Reply to anonymous Reviewer #1

General Comments

We would like to thank the reviewer for his/her thoughtful revision of the manuscript. We hope that we were able to address the major concerns of the reviewer in the revised version of the manuscript.

The study presented by Cammalleri et al. addresses a societally relevant question, i.e. how does global warming affect droughts in Europe with respect to duration, deficit, and frequency? While the study in itself is well motivated, the novelty of the approach could be made clearer and I see potential ways of extending the analyses into domains which have so far not received as much attention. I see many parallels to the study by [Marx et al., 2018] who studied low flow characteristics under different global warming levels for Europe. The main advancement of this study compared to the study by [Marx et al., 2018] are in my view threefold: (1) the authors use a drought definition instead of a simple low flow index which allows them to look at different drought characteristics including deficit and duration; (2) their model allows for the consideration of human flow modifications; and (3) they combine the hazard with an exposure analysis. I would make this clear in the introduction and clearly state what the added value of considering these three aspects is.

We revisited the introduction to make more evident these three key points.

In my opinion, the study presented could gain in profile, if the authors intensified the analysis of these aspects. Point 3 is probably easiest to tackle. They authors could highlight the exposure analysis in the introduction as this is something which goes beyond what previous studies have done.

We have expanded the focus on the exposure analysis in the introduction.

Points 1 and 2 could profit from some additional analyses. Regarding point 1, I would find a bivariate frequency analysis of deficit and duration interesting.

We agree that exploring a multi-variate analysis of different drought characteristics is an interesting future researches topic. Drought deficit and duration, however, are typically strongly correlated, hence a bivariate analysis of these two indicators would likely not deviate strongly from the analysis presented in our study. We think that a proper multi-variate analysis is worth of a full paper dedicated to the topic.

Regarding point 2, it would be very interesting to show how drought characteristics change in a human-modified world as opposed to a world where such modifications are not considered (i.e. run model with and without the water use module and compare the changes in drought characteristics resulting from the different model runs).

We agree with the reviewer that the effect of human water use is relevant for the analysis of drought. This is also why we considered this in our analysis. Forzieri et al. (2014) showed in detail how water use alters river flows and streamflow drought indicators in different regions of Europe performing the analysis as suggested by the reviewer. In this study, a more detailed modeling of the dynamic socioeconomic conditions is included, focusing on different aspects, namely on understanding drought hazard and exposure in a future world in case of climate inaction and different mitigation targets (warming levels). We believe that in order to address these questions a dynamic socioeconomic setting based on EU demographic, economic and budgetary projections is more appropriate and worth of the full focus of the paper.

While the results of this study are well presented and tell a nice story, the methods section is in my opinion very vague and it is hard to judge how suitable the model strategy is with respect to the analysis presented. The methods section would profit from specifications regarding model calibration and evaluation (was it calibrated at all?), an evaluation of the model simulations regarding the two drought characteristics deficit and duration (is the model able to well reproduce the phenomena studied?), a description of how the water demand estimates for the different sectors considered were derived (how was the disaggregation done?), and more information on the climate projections used.

We expanded the methodology section to address reviewer's main questions (see specific comments). However, since the LISFLOOD hydrological model has been extensively used/tested in several pan-European studies on hydrology, climate and drought we referred to the relevant literature where needed in order to keep the section concise.

I think that this study will be a nice contribution to documenting future changes in drought characteristics once/if the validity of the methodology is clearly demonstrated and the novelty of the paper is clearly worked out.

We hope that the new version of the manuscript better highlighted the novelties of the study.

Specific comments

Introduction: I would strengthen the two novel aspects of the study and use them as a motivation for the study: (1) the drought modeling considers water use and (2) the future evolution of drought exposure is assessed. I would also address the topic of drought definition and already point out here that you are using a fixed threshold to define droughts.

We modified the introduction to better highlight the novelties of the study.

Methods: The methods section is in my opinion very vague and it is hard to judge the validity of the results in the absence of methodological detail. I suggest to address the following questions by making specifications accordingly:

1. Which quantile mapping approach was used? (L.102)

2. What is the reason for using the dataset EOBSv10 as an observed dataset? (L.103)

The forcing dataset was produced by Dosio (2020) in the framework of the PESETA 4 project (https://ec.europa.eu/jrc/sites/jrcsh/files/pesetaiv_task_1_climate_final_report.pdf), as it was not specifically made only for this study. Detailing the bias correction is out of the scope of this paper, but we clarified the relevant reference and source in the new version of the manuscript.

3. Was the assumption that 'between-pathway differences are generally much smaller than the within-pathway variability' verified for the drought characteristics analyzed? This assumption does not seem to be very intuitive to me. (L.107-109)

This is a result of the recent study published by Mentaschi et al. (2020) on the same dataset and on the annual minimum (drought), average and maximum flow (flood). Tests were also made for severity but not included in the publication. In this study it is shown the independence of changes at a certain warming level from the adopted pathway. We reworded the sentence to clarify.

4. Was the LISFLOOD model calibrated, if so, how? If not, why not? (L.114)

Yes, the model has been calibrated as part of its operational implementation in EFAS (https://www.efas.eu/). We added the corresponding reference to the new version of the manuscript.

5. How was the LISFLOOD model evaluated for the drought characteristics under study? Some evaluation plots are in my opinion required to prove the suitability of the model setup for the analysis performed (e.g. distribution of simulated vs. observed drought durations and deficits).

The model has been evaluated specifically for drought at both European and Global scale as part of its implementation for operational drought monitoring in the European and Global Drought Observatories (https://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1000). We better clarified this in the section 2.3 of the new version of the manuscript.

6. Is it correct that no downstream routing is performed but that the results presented are based on a grid-by-grid analysis of local streamflow generation? Please specify. (L.119-120).

The model has a routing component, which is described in the methodology: "the surface runoff generated in each cell is channeled to the nearest river network cell by means of a routing component based on a 4-point implicit finite-difference solution of the kinematic wave (Chow et al., 1988)". We slightly reworded the sentence to avoid any miscommunication.

7. How is irrigation water demand estimated? I.e. what does 'dynamically' mean and how was crop transpiration estimated? (L.122-123)

We added some detailed on the supply-demand approach used for the irrigation modeling in crops and constant water level for paddy-rice. As for all the other sectors, further details can be found in Bisselink et al. (2018).

*8. How was water demand estimated for the industrial, energy, livestock, and the domestic sectors? I.e. what was downscaled, how, and to which resolution (5*5km)? (L.125-126)*

Data at country level were obtained from sources like EUROSTAT, and then downscaled to the LISFLOOD grid using different techniques and proxy variables. More details on the downscaling are reported in the new version of the manuscript.

9. How are economic, budgetary, and demographic projections assumed to affect the individual water demand sectors considered? (L.126-128)

According to the downscaling procedure used for each sector, the future projections were used as proxy for the downscaling of the future water uses. We completely re-organized this section to better clarify the procedure.

10. How does the Territorial Modelling Platform perform the downscaling? (L.129-131)

The high resolution data from the LUISA platform were used to downscale water demand for the different sectors. We re-elaborated the entire paragraph to clarify.

11. Why were the population and land use projections assumed to be static after 2050? (L.131-132).

Data for the LUISA platform are available until 2050. We clarified this in the new version of the manuscript.

12. What is the reason for the threshold choice? I assume that a fixed threshold is used? See e.g. [Thiel et al., 2018] (L.138-139).

The use of the historical threshold for the future projections is a widely adopted approach, aiming at evaluating how present day droughts will be perceived in the future. In this framework, a transient threshold will not be suitable for such analysis. We clarified this assumption in the new version of the manuscript as “derived for the present climate as a threshold both in the present and future scenarios, with the aim to estimate how present condition droughts will be projected under climate change”.

13. Did you do any smoothing to ensure the independence of events as e.g. suggested in [Tallaksen and Hisdal, 1997].

We did not perform smoothing on the data, but we applied pooling of consecutive close events (Zelenhasić and Salvai, 1987) and removal of isolated minor events (Jakubowski and Radczuk, 2004) to ensure both the independence of events and the absence of distortion in the fitting through minor events. We clarified the role of these two procedures in the revised version of the manuscript.

14. Why did you choose the Pareto Type II distribution to model drought deficits instead of the commonly used Generalized Pareto Distribution for partial duration series [Coles, 2001] and why is the threshold zero? Some goodness-of-fit test is required here (e.g. Anderson-Darling [Chernobai et al., 2015]) (L.158-159).

The Lomax distribution is just a special case of the Generalized Pareto Distribution (GPD), when the μ parameter is set to 0. We found this distribution to perform adequately at global scale (see Cammalleri et al. 2020, where a proper goodness-of-fit test is performed) for drought deficit, since this variable is limited at zero as lower threshold. We reworded the section to clarify how the distribution has been previously tested in another study.

15. How was the return period defined? (L. 163-165) The definition of a univariate return period of T=1/1−p is valid when using annual maxima or annual minima time series. In the case of partial duration series as identified through a threshold level approach, the definition is T=μ/1−p', where μ is the mean inter-arrival time between events (see e.g. [Gräler et al., 2013; Brunner et al., 2016]).

This is correct. We applied the correct definition of the return period, as now clarified in the revised definition of the return period in the text (including a reference to Serinaldi, 2015).

16. I am lost in the sentence in L.184-186. We would expect a 10-yearly event to occur on average every 10 years. This would expose all the people in the corresponding region to the event once every 10 years on average. How do you go to the assumption that one tenth of the population per NUTS 2 region is affected every year? I do not see the reasoning here because droughts are mostly larger scale phenomena and we can expect that most people in a region will be exposed at the same time instead of one 10th of the population being exposed every year.

We notice that this section caused misunderstanding for both reviewers, and we revisited the text to clarify the goal of this part of the study. Your interpretation is correct, and we agree that droughts usually occur over large areas, hence it is likely that all population will be affected at the same time rather than 1/10 every year.

Here, we estimate the expected average annual exposure in the 30-year periods, which is a theoretical expected exposure that would occur in any given year if exposure from all drought probabilities and magnitudes are spread out equally over time (here those with return period of 10 years or less frequent). As correctly pointed out by the reviewer, this does not mean that each year has the same exposure to drought. Rather, in some years there will be high exposure, while in (most) others there will be low or no exposure.

Results: The figures are clear and the results well presented. I think that the results section would profit from a display of the 'reference' situation and the seasonality of droughts over Europe (especially to highlight that drought seasonality using a fixed threshold will in Alpine regions happen during winter).

The language used is pretty deterministic even though the results of projections are presented. I would rephrase sentences such as 'will increase', 'will last',… to something expressing that these results are uncertain e.g. 'are projected to increase', 'are expected to last',…

We agree that projections of climate and consequently drought characteristics are uncertain. We were careful in trying to convey this uncertainty in our discussion, but we revisited the text to remove the instances where a deterministic language is misused.

Furthermore, it would just be interesting to present a few more results. Here, some suggestions for further analyses:

1. It would be interesting to see Figure 3 for two more return periods (e.g. 5 and 50 years) representing more frequent and rarer events, respectively to see how changes in frequency depend on the magnitude of events.

We observed that there is a rather strong relationship between the results at different return periods. We added a figure summarizing these results (Figure 4 in the new version of the manuscript), without replicating the same figure for different return periods, which may be too redundant and break the flow of the text.

2. It would be interesting to look at drought duration return periods and at bivariate return periods of deficits and durations.

As detailed above, we agree on the interest of the topic, but we consider the subject worth of a full paper that is currently under consideration.

3. It would be very nice if the model could be run another time without the human water use component/module to illustrate the impact of human impact on future changes in drought characteristics. Adding this aspect would make this a truly novel analysis.

As discussed above, this topic has been explored by other research studies, albeit with a less sophisticated modeling of socioeconomic conditions (e.g., Forzieri et al., 2014). Here we focus on the expected impact and exposure in case of climate inaction and different mitigation when the dynamic socioeconomic conditions are modeled at the best of our possibilities.

The study reads generally well but would still profit from editing.

During the revision we have carefully checked the paper throughout.

Minor points

- *Title: I personally would use the word 'characteristics' instead of 'traits'. This comment applies to the whole manuscript.*

We have used traits in other related studies, so we prefer to leave the title as it is, since this is not a major correction.

- *L.14: I would not talk about an index in this case. I would already point out in the abstract that you are looking at drought characteristics derived using a threshold-level-approach with a fixed threshold.*

We agree and reworded the abstract accordingly.

- *L.15: I would mention the model name already in the abstract.*

Done.

- *L.22: by 'interested', do you mean 'characterized'?*

Done.

- *L.23: specify reduction in what? Drought durations, deficits, and frequency.*

Clarified.

- *L.27: by 'this', do you refer to 'the regions most affected by changes'?*

Yes, we reworded the sentence to clarify.

- *Keywords: I would add LISFLOOD and global warming level.*

Done.

- *L.41: Yes, but the drought definition chosen also depends on the question at hand/problem of interest.*

- *L.41-43: the sentence seems incomplete. Suggested rephrasing: droughts are commonly looked at from a meteorological (), agricultural (), or hydrological () perspective*

We reworded the paragraph as: "Depending on the degree of penetration of the water deficit into the hydrological cycle, drought is commonly classified into meteorological (e.g., precipitation), agricultural (e.g., soil moisture) and hydrological (e.g., river discharge) drought (Wilhite, 2000). Each class of drought may be seen more relevant depending on the specific application, and different effects of climate change are likely to be observed depending on the corresponding analysed indicators (Feng, 2017)".

- *L.44-47: I agree that there are more studies on meteorological drought than on soil moisture or streamflow drought. But there are many more potential examples for hydrological drought studies, e.g. [Hao and Aghakouchak, 2014; Laaha et al., 2017; Brunner et al., 2019].*

We agree that there are many more examples in the literature (and the same is true for meteorological drought). Here we reported only few examples of studies on climate projection of drought at continental scale. We rephrased to clarify that.

We also added the reference to Brunner et al. (2019) in the discussion on regional/local studies.

- *L.48: by 'This', do you refer to the smaller number of non-precipitation drought based studies?*

Reworded.

- *L.48: I would challenge the statement 'meteorological drought indicators have lower input data requirements than streamflow or soil moisture drought indicators'. If one would like to compute the Standardized runoff index [Shukla and Wood, 2008] instead of the SPI, a streamflow instead of a precipitation time series is needed, which is the same amount of data, i.e. one time series.*

We reworded the sentence to clarify our point.

- *L.49: specify 'this'. The focus on meteorological drought?*

Done.

- *L.52-54: cite the European Drought Impact Report Inventory (EDII) here?*

Done.

- *L.60-62: sentence would profit from rephrasing.*

Done.

- *L.62: There are some studies that have looked at drought characteristics on a European scale and expected changes, e.g. [Marx et al., 2018; Samaniego et al., 2018; Brunner and Tallaksen, 2019].*

We referred to some studies, including Marx et al. (2018), in the next paragraph. Keep in mind that here we are discussing only hydrological drought at this point, hence the missing reference to Samaniego et al. (2018) (cited early in te text).

- *L.64-69: I would split this long sentence into two.*

Done.

- *L.74: is there a reference documenting this paradigm shift?*

This shift is a consequence of the focus in the Paris agreement, , where a target to limit global warming to well below 2 degrees Celsius. This make more relevant to analyze warming levels rather than specific emission target at given years (i.e., Kyoto protocol). We do not think that there is a more relevant reference than the Paris agreement itself, already cited in the text.

- *L.82: 90th percentile of annual minima? or of annual mean? Do you actually mean the 10-th percentile with respect to non-exceedance probabilities? The 90th percentile is more commonly used for floods but I am aware that the drought and flood communities sometimes follow different conventions. Statistically, however, it would be more correct to talk about the 10th percentile.*

They used the 90th percentile of exceedance, as now clarified in the text. We prefer to keep this definition to be consistent with the original paper.

- *L.89: which mitigation targets are you referring to here?*

We reworded to clarify the connection to the Paris agreement.

- *L.90: water 'availability' instead of water 'budget'?*

Done.

- *L.92: I would specify the model name.*

Done.

- *L.90-95: split long sentence into two.*

The sentence was reworded.

- *L.93: I would add a reference to [Moss et al., 2010].*

Done.

- *L.102: Euro-CORDEX initiative.*

Done.

- *L.168-171: I would move this information to the introduction.*

We agree that this paragraph was out of place. We partially move this information in the expanded section of the introduction dedicated to the exposure analysis, and reworded this paragraph to harmonize the content.

- *L.173-174: this statement is not very true for hydropower production, which mostly happens in mountainous areas which are not very densely populated. And it is neither true for ecological purposes which can also be highly impacted by droughts but not considered in this study.*

We reworded to clarify the reasoning behind our approach. Also, we clarified in the introduction how ecological impacts are not considered in this study.

- *L.177: could you shortly describe the properties of the LUISA projections?*

Some details were added, including an additional reference to the full description of the platform. A description of the platform is out of the scope of the paper.

- *L.178: what is the average scale of these NUTS 2 areas?*

NUTS2 regions vary country by country (e.g., in Germany correspond to the Regierungsbezirke, in Italy the Regioni and in UK the Counties). By definition, on average, they have between 800,000 and 3,000,000 inhabitants.

- *L.182: do you mean to refer to a '10-yearly' event, i.e. an event with a return period of 10 years?*

Yes, we reworded to clarify.

- *Figure 3: I would add a vertical line at 10 years as a reference, e.g. in light grey.*

We added the vertical lines to demark the 10-year return period.

- *L.205:209: I would move this information to the introduction of the methods section.*

This information was derived from the results of the analysis and we prefer to keep it here to avoid confusion in the flow of the text (i.e., reference to this figure in the methods section). However, we reshaped the paragraph in order to clarify how the macro-regions were derived, following the suggestion of the other reviewer.

- *L.223: I would indicate the Seine river basin on one of the maps (for non-European readers).*

We reworded the text to clarify the spatial location of the river basin.

- *L.354-355: start new sentence?*

We reworded the sentence.

- *L.356: reduction in drought severity and frequency?*

Fixed.

- *L.391-394: could you clarify this sentence?*

We reshaped the full paragraph to improve the clarity of the message.

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Reply to anonymous Reviewer #2

General Comments

This study examines the projected change in hydrologic drought severity, duration, and frequency due to climate change across Europe. It employs a unique GWL perspective to merge projections and represents a significant effort to combine climate, land cover, and population projections with hydrologic modeling to estimate drought exposure. Overall the work is of a high quality; however, I have a number of reservations, as described below. The majority of these issues are clarifications of the methodology, which are needed to fully assess the findings. It is also important to clarify the interpretation of some results. I therefore recommend a significant revision.

We thank the reviewer for the constructive comments on the manuscript. We hope that the major issues are now addressed in the revised version of the manuscript.

Major issues

M1. Is it possible to provide the range of years the ensemble members reach the GWLs for context? It would help to confirm that the present conditions have not surpassed 1.5K and provide some context to how fare off +1.5K is from the present. If this is not possible, at least provide delta K for the reference period.

We agree that this information will give more context to our results. We will provide the temperature difference between the preindustrial period and the baseline (delta K = +0.7K) and an indication of the ensemble variability in the years to reach GWLs for the two RCPs.

M2. Related to A1, you are incorporating changes in population, land cover, and water abstraction with time through 2050. But, because the endpoints are tied to GWL, rather than a year, each member of your ensemble will have slightly different values for these model inputs. Are you accounting for this? Can you provide a relative estimate of the water abstraction changes? This would help provide sensitivity/scale for this portion of the model.

We are indeed accounting for this, and the reviewer is correct that ensemble members may have slightly different values for some of the underlying socioeconomic variables. The projected changes in socioeconomic variables are available in 5-year time steps. Demographic and land use changes in Europe are relatively mild up to 2050, while they remain constant afterwards. Hence, spread in water abstraction driven by the socioeconomic drivers and the effect on water availability are small compared to the effects of climate change, with the latter also affecting water demand for crops irrigation.

We revisited the description of the water use modules, which now provides more details on the modelling procedure.

M3. Changes in snowmelt patterns and seasonality have a potential impact on future hydrologic changes at higher elevations and latitudes. You mention this on Line 372. Does your model incorporate a snow accumulation/melt module?

Yes, LISFLOOD has a snow module that is based on the degree-day factor method. We will better emphasize this in the model description.

M4. Please provide more clarification as to how the return periods are being derived. More detail is needed than the reference to Cammalleri et al (2017) paper. It appears you are using a peak-over-threshold/partial duration series approach. I am most familiar with using the generalized pareto distribution for return periods in this context. It appears like you are using the Pareto Type II. Please explain this choice. Also, be aware that in the context of a partial duration series, your statement on line 163 "the probability that one event is topped in any one year" is slightly less accurate than for an annual maximum series.

The Pareto Type II is a special case of the Generalized Pareto distribution, hence analogous considerations can be made (we now clarified this in the text). We agree with the reviewer that the statement on the return period can be confusing in our specific case for readers that are only familiar with annual min/max series. We revisited the text to clarify the definition and added a reference to a relevant publication.

M5. Please provide the methodology for calculating the change in drought duration shown in Figure 2. Does days/year represent a summation of all drought days during the reference period? I believe this is the correct interpretation. My confusion is because the Severity (D) analysis focuses on the severity of an individual event, whereas this Duration analysis focuses on a cumulative metric.

Also, as part of this, please revise your interpretation in Section 3.1.2. If you are summing up the days under drought conditions, then you cannot say that "droughts will last longer", as you do in Line 252. I interpret longer droughts as the individual drought events lasting longer, but this metric could increase due to more frequent, but similar duration droughts. Without knowing the number of unique droughts, you cannot make this statement, only that the total time spent in drought will increase.

The reviewer's interpretation of the definition of duration in the original version of the manuscript is correct. Following your considerations, we updated the figure by focusing on the duration of the event, and revisited the text accordingly. We agree that this quantity, rather than the total number of drought days in a year, is fitting better the rest of the analyses performed in the study.

M6. There is no significance testing for any of these claims. It is difficult to determine whether these trends are a significant signal or noise. The consistent regional patterns suggest a true trend. But, I would strongly recommend significance testing to quantify *how much agreement there is among ensemble models (Fig 1) or how significant these changes are regionally (Fig 2/3).*

The robustness of the changes has been accounted by reporting the areas where at least 2/3 of the ensemble models agree on the sign of the change. The area with no-agreement (usually in grey) are the ones where this condition is not met. We better clarified this choice in the revised version of the text.

M7. Line 426 - This interpretation, which depends on your assumption on Line 184, assumes independence among sites, which is not true. Regions enter drought at the same time, so it is not fair to say that 10% of the region will be exposed to a 10 year drought in any given year. More likely, a majority of the Mediterranean (or at least the eastern/western portions) will enter drought at the same time.

Associated with this is the interpretation of Figure 4/5. Is this based on the 10-year drought only or all droughts?

We agree that drought usually occur over large areas, hence it is likely that all population will be affected at the same time rather than 1/10 every year. We estimate and present the expected average annual exposure for each 30-year period, which is the exposure that would occur in any given year if exposure from all drought probabilities and magnitudes are spread out equally over time (here those with return period of 10 years or less frequent). As correctly pointed out by the reviewer, this does not mean that each year has the same exposure to drought. Rather, in some years there will be high exposure, while in (most) others there will be low or no exposure. We understand that this caused some confusion, since it has been pointed out by both reviewers. We revisited the text to clarify this, and added a figure on the relationship between different return periods, as suggested by the other reviewer.

M8. Please provide a data availability statement. This is required by HESS and is not included in the version I had access to.

All the data produced by the JRC are freely available to the public upon request. We are also planning to disseminate some of the key outputs throughout our Risk Data Hub (https://drmkc.jrc.ec.europa.eu/risk-data-hub). We will add this information to the manuscript.

Minor issues:

- You are defining your GWLs relative to a pre-industrial baseline. Please provide the years for this baseline. Is it the 1881–1910 baseline used in Donnelly et al. (2017)?

Yes, we added this information to the new version of the manuscript.

- Line 160 - If you are using Maximum Likelihood to fit the Lomax distribution, this is not an "empirical" cumulative distribution, but rather an estimate of the population's cumulative distribution.

We were referring to the frequency distribution of D values before the fitting. We reworded to avoid any misunderstanding.

- Figure 1 - This figure caption and legend do not indicate that this is showing the change in the 10-year drought.

Thanks for point out this oversight. We modified both the caption and the legend to clarify that.

- Line 196 - Please indicate where these macro regions were derived from.

We reorganized this section, also following the suggestion of reviewer #1. Now we clarified how the regions were derived from, and how they were compared with the ones used by IPCC.

- Line 241 - I suggest you use "climate change-induced" here. Much of this trend is likely driven by changes in precipitation, rather than warming specifically. Similarly, on Line 423.

We agree on the change here. In Line 423 we replace with GWL since we are referring to the analyzed global warming level.

- Figure 3 - What is this x-axis? Is it standard normal deviates spacing? There isn't quite enough tick marks to know for sure. Can you please explain this in the caption?

The data are equally spaced in frequency, we added this information in the caption.

- Figure 3 - Please add some type of reference point to this figure to highlight the 10 year drought event, as defined by the reference period. In its current format, there is not even a label of the 10 year event. At a minimum, add this label, preferably add a vertical line so the reader can compare with the plotted distributions.

We added a vertical line to identify the 10 year frequency.

- Line 345 - You may also consider adding the following references, which provide additional support for this regional pattern of meteorological drought. They both attempt to parse the affect of precipitation trends from temperature/evapotranspiration trends.

Dubrovský, M., Hayes, M., Duce, P., Trnka, M., Svoboda, M., & Zara, P. (2013). Multi-GCM projections of future drought and climate variability indicators for the Mediterranean region. Regional Environmental Change, 14(5), 1907–1919. doi:10.1007/s10113-013-0562-z

Stagge, J.H., Kingston, D.G., Tallaksen, L.M. et al. Observed drought indices show increasing divergence across Europe. Sci Rep 7, 14045 (2017). https://doi.org/10.1038/s41598-017-14283-2

Thanks for suggesting those references. They were added to the new version of the manuscript.

Line 349 - The word "severe" is misspelled.

Fixed.

Diverging hydrological drought traits over Europe with global warming

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Abstract

Climate change is anticipated to alter the demand and supply of water at the earth's surface. Since many societal impacts from a lack of water happen under drought conditions, it is important to understand how droughts may develop with climate change. This study shows how hydrological droughts will change across Europe with increasing global warming levels (GWL of 1.5, 2 and 3 K above preindustrial temperature). We employ a low-flow analysis based on river discharge simulations of the LISFLOOD spatially-distributed physically-based hydrological and water use model, which was forced with a large ensemble of regional climate model projections under a high emissions (RCP8.5) and moderate mitigation (RCP4.5) pathway. Different traits of drought, including severity, duration and frequency, were investigated using the threshold level method. The projected changes in these traits identify four main sub-regions in Europe that are characterized by somehow homogeneous and distinct behaviours with a clear southwest/northeast contrast. The Mediterranean and Boreal sub-regions of Europe show strong, but opposite, changes at all three GWLs, with the former area mostly characterized by stronger droughts (with larger differences at 3 K) while the latter sees a reduction in all drought traits. In the Atlantic and Continental sub-regions the changes are expected to be less marked and characterized by a larger uncertainty, especially at the 1.5 and 2 K GWLs. Combining the projections in drought hazard with population and agricultural information shows that with 3 K global warming an additional 11 million people and

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4.5 million ha of agricultural land are projected to be exposed to droughts every year, on average, with the most affected areas located in the Mediterranean and Atlantic regions of Europe.

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Keywords: climate change, LISFLOOD, drought, low flow index, Paris agreement, global warming levels.

1. Introduction

As a natural phenomenon, drought occurs in all climates due to a temporary lack of precipitation, which can propagate through the different compartments of the water cycle (Van Loon and Van Lanen, 2012). Drought conditions can be exacerbated by high temperatures, causing an increase in evapotranspiration demand and soil water content draining (e.g., Teuling et al., 2013), and their impacts can be further intensified in areas with an overexploitation of available water resources (Van Loon and Van Lanen, 2013). The strong dependency of drought conditions on the key meteorological forcing suggests likely effects of climate change on future drought severity, duration and frequency, mainly through an alteration of the water balance dynamics (Stagl et al., 2014).

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Depending on the degree of penetration of the water deficit into the hydrological cycle, drought is commonly classified into meteorological (e.g., precipitation), agricultural (e.g., soil moisture) and hydrological (e.g., river discharge) drought (Wilhite, 2000). Each class of drought may be seen more relevant depending on the specific application, and different effects of climate change are likely to be observed depending on the corresponding analysed indicators (Feng, 2017). In spite of the strong connection between the socioeconomic impacts of droughts and negative soil moisture and river discharge anomalies, fewer studies (e.g., Samaniego et al., 2018; Forzieri et al., 2014) have focused on the climate projection of agricultural and hydrological droughts at European scale compared to meteorological events (e.g., Heinrich and Gobiet, 2012; Spinoni et al., 2018). This focus on meteorological drought mainly relates to the relative simplicity and lower input data requirements of calculating meteorological drought indicators (i.e., Standardised Precipitation Index, SPI) compared to agricultural and hydrological drought indices, with the latter usually requiring simulations from hydrological models. This is also highlighted by the larger emphasis placed on meteorological drought hazard in operational monitoring systems (Barker et al., 2016). Scientific and practical interest in hydrological drought is motivated by the direct and indirect impacts on several socioeconomic sectors, such as energy production, inland water transportation,

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irrigated agriculture, and public water supply (see the European Drought Impact Inventory, https://www.geo.uio.no/edc/droughtdb/). In particular, streamflow drought complements meteorological and soil moisture droughts thanks to its more rapid response to precipitation aberrations compared to groundwater (Tallaksen and van Lanen, 2004).

With the raising awareness of climate change, a number of local and regional studies have assessed the potential impacts of climate change on hydrological drought in recent years (e.g., Brunner et al., 2019; Cervi et al., 2018; Hellwig and Stahl, 2018; Nerantzaki et al., 2019; Rudd et al., 2019; Van Tiel et al., 2018). These studies provide highly detailed insights on the local processes, but their limited spatial extent and lack of homogeneity in the adopted drought indicators, modelling framework and climate scenarios complicate the understanding of large-scale patterns of changes. In spite of the value of continental-scale analyses, few studies have looked at how hydrological droughts could develop across Europe with climate change. They are typically based on pan-European hydrological models forced by climate projections (Feyen and Dankers, 2009; Forzieri et al., 2014; Lehner et al., 2006; Marx et al., 2018; Roudier et al., 2016), with ever improved representation of processes in the hydrological models. These improvements include accounting for the effects of water use, more detail in the climate projections (by the use of higher resolution regional climate models), and better accounting for climate uncertainty through multi-model ensembles.

Most of past studies portrayed how drought conditions across Europe could look at future points in time (mid- or end- of century) for alternative scenarios of greenhouse gas emissions. However, following the UNFCCC (United Nations Framework Convention on Climate Change) Paris Agreement (UNFCCC, 2015) and the focus on limiting the increase in global average temperature to well below 2 K above the pre-industrial level, the paradigm in climate change studies has shifted from analysing the effects at specific future time windows to evaluating the effect at specific global warming levels (GWLs). To date, there are only few studies that provide insights on how hydrological droughts could change at different GWLs. Roudier et al. (2016) used

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three hydrological models forced with high resolution regional climate projections to evaluate changes in 10- and 100-year streamflow drought events, with a focus solely on the 2 K scenario. Marx et al. (2018) used three different hydrological models forced by coarse-resolution global climate projections that were downscaled accounting for altitude effects in temperature and precipitation. They used a simple annual 90-th percentile of exceedance of river discharge as index, which is representative of the low flow spectrum. Both studies do not take into account water consumption, which is a key to represent feedbacks between droughts and human activities (Van Loon et al., 2016).

To further deepen the understanding on this issue, we evaluate changes in hydrological droughts across Europe between present climate and climate corresponding to different GWLs. We look specifically at 1.5, 2 and 3 K global warming, which represent the different Paris agreement climate change mitigation targets. The study focuses on the threshold level method, allowing for a detailed analysis of different streamflow drought traits, including severity, duration and frequency of the events following an extreme value analysis. These quantities are derived from daily streamflow simulations for the pan-European river network, which are obtained with the LISFLOOD spatially-distributed hydrological model forced with an ensemble of 11 bias-corrected regional climate projections for RCP4.5 and RCP8.5 (Moss et al., 2010). The model incorporate water use modules to reproduce the major sectorial water demands, accounting for the human impact on streamflow propagation, and resulting in a streamflow deficit that represents the integrated deficiency in water availability over the entire upstream catchment.

In addition, the effects of the projected changes on two key exposed quantities is evaluated through a drought exposure analysis. It is well-known that droughts affect a large variety of socioeconomic sectors, including agriculture, water supply, energy production and inland water transportation (Meyer et al., 2013), as well as causing losses of ecosystem and biodiversity (Crausbay and Ramirez, 2017). The full quantification of drought risk for all the impacted sectors is a challenging task (Naumann et al., 2015) that goes beyond the scope of this study. Here we focus

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on the changes between the present and future exposed population and agricultural land, which are key quantities in the major social and economic sectors impacted by drought (e.g., agriculture and livestock farming, and public water supply). The same datasets underlay both the modelling of water usage and the exposure analysis, ensuring consistency in the streamflow drought exposure.

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2. Materials and Methods

2.1 Climate forcing

In this study, we used projections from 11 combinations of global and regional climate models under two Representative Concentration Pathways (RCP4.5 and RCP8.5) obtained from the EURO-CORDEX initiative (Jacob et al., 2014). The climate projections used in this study were produced by Dosio (2020) by applying a bias-correction quantile mapping approach (Dosio et al., 2012) using the observational dataset EOBSv10 (Haylock et al., 2008). The analysis focuses on 30-year time windows centred on the year when the global models project an increase in global average temperature of 1.5, 2 and 3 K above preindustrial (1881-1910) temperature. For these periods, drought characteristics were contrasted against those derived for the baseline reference period (1981-2010), which has a 0.7 K temperature increase over the preindustrial period.

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The two RCPs reach the 1.5 and 2 K GWLs around the year 2030 and 2053 (RCP4.5), 2025 and 2040 (RCP8.5), on average. The RCP8.5 simulations reach the 3 K GWL at 2063 on average, whereas only one model reaches 3 K warming for RCP4.5. According to the independence of the projected river flow changes from the adopted pathway observed in Mentaschi et al. (2020) for annual minimum (drought), average and maximum (flood) flows, the outputs from both RCPs are merged into a single ensemble. Given that only one model reaches 3 K warming for RCP4.5, the model ensemble is composed by a total of 22 members for the 1.5 and 2 K GWLs and only 12 members for the 3 K GWL.

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Eliminato: , under the assumption that between-pathway differences are generally much smaller than the within-pathway variability (Mentaschi et al., 2020). It should be noted that only one model reaches 3 K warming for RCP4.5, hence

2.2 Hydrological modelling

Simulations of daily river discharge (*Q*) were produced at 5 × 5 km spatial resolution over Europe by forcing the LISFLOOD model (De Roo, 2000) with the bias-corrected climate projections. LISFLOOD is a spatially-distributed physically-based hydrological model that simulates all the main hydrological processes occurring in the land-atmosphere system, including evapotranspiration fluxes (separately for crop transpiration and direct evaporation), infiltration (Xinanjiang model), soil water redistribution in the vadose zone (Darcy 1-D vertical flow model), groundwater dynamics (two parallel linear reservoirs), snowmelt (degree-day factor method) and surface runoff (for further details on each module, see Burek et al., 2013). The surface runoff generated in each cell is channelled to the nearest river network cell by means of a routing component based on a 4-point implicit finite-difference solution of the kinematic wave (Chow et al., 1988). The model has been calibrated and validated at global scale on more than 1,200 stations (Hirpa et al., 2018) as part of the EFAS (https://www.efas.eu/) and GloFAS (https://www.globalfloods.eu/) flood early warning systems.

Water abstractions in LISFLOOD consist of five components: (manufacturing) industrial, energy, livestock, domestic and irrigation water demand. While irrigation water demand is modelled dynamically within LISFLOOD, the other four components are downscaled to the model grid cells from country-level data obtained from EUROSTAT and AQUASTAT. High resolution data from the Land-Use based Integrated Sustainability Assessment (LUISA) Territorial Modelling Platform (Jacobs-Crisioni et al., 2017) were used for the spatial downscaling of the socioeconomic drivers of present and future water use, with projected data consistent with the EU economic, budgetary, and demographic projections (EC, 2015). These data are produced as part of the "production and visualization of territorial indicators" component of the LUISA platform and distributed through the Territorial Dashboard (http://urban.jrc.ec.europa.eu/t-board). Maps cover the EU Member States and several Western Balkan countries until 2050 at a detailed spatial resolution (~ 100m^2) (Jacobs-Crisioni et al., 2017). Since the LUISA population and land use projections cover up to 2050, these quantities were assumed static thereafter.

In detail, irrigation is estimated dynamically at the model time step (daily in this study) based on two distinct methods for crop irrigation and paddy-rice irrigation, as defined from land use maps. In the former, the demanded water amount by the crop (transpiration) is compared to the available water in the soil and the irrigation is modelled to keep the soil water content at field capacity (also accounting for the different efficiency of the irrigation systems). In the paddy-rice irrigation instead, a defined water-level is maintained during the whole irrigation season (also accounting for soil percolation). Maximum crop transpiration is function of potential evapotranspiration through a crop-specific efficiency coefficient.

Downscaling of the livestock water demand at grid scale was performed as described in Mubareka et al. (2013), by computing the water demand of each livestock category (e.g., cattle, pigs, sheep) separately. Public water withdrawal was downscaled using a land use proxy approach (Vandecasteele et al., 2014), assuming that public water withdrawal is the total water withdrawn in urban areas (i.e., commercial/service are negligible). Similarly, industrial water demand was disaggregated using the corresponding land use classes in the LUISA platform (Bisselink et al., 2018), and projections of the Gross Value Added of the industrial sector were used to simulate future demand. Water demand for energy and cooling is computed with a relatively similar approach, with national data downscaled to the locations of large power thermal power stations registered in the European Pollutant Release and Transfer Register data base (E-PRTR). Future changes in energy water use are simulated according to the electricity consumption projections from the POLES model (Prospective Outlook on Long-term Energy Systems, Keramidas et al., 2017).

2.3 Drought modelling

The hydrological drought modelling approach used in this study is analogous to the methodology used to estimate the low-flow indicator used in the European Drought Observatory (EDO) (Cammalleri et al., 2017). The key quantity is the water deficit computed from an unbroken sequence of discharge (*Q*) values below a defined low-flow threshold. We used the 85-th percentile, Q_{85}, derived for the present climate as a threshold both in the present and future scenarios, with the

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Eliminato: <#>Future water use is based on projections of population, land use, energy demand and economic output of sectors according to the EU economic, budgetary, and demographic projections (EC, 2015). The Land-Use based Integrated Sustainability Assessment (LUISA) Territorial Modelling Platform was used for the spatial downscaling of the socioeconomic drivers of present and future water use (Jacobs-Crisioni et al., 2017). The population and land use projections are limited to 2050 and were assumed static thereafter. A more elaborate description of the different water use modules can be found in Bisselink et al. (2018). ¶

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aim to estimate how droughts under present climate conditions will be projected under climate change.

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According to the theory of runs (Yevjevich, 1967), a continuous period with river flow values below the defined low-flow threshold is considered as a drought event, of which the severity is quantified by the total deficit (*D*, represented by the area enclosed by the threshold and the streamflow time series). Other key traits of drought are the duration, quantified by the length of the drought in days (*N*), and the temporal frequency of the events, which can be expressed as return period (*T*).

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In order to avoid potential bias in the analysis with the inclusion of minor events and to ensure the independence among events, two post-processing corrections were applied after selection of the events below the threshold: 1) consecutive events with an inter-event time smaller than 10 days were pooled together (Zelenhasić and Salvai, 1987), and 2) small isolated events (of duration less than 5 days) were removed from the analysis (Jakubowski and Radczuk, 2004). Specifically, the first correction accounts for the potential statistical inter-dependency of events that are close in time, whereas the second reduces the effects of the uncertainty in the defined threshold by removing the events with discharge values very close to the threshold only for a short period of time.

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Following this definition, a sequence of drought events for both the baseline period and the three GWLs were derived. Given the huge variability of *D* values across the European domain due to differences in hydrological regimes and size of river basins, the changes in drought severity are expressed as relative differences (%) from the values in the baseline period (1981-2010). The series of *D* events was fitted according to the Pareto Type II distribution (also known as Lomax distribution, a special case of the Generalized Pareto Distribution with location parameter equal to zero), formally expressed as:

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$$F(D;\alpha;\lambda) = 1 - \left(1 + \frac{D}{\lambda}\right)^{-\alpha} \qquad (1)$$

where α and λ are the strictly positive shape and scale parameters, respectively, derived from the sample according to the maximum likelihood method. The fitted distributions allow computing the return period associated to a specific D value (*T*, the average occurrence interval which refers to the expected value of the number of realizations to be awaited before observing an event whose magnitude exceeds *D*; Serinaldi, 2015), or to be used in reverse to estimate the D value associated to a specific return period. More details on the implementation of the drought indicator over Europe can be found in Cammalleri et al. (2017), including a validation against some major past drought events. An analogous validation at global scale can be found in Cammalleri et al. (2020), where a goodness-of-fit test for the Lomax distribution is also performed.

2.4 Population and agricultural land exposed to streamflow drought

In order to quantify how global warming could change exposure to streamflow drought in Europe, different exposed quantities can be analysed depending on the impacted sector. Agriculture and livestock farming, and public water supply seem to be the two most reported economic sectors according to the European Drought Impact Inventory (EDII, https://www.geo.uio.no/edc/droughtdb/). As a result, we focus the exposure analysis on population and agricultural land. For the baseline we used the map of agricultural areas from the CORINE land Cover (EEA, 2016) and the population density from the LUISA Territorial Modelling Platform (Batista e Silva et al., 2013). Consistently with the hydrological simulations, for future time slices the land use and population projections of LUISA were used up to 2050.

The spatial data of population and agricultural land were summed over NUTS 2 statistical regions (or equivalent for EU-neighbour countries according to Eurostat, https://ec.europa.eu/eurostat/web/nuts/statistical-regions-outside-eu). Then, the expected year-average exposed population and agricultural land were computed by equally dividing over time the changes in drought exposure caused by the median (over the NUTS 2) changes in drought frequency of an event with a 10-year return period in the baseline. Following this approach, the exposure associated to a present 10-year or more intense drought is simply averaged over the

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period, obtaining a standardized year-average quantity. Finally, changes over NUTS 2 regions were further aggregate to country scale.

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3. Results

3.1 Evaluation of the changes in main drought traits

3.1.1 Drought severity

Figure 1 shows the ensemble-median relative change in severity of a 10-year drought between the baseline and the GWLs, with positive (negative) values indicating a higher (lower) drought severity with warming compared to the reference. The projected changes are considered robust when at least 2/3 of the ensemble members agree on the sign of change (no-agreement otherwise), which is a simplification of the approach proposed by Tebaldi et al. (2011) and applied over Europe by Dosio and Fischer (2018).

The spatial maps depicted in Figure 1 highlight a strong divergence in the projected changes of drought severity with warming over Europe, with four macro-regions (delimited in Figure 1 lower-right panel) displaying somewhat homogeneous behaviour. The four macro-regions were derived by computing for each country the predominant change for the three GWLs, then by combining the countries with similar features. A similar rough subdivision, which is in line with the IPCC AR5 European macro regions (Kovats et al., 2014) derived from a principal component analysis of 20 environmental-relevant variables performed by Metzeger et al. (2005), has been already used in previous early studies at continental-scale (i.e., Feyen and Dankers, 2009; Lehner et al., 2006), and for this reason it will be adopted in all the subsequent analyses.

In the Mediterranean sub-region (i.e., Iberian Peninsula, Italy, Greece and the Balkans) generally more severe droughts are projected, whereas in the Boreal sub-area (i.e., Scandinavia peninsula and Baltic countries) drought severity is expected to reduce almost everywhere. The projected changes are less marked in two transition regions, but, in general, they point towards more severe droughts in the Atlantic (i.e., British Isles, France, Belgium and the Netherlands) and less

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severe droughts over the Continental sub-area (Germany, Poland and eastern European countries). Overall, these patterns of change become stronger and more robust with increasing warming.

The strongest increase in drought severity is projected for Portugal, Spain and Greece, where the fraction of rivers with an increase in deficit of more than 50% at 3 K is 99, 80 and 75%, respectively. If climate stabilizes at 2 K, streamflow drought severity is lower than at 3 K, but still at least 50% higher than in the baseline for halve of the rivers of Portugal and Spain, and 35% of Greece. Capping global warming at 1.5 K would further limit the increase in severity, with only 21, 20 and 14% of the rivers of Portugal, Spain and Greece expected to experience an increase in drought severity of more than 50%.

Eliminato: The same rough subdivision, which is in line with the IPCC AR5 European macro regions (Kovats et al., 2014) derived from a principal component analysis of 20 environmental-relevant variables performed by Metzeger et al. (2005), has been already observed even in previous early studies at continental-scale (i.e., Feyen and Dankers, 2009; Lehner et al., 2006), and for this reason it will be adopted in all the subsequent analyses. ¶

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Over the Atlantic region (apart from Iceland), streamflow droughts are generally projected to also become more severe with global warming. The south of France shows a pattern towards more severe flow deficits with warming that is similar to that projected for most of the Mediterranean. For the other parts of the Atlantic sub-region the changes are less pronounced. Keeping warming to 2 K or below would limit the increase in severity for most of the region to below 25% compared to the baseline. At 3 K warming, the increase in severity could reach up to 50%. In some parts of the Atlantic sub-region, such as the Seine river catchment in France (northern France), at lower levels of warming the climate models do not agree on the sign of the change, or show a small trend towards less severe droughts. Yet, with stronger warming the signal of change reverses towards more severe droughts.

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Over most of the Continental sub-region there is a trend towards less severe droughts with global warming. On the one hand, this trend is somewhat more pronounced in upstream Danube tributaries that drain the Alps to the east. In many downstream Danube tributaries in Hungary, Romania and Bulgaria, on the other hand, streamflow droughts are projected to become more severe (in agreement with the results reported in Stagl and Hattermann, 2015). At low levels of global warming (1.5 and 2 K) most of Germany is expected to experience less severe droughts. At high

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levels of warming (3 K), however, western parts of Germany are projected to experience and inverse trend while the rest shows a large uncertainty in the projected changes. In contrast to most of the Continental sub-area, projections of streamflow drought severity show an increase with global warming over Denmark.

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Finally, in most of the Boreal region, streamflow drought deficits is expected to become progressively less severe with warming. At 3 K warming streamflow droughts could be half as severe compared to the baseline, with few notable exceptions in southern Sweden.

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3.1.2 *Drought duration*

Figure 2 shows the fraction of each sub-region (presented in the lower-right panel of Figure 1) for which a certain degree of change in drought duration is projected for the different warming levels. There is a clear upward climate change-induced trend in the fraction of the Mediterranean sub-region that will be exposed to longer droughts. When keeping global warming limited to 1.5 K, droughts are projected to last more than 5-days longer in about 40% of the Mediterranean, with a prolongation above 15 days in slightly more than 5% of the area. At 3 K warming, however, streamflow droughts will last longer in 80% of the area and nearly half of the sub-region could face an increase in drought duration of at least 10 days.

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An upward, but less pronounced, trend in drought duration with global warming is also projected for most of the Atlantic sub-region. At 1.5 K GWL, the area with a decrease in drought duration (about 30%) is comparable to the area with an increase, with no clear signal in about 40% of the domain. With higher levels of warming, the area with a shorter drought duration shrinks, while the fraction of land that is expected to face longer droughts steadily expands. At 3 K GWL, droughts are projected to last longer in about 75% of the sub-region, hence similar to what can be observed for the Mediterranean. Yet, for only 10% of the area, drought duration is expected to increase by more than 10 days.

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In the Continental sub-region, the area that shows a decrease in drought duration is around 65% at 1.5 K, which slightly reduces in extent with increasing warming. Yet, over this area droughts are expected to progressively shorten with further warming. At 3 K warming, with droughts lasting at least 10 and 15 days shorter over more than 30 and 10% of the region, respectively. Drought duration is projected to increase over a small part (20% at 3 K) of the domain, mainly corresponding to Bulgaria.

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Over the Boreal sub-region, droughts are projected to become shorter with global warming over practically the whole domain. At 1.5 K warming, drought duration is expected to be at least 15 days shorter in 20% of the area, which grows to 50% of the area at 3 K warming. For all sub-regions, the fraction of area with no-agreement in future drought duration tends to reduce with increasing global warming, and this signal is very consistent among all the climate projections. At 3 K warming, projections show that less than 15% of the domain under study have no agreement in the direction of change in drought duration.

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3.1.3 *Drought frequency*

Figure 3 shows the frequency distribution of drought return periods for the three GWLs corresponding to an event with a return period (T) of 10 years under baseline climate. In these plots, values greater than 10 can be interpreted as a reduction in drought frequency (an event with $T = 10$ years in the baseline will become rarer), whereas values lower than 10 represent an increase in drought frequency (an event with $T = 10$ years in the baseline will become more common).

The frequency distributions of T values for the Mediterranean (upper-left panel) show a clear shift towards more recurrent droughts. At 1.5 K warming the peak value is around 8 years, which further reduces to 7 and 6 years at 2 and 3 K warming, respectively. At 3 K warming the lower tail of the distribution falls below 4 years. In nearly 10% of the rivers, drought deficits that in baseline climate happen once in 10 years are expected to occur at least 2.5 times more frequent with 3 K warming. In the Atlantic sub-region the central value also reduces with warming, yet the overall

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reduction is less pronounced than in the Mediterranean sub-area, with a median value around 7 years at 3 K warming. In the Continental region, droughts will in general become less frequent with a central value between 12 and 13 years at all warming levels, even if the fraction of river cells with an increase in frequency (around 28% at 3 K) is larger than that with an increase in drought duration (less than 20% at 3 K, see Figure 2). In the Boreal sub-area the shift towards less frequent droughts is much more pronounced, with projected return periods concentrated around 20, 30 and 40 years for 1.5, 2 and 3 K warming, respectively.

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In addition to the shifts in central value of the frequency distributions, it is possible to observe an increase with warming in the spread around the central value for all regions. Additionally, changes opposite to the general trend can be observed in all regions. For example, over very few locations in the Mediterranean sub-region, such as some Alpine mountain drainage basins in northern Italy, drought conditions could become less severe and frequent (see also drought severity changes in Figure 1). In the Atlantic region, the small secondary peak of T values > 20 years corresponds to areas where droughts are projected to occur less frequently with global warming, such as Iceland and few tributaries from the Rhône that originate in the Alps (similarly to what was observed on drought severity in Figure 1). Even in the Boreal region a small fraction of the sub-domain shows an increase in drought frequency, while drought duration is projected to reduce practically everywhere. This is confirmed by the slight reduction in the frequency median value at 3 K GWL (26 years, compared to 27 years at 2 K).

The results reported in Figure 3 for the 10-year return period can be seen as representative of the behaviour at other return periods as well. To support this consideration, the data in Figure 4 report the sub-region median relative changes at the three GWLs for events with a baseline return period of 3, 5, 10, 20 and 50 years. The plots clear show how all the return periods have similar dynamics, with the only notable exception represented by the more marked reduction in median relative change of high return periods for the 3 K GWL in the Boreal sub-region (i.e., 20 and 50 years). It is also worth to point out how even if the dynamics are comparable among the different return periods, the magnitude of the relative changes is higher for the longer return periods.

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3.2 Population and agricultural land exposed to drought

Figure 5 shows the changes with respect to the baseline in population projected to be exposed to streamflow drought at country scale (percentage relative changes are also reported as numbers next to the bars). Total changes for the four macro-regions and the entire domain (TOT) are summarised in Table 1. Aggregated over the whole domain, about 1.5 million fewer people are expected to be annually exposed to drought at 1.5 K GWL compared to the baseline period, which reverses to an increase of about 2.5 and 11 million people/year compared to baseline human exposure at 2 and 3 K GWLs, respectively. This is because at 1.5 K the increase in population exposed annually in the Mediterranean (2.4 million) and Atlantic (less than 0.1 million) sub-regions is outweighed by the reduction in exposure in the Boreal (-0.6 million) and, most importantly, Continental (-3.4 million) sub-regions. Projections in the Mediterranean and Atlantic sub-regions show a progressive increase in population exposed (up to a total of 15.8 million people/year for 3 K GWL over the two regions), while in the Boreal and Continental combined human exposure to droughts is expected to remain roughly the same for all three GWLs (i.e., -3.9, -5.4 and -4.7 million/year at 1.5, 2 and 3 K, respectively).

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Spain is projected to have the largest absolute increase in population exposed to drought with global warming, with an almost doubling (+3.8 million/year) of the number of people exposed to drought each year at 3 K GWL. In relative terms, the relative increase in population exposure at 3K is also high in Portugal (+81%), United Kingdom (+58%) and France (+52%). The largest absolute decrease in population exposed is expected for Germany at 1.5 and 2 K GWL (-1.8 and -1.7 million people/year) and Poland at 3 K GWL. The transition of several areas in Germany from a decrease in drought to uncertain conditions (see as an example western Germany in Figure 1) explains the lower number of exposed people at 3 K (-0.9 million people/year) compared to Poland (-1.2 million

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people/year). The strongest reduction in population exposure in relative terms is expected for Norway, Iceland and Lithuania (up to 65, 87 and 85%, respectively).

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Exposure of agricultural land (Figure 6 and Table 2) shows similar trends as for population. Aggregated over Europe, the change in exposure is projected to be balanced in the exposed agricultural land at 1.5 K GWL (net increase of 0.1 million ha/year), whereas at higher warming levels exposure of agricultural land increases to 1.2 and 4.5 million ha/year at 2 and 3 K, respectively. This can be explained by the expected steady increase in agricultural land exposed to drought in the Mediterranean and Atlantic sub-regions (up to 6 million ha/year combined at 3 K), which is not counterbalanced at the highest warming by the agricultural land being less exposed to drought in the Boreal and the Continental sub-regions (-1.3 million ha/year at 1.5 K and -1.5 million ha/year at 3 K). In absolute numbers, Spain shows the largest projected increase in the agricultural land exposed at all GWLs, with an additional 0.9 million ha/year at 1.5 K to 2.6 million ha/year at 3 K (corresponding to a relative increase of about 35 and 97%, respectively). Relative changes are expected to be quite notable for other Mediterranean countries as well, such as Portugal and Greece, reaching almost 120 and 77% at 3 K, respectively.

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4. Discussion

The projections of severity, duration and frequency underline some common features in future streamflow drought in Europe. The uncertainty in the projections is more marked at the 1.5 and 2 K GWLs, whereas patterns are more statistically robust at higher warming, as also observed by Marx et al. (2018) for minimum flows. The magnitude of the projected changes increases in general with warming for all the drought traits, with only limited areas interested by an inversion in the trend. The main pattern is a strengthening of the dichotomy between southern but also western parts of Europe that will become more prone to droughts and a wetting north, which is a trend that is already ongoing according to Stagge et al. (2017). This result is also in line with other studies that projected streamflow droughts focusing on specific temporal horizons (Lehner et al., 2006; Feyen and

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Dankers, 2009; Stahl et al., 2012; Forzieri et al., 2014) or on agricultural (e.g., Samaniego et al., 2018) and meteorological (e.g., Gudmundsson and Seneviratne, 2016; Spinoni et al., 2018) droughts. Hence, there is growing consensus in the community on the main patterns of climate-induced changes on drought conditions in Europe.

Overall, the Mediterranean sub-region shows the strongest negative change, with droughts projected to become more severe, last longer and happen more frequently already at 1.5 K GWL. The combined effects of increasing temperature and decreasing summer precipitation (Dubrovský et al., 2014; Vautard et al., 2014) are expected to result in a further exacerbation of water deficits in an area already prone to limited water resources. This agrees with global studies that identify the Mediterranean as a hot spot for climate change, even if the targets set by the Paris agreement will be met (Gu et al., 2020), and also with the study of Guerreiro et al. (2017) on the potential occurrence of multi-year droughts in major Iberian water resource regions.

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Symmetrically, the Boreal sub-region is projected to experience a general reduction in all drought traits, as the increase in precipitation will likely outweigh the increase in evaporative demand due to elevated temperatures (Jacob et al., 2018). Over this region, similarly to the Alps (Donnelly et al., 2017), increasing winter precipitation and higher temperatures is expected to result in higher winter flows, when river flows are typically at their lowest (Gobiet et al., 2014).

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In the other two sub-regions the projections are less uniform, with more variation in the signal and robustness of the projections with global warming. In the Atlantic sub-region the increase in droughts at 3 K is expected to be less pronounced compared to the Mediterranean, but similarly robust, while at lower warming levels there is large uncertainty in the projections. In some river basins, such as the Seine in northern France, a positive (i.e., less droughts) or uncertain trend is projected for low levels of global warming, while at higher levels of warming drought conditions are projected to worsen. This is related to the fact that at higher levels of warming the atmospheric demand (evapotranspiration) rises faster than supply due to the combination of a strong rise in temperature and a slight or uncertain increase in annual precipitation and a decline in summer precipitation (Kotlarski et al., 2014).

In the Continental sub-region the projected overall decrease in droughts is rather inhomogeneous in strength. In upstream Danube tributaries draining the Alps there is a strong trend towards less severe droughts as winter flows increase due to changes in snow accumulation and melt caused by increased winter precipitation and higher temperatures (Forzieri et al., 2014; Marx et al., 2018). In downstream reaches of the Danube, more severe droughts are projected due to a reduction in summer flows caused by an increased evaporative demand and less precipitation. Also in Germany, the trend towards less severe droughts for the Paris warming targets is reversed at higher warming as the increasing natural and human demand in drier summers outbalance higher annual supply. This is the case especially in western parts of Germany such as downstream reaches of the Rhine (Bosshard and Kotlarski, 2014).

This shows that the projected trends relate to the interplay between supply (precipitation), atmospheric demand (evapotranspiration) and human water use. Dosio and Fischer (2018) showed that precipitation will increase over most continental and northern parts of Europe (by +10-25% at 3 K), but to a lesser extent in summer months (changes with 3 K between -5% at middle latitudes of Continental Europe to +10-15% at higher latitudes in the Boreal region), when natural and human demand are highest. As a result, short duration droughts could happen more frequently in some catchments even when summer supply does not change drastically due to the growth in natural (because of rising temperatures) and human demand. In the case of longer drought events, the imbalances between supply and demand over summer may be mitigated by the increase in subsurface storages at the start of the summer season due to elevated precipitation amounts during the other seasons, but also potentially exacerbated in case of multi-annual summer droughts. In high-regulated basins in Europe, accounting for water uses and its temporal evolution is key to accurately represent streamflow drought in the anthropocene, when both natural and human induced factors influence drought propagation even further (Van Loon et al., 2016).

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5. Summary and Conclusions

This study analysed how the main characteristics of hydrological droughts are expected to change over Europe due to global warming. Projections in drought severity, duration and frequency based on river water deficits highlight some common features and spatial patterns in future drought conditions across Europe. The Mediterranean sub-region, which already suffers most from water scarcity, is projected to experience the strongest negative effects of climate change on drought conditions. With increasing global warming, streamflow deficits in this region expected to happen more frequently, become more severe and last longer. Symmetrically, the Boreal sub-area is projected to face a consistent decrease in drought severity, duration and frequency.

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In the Atlantic and Continental sub-regions the projections are less uniform, although over most of the Atlantic drought conditions are projected to worsen, while they generally will become less intense over Continental Europe. Despite the use of a large ensemble of climate models, there is still a substantial uncertainty in the projections in these regions, even if changes at 3 K are mostly well defined. The uncertainty is bigger for the 1.5 and 2 K GWLs, which suggests that there is still large disagreement among the models in possible changes in drought conditions in these areas when warming could be stabilised at the targets set in the Paris climate agreement.

The general patterns observed in this study are in line with other studies focused on specific temporal horizons rather than warming levels (Forzieri et al., 2014; Spinoni et al., 2018; Stahl et al., 2012), as well as with the results of Marx et al. (2018) on the simple daily streamflow percentile. In addition to that, this study provides a comprehensive analysis of different traits of streamflow droughts (i.e., severity, duration and frequency), it accounts for of the effects of human activities through the modelling of water demand, and it focuses on policy-relevant GWLs. The findings provide information that can be used as a basis to evaluate the implications at European scale of climate mitigation policies.

In this regard, it is clear that with higher warming the changes in drought traits are expected to be more marked, even if the spatial patterns of the areas with increasing/decreasing drought conditions are rather similar for the three GWLs here analysed. The exposure analysis with population density and agricultural land highlights how at lower warming levels positive and negative changes in exposure are expected to be balanced across Europe. However, at higher GWLs the increase in population and agricultural exposure in southern and western parts of Europe is projected to outweigh the effects of less severe droughts in the less populated north and most of continental and eastern Europe. At 3 K warming this could result in an additional 11 million people and 4.5 million ha exposed each year to drought conditions that currently are expected to happen once every 10 years or less. The projected changes in exposure to drought will pose considerable challenges for agriculture and water provision in densely populated and economically pivotal areas, especially in southern Europe.

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Data availability. All data are available via the EDO web portal (https://edo.jrc.ec.europa.eu/) upon request. A selected subset of the outputs will be made available through the JRC-DRMKC Risk Data Hub (https://drmkc.jrc.ec.europa.eu/risk-data-hub).

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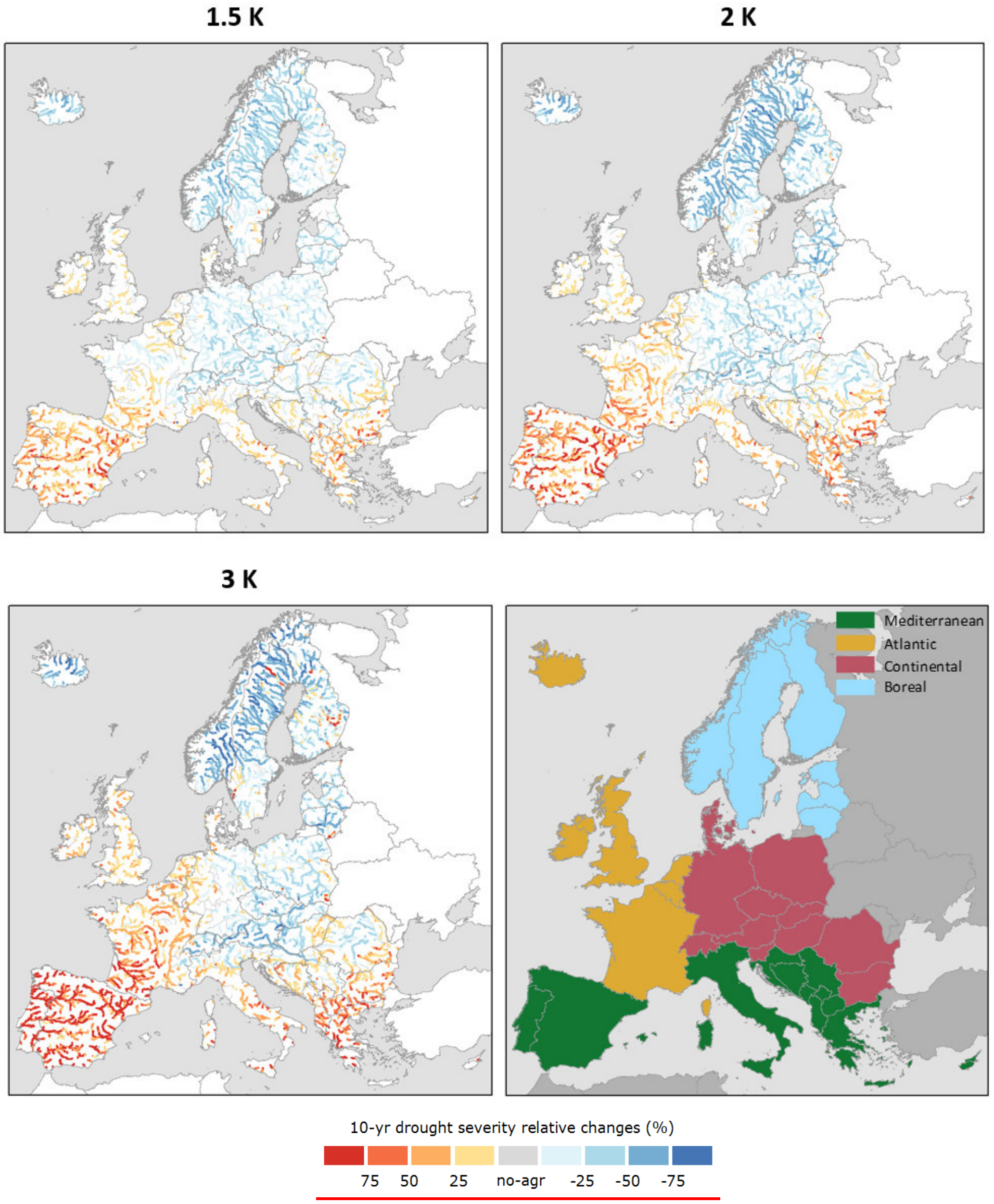

Fig. 1. Spatial distribution of the ensemble-median relative changes in drought severity of a 10-year drought (%) between reference period and the three GWLs (1.5 K in the upper-left panel, 2 K in the upper-right panel, 3 K in the lower-left panel). Positive values represent an increase in drought severity with warming. The no-agreement (no-agr) class identifies the cells where less than 2/3 of the climate ensemble members agree on the sign of the change. The lower-right panel represents the four sub-regions used for aggregation, which are in line with the IPCC AR5 European macro regions (Kovats et al., 2014).

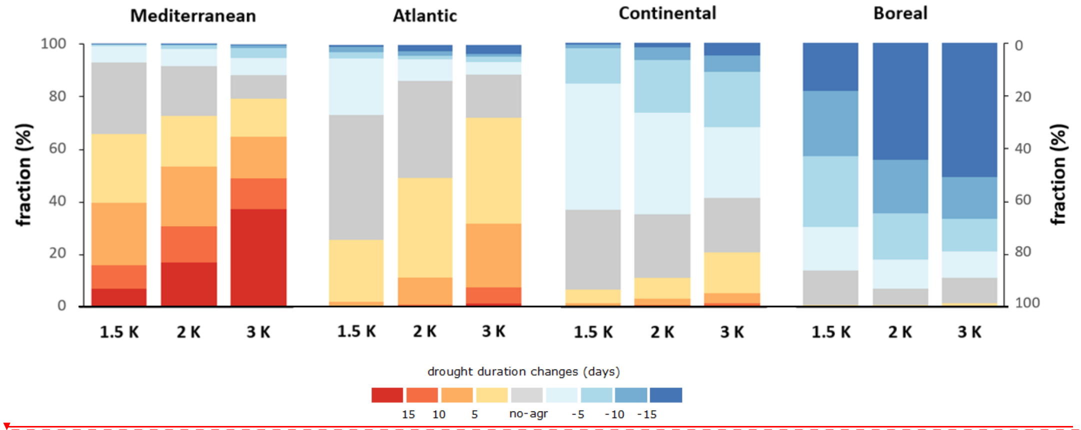

Fig. 2. Fraction of each sub-region within ranges of change in drought duration (days) for different GWLs.

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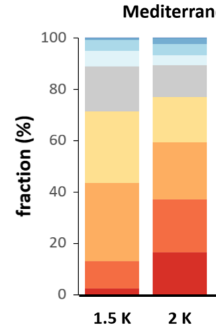

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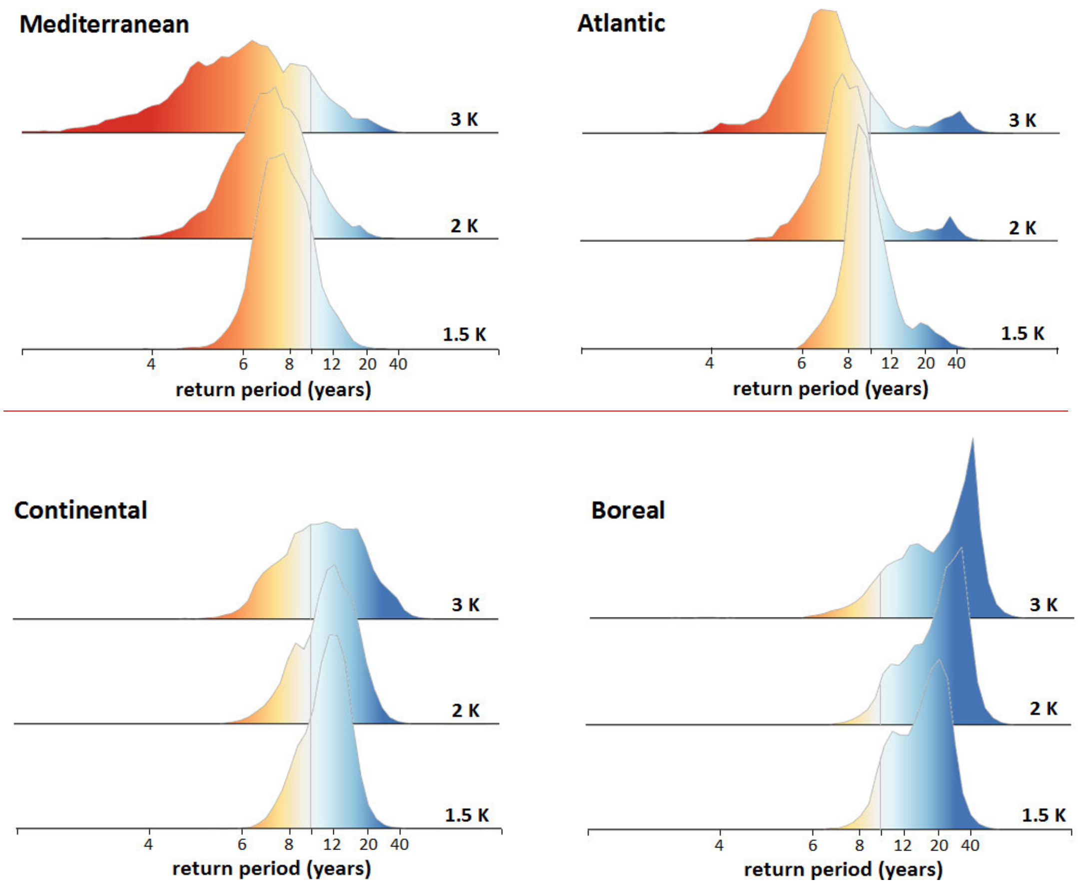

Fig. 3. Frequency distribution of the return period (years) for different GWLs corresponding to an event with a return period of 10 years in the reference baseline. Values lower (higher) than 10 represent an increase (reduction) in drought frequency. The vertical grey lines demark the 10-year return period, and the tick marks are uniformly spaced in frequency.

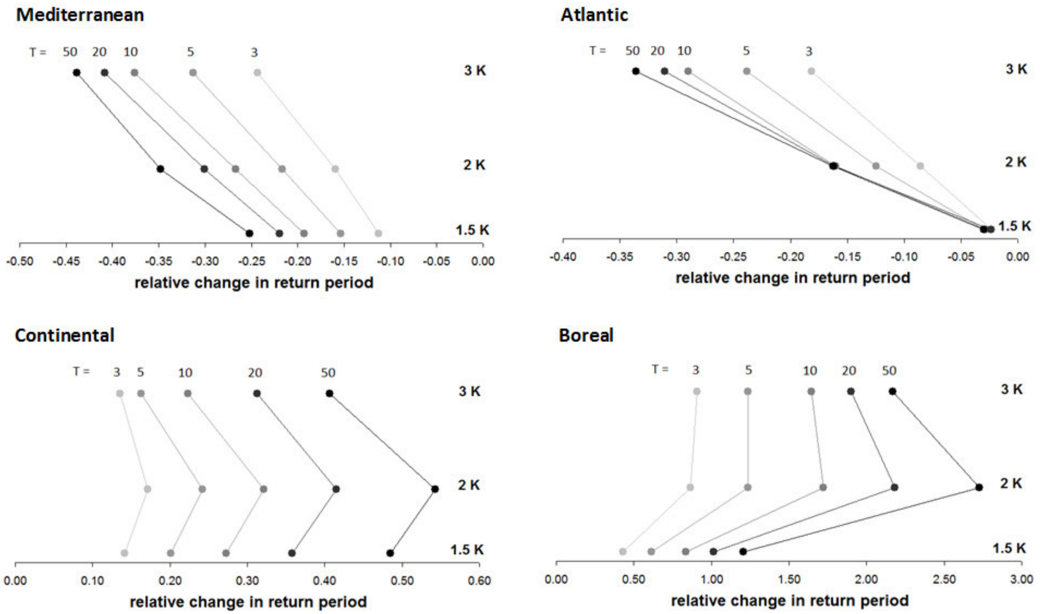

Fig. 4. Relative changes in sub-regional median return period (years) for different GWLs corresponding to events with a return period of 3, 5, 10, 20 and 50 years in the reference baseline. Negative (positive) values represent an increase (reduction) in drought frequency.

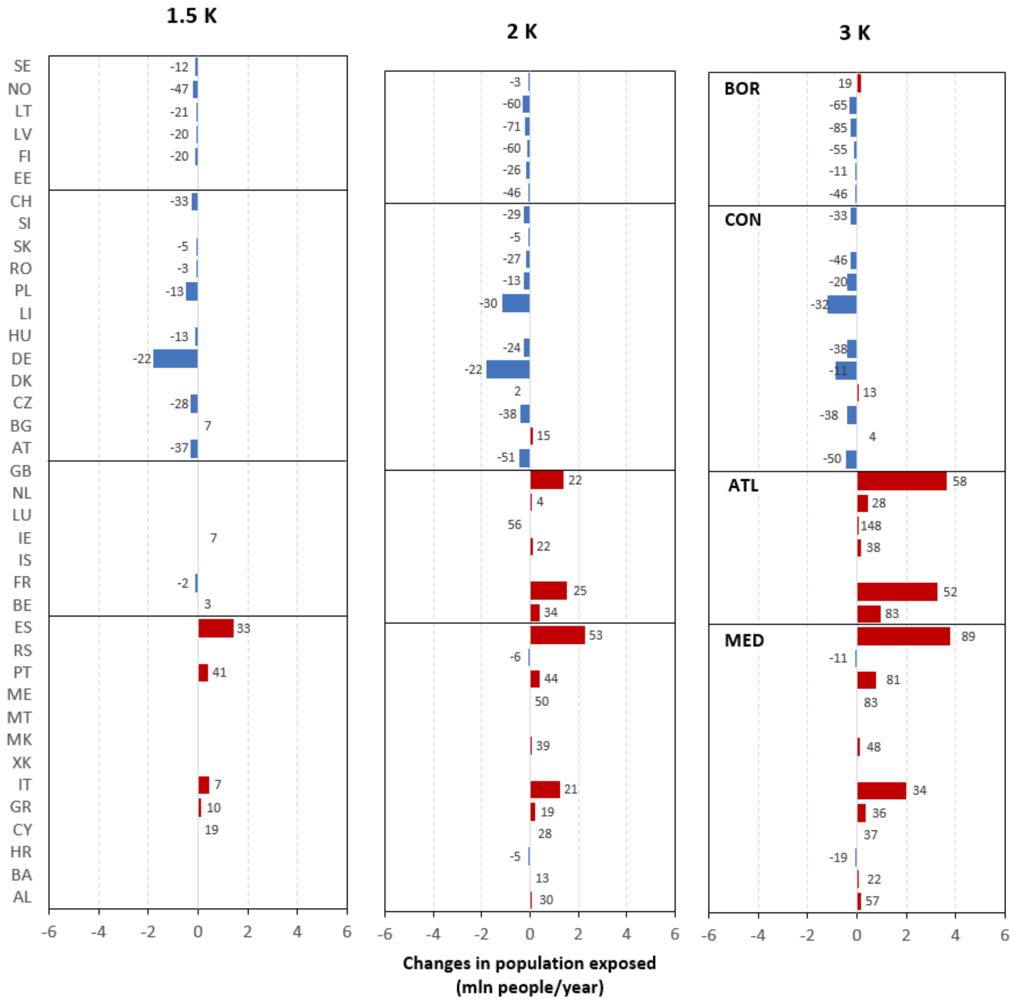

Fig. 5. Changes in population exposed per country (million people/year). Positive values indicate an increase in the population exposed. The numbers near the bars represent the percentage changes relative to the baseline (only if greater than 1%).

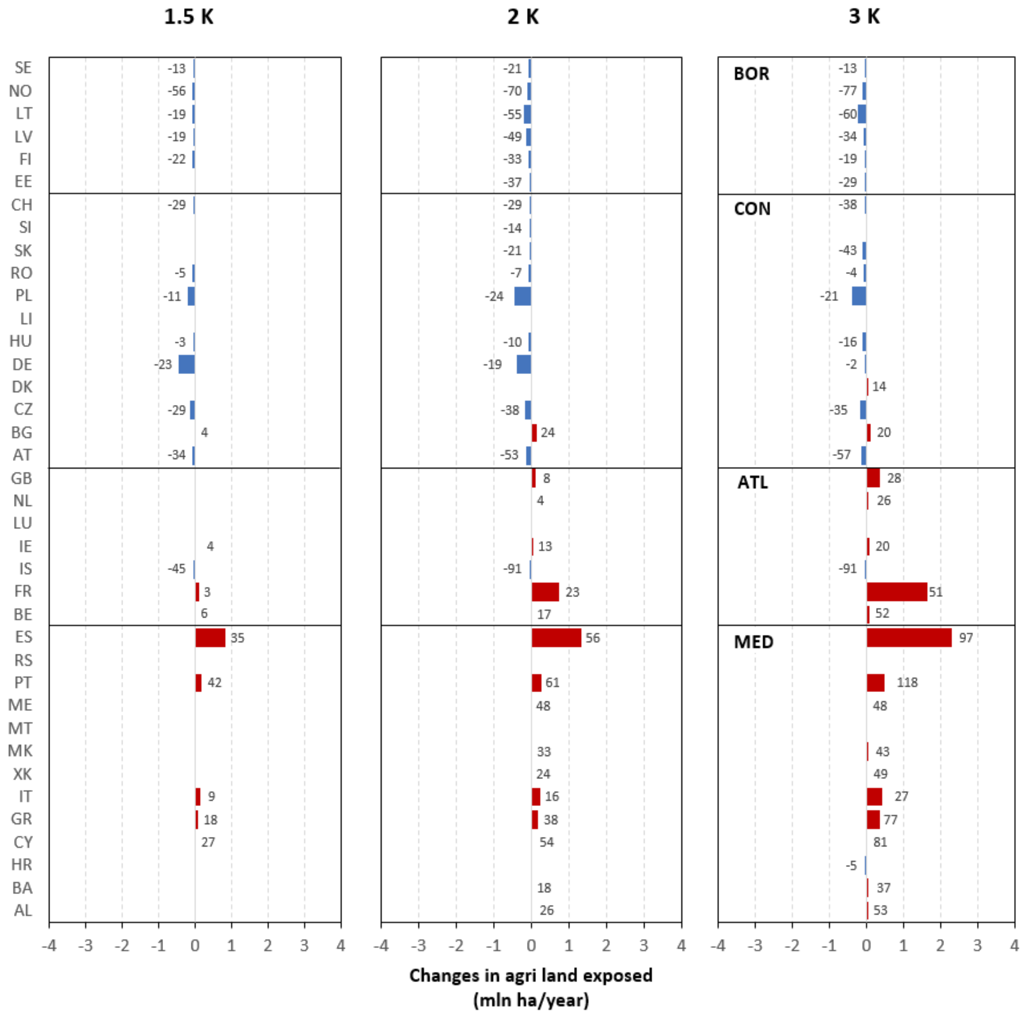

Fig. 6. Changes in agricultural land exposed per country (million ha/year). Positive values indicate an increase in the area exposed. The numbers near the bars represent the percentage changes relative to the baseline (only if greater than 1%).

Table 1. Total population exposed per sub-regions (million people/year).

Name	baseline	1.5 K	2 K	3 K
MEDITERRANEAN	14.4	16.8	18.8	21.7
ATLANTIC	16.0	16.1	19.5	24.5
CONTINENTAL	19.6	16.2	15.0	15.5
BOREAL	2.5	2.0	1.7	1.9
TOT	52.5	51.1	55.0	63.6

Table 2. Total agricultural land exposed per sub-regions (million ha/year).

Name	baseline	1.5 K	2 K	3 K
MEDITERRANEAN	5.8	7.1	8.0	9.6
ATLANTIC	5.4	5.5	6.3	7.6
CONTINENTAL	7.7	6.8	6.5	6.8
BOREAL	1.6	1.3	0.9	1.0
TOT	20.5	20.6	21.7	25.0