correlation to compare model output, which I imagine could be applied here, as could some sort of wavelet/coherence analysis between volcanic forcing time series and the OWDA and CESM data. Also, Superposed Epoch Analysis or Composite Analysis could be used with volcanic forcing time series/large eruptions. At minimum, it would be great to see a time series showing the external forcing to be able to compare to the drought time series in Figure 2.

The duration plots are updated (figure 5 in the manuscript or at the end of the responses), and we believe that this change makes it easier to visually compare the drought indices. Additionally, a wavelet analysis is performed to address more clearly the role of volcanic forcing on droughts (Sect. 3.2,lines 333 - 341 and figure 6). Also refer to the last paragraph of our response #16.

29. Line 209-210: sentence wording is confusing/complicated.

We changed the sentence as: "In the next sections, we investigate the underlying dynamics using only the SOIL as the drought indicator in order to understand the role of the internal variability in Mediterranean droughts.", lines 342 – 343.

30. Lines 211-215: So if the r value is 0.78, doesn't this imply that only 60% of variance is shared by the two time series?

We provided the same response as the first response phase: yes, in which we think it is a good percentage of variance shared by two time series.

31. Lines 218-220: 'control simulation presents 29 droughts'- this comparison with the transient simulation is non-sensical/misleading given the two simulation lengths are different. Can the authors instead present the average numbers of droughts of various lengths per century (e.g., Parsons et al., 2018; Coats et al., 2015, Figure 5). This gets around the issue of having different length time series and gives more meaningful information about drought risk standardized to a given time window (e.g., number of droughts per 100 or 500 years).

We changed these numbers by mentioning the number of events/100 years, lines 362 – 363.

32. 222-224: Is this the first time these patterns have been presented? Seems that a paper like Markonis et al. 2018 (Nature Communications) or other similar papers have previously presented similar patterns associated with hydroclimatic variability.

This is the same response as the first response phase: we mentioned in our manuscript that more similar patterns are found in Xoplaki et al.(2003), and we discussed about the similarity in detail in lines 381 - 390.

33. Lines 229-236: Similar to the point I raise in Main Concern (5)- It is well documented that this model simulates ENSO events that are too strong and too frequent (e.g., Bellenger et al., Clim. Dyn., among others)- how does that impact these results? For example, if the model simulates too strong, too regular ENSO events that unrealistically influence global climate, then is it surprising that a signal from ENSO is apparent in European drought/climate? And is this finding meaningful if it's based on model bias?

Refer to our response #8. About the response of ENSO in European climate has been addressed in some literature before (Mariotti et al., 2002; 2008; Brönnimann, 2007; Brönnimann et al., 2007), which we mentioned in the introduction of our manuscript.

34. Figure 3 caption: the caption states 'means are not statistically significant'- unclear. Please be more specific. Also please clarify if data are annual, JJA, etc. in figure caption. Additionally, the significance dots are nearly impossible to see on the dark red/blue background

We updated the captions and the plots.

35. Lines 246-250: Are these % changes in drought/rainfall meaningful (e.g., for agriculture, ecosystems), or do these changes fall well within normal climate variations that don't have a large impact?

We included sentences explaining about these rates.

Sect. 3.3. lines 392 – 395) "These changes in precipitation are in the range of the rates of expected decrease in annual precipitation over the Mediterranean region in the future scenario. In the future, the regional precipitation is expected to reduce by 5 – 30 % from its present-day value and this will cause water shortage related issues in the region (Dubrovsky et al., 2014, Mariotti et al., 2008)."

36. Also, is the background variability (e.g., standard deviation, mean) of rainfall in the CESM realistic, or can we chalk this up to model bias?

To address this point, we included the comparison of mean seasonal spatial and annual cycle of precipitation between the observation and model in the validation section (Sect. 3.1., lines 239 – 244). Also refer to our response #6.

37. Lines 254-255: similar to Main Concern (4), what about in 20th century reanalysis, ERA5, or some similar reanalysis product vs GPCCv2018 or CRU precip? Or Dai PDSI?

Refer to our responses #6 and #7.

38. Lines 257-260: 'The starting point is. . .to one or both of them'- confusing wording

We changed the sentence as: "In the following, we investigate the origin and the evolution of Mediterranean long droughts associated to NAO, ENSO-like condition and drought high using the transient simulation up to 1849 AD." in lines 404 – 406.

39. Lines 262-269: So in other words, there is about equal odds of being in a drought during various NAO or ENSO phases? This seems important because the authors claim on lines 294-295 that a certain combination of NAO and ENSO conditions are important for initiating drought. . .but it appears to me as though there are nearly equal odds of this happening (60%) based on the phase of NAO/ENSO. Is this interpretation incorrect?

This part is updated because we modified the thresholds to discern positive/negative NAO and ENSO: The phases of NAO and ENSO are defined with respect to the non-drought periods: the values below 25 (above 75) percentile of NAO and ENSO during the non-droughts periods are considered as negative (positive) phases of NAO and ENSO respectively. We updated the texts (Sect. 3.4. lines 407 - 433) and respective plot (figure 9 in the manuscript or at the end of the responses) according to the modified values. As the text is long, we do not include here the modified paragraph. Note that the occurrence of NAO and ENSO in different stages of droughts are more distinguishable.

40. Lines 298-310: I don't see how Fig 8 proves the point. Basically, it looks to me as though drought starts off dry and then transitions to less dry conditions at end of drought, and this is distinct from wet years.

Here, we provide the same response as the first response phase: we agree that droughts start off dry and become less dry with time. Here, we want to emphasize the importance of development of anticyclonic center associated with the high geopotential height anomaly which would be the driver that maintains the dry condition over the region for long time while the roles of the large-scale circulation patterns are decreasing from the transition to the last stage of droughts.

We reframed the related paragraph in the Sect. 3.4. in order to clarify this question.

Sect. 3.4. lines 443 - 447) "The mean circulation in each stage shows that the development of the high pressure system, namely the drought high in the Fig. 7, takes place in the transition years. This indicates that some mechanisms associated with this circulation is possibly important at determining the longevity of droughts after the initiation years. A possible candidate of an important process for the transition stage of Mediterranean droughts is the interaction among regional atmospheric and soil variables initiated by the anticyclonic circulation system over the region."

Also, we found that the figures 8 and 9 in the previous manuscript were quite repetitive to show our main point (that the drought high is developed in the transition years), thus, we only provide one figure for the mean circulation in different stages of droughts without separating NAO and ENSO (figure 10 in the revised manuscript).

41. Lines 325-327: Similar to Main Concern (4); I have not been shown how the model performs compared to instrumental/reanalysis for the relevant variables over Europe/Mediterranean, so these conclusions don't mean a lot to me.

Refer to our responses #6 and #7.

42. Lines 337-340: 1) I see no major changes in distribution of drought in Figure 10 - are these distributions distinct? Please see previous comments related to statistically distinguishing distributions (and not visually distinguishing), especially when they appear to overlap. 2) Any future changes in ENSO in this model should be interpreted with caution as most CMIP5 models, including this one as far as I can remember, struggle to reproduce the observed trends in the tropical Pacific (see Coats and Karnauskas, 2017, GRL as well as Seager et al., 2019, Nature Climate Change).

1) We performed Mann Whitney U-test and the corresponding paragraph is updated accordingly:

Sect. 3.5. lines 498 – 501) "For the detrended variables, the means of GP and SOIL during droughts show that they are statistically indifferent to the 850-1849 AD values (p-value of 0.09 for GP and 0.44 for SOIL). The same is also true for the NAO and ENSO during droughts

(p-values of 0.19 and 0.29 for each). The detrended TS over the region is statistically similar from the 850-1849 AD value but only at 2% confidence level (p-value of 0.02).”

2) We included a brief discussion on the uncertainties associated with the ENSO and NAO in models and possible implication in our result in the conclusion (Sect. 4), lines 543 – 550. Also refer to our response #8.

Sect. 4. lines 545 – 552) “The model inherent biases in representing ENSO and NAO (Bellenger et al., 2014; Fasullo et al., 2020) can have some implications in our results on the frequencies of ENSO and NAO at different stages of droughts. The model may produce too frequent and strong La Niña conditions and positive NAO during droughts due to its amplified, decadal for ENSO and seasonal for NAO, variability. Moreover, due to the uncertainty associated with the changes in these modes in the future scenario, caution is required when interpreting the connection between droughts and modes of variability in the future warming scenario.”

43. Lines 344-345: As figure 9 shows, trends in the region are not linear 1850-2100, so trend removal is problematic over this time period. Perhaps it makes sense to remove the trend 2000-2099, but otherwise the authors could be adding an artifact of trend removal into the analysis.

We addressed this issue in our response #20.

44. Lines 358-359: ‘our analysis shows that the overall similarities’: as stated above, the authors never actually showed this statistically, just a visual comparison.

We updated the texts according to the added analysis. Refer to our response #3.

45. Line 383: ‘climate over the region to a drier climate have started earlier than reported in the modern observational era’: to back up a statement like this, I’d again like to see that the model is simulating instrumentally observed climate during the relevant temporal overlap in the historical run (e.g., show Mediterranean precip./PDSI time series in model and instrumental data) before claiming that any drying has happened earlier than reported.

We modified the sentence to “This means that the intensification of droughts and the shift of the mean climate over the region to a drier climate have already started since the pre-industrial era.”, lines 554 – 555.

Figures

For the comments #4, #27 and #28:

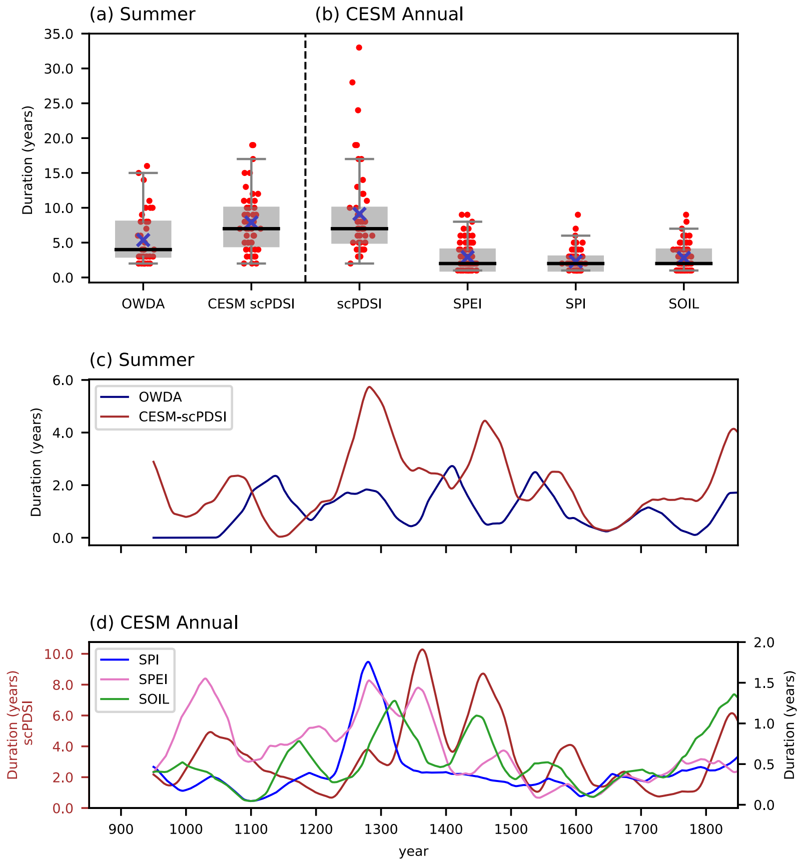

Fig 5. (a) Distribution of duration of droughts for the summer scPDSIs in OWDA and CESM, and for (b) the annual drought indices in CESM during 850 – 1849 AD. Red points indicate individual drought events, black lines on the boxes are the medians and blue crosses are the means of duration. (c) 100-years running means of duration of droughts for the summer scPDSIs and (d) the annual drought indices. The indices are the scPDSI from Old World Drought Atlas (OWDA), summer scPDSI from CESM (CESM-scPDSI), annual Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), soil moisture anomaly (SOIL), and annual scPDSI. Note that the annual scPDSI (brown line in (d)) has a separate y-axis for its duration. The p-value from Mann-Whitney U-test between the duration of summer scPDSI in OWDA and CESM is 0.003, which indicates the means are statistically different. For the annual indices, the means among each other are also statistically different, except between the SPEI and SOIL (p-value of 0.87).

For the comment #7:

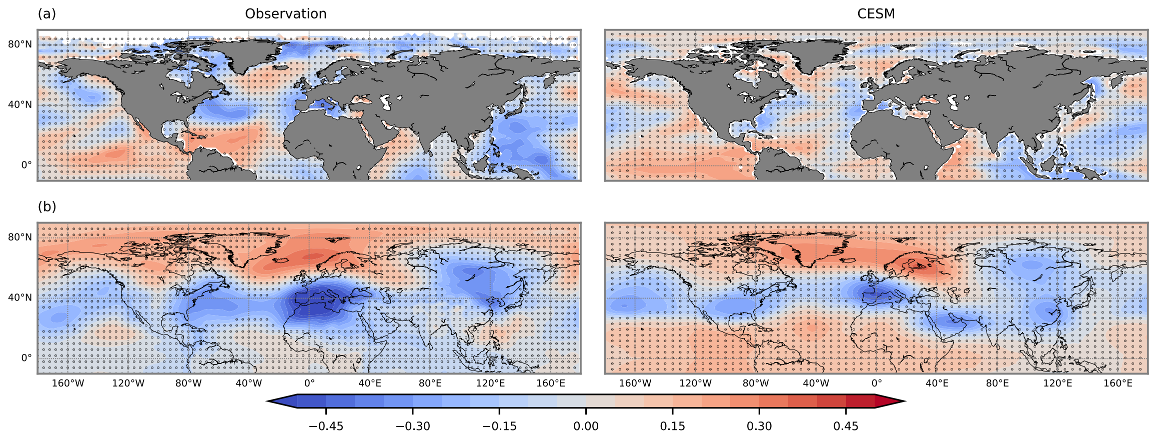

Fig 4. Maps of Pearson correlation between the scPDSI and anomalies of (a) Sea Surface Temperature from ERSST v5 and (b) Geopotential height at 850 hPa from the CR21 for the observation (left) and CESM (right) during the period of 1901-2000 AD. The linear trends of variables are removed before applying the correlation. Black dots on the maps show the regions where correlations are statistically not significant at 5% confidence level.

For the comment #39:

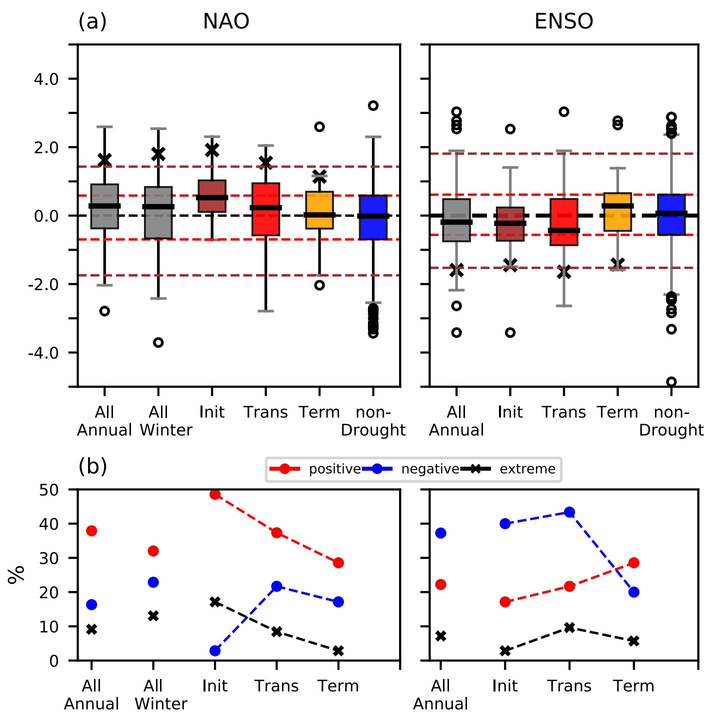

Fig 9. (a) Box plots of NAO and ENSO during multi-year Mediterranean droughts. The black crosses indicate 95 percentile value for NAO, and 5 percentile value for ENSO. Dashed red lines indicate the 25 and 75 percentiles of non-drought periods, which are the thresholds

to discern negative/positive states of NAO and ENSO. Dashed brown lines indicate 5 and 95 percentile of non-drought periods. (b) Frequencies of occurrences of positive and negative states of NAO (left) and ENSO (right) for annual and winter total, and each stage of droughts. Black crosses indicate the frequencies of occurrence of extreme positive NAO and extreme negative ENSO.

Dynamics of the Mediterranean droughts from 850 to 2099 AD in the Community Earth System Model

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Abstract.

In this study, we analyze the dynamics of multi-year long droughts over the western and central Mediterranean region for the period of 850 - 2099 AD using the Community Earth System model version 1.0.1. Our study indicates that Mediterranean droughts during the period of 850 - 1849 AD are mainly driven by the internal variability of the climate system. A barotropic high pressure system together with a positive temperature anomaly over central Europe and the Mediterranean region is the prominent pattern that occurs in all seasons with droughts. Also, the modes of variability, i.e. the North Atlantic Oscillation (NAO) and El Niño Southern Oscillation (ENSO), are associated with Mediterranean multi-year droughts, showing that droughts occur more frequently with positive NAO and La Niña-like conditions. These modes of variability play a more dominant role during the initial stage of droughts. However, their role diminishes with the evolution of droughts, and after the initial stage, the persistence of multi-year droughts is determined by the interaction between the regional atmospheric and soil moisture variables. This atmosphere – soil interaction becomes stronger during the 1850 – 2099 AD period, reducing the importance of modes of variability on droughts and inducing a constant dryness over the Mediterranean region. Additionally, the discrepancy among diverse drought metrics in representing duration and frequencies of past droughts is presented, re-affirming the necessity of assessing a variety of drought indices even in the paleoclimate context.

1 Introduction

Drought is an extreme weather and climate event characterized by a prolonged period with persistent depletion of atmospheric moisture and surface water balance from its mean average condition. Drought is also characterized by a slow onset and devastating impacts on society, the economy and the environment (Wilhite, 1993; Dai, 2011; Mishra and Singh, 2010), and it can be classified in four types: meteorological drought, associated with the decrease in precipitation; agricultural drought, associated with the depletion of soil moisture and impacts on crops and plants; hydrological drought, characterized by the depletion of streamflow and water reservoirs, and lastly socio-economic drought, that occurs when the other types of droughts cause impacts on society, in a way that the water supply cannot meet the demand from society (Mishra and Singh, 2010). If a drought lasts for a longer time period, meteorological drought is transformed to other kind of droughts, agricultural and/or hydrological, and different types of droughts become interconnected to each other (Wang et al., 2016; Zhu et al., 2019). The severity and duration of a drought can be quantified through different indices that capture hydrological conditions associated with a regional water balance (Dai, 2011). However, a single universal index cannot characterize the entire complexity of the nature of droughts (Lloyd-Hughes, 2014) and interconnection among different types of droughts (Mukherjee et al., 2018). Thus, one index does not necessarily produce a value that is similar to other indices even for the same region and period (Raible et al., 2017; Mukherjee et al., 2018). Some of the widely used indices are the self-calibrated Palmer Drought Severity Index (Wells et al., 2004), the Standardized Precipitation Index (McKee et al., 1993), and the Standardized Precipitation Evapotranspiration Index (Vicente-Serrano et al., 2009), among many others.

The Mediterranean region is known as a climate change hot-spot (Giorgi, 2006), meaning that the region is one of the most responsive to the current and future global warming, mainly associated with the decrease in precipitation and increase in drought episodes (Dubrovský et al., 2014; Liu et al., 2018). The climate of the Mediterranean is characterized as semi-arid with a pronounced annual cycle, thus, high temporal and spatial variability of the availability of water resources (Lionello et al., 2006). Therefore, droughts or periods with scarcity of water are intrinsic parts of the climatic conditions over Mediterranean. Overall, the region shows mild and wet winters, and hot and dry summers (Lionello et al., 2006). The variability of precipitation is not uniform across the entire Mediterranean area. The western and eastern regions show different precipitation regimes during the winter. A regional mode of circulation that explains a large percentage of the variability in winter is characterized by opposite pressure and precipitation patterns between the west-central and eastern Mediterranean regions, known as Mediterranean Oscillation (Dünkeloh and Jacobeit, 2003). Besides, the regional precipitation is strongly influenced by the mid-latitude storm tracks and cyclones, which become stronger during the winter (Lionello et al., 2016; Raible et al., 2007, 2010; Ulbrich et al., 2009), regional cyclones (Alpert et al., 1990), and large-scale modes of variability, such as the North Atlantic Oscillation (NAO), East Atlantic - West Russian pattern (EA - WR) and El Niño-Southern Oscillation (ENSO) (Lionello et al., 2006; Raible, 2007). The influence of these large-scale patterns also varies within the region. The NAO exerts its control on precipitation by affecting the strength of westerlies and latitudinal movement of the storm tracks. This influence largely becomes stronger during the wintertime. The precipitation decreases during the positive NAO, mostly in the west-central Mediterranean region, and the opposite condition occurs during the negative NAO (Wallace and Gutzler, 1981; Hurrell, 1995). The influence of EA-WR in European hydroclimate is also stronger in the winter. During the positive (negative) phase, the southeastern Mediterranean region experiences drier (wetter) condition than on average (Barnston and Livezey, 1987; Krichak and Alpert, 2005). The response of the Mediterranean climate on ENSO is more complex and not straightforward: it varies over time, discussed for a few historical cases (Brönnimann, 2007; Brönnimann et al., 2007), it depends on the maturity of the ENSO state (Vicente-Serrano, 2005), on the seasons (Mariotti et al., 2002) and on the co-occurrence with NAO (Brönnimann, 2007; Raible et al., 2001, 2003). Mariotti et al. (2002) demonstrated that precipitation decreases over the western Mediterranean during La Niña in autumn and spring. Brönnimann (2007) showed a connection between La Niña (El Niño) and the positive (negative) phase of the NAO in the late winter.

In the Mediterranean region, the increases in the severity and number of droughts over the region have been already detected in the modern observational records since the mid to late 20th century through different drought indices (e.g., Mariotti et al., 2008; Philandras et al., 2011; Sousa et al., 2011; Seager et al., 2014; Vicente-Serrano et al., 2014; Spinoni et al., 2015).

Furthermore, in recent decades, the occurrence of droughts with pan-European characteristic that cover a large part of the west-central Mediterranean region have been detected (García-Herrera et al., 2019; Spinoni et al., 2017). The increase in dryness is attributed to the increase in the atmospheric greenhouse gases (GHG) concentration, which causes a strong increase in the surface temperature and decrease in precipitation over the region (Mariotti et al., 2008). General circulation models (GCMs) project that this drying trend together with the increases in dry days and drought episodes will be intensified in the future under the business-as-usual scenario, causing important socio-economic impacts and changes in the region (Mariotti et al., 2008; Field et al., 2012; Lehner et al., 2017; Naumann et al., 2018). The future changes in the Mediterranean droughts are due to the tropical SST warming (Hoerling et al., 2011), changes in mean regional circulation associated with intensified subsidence and low-level mass divergence (Seager et al., 2014), expansion of the Hadley cell and the expansion of the subtropical subsidence zones (Previdi and Liepert, 2007), intensification of subtropical highs (Li et al., 2012), and northward shift of the storm tracks (Raible et al., 2010).

Though the dryness projected in the future scenarios by GCMs is unprecedentedly intense, multi-years long desiccation is not a completely new phenomenon over the Mediterranean area. Using the summer self-calibrated Palmer Drought Severity Index (scPDSI) based on tree rings (also known as the Old World Drought Atlas; OWDA; Cook et al. 2015), Cook et al. (2016a) showed that there have been several dry periods during the last 900 years over the region, some with persistent pan-Mediterranean characteristics. The region has experienced drought variability with frequencies of not only interannual, but multidecadal timescales. Although, the causes of those droughts in the past are still unclear, they show some connection with the large-scale patterns such as NAO, ER-WR and Scandinavian pattern.

Besides natural climate proxies, GCMs have been used to study long-term changes and continuous variability of global and regional hydroclimate and extreme events during the last millennium (PAGES Hydro2k Consortium, 2017; Haywood et al., 2019). Modelling studies on the long-term variability of droughts are focused on the U.S continent, mainly to investigate the continuous variability and mechanisms of South Western United States (SW) droughts, the Medieval Climate Anomaly (MCA) SW megadroughts, and North American pan-continental droughts (e.g., Coats et al., 2013, 2016; Coats and Karnauskas, 2017; Cook et al., 2016b; Parsons et al., 2018; Parsons and Coats, 2019). The results show that different GCMs are able to reproduce the duration and intensity of SW megadroughts and North American pan-continental droughts, indicating the internal variability as the main driver, though specific causing modes of variability are largely model dependent. Parsons and Coats (2019) investigated the evolution of SW multi-year droughts and their associated modes of variability using the Community Earth System Last Millennium Ensemble (CESM-LME; Otto-Bliesner et al. 2016). Their study suggests that the connection between the Tropical Equatorial Pacific and SW droughts changes with the stage of multi-year droughts, showing that La Niña is more common during the initiation years, then, cool and neutral Tropical Pacific condition and tendency to El Niño increase in middle years. Previously, Namias (1960) also analyzed the evolution of droughts by associating different stages of droughts with the atmospheric circulation in the Northern Hemisphere.

Stevenson et al. (2018) used the CESM - LME to examine the connection between past global hydrological mega-events, and climate variability and external forcings during the last millennium. Among the major modes of climate variability, the influences of ENSO and AMO on mega-events have been found, both significantly altering the megadrought risks and persistence in drought-prone regions, for instance, the southern Australia, the Sahel and the southern United States. The study provides insights into the dynamic of megadroughts associated with different mode of variability in global scale, though, a detailed analysis on southern Europe and the Mediterranean is missing.

In studies of the hydroclimate during last millennium over the European domain, Ljungqvist et al. (2019) examined a long-term covariability between the summer temperature and hydroclimate during the Common Era. By comparing the instrumental records, tree ring-based reconstructions, and model simulations, they found that a warm-dry relationship with multi-decadal variability is more dominant in the southern Europe. Though, all datasets share some common leading modes of covariability across different time frequencies, there are some discrepancies among instrumental records, proxies, and model. The proxies present a stronger positive temperature-hydroclimate relationship, while the model exhibits a stronger negative relationship than the instrumental records. Xoplaki et al. (2018) investigated the interaction between the past central and eastern Mediterranean societies and the hydroclimate conditions including droughts, by comparing the historical records, proxies and GCM simulations. Analyzing three particular historical periods, they concluded that the multidecadal variability of precipitation in the region is driven by internal dynamics of the climate system: large discrepancies between the model trajectories are detected. Therefore, no agreement in timing between models-proxies-historical records can be expected. Nevertheless, the models elucidate some possible explanations about the dynamics of extreme dry and wet events in some past periods.

Despite a number of studies on past hydrological variability, a long-term continuous perspective on the mechanisms of past extreme hydrological events, specifically of droughts over the Mediterranean during the last millennium is still not fully explored. As a long trend of dryness has already been detected in the instrumental era and is expected to intensify in the future scenario, it is necessary to provide a long-term picture on the variability and changes of past dry events and their mechanisms. Therefore, we aim to examine the physical mechanisms involved in yearly and multi-year long droughts during the Common Era (850 - 1849 AD) and historical, present and future periods (1850 - 2099 AD) over the west-central Mediterranean region. We choose this specific area, as this region has been affected by recent large scale droughts (García-Herrera et al., 2019; Spinoni et al., 2017), which can be seen as pan-west-central Mediterranean droughts. Moreover, the region shows coherent desiccation in the future scenario (Dubrovský et al., 2014). From now on, for simplicity, we refer to the west-central Mediterranean region in our study simply as the Mediterranean region. We focus on understanding the dynamics that induce past persistent pan-regional multi-year droughts, and whether the dynamics that induce droughts in the past will change in the historical and future periods with the anthropogenic increase in GHG.

For our purpose, we use the Community Earth System Model version 1.0.1 (CESM), which includes the active biogeochemical cycle and has the horizontal resolution of $1.25°$ x $0.9°$ (Lehner et al., 2015). The spatial resolution of the model is a clear advantage for our study on a relatively small confined area. The precipitation of the region is strongly influenced by extratropical cyclones and in general, GCMs have difficulties in reproducing the dynamics and precipitation associated with these meso-scale phenomena (Raible et al., 2007; Watterson, 2006). Nevertheless, these atmospheric dynamics and precipitation are better represented in GCMs with finer spatial resolution (Champion et al., 2011; Watterson, 2006). Hence, using a model that provides a seamless simulation for period 850 – 2099 AD guarantees an improved representation of precipitation related processes, thus, drought associated mechanisms over the region.

This paper is composed of the following sections: in section 2, we introduce the model and simulations, the hydrological variables given by the model, definition of droughts, drought indices, proxy and observation datasets and methods. In section 3, we present the results of our analysis: first, we compare the simulations, proxy reconstructions and observation to validate our model; second, we describe how the model depicts past droughts, whether the quantification of past droughts over the region is sensitive to the choice of drought metrics, and whether there is some possible association between the volcanic eruptions and droughts; third, we report the climate conditions associated with the past Mediterranean droughts and their connection with regional scale circulation and modes of variability, i.e. the NAO and ENSO; lastly, we discuss whether mechanisms that induce past droughts have changed in the historical and future periods. In section 4, we present a conclusion of our analysis.

2 Model description and methods

2.1 Description of the model and simulations

We use the Community Earth System model version 1.0.1 and its continuous transient simulation of 1250 years (850 - 2099 AD) where the 2005 – 2099 AD is run with the RCP 8.5 scenario, and control simulation of 400 years at perpetual 850 AD conditions (Lehner et al., 2015). In the simulations, the atmosphere has the horizontal resolution of $1.25° \times 0.9°$ and 26 vertical layers, and the land has the same horizontal resolution as the atmosphere with 15 sub-surface layers. The ocean has the horizontal resolution of $1.25° \times 0.9°$ with displaced pole grids with 60 ocean layers.

The control simulation uses constant forcing parameters set to the 850 AD values: the land use changes, the total solar irradiance in which the value is 1360.228 W m^{-2}, the GHG concentration, such as the CO_2 of 279.3 ppm, CH_4 of 674.5 ppb and the N_2O of 266.9 ppb. Unlike other forcings, the orbital parameters are set to 1990 AD conditions.

The transient simulation includes the active biogeochemical cycle and forcings, such as the land use changes, total solar irradiance, volcanic eruptions and greenhouse gases concentrations that vary over time (Schmidt et al., 2012). The GHG concentrations and land use changes vary little before 1850, showing pronounced changes and increases after that year. A more detailed overview of the forcings and initial set-up of the simulations is presented in Lehner et al. (2015).

2.2 Region of study, analysis and methods

The focus area of the study is the western and central Mediterranean region confined to 15°W - 28°E and 33° - 45°N (Fig. 1). The extent of the region is selected based on Empirical Orthogonal Function analysis on the monthly precipitation from the observation (gridded station precipitation from U.Delaware v5.01; Willmott and Matsuura 2001). The region shares overall a similar variability in the first EOF (13.28%) and second EOF (11.01%), in which this similarity also can be attributed to the influence of North Atlantic Oscillation in precipitation over the region (Dünkeloh and Jacobeit, 2003).

For the analysis, the monthly anomalies of the variables associated with the hydrological condition, such as the surface and air temperatures, precipitation, zonal and meridional winds, geopotential heights, and sea level pressure are calculated with respect to the 1000-1849 AD (850 years) mean annual cycle for each grid point in the transient simulation. For the control simulation, the entire 400 years are taken as a reference period to calculate the anomalies.

We split the transient simulation into two parts: the first period from 850 to 1849 AD is used to study the natural variability of droughts excluding the effect of accelerated increase in the GHGs, and the second period from 1850 to 2099 AD is used to examine the effects of anthropogenic changes on the natural variability of droughts.

The drought condition during the first period (850 – 1849 AD) is compared to the control simulation to assess the influence of the natural variability and forcings. The statistical tests to compare the transient to the control simulations are performed with the Mann-Whitney U significance test for the means at a 5% confidence level. First, the test is performed without considering the difference in the length of each simulation. Then, as the transient simulation is longer than the control one, we select 5 sets of random 89 years with droughts from the transient simulation and apply the tests against the control simulation.

For the second period (1850 - 2099 AD), the anomalies are linearly detrended in order to examine the background mechanisms associated with dryness during this period without the anthropogenic influence on climate. This is performed by splitting the time period into two and applying the least squares method to the each of the period separately: from 1850 to 2000 and from 2001 to 2099 AD. Then, the detrended anomalies are compared against the non-detrended anomalies for the same period and also for the first period.

Composites of positive and negative phases of two modes of variability are also investigated: the NAO and ENSO. The NAO is taken as the difference in the sea level pressure anomalies between the regions confined to 33° - 21°W / 35° - 39°N and 25° - 13°W / 63° - 67°N, which reflects the Azores high and the Iceland low respectively (Wallace and Gutzler, 1981; Trigo et al., 2002). The ENSO is characterized by the annual mean sea surface temperature anomalies over Niño 3.4 region in the Tropical Equatorial Pacific (170° - 120°W and 5°S - 5°N) (Trenberth, 1997).

We further perform wavelet coherence analysis (Grinsted et al., 2004; Gouhier et al., 2018) in order to find a possible time-varying association between droughts and volcanic eruptions, using the time series of volcanic eruptions (Gao et al., 2008) and of drought indices (Sect. 2.3). The time series are normalized to have a zero mean and one standard deviation.

2.3 Drought definitions

We use some drought metrics to quantify droughts and to perform the comparison among them: the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), self-calibrated Palmer Drought Severity Index (scPDSI), and annual soil moisture anomaly (SOIL).

The SPI only requires a long-term precipitation record, and the accumulated precipitation is fitted to a probabilistic distribution, in our case a gamma distribution. Then, the fitted distribution is transformed to a normalized Gaussian distribution (McKee et al., 1993). The SPEI is similar to the SPI, but instead of only using a precipitation record, it considers the climate water balanzce given by the difference between the precipitation and atmospheric evaporative demand. This difference is fitted to a log-logistic probability distribution, then, transformed to a normal distribution (Vicente-Serrano et al., 2009). For the atmospheric evaporative demands, we use the potential evapotraspiration derived from Thornthwaite equation, which only requires surface temperature and latitude (Thornthwaite et al., 1948). The scPDSI computes the water balance by assuming a two-layer soil bucket model, and it requires temperature and potential evapotranspiration records. Other necessary variables, such as runoff and losses, are estimated from the temperature and potential evapotranspiration (Palmer, 1965; Wells et al., 2004; Zhong et al., 2018). Again, the potential evapotranspiration is calculated by using Thornthwaite equation same as the SPEI. The SOIL is the upper 10 cm soil moisture anomaly calculated with respect to the 850 years-mean (1000-1849 AD) annual cycles. The soil moisture is a direct output from the model.

All indices are calculated with respect to the same reference period (1000-1849 AD), and with the 12 months-annual time scale for the SPI, SPEI and SOIL. The scPDSI has an inherent time scale that ranges from 9 to 14 months depending on the region (Vicente-Serrano et al., 2010, 2015). Thus, we use a 12 month-time scale for the other indices in order to be comparable to the scPDSI. Then, all indices are area weighted averaged over the Mediterranean region (Fig. 1). The summer scPDSI is also calculated by averaging the June-July-August scPDSI, in order to compare with the summer scPDSI from the tree ring-based reconstruction, the Old Word Drought Atlas (OWDA; Cook et al. 2015).

For all indices, we define a drought event as consecutive years with negative indices, in which at least one year with the index falling below the 10 percentiles of its 850-year (1000 - 1849 AD) distribution. In such way, we assure that the dry condition is maintained consistently during drought years, without being interrupted by one wet year or season. This method that imposes a threshold based on the extreme percentiles, assures that strong negative anomalies persist throughout the entire year with droughts, thus, we only take relatively severe droughts for our analysis.

Droughts with a duration of more than 3 years are considered as multi-year droughts. In the Sect. 3.3., we analyze the mean condition during droughts in the control and transient simulations taking into account all short (1 and 2 years of duration) and long (more than 3 years of duration) Mediterranean droughts. For the next part of the analysis in the Sect. 3.4., we examine the dynamics associated with persistent multi-year droughts (more than 3 years of duration). These long droughts are separated into three stages: the initiation years as the first years of droughts, the termination years as the last years, and the rest as the transition years. The evolution of droughts is analyzed for each of the stages. This separation method is similar to the one used by Parsons and Coats (2019).

Lastly, in order to define droughts with pan-west-central Mediterranean characteristic, we select only drought events where more than 70% of the region of study is occupied by negative indices (Fig. 1.(b)). Though, for multi-year droughts, we allow that this condition does not need to be fulfilled for the initiation and termination years but only for the transition years: a drought can start weak and with a more local characteristic, then expand to a larger proportion of the Mediterranean, and weaken again in the termination years.

2.4 Observation and proxy reconstruction datasets

For the validation of the model, we compare mean seasonal precipitation and mean climate conditions associated with droughts among the observation, proxy reconstruction and model for the period of 1901 – 2000 AD. We use the gridded station data for temperature and precipitation from U.Delaware v5.01 (Willmott and Matsuura, 2001), the sea surface temperature from the Extended Reconstructed Sea Surface Temperature v5 (ERSST v5; Huang et al. 2017), and geopotential heights from the 21th Century Reanalysis v2 (CR v2; Compo et al. 2011). The scPDSI is calculated using the U.Delaware v5.01 temperature and precipitation. Furthermore, we take the gridded tree-ring-based reconstruction of European summer scPDSI, OWDA (Cook et al., 2015). The analysis on drought associated patterns is performed using the spatial correlation analysis between the monthly scPDSI and SST, scPDSI and geopotential heights. Among all drought indices, we use only scPDSI for comparison and validation, as the OWDA only provides this specific drought metric. The anomalies of variables are calculated by extracting the mean annual cycles with respect to 1950 – 1979 AD. To calculate the scPDSI for the observation and model, the same period is used as the calibration period.

3 Results

3.1 Validation of CESM: comparison among observation, proxy and model (1901 – 2000 AD)

In this section, we compare the mean precipitation, mean scPDSI, number and duration of droughts and atmospheric conditions associated with Mediterranean dry conditions among the observation, OWDA and CESM simulation for the period of 1901 – 2000 AD.

The Fig. 2 shows that the model exhibits similar spatial patterns of mean seasonal precipitation to those from the observation. Though, there are some regions where the seasonal means between the observation and model are statistically different. In the summer, both central and western Mediterranean present dry conditions, whereas in the winter, both regions are less dry than the summer with wet conditions over Portugal and Balkans. For the mean annual cycle, the model in general shows less precipitation than the observed values over both central and western Mediterranean. Nevertheless, the model reproduces well the annual precipitation cycle, depicting correctly the maximum and minimum periods of precipitation.

In terms of the droughts (Fig. 3.(a)), the means from the summer scPDSI between the model and OWDA are statistically similar to each other (p-value from the t-student test of 0.28). This is also the case between the OWDA and observation but with much lower confidence level of 1% (p value of 0.01). However, both summer and annual scPDSI from the model are statistically different to those from the observation (p-values of 0.001). In terms of the number of droughts (Fig. 3.(b)), the observation presents 4, OWDA 7 and CESM 3 events during the last century. For the duration of droughts, the mean (5.43 years) and median (3 years) from OWDA are different to those from the observation (11.50 and 12.50 years respectively), with OWDA exhibiting lower values. CESM also presents a lower median in the duration of droughts (6 years) compared to the observation, though, its mean (9.67 years) resembles better the observation than the one from OWDA. The discrepancies in the means and medians of droughts between the observation and CESM are still present in annual droughts.

We observe that the model tends to underestimate the duration of present-day droughts than those from the observation. However, the model still shows to a certain extent its ability to reproduce persistent long droughts, simulating droughts of few years long, and with longer duration than those from OWDA. Still, the analysis on annual-scale extreme dry events based on a relatively short present period of 100 years is not sufficient to draw comprehensive conclusions of present-day multi-years droughts, due to the limited number of events.

One of the reason for the difference in the overall scPDSI between the model and observation is potentially related to the model performance on meso-scale phenomena, which play an important role for the regional precipitation during the wet season (Alpert et al., 1990; Ulbrich et al., 2009; Champion et al., 2011; Watterson, 2006). Additionally, the model performance on internal variability may contribute to this discrepancy, which will be discussed in the following paragraphs. The same can also explain the case of OWDA and observation, that shows a p-value at the limit of 1% confidence level. The annually resolved OWDA is based on tree rings, which are known to be biased towards the growing season, so that the full annual signal might be not fully preserved in such a reconstruction. Moreover, proxy model observation comparison studies show that tree ring-based reconstructions tend to deviate in their spectral behavior (Franke et al., 2013), and the distribution of tree rings used to generate the gridded reconstruction over Mediterranean (Cook et al., 2015) may not be enough to capture precipitation events associated with regional-scale cyclones and to fully explain dry/wet variability for the entire region (Babst et al., 2018).

After all, the model and observation share many common patterns associated with the scPDSI. The ocean and atmospheric condition associated with the variability of scPDSI in the observation and model are presented in Fig. (4) through the correlation patterns between the scPDSI and SST, and the scPDSI and geopotential height at 850hPa. The observation and model exhibit significant positive correlations over the central Equatorial Pacific, though in the observation, the region with statistically significant correlation is located more on the north-central Pacific than in the model. The observation and model share a significant wave-like pattern over the extratropical latitudinal belt, that extends from the North Pacific to Siberia. Within this wave-like pattern, a bipolar pattern with a significant negative correlation centered over Mediterranean region and a positive correlation over the northern high latitudes are prominent. In the observation, the area of negative correlation over Europe is larger and the positive correlation of the bipolar pattern is shifted more to the Scandinavian region than in the model. The observation and model present some common patterns occurring over the regions of ENSO and NAO.

It is known that the variability of ENSO is too strongly represented in CESM (Parsons et al., 2017; Stevenson et al., 2018). Nevertheless, the model is able to capture relatively well the hydroclimate condition associated with the ENSO teleconnection (Stevenson et al., 2018). In case of NAO, the seasonal variability of NAO seems to be amplified in many CMIP models (Fasullo et al., 2020). The CESM, however, resembles the present-day NAO pattern well and the spatial precipitation and temperature associated with this mode of variability in Europe (Deser et al., 2017). These inherent biases with respect to modes of variability (in particular for ENSO) can partially explain the differences we observe here between the model and observation.

Overall, the model is able to reproduce the climate condition associated with the variability of present-day scPDSI, despite the fact presents some discrepancy to the observation exist. Moreover, the model does not significantly underestimate the persistence of multi-year droughts. As it also shows statistical similarity to OWDA over the region, we consider that the model can be used for the analysis on past Mediterranean droughts. We take into account these differences of model to the observation and biases on modes of variability to discuss the implications of them in our results more in detail in the Sect. 4.

3.2 Variability of Mediterranean droughts during the 850 - 1849 AD and their connection to the volcanic forcing

To gain an overview of drought conditions in the Mediterranean, we assess the indices defined in the Sect. 2.3 using the period 850 to 1849 AD and focusing on the drought events and their duration. In the beginning, we compare the variability and duration of droughts of the summertime scPDSI from CESM with those from OWDA. We do not aim to make a direct comparison between the proxies and the model simulation, as this cannot be made due to the different initial conditions between the proxies and model (PAGES Hydro2k Consortium, 2017; Xoplaki et al., 2018). Here, we rather focus on comparing the simulated summer drought variability with the one of the OWDA. Additionally, we assess whether the simulated and reconstructed droughts respond similarly to the same external forcing, i.e. the volcanic eruptions.

The Fig. 5.(a) and (c) exhibits the distribution and the 100 years running mean of duration of summer (June-July-August mean) in OWDA and CESM. In terms of duration of summer droughts (Fig. 5.(a)), the discrepancy between CESM and OWDA is clear, with OWDA presenting the mean duration of 5.38 years and CESM with 7.89 years. These means are statistically different to each other. This seems to be consistent with the result in the previous section (Sect. 3.1) that shows that OWDA has droughts with shorter duration compared to the present-day observation and CESM over the Mediterranean region. Thus, this characteristic is still present during the entire last millennium. The variability of droughts over time in OWDA and CESM is also different to each other (Fig. 5.(c)), without a specific common period of increase in droughts. This gives us a first hint that the occurrence of droughts over the region are not mainly driven by the external natural forcings. Both time series present a common period of decrease in droughts around 1600 AD.

Similarly, the Fig. 5.(b) and (d) show the distributions and running means of duration of annual Mediterranean droughts in CESM quantified using different indices. As expected, different indices do not exactly behave similarly in terms of the occurrence, number of events, and duration (Raible et al., 2017; Mukherjee et al., 2018). However, the indices coincide for some years: in total 89 years of the 850 - 1849 AD period, all indices indicate the same overlapped drought periods. In terms of duration, the scPDSI is the one which shows more longer lasting droughts than other indices, with a mean duration of 9.1 years. Then, the SPEI, SOIL and SPI follow it with the mean durations of 2.9, 2.8, and 2.3 years, respectively. The SPI presents more events than other indices, but with shorter duration. All these means are statistically different among each other, except the means between SPEI and SOIL, which are statistically indifferent (p-value of 0.87).

The difference in duration of droughts among indices can be attributed to the water balance variables involved in the computation of each index. For instance, the SPI only takes precipitation as its input variable. Thus, it does not consider the atmospheric evaporative demands, which can be intensified during dry periods. Therefore, we expect that the SPI shows a reduced duration of droughts compared to the scPDSI and SPEI, which include the potential evapotranspiration in their water balance. The same holds true for the SOIL index. Though, the soil moisture in the model is closely connected to the hydrological cycle reflecting the balance between the precipitation and actual evapotranspiration, the magnitude of actual evapotranspiration over the region is smaller than the potential evapotranspiration derived from the Thornthwaite method. Hence, the water balance involved in SOIL is affected in such a way that the drought duration is reduced compared to the scPDSI and SPEI. Lastly, droughts with relatively longer duration in the scPDSI can be explained by the memory effect embedded in the calculation scheme of scPDSI (Palmer, 1965; Wells et al., 2004), which other indices that are obtained by being normalized with respect to certain statistical distribution families do not present. The scPDSI is an accumulating index; therefore, during the calculation process, the weighted value of preceding months is used to estimate the index for the current month, implying a persistence of the events. Hence, with the scPDSI, an intense yearly drought would likely induce a drought in the following year and this effect can be exacerbated in the context of intense multi-year droughts.

In terms of variability over the period of 850 - 1849 AD (Fig. 5.(d)), at first glance, similarly to the summertime OWDA and CESM, no noticeable coherent changes among all indices, such as a common period of increase in the occurrence of droughts over time, is noticed. Although each index captures slightly different aspects of water balance, we expect to see a similar common response to external forcing among all the indices, if droughts are influenced by the same externally forced variability, e.g., the volcanic forcing. However, this is not the case. The wavelet coherence analysis between the drought indices and volcanic eruptions corroborates the absence of a connection between these two variables (Fig. 6). The signals of statistically significant coherent variability between drought indices (SOIL and scPDSI) in CESM and volcanic eruptions are not uniform across the period-year frequency bands. Before 1100 AD, the anti-phase relationship between the two variables dominates, while after 1100 AD is the opposite, an in-phase relationship is more visible. Moreover, the leading variables of association also change over the time and frequency band. This is the same for OWDA. Besides, OWDA does not show strong significant signal during the 1257 Samala eruption, which was the strongest eruption in the last millennium (Gao et al., 2008). Hence, the analysis confirms that the occurrence of yearly and multi-year Mediterranean droughts are not driven by the volcanic eruptions, rather, the driver can be attributed to the internal variability.

In the next sections, we investigate the underlying dynamics using only the SOIL as the drought indicator in order to understand the role of the internal variability in Mediterranean droughts. The focus on one indicator is motivated by the fact that soil moisture reflects the regional hydrological balance associated with the precipitation and evapotranspiration, and it is also an indicative of water stress on plants and ecosystem (Berg et al., 2017; Swann, 2018). Another advantage of this index is that the variable is a direct output from the model, thus, it does not require any further step, except for calculating the anomalies, and statistical assumptions as other indices do. Moreover, using the SOIL helps us to avoid the overestimation of drought risk and severity that occurs with many offline drought indices. The offline estimation of droughts by some common drought metrics, such as scPDSI, tends to magnify the impact of increase in temperature, therefore in potential evapotranspiration, on drought-associated atmosphere - surface feedback (Seneviratne et al., 2010). Hence, in the warming scenario, the indices that are constructed based on atmospheric supply and demand of moisture, such as scPDSI and SPEI, strongly overestimate future drought risks (Berg et al., 2017; Cook et al., 2018; Swann et al., 2016).

In our analysis, the SOIL overlaps full or a part of drought periods given by the other three indices, without significantly underestimating the multi-year duration of droughts. The droughts in SOIL overlap the 36%, 25% and 29% of droughts in the scPDSI, SPEI and SPI, respectively. Also, the SOIL and each of the indices are statistically correlated at 1% confidence level for the entire period of 850 -1849 AD with Pearson correlation coefficients of 0.81 (thus, 66% of variance) with scPDSI, 0.78 (0.61%) with SPEI and 0.86 (74%) with SPI. Hence, the results in the following sections can be transferred to the other indices. To guarantee the transferability, the analysis in the next sections was repeated with each of the drought indices, showing similar results as for SOIL (therefore figures not shown).

3.3 Atmospheric circulation associated with Mediterranean droughts (850 - 1849 AD)

In this section, the atmospheric circulation associated with Mediterranean droughts is investigated by using the SOIL in the control and transient simulations up to 1849 AD. The control simulation presents 7.25 droughts every century, with the mean duration of 3.06 years and the transient simulation has 8 droughts every century with the mean duration of 2.81 years.

To get a first glance of the atmospheric circulation during drought conditions, Fig. 7 shows the anomalies of geopotential height at 850 hPa and surface temperature during Mediterranean droughts for each simulation. The structures of geopotential height and temperature anomalies during Mediterranean droughts are similar, with a high-pressure system centered over central Europe accompanied by a positive temperature anomaly. This high-pressure anomaly, which from now on is called the drought high, is found in all heights from the 850 to 300 hPa (figures not shown), indicating a barotropic nature of this atmospheric circulation system. Additionally, a low pressure anomaly is situated over the area of Scandinavia to Russia. Thus, the atmospheric circulation shows a north easterly shift of the westerlies over Europe, so that moist air masses from the North Atlantic are passed around the Mediterranean.

Outside the European continent, a negative temperature anomaly over the Tropical Equatorial Pacific and a positive anomaly over the North Pacific are prominent in both simulations. These temperature patterns resemble the cold phase of ENSO and the positive phase of Pacific Decadal Oscillation (PDO), respectively. Besides, a positive geopotential height anomaly at the mid-latitudes and a negative anomaly at the high latitudes over the North Atlantic region is another pattern that both simulations share in common during droughts. This pattern is similar to the positive phase of the NAO; however, the southerly center of action is shifted to central Europe, which also resembles partially the East Atlantic Pattern (EA). The means of these common patterns are also statistically indifferent between both simulations, indicating that they are derived from the same statistical populations. Thus, they share common mechanisms associated with droughts, mainly driven by the internal variability of the climate system in the model, embedded both in control and transient simulations.

The drought high is a clear feature that appears during all droughts over the region. This pattern over central Europe and the western Mediterranean is similar to the pattern of the first mode of canonical correlation described by Xoplaki et al. (2003). In Xoplaki et al. (2003), this pattern is associated with the variability of temperature during the summertime in the Mediterranean region. In our study, the high-pressure system is present during all seasons of years with droughts, showing a relatively stronger intensity in winter and spring compared to summer (Fig. 8). This is expected, as the variability of the geopotential height fields over Europe and the North Atlantic is reduced in summer compared to the other seasons, because the meridional temperature gradient on the Northern Hemisphere is also reduced. Therefore, the main forcing of the atmospheric circulation is weakened. Our findings show that the atmospheric conditions in wet seasons, i.e. winter and spring, are determinant at controlling the annual mean hydroclimate, thus, indicating the importance of precipitation and dynamics during the wet season in annual-scale Mediterranean droughts (Lionello et al., 2006; Xoplaki et al., 2004; Zveryaev, 2004).

As expected, a decrease in precipitation occurs in all seasons during droughts: the winter and spring precipitation decreases by around 13%, and the summer and autumn precipitation by 11% compared to non-drought periods. These changes in precipitation are in the range of the rates of expected decrease in annual precipitation over the Mediterranean region in the future scenario. In the future, the regional precipitation is expected to reduce by 5 – 30% from its present-day value and this will cause water shortage related issues in the region (Dubrovský et al., 2014; Mariotti et al., 2008). The temperature shows a positive anomaly over the region in all seasons, with strongest signals during summer and autumn, a finding which is in line with, e.g., Xoplaki et al. (2003). This indicates that Mediterranean droughts are more associated with anomalously warmer atmospheric conditions.

3.4 Dynamics of multi-year droughts

For the analysis on multi-years Mediterranean droughts, among all drought events, we take only droughts with a minimum duration of 3 years. As shown in the previous section in Fig. 7, the drought high is a prominent atmospheric circulation pattern with the negative geopotential height anomaly north-east to it. The entire pattern resembles the positive NAO-like pattern, although with a shift to the North-East. At the same time, a colder than normal condition over the Tropical Equatorial Pacific is detected, which is similar to a La Niña-like condition. In the following, we investigate the origin and the evolution of Mediterranean long droughts associated to NAO, ENSO-like condition and drought high using the transient simulation up to 1849 AD.

The phases of NAO and ENSO are defined with respect to the non-drought periods: the values below 25 (above 75) percentile of NAO and ENSO during the non-droughts periods are considered as negative (positive) phases of NAO and ENSO respectively (Fig. 9). For the co-occurrence of droughts and the positive phase of NAO, the simulation shows that droughts occur more frequently during the positive phase of annual and winter NAO than during normal years without droughts: 38% of the drought years show the positive phase of annual NAO and 32% for the winter, while the negative annual NAO occupies 16%, and 23% in the winter. However, the positive NAO condition does not persist throughout the entire years of droughts. Rather, it fluctuates from the positive to negative phases during multi-year droughts. Assessing the co-occurrence between droughts and cold Tropical Equatorial Pacific (La Niña-like) conditions, we find that during droughts, La Niña-like conditions are present in 37% of total drought periods, El Niño-like in 22%. Similar to NAO, La Niña-like conditions do not persist throughout the entire drought years.

The extreme positive NAO, defined as values above 95 percentiles of NAO during non-drought periods, occurs slightly more frequent during droughts, and the mean of this extreme NAO is statistically different from the mean extreme NAO during non-drought periods at 5% confidence level, for both annual and winter NAO (p-values from MW-U test of 0.02 for annual and 0.002 for winter). However, for ENSO, there is no statistically significant change in the mean and frequency of extreme La Niña-like condition compared to the non-drought periods.

To examine the behavior of the atmosphere during multi-years Mediterranean droughts, the frequency of modes of variability and mean composites of circulation during droughts are split in three stages: initiation, transition and termination years (Sect. 2.3). The frequencies of occurrence of NAO and ENSO in each stage is presented in the Fig.9. The positive NAO occurs more frequently in the initiation years than in the transition and the termination years of droughts. The positive NAO occupies 49% in the initiation years, then it decreases throughout the development of droughts, falling to 29% in the termination years. The frequency of extreme positive NAO also decreases over time. In case of ENSO, the frequency of La Niña-like is 40% in the initiation years. The occurrence of La Niña-like conditions increases slightly in the transition years, though, this increase is not statistically significant compared to the previous stage. Then, it decreases to 20% in the termination years. After the initiation years, there are increases in negative NAO and El Ni ño-like states. These changes in the frequencies of NAO and ENSO in each stage of droughts indicate a weakening role of large-scale circulation patterns at sustaining the persistence of droughts over time. As the intensities of droughts become more severe with their duration, some other factors need to be involved in sustaining the longevity of multi-years Mediterranean droughts from the transition to termination years.

The mean circulation and atmospheric conditions during the development of multi-years Mediterranean droughts are shown in the Fig. 10 depicted by the specific humidity, temperature, and winds at 925 hPa level. In the initiation years, the southerly winds prevail over the southern Mediterranean region. These southerlies block the intrusion of the westerly systems from the North Atlantic, and together with the cyclonic winds in the East Atlantic distribute dry and warm air masses from the East Atlantic, southern Mediterranean and west Africa to the continent. In the transition years, a complete anticyclonic circulation associated with the high over central Europe and the Mediterranean region is developed. This anticyclonic system distributes the dry and warm air to the north and west of the continent and sustains dry and warm condition over the region. During these years, the westerlies from the North Atlantic are clearly weakened. In the termination years, the anticyclonic circulation over Europe is not observed anymore, indicating a break-up of the high.

The mean circulation in each stage shows that the development of the high pressure system, namely the drought high in the Fig. 7, takes place in the transition years. This indicates that some mechanisms associated with this circulation is possibly important at determining the longevity of droughts after the initiation years. A possible candidate of an important process for the transition stage of Mediterranean droughts is the interaction among regional atmospheric and soil variables initiated by the anticyclonic circulation system over the region.

This is supported by the increases in frequencies of positive surface temperature (TS) and negative soil moisture (SOIL), evapotranspiration (EV), sensible (SH) and latent (LH) heat flux anomalies in the transition years (Fig.11). The mechanism associated with these regional atmospheric and soil variables is explained as follows: a decrease in precipitation supported by the positive NAO and/or La Niña-like induce initial regional dryness and a stable atmospheric condition associated with the increase in geopotential high anomaly (GP) over the region. A positive GP induces an initial increase in the regional TS. This positive TS decreases SOIL and EV. The latter increases SH and decreases LH during the initiation year. During the transition years, due to the stable atmospheric condition that still persists (positive GP) and the increase in SH and loss of LH in the previous stage, the positive TS is even magnified. TS in turn again increases SH, decreases EV and LH, thus, decreases SOIL. Over time, the complete high is developed and persists, fueling again this positive temperature - soil moisture feedback mechanism (Seneviratne et al., 2010; Yin et al., 2014). Thus, during the transient years, the means and occurrence of these variables associated with the feedback (positive TS, negative SOIL, negative EV, positive SH, negative LH) are clearly larger than their values during the initiation years (Fig.11). This mechanism continues until the termination years. During the termination years, the positive GP and TS still prevail over the region, though, with reduced anomalies. Also, the magnitudes of other variables are reduced compared to the previous stage.

This result indicates that once the drought high is developed, the temperature - soil moisture feedback is a more important mechanism than the connection to NAO and La Niña-like patterns in order to sustain the continuous depletion of soil moisture, which means the duration of droughts. Though the large scale circulation patterns help to support the regional dry conditions, after the initiation years, their roles in sustaining droughts are diminished.

3.5 Historical and Future condition on droughts: 1850 to 2099 AD

Here, the behavior of Mediterranean droughts as well as the associated mechanisms for the period 1850 - 2099 AD are presented. For an overview, the time series of the soil and precipitation anomalies (with respect to the mean of the period 1000 -1849 AD) over the Mediterranean region for the period 1850 - 2099 AD are shown in the Fig. 12. The simulation indicates that the region becomes drier for the period 1850 -2099 AD than the past, which is reflected in pronounced decreases in soil moisture and precipitation. The reduction in these two variables is already noticed from the beginning of 1850 AD concomitantly with the anthropogenic increase in GHG. By the end of the 21st century, the region experiences a constant drought situation without any wet anomaly with respect to the 1000 - 1849 AD condition. This indicates a shift of the mean climate of the region to a drier climate under the RCP 8.5 scenario, which is in line with other previous studies on the future projection of the region (e.g., Dubrovský et al., 2014; Naumann et al., 2018). Next, we analyze whether the mechanisms associated with Mediterranean droughts presented in the previous sections have changed during this period by comparing the non-detrended and detrended drought related variables. The detrending process is performed following the steps mentioned in the Sect. 2.2. In this way, we exclude the trends caused by the anthropogenic changes during these 250 years to observe the background climate during droughts.

Previously, it is shown that past Mediterranean droughts are associated with the intense positive geopotential height and temperature anomalies over central Europe and the Mediterranean. These features are also observed during droughts in the non-detrended 1850 - 2099 AD condition, but with more intense positive geopotential height (GP) and temperature (TS) anomalies than during the period 850 - 1849 AD (Fig. 13.(a)). The variances of GP, TS and SOIL are also enlarged compared to the past; therefore, their medians and extreme tails are also magnified, which imply that the dryness and its associated atmospheric conditions become more frequent and severe in 1850 - 2099 AD. The increases in GP and TS clearly intensify the above mentioned interaction among regional atmospheric and soil variables, i.e the positive temperature – soil moisture feedback. This intensification aids the longevity and intensity of droughts, which is also reflected as a reduction in the surface soil moisture anomaly (Fig. 9). Additionally, the precipitation - soil moisture interaction is involved, i.e. a continuous reduction in precipitation decreases soil moisture, thus, inducing less evapotranspiration, which leads again to a reduction in precipitation (Seneviratne et al., 2010).

Related to the modes of variability, the frequencies of positive NAO and La Niña-like conditions during droughts also seem to be affected by the overall change in global temperature (Fig. 13.(b)). Compared to 850 – 1849 AD, the non-detrended 1850 – 2099 AD period shows a slight reduction in the preference toward the positive NAO and La Niña-like conditions during droughts. This result is in line with the previously mentioned regional circulation associated with droughts: in this situation where the regional atmospheric variables have a more dominant role in the regional desiccation aided by the intense GP and

TS, the importance of modes of variability is reduced, even during the initial stages of droughts. Hence, the role of positive NAO and La Niña-like through different stages of droughts is diminished.

For the detrended variables, the means of GP and SOIL during droughts show that they are statistically indifferent to the 850-1849 AD values (p-value of 0.09 for GP and 0.44 for SOIL). The same is also true for the NAO and ENSO during droughts (p-values of 0.19 and 0.29 for each). The detrended TS over the region is statistically similar from the 850-1849 AD value but only at 2% confidence level (p-value of 0.02). This indicates that the detrending method is not enough to fully exclude the strong effects of anthropogenic changes on temperature in future droughts. Nevertheless, the mean spatial composites of the detrended surface temperature and geopotential height at 850 hPa during Mediterranean droughts (Fig. 14) support the indifference between these two periods over the large portion of the Mediterranean region, exhibiting the circulation patterns which are similar to those during the 850 - 1849 AD period (Fig. 7). This result shows that the natural mechanisms associated with droughts remain the same as it is in the past period, thus, no natural changes on drought mechanisms occur for the period of 1850 – 2099 AD. This means that the intensification of Mediterranean droughts is clearly due to the anthropogenic influences: in the future scenario, the intensity of atmosphere - soil feedback is magnified, due to the increase in GP and TS, and this mechanism becomes the dominant one at controlling the desiccation over the region.

4 Conclusions

We have investigated the variability and mechanisms of multi-years droughts over the western and central Mediterranean region with pan-regional characteristic for the period of 850 - 1849 AD and whether these mechanisms associated with Mediterranean droughts have changed after the pre-industrial period from 1850 to 2099 AD with the anthropogenic increase in GHG. We have performed our analysis by using CESM simulations.

First of all, our result shows that though some overlapping years in drought periods among indices exist, the quantification of droughts is sensitive to the choice of drought index even in the paleoclimate context. For example, the scPDSI exhibits drought events with longer duration than the other indices, while the SPI is opposite, presenting more shorter lasting events. Though, the major mechanisms that induce multi-years droughts over the region remain similar due to the same overlapping periods and statistically significant correlation among indices, this discrepancy among indices can lead to a different conclusion, mostly in the number and duration of past drought events. This shows that using just one unique index is still complicated, even in the paleoclimate context. Hence, the uncertainty associated with different indices must be taken into account when comparing indices in drought studies (Dai, 2011; Raible et al., 2017; Mukherjee et al., 2018), in particular, in the case when only a single drought index is used and the focus is on the assessment of the duration of extreme hydrological events in past periods.

Secondly, we found that the past Mediterranean droughts are mainly induced by the internal dynamics of climate system supporting the finding of Xoplaki et al. (2018): the patterns of surface temperature and circulation over the Mediterranean during droughts in the control simulation is statistically indifferent from those of the transient simulation with full external forcing. A causal connection between volcanic eruptions and Mediterranean dry conditions was not identified, resembling findings of some previous studies, which indicate that past strong volcanic eruptions are more associated with wet events over the region (McConnell et al., 2020; Rao et al., 2017). One of the distinct patterns found during Mediterranean droughts is a barotropic high pressure system accompanied by a positive temperature anomaly over central Europe and the Mediterranean region. This warm high persists during all seasons when droughts occur over the region, showing stronger intensity during winter and spring. This result emphasizes the importance of the wet cold seasons, i.e. winter and spring climate and circulation in annual Mediterranean droughts. Other patterns occurring during droughts are the positive NAO and the cold Tropical Equatorial Pacific (La Niña-like condition).

Thirdly, the mechanisms associated with sustaining multi-years droughts change through the stages of droughts. We found that these large-scale circulation patterns, such as the positive NAO and negative ENSO, play a more important role during the early stage of droughts, by providing dry condition over the western and central Mediterranean region to initiate such events. Then, the longevity of droughts is determined by the interaction of regional circulation variables, which involve stable atmospheric conditions, a temperature increase, changes in evapotranspiration and surface heat fluxes. Namely, this is the temperature - soil moisture feedback, which continues until the termination of droughts. During these transition years of droughts, the role played by the large-scale patterns is reduced. Hence, the persistence and duration of multi-years droughts should not be fully attributed to the states of large-scale circulation patterns, such as NAO and ENSO, as the roles of regional feedback and circulations on droughts become as important as or more important than large-scale modes after the initial development of droughts.

The model inherent biases in representing ENSO and NAO (Bellenger et al., 2014; Fasullo et al., 2020) can have some implications in our results on the frequencies of ENSO and NAO at different stages of droughts. The model may produce too frequent and strong La Niña conditions and positive NAO during droughts due to its amplified, decadal for ENSO and seasonal for NAO, variability. Moreover, due to the uncertainty associated with the changes in these modes in the future scenario, caution is required when interpreting the connection between droughts and modes of variability in the future warming scenario. Nonetheless, this problem does not affect our conclusion: the roles of ENSO and NAO become weaker with the longevity of droughts, while the regional circulation and feedback become more dominant at maintaining the persistence of droughts, which is also found in the future warming scenario.

Fourthly, the decreases in soil moisture and precipitation anomalies are already detected since the pre-industrial period concomitantly with the anthropogenic increase in GHG. This means that the intensification of droughts and the shift of the mean climate over the region to a drier climate have already started since the pre-industrial era. This regional desiccation is principally caused by the anthropogenic increase in GHG, which induces the intensification of interactions between the regional atmospheric and soil variables, associated with the temperature- soil moisture and precipitation - soil moisture feedbacks. If the increase in temperature and decreases in precipitation continue, intensifying the depletion of soil moisture in the future, the region will suffer from a continuous desiccation instead of droughts, as droughts are the deviation from the mean hydrological condition.

Fifthly, it is important to mention that our analysis is based on a single model output and this raises questions related to single model studies, such as boundary condition problems and model-dependent biases and physics (PAGES Hydro2k Consortium, 2017). Nevertheless, for a small confined area that surrounds a large body of water mass, the Mediterranean Sea, and the land coverage is limited, we found the necessity to use a simulation with a finer resolution to represent the regional climate better. In the end, our study provides a useful understanding on the long-term variability and mechanisms of Mediterranean droughts by analyzing the entire last millennium. We addressed the influences of external and internal variability on Mediterranean droughts and distinctly different roles of the large-scale modes of variability and regional circulation during the different stages of multi-year droughts.

Lastly, we emphasize again the importance of assessing different drought indices in the paleoclimate context, but also in the present and future warming scenario. Assessing different drought metrics is important for drought studies, as the most commonly used drought indices are based on water balance only from the atmospheric moisture supply and demand, and they tend to magnify drought risks in the future warming scenario (Berg et al., 2017; Mukherjee et al., 2018; Swann et al., 2016). For a more comprehensive picture, droughts need be quantified with indices that can also reflect water stress on plants and ecosystem, and complex interactions among soil, atmosphere and vegetation. We used the upper 10 cm soil moisture anomaly to partially tackle this issue and derived spatial patterns associated with Mediterranean droughts based on this index. Still, the upper 10 cm soil moisture does not fully involve a complex interaction in the soil and atmosphere occurring during droughts. As vegetation is known to have more complex responses to the changing climate and droughts (Swann, 2018; Swann et al., 2016), the role of vegetation in extreme hydrological events can provide a more comprehensive view on drought mechanisms.

The Mediterranean region is considered as one of the most vulnerable regions under the current climate change scenario (e.g. Giorgi and Lionello, 2008; Lehner et al., 2017) and human impacts can modify the natural mechanisms and propagation of droughts (Van Loon et al., 2016), increasing droughts risks and water shortage issues over the region. Hence, more studies on the topics related to droughts and permanent future desiccation in the Mediterranean region including the role of vegetation are necessary to develop a better preparedness for upcoming changes.

Code availability. Two R packages were used to calculate the drought indices: the *scPDSI* (Zhong et al., 2018) and the *SPEI* (Vicente-Serrano et al., 2009). The *biwavelet* (Gouhier et al., 2018) was used for the wavelength coherence analysis.

Data availability. The summer scPDSI from the Old World Drought Atlas (Cook et al., 2015) and the Sea Surface Temperature ERSST v5 (Huang et al., 2017) are available on https://www.ncdc.noaa.gov/ . The 20th Century Reanalysis V2 (Compo et al., 2011) and UDel_AirT_Precip data (Willmott and Matsuura, 2001) are provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at https://psl.noaa.gov/. The CESM simulations (Lehner et al., 2015) are available on request at the University of Bern.

Author contributions. WK and CR discussed and set up the initial research idea. WK performed the analysis and drafted the manuscript under the supervision of CR. CR provided critical feedback on the results and the manuscript. Both authors contributed to the interpretation and discussion of the results and edited the manuscript together.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. The study is funded by the Swiss National Science Foundation (SNSF, grant 200020_172745). We acknowledge that some simulations were performed at the Swiss National Super Computing Centre (CSCS). Support for the Twentieth Century Reanalysis Project dataset is provided by the U.S. Department of Energy, Office of Science Innovative and Novel Computational Impact on Theory and Experiment (DOE INCITE) program, and Office of Biological and Environmental Research (BER), by the National Oceanic and Atmospheric Administration Climate Program Office, and by the National Oceanic and Atmospheric Administration Climate Program Office, and by the NOAA Physical Sciences Laboratory. The 20th Century Reanalysis V2 and UDel_AirT_Precip data are provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at https://psl.noaa.gov/

References

Alpert, P., Neeman, B., and Shay-El, Y.: Climatological analysis of Mediterranean cyclones using ECMWF data, Tellus A: Dynamic Meteorology and Oceanography, 42, 65–77, https://doi.org/10.3402/tellusa.v42i1.11860, 1990.

Babst, F., Bodesheim, P., Charney, N., Friend, A. D., Girardin, M. P., Klesse, S., Moore, D. J., Seftigen, K., Björklund, J., Bouriaud, O., et al.: When tree rings go global: challenges and opportunities for retro-and prospective insight, Quaternary Science Reviews, 197, 1–20, https://doi.org/10.1016/j.quascirev.2018.07.009, 2018.

Barnston, A. G. and Livezey, R. E.: Classification, seasonality and persistence of low-frequency atmospheric circulation patterns, Monthly weather review, 115, 1083–1126, https://doi.org/10.1175/1520-0493(1987)115<1083:CSAPOL>2.0.CO;2, 1987.

Bellenger, H., Guilyardi, É., Leloup, J., Lengaigne, M., and Vialard, J.: ENSO representation in climate models: From CMIP3 to CMIP5, Climate Dynamics, 42, 1999–2018, https://doi.org/10.1007/s00382-013-1783-z, 2014.

Berg, A., Sheffield, J., and Milly, P. C.: Divergent surface and total soil moisture projections under global warming, Geophysical Research Letters, 44, 236–244, https://doi.org/10.1002/2016GL071921, 2017.

Brönnimann, S.: Impact of El Niño–southern oscillation on European climate, Reviews of Geophysics, 45, https://doi.org/10.1029/2006RG000199, 2007.

Brönnimann, S., Xoplaki, E., Casty, C., Pauling, A., and Luterbacher, J.: ENSO influence on Europe during the last centuries, Climate Dynamics, 28, 181–197, https://doi.org/10.1007/s00382-006-0175-z, 2007.

Champion, A. J., Hodges, K. I., Bengtsson, L. O., Keenlyside, N. S., and Esch, M.: Impact of increasing resolution and a warmer climate on extreme weather from Northern Hemisphere extratropical cyclones, Tellus A: Dynamic meteorology and oceanography, 63, 893–906, https://doi.org/10.1111/j.1600-0870.2011.00538.x, 2011.

Coats, S. and Karnauskas, K.: Are simulated and observed twentieth century tropical Pacific sea surface temperature trends significant relative to internal variability?, Geophysical Research Letters, 44, 9928–9937, https://doi.org/10.1002/2017GL074622, 2017.

Coats, S., Smerdon, J. E., Seager, R., Cook, B. I., and González-Rouco, J. F.: Megadroughts in southwestern North America in ECHO-G millennial simulations and their comparison to proxy drought reconstructions, Journal of climate, 26, 7635–7649, https://doi.org/10.1175/JCLI-D-12-00603.1, 2013.

Coats, S., Smerdon, J. E., Cook, B., Seager, R., Cook, E. R., and Anchukaitis, K. J.: Internal ocean-atmosphere variability drives megadroughts in Western North America, Geophysical research letters, 43, 9886–9894, https://doi.org/10.1002/2016GL070105, 2016.

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., Gleason, B. E., Vose, R. S., Rutledge, G., Bessemoulin, P., et al.: The twentieth century reanalysis project, Quarterly Journal of the Royal Meteorological Society, 137, 1–28, https://doi.org/10.1002/qj.776, 2011.

Cook, B. I., Anchukaitis, K. J., Touchan, R., Meko, D. M., and Cook, E. R.: Spatiotemporal drought variability in the Mediterranean over the last 900 years, Journal of Geophysical Research: Atmospheres, 121, 2060–2074, https://doi.org/10.1002/2015JD023929, 2016a.

Cook, B. I., Cook, E. R., Smerdon, J. E., Seager, R., Williams, A. P., Coats, S., Stahle, D. W., and Díaz, J. V.: North American megadroughts in the Common Era: Reconstructions and simulations, Wiley Interdisciplinary Reviews: Climate Change, 7, 411–432, https://doi.org/10.1002/wcc.394, 2016b.

Cook, B. I., Mankin, J. S., and Anchukaitis, K. J.: Climate Change and Drought: From Past to Future, Current Climate Change Reports, 4, 164–179, https://doi.org/10.1007/s40641-018-0093-2, 2018.

Cook, E. R., Seager, R., Kushnir, Y., Briffa, K. R., Büntgen, U., Frank, D., Krusic, P. J., Tegel, W., van der Schrier, G., Andreu-Hayles, L., et al.: Old World megadroughts and pluvials during the Common Era, Science advances, 1, e1500 561, https://doi.org/10.1126/sciadv.1500561, 2015.

Dai, A.: Drought under global warming: a review, Wiley Interdisciplinary Reviews: Climate Change, 2, 45–65, https://doi.org/10.1002/wcc.81, 2011.

Deser, C., Hurrell, J. W., and Phillips, A. S.: The role of the North Atlantic Oscillation in European climate projections, Climate dynamics, 49, 3141–3157, https://doi.org/10.1007/s00382-016-3502-z, 2017.

Dubrovský, M., Hayes, M., Duce, P., Trnka, M., Svoboda, M., and Zara, P.: Multi-GCM projections of future drought and climate variability indicators for the Mediterranean region, Regional Environmental Change, 14, 1907–1919, https://doi.org/10.1007/s10113-013-0562-z, 2014.

Dünkeloh, A. and Jacobeit, J.: Circulation dynamics of Mediterranean precipitation variability 1948–98, International Journal of Climatology: A Journal of the Royal Meteorological Society, 23, 1843–1866, https://doi.org/10.1002/joc.973, 2003.

Fasullo, J. T., Phillips, A., and Deser, C.: Evaluation of Leading Modes of Climate Variability in the CMIP Archives, Journal of Climate, 33, 5527–5545, https://doi.org/10.1175/JCLI-D-19-1024.1, 2020.

Field, C. B., Barros, V., Stocker, T. F., and Dahe, Q.: Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change, Cambridge University Press, 2012.

Franke, J., Frank, D., Raible, C. C., Esper, J., and Brönnimann, S.: Spectral biases in tree-ring climate proxies, Nature Climate Change, 3, 360–364, https://doi.org/10.1038/nclimate1816, 2013.

Gao, C., Robock, A., and Ammann, C.: Volcanic forcing of climate over the past 1500 years: An improved ice core-based index for climate models, Journal of Geophysical Research: Atmospheres, 113, https://doi.org/10.1029/2008JD010239, 2008.

García-Herrera, R., Garrido-Perez, J. M., Barriopedro, D., Ordóñez, C., Vicente-Serrano, S. M., Nieto, R., Gimeno, L., Sorí, R., and Yiou, P.: The European 2016/17 Drought, Journal of Climate, 32, 3169–3187, https://doi.org/10.1175/JCLI-D-18-0331.1, 2019.

Giorgi, F.: Climate change hot-spots, Geophysical research letters, 33, https://doi.org/10.1029/2006GL025734, 2006.

Giorgi, F. and Lionello, P.: Climate change projections for the Mediterranean region, Global and Planetary Change, 63, 90–104, https://doi.org/10.1016/j.gloplacha.2007.09.005, 2008.

Gouhier, T. C., Grinsted, A., and Simko, V.: R package biwavelet: Conduct Univariate and Bivariate Wavelet Analyses, https://github.com/tgouhier/biwavelet, (Version 0.20.17), 2018.

Grinsted, A., Moore, J. C., and Jevrejeva, S.: Application of the cross wavelet transform and wavelet coherence to geophysical time series, Nonlinear Processes in Geophysics, 11, 561–566, https://hal.archives-ouvertes.fr/hal-00302394, publisher: European Geosciences Union (EGU), 2004.

Haywood, A. M., Valdes, P. J., Aze, T., Barlow, N., Burke, A., Dolan, A. M., von der Heydt, A. S., Hill, D. J., Jamieson, S. S. R., Otto-Bliesner, B. L., Salzmann, U., Saupe, E., and Voss, J.: What can Palaeoclimate Modelling do for you?, Earth Systems and Environment, 3, 1–18, https://doi.org/10.1007/s41748-019-00093-1, 2019.

Hoerling, M., Eischeid, J., Perlwitz, J., Quan, X., Zhang, T., and Pegion, P.: On the Increased Frequency of Mediterranean Drought, Journal of Climate, 25, 2146–2161, https://doi.org/10.1175/JCLI-D-11-00296.1, 2011.

Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore, J. H., Menne, M. J., Smith, T. M., Vose, R. S., and Zhang, H.-M.: Extended reconstructed sea surface temperature, version 5 (ERSSTv5): upgrades, validations, and intercomparisons, Journal of Climate, 30, 8179–8205, https://doi.org/10.1175/JCLI-D-16-0836.1, 2017.

Hurrell, J. W.: Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation, Science, 269, 676–679, https://doi.org/10.1126/science.269.5224.676, 1995.

Krichak, S. O. and Alpert, P.: Decadal trends in the east Atlantic–west Russia pattern and Mediterranean precipitation, International journal of climatology: a journal of the Royal Meteorological Society, 25, 183–192, https://doi.org/10.1002/joc.1124, 2005.

Lehner, F., Joos, F., Raible, C. C., Mignot, J., Born, A., Keller, K. M., and Stocker, T. F.: Climate and carbon cycle dynamics in a CESM simulation from 850 to 2100 CE, Earth System Dynamics, 6, 411–434, https://doi.org/10.5194/esd-6-411-2015, 2015.

Lehner, F., Coats, S., Stocker, T. F., Pendergrass, A. G., Sanderson, B. M., Raible, C. C., and Smerdon, J. E.: Projected drought risk in 1.5°C and 2°C warmer climates, Geophysical Research Letters, 44, 7419–7428, https://doi.org/10.1002/2017GL074117, 2017.

Li, W., Li, L., Ting, M., and Liu, Y.: Intensification of Northern Hemisphere subtropical highs in a warming climate, Nature Geoscience, 5, 830–834, https://doi.org/10.1038/ngeo1590, 2012.

Lionello, P., Malanotte-Rizzoli, P., Boscolo, R., Alpert, P., Artale, V., Li, L., Luterbacher, J., May, W., Trigo, R., Tsimplis, M., Ulbrich, U., and Xoplaki, E.: The Mediterranean climate: An overview of the main characteristics and issues, in: Developments in Earth and Environmental Sciences, edited by Lionello, P., Malanotte-Rizzoli, P., and Boscolo, R., vol. 4 of *Mediterranean*, pp. 1–26, Elsevier, https://doi.org/10.1016/S1571-9197(06)80003-0, 2006.

Lionello, P., Trigo, I. F., Gil, V., Liberato, M. L., Nissen, K. M., Pinto, J. G., Raible, C. C., Reale, M., Tanzarella, A., Trigo, R. M., et al.: Objective climatology of cyclones in the Mediterranean region: a consensus view among methods with different system identification and tracking criteria, Tellus A: Dynamic Meteorology and Oceanography, 68, 29 391, https://doi.org/10.3402/tellusa.v68.29391, 2016.

Liu, W., Sun, F., Lim, W. H., Zhang, J., Wang, H., Shiogama, H., and Zhang, Y.: Global drought and severe drought-affected populations in 1.5 and 2 C warmer worlds, Earth System Dynamics, 9, 267, https://doi.org/10.5194/esd-9-267-2018, 2018.

Ljungqvist, F. C., Seim, A., Krusic, P. J., González-Rouco, J. F., Werner, J. P., Cook, E. R., Zorita, E., Luterbacher, J., Xoplaki, E., Destouni, G., García-Bustamante, E., Aguilar, C. A. M., Seftigen, K., Wang, J., Gagen, M. H., Esper, J., Solomina, O., Fleitmann, D., and Büntgen, U.: European warm-season temperature and hydroclimate since 850 CE, Environmental Research Letters, 14, 084 015, https://doi.org/10.1088/1748-9326/ab2c7e, 2019.

Lloyd-Hughes, B.: The impracticality of a universal drought definition, Theoretical and Applied Climatology, 117, 607–611, https://doi.org/10.1007/s00704-013-1025-7, 2014.

Mariotti, A., Zeng, N., and Lau, K.-M.: Euro-Mediterranean rainfall and ENSO—a seasonally varying relationship, Geophysical research letters, 29, 59–1, https://doi.org/10.1029/2001GL014248, 2002.

Mariotti, A., Zeng, N., Yoon, J.-H., Artale, V., Navarra, A., Alpert, P., and Li, L. Z.: Mediterranean water cycle changes: transition to drier 21st century conditions in observations and CMIP3 simulations, Environmental Research Letters, 3, 044 001, https://doi.org/10.1088/1748-9326/3/4/044001, 2008.

McConnell, J. R., Sigl, M., Plunkett, G., Burke, A., Kim, W. M., Raible, C. C., Wilson, A. I., Manning, J. G., Ludlow, F., Chellman, N. J., et al.: Extreme climate after massive eruption of Alaska's Okmok volcano in 43 BCE and effects on the late Roman Republic and Ptolemaic Kingdom, Proceedings of the National Academy of Sciences, 117, 15 443–15 449, https://doi.org/10.1073/pnas.2002722117, 2020.

McKee, T. B., Doesken, N. J., Kleist, J., et al.: The relationship of drought frequency and duration to time scales, in: Proceedings of the 8th Conference on Applied Climatology, vol. 17, pp. 179–183, American Meteorological Society Boston, MA, 1993.

Mishra, A. K. and Singh, V. P.: A review of drought concepts, Journal of hydrology, 391, 202–216, https://doi.org/10.1016/j.jhydrol.2010.07.012, 2010.

Mukherjee, S., Mishra, A., and Trenberth, K. E.: Climate Change and Drought: a Perspective on Drought Indices, Current Climate Change Reports, 4, 145–163, https://doi.org/10.1007/s40641-018-0098-x, 2018.

Namias, J.: Factors in the initiation, perpetuation and termination of drought, International Association of Scientific Hydrology Commission on Surface Waters Publication, 51, 81–94, 1960.

Naumann, G., Alfieri, L., Wyser, K., Mentaschi, L., Betts, R., Carrao, H., Spinoni, J., Vogt, J., and Feyen, L.: Global changes in drought conditions under different levels of warming, Geophysical Research Letters, 45, 3285–3296, https://doi.org/10.1002/2017GL076521, 2018.

Otto-Bliesner, B. L., Brady, E. C., Fasullo, J., Jahn, A., Landrum, L., Stevenson, S., Rosenbloom, N., Mai, A., and Strand, G.: Climate variability and change since 850 CE: An ensemble approach with the Community Earth System Model, Bulletin of the American Meteorological Society, 97, 735–754, https://doi.org/10.1175/BAMS-D-14-00233.1, 2016.

PAGES Hydro2k Consortium: Comparing proxy and model estimates of hydroclimate variability and change over the Common Era. Clim Past 13: 1851–1900, https://doi.org/10.5194/cp-13-1851-2017, 2017.

Palmer, W. C.: Meteorological drought, vol. 30, US Department of Commerce, Weather Bureau, 1965.

Parsons, L. A. and Coats, S.: Ocean-atmosphere trajectories of extended drought in Southwestern North America, Journal of Geophysical Research: Atmospheres, 124, 8953–8971, https://doi.org/10.1029/2019JD030424, 2019.

Parsons, L. A., Loope, G. R., Overpeck, J. T., Ault, T. R., Stouffer, R., and Cole, J. E.: Temperature and precipitation variance in CMIP5 simulations and paleoclimate records of the last millennium, Journal of Climate, 30, 8885–8912, https://doi.org/10.1175/JCLI-D-16-0863.1, 2017.

Parsons, L. A., Coats, S., and Overpeck, J. T.: The continuum of drought in Southwestern North America, Journal of Climate, 31, 8627–8643, https://doi.org/10.1175/JCLI-D-18-0010.1, 2018.

Philandras, C., Nastos, P., Kapsomenakis, J., Douvis, K., Tselioudis, G., and Zerefos, C.: Long term precipitation trends and variability within the Mediterranean region, Natural Hazards and Earth System Sciences, 11, 3235, https://doi.org/10.5194/nhess-11-3235-2011, 2011.

Previdi, M. and Liepert, B. G.: Annular modes and Hadley cell expansion under global warming, Geophysical Research Letters, 34, https://doi.org/10.1029/2007GL031243, 2007.

Raible, C.: On the relation between extremes of midlatitude cyclones and the atmospheric circulation using ERA40, Geophysical research letters, 34, https://doi.org/10.1029/2006GL029084, 2007.

Raible, C., Luksch, U., Fraedrich, K., and Voss, R.: North Atlantic decadal regimes in a coupled GCM simulation, Climate Dynamics, 18, 321–330, 2001.

Raible, C., Yoshimori, M., Stocker, T., and Casty, C.: Extreme midlatitude cyclones and their implications for precipitation and wind speed extremes in simulations of the Maunder Minimum versus present day conditions, Climate Dynamics, 28, 409–423, https://doi.org/0.1007/s00382-006-0188-7, 2007.

Raible, C. C., Luksch, U., and Fraedrich, K.: Precipitation and northern hemisphere regimes, Atmospheric Science Letters, 5, 43–55, https://doi.org/10.1016/j.atmoscilet.2003.12.001, 2003.

Raible, C. C., Ziv, B., Saaroni, H., and Wild, M.: Winter synoptic-scale variability over the Mediterranean Basin under future climate conditions as simulated by the ECHAM5, Climate dynamics, 35, 473–488, https://doi.org/10.1007/s00382-009-0678-5, 2010.

Raible, C. C., Bärenbold, O., and Gómez-navarro, J. J.: Drought indices revisited – improving and testing of drought indices in a simulation of the last two millennia for Europe, Tellus A: Dynamic Meteorology and Oceanography, 69, 1287 492, https://doi.org/10.1080/16000870.2017.1296226, 2017.

Rao, M. P., Cook, B. I., Cook, E. R., D'Arrigo, R. D., Krusic, P. J., Anchukaitis, K. J., LeGrande, A. N., Buckley, B. M., Davi, N. K., Leland, C., and Griffin, K. L.: European and Mediterranean hydroclimate responses to tropical volcanic forcing over the last millennium, Geophysical Research Letters, 44, 5104–5112, https://doi.org/10.1002/2017GL073057, 2017.

Schmidt, G. A., Jungclaus, J. H., Ammann, C. M., Bard, E., Braconnot, P., Crowley, T. J., Delaygue, G., Joos, F., Krivova, N. A., Muscheler, R., Otto-Bliesner, B. L., Pongratz, J., Shindell, D. T., Solanki, S. K., Steinhilber, F., and Vieira, L. E. A.: Climate forcing reconstructions for use in PMIP simulations of the Last Millennium (v1.1), Geoscientific Model Development, pp. 185–191, https://doi.org/10.5194/gmd-5-185-2012, 2012.

Seager, R., Liu, H., Henderson, N., Simpson, I., Kelley, C., Shaw, T., Kushnir, Y., and Ting, M.: Causes of Increasing Aridification of the Mediterranean Region in Response to Rising Greenhouse Gases, Journal of Climate, 27, 4655–4676, https://doi.org/10.1175/JCLI-D-13-00446.1, 2014.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A. J.: Investigating soil moisture–climate interactions in a changing climate: A review, Earth-Science Reviews, 99, 125–161, https://doi.org/10.1016/j.earscirev.2010.02.004, 2010.

Sousa, P. M., Trigo, R. M., Aizpurua, P., Nieto, R., Gimeno, L., and Garcia-Herrera, R.: Trends and extremes of drought indices throughout the 20th century in the Mediterranean, Natural Hazards and Earth System Sciences, 11, 33–51, https://doi.org/10.5194/nhess-11-33-2011, 2011.

Spinoni, J., Naumann, G., Vogt, J. V., and Barbosa, P.: The biggest drought events in Europe from 1950 to 2012, Journal of Hydrology: Regional Studies, 3, 509–524, https://doi.org/10.1016/j.ejrh.2015.01.001, 2015.

Spinoni, J., Naumann, G., and Vogt, J. V.: Pan-European seasonal trends and recent changes of drought frequency and severity, Global and Planetary Change, 148, 113–130, https://doi.org/10.1016/j.gloplacha.2016.11.013, 2017.

Stevenson, S., Overpeck, J. T., Fasullo, J., Coats, S., Parsons, L., Otto-Bliesner, B., Ault, T., Loope, G., and Cole, J.: Climate variability, volcanic forcing, and last millennium hydroclimate extremes, Journal of Climate, 31, 4309–4327, https://doi.org/10.1175/JCLI-D-17-0407.1, 2018.

Swann, A. L.: Plants and drought in a changing climate, Current Climate Change Reports, 4, 192–201, https://doi.org/10.1007/s40641-018-0097-y, 2018.

Swann, A. L., Hoffman, F. M., Koven, C. D., and Randerson, J. T.: Plant responses to increasing CO2 reduce estimates of climate impacts on drought severity, Proceedings of the National Academy of Sciences, 113, 10 019–10 024, https://doi.org/10.1073/pnas.1604581113, 2016.

Thornthwaite, C. W. et al.: An approach toward a rational classification of climate, Geographical review, 38, 55–94, https://doi.org/10.2307/210739, 1948.

Trenberth, K. E.: The Definition of El Niño, Bulletin of the American Meteorological Society, 78, 2771–2778, https://doi.org/10.1175/1520-0477(1997)078<2771:TDOENO>2.0.CO;2, 1997.

Trigo, R., Osborn, T., and Corte-Real, J.: The North Atlantic Oscillation influence on Europe: climate impacts and associated physical mechanisms, Climate Research, 20, 9–17, https://doi.org/10.3354/cr020009, 2002.

Ulbrich, U., Leckebusch, G., and Pinto, J. G.: Extra-tropical cyclones in the present and future climate: a review, Theoretical and Applied Climatology, 96, 117–131, https://doi.org/10.1007/s00704-008-0083-8, 2009.

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A. J., Tallaksen, L. M., Uijlenhoet, R., et al.: Drought in the Anthropocene, Nature Geoscience, 9, 89, https://doi.org/10.1038/ngeo2646, 2016.

Vicente-Serrano, S. M.: El Niño and La Niña influence on droughts at different timescales in the Iberian Peninsula, Water Resources Research, 41, https://doi.org/10.1029/2004WR003908, 2005.

Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index, Journal of Climate, 23, 1696–1718, https://doi.org/10.1175/2009JCLI2909.1, 2009.

Vicente-Serrano, S. M., Beguería, S., López-Moreno, J. I., Angulo, M., and El Kenawy, A.: A new global 0.5 gridded dataset (1901–2006) of a multiscalar drought index: comparison with current drought index datasets based on the Palmer Drought Severity Index, Journal of Hydrometeorology, 11, 1033–1043, https://doi.org/10.1175/2010JHM1224.1, 2010.

Vicente-Serrano, S. M., Lopez-Moreno, J.-I., Beguería, S., Lorenzo-Lacruz, J., Arturo Sanchez-Lorenzo, García-Ruiz, J. M., Azorin-Molina, C., Morán-Tejeda, E., Revuelto, J., Ricardo Trigo, Coelho, F., and Espejo, F.: Evidence of increasing drought severity caused by temperature rise in southern Europe, Environmental Research Letters, 9, 044 001, https://doi.org/10.1088/1748-9326/9/4/044001, 2014.

Vicente-Serrano, S. M., Van der Schrier, G., Beguería, S., Azorin-Molina, C., and Lopez-Moreno, J.-I.: Contribution of precipitation and reference evapotranspiration to drought indices under different climates, Journal of Hydrology, 526, 42–54, https://doi.org/10.1016/j.jhydrol.2014.11.025, 2015.

Wallace, J. M. and Gutzler, D. S.: Teleconnections in the Geopotential Height Field during the Northern Hemisphere Winter, Monthly Weather Review, 109, 784–812, https://doi.org/10.1175/1520-0493(1981)109<0784:TITGHF>2.0.CO;2, 1981.

Wang, W., Ertsen, M. W., Svoboda, M. D., and Hafeez, M.: Propagation of drought: from meteorological drought to agricultural and hydrological drought, https://doi.org/10.1155/2016/6547209, 2016.

Watterson, I.: The intensity of precipitation during extratropical cyclones in global warming simulations: a link to cyclone intensity?, Tellus A: Dynamic Meteorology and Oceanography, 58, 82–97, https://doi.org/j.1600-0870.2006.00147.x, 2006.

Wells, N., Goddard, S., and Hayes, M. J.: A Self-Calibrating Palmer Drought Severity Index, Journal of Climate, 17, 2335–2351, https://doi.org/10.1175/1520-0442(2004)017<2335:ASPDSI>2.0.CO;2, 2004.

Wilhite, D.: Understanding the Phenomenon of Drought, Drought Mitigation Center Faculty Publications, https://digitalcommons.unl.edu/droughtfacpub/50, 1993.

Willmott, C. J. and Matsuura, K.: Terrestrial air temperature and precipitation: Monthly and annual time series (1950–1999) Version 1.02, Center for Climatic Research, University of Delaware, Newark, 2001.

Xoplaki, E., González-Rouco, J. F., Luterbacher, J., and Wanner, H.: Mediterranean summer air temperature variability and its connection to the large-scale atmospheric circulation and SSTs, Climate Dynamics, 20, 723–739, https://doi.org/10.1007/s00382-003-0304-x, 2003.

Xoplaki, E., González-Rouco, J., Luterbacher, J., and Wanner, H.: Wet season Mediterranean precipitation variability: influence of large-scale dynamics and trends, Climate dynamics, 23, 63–78, 2004.

Xoplaki, E., Luterbacher, J., Wagner, S., Zorita, E., Fleitmann, D., Preiser-Kapeller, J., Sargent, A. M., White, S., Toreti, A., Haldon, J. F., Mordechai, L., Bozkurt, D., Akçer-Ön, S., and Izdebski, A.: Modelling Climate and Societal Resilience in the Eastern Mediterranean in the Last Millennium, Human Ecology, 46, 363–379, https://doi.org/10.1007/s10745-018-9995-9, 2018.

Yin, D., Roderick, M. L., Leech, G., Sun, F., and Huang, Y.: The contribution of reduction in evaporative cooling to higher surface air temperatures during drought, Geophysical Research Letters, 41, 7891–7897, https://doi.org/10.1002/2014GL062039, 2014.

Zhong, R., Chen, X., Wang, Z., and Lai, C.: scPDSI: Calculation of the Conventional and Self-Calibrating Palmer Drought Severity Index, https://CRAN.R-project.org/package=scPDSI, r package version 0.1.3, 2018.

Zhu, Y., Liu, Y., Wang, W., Singh, V. P., Ma, X., and Yu, Z.: Three dimensional characterization of meteorological and hydrological droughts and their probabilistic links, Journal of Hydrology, 578, 124 016, https://doi.org/10.1016/j.jhydrol.2019.124016, 2019.

Zveryaev, I. I.: Seasonality in precipitation variability over Europe, Journal of Geophysical Research: Atmospheres, 109, https://doi.org/10.1029/2003JD003668, 2004.

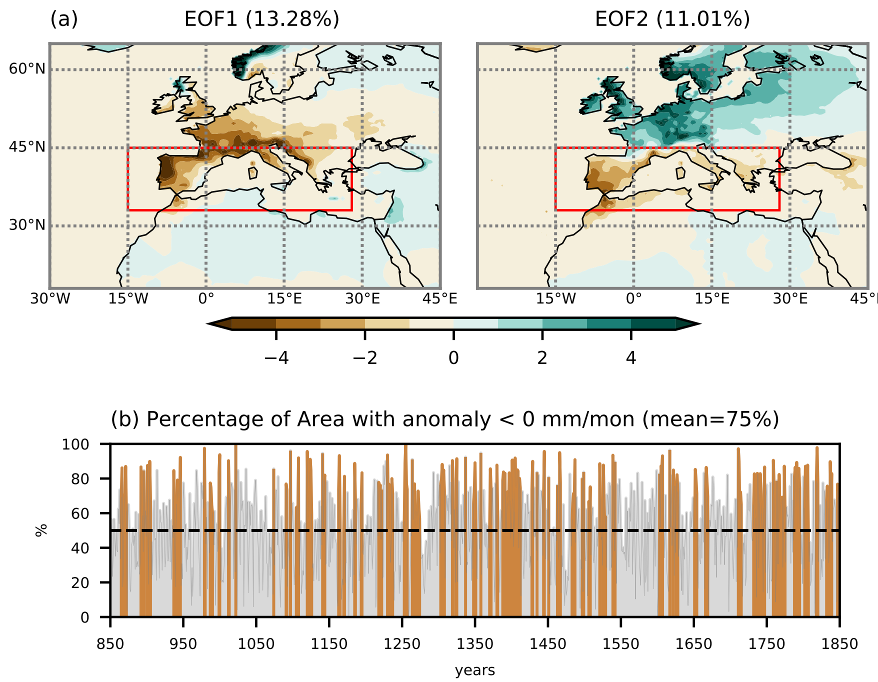

Figure 1. (a) Variance explained by the first EOF and second EOF in the observed monthly precipitation from U.Delaware v5.01 dataset for the period of 1901 – 2000 AD. The red rectangle indicates our region of study: west- and central Mediterranean. (b) Percentage of area with the soil moisture anomaly below 0 mm.mon^{-1} in the region of study during the last millennium in CESM. Shaded in brown indicates years with droughts.

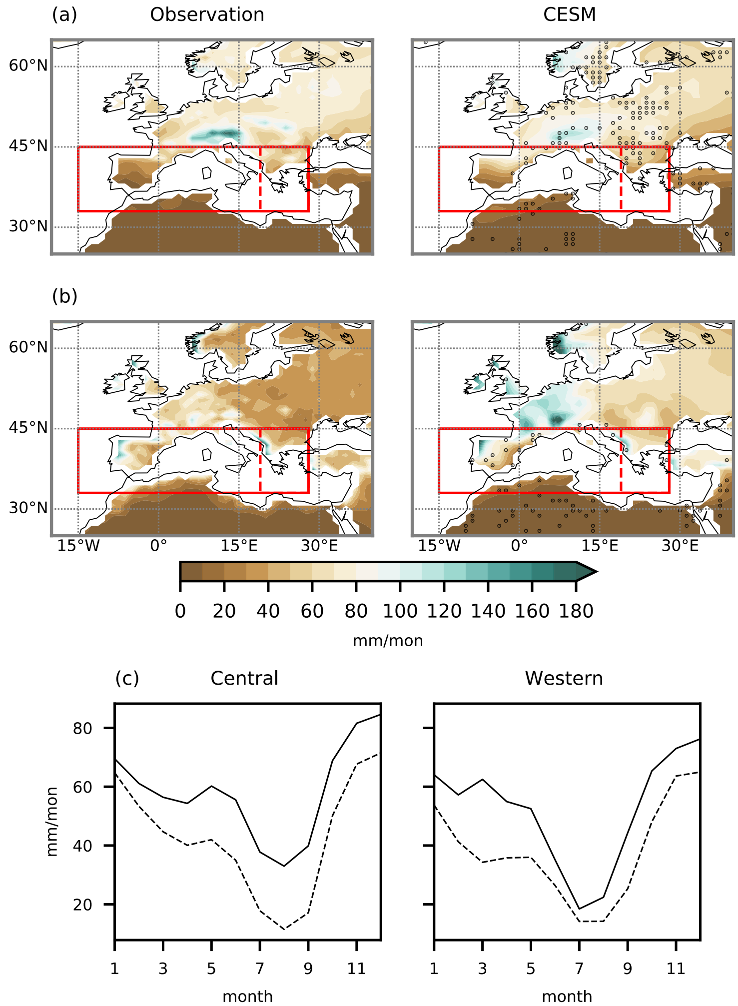

Figure 2. Mean seasonal precipitation for the observation (left) and CESM (right) in the (a) summer and (b) winter for the period of 1901 – 2000 AD. Black dots on the composites of CESM indicate the regions where the means between the observation and model are not statistically similar at 5% confidence level. (c) Mean annual cycles of precipitation for the same period over the areas in the rectangles. The observation is in continuous lines and CESM in dashed lines.

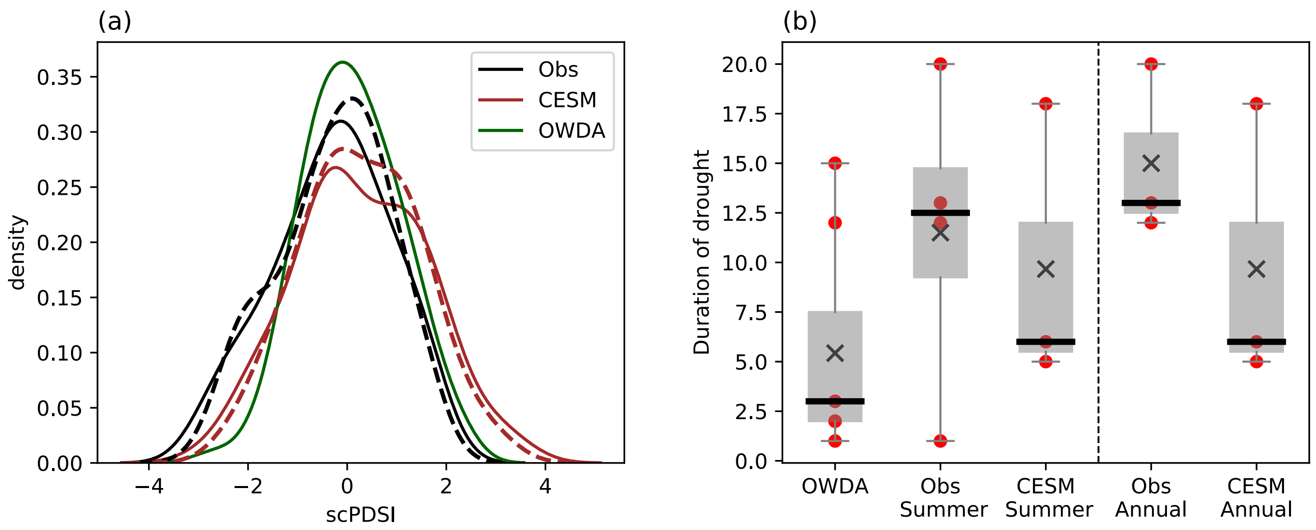

Figure 3. (a) Probabilistic distribution of monthly self-calibrated Palmer Drought Severity Indices (scPDSI) from the observation (black), CESM (red) and OWDA (green) smoothed by kernel density estimate using Gaussian kernels. Continuous lines indicate the summer and dashed lines the annual scPDSIs. The p-value from the t-student test between the summer scPDSI from CESM and OWDA is 0.28. The p-value between the OWDA and observation is 0.01, and between the CESM and Observation for the summer and annual, both p-values are 0.001. (b) Distribution of duration of annual-scale droughts in different datasets. Red points on each box shows the data points, thus number of droughts, black lines are the medians and crosses are the mean values of duration.

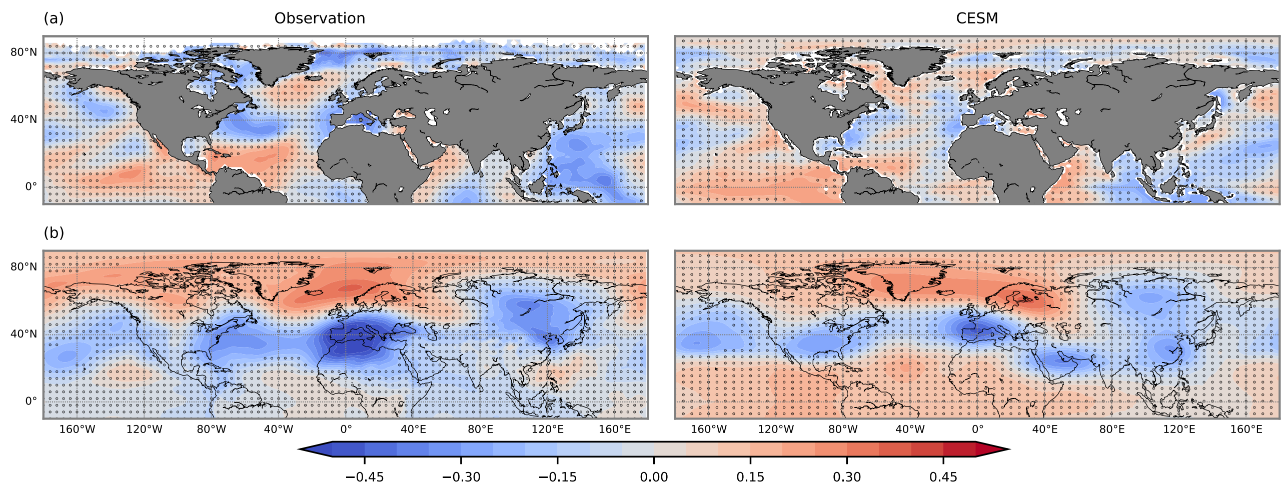

Figure 4. Maps of Pearson correlation between the scPDSI and anomalies of (a) Sea Surface Temperature from ERSST v5 and (b) Geopotential height at 850 hPa from the CR21 for the observation (left) and CESM (right) during the period of 1901-2000 AD. The linear trends of variables are removed before applying the correlation. Black dots on the maps show the regions where correlations are statistically not significant at 5% confidence level.

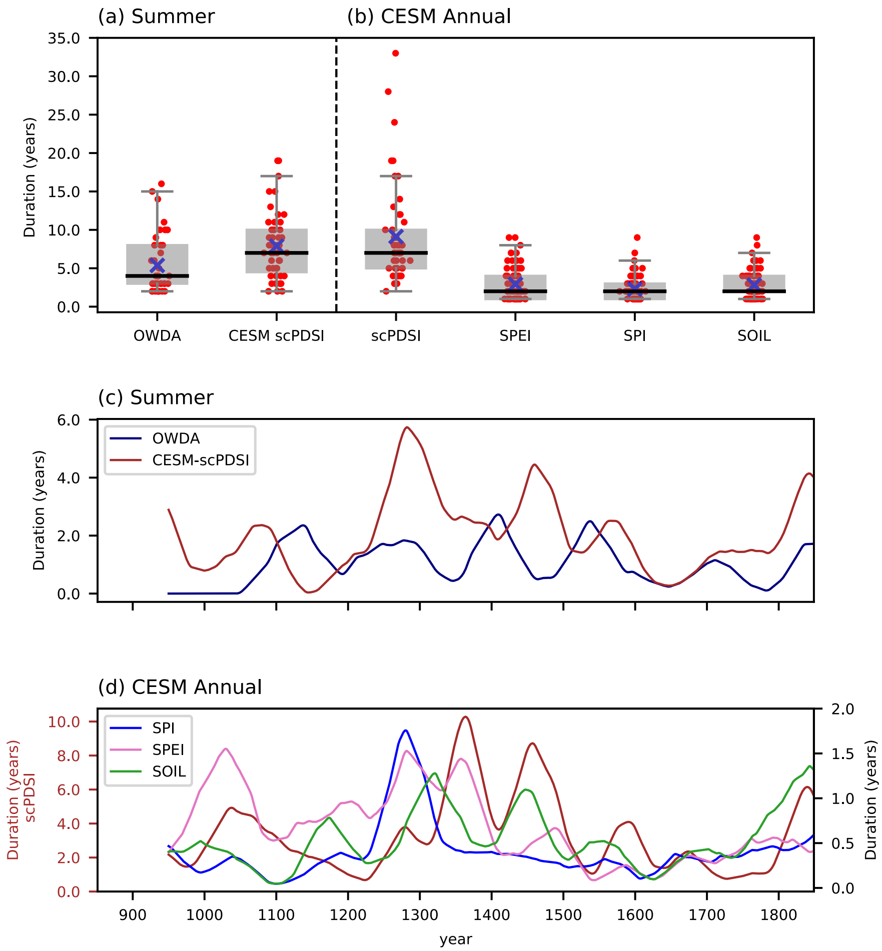

Figure 5. (a) Distribution of duration of droughts for the summer scPDSIs in OWDA and CESM, and for (b) the annual drought indices in CESM during 850 – 1849 AD. Red points indicate individual drought events, black lines on the boxes are the medians and blue crosses are the means of duration. (c) 100-years running means of duration of droughts for the summer scPDSIs and (d) the annual drought indices. The indices are the scPDSI from Old World Drought Atlas (OWDA), summer scPDSI from CESM (CESM-scPDSI), annual Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), soil moisture anomaly (SOIL), and annual scPDSI. Note that the annual scPDSI (brown line in (d)) has a separate y-axis for its duration. The p-value from Mann-Whitney U-test between the duration of summer scPDSI in OWDA and CESM is 0.003, which indicates the means are statistically different. For the annual indices, the means are also statistically different among each other, except between the SPEI and SOIL (p-value of 0.87).

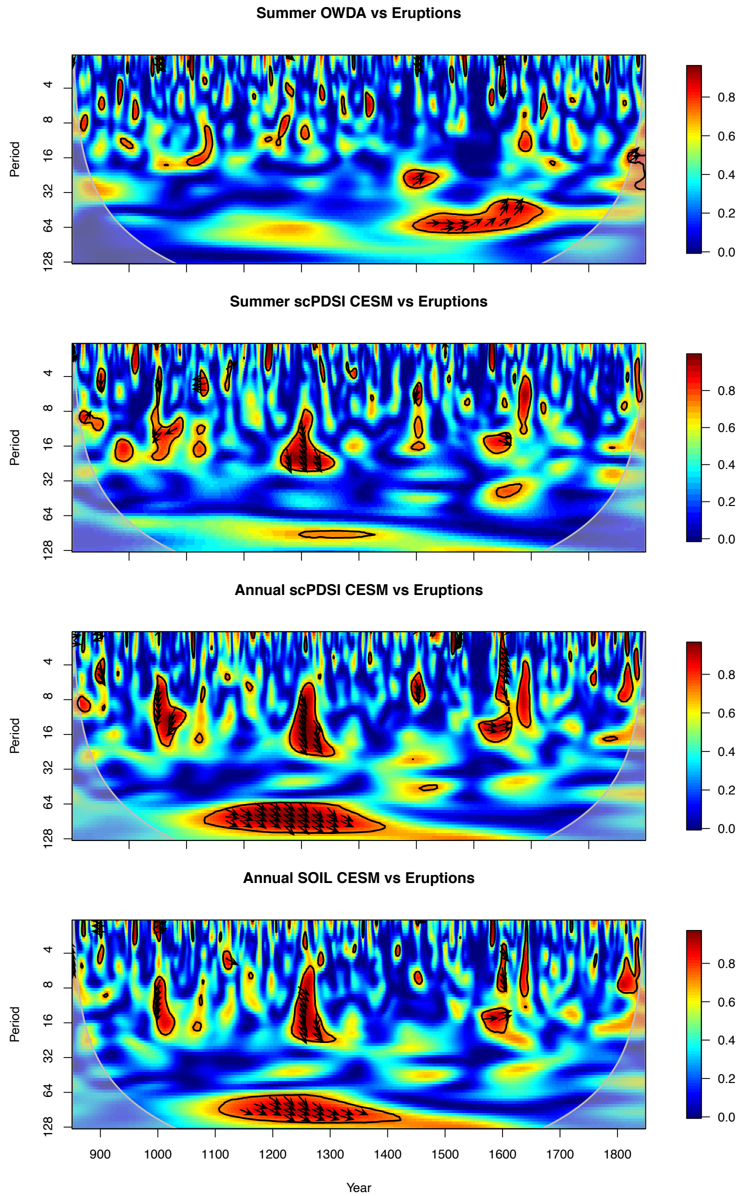

Figure 6. Wavelength coherence between drought indices (OWDA, summer and annual CESM scPDSI, and SOIL) and volcanic eruptions for 850 – 1849 AD. The red shaded regions indicate where the coherence of two time series are statistically significant at 5% confidence level. The directions of arrow provide information on the association between two variables, whether they are in-phase (to the right) or anti-phase (to the left), the first variable (right-down or left-up) or the second variable (right-up or left-down) plays the causal role.

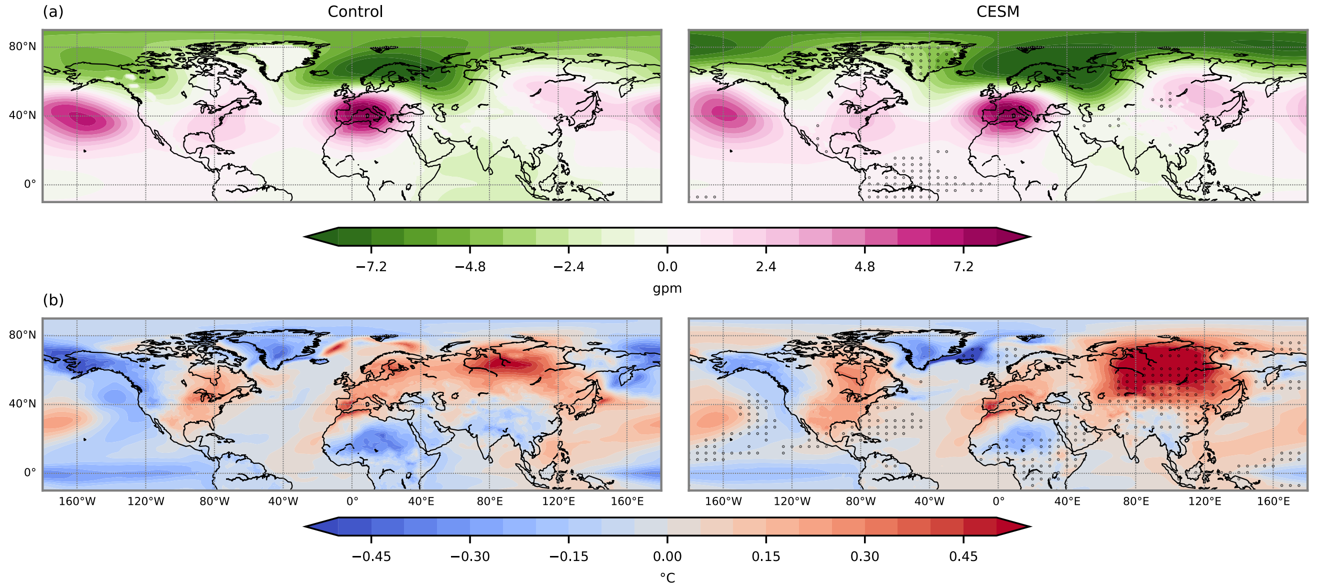

Figure 7. (a) Mean geopotential height anomaly at 850 hpa, and (b) mean surface temperature anomaly, for the control (left) and transient (right) simulations during Mediterranean droughts in 850 – 1849 AD. Black dots on the composites of the transient simulation indicate the regions where the means between the control and transient simulations are statistically not significant at 5% confidence level.

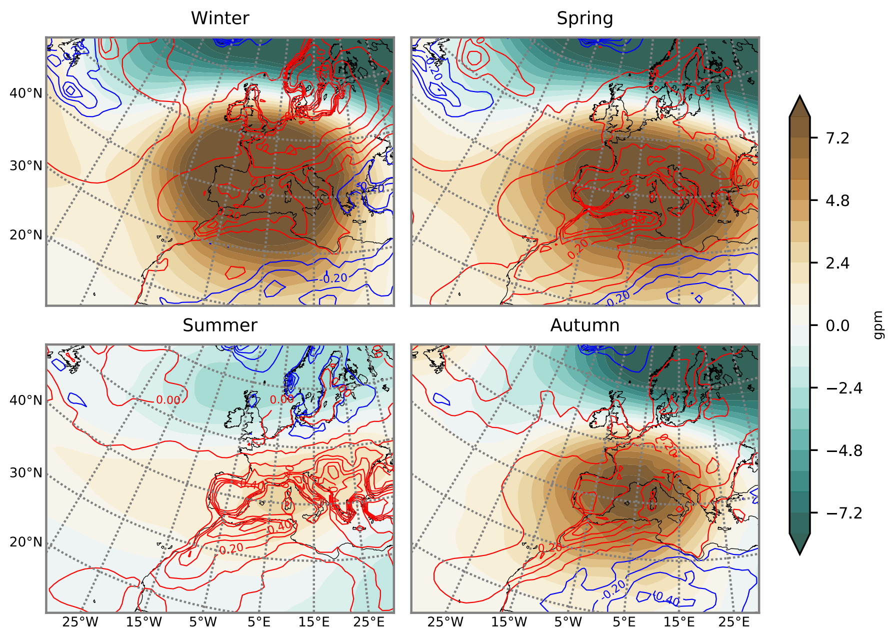

Figure 8. Mean geopotential height anomaly at 850 hpa (color shaded) and surface temperature anomaly (contours every $0.2C^{\circ}$, positive in red and negative in blue) during Mediterranean droughts for each season in the transient simulation.

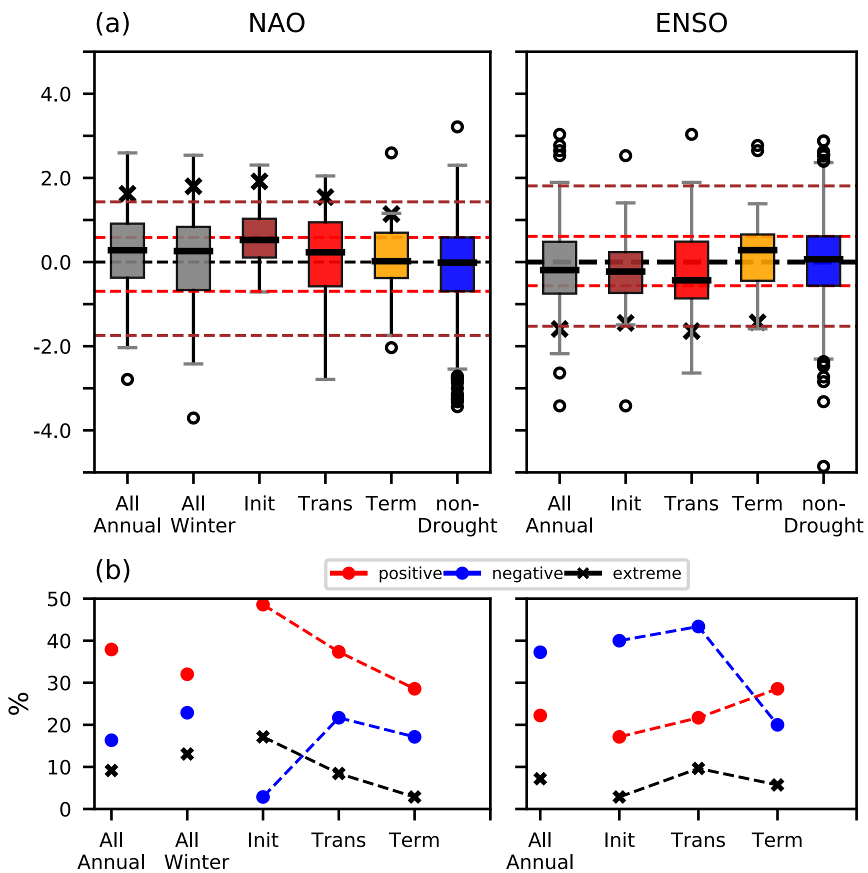

Figure 9. (a) Box plots of NAO and ENSO during multi-year Mediterranean droughts. The black crosses indicate 95 percentile value for NAO, and 5 percentile value for ENSO. Dashed red lines indicate the 25 and 75 percentiles of non-drought periods, which are the thresholds to discern negative/positive states of NAO and ENSO. Dashed brown lines indicate 5 and 95 percentile of non-drought periods. (b) Frequencies of occurrences of positive and negative states of NAO (left) and ENSO (right) for annual and winter total, and each stage of droughts. Black crosses indicate the frequencies of occurrence of extreme positive NAO and extreme negative ENSO.

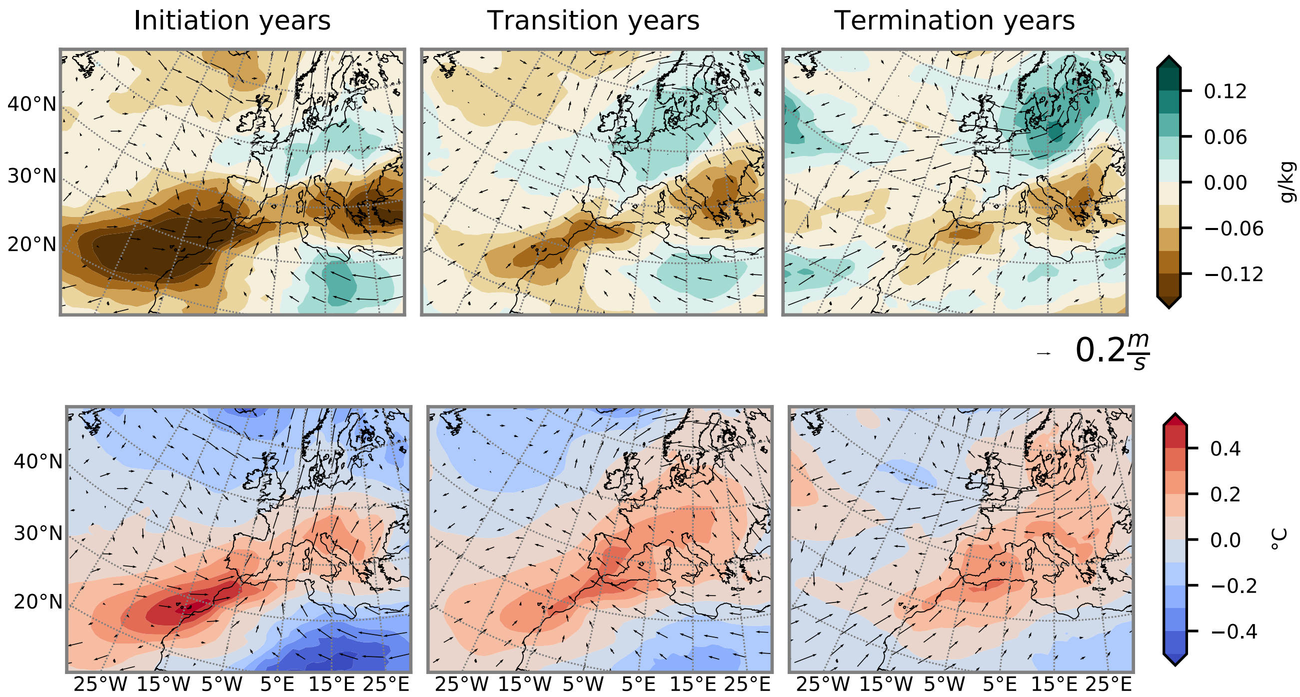

Figure 10. Evolution of atmospheric conditions in each stages of droughts. Anomalies of (above) specific humidity, and (below) temperature, both at 925 hPa during initiation, transition and termination years. Arrows indicate winds at 925 hPa.

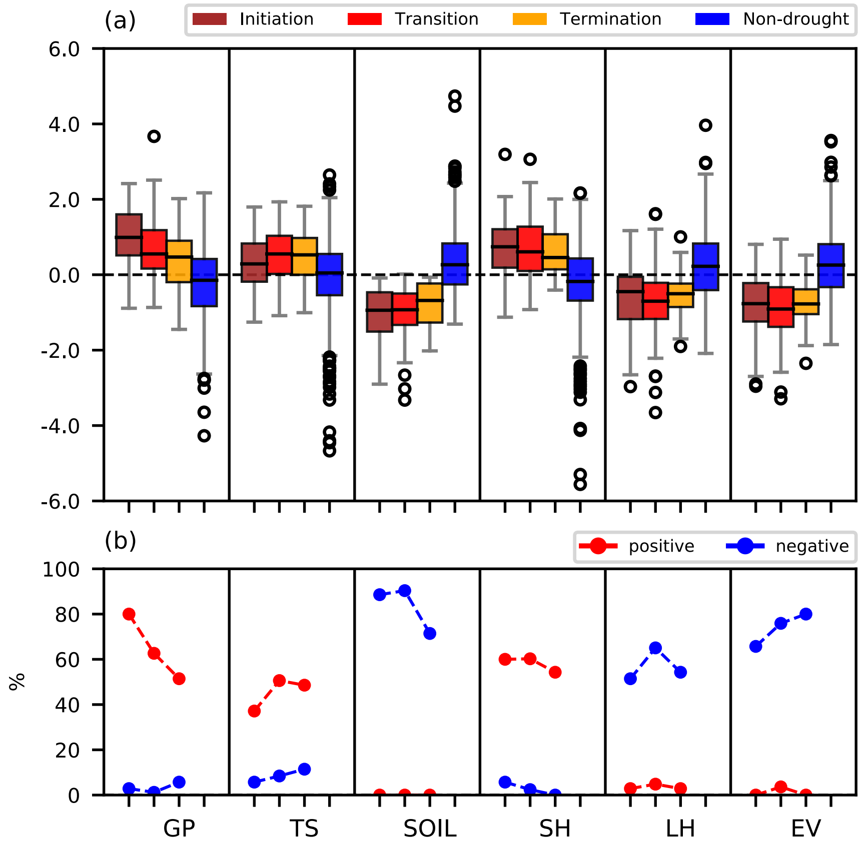

Figure 11. Same boxplot as Fig. 9 but for standardized regional atmospheric and soil variables over the region of study during Mediterranean droughts: anomalies of geopotential height at 850 hPa (GP), surface temperature (TS), soil moisture (SOIL), sensible heat flux (SH), latent heat flux (LH) and evapotranspiration (EV). (b) Frequencies of occurrences of positive and negative anomalies in each stage of droughts in order: initiation, transient and termination years.

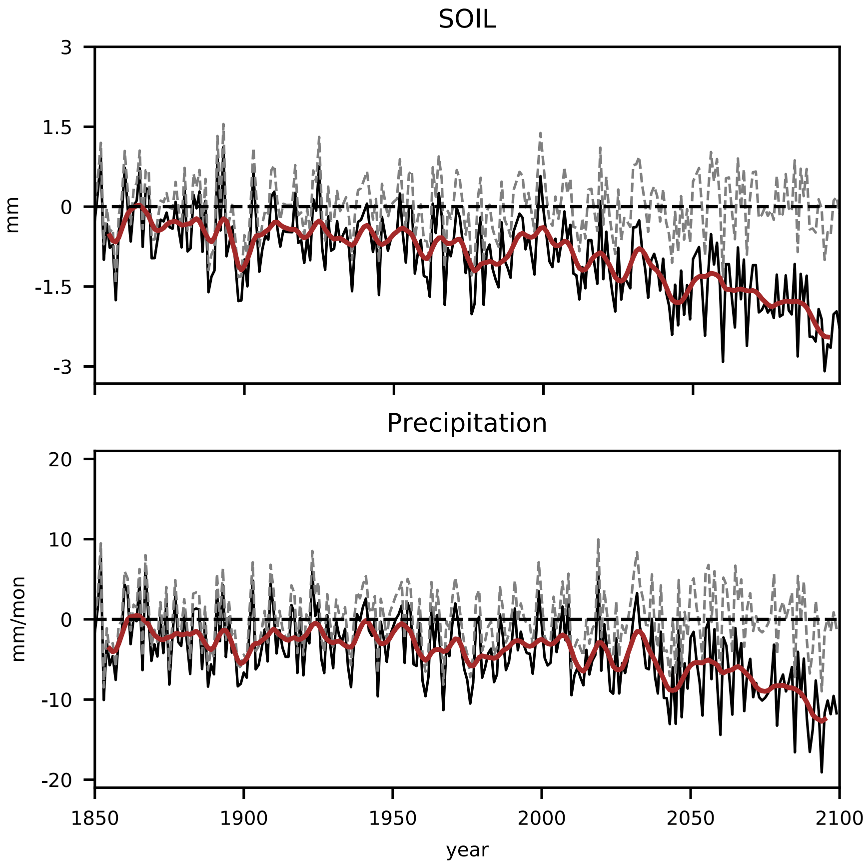

Figure 12. Time series of annual soil moisture (SOIL), and precipitation anomalies from 1850 to 2099 AD with respect to the 1000 - 1849 AD means. Brown lines indicate smoothed 10 years running mean, and dashed lines the detrended time series.

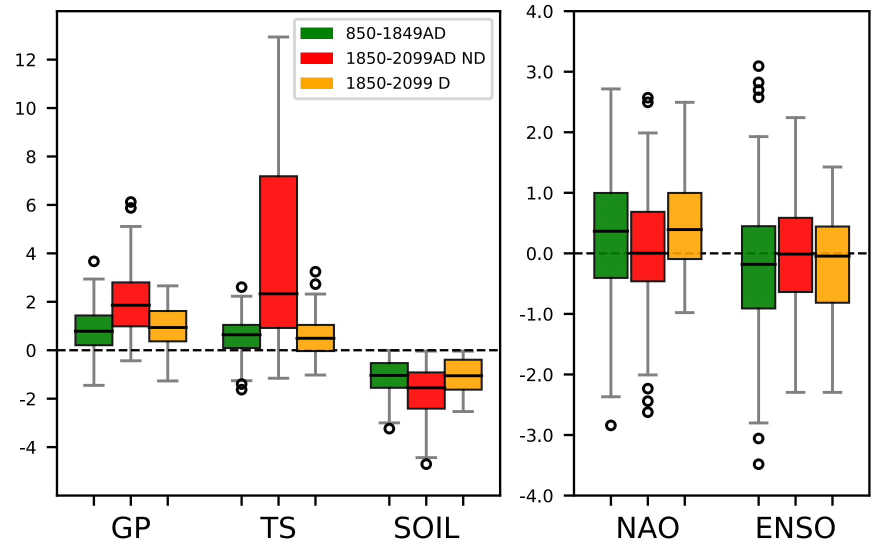

Figure 13. (a) Standardized regional variables: anomalies of geopotential height at 850 hPa (GP), surface temperature (TS) and soil moisture (SOIL) over the region of study, and (b) indices of large scale circulation patterns: NAO and ENSO during Mediterranean droughts for the period of 850 - 1849 AD (green), non-detrended 1850 - 2099 AD (red) and detrended 1850 - 2099 AD (yellow). The GP, TS and SOIL between the detrended 1850 – 2099 AD and the 850 – 1849 AD periods present p-values from Mann-Whitney U test of 0.09, 0.02 and 0.29, respectively. For NAO and ENSO, the p-values are 0.19 and 0.29 for each.

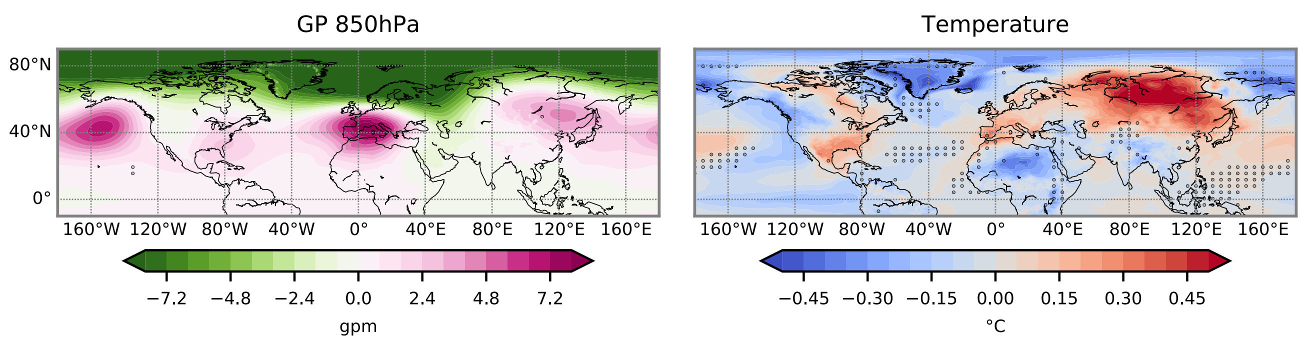

Figure 14. Detrended mean geopotential height anomaly at 850 hpa and surface temperature anomaly during Mediterranean droughts for the 1850 - 2099 AD. Black dots indicate the regions where the means between the detrended 1850 – 2099 AD and 850 – 1849 AD are statistically not significant at 5% confidence level (Fig. 7).