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Will drought events become more frequent and severe in Europe?

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ABSTRACT: As a result of climate change in recent past and unsustainable land management, drought became one of the most impacting disasters and, with the projected global warming, it is expected to progressively cause more damages by the end of the 21st century. This study investigates changes in drought occurrence, frequency, and severity in Europe in the next decades. A combined indicator based on the predominance of the drought signal over normal/wet conditions has been used. The indicator, which combines the standardized precipitation index (SPI, which accounts for anomalous low rainfall), the standardized precipitation evapotranspiration index (SPEI, which accounts for high temperatures and scarce precipitations), and the reconnaissance drought indicator (RDI, similar to SPEI but more affected by extreme events), has been computed at 3- and 12-month accumulation scales to characterize trends in seasonal and annual events from 1981 to 2100. Climate data from 11 bias-adjusted high-resolution (0.11°) simulations from the EURO-CORDEX (coordinated regional climate downscaling experiment) have been used in the analyses. For each simulation, the frequency and severity of drought and extreme drought events for 1981–2010, 2041–2070, and 2071–2100 have been analysed. Under the moderate emission scenario (RCP4.5), droughts are projected to become increasingly more frequent and severe in the Mediterranean area, western Europe, and Northern Scandinavia, whereas the whole European continent, with the exception of Iceland, will be affected by more frequent and severe extreme droughts under the most severe emission scenario (RCP8.5), especially after 2070. Seasonally, drought frequency is projected to increase everywhere in Europe for both scenarios in spring and summer, especially over southern Europe, and less intensely in autumn; on the contrary, winter shows a decrease in drought frequency over northern Europe.

KEY WORDS climate projections; climate scenarios; drought; EURO-CORDEX; Europe

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1. Introduction

Among weather and climate-related natural disasters in the last decades (IPCC, 2014b, 2014a), drought can be considered a special case, as its global tendency towards more or less frequent drought events is still an open and debated issue (Dai, 2011, 2013; Sheffield *et al.*, 2012; Spinoni *et al.*, 2014; Trenberth *et al.*, 2014; Schubert *et al.*, 2016). This is mainly due to the complex characteristics of drought, which usually evolves slowly but can last for months or years (Vogt and Somma, 2000; Wilhite *et al.*, 2007). In addition, its impacts can affect different sectors in different ways (Sivakumar and Wilhite, 2002; Ding *et al.*, 2011; Blauhut *et al.*, 2015a, 2015b). Moreover, its complexity is reflected in the lack of a unique definition (Mishra and Singh, 2010; Lloyd-Hughes, 2014) and in the great variety of indicators used to analyse meteorological, agricultural, hydrological, and socioeconomic droughts (Heim, 2002; Hayes *et al.*, 2011; Mishra and Singh, 2011).

However, there is an established consensus about recent trends of meteorological and hydrological droughts in Europe: in the last decades, southern Europe experienced increasing drought frequency and severity (Briffa *et al.*, 2009; Vicente-Serrano *et al.*, 2014; Gudmundsson and Seneviratne, 2015; Spinoni *et al.*, 2015a, 2015b) with the Mediterranean region as a hotspot (Hoerling *et al.*, 2012) especially in spring and summer (Spinoni *et al.*, 2017a); a clear increase was also evident in the Carpathian region (Spinoni *et al.*, 2013, 2014). Northern Europe, on the contrary, showed a tendency towards wetter conditions (Bordi *et al.*, 2009; Seneviratne, 2012; Kingston *et al.*, 2015). Although climate projections are characterized by uncertainties (Knutti *et al.*, 2010; Knutti and Sedláček, 2013), there is a general consensus on the projected increase of extreme events in Europe in the 21st century (Forzieri *et al.*, 2016), fostered by a temperature rise in the context of global warming (IPCC, 2014b). Consequently, drought impacts recorded in the recent past in Europe (e.g. Ciais *et al.*, 2005; Naumann *et al.*, 2015; Blauhut *et al.*, 2015a, 2015b; Stagge *et al.*, 2015a; Stahl *et al.*, 2016) could become more substantial in the future, making the identification of areas where droughts are projected to become more frequent and severe a very important subject.

While drought trends over the last decades have been thoroughly studied, the investigation of future drought projections in Europe is far from being completed.

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Table 1. Bias-adjusted EURO-CORDEX simulations used in this study.

GCM	RCM	GCM members	Data period	Contributor
CNRM-CM5-LR	CCLM4–8-17	r1i1p1	1981–2100	CLMcom
EC-EARTH		r12i1p1		
MPI-ESM-LR		r1i1p1		
EC-EARTH	HIRAM5	r3i1p1	1981–2100	DMI
IPSL-CM5A-LR	WRF331F	r1i1p1	1981–2100	IPSL/INERIS
EC-EARTH	RACMO22E	r1i1p1	1981–2100	KNMI
CNRM-CM5	RCA4	r1i1p1	1981–2100	SMHI
EC-EARTH		r12i1p1		
IPSL-CM5A-MR		r1i1p1		
HadGem2-ES			1981–2098	
MPI-ESM-LR			1981–2100	

GCM stands for global climate model, RCM for regional climate model.

Many works have investigated projections of agricultural (Wang, 2005), hydrological (Roudier *et al.*, 2015; Wanders and Wada, 2015), streamflow (Feyen and Dankers, 2009; Forzieri *et al.*, 2014), and socioeconomic droughts (Alcamo *et al.*, 2007). On the other hand, European drought projections based on meteorological variables as input made use of outdated climate simulations (e.g. Heinrich and Gobiet, 2012; Lehner *et al.*, 2006; Blenkinsop and Fowler, 2007; Weiss *et al.*, 2007; Sheffield and Wood, 2008; Vidal *et al.*, 2012) involve relatively small regions (e.g. Haslinger *et al.*, 2016) or are based on single indicators (Stagge *et al.*, 2015b) or single model simulations and scenarios (Spinoni *et al.*, 2015c). In this study, therefore, we aim at providing a comprehensive picture of drought trends until the end of the 21st century by means of a combined indicator based on the result of a large multi-model ensemble of high-resolution climate projections.

This study builds on a previous study (Spinoni *et al.*, 2015a), which investigated drought frequency and severity trends over Europe from 1950 to 2012. We adopted the same methodological approach that is integrating three frequently used indicators into a single indicator, based on the predominance of drought conditions over normal or wet conditions: the standardized precipitation index (SPI; McKee *et al.*, 1993, 1995), the standardized precipitation evapotranspiration index (SPEI; Vicente-Serrano *et al.*, 2010; Begueria *et al.*, 2014), and the reconnaissance drought indicator (RDI; Tsakiris and Vangelis, 2005; Tsakiris *et al.*, 2007). As input data, regional climate model (RCM) runs from the EURO-CORDEX (coordinated regional climate downscaling experiment) initiative have been used, after bias correction as described in Dosio (2016). From the combined indicator and for each simulation, we derived drought and extreme drought frequency and severity for the period 1981–2100 under two emission scenarios, RCP4.5 and RCP8.5, which for the end of the 21st century assume a CO_2 equivalent of about 650 and 1370 ppm, respectively, and a corresponding global temperature increase of approximately 1.8 and 4.0 °C compared to the recent past (Riahi *et al.*, 2007, 2011; Moss *et al.*, 2010; Thomson *et al.*, 2011; Van Vuuren *et al.*, 2011).

This paper is structured as follows: after the introduction, Section 2 describes the model and the methodology to calculate the combined indicator and derived quantities; Section 3 presents the drought climatologies for the near future (2041–2070) and far future (2071–2100) compared to the recent past (1981–2010) at annual and seasonal scale and discusses which regions are inclined to become drought hotspots in Europe; Section 4 concludes the paper and focuses on the most important findings and possible improvements.

2. Data and methods

2.1. Input data: the EURO-CORDEX simulations

CORDEX is an initiative endorsed by the World Climate Research Program (WRCP) and aimed at producing high-resolution climate projections at regional scale which can be used as input for climate change impact and adaptation studies (Giorgi *et al.*, 2009; IPCC, 2014a, 2014b). The CORDEX simulations covering the European domain, known as EURO-CORDEX, have been chosen as input data for this study for two main reasons: First, the spatial resolution is the highest for Europe (0.11°) among the last generation simulations (Jacob *et al.*, 2014), thus allowing to capture future drought patterns at relatively high spatial resolution; second, a subset of these projections (Table 1) has been bias-adjusted for temperature and precipitation (Piani *et al.*, 2010; Dosio and Paruolo, 2011; Dosio *et al.*, 2012; Dosio, 2016). This procedure is very important when dealing with climate projections (Christenson *et al.*, 2006; Katragkou *et al.*, 2015), in particular for drought projections (Johnson and Sharma, 2015), in order to reduce uncertainties related to parameter space and structural biases in the climate modelling process which could potentially lead to unreliable outputs (Burke and Brown, 2008; Orlowsky and Seneviratne, 2013).

The bias correction technique is based on transfer functions estimated on recent past climate, which affect the whole Probability Distribution Function (PDF) of variables, assumed constant between current and future climate. Results show that the ensemble mean climate change signal and its inter-model variability are generally conserved (Dosio *et al.*, 2012). The transfer functions are estimated as a two parameter linear functional form for temperature, while for precipitation up to four parameter functions have been used (Piani *et al.*, 2010; Dosio and Paruolo, 2011). Bias correction parameters are calculated by employing the E-OBS dataset (Haylock *et al.*, 2008), which includes daily observations of temperature and precipitation covering the whole of Europe. The technique proved to perform successfully over large parts of Europe for all seasons and the PDFs of both temperature and precipitation are greatly improved, increasing the capability of reproducing extreme events (Piani *et al.*, 2010; Dosio and Paruolo, 2011). We highlight that limitations are present in the observational dataset, such as sparse spatial and temporal heterogeneities, in particular over mountain areas (Lenderink, 2010), and this could result in non-negligible differences especially for summer temperature climate change signals localized mostly in southern Europe (Dosio *et al.*, 2012; Dosio, 2016).

Each of the 11 bias-adjusted simulations includes daily precipitation, minimum and maximum temperature data from 1981 to 2100; from 2006 to 2100 the simulations are driven by two greenhouse gas concentration trajectories (RCP4.5 and RCP8.5), while modelled past data (1981–2005) are the same for both scenarios. For each grid point, simulation, and scenario, daily precipitation and minimum and maximum temperature have been converted into monthly data, which have then undergone further quality checks (outliers, spurious data, and spatial coherence) and homogeneity tests using the Multiple Analysis of Series for Homogenization software (MASH v3.03; Szentimrey, 1999, 2011).

From monthly temperature data, we derived potential evapotranspiration using the Hargreaves–Samani equation (Hargreaves and Samani, 1982, 1985; Samani, 2000), which indirectly estimates solar radiation using minimum and maximum temperature. Methods implying the use of minimum and maximum temperature to obtain Potential Evapotranspiration (PET) are considered better than those based on mean temperature only (Weiss and Menzel, 2008; Shahidian *et al.*, 2012) and the Hargreaves–Samani equation is preferred over the Thornthwaite's equation (Thornthwaite, 1948), which tends to overestimate droughts in dry periods exacerbated by extremely hot temperatures (Boberg and Christensen, 2012; Begueria *et al.*, 2014). As discussed in Spinoni *et al.* (2015a, 2017a), we are aware that a better option would have been the Penman–Monteith's method (Allen *et al.*, 1998), as it also includes solar radiation, vapour pressure, and relative humidity and consequently provides more realistic estimations of PET (Sheffield *et al.*, 2012; Trenberth *et al.*, 2014). However, the unavailability of these climate variables in the bias-adjusted EURO-CORDEX simulations forced us to discard the Penman–Monteith's method.

The EURO-CORDEX simulations have already been used in climate-related studies (e.g. Vautard *et al.*, 2013; Jacob *et al.*, 2014; Kotlarski *et al.*, 2014), but this is the first time the bias-adjusted version is applied to characterize drought events, though it has been recently applied to degree-day projections for Europe (Spinoni *et al.*, 2017b). The advantage of using bias-adjusted data has been evaluated as follows: we computed the SPI and the SPEI at 12-month accumulation scale over the period 1981–2005 using an independent dataset made of more than 4000 stations (Spinoni *et al.*, 2015d), the 11 EURO-CORDEX bias-adjusted simulations, and the corresponding non-adjusted EURO-CORDEX simulations. The independent dataset has been constructed using daily observations from the agrometeorological Monitoring Agricultural ResourceS (MARS) database, hosted by the European Commission's Joint Research Centre (JRC, https://ec.europa.eu/jrc/en/mars), the Global Historical Climatology Network dataset of the National Climatic Data Center of the US Department of Commerce (NCDC-GHCNv3; Menne *et al.*, 2012), and the European Climate and Assessment Dataset of the Royal Meteorological Institute of the Netherlands (KNMI-ECA&D; Klein Tank *et al.*, 2002). More details on how this dataset has been quality-checked and homogenized can be found in Spinoni *et al.* (2015d).

Comparing the results from the two EURO-CORDEX datasets against the results from the independent dataset, it turned out that for the SPI, the frequency of drought events is very similar over the whole of Europe. For extreme droughts, however, the bias-adjusted data removed the underestimation resulting from the non-adjusted EURO-CORDEX data especially over northern Europe, though some biases are still present in the Alpine and Carpathian areas. According to the SPEI, which includes the effect of temperature, larger underestimations of extreme droughts by non-adjusted EURO-CORDEX data can be found over southern Europe, in particular over Spain, the Balkans, and Greece, but the bias-adjusting procedure removed almost all the bias. This suggests that the bias-adjustment proves to be important, as it effectively reduced the underestimation of extreme drought events driven by rainfall deficits over mountainous regions and those driven by hot temperatures over southern Europe. However, some underestimation of extreme droughts is still present even when using the bias-adjusted EURO-CORDEX simulations.

2.2. The combined drought indicator and derived drought variables

Owing to the complex nature of drought events, the use of multi-variate indicators has become more frequent over the last years (Hao and Singh, 2015). In particular, combined indicators which take into account multiple drought characteristics have been successfully applied for drought detection (Ziese *et al.*, 2014), monitoring (Sepulcre-Cantò *et al.*, 2012; Cammalleri *et al.*, 2017), and prediction (Hao *et al.*, 2016). Following this approach, we decided to combine three indicators, although they were developed for different purposes, in order to avoid relying on a single indicator only, which might result in omitting important features of drought events. The combined drought indicator incorporates three indicators: the SPI (McKee *et al.*, 1993), which depends only on precipitation and consequently accounts for drought events induced by a lack of

Table 2. Combined indicator values according to the three single indicators.

Single indicators (SPI, SPEI, RDI)		Combined	Conditions
2+ indicators $\in (0, +\infty)$	All cases	1	Normal/wet
2+ indicators $\in (-\infty, 0]$	2+ indicators $\in (-\infty, -1]$	**−1**	Drought
	2+ indicators $\in (-\infty, -1]$ and also 2+ indicators $\in (-\infty, -2]$	**−2**	Extreme drought
	All other cases	−0.5	Dry

2+ stands for at least two out of three input indicators.

rainfall, the SPEI (Vicente-Serrano *et al.*, 2010), which depends on the climatic water balance (precipitation minus PET) and includes the effect of hot temperatures together with dry conditions, and the RDI (Tsakiris and Vangelis, 2005), which depends on the ratio between precipitation and PET and is particularly suitable to take meteorological extreme events into account. We highlight that the same approach was chosen in the previous studies of Spinoni *et al.* (2015a, 2015b), consequently we decided to adapt it to this study in order to give continuity.

We selected two aggregation periods to compute the indicators, namely 3 and 12 months. We selected the 3-month scale to capture seasonal drought patterns and the 12-month scale to account also for annual drought patterns. Such time scales in general apply to meteorological, agricultural, and hydrological droughts, depending on the definitions and on the goal of the study (Mishra and Singh, 2010, 2011); however, we highlight that the indicators used in this study have been computed using meteorological variables as input, consequently the drought events analysed best fit into the meteorological drought category.

First, the three indicators have been computed at 3-month scale and then separately at 12-month scale. This means that the SPI-3 (SPI-12) values represent anomalies of accumulated precipitation for the given month and the two (eleven) previous months. The input data have been fitted to Gamma (Thom, 1958), log-logistic (Shoukri *et al.*, 1988), and log-normal (Heyde, 1963) distributions for SPI, SPEI, and RDI, respectively. The choice of the baseline period is a key issue for standardized drought indicators (Guttman, 1999) and we decided to use the entire period 1981–2100 as baseline. As discussed in Spinoni *et al.* (2015c) the reasoning behind this choice is that if a shorter period (e.g. 1981–2010) was used as baseline and the selected period was characterized by frequent and severe droughts, this would influence the computation of the indicator over the entire period, with the other periods bound to be characterized by less frequent and severe droughts. This study does not focus on the absolute number and severity of droughts in a certain period, but investigates whether the droughts will be less or more severe and/or frequent in the future than the recent past, consequently an analysis using the entire baseline ensures more robust comparisons. Using the longest period possible as baseline in order to obtain more robust outputs has been also suggested by Wu *et al.* (2005) dealing with standardized drought indicators as the SPI (Guttman, 1999). Moreover, drought is different from other natural disasters and takes place when a significant deviation from the normal hydrologic conditions of an area occurs (Palmer, 1965). Thus, using as baseline the past decades for estimating droughts over 100 years in the future might be problematic, as in a warming world normal conditions will progressively change and consequently future events could be unrealistically extreme, especially regarding drought severity. Due to statistical reasons they would fall in the most extreme tails of the distributions, which have been fit using a period in which similar events were unlikely to happen.

The single indicators at 3-month (12-month) scale have therefore been merged into the combined indicator at 3-month (12-month) scale and separate analyses for the two temporal scales have been performed. For simplicity we describe the procedure for the indicator at 3-month scale only. The combined indicator at 3-month scale is assigned a value corresponding to extreme drought conditions (−2) if at least two single indicators show values below −2, to moderate drought conditions (−1) if at least two single indicators show values below −1 and above −2, to normal/wet conditions (1) if at least two single indicators show positive values, and to dry conditions (−0.5) in all other cases (Table 2). A drought event “starts” when, after normal/wet or dry months, the combined indicator depicts drought (or extreme drought) conditions for at least two consecutive months and the first of these months is considered the starting month of the drought event. An event “ends” when the combined indicator depicts normal/wet conditions. If during the drought event, at least two consecutive months show extreme drought conditions, the event is considered extreme. The same approach was used in Spinoni *et al.* (2013, 2014, 2015a, 2015b) and is based on the definitions provided by McKee *et al.* (1993, 1995).

This way, the combined indicator focuses at drought conditions, while normal and wet conditions are relevant only to define the end of the event. The drought (and the extreme drought) event based on the combined indicator at 12-month (3-month) scale is assigned to the year (season) in which it starts. Climatological seasons are used, that is, winter from December to February, spring from March to May, summer from June to August, and autumn from September to November; consequently, a seasonal drought event (based on 3-month scale) whose first month is June is classified as summer drought.

The severity of each drought event is calculated as the absolute value of the arithmetic sum of the negative values of the combined indicator during the event. Drought duration and severity, as defined in Spinoni *et al.* (2014, 2015a, 2015c), tend to show similar results because they are intrinsically correlated. For this reason, we here present the analyses only for drought severity, which also includes the intensity of the event as it corresponds to the integral of the values of the indicator and not only to the number of months in drought conditions.

For each simulation and scenario, we computed the frequency of drought events and extreme drought events for the recent past (1981–2010), near future (2041–2070), and far future (2071–2100) expressed in the number of events per decade. As this study focuses on the characteristics of the events, the drought severity for each of the three periods refers to the average severity of single drought events during each period. We show the results as differences between near future and recent past and between far future and recent past. To account for the variability introduced by the RCMs inter-model variability, we show the standard deviations of the 11-member ensemble and we also discuss how many simulations agree on sign (decrease or increase).

3. Results and discussion

3.1. Droughts at annual scale in near and far future

In order to investigate the spatial and temporal patterns of future drought events, we chose to compare drought frequency and severity of near (and far) future *versus* the period 1981–2010 as reference period. Consequently, we first show the absolute drought frequency and severity of events for the reference period (Figure 1). The drought frequency (Figure 1, top) is found to be largest over southern and western Europe in the recent past, showing values up to three events per decade over the Mediterranean region. Similar spatial patterns are found for extreme droughts (Figure 1, middle), with a few exceptions, such as central France, Poland, and Iceland showing very small extreme drought frequencies but moderately large drought frequencies. Drought severity (Figure 1, bottom) shows opposite spatial patterns, with regions affected by rare drought events – in particular the Baltic Republics and Belarus – being characterized by a large mean severity of the events. When combining frequency and severity of droughts and obtaining total drought severity as described in Spinoni *et al.* (2015a), southern Europe stands out, as depicted also in Spinoni *et al.* (2015a, 2015b). Overall, the only region which appears biased is the Carpathian mountain ridge, which shows notable smaller drought frequency than reported in Bartholy *et al.* (2013) and Spinoni *et al.* (2013), probably due to the mentioned unsatisfactory performance of model simulations over mountain regions, which could not be improved by the bias-correction due to the low density of stations in the E-OBS grids for this region.

Figure 2 shows the ensemble mean difference of drought and extreme drought frequency and severity between near future (2041–2070) and recent past (1981–2010). Under RCP4.5 (left column), the regions expected to experience the largest drought frequency increase are southern Europe, France, the British Islands, and north-eastern Scandinavia, with an increase of more than one event per decade. The same regions show the largest increase according to RCP8.5 (right column) with the Iberian Peninsula close to an increase of two events per decade. Only northern Iceland shows a strong negative tendency for both RCPs, while a slight negative tendency is projected over eastern Europe for RCP8.5. Central Europe, southern Scandinavia, and western Russia show a moderate increase for both RCPs.

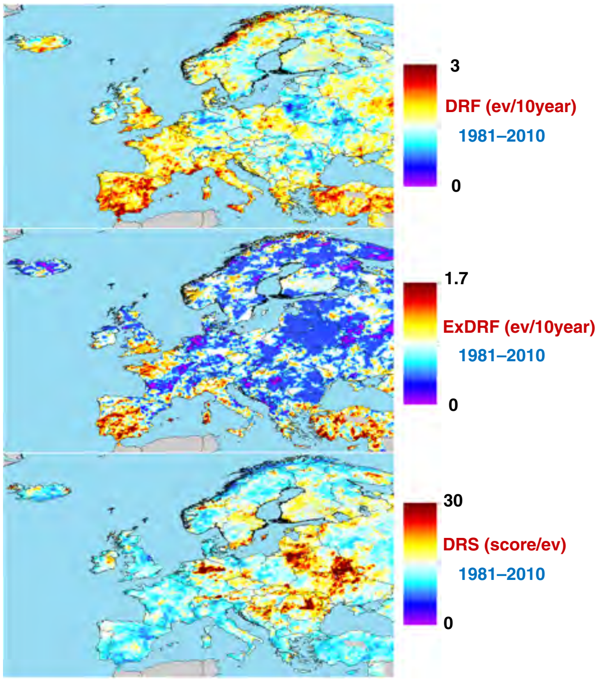


Figure 1. Drought frequency (DRF), extreme drought frequency (ExDRF), and drought severity (DRS) for recent past (1981–2010) computed at 12-month accumulation scale. DRF and ExDRF are expressed in events per decade, DRS score refers to the mean event for the period investigated. [Colour figure can be viewed at wileyonlinelibrary.com].

On a spatial basis, frequency of droughts and extreme droughts show similar patterns, but for extreme events RCP8.5 simulations show a slightly smaller increase than RCP4.5 in localized areas over the Iberian Peninsula, France, the Balkans, and Turkey, representing however less than 2.5% of total area. This is mainly due to the fact that RCP8.5 projections result in higher frequencies of intense rainfall events in these localized areas than RCP4.5 projections, which has been verified by analysing the precipitation data from the 11 simulations. Although being in a drying climate, this results in sufficient cumulated rainfall to prevent at least two of the single drought indicators (especially SPI and SPEI) falling below the threshold set for extreme events for two or more consecutive months. Consequently, the combined indicator will depict a drought event instead of an extreme one. This does not occur in the far future because in the last decades of the 21st century the RCP8.5 projects fewer extreme rainfall events in these regions and longer dry periods. Moreover, according to our analyses, the simulations

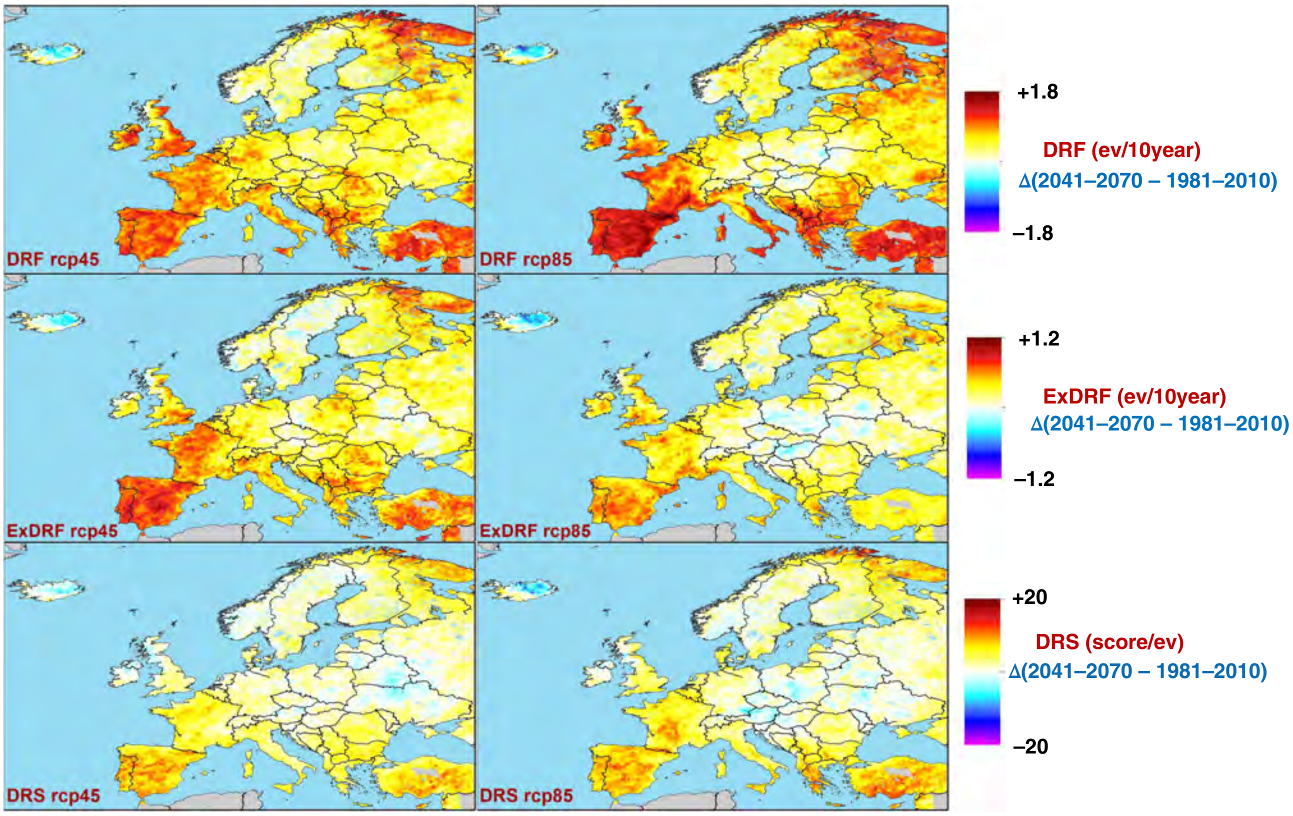


Figure 2. Difference of drought frequency (DRF, top panels), extreme drought frequency (ExDRF, middle panels), and drought severity (DRS, bottom panels) between near future (2041–2070) and recent past (1981–2010), averaged over the 11 simulations and computed at 12-month accumulation scale. Left panels refer to RCP4.5, right panels to RCP8.5. [Colour figure can be viewed at wileyonlinelibrary.com].

under the RCP4.5 are characterized by a larger degree of precipitation variability in the interval of rising emissions (until mid-2050s) than in the plateau phase (especially after 2070), in particular in localized areas over southern and western Europe. In these areas extreme drought events, therefore, tend to be more recurrent under the RCP4.5 during the central decades of 21st century. On the other hand, considering that this study makes use of indicators that are standardized over the entire period and that it focuses on temporal differences, the progressive increase in the frequency of extreme drought events under the RCP8.5, which becomes even faster and larger in the last decades of 21st century, results in slightly underestimated results in the near future under the extreme emission scenario.

Regarding the average severity of droughts (Figure 2, bottom row), southern and western Europe, the Balkans, Denmark, and northern Scandinavia are projected to face more severe events in 2041–2070 than 1981–2010 for both RCPs, but the events tend to be more severe under RCP8.5 than RCP4.5, especially over France and Greece. Less severe events will occur, on average, over Iceland, Northern Ireland, Scotland, Austria, Slovakia, Poland, Belarus, and Ukraine. Over eastern Europe this tendency is more pronounced for RCP8.5.

Figure 3 shows the same quantities of Figure 2 but related to the far future (2071–2100) *versus* recent past. In general, RCP8.5 projects a general increase of drought quantities larger than projected by RCP4.5. Compared to the near future, drought frequency values are similar under RCP4.5, with predominance of an increasing frequency over southern Europe and a more evident increase also over the British Islands; central Europe, eastern Europe, and southern Scandinavia show a moderate increase (rarely over one more event per decade), and a decreasing frequency is found only over parts of Iceland. Under RCP8.5, drought and extreme drought frequency are estimated to increase everywhere in Europe in the far future, excluding central Iceland; the largest increases are observed over southern Europe where droughts and extreme droughts could be up to 50% more frequent, as well as over France and the British Islands (up to +40%), but also over central Europe and Russia for RCP8.5 (up to +35%), while for RCP4.5 they generally show smaller values. Under RCP4.5 drought events are calculated to become considerably more severe in the period 2071–2100 than 1981–2010 only over the Mediterranean region, for RCP8.5 the increase will be widespread and larger also over France, northern Italy, the Balkans, eastern Ukraine, and northern Scandinavia, with the entire Europe – except Iceland and western Norway – subject to more severe droughts than in current decades.

Considering that southern Europe shows both the largest drought frequency values over the recent past and the largest increase in future periods, these findings reinforce the view of the Mediterranean area as a drought hotspot for the entire 21st century (Giorgi, 2006; Giorgi and Lionello,

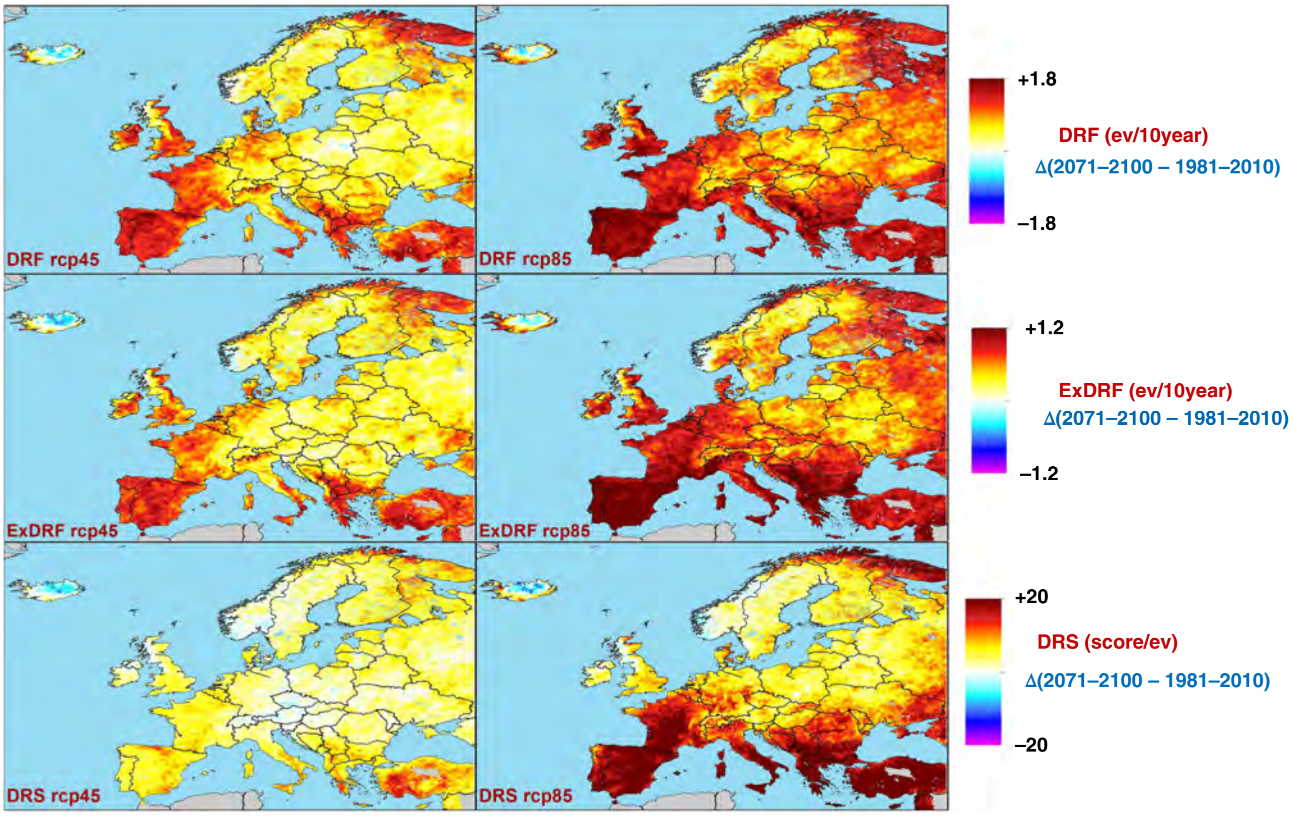


Figure 3. As in Figure 2, but the difference is between far future (2071–2100) and recent past (1981–2010). [Colour figure can be viewed at wileyonlinelibrary.com].

2008), also because such events are also projected to become much more severe (and longer) in that part of Europe. Combining frequency and severity (not shown in figures), the Mediterranean region also stands out as the area that will be involved by the largest increase of total drought severity (calculated as the sum of severity of all drought events in a given period) as the 21st century progresses under either scenario.

Figure 4 shows the uncertainty introduced by the inter-model variability of the ensemble of 11 simulations. The uncertainty is estimated as the standard deviation of the drought frequency difference between periods and computed over the 11 simulations. The underlying grid represents the points at which fewer than 10 models out of 11 agree on the sign of the positive or negative tendency represented by the ensemble mean. This means that over the areas not masked by the underlying grid, all the simulations (with the exception of maximum one simulation) agree on the sign of drought frequency change, that is, at least 10 out of 11 simulations project an increase (decrease) of drought frequency compared to the recent past.

Because, according to our analyses, the inter-annual variability of drought (and extreme drought) frequency and severity is characterized by very similar spatial patterns, we present maps regarding drought frequency only. For the near future, the regions showing the largest variability are Iceland, western Scandinavia, and the border region between France and Belgium; for the far future, northern and eastern regions show larger variabilities than southern and western ones. It is interesting to notice that the agreement between simulations is highest over southern Europe, excluding the winter season (not shown), which is projected to face more frequent and severe droughts in future decades for both RCPs; instead, central Europe, Scandinavia, and Iceland show localized areas in which three or more simulations disagree with the rest. We also highlight that the areas featuring such uncertainty reduce in far future projections compared to the near future. Overall, these results show that the paradigm *warm gets warmer*, *dry gets drier*, *wet gets wetter*, which is usually referred to global scale (Allan *et al.*, 2014; Trenberth *et al.*, 2014; Feng and Zhang, 2015), can be also applied to Europe for the 21st century under scenarios RCP4.5 and RCP8.5.

3.2. Droughts at seasonal scale in near and far future

The combined indicator, computed at 3-month accumulation scale, is used to study the seasonal occurrence and severity of drought events. In this section, we discuss the drought frequency results for near and far future. As for annual drought events, we first show the frequency of droughts related to the recent past (Figure 5). In 1981–2010 winter droughts are found to be infrequent in Iceland, central and eastern Europe; spring shows rare events over northern Europe and more frequent ones over southern Europe; summer droughts in 1981–2010 are found to be frequent especially over central Europe, but this season was in general the most drought prone in the

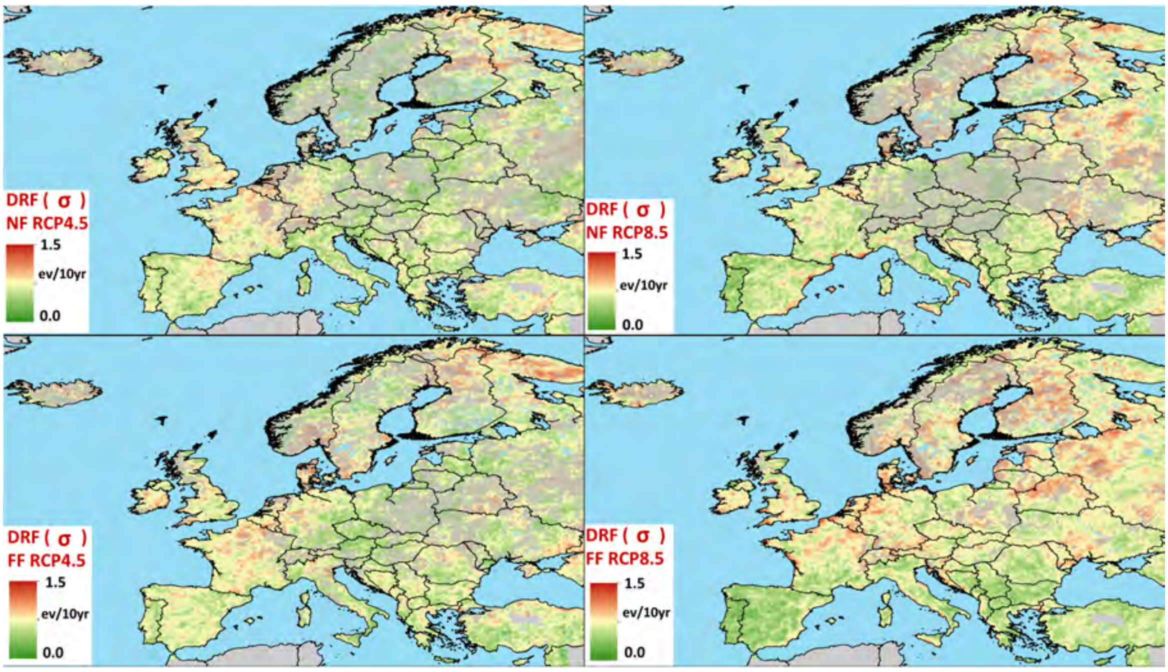


Figure 4. Uncertainty in drought frequency computed at 12-month accumulation scale due to inter-model variability (standard deviation of the 11 models). Top panels refer to near future (NF), bottom panels to far future (FF), left panels to RCP4.5, and right panels to RCP8.5. The underlying grey grids represent the grid points at which fewer than 10 out of 11 simulations agree on sign (positive for increase, negative for decrease). [Colour figure can be viewed at wileyonlinelibrary.com].

last decades; autumn shows diverse spatial patterns with more frequent droughts in south-western and north-eastern Europe.

Both scenarios (Figure 6) project a decrease of winter droughts in 2041–2070 over central, eastern, and northern Europe. Also summer droughts are predicted to be less frequent in near future than recent past (1981–2010) over Scandinavia and the Baltic Republics for RCP4.5; however, such decrease is limited to southern Scandinavia and Estonia. The most relevant increase can be found for spring droughts for RCP8.5, which are estimated to increase for either scenario over entire Europe (excluding Poland). Summer and autumn droughts show an increase over western and southern Europe for both scenarios; for RCP8.5 autumn droughts are projected to increase generally, excluding the Alpine region. Overall, the largest increase is observed over the Mediterranean region for summer droughts (up to 40% more frequent droughts for the RCP8.5) and the largest decrease over Scandinavia during winter (down to 30% less frequent for the RCP8.5).

Regarding the far future (Figure 7), both scenarios show similar tendencies as observed for near future, but with larger values. Thus, where and for which season for RCP4.5 drought frequency is projected to increase (decrease) in the near future, it is likewise projected to increase (decrease) more in the far future. The only exception is the disappearance of localized areas with decreased frequency of autumn droughts over central Norway and Switzerland. For RCP8.5, southern Europe is characterized by a drought frequency increase in all seasons and the largest values can be found over southeastern Europe in winter, the Mediterranean area in spring, and southwestern Europe in summer and autumn. Central and eastern Europe show a drought frequency decrease in winter, moderate increase in autumn, and large increase in spring and summer. As for RCP4.5, northern Europe shows a widespread decrease in winter, a moderate decrease over Finland and Sweden in summer, and a general increase in spring and autumn.

In general, winter is the season less affected by drought events, both in the recent past and the future. Consequently, some regions such as southern Scandinavia and the Baltic Republics are projected to be hit by less than one event per decade (in winter) at the end of the 21st century under either scenario. Oppositely, the worst scenario is found for summer droughts in central Europe and the British Islands under RCP8.5. There, more than three events per decade are projected to occur during the hottest months, potentially causing devastating effects on agriculture but also prolonged periods of water scarcity and unhealthy conditions.

Figure 8 shows the multi-model variability of future winter and summer droughts. In winter, the projections under RCP4.5 show generally lower uncertainties than RCP8.5, the highest variability being over northernmost Scandinavia (winter, both RCPs), southern Turkey (winter, near future, RCP8.5), and Baltic Republics (winter, far future, RCP8.5). The agreement on sign between the 11 simulations is in general high over northern and eastern European countries; on the other hand, over the Baltic Republics, Poland, and central Turkey there are localized areas where fewer than seven simulations agree. Regarding summer, the uncertainty is overall lower than in winter, with the exception of central Europe, the Alpine area, and western

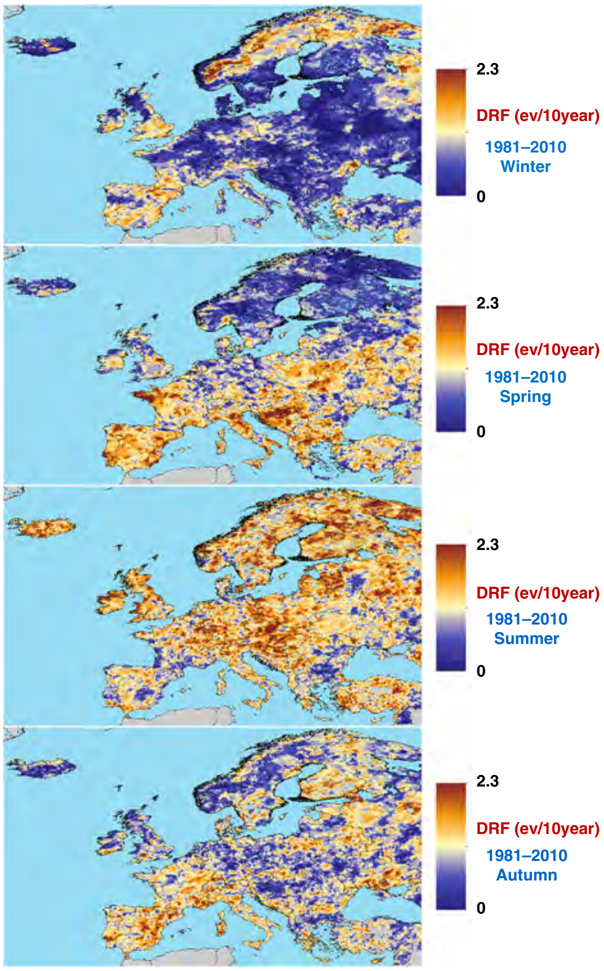


Figure 5. Drought frequency for the four seasons for the period 1981–2010 and computed at 3-month accumulation scale. Values are expressed in number of events per decade. [Colour figure can be viewed at wileyonlinelibrary.com].

Spain in the far future for RCP8.5; this is mainly due to corresponding high absolute summer drought frequency values, especially over the Iberian Peninsula. It is worth noticing that over southern Europe, excluding mountainous areas in Italy and Greece, summer drought increase is very robust, as at least 10 simulations agree on the sign for all periods and scenarios analysed.

To focus on areas expected to face more frequent droughts over all seasons, we assigned to each grid point a score of +1 for every simulation projecting a drought frequency increase for all seasons, and a score of −1 for every simulation projecting a decrease for all seasons (Figure 9). According to our analyses, it never happens that a simulation projects an increase (decrease) of drought frequency for all four seasons and at least another simulation simultaneously projects an opposite decrease (increase) of drought frequency for all seasons. Under the RCP4.5 scenario (Figure 9, left panels), only in localized areas over Spain and Turkey drought frequency is found to increase in all seasons for at least six simulations; instead, under the RCP8.5 scenario (Figure 9, right panels), almost the entire southern European area is projected to see increased frequencies of drought events in the far future, while in near future this is true only for extended parts of Spain and Turkey, and for parts of Greece and Bulgaria.

3.3. Discussion

Figure 10 shows how many simulations project an increase (or decrease) of both drought frequency and severity, according to 12-month accumulation scale. Though spatial patterns for RCP4.5 and RCP8.5 are generally similar, RCP8.5 projects more extreme and extended increases, especially over southern Europe in the far future, where the simultaneous increase of frequency and severity of droughts is projected for at least nine simulations at latitudes south to the Alps. Only northern Iceland and localized areas over Scandinavia and eastern Europe show a decrease for both drought quantities, but never for more than seven simulations out of 11. Northern and northeastern Scandinavia, southern England, and western and southern Europe are projected to face the largest increase of drought frequency and severity. This is true to a varying strength for estimations based on the extreme (RCP8.5) and moderate scenario (RCP4.5), making these regions possible hotspots for drought hazard and risk in future decades. Over southern Europe, the projected tendency towards a higher frequency of extreme rainfall events combined with a general decrease of total precipitation (Nikulin *et al.*, 2011; Heinrich and Gobiet, 2012; Kjellström *et al.*, 2013; IPCC, 2014a, 2014b; Madsen *et al.*, 2014) and a projected temperature rise, including a higher probability of severe heat waves (Beniston *et al.*, 2007; Jacob *et al.*, 2014; Russo *et al.*, 2014; IPCC, 2014a), drives the projected increase of drought frequency and severity. Over northern Europe, the projected temperature rise, resulting in an increased evaporative demand, outbalances the projections of increasing precipitation (Heinrich and Gobiet, 2012; Forzieri *et al.*, 2014; Sein *et al.*, 2014; IPCC, 2014a), leading to a projected increase of droughts over northernmost Scandinavia. Another important finding is the tendency towards more frequent and severe events over southern and eastern England and France, which are usually considered transition zones between drying southern Europe and wetting northern Europe (Rajczak *et al.*, 2013; IPCC, 2014a; Forzieri *et al.*, 2016).

Previous studies (Spinoni *et al.*, 2015a, 2015b, 2017a) observed past drought trends over Europe on both annual basis (from 1950 to 2012) and seasonal basis (from 1950 to 2015). To provide a complete picture of drought trends from 1951 to 2100, here we used the newest available E-OBS grids (v13.1 and v14, http://www.ecad.eu/download/ensembles/download.php) to obtain trends of drought frequency from 1951 to 2010, using the same methodology as discussed in Section 2. In this way we compared results derived from measured climate variables for the past with those obtained using climate simulations for future projections. Drought trends have therefore been averaged over nine macro-regions: Iceland, continental northern Europe (Scandinavia and Baltic Republics), British Islands, France plus Benelux, central Europe, eastern Europe plus European Russia, the Alps, Iberian Peninsula, and the rest of Mediterranean region

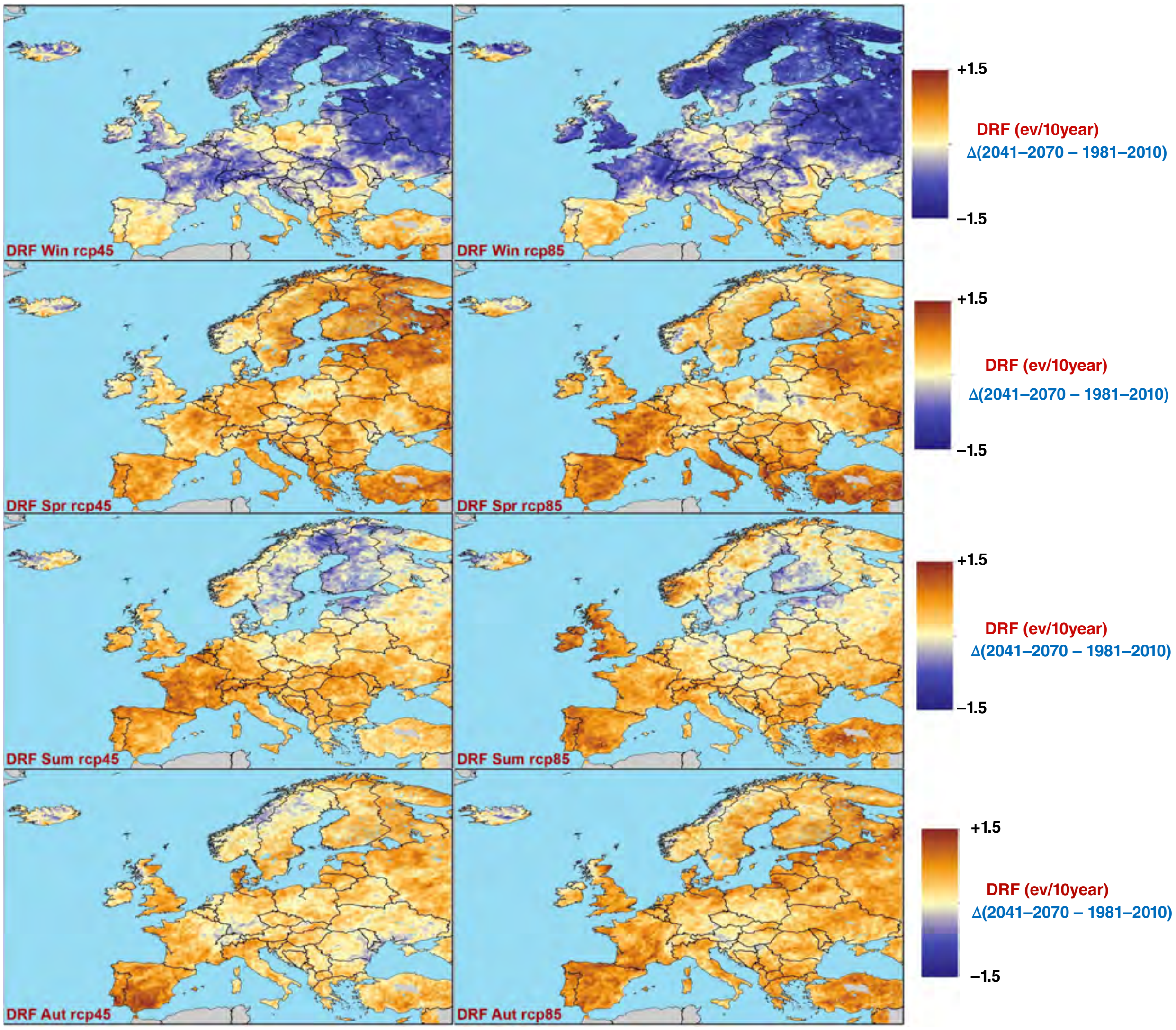


Figure 6. Difference of drought frequency between near future (2041–2070) and recent past (1981–2010) for winter (top panels), spring (second row), summer (third row), and autumn droughts (bottom panels) averaged over 11 simulations under RCP4.5 (left column) and RCP8.5 (right column) and computed at 3-month accumulation scale. [Colour figure can be viewed at wileyonlinelibrary.com].

(including the Balkans). Table 3 provides a summary of annual and seasonal drought tendencies over Europe from 1951 to 2100. In the following discussion, we refer to an increase (decrease) of drought frequency simply as a drought increase (decrease).

Iceland was characterized by drought decrease from 1951 to 2010 for all seasons. Under RCP4.5 and RCP8.5, a further decrease is projected, especially over central Iceland in autumn and winter, but an increase over southern Iceland is visible, especially in winter and spring, and also at annual scale (Figures 3 and 7). In the past, a precipitation increase over Iceland (Crochet *et al.*, 2007) outbalanced the temperature rise and caused a drought decrease; on the other hand, the projected warming (Zahn and von Storch, 2010) outbalances the further precipitation increase (Jonsdottir, 2008) and, as a consequence, more frequent droughts are expected over Iceland, excluding its mountainous areas, in spring and partly in summer and autumn (especially under RCP8.5).

Northern Europe and in particular Scandinavia shows a change of tendency, passing from drought decrease in the last six decades (more evident in winter, spring, and autumn) to an increase in the future, especially over northern Scandinavia, at annual scale and especially in spring and autumn. Analysing the projected increase over central Scandinavia in summer, we highlight that this tendency, resulting from the average of 11 simulations, is subject to a high uncertainty and, moreover, the agreement between simulations on sign (decrease for summer) is lower than over most of the other European regions (Figure 9). As for past decades, winter droughts show continuous decrease until 2100 for both RCPs. Northern European precipitations are highly dependent on the North Atlantic Oscillation (Uvo, 2003) and their continuous increase from past to present and from present to future (Hanssen-Bauer *et al.*, 2005) may possibly lead to drought decrease in winter, but the extreme warming projected for Scandinavia, expected to be highest from

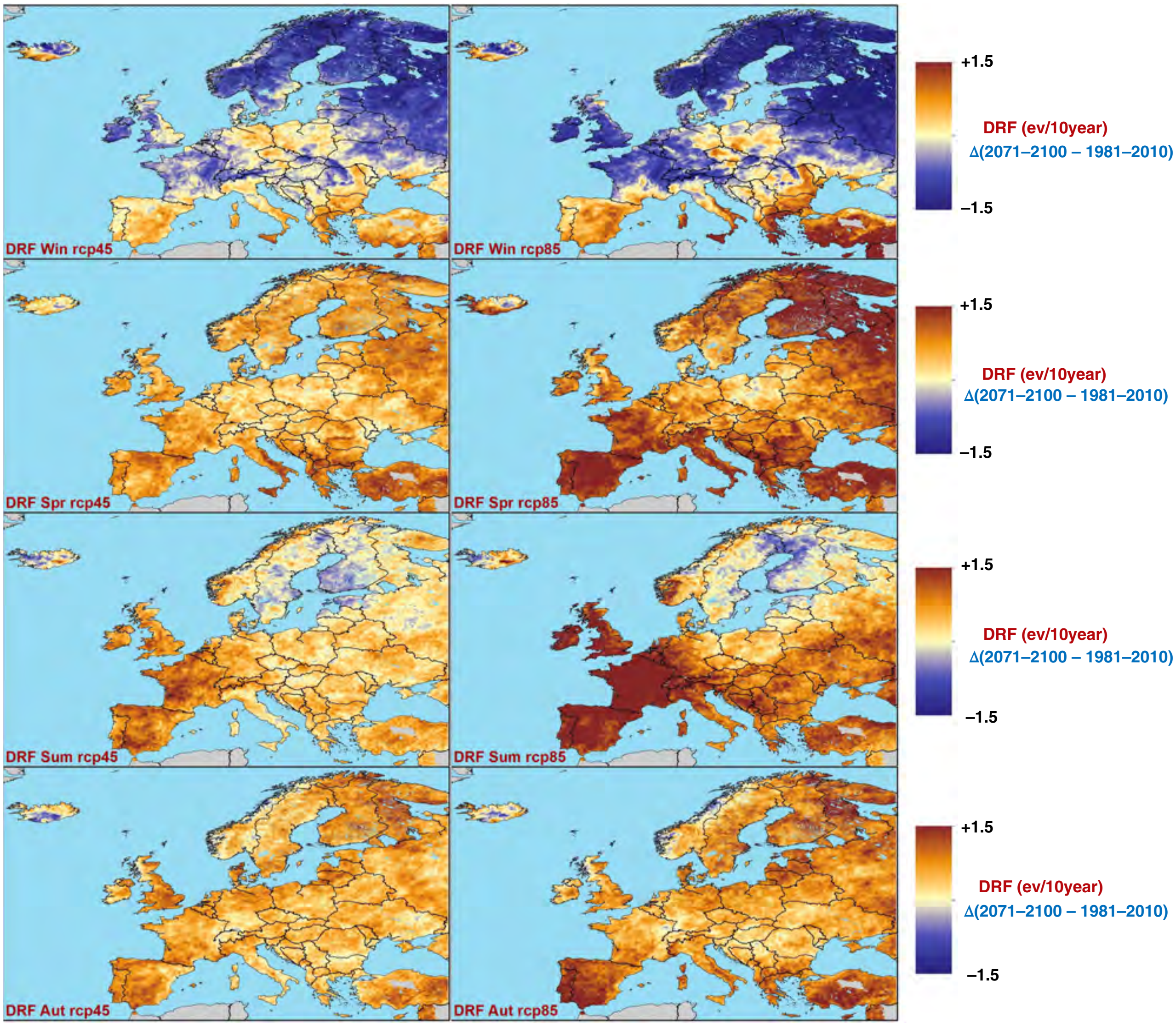


Figure 7. As in Figure 6, but difference is between far future (2071–2100) and recent past (1981–2010). [Colour figure can be viewed at wileyonlinelibrary.com].

spring to late summer (Rowell and Jones, 2006), could foster more frequent and severe droughts in other seasons, despite a moderate precipitation increase (Kendon *et al.*, 2010) and a notable increase of extreme precipitations (Frei *et al.*, 2006; Nikulin *et al.*, 2011). The uncertainty is also partly due to the low density of stations leading to the E-OBS version used in the bias-adjustment, especially in coastal regions of Norway, as discussed in Spinoni *et al.* (2017a).

From 1951 to 2010, the British Islands show decreasing droughts over Scotland and Northern Ireland – similar to northern Europe – and increasing droughts over Ireland, Wales, and England, similar to France and western Europe, possibly due to the influence of the North Atlantic Oscillation over Great Britain (Burt and Howden, 2013). Regarding future projections on annual scale, drought frequency is found to increase over the entire region for both RCPs (but severity shows a smaller increase over Scotland, Figures 2 and 3). Seasonally, the frequency of droughts is found to decrease in winter, while in the other seasons to increase. Northern Great Britain, in particular the Scottish Highlands, was subject to increasing rainfall frequencies and total amounts, larger than bordering areas in the last decades (Osborn *et al.*, 2000; Maraun *et al.*, 2008; Jones *et al.*, 2014) and the same is projected for the next decades (Fowler and Ekström, 2009), which could be the reason why Scotland is less prone to drought events, though it was and is projected to be subject to warming in the same order of magnitude as the bordering areas (Perry and Hollis, 2005; Watts *et al.*, 2015).

Northern France and Benelux show drought tendencies similar to southern England, whereas southern France is similar to the Iberian Peninsula and the Mediterranean region. In the past, droughts increased especially in spring and summer and this trend accelerated in the last two decades. Winter droughts are projected to decrease over France and Benelux as well as northern Europe, but in other seasons they are projected to increase in these areas,

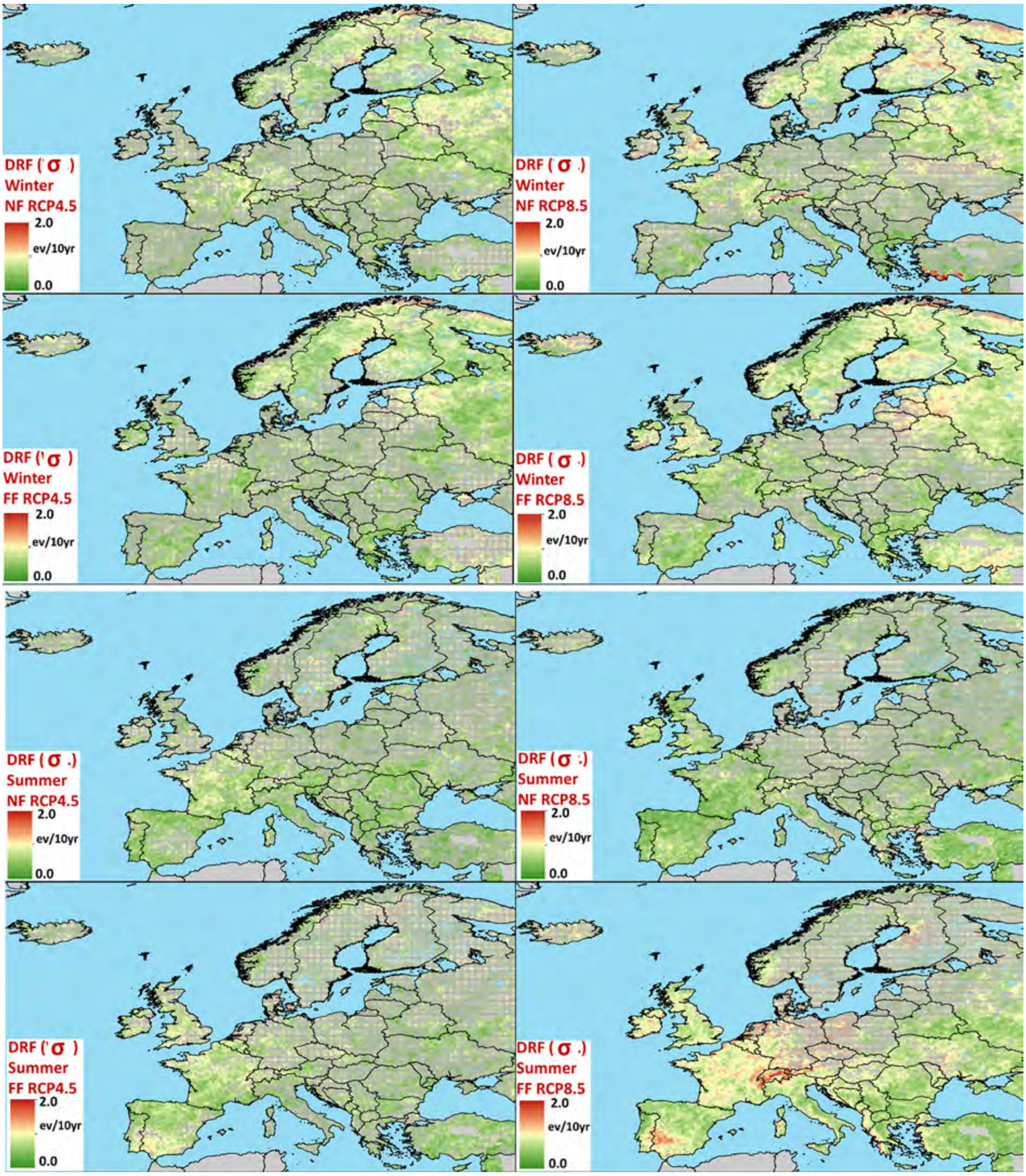


Figure 8. As in Figure 4 and computed at 3-month accumulation scale, but related to winter droughts (top panels) and summer droughts (bottom panels). [Colour figure can be viewed at wileyonlinelibrary.com].

with the largest increase in summer under RCP8.5. On an annual scale, the RCP8.5 projects an increase of both drought frequency and severity, while for RCP4.5 only frequency increases (Figures 2 and 3). The projected winter decrease, opposed to the summer increase, is mostly driven by corresponding precipitation trends over France (Terray and Boé, 2013). The recent temperature rise and increased occurrence of extreme summer heat waves, especially over southern France, caused this region to be affected by more severe droughts from the late 1990s (Poumadere *et al.*, 2005; Spinoni *et al.*, 2015b) and this tendency is expected to continue, and even be enhanced, in the future (Roudier *et al.*, 2015).

Central Europe is known to be the transition area between wetting northeastern and drying southwestern European countries in the last decades (Moberg *et al.*, 2006; Hänsel *et al.*, 2009; IPCC, 2014a) and this was reflected in mixed or negligible drought tendencies from 1951 to 2010, with the exception of recently increasing summer droughts (Spinoni *et al.*, 2015b), mostly due to frequent heat waves hitting central Europe (Twardosz and Kossowska-Cezak, 2013)

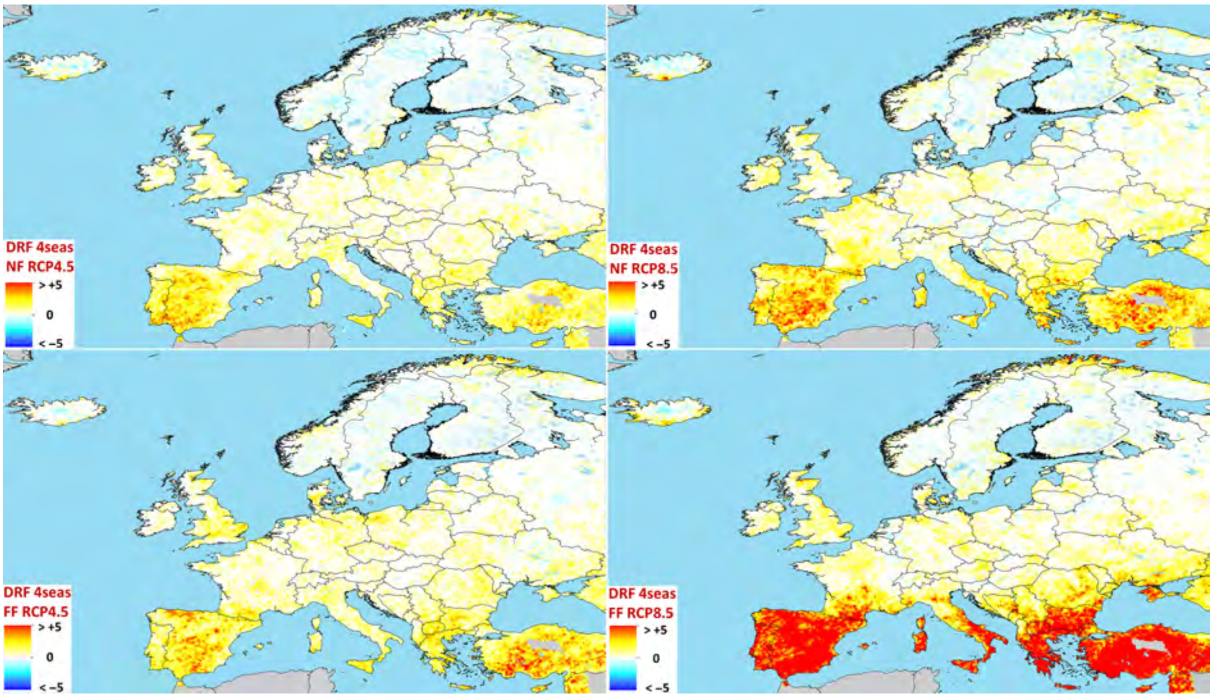


Figure 9. Number of simulations indicating drought frequency increase (positive values) or decrease (negative values) for all seasons for RCP4.5 (left) and RCP8.5 (right). Top panels show results for the near future while far future is shown in the bottom panels. Values larger than 5 and smaller than −5 have been grouped into single categories. [Colour figure can be viewed at wileyonlinelibrary.com].

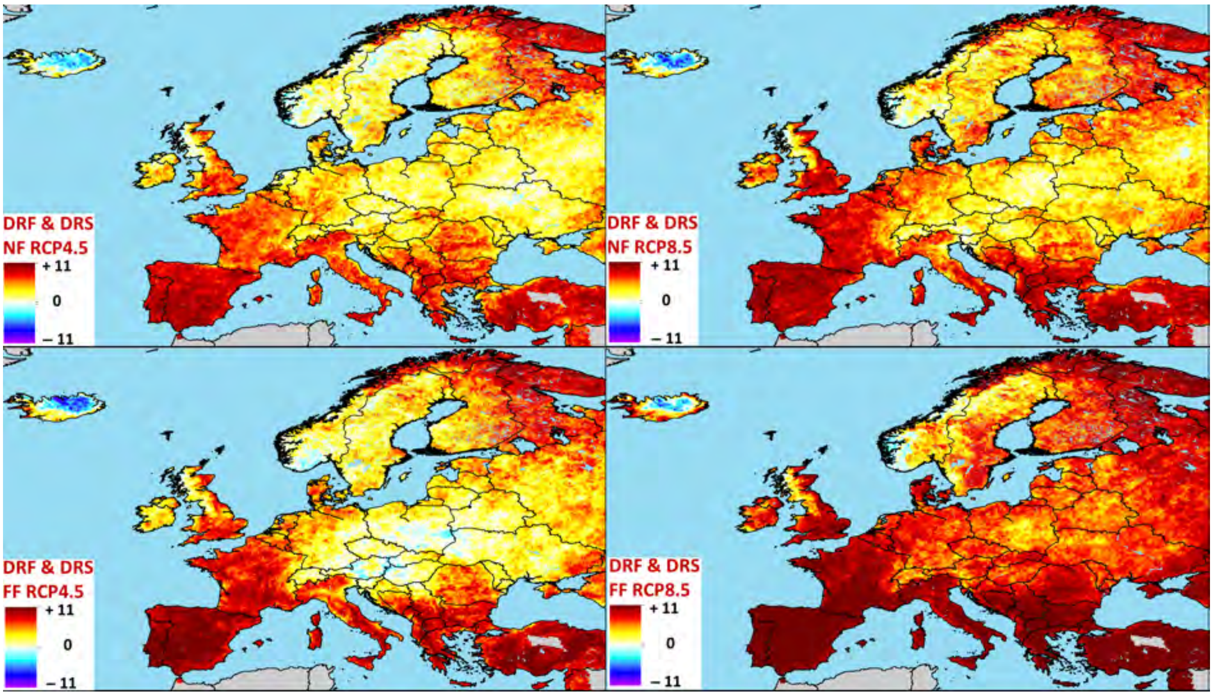
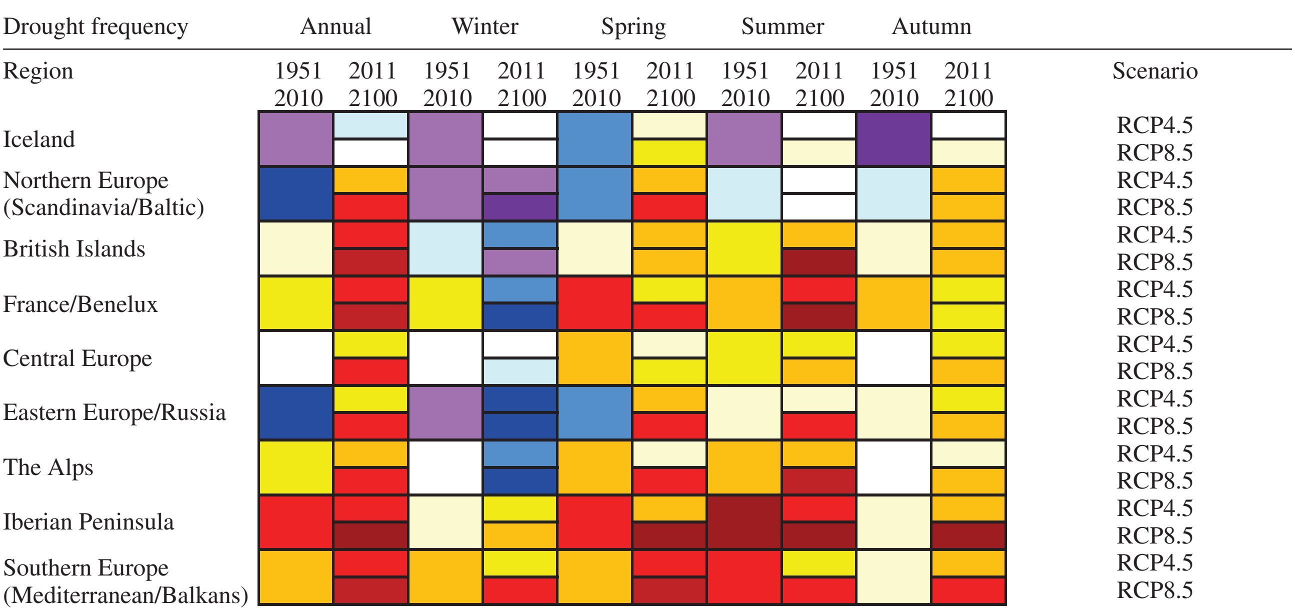


Figure 10. Number of simulations indicating contemporary increase (positive values) or decrease (negative values) of drought frequency and severity at annual scale in near (top panels) and far future (bottom panels). Left panels refer to RCP4.5, right panels to RCP8.5. [Colour figure can be viewed at wileyonlinelibrary.com].

as, for example, in 2003 (García-Herrera *et al.*, 2010), 2006 (Rebetez *et al.*, 2009), 2007 (Eremenko *et al.*, 2008), and 2010 (Barriopedro *et al.*, 2011). The mixed tendencies over central Europe are also projected by RCP4.5, while simulations based on RCP8.5 project an increase in drought frequency, especially in spring and summer, Poland being an exception, though it will not be excluded from global warming (Szwed *et al.*, 2010; IPCC, 2014a).

While European Russia shows past and future drought tendencies in agreement with northern Europe, eastern Europe also acts as transition area of recent climate

Table 3. Summary of annual and seasonal drought frequency trends from 1951 to 2100. [Colour table can be viewed at wileyonlinelibrary.com].



Legend – changes in drought frequency

Colour	Description
🟥	Strong (> + 1 ev/10 year) increase almost everywhere (>80% of the area)
🟥	Strong increase in the most of the region (50–80%)
🟧	Increase (from +0.5 to +1 ev/10 year) in the most of the region
🟨	Moderate increase (from +0.1 to +0.5 ev/10 year) in the most of the region
🟨	Moderate sparse (<50%) increase and very sparse (<10%) decrease
⬜	Mixed decrease and increase tendencies
🟦	Moderate sparse decrease (from −0.1 to 0.5 ev/10y) and very sparse increase)
🟦	Moderate decrease in the most of the region
🟦	Decrease (from −0.5 to −1 ev/10 year) in the most of the region
🟪	Strong decrease (−1 ev/10 year) in the most of the region
🟪	Strong (<−1 ev/10 year) decrease almost everywhere

change (e.g. Haylock *et al.*, 2008) and is projected to be affected by less intense climate change compared to other European regions (Nikulin *et al.*, 2011). This is reflected in moderate drought trends in past and future decades, though spring and summer drought frequency is found to increase especially from the 2070s onwards for RCP8.5. The Carpathian Region is an exception: in the past it was affected by increasingly frequent and severe droughts (Spinoni *et al.*, 2013), due in particular to increasing temperatures (Spinoni *et al.*, 2015e) and heat waves (Spinoni *et al.*, 2015f); future drought projections hint at more extreme changes in the Carpathian Mountains than surrounding regions, namely more frequent droughts in spring and summer and a stronger decrease of winter droughts. A similar behaviour is observed for the Alpine region, which, especially for RCP8.5, is found to experience stronger drought differences between present and future decades than surrounding regions. However, the Alps did not show significant drought trends in the recent past, though the effects of climate change have been particularly notable in this area (Paul *et al.*, 2004; Calanca, 2007).

There is wide scientific consensus on the fact that southern Europe, and in particular the Mediterranean region, can be considered a climate change hotspot in both the recent past and the upcoming future (Giorgi, 2006; Diffenbaugh *et al.*, 2007; Giorgi and Lionello, 2008). This area experienced a broad increase in drought frequency and severity (Hoerling *et al.*, 2012; Spinoni *et al.*, 2015a, 2015b), especially in summer (Zampieri *et al.*, 2009, Spinoni *et al.*, 2017a); such increase affected also the Iberian Peninsula (Vicente-Serrano, 2006; Vicente-Serrano *et al.*, 2014) and, according to our findings, is projected to be large in all seasons over the entire southern Europe, from Portugal to Cyprus. This is due to the combination of temperature rise and decrease of precipitation totals on which the vast majority of future climate simulations agree (Heinrich and Gobiet, 2012; Sillmann *et al.*, 2013; Jacob *et al.*, 2014; IPCC, 2014b). The Balkans are frequently climatologically associated with southern Europe (Giannakopoulos *et al.*, 2009) and this is also valid for droughts. For the 21st century, droughts over the Balkans show similar tendencies to the Mediterranean region, except for winter droughts that are not projected to increase.

4. Summary and conclusions

This work builds on a previous study, in which we investigated drought trends in Europe over the last six decades on an annual scale (Spinoni *et al.*, 2015a). This study aims at exploring projections of drought trends until the end of the 21st century and providing a more complete picture of drought tendencies over Europe from 1951 to 2100. As input data, we used an ensemble of 11 bias-adjusted simulations from the EURO-CORDEX datasets (Jacob *et al.*, 2014), which include climate projections for two scenarios, RCP4.5 and RCP8.5. As in Spinoni *et al.* (2015a), drought events are defined according to a composite indicator based on the combination of SPI, SPEI, and RDI and computed for 3- and 12-month accumulation periods, to investigate the events at annual and seasonal scales.

Under the moderate emission scenario (RCP4.5) and compared to the recent past, southern Europe, western Europe, and northern Scandinavia are projected to be characterized by an outstanding increase in drought frequency by the end of 21st century, while central Europe, eastern Europe, and southern Scandinavia show only a moderate increase, and Iceland is characterized by a moderate decrease in drought frequency. Instead, the severity of drought events will increase significantly over the Mediterranean area only. Under the extreme emission scenario (RCP8.5), the frequency of droughts is projected to increase over the whole of Europe, with few exceptions: moderate increase over Switzerland, Hungary, Poland, Belarus, Lithuania, and central Scandinavia, and mixed tendencies over Iceland. The severity of droughts is projected to strongly increase over the southern third of Europe and over northernmost Scandinavia. Excluding central Iceland and southern Norway, the entire European continent will be affected by more frequent and severe droughts as the century passes.

On a seasonal scale, both RCPs project northern Europe to experience fewer winter droughts in the future than during the last decades but more frequent droughts in spring and autumn; over western Europe fewer winter droughts, but more frequent droughts in other seasons will take place, especially in summer; Central and eastern Europe will be involved by more frequent droughts in spring and summer; and southern Europe by more frequent droughts in all seasons. RCP8.5 projects larger increases (or decreases) than RCP4.5 also on seasonal scale, with no change from increase to decrease or vice versa from one RCP to the other.

From the 1950s to the 2010s, drought frequency and severity showed decreasing tendencies over northern Europe, increasing tendencies over southern and western Europe, with central and eastern Europe acting as transition zone (Spinoni *et al.*, 2015a, 2015b, 2017a). According to the combined indicator, the increasing drought trend is projected to continue and grow stronger until the end of the 21st century over southern and western Europe for both scenarios investigated, while northern Europe is projected to revert the past trend to see more frequent and severe droughts especially from the 2070s onwards and under RCP8.5. Central Europe still shows the smallest changes, in particular for drought severity and RCP4.5, while the frequency increase is larger for RCP8.5. The only region showing decreasing tendencies for the past and future is central Iceland. However, the uncertainty introduced by the ensemble of simulations should be taken into consideration, especially over those regions that are characterized by a disagreement on the sign of the drought tendency between simulations. This is true for the case of Iceland and parts of Scandinavia and central Europe, in particular over Poland.

Drought events caused significant impacts over Europe in the last decades (Wilhite *et al.*, 2007; Naumann *et al.*, 2015; Stagge *et al.*, 2015a, 2015b; Blauhut *et al.*, 2015b), consequently the results of this study point at an increasing risk of devastating and long-term drought impacts almost over the entire European continent in the upcoming decades. Our results can serve as a basis for estimating the impacts of future drought events, and therefore support scientists, stakeholders, and decision makers to develop adequate mitigation and adaptation strategies, which are particularly important under climate change (Lehner *et al.*, 2006; Logar and van den Bergh, 2013; Cai *et al.*, 2015). A study on the possible impacts of an increased drought frequency and severity over Europe is currently being planned and will be considered as the follow-up of this study.

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