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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 index derived from river discharge simulations of a 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. The projected changes in these treats 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 interested by stronger droughts (with larger differences at 3 K) while the latter sees a reduction in droughts. In the Atlantic and Continental sub-regions the changes are 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 4.5 million ha of agricultural land will be exposed to droughts

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every year, on average. These are mostly located in the Mediterranean and Atlantic regions of Europe.

Keywords: climate change, drought, low flow index, Paris agreement.

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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). 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).

Depending on the degree of penetration of drought into the water cycle, drought is commonly classified into meteorological (e.g., precipitation), agricultural (e.g., soil moisture) and hydrological (e.g., river discharge) (Wilhite, 2000). 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 these typologies of droughts compared to meteorological events (e.g., Heinrich and Gobiet, 2012; Spinoni et al., 2018). This relates mainly 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. 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, irrigated agriculture, and public water supply. 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).

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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., Cervi et al., 2018; Hellwig and Stahl, 2018; Nerantzaki et al., 2019; Rudd et al., 2019; Van Tiel et al., 2018). Despite the high detail and insight on local processes these studies provide, their limited spatial coverage and the use of different drought indicators, models and scenarios complicates 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, including 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 droughts 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 goal of 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 given 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 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 river discharge as index, which is

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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 different climate change mitigation targets. We use streamflow deficit as an indicator of drought as it represents the integrated deficiency in water budget over the upstream catchment. The indicator is derived from daily streamflow simulations for the pan-European river network, which are obtained with a continental spatially-distributed hydrological and water use model forced with an ensemble of 11 bias-corrected regional climate projections for RCP4.5 and RCP8.5. We performed extreme value analysis on the streamflow deficits in order to evaluate changes in drought traits, such as duration, severity and frequency. In addition, spatial maps of present and future population and agricultural land were combined with the drought projections in order to identify changes in streamflow drought exposure.

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 EURO-CORDEX (Jacob et al., 2014). The climate projections were adjusted for bias with a 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 temperature. For these periods, drought characteristics were contrasted against those derived for the baseline reference period (1981-2010). Outputs from both RCPs are merged, 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 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.

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, infiltration, soil water redistribution in the vadose zone, groundwater dynamics, and surface runoff (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).

Water abstractions in LISFLOOD consist of five components: (manufacturing) industrial, energy, livestock, domestic and irrigation water demand. Irrigation is estimated dynamically within the model based on the required amount for crop transpiration that cannot be supplied by soil moisture above the wilting point. Water demand in the other four sectorial components is derived from country-level data (EUROSTAT, AQUASTAT) with different modelling and downscaling techniques for each component (see Vandecasteele et al., 2014; Mubareka et al., 2013). 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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2.3 Drought indicator

The hydrological drought index used in this study is analogous to 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.

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 number of drought days (N), and the temporal frequency of the events, which can be expressed as return period (T).

In order to avoid the inclusion in the analysis of minor 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). The first of these corrections allows accounting for the 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.

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

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empirical cumulative frequency of the D events was fitted according to the Pareto Type II distribution with zero threshold (also known as Lomax distribution), formally expressed as:

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

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 (T, inverse of the probability that one event is topped in any one year) associated to a specific D value, or to be used in reverse to estimate the D value associated to a specific return period. More details on the validation of the drought indicator over Europe and its operational implementation in EDO can be found in Cammalleri et al. (2017)

2.4 Population and agricultural land exposed to streamflow drought

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 quantification of drought risk is a challenging task (Naumann et al., 2015), and beyond the scope of this work. Here we quantified how global warming could change exposure to streamflow drought in Europe. Apart from agriculture, most of the sectors affected by drought are located close to where there is human presence. 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). For future time slices the land use and population projections of LUISA were used..

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), and changes in the population and agricultural land exposed to drought per year were computed by combing those data with the

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median (over the NUTS 2) changes in drought frequency of a 10-year baseline event. This approach assumes that, on average over a longer time window (such as a 30-year time slice), one-tenth of the people and agricultural land of a NUTS 2 region are expected to be exposed each year to a present 10-year or more intense drought, and that the expected annual exposure changes accordingly to the changes in drought frequency. Changes over NUTS 2 regions were further aggregate to country scale.

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).

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. 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 will 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 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 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.

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 experiencing an increase in drought severity of more than 50%.

Over the Atlantic region (apart from Iceland), streamflow droughts will in general 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, 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.

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 will experience less severe droughts. At high levels of

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

Finally, in most of the Boreal region, streamflow drought deficits will 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.

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 warming-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 10-days longer per year in about 45% of the Mediterranean, with a prolongation above one month/year in less than 5% of the area. At 3 K warming, however, streamflow droughts will last at least 10 days/year longer in 70% of the area and nearly half of the sub-region could face an increase in drought duration of at least 30 days/year.

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 (about 38%) in drought duration is slightly larger than the area with an increase (about 26%), with no clear signal in about one third of the domain. With higher levels of warming, the area with a shorter drought duration shrinks, while the fraction of land that will face longer droughts steadily expands. At 3 K GWL, droughts will last longer in about 80% of the sub-region, hence similar to what can be observed for the Mediterranean. Yet, for only 13% of the area, drought duration is expected to increase by more than a month/year.

In the Continental sub-region, the area that shows a decrease in drought duration is around 80% at 1.5 K, which slightly reduces in extent with increasing warming. Yet, over this area droughts will

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progressively shorten with further warming. At 3 K warming, droughts will last at least 10, 20 and 30 days shorter over more than 60, 40 and 20% of the region, respectively. Drought duration is projected to increase over a small part (10% at 3 K) of the domain, mainly corresponding to Bulgaria.

Over the Boreal sub-region, droughts are projected to become shorter with global warming over practically the whole domain. At 1.5 K warming, droughts will last at least one month/year shorter in 25% of the area, which grows to 80% of the area at 3 K warming. For all sub-regions, the fraction of area with no-agreement in future drought duration decreases with increasing global warming, and this signal is very consistent among all the climate projections. At 3 K warming, less than 10% of the domain under study will have no agreement in the direction of change in drought duration.

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 average 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

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a central value of around 12 years at all warming levels, even if the fraction of river cells with an increase in frequency (around 25% at 3 K) is larger than that with an increase in drought duration (around 10% at 3 K, see Figure 2). In the Boreal sub-area the shift towards less frequent droughts is much more pronounced, with future return periods concentrated around 20, 30 and 40 years for 1.5, 2 and 3 K warming, respectively.

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.

3.2 Population and agricultural land exposed to drought

Figure 4 shows the changes with respect to the baseline in population 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 will 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

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in the Boreal (-0.6 million) and, most importantly, Continental (-3.4 million) sub-regions. In the Mediterranean and Atlantic sub-regions there will be 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 remains 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).

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 observed 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 Fig. 1) explains the lower number of exposed people at 3 K (-0.9 million people/year) compared to Poland (-1.2 million people/year). The strongest reduction in population exposure in relative terms is observed for Norway, Iceland and Lithuania (up to 65, 87 and 85%, respectively).

Exposure of agricultural land (Figure 5 and Table 2) shows similar trends as for population. Aggregated over Europe, the change in exposure is 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 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 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 also quite notable for other

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Mediterranean countries, such as Portugal and Greece, reaching almost 120 and 77% at 3 K, respectively.

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 observed 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. This is in line with other studies that projected streamflow droughts focusing on specific temporal horizons (Lehner et al., 2006; Feyen and 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 sever, last longer and happen more frequently already at 1.5 K GWL. The combined effects of increasing temperature and decreasing summer precipitation (Vautard et al., 2014) will result in a further exacerbation of water deficits in an area already prone to limited water resources. This is in agreement 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), as well as with the potential occurrence of mega droughts in major Iberian water resource regions (Guerreiro et al., 2017).

Symmetrically, the Boreal sub-region will experience a general reduction in drought, as the increase in precipitation will outweigh the increase in evaporative demand due to elevated

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temperatures (Jacob et al., 2018). Over this region, similarly to the Alps (Donnelly et al., 2017), increasing winter precipitation and higher temperatures results in higher winter flows, when river flows are typically at their lowest (Gobiet et al., 2014).

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 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 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 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. In some catchments, short duration droughts could happen more frequently when summer supply does not change drastically but natural demand grows due to rising temperatures in combination with high human demand. In the mostly high-regulated basins in Europe, accounting for water uses and its temporal evolution is key in studying streamflow drought in the anthropocene, when both natural and human induced factors influence drought propagation even further (Van Loon et al., 2016). Longer drought events reflect imbalances in precipitation over longer time spans in which possible imbalances between supply and demand over summer are counter balanced by increased subsurface storages at the start of the summer season due to elevated precipitation amounts in the other seasons.

5. Summary and Conclusions

This study analysed how the main characteristics of hydrological droughts will 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, will experience the strongest negative effects of climate change on drought conditions. With increasing global warming, streamflow deficits in this region will happen more frequently, become more severe and last longer. Symmetrically, the Boreal sub-area will face a consistent decrease in drought severity, duration and frequency.

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

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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 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 balanced across Europe. However, with higher levels of global warming the increase in population and agricultural exposure in southern and western parts of Europe will 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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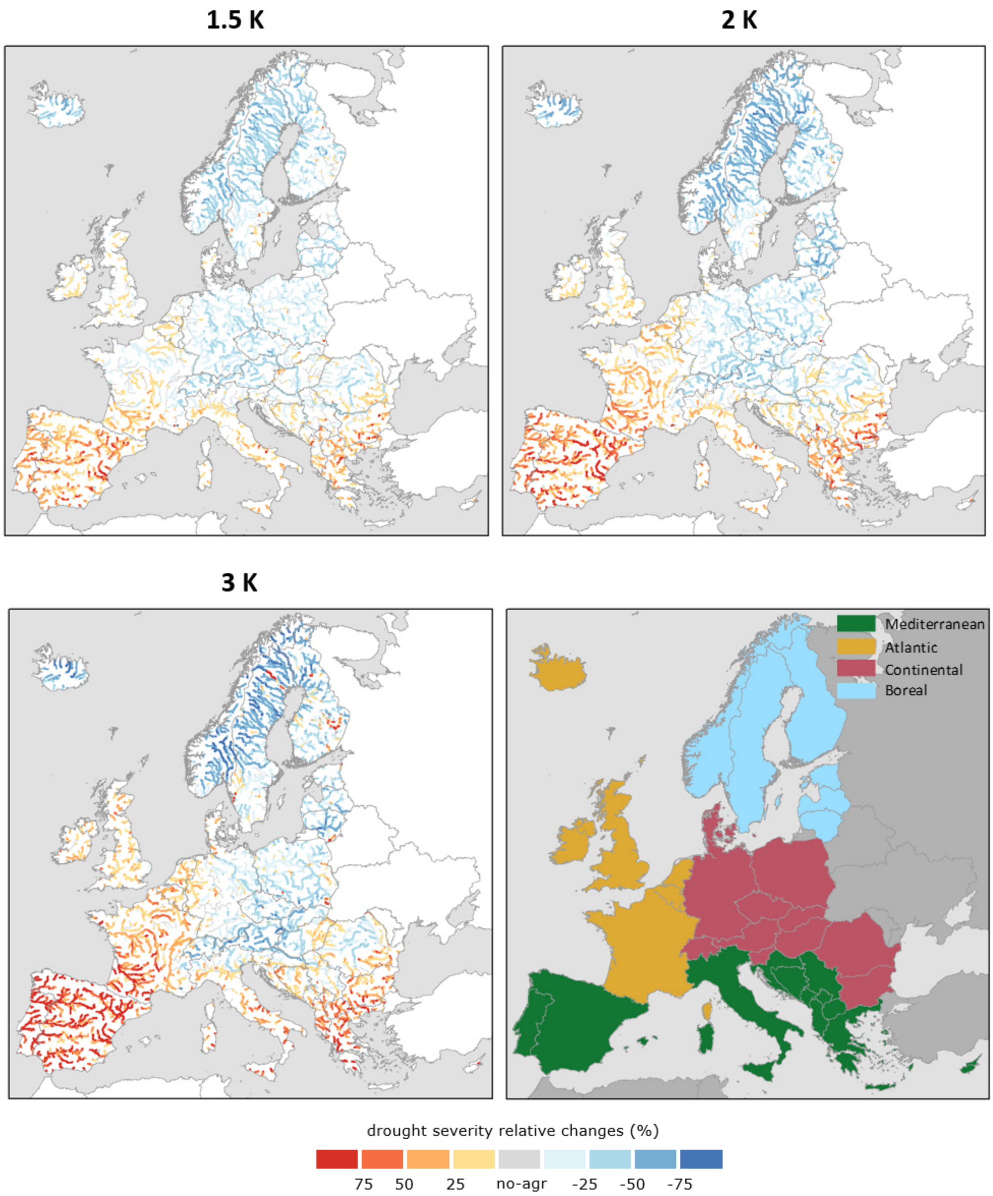

Fig. 1. Spatial distribution of the ensemble-median relative changes in drought severity (%) between reference period and the three GWLs (1.5 K in the upper-left panel, 2 K in the upper-right panel, 3 K in the lower-left panel). Positive values represent an increase in drought severity with warming. 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).

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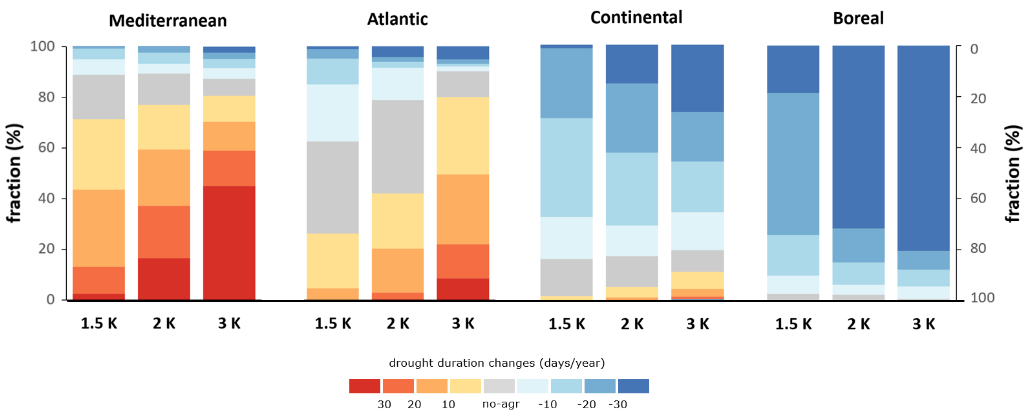
625 

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

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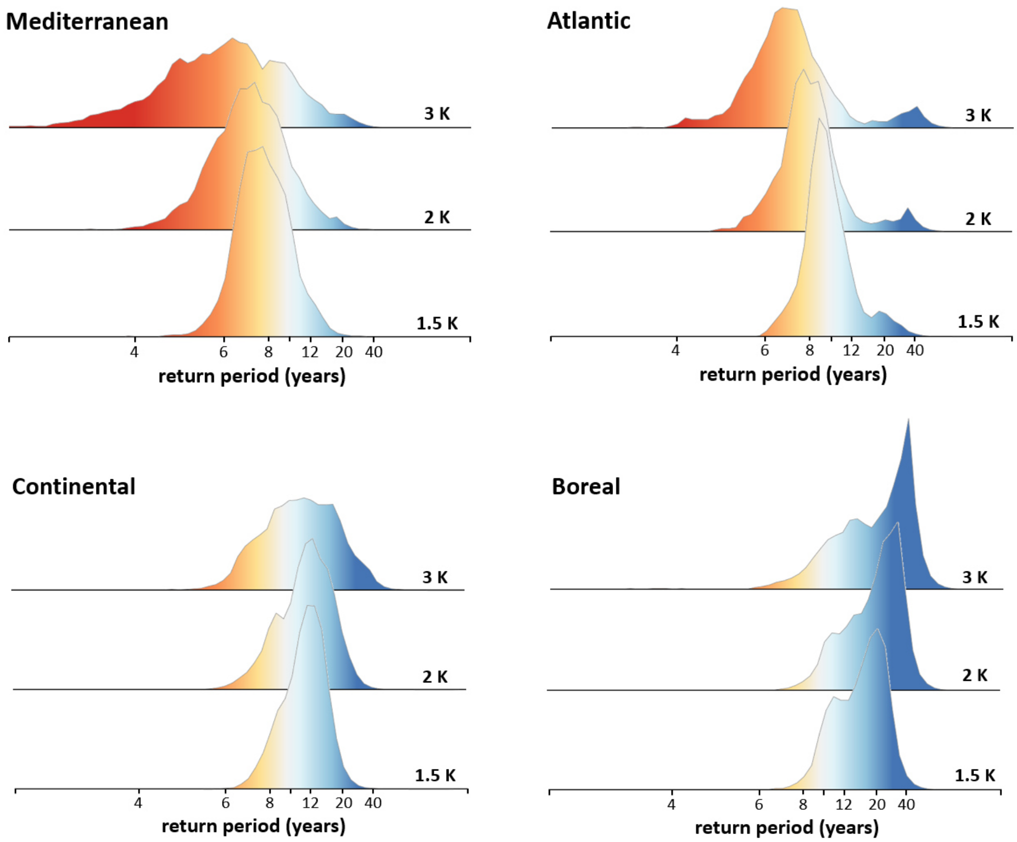

Fig. 3. Frequency distribution of the return period (years) for different GWLs corresponding to an event with a return period of 10 years in the reference baseline. Values lower (higher) than 10 represent an increase (reduction) in drought frequency.

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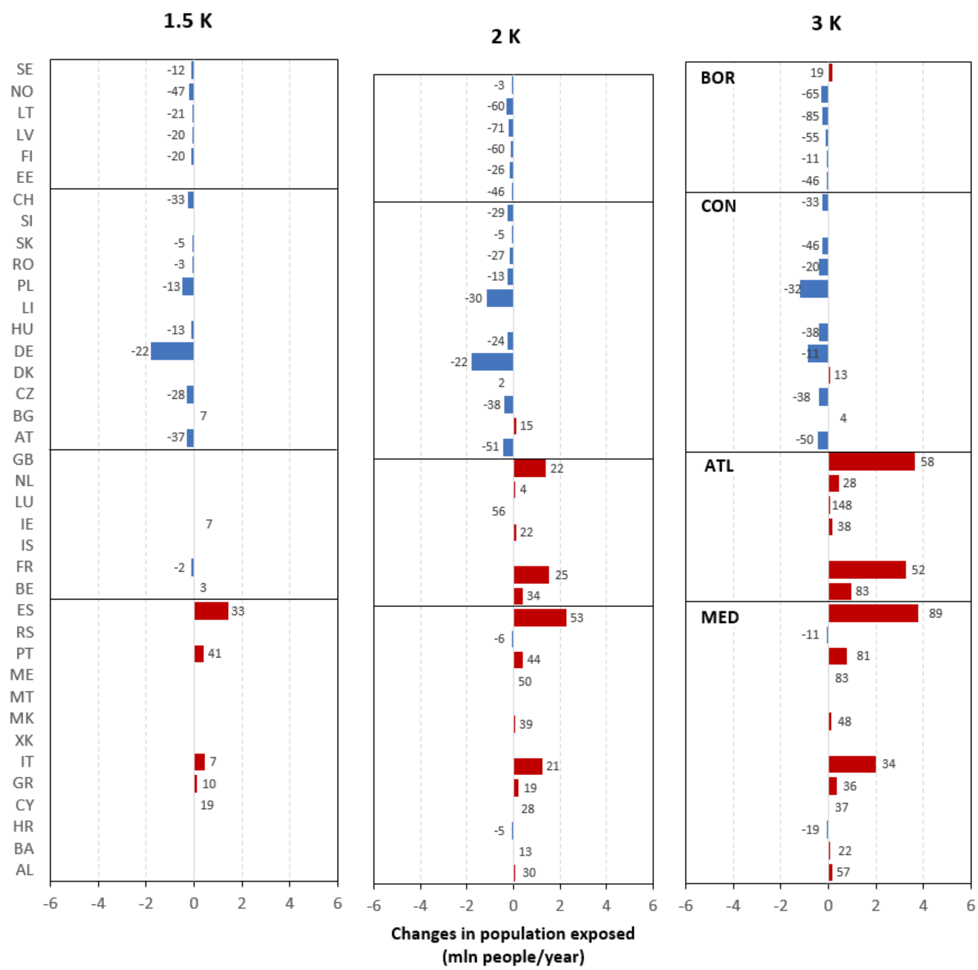

Fig. 4. Changes in population exposed per country (million people/year). Positive values indicate an increase in the population exposed. The numbers near the bars represent the percentage changes relative to the baseline (only if greater than 1%).

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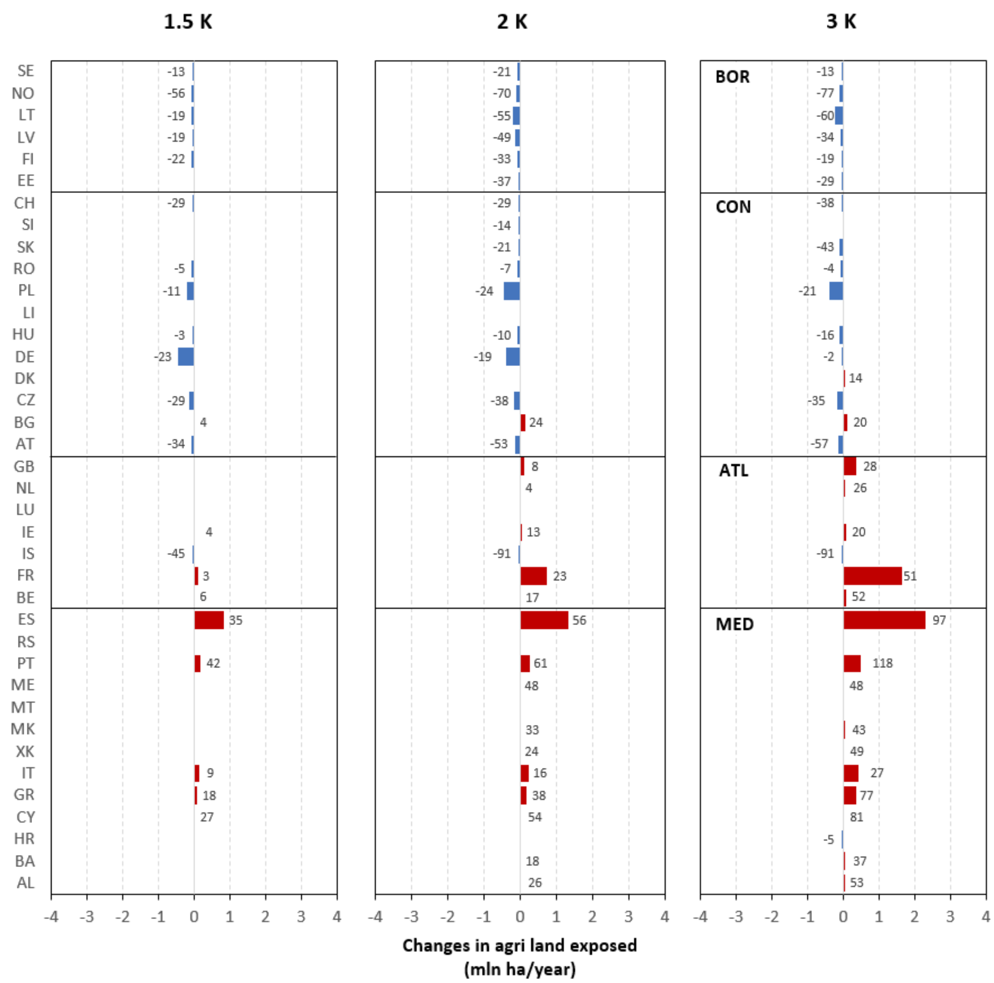

Fig. 5. Changes in agricultural land exposed per country (million ha/year). Positive values indicate an increase in the area exposed. The numbers near the bars represent the percentage changes relative to the baseline (only if greater than 1%).

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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