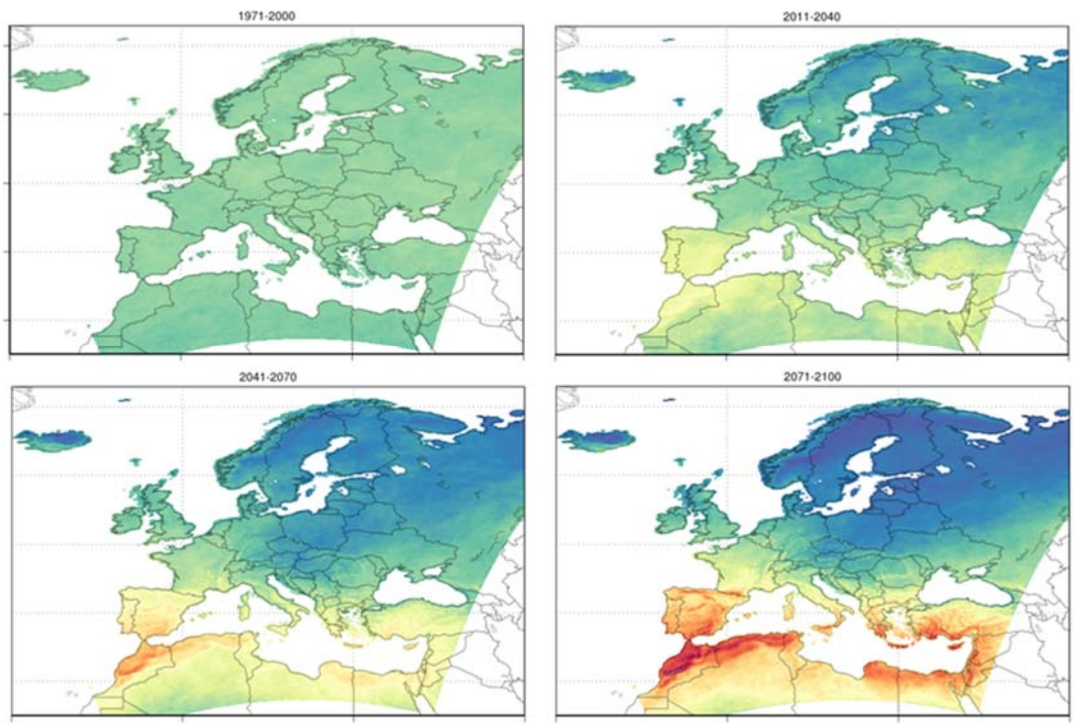
Technical Report No. 25

FUTURE METEOROLOGICAL DROUGHT: PROJECTIONS OF REGIONAL CLIMATE MODELS FOR EUROPE



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Date:30 March 2015

DROUGHT-R&SPI (Fostering European Drought Research and Science-Policy Interfacing) is a Collaborative Project funded by the European Commission under the FP7 Cooperation Work Programme 2011, Theme 6: Environment (including Climate Change, ENV.2011.1.3.2-2: Vulnerability and increased drought risk in Europe (Grant agreement no: 282769). The DROUGHT-R&SPI project started 01/10/2011 and will continue for 3 years.

Title:	Future Meteorological Drought: Projections of Regional Climate Models for Europe
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Submission date:	30/03/2015
Function:	This report is an output from Work Package 3; Task 3.2
Deliverable	DROUGHT-R&SPI deliverable D3.3

Cover picture: Reproduced from Figure 9. Colors represent the proportion of moderate drought months RCP8.5 (bottom) scenario.

Abstract

This study makes use of the most current Regional Climate Models (RCMs) forced with CMIP5 climate projections to quantify the projected change in meteorological drought for Europe during the next century at a fine gridded scale. Meteorological drought is quantified using the Standardized Precipitation Index (SPI), which normalizes accumulated precipitation for a specific location and time of year. Climate projections are based on output from CORDEX (the Coordinated Regional Climate Downscaling Experiment), which provides high resolution regional downscaled climate scenarios that have been extensively tested for numerous regions around the globe, including Europe. SPI is calculated on a gridded scale at a spatial resolution of 0.11 degrees (~12.5km) for the three projected emission pathways (rcp26, rcp45, rcp85). Models are first validated with respect to observed historical trends in meteorological drought from 1970-2005 and then comparing drought severity and frequency during three future time periods (2011-2040, 2041-2070, 2071-2100) to the historical control period (1971-2000). Historical and future projections are analyzed with regard to mean, variance, frequency of moderate and severe droughts, the distribution of drought durations, number of drought events, and the maximum drought duration. Results show significant increases in meteorological drought frequency and severity for the Mediterranean region along with increases for areas along the Atlantic coast and in southeastern Europe. The majority of northern Europe is projected to experience fewer precipitation-based droughts, as precipitation is projected to increase in these regions, though incorporating increased evapotranspiration may affect these drought projections. All results are robust, with good consensus among the suite of GCM/RCM model projections.

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1. Introduction

In response to the major European drought events of the last decade, projecting future drought frequency and severity in a non-stationary climate is a major concern for Europe. Climate change has the potential to increase drought risk by subjecting regions to levels of drought not previously experienced. Prior drought studies have identified regional hotspots in the Mediterranean and Eastern European regions (Blenkinsop and Fowler, 2007; Dai, 2012; Giorgi and Lionello, 2008; Orlowsky and Seneviratne, 2013), but have produced conflicting results with regard to future drought severity. Some of this disagreement is likely related to the relatively coarse resolution of Global Climate Models (GCMs) and regional averaging, which tends to smooth extremes. This study examines the effects of climate change on drought frequency, duration, and severity at the European scale using the most recent climate change projections processed through Regional Climate Models at a much finer spatial resolution.

The Standardized Precipitation Index (SPI) is a commonly used index of meteorological drought (e.g., McKee et al., 1993; Lloyd-Hughes and Saunders, 2002) characterising precipitation deficits or surpluses over different time scales. Orlowsky and Seneviratne (2013) concluded, based on the SPI3 and SPI12 (3 and 12 month time scale, respectively), that aggregated regional trends of SPI over the last decades remain mostly inconclusive in observations and CMIP5 simulations, although Soil Moisture Anomalies (SMAs) simulations hint at slightly increased drought in the Mediterranean. They further found that future projections of meteorological (SPI) and soil moisture (SMA) drought in CMIP5 display large uncertainties over all time frames, however, analyses of the frequencies rather than magnitudes of future drought, display more robust signal-to-noise ratios with detectable trends towards more frequent drought by the end of the 21st century in the Mediterranean. In this study we add to these findings by:

i) Examining future changes in meteorological drought during the next century (until 2100) using the SPI for different accumulation periods (3, 6, and 12 month),
ii) Using a suite of high resolution (0.11 x 0.11 degree) Regional Climate Models (EURO-CORDEX) forced with the best available Global Climate Model (GCM) projections under three emissions scenarios,
iii) Analyzing changes in mean and variance of the SPI, as well as the frequency, duration, and severity of drought events, and
iv) Presenting a first attempt to link projected future changes in drought to drought-related impacts, such as agriculture and water supply.

This approach allows for extremely high spatial resolution analyses of drought change over the European continent, with estimates of prediction robustness based on agreement among the models.

2. Methods

2.1 Overview of Analysis

In order to estimate the effects of climate change on drought, time series of the Standardized Precipitation Index (SPI) were calculated for each grid cell of the available GCM/RCM projections in the CORDEX dataset. The CORDEX project and dataset are described in detail below. The SPI is a meteorological drought index (McKee et al., 1993; Lloyd-Hughes and Saunders, 2002) that normalizes precipitation anomalies over several months relative to a reference climate for a given location and time of year. In this case, the SPI was normalized based on the control run of each projection (1971-2000) and then projected on the control and future scenarios.

Gridded future SPI time series were then compared to the reference period (1971-2000) using the same model to determine whether there were statistically significant changes in drought for the 30 year time intervals: 2011-2040, 2041-2070, and 2071-2100. By always comparing future drought relative to the control run, consistent biases in the GCM/RCMs are accounted for. Statistical analyses were performed at the native grid resolution (0.11°, ~12 km) to allow for spatial analysis. Results of the grid-based statistical tests were then compiled into summary statistics for each model, emissions scenario, and time period.

2.2 CORDEX Climate Projections

Global Climate Models generally project future climate at gridded scales of around 1000 x 1000 km, which tends to be too coarse to accurately resolve landscape effects. In order to produce climate models with better spatial resolution, results from these global models are downscaled to regional climate models. The COordinated Regional climate Downscaling Experiment (CORDEX; Giorgi et al., 2006) was designed to produce an improved generation of regional climate change projections as part of the IPCC Fifth Assessment Report (AR5) and to standardize the generation and evaluation of regional climate projections across multiple modelling centres. As part of the CORDEX project, several regions were established with explicitly defined domains and model resolutions. This study relies on the EURO-CORDEX dataset, which contains regionally downscaled CMIP5 climate projections (Taylor et al., 2012) for Europe.

A total of 23 model projections were used in this study, resulting from 5 GCM and 5 RCM combinations within the EURO-CORDEX repository (Table 2). Only the EUR-11 output was used in this study, which has a spatial resolution of 0.11 x 0.11 degrees, or approximately 12.5 km. The spatial extent and resolution of the EURO-CORDEX models is shown in Figure 1. This exceptionally fine spatial resolution allows for more accurate models of orographic effects, among other benefits. Assessments of the EURO-CORDEX models have proven that they are capable of accurately reproducing large-scale climate, especially when using the 0.11 degree resolution (Jacobs et al., 2013; Vautard et al., 2013; Kotlarski et al., 2014; Truhetz et al., 2014). Coarser resolution CORDEX data exists (0.44 deg); however, this has been shown to be less accurate, particularly in orographically influenced areas such as mountains (Truhetz et al. 2014). The coarser CORDEX models (0.44 deg) tend to slightly overestimate summer temperature exptremes in the Meditteranean, underestimate temperatures in Scandinavia, and simulate heat waves that retained too much persistence. However, use of the finer resolution RCMs improved these issues (Vautard et al., 2013).

Three emissions scenarios are used, termed Representative Concentration Pathways (RCP) by the IPCC and explained in detail in Moss et al. (2010). All scenarios specify radiative forcing relative to pre-Industrial conditions, with the 20th century increasing from 1.04 W/m^2 to 2.08 W/m^2 during the period 1971 to 2005. The emissions scenarios deviate at 2005 and are named based on their radiative forcing values in 2100. The RCP8.5 scenario is the most severe, with greenhouse gases continuing to increase through the next century, resulting in radiative forcings of 8.5 W/m^2, CO_2 concentrations of 1370 pppm and a temperature anomaly of 4.9° C by 2100. The RCP4.5 scenario represents a medium future scenario, where greenhouse gases and therefore radiation stabilize by the end of the century with an overshoot at 4.5 W/m^2, 650 ppm CO_2, and a temperature anomaly of 2.4° C. The least severe future scenario is the RCP2.6, which includes a mid-century peak at 3 W/m2 before declining to 2.6 W/m2, 490 ppm CO2, and a temperature anomaly of 1.5 ° C.

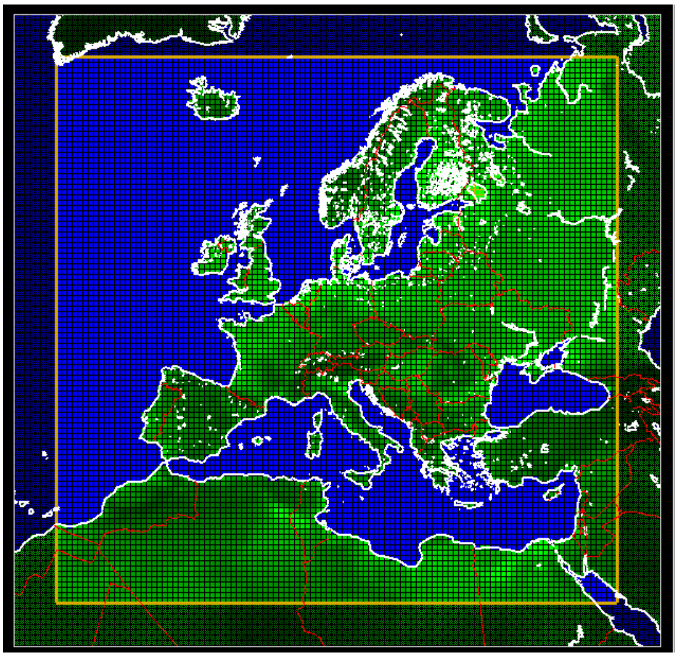

Figure 1. Map of the EURO-CORDEX domain.

Calculation of the SPI drought index relies only on near-surface precipitation (pr, kg m-2s-1), simulated at the monthly temporal resolution. A total of 23 CORDEX EUR-11 ensemble members were used in this study, which includes 11 scenarios for RCP4.5 and 8.5 and 1 scenario for the RCP2.6 (Table 1). Because only one RCP2.6 scenario was included, it was used to estimate changes, but results cannot be tested for robustness. For some GCMs, different realizations were used, describing equally realistic initial conditions. These are shown in brackets in Table 1. More detail regarding the parameters of each RCM is provided in Appendix 1, Table A1.1.

Table 1 GCM and RCM combinations used from CORDEX. Centred numbers in the cells correspond to the RCP scenarios used, while numbers in brackets correspond to the ensemble member.

RCM / GCM	CCLM	HIRHAM	RACMO	RCA	WRF	Total Scenarios
CNRM-CM5	4.5 8.5 [r1]			4.5 8.5 [r1]		4
EC-EARTH	4.5 8.5 [r12]	4.5 8.5 [r3]	4.5 8.5 [r1]	2.6 4.5 8.5 [r12]		9
HadGEM2-ES				4.5 8.5 [r1]		2
IPSL-CM5A-MR				4.5 8.5 [r1]	4.5 8.5 [r1]	4
MPI-ESM-LR	4.5 8.5 [r1]			4.5 8.5 [r1]		4
Total Scenarios	6	2	2	11	2	23

2.3 Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI, McKee et al. 1993; Guttman, 1999; Lloyd-Hughes and Saunders, 2002) was selected to quantify meteorological drought across Europe. This index measures normalized anomalies in precipitation and has been recommended as a key drought indicator by the World Meteorological Organization (WMO, 2006), the Lincoln Declaration on Drought (Hayes et al., 2011), and the DROUGHT R&SPI project (Gudmundsson et al., 2014). By converting accumulated precipitation to the standard normal distribution, meteorological drought can be compared objectively across regions with different climatologies and highly non-normal precipitation distributions.

The SPI was calculated using the gamma distribution, a reference period from 1971-2000, and the zero-handling recommendations described in Stagge et al. (2014). Distributions were fit and normalized using the SCI package in R (Gudmundsson and Stagge, 2015). Accumulation periods of 3, 6, and 12 months were calculated for each realization.

2.4 Statistical Tests of Drought Change

Each grid cell was analyzed individually to determine both the magnitude and statistical significance of changes in drought. As recognized by the IPCC (2001), climate changes may present as an overall shift (i.e. a change in central values), a change in variance (i.e. a change in the spread of values), or a change in the overall distribution, which could produce simultaneous shifts in the central tendency, variance, or skew (Figure 2). Therefore, different statistical tests were used to capture these different modes of change as they related to future drought in Europe. These tests are summarized in Table 2 and described in greater detail below.

Each statistical test was calculated at the land grid-cell resolution, always comparing the metric from the historical control period (1971-2000) to the 30 year future periods. In this way, the sample size was always constant. For all tests, an alpha of 5% was used as a standard threshold for statistically significant changes.

Table 2. Statistical tests used for drought analysis.

Metric	Statistical Test
Central value	2 Sample T-Test (normal) Mann-Whitney Test (non-parametric)
Variance	2 Sample F-Test
Drought Frequency SPI < -1 (Moderate) SPI < -2 (Severe)	X^2 (Chi-squared) Test
Drought Duration	X^2 (Chi-squared) Test

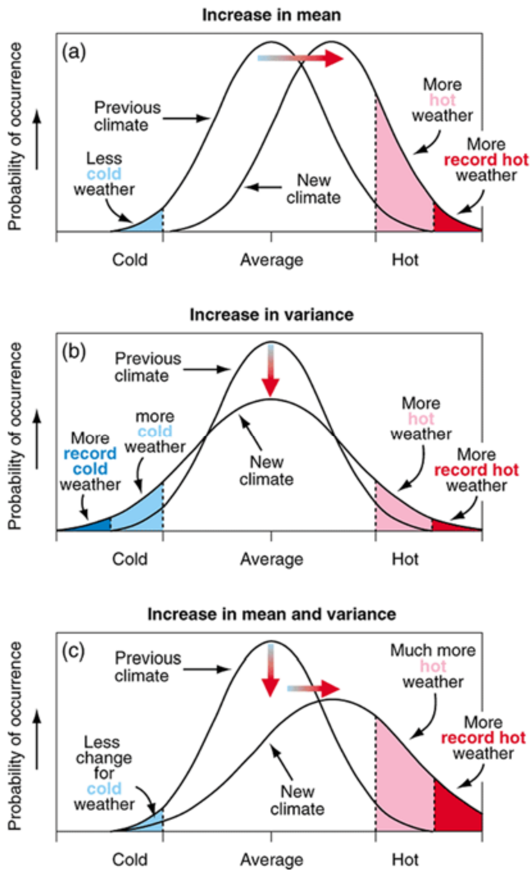

Figure 2. Schematic showing the modes of distribution changes due to climate change: (a) the mean shifts, (b) the variance changes, or (c) both the mean and variance change. Reproduced from IPCC (2001).

Central values were tested using the parametric two sample t-test and the non-parametric Mann-Whitney test. These test whether the overall statistical distribution of the SPI is projected to increase or decrease relative to the reference period. This corresponds to an overall wetter or drier future climate. The two sample t-test specifically tests whether the historical and future means are equal, assuming normal distributions. This is a reasonable assumption, given that SPI values in the historical period are normally distributed by definition. Welch's approximation is used for the t-test, which allows for unequal variance. The Mann-Whitney test is a non-parametric variant, which does not assume normality, which may be of use when future projections produce non-normal SPI values.

The F-test was used to determine whether the variance of future SPI values is significantly different from the historical distribution. By definition, the standard deviation of the SPI from the control period is 1. Therefore, an increase in variance above 1 suggests more extreme values, both towards wetter and drier periods (Figure 2).

Drought frequency was calculated for two thresholds, SPI < -1 and SPI < -2, corresponding to moderate and severe droughts, respectively. The theoretical frequencies for these levels are 15.9% and 2.3%, respectively. The Chi-squared (X^2) test was used to determine whether the frequency of SPI below these thresholds is projected to change significantly from the historical reference period.

The distribution of drought durations was tested in a similar manner, using the Chi-squared test. For duration calculations, drought events were defined as periods with an SPI < -1 and drought duration was defined as the period during which the SPI continuously remained less than -1. The distribution of drought durations was then binned and used to calculate the Chi-squared statistic, showing the difference in the overall distribution of drought durations between the historical period and future periods. For this calculation, the same bins were used for historical and future periods. In addition to calculating the Chi-squared statistic for drought durations, the number of drought events was recorded, as well as the maximum drought duration.

2.5 Summary Measures

While the cell-based statistical tests provide a significance measure of the projected change signal relative to natural variability, the use of multiple GCM and RCM combinations provides an estimate of signal robustness to atmospheric models and initial conditions. If the more than 50% of the model runs agree on a statistically significant change, it is considered to be robust. While this threshold is slightly lower than the 66% level recommended in Jacob et al. (2014), this report also requires a statistically significant difference rather than simply agreement in sign, as in Jacob et al. (2014).

Projected changes are summarized across models and emissions scenarios using two approaches. First, the percent area fraction of Europe with a significant increase or decrease was calculated for each time step and scenario. For the purposes of area calculations, Europe is defined as the area bound by 33° to 72° Latitude and -28° to 48° Longitude. This definition is slightly more restrictive than the larger CORDEX Eur-11 domain and is designed to remove portions of the northern Sahara and northern Russia.

In the second approach, the results are summarized across models focused on presenting consistent changes spatially by calculating a trend robustness score:

$$\text{Trend Robustness} = \Sigma \text{ Models significant } (+) - \Sigma \text{ Models significant } (-)$$

where the number of models with negative statistically significant trends are subtracted from the models with positive statistically significant trends. In this way, if the majority of models agree on the direction of change, the index will be 100% in the direction of change. If the models equally disagree on the direction of change or if the change is not statistically significant, the index will be zero, showing no confidence in the projected change.

3. Results

3.1 Changes in Overall Dryness

Climate projections of the central values (mean/median) for the SPI show that two opposing patterns are projected to develop over the next century, with northern Europe tending towards wetter overall conditions and the Mediterranean region tending towards drier overall conditions. Results for the mean and median SPI are extremely similar in severity and statistical significance, so this discussion will focus on the median values. Figure 1 shows the agreement among tested GCM/RCM combinations in the statistically significant direction of change for the median SPI6. Regions expected to become significantly ($p < 5\%$) drier relative to the historical control period (1971-2000) include the Iberian peninsula, southern Italy, Greece, Cyprus, western Turkey, and nearly all of Mediterranean north Africa. Within the first 30 year period (2011-2040), this change is less detectable, with less than 60% of the models agreeing on a statistically significant change; however, by the end of the century (2071-2100), nearly all model projections show a statistically significant decrease in the mean/median SPI. This is particularly noticeable for the most extreme emissions scenario (RCP 8.5). Similarly, nearly all

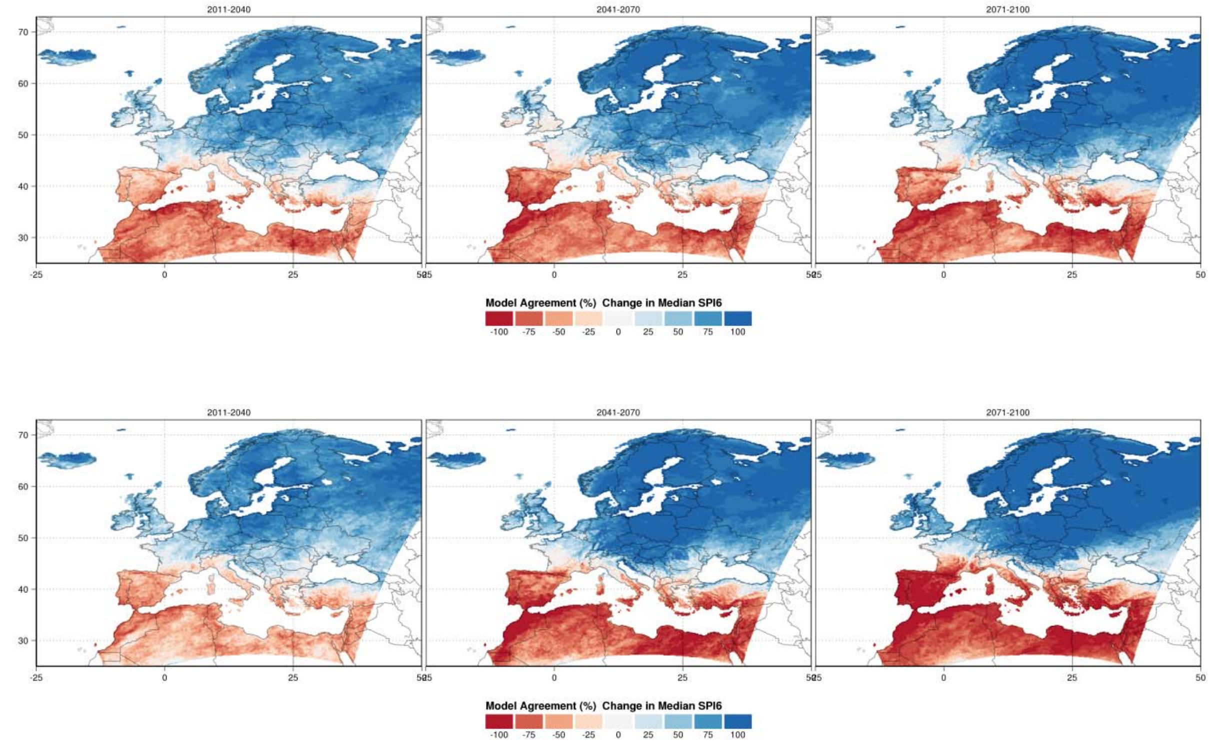

Figure 3. Model agreement (% of models) regarding a statistically significant change in the median SPI6 for the RCP4.5 (top) and RCP8.5 (bottom) scenarios.

projections agree on a statistically significant shift towards overall wetter conditions by the end of the century in northern and central Europe (RCP8.5).

These projections of changes in overall precipitation show that 15% to 23% of the European land mass will experience an overall drier climate in the next century, while 40% to 60% of the land mass will become wetter overall, i.e. higher SPI (Figure 4). During the first 30 years of this century (2011-2040), there is little discernible difference in the area affected by increased drying (Figure 4); however, by the end of the century, there is a clear distinction between the RCP 2.6, 4.5, and 8.5 emissions scenarios. As also demonstrated by the spatial plots (Figure 3), the percent area affected by a significantly drier climate has the greatest increase under the most severe emissions scenario (Figure 4). While the time period and emissions scenario affect the strength and significance of changes, the spatial patterns are relatively robust and do not change (Figure 3). The percent area predicted to become drier (Figure 4) follows the radiation patterns of the emissions scenarios, with the RCP8.5 increasing steadily, the RCP4.5 reaching a plateau, and the RCP2.6 reaching a peak in the mid-century and then decreasing.

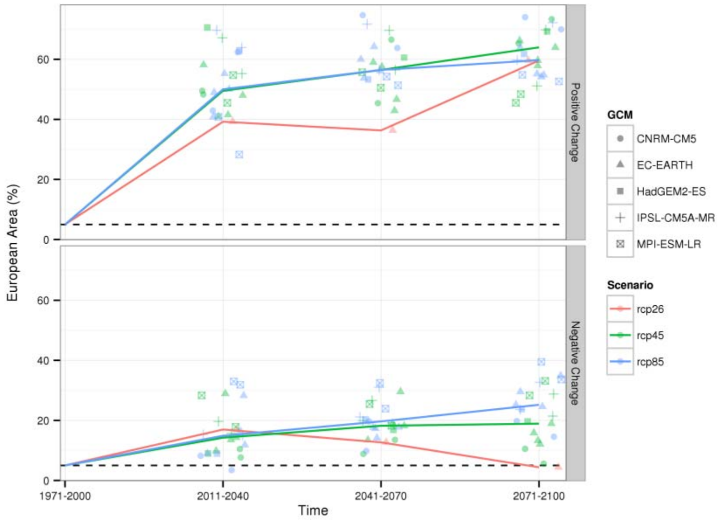

Figure 4. Fraction of European area (%) with statistically significant increases (top) and decreases in the median SPI6, according to the Mann-Whitney test. GCM forcing models are shown as shapes, while emission scenarios are shown as colors.

Projections of increased drier conditions in the south and wetter conditions in the north are more pronounced for longer accumulation periods, such as the SPI12, than shorter periods, such as the SPI3. The stronger signal for slow accumulating droughts may be due to its greater persistence and lack of statistical noise. This could also be related to seasonal affects, with the SPI3 responding to changes in seasonality and the SPI12 smoothing these seasonal effects.

3.2 Changes in Variance (Wet and Dry Extremes)

Changes in the overall SPI variance measures whether climate projections of precipitation are projected to become more extreme, with more time spent in the extreme tails of the SPI distribution, or less extreme, with more time spent near the “typical” historical conditions. This is based on the principle that the reference period SPI is normally distributed with a standard deviation of 1. Unlike the projected shift in dryness/wetness that shows two competing spatial patterns, the results show that SPI variance is projected to increase across much of Europe (30-60%), with statistically negligible regions (≈ 5%) predicted to decrease in variance (Figure 5). This suggests an increase towards more erratic or extreme events, with higher wet SPI values and lower dry SPI values. The increase in variance is strongly related to the RCP emissions scenario, with the scenarios deviating immediately and the most extreme scenario (RCP8.5) increasing the SPI variance across 62% of the total European land area (Figure 5).

The majority of the regions expected to significantly increase in variance are located along the Atlantic Coast (Figure 6). This shift towards more extreme values of SPI includes “hot spots” in areas of France, Germany, and the UK that did not show consistent overall changes in dryness/wetness. These regions therefore correspond to the case shown in Figure 2b, where the central values remain relatively similar, but the distribution of precipitation changes towards the more extreme. The Iberian peninsula, Spain and Portugal, is also a “hot spot” of increasing extremes; however, this region also includes a consistent shift towards drier conditions, which may produce exceptional drought conditions.

As shown by significant increases in SPI variance across up to 80% of European area, in the most extreme runs, nearly all of Europe is projected to increase in SPI variance, particularly for the RCP8.5 scenario (Figure 5). In the more moderate RCP4.5 scenario, there are some small regions that are projected to become less extreme, particularly areas with high elevation located in colder climates (Scandinavia and eastern Europe) (Figure 6).

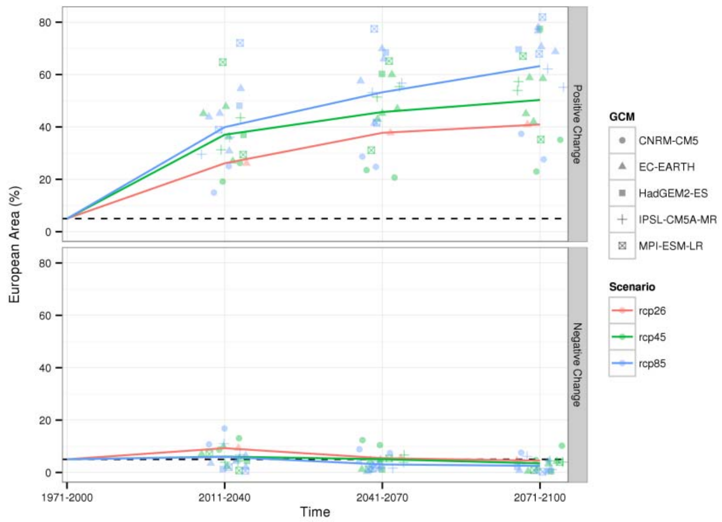

Figure 5. Fraction of European area (%) with statistically significant increases (top) and decreases in SPI6 variance, according to the F-test. GCM forcing models are shown as shapes, while emission scenarios are shown as colors.

The statistically significant increase in SPI variance is more pronounced for shorter, seasonal drought indices, SPI3 and SPI6, while the annual drought index, SPI12, has a weaker signal. Still, the SPI12 projects approximately 40% of the European land mass to shift to more extreme values of both higher accumulated precipitation (wetter) and lower (drier).

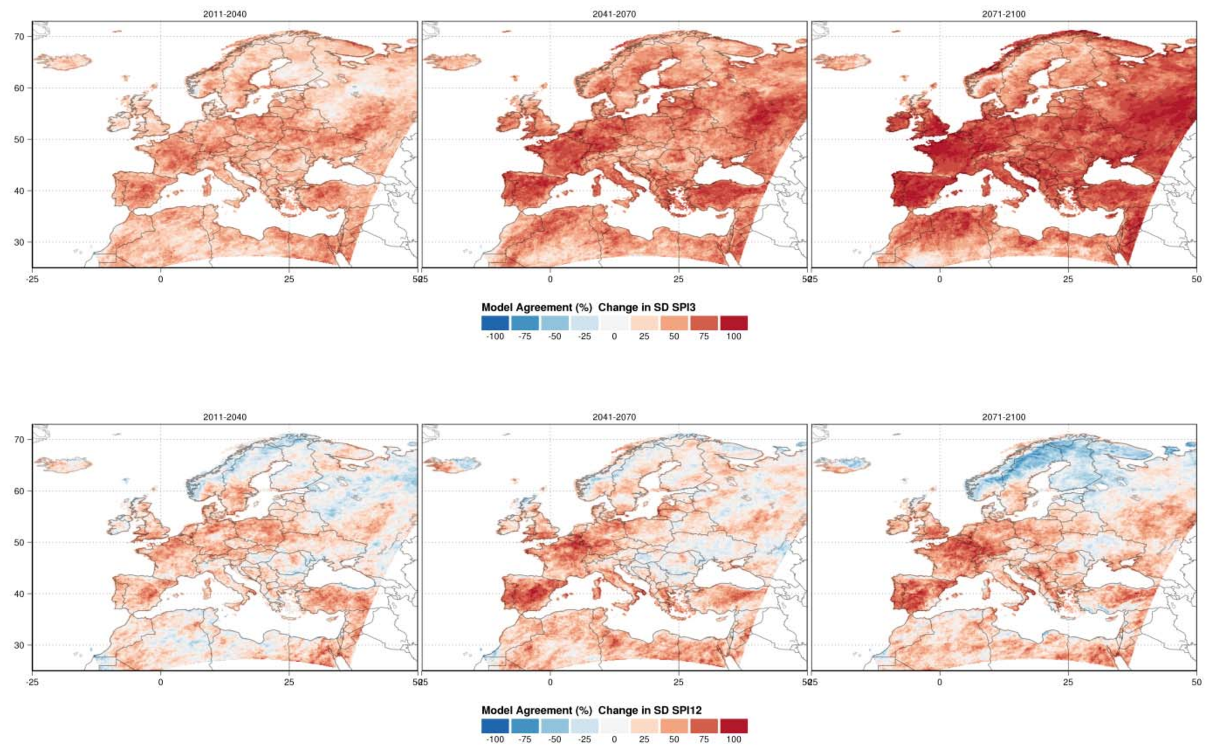

Figure 6. Model agreement (% of models) regarding a statistically significant change in the variance of SPI3 (top) and SPI12 (bottom) while simulating the RCP8.5 scenario.

3.3 Changes in Drought Frequency

Results of the SPI mean and variance from the CORDEX data set are similar to previous evaluations of the precipitation fields for this and other future projections (Blenkinsop and Fowler, 2007; Dai, 2012; Giorgi and Lionello, 2008; Orlowsky and Seneviratne, 2013; Jacob et al., 2014). However, drought impacts are related to complex interactions of extreme values, frequency, and duration. In order to estimate the effect of climate change on drought, the proportion of moderate and severe drought months was calculated, using SPI < -1 and SPI < -2 as thresholds, respectively.

Changes in the proportion of moderate and severe drought months has a similar, but more complex spatial pattern than the SPI mean and variance, because it measures the extreme negative tail of a distribution which is affected by both of these parameters. Driven by a shift towards a drier overall future climate, the Mediterranean region is projected to have an increase in both moderate and severe drought months (Figure 7). But, also due to a more extreme climate, Atlantic regions such as France and the UK are projected to have a slight increase in drought months, along with portions of the Balkans, Romania, and southern Ukraine. Regions of central and northern Europe, with significant shifts towards a wetter climate, show a corresponding decrease in drought months.

Overall, these changes in the occurrence of moderate and severe droughts means that roughly 20% of the European land mass is projected to have significant increases in moderate and severe drought months during the next 30 years (2011-2040), regardless of the long-term emission scenarios (Figure 8). The role of emissions becomes more important by the end of the century, with the area affected by increases in moderate and severe droughts projected to increase to 34% and 37% by the end of the century, respectively, under the RCP 8.5 scenario. Simulations using the RCP 4.5 scenario project a relatively limited area of increased drought frequency, near 20% and centered on the Mediterranean.

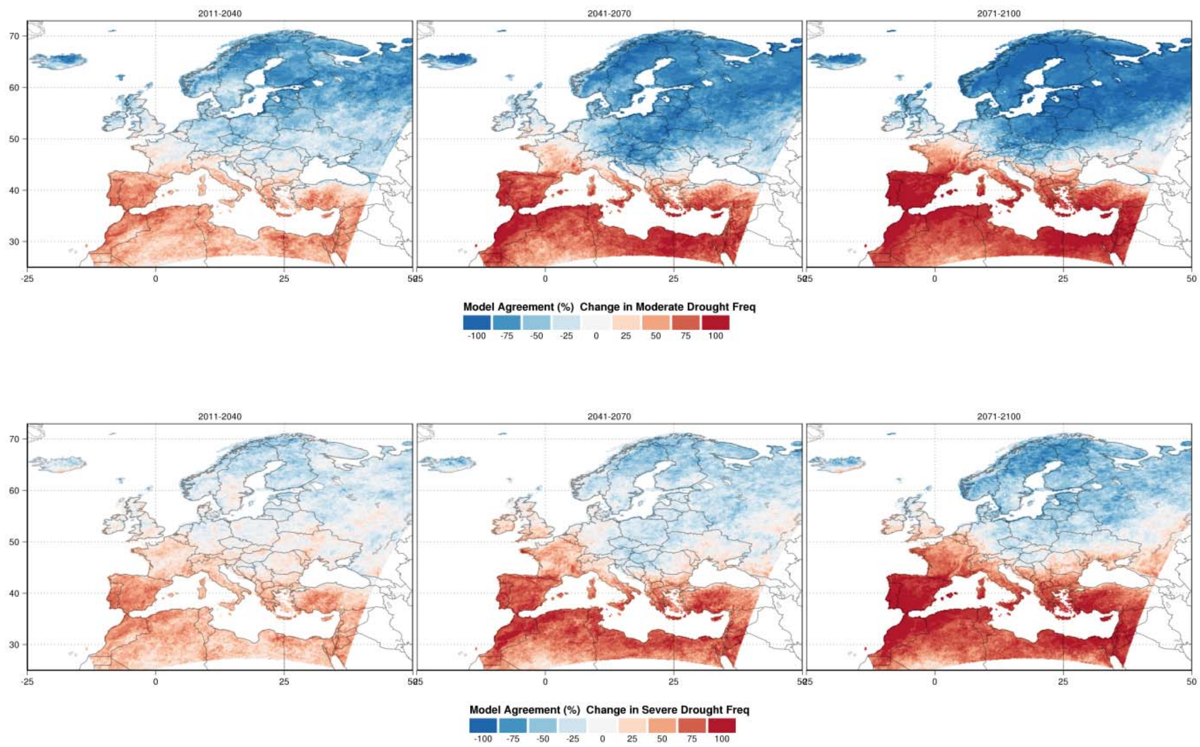

Figure 7. Model agreement (% of models) regarding a statistically significant change in the frequency of moderate droughts (SPI6 < -1, top) and severe droughts (SPI6 < -2, bottom) using the RCP8.5 scenario.

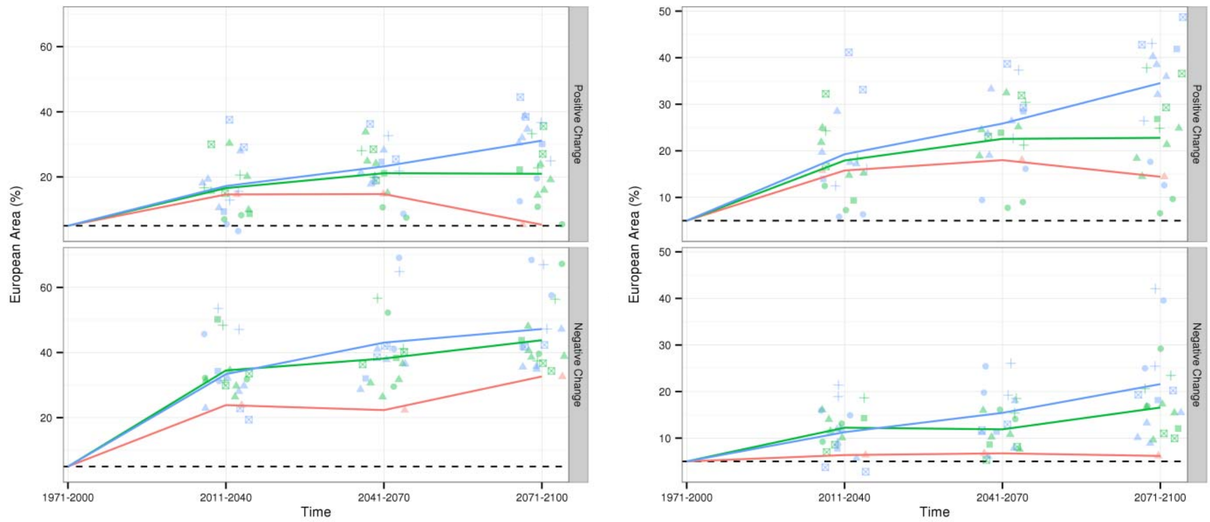

Figure 8. Fraction of European area (%) with statistically significant changes in frequency of moderate (left) and severe (right) drought SPI6 variance, according to the F-test. GCM forcing models are shown as shapes, while emission scenarios are shown as colors.

Patterns of drought frequency follow the RCP scenarios, with the RCP8.5 continuously increasing, RCP4.5 stabilizing by the end of the century, and RCP2.6 reaching a peak and then decreasing. The total area with significant decreases in drought frequency is projected to increase throughout the century, with 35-65% of the total area decreasing in moderate drought frequency and 10-30% decreasing in severe drought frequency (Figure 8). Model agreement is strongest for moderate droughts (Figure 7), which is likely related to both uncertainty in simulating highly extreme weather in GCM/RCMs and the relatively low frequency of severe droughts, which reduces the statistical power of the Chi-squared test to estimate statistically significant changes in frequency.

In terms of actual drought frequency, these projections show a shift from the theoretical frequency for moderate droughts (SPI < -1) of 15.9% to roughly 40-50% of all months in parts of the Iberian peninsula,

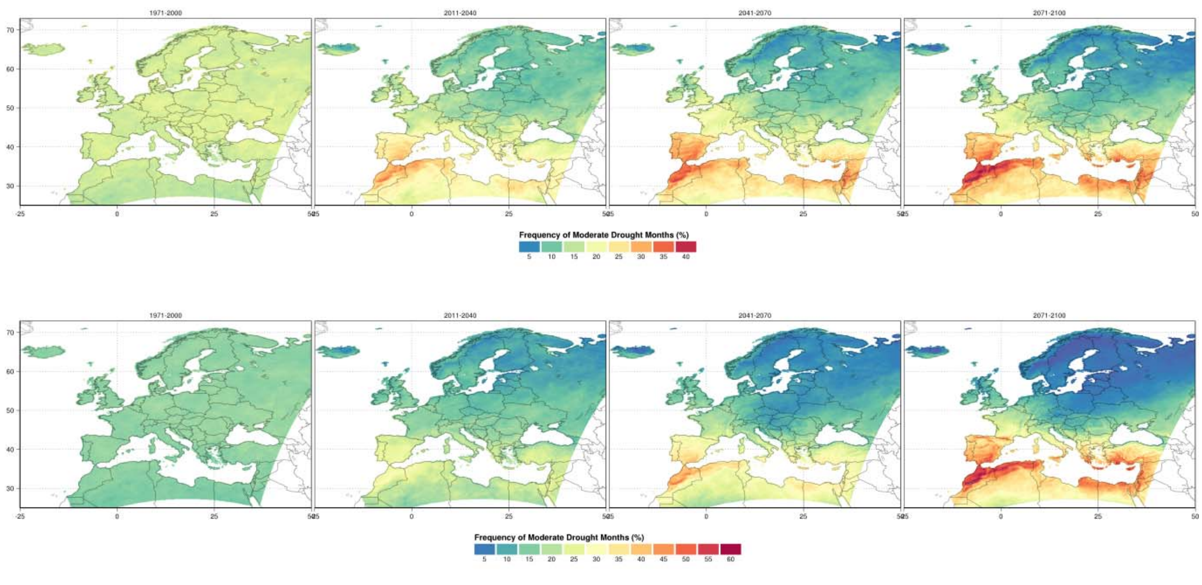

Figure 9. Ensemble mean showing the proportion of moderate drought months (SPI6 < -1) for the RCP4.5 (top) and RCP8.5 (bottom) scenarios.

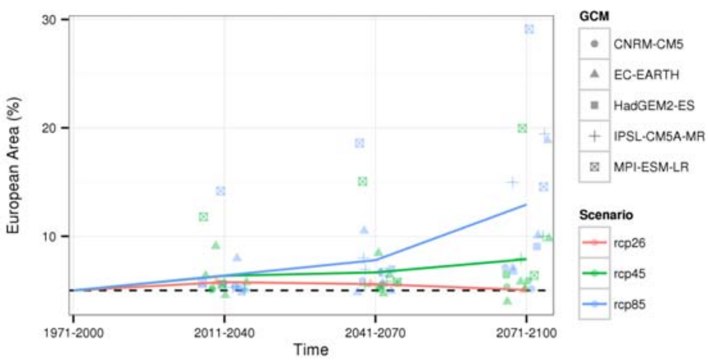

Figure 10. Fraction of European area (%) with statistically significant changes in the distribution of drought durations.

southern Italy, the eastern Mediterranean, and north Africa by the end of the century (Figure 9). The number of drought months is expected to increase to 20-30% for the Atlantic coastal region and parts of southeastern Europe. Regions with decreases in drought frequency, such as Scandinavia are projected to experience meteorological drought conditions during only 5-10% of the time period (Figure 9). As described above, this effect is most pronounced for the extreme emissions scenario and slightly less extreme for the moderate scenario, though it is still very noticeable for much of Europe.

3.4 Changes in Drought Events and Duration

Drought has an important temporal component that cannot be captured purely by frequency below a threshold. In order to capture this temporal component, each projection was analyzed to determine the duration and number of drought events, defined as continuous periods below SPI of -1. In order to test changes in the distribution of drought durations, the Chi-squared test was applied to tables of binned drought durations for all drought events during the period. This test cannot determine increases or decreases in drought duration, but tests whether the overall characteristics of droughts have changed. Results of this test show that the duration of drought events is not projected to change significantly in the next 30 years, but may be significantly different for 10-30% of the European land mass by 2070-2100 under the RCP 8.5 scenario (Figure 10). Similar to the proportion of drought months, the areas with significant changes in drought duration are predominantly located in the Mediterranean and Atlantic coastal regions (Figure 11).

This shift in the distribution of drought duration is related to both an increase in the number of drought events and a change in the total duration of events. The number of multi-month drought events (> 2 consecutive months with SPI < -1) is highly related to the SPI accumulation period. The SPI12 has a much higher persistence because it measures accumulated precipitation over 12 months, rather than the SPI3 which is much more affected by individual months and therefore has a noisier signal. However, in the Mediterranean and coastal Atlantic, the number of multi-month droughts is projected to double by the end of the century, with the number of SPI3 drought events increasing from 12-15 to 25-30 and SPI12 events increasing from 6-7 to 12-15.

In addition to increases in the number of drought events, caused by a combination of lower SPI values and more extreme precipitation, the maximum drought duration is projected to increase across similar regions. During the historical control period, the maximum SPI6 drought duration was 8-12 months, with minor spatial variability in the distribution of maximum duration (Figure 12). However, in the affected

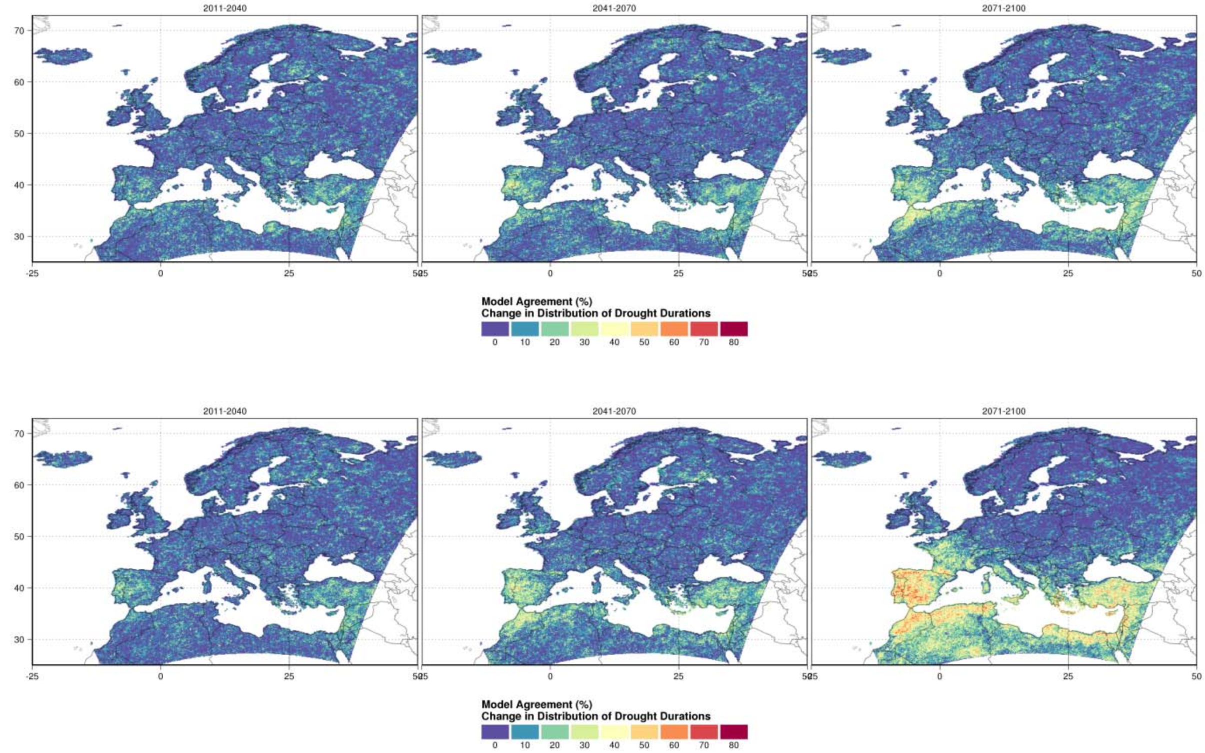

Figure 11. Model agreement (% of models) regarding a statistically significant change in drought durations for the RCP4.5 (top) and RCP8.5 (bottom) scenarios.

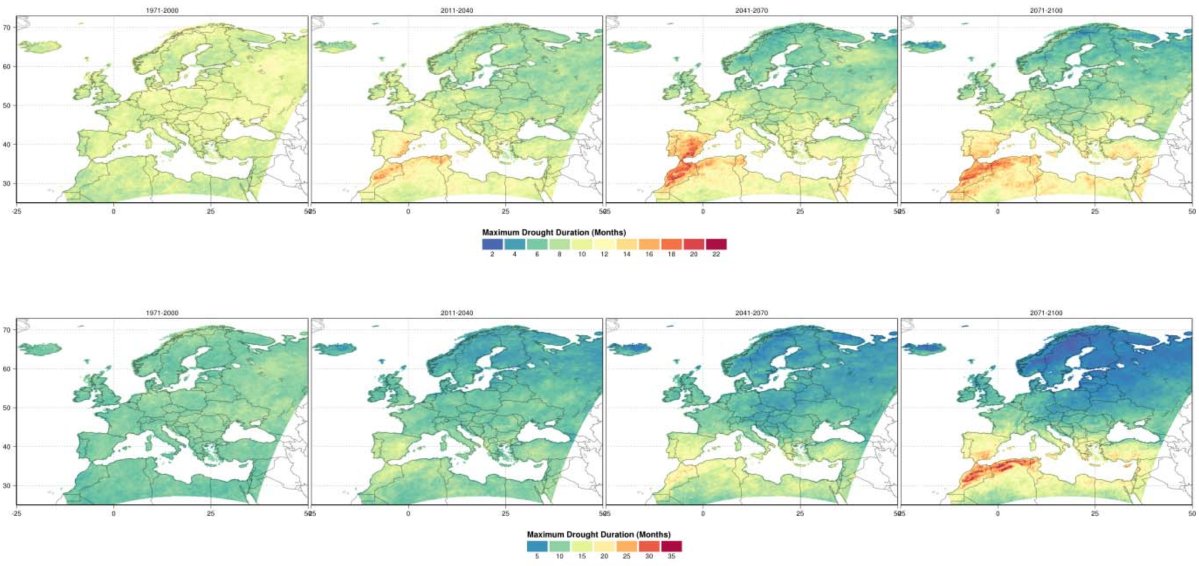

Figure 12. Ensemble mean showing the maximum drought duration for the RCP4.5 (top) and RCP8.5 (bottom) scenarios.

regions, the maximum drought duration typically increased to 14-18 months under the RCP4.5 scenario and 20-25 months under the RCP8.5 scenario.

4. Discussion

4.1 Drought Projections for Europe

Meteorological drought projections for Europe can be separated spatially into the Mediterranean / Atlantic coastal regions and northern/central Europe. Drought is projected to increase throughout the Mediterranean, including the eastern Mediterranean and north Africa, and the Atlantic coastal region, including France, the UK, and the Rhine river valley. These increases are due to a general shift towards a drier climate in the Mediterranean and an increase in precipitation variability along the Atlantic coast. This results in an overall increase in both moderate and severe drought frequency for the entire region, with significant increases in the number of drought events, and an increase in maximum drought duration for the Mediterranean region.

In all cases, the most extreme emissions scenario, RCP8.5, produced either equal or more severe drought responses than the moderate scenario, RCP4.5. In most cases, the RCP8.5 projections continued to increase drought severity throughout the next century, while the RCP4.5 often reached a plateau by the mid-century (2041-2070). This follows the pattern of greenhouse gases and radiation defined in these scenarios. It is difficult to conclude regarding the RCP 2.6 scenario because only one simulation is currently available within the CORDEX database. While many projections showed a plateau mid-century followed by a slight decrease by the end of the century, which mirrors the radiative forcing, this conclusion is not robust.

The predictions of a generally drier Mediterranean and wetter northern Europe are similar to previous studies on SPI12 using CMIP5 results globally (Orlowsky and Seneveratne, 2013) and analysis of the CORDEX dataset for overall precipitation changes (Jacob et al. 2013). However, the analysis presented here which examines drought duration, frequency, and severity adds additional detail for both spatial resolution and drought metrics.

Spatial patterns of maximum drought duration are more similar to patterns of mean and median SPI, suggesting that maximum drought duration is more closely related to shifts in the overall dryness. Conversely, the number of drought events more closely resembles the SPI variance, which controls how extreme the SPI distribution is. These conclusions are physically interpretable, as a general shift to drier conditions can increase runs of consistently low values, while an increase in variance creates a noisier SPI signal, with increased drought events followed by increased wet events.

4.2 Future drought impacts

The changes found will have implications for the occurrence of drought impacts on environment, society and economy. Whereas the major large-scale drought events that occurred in Europe over the past few decades had SPI values below -2 for extended regions (Stagge et al., 2013), a variety of drought impacts have also occurred for values below about -1 or -1.5 (De Stefano et al., 2015; Stahl et al., 2015b). Figure 13 shows the median of the annual minimum SPI-6 and SPI-12 values for years in which drought impacts were reported for the sector "Agriculture and Livestock farming" (source: European Drought impact report inventory (EDII), Stahl et al., 2012). The maps show that thresholds for impact occurrence in this sector are somewhere between SPI<-1 and <-2 in most regions, with slightly more severe conditions required for SPI-6 to cause impacts. Hence, the projections of future changes for SPI6 and 12 between -1 and -2 are highly relevant to drought impact occurrence on agriculture.

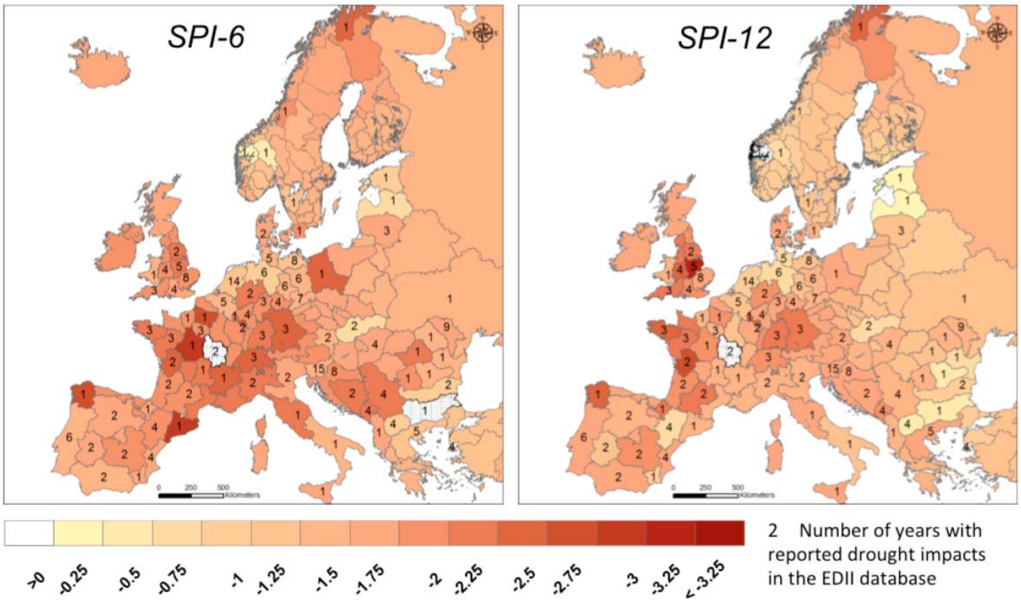

Figure 13. SPI values related to impact occurrence in the category "Agriculture and livestock farming" for NUTS-2 regions with impact reports. Index value for regions with no data was interpolated from neighboring regions.

Reports on other drought impacts have a more patchy coverage across Europe and it is not possible to create similar pan-European maps of corresponding SPI values at such high spatial resolution. However, regional studies found that impacts on water supplies, freshwater ecosystems, and energy and industry, which all rely on surface or groundwater resources, are more sensitive to long-duration droughts. These are best indicated by SPI-12 to -24. In addition, there are regional differences. Generally, the Mediterranean, which has adapted to lower precipitation and longer dry periods with reservoir storage and irrigated agriculture is less sensitive to short precipitation anomalies and is affected most by long accumulated precipitation deficits. The remainder of Europe responds to more seasonal droughts.

The analyses of future SPI changes shows that within the Mediterranean region, drought frequency and severity are both projected to increase, thereby increasing both the frequency and severity of drought-related impacts in the region. While many parts of these regions already employ multi-year reservoir storage, an increase in maximum drought duration of more than a year may affect the ability of water managers to respond to this natural hazard. In addition, the metric of maximum drought duration does not consider antecedent droughts. In other words, a one year drought might be followed by a short period where conditions return to near normal before entering the maximum drought duration of 24 months.

Regions outside the Mediterranean that are projected to increase in drought frequency or severity are the Atlantic coast, including France, the UK and the Rhine valley, and southeastern Europe, including parts of Romania, Ukraine, and Russia. All these regions have experienced severe drought impacts in the last decades, with France having suffered severe agriculture losses in the event of 2003, the UK having experienced ecosystem impacts and nearly disastrous water supply shortages in 2011-12, and the river Rhine having limited navigability with high economic losses in 2011 (source: EDII database edc.uio.no/droughtdb). These rather different examples illustrate the type of impacts that these regions may be faced with more frequently in the future. Outside the Mediterranean, Eastern Europe may be particularly susceptible to drought impacts in the future, as agricultural impacts from relatively short and weak precipitation anomalies already comprise the largest proportion of drought impacts reported (Stahl et al., 2015a) and the region has high vulnerability due to a low adaptive capacity (De Stefano et al., 2015).

Central and northern Europe are projected to increase in precipitation due to climate change. However, this study only focused on the effects of precipitation. While impacts due only to precipitation are projected to decrease for these regions, drought may also be related to changes in evapotranspiration. Therefore, more research is needed to project evapotranspiration estimates under future climate conditions. This would allow calculation of a companion meteorological drought index, the Standardized Precipitation-Evapotranspiration Index (SPEI), which is used in the impact models described above. While precipitation is the primary driving factor for drought and is therefore useful for large-scale studies, evapotranspiration can play an important role in increasing drought severity. The studies that selected 'best indices' based on statistical significance often found SPEI to be more closely linked to impacts than SPI (e.g. Stagge et al., in rev. and others summarized by Stahl et al. (2015b)). Because evapotranspiration is driven primarily by radiation and surface temperatures, the future projections of the SPEI are expected to be more sever, given the radiation increases and temperature increases of 1.5-4.9° C across the future RCP scenarios. In this way, predictions of drought impacts using the SPI may be conservative.

As evapotranspiration is driven primarily by radiation and surface temperatures, projected increases in radiation and temperature within the CORDEX data set suggest that droughts based on the SPEI will be more severe and regions that showed a slight increase in precipitation might be offset by increases in evapotranspiration.

In summary, the results of statistically significant increase in SPI variance is more pronounced for shorter, seasonal drought indices, SPI3 and SPI6. Based on the obtained knowledge on linking specific impacts to different drought indices this suggests a risk for future increases of negative impacts on agriculture in particular, but also for example on wildfire activity. Both impacts are highly related to short, seasonal droughts. The changes found are less strong for SPI12. Exceptions, however, are particularly those regions, in which past impacts in fact have shown to be linked to longer accumulation periods such as in the southeast of the UK and in the Benelux countries. These are regions with high population densities and water supply systems that presently rely on regular recharge of their groundwater and surface water resources. Nevertheless, these are also regions, where awareness of drought hazard has increased in recent years, and resilience building will likely take place.

5. Conclusions

This report shows the projected effects of climate change on meteorological drought at the pan-European scale using the highest resolution RCMs available forced with the current best CMIP5 GCM projections. Results show significant increases in meteorological drought frequency and severity for the Mediterranean region along with increases for areas along the Atlantic coast and in southeastern Europe. The majority of northern Europe is projected to experience fewer precipitation-based droughts, as precipitation is projected to increase in these regions, though incorporating increased evapotranspiration may affect these drought projections. Droughts are affected by emissions, with the most severe emission scenario producing the largest affect on drought severity, frequency, and duration. For the RCP 4.5 and 8.5 scenarios, the effects are projected to either intensify or plateau by the end of the century, with no projected returns to historical conditions. The increases in drought frequency and duration between SPI values of -1 and -2 translate to increases in a variety of drought-related impacts, with shorter anomalies (SPI3,6) affecting agriculture and wildfire extent, and longer anomalies (SPI12) affecting water supply.

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Annex 1 RCM Parameters

Table A1.1 RCM model parameters, reproduced from Jacobs et al. (2014).

	RCA4	CCLM	RACMO2	WRF	HIRHAM
Institution	SMHI	CLMCOM[1)]	KNMI	IPSL-INERIS	DMI
Grid resolution	0.11 º x0.11º	0.11 º x0.11º	0.11 º x0.11º	0.11 º x0.11º	0.11 º x0.11º
Grid (lat*lon)	438* 456	450*438	444*456	442 * 454	452*432
Rotation	lon -162° lat 39.25°	lon -162° lat 39.25°	lon -162° lat 39.25°	CORDEX specifications	lon -162° lat 39.25°
Vertical levels	40	40	40	32	31
Boundary layer scheme	Cuxart et al 2000	Louis 1979	Lenderink and Holtslag 2004; Siebesma et al. 2007	YSU, Hong et al. 2006	Louis 1979
Number of points (sponge zone)	10	12	8 (16)[3)]		
Convection	Kain and Fritsch 1990, 1993; Kain 2004; Jones and Sanchez 2002	Tiedtke 1989	Tiedtke 1989; Nordeng 1994; Neggers et al 2009	Grell and Devenyi 2002	Tiedtke 1989
Microphysics	Rasch and Kristjánsson 1998	Doms et al. 2007; Baldauf and Schulz 2004	Tiedtke 1993; Tompkins et al, 2007; ECMWF-IFS 2007;Neggers 2009	Hong et al. 2004	Lohmann and Roeckner 1996
Radiation	Savijärvi 1990; Sass et al. 1994	Ritter and Geleyn 1992	Fouquart and Bonnel 1980; Mlawer et al.1997	RRTMG, Lacono et al, 2008	Morcrette et al 1986; Giorgetta and Wild 1995
Land surface scheme	Samuelsson et al. 2006	TERRA-ML Doms et al. 2007	Van den Hurk et al 2000; Balsamo et al. 2009	NOAH	Hagemann 2002
Soil thermal layers	5	10	4	4	5
Soil moisture layers	3	8	4	4	1
Main references	Samuelsson et al. 2011; Kupiainen et al. 2011	Rockel et al. 2008; http://www.cosmo-model.or	Meijgaard van et al. 2012	Version 3.3.1, Skamarock et al. 2008	Christensen et al. 1998