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Meteorological Droughts in Europe

Events and Impacts

Past Trends and Future Projections

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Executive Summary

Observational records from 1950 onwards and climate projections for the 21st century provide evidence that droughts are a recurrent climate feature in large parts of Europe, especially in the Mediterranean, but also in western, south-eastern and central Europe. Trends over the past 60 years show an increasing frequency, duration and intensity of droughts in these regions, while a negative trend has been observed in north-eastern Europe. With a changing climate, this tendency is likely to be reinforced during the 21st century, affecting a wide range of socioeconomic sectors.

Introduction

The findings presented in this report result from the analysis of climatological data and climate projections made as part of the GAP-PESETA project. This project aimed to gain insights into the patterns of climate change impacts in Europe until the end of the 21st century. The report provides a detailed description of the characteristics of drought events (i.e. their frequency, duration, intensity, severity) across Europe, and their evolution over the period 1950 to 2012, as well as projections until the end of the 21st century. A pan-European database of meteorological drought events for the period 1950-2012 and of their related sectorial impacts has been built and a framework developed that links drought severity to expected damages under present and future climate.

Drought events and their characteristics

From 2006 to 2010, 15% of the EU territory and 17% of the EU population were affected by drought on an annual basis, which caused considerable damages and economic losses. The latter were estimated at over €100 billion (EC, 2007[1]). While in the past the Mediterranean area was a region of major concern in Europe, central and eastern Europe and the Carpathian region have also become drought hotspots over the past decades. Due to climate change and increasing pressures on water resources, drought impacts are likely to be more severe in the future, and will therefore require constant monitoring, assessment and adaptation.

Drought events were analysed at different spatial scales (e.g. country, region) using gridded climatological data and three different drought indicators: the Standardized Precipitation Index (SPI, which is based on precipitation only), the Standardized Precipitation-Evapotranspiration Index (SPEI) and the Reconnaissance Drought Indicator (RDI), the latter two of which depend on precipitation and potential evapotranspiration. Finally, all three indicators were merged into a composite indicator to derive key drought characteristics over the period analysed.

[1] European Commission, 2007. Water Scarcity and Droughts, Second Interim Report, June 2007, http://ec.europa.eu/environment/water/quantity/pdf/comm_droughts/2nd_int_report.pdf.

Based on the analysis of the composite indicator, a new database of meteorological drought events was constructed. This database also reports the twenty-one major droughts that hit Europe from 1950 to 2012, six of which occurred after 2000. Each meteorological drought event has been assigned a set of statistical parameters, including start, end, peak, duration, severity, intensity and area involved. Finally, a climatology of the most relevant drought events was developed for every European country and region from 1950 to 2012. Figure S1 shows key drought characteristics (frequency, duration and severity) for the periods 1951 to 1970, 1971 to 1990, and 1991 to 2010.

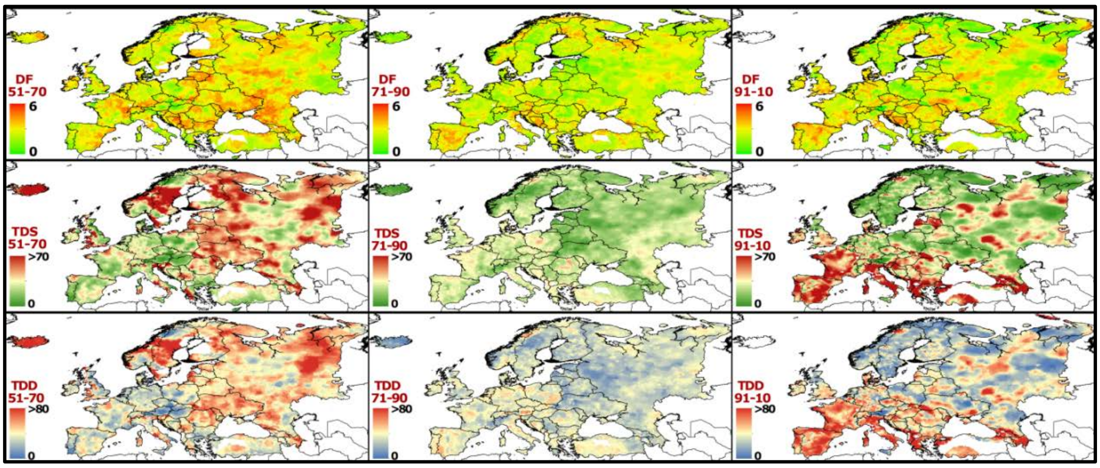

Figure S1 - European drought characteristics for the periods 1951-70 (left), 1971-90 (centre), and 1991-2010 (right): frequency (DF, number of events per decade), total drought severity (TDS, dimensionless score), and total drought duration (TDD, months under drought per decade).

While the 1950s and 1960s show drought hotspots in Scandinavia and Russia, the 1970s and 1980s show no outstanding spatial pattern, and the 1990s and 2000s are characterised by drought hotspots in the Mediterranean and the Carpathian Region. A linear trend analysis for the three key drought characteristics shows that, over the entire period 1951 to 2010, Europe can be split into two big areas: the North-East, which experienced decreasing trends, and the South-West, which experienced opposite increasing trends (Figure S2).

Drought frequency (DF, Figure S2 - top) is shown to have increased in the Iberian Peninsula, southern France, the British Isles, northern Germany, Austria, Hungary, the Czech Republic, Slovakia, the Urals, and Cyprus; a decrease can be seen in Iceland, Scandinavia, eastern Europe, and Russia. Regarding long events (≥ 6 months), a more prominent increase can be seen in the Iberian Peninsula and Italy, and a more prominent decrease in Ukraine.

Similar patterns are found for total drought severity (TDS, Figure S2 - middle) and total drought duration (TDD, Figure S2 - bottom): an increase in the Mediterranean region (in particular the Iberian Peninsula, southern France, and Albania), the Carpathian region (in particular Hungary and Slovakia), Ireland, along the Black Sea coast and the Caucasus; by contrast, they are shown to have decreased in Iceland, Scandinavia, Belarus, Ukraine, and Russia. Regarding long events, the only remarkable differences are a more prominent increase in drought duration in France and northern Italy, and a more pronounced decrease in Ukraine and Belarus.

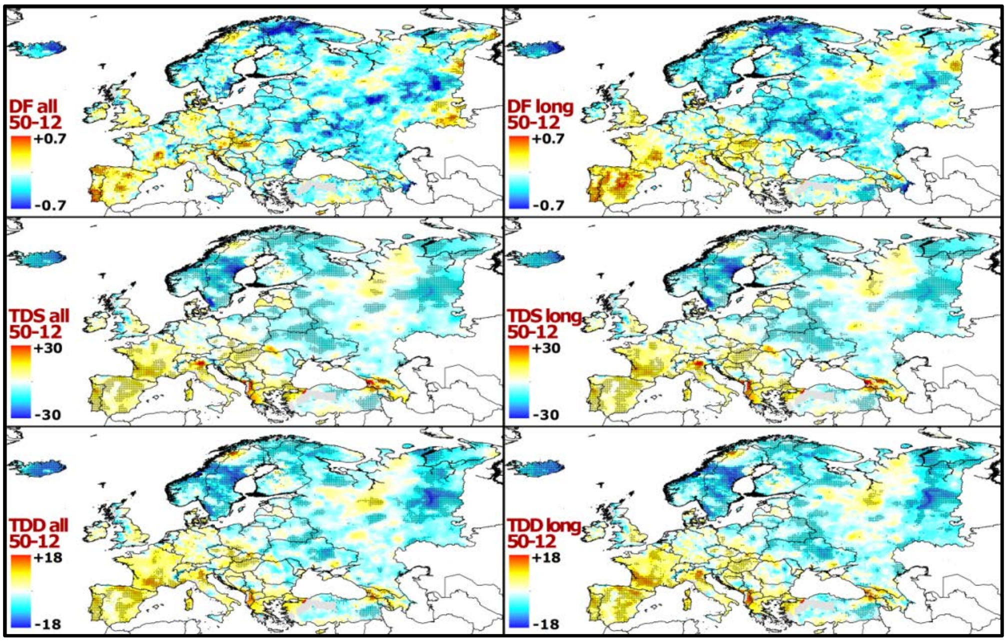

Figure S2. - European drought trends for the period 1951-2012: drought frequency (DF, number of events per decade, top), total drought severity (TDS, dimensionless score, middle), and total drought duration (TDD, months under drought per decade, bottom). The left column shows results for all events lasting at least two months, while the right column only shows results for long events, lasting six months and more.

Present and projected drought damages

Based on the drought event characteristics on the one hand, and impact data derived from various data sources on the other, the correlation between historical droughts (physical aspects) and their impacts (losses) was analysed and a set of damage functions for different economic sectors was developed and tested. For the time being, power-law-based damage functions for cereal production and hydropower production have been retained. These damage functions are univocal for each country and sector investigated.

Results show that it is feasible to use such functions to better understand the links between cereal and hydropower production and drought events. The validation statistics suggest building the damage functions from meteorological data accumulated over three months for cereal production and accumulated over 12 months for hydropower generation.

Results show that droughts do affect a given sector differently in different countries, depending on the country's intrinsic exposure and vulnerability, as well as on existing mitigation measures and the adaptive capacity of the society. The calibrated damage functions were used to project drought impacts until the end of the 21st century.

Climate projections of the Royal Netherlands Meteorological Institute (KNMI) regional climate model (RACMO 2) under the A1b climate scenario were then used to compute drought indicators over the period 1950-2100, followed by an analysis of drought trends for the near future (2041-2070) and the far future (2071-2100). Results show that, over the course of the 21st century, meteorological drought events will tend to become longer, more frequent, intense, and severe in southern Europe – especially in the Mediterranean region and the Balkans - mainly due to the key role of continuous warming. In northern Europe, meteorological drought events will tend to become shorter, less frequent, intense, and severe – especially in Scandinavia - mainly due to a projected increase in precipitation.

The projected tendency towards a drier future for southern Europe and a wetter future for northern Europe causes an opposite behaviour regarding possible drought impacts. Damage functions, calibrated over the past recorded events and applied over the entire range of the scenario outputs, show that cereal yield reductions due to drought are projected to increase in southern Europe and decrease in northern Europe (Figure S3, top) in terms of both frequency and absolute values. Similarly, reductions in hydropower production are projected to increase in southern Europe and decrease in northern Europe (Figure S3, bottom). However, the spatial gradient for hydropower is not as homogeneous as that for cereal production.

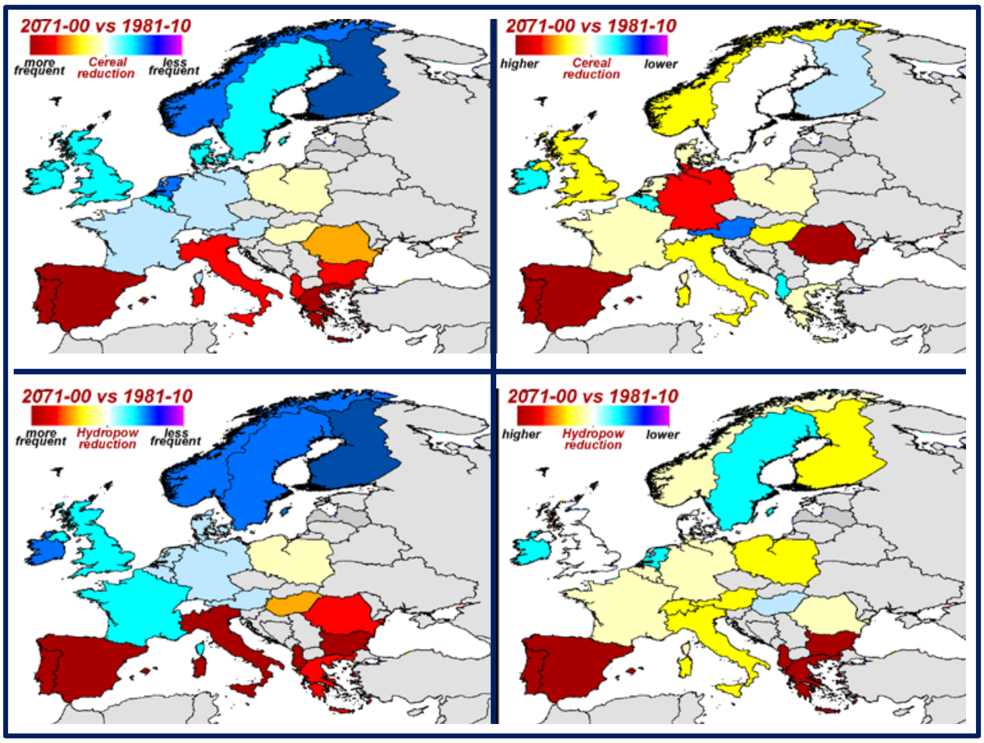

Figure S3 - Projected reduction in cereal (top) and hydropower (bottom) production, when comparing the far future (2071 to 2100) to the recent past (1981 to 2010). Left: change in frequency. Right: relative impact on absolute values.

The results of this study open the way for new studies on drought impacts in different sectors. Although further improvements of the presented methodologies are desirable, the most urgent need is for the collection of standardised and quality-controlled data on drought impacts at regional level.

Directions for future research

Future research to improve our understanding of the links between droughts and their impacts in different economic sectors should include efforts to improve and extend the database of past drought events and their impacts (based on additional climatological datasets, additional drought indicators, and standardised impact data), testing new damage functions for different sectors (including feedbacks between droughts and other human-induced disasters), refining the drought projections into the future with an ensemble of models and scenarios (e.g. CMIP 5 or later), analysing feedbacks with other climate extremes (e.g. floods, forest fires and heat waves), and developing a network of experts to discuss best practices and methodologies for analysing droughts and their impacts. The latter could possibly be achieved under the umbrella of the European Drought Observatory (EDO).

1. Introduction

The European Commission's PESETA II project focused on different climate–related hazards in Europe, with the aim of quantitatively modelling climate change impacts in the past and future (Ciscar et al., 2014). The project dealt with a variety of topics, including agriculture, energy production, river floods, low flows, forest fires, transport infrastructure, coasts, tourism, habitat suitability of forest tree species, and human health. However, some topics were studied in detail, e.g. the impacts on agriculture (Donatelli et al., 2012), whilst others, e.g. drought impacts, have only been partly investigated, considering only streamflow droughts (Forzieri et al., 2014). In order to analyse the impacts on wildfires, coasts, ecosystems and droughts in more detail, a pilot study, named GAP-PESETA, was launched by DG CLIMA and the JRC in early 2014.

Drought is a slowly developing phenomenon which affects large areas and populations, and propagates through the full hydrological cycle, with possible long-term economic and environmental impacts (Vogt et al., 2011). It is a natural phenomenon that occurs in all climates, and is one of the most relevant natural hazards that results in significant economic, social, and environmental costs (Vogt and Somma, 2000). Though prolonged droughts can foster land degradation in arid and semi-arid areas, with possible irreversible damage to ecosystems (Winslow et al., 2011), drought is a temporary condition as it is basically a temporary decrease in natural water availability.

Due to its complexity, there is no single definition of drought, and meteorological, agricultural, hydrological, groundwater, and socioeconomic droughts are often distinguished (Heim, 2002; Smathkin and Schipper, 2008; Mishra and Singh, 2010). However, a meteorological drought (i.e. a prolonged rainfall deficit) is the primary cause of a drought, while the other types of drought describe secondary effects on specific ecological and economic compartments (e.g. soil moisture, river flows, reservoirs, and economic sectors). In this study, we therefore focus on **meteorological drought**, which can be seen as a prolonged deficit in precipitation over a defined region and period of time as compared to average climatological values: the longer and the more spatially extensive the lack of precipitation, the more likely it is that different types of droughts will occur. Temperature (and therefore evapotranspiration) is also used in some of the indicators used in this study, since meteorological drought conditions can be aggravated by, for example, high temperatures, low relative humidity, or strong and persisting desiccating winds (Zampieri et al., 2009; Lei and Duan, 2011). Precipitation provides a direct measurement of water supply conditions over different time scales, and several commonly used drought indicators rely on precipitation measurements only or on simplified water balance models that include evapotranspiration (Heim 2002; Vicente-Serrano, 2010a). As this study deals with meteorological drought events, it is based on **meteorological drought indicators** such as the Standardized Precipitation Index (SPI, McKee et al., 1993), the Standardized Precipitation-Evapotranspiration Index (SPEI: Vicente-Serrano et al., 2010b), and the Reconnaissance Drought Indicator (RDI: Tsakiris and Vangelis, 2005). However, we also consider drought impacts on areas such as agriculture (Olesen and Bindi, 2002; Ciais et al., 2005), soil (Hirschi et al., 2011), ecology (McDaniels et al., 1997) and energy production (Hightower and Pierce, 2008).

In the recent scientific literature, one can find meteorological drought climatologies regarding Europe that are based on single indicators (van der Schrier et al., 2006), focused on some regions only (Vicente-Serrano et al., 2014) or out of date (e.g. Lloyd-Hughes and Saunders, 2002). Moreover, there are many papers that deal with single European drought case studies (see Bradford, 2000, for a collection) and websites that provide European drought bulletins, forecasts, or reports (e.g. the European Drought Observatory - EDO, http://edo.jrc.ec.europa.eu/; the Drought Management Centre for South-Eastern Europe - DMCSEE, http://www.dmcsee.org/; the European Drought Centre – EDC, http://www.geo.uio.no/edc/). However, there is still no unique database of European drought events over the past decades, based on a robust statistical methodology and on a multi-indicator approach. This report describes the construction of such a **database of meteorological drought events**. The events have been classified - per country and region - according to a set of parameters: duration, severity, intensity, peak and area involved. A list of the biggest drought events over two different accumulation periods (3 and 12 months) that occurred in Europe over the past six decades is also provided.

Besides the construction of the database, we investigated European drought frequency, duration, and severity patterns at high spatial resolution (0.25°x0.25°) for the entire period (1950-2012) and for three 20-year intervals (1951-1970, 1971-1990, and 1991-2010). In the past decades, drought occurrence has shown a slight increasing tendency at a global level (Dai, 2011a; Sheffield et al., 2012; Spinoni et al., 2014a; Trenberth et al., 2014). While Europe as a whole can be seen as a climate change hotspot (Giorgi, 2006; IPCC, 2014), increasing drought tendencies proved to be more evident in Mediterranean Europe (Briffa et al., 2009). However, in Europe, drought does not only affect semi-arid areas such as the Mediterranean region (Hoerling et al., 2012), but extended drought events have also repeatedly occurred in western and central Europe (Rebetez et al., 2006), the British Isles (Perry, 1976), Scandinavia (Hisdal et al., 2006), eastern Europe (Spinoni et al., 2013), and Russia (Arpe et al., 2012). In this report, we present maps and tables regarding **European meteorological drought hotspots and trends**, under the assumption that a complete picture of the areas that suffered frequent and severe droughts in the past could help scientists, politicians, and stakeholders to respond to future drought challenges (Wilhite, 1997; European Commission, 2007a). Moreover, this may push towards the development of better frameworks for drought assessment, adaptation, and mitigation in a possibly drier future (Sherwood and Fu, 2014).

In the absence or prolonged reduction of precipitation, a meteorological drought can develop quickly and sometimes abruptly. The consequences of repeated drought events include, for example, decreased agricultural production, forest fires, inadequate public water supplies, reduced energy production, permanent land degradation, and desertification (Ciais et al., 2005; Wilhite et al., 2007). Due to the complexity and slow development of droughts (Mishra and Singh, 2010), drought impacts are much more difficult to assess than impacts of other climate-related disasters. In fact, publications about flood impacts are frequently reported in the literature (e.g. Hajat et al., 2005; Dankers and Feyen, 2008; Barredo, 2009; Marchi et al., 2010), because floods cause obvious damages that can be relatively easily quantified. Similarly, wildfires develop abruptly and the resulting impacts are immediately evident (e.g. Moreira et al., 2011).

This is also true for earthquakes (Newmark, 1965; Rose et al., 1997), volcanic eruptions (Stothers, 1999; Trenberth and Dai, 2007), heat waves and cold waves (Huynen et al., 2001; Fouillet et al, 2006; Kovats and Kristie 2006).

On the other hand, **drought impacts** may take months or even years to develop (Vogt and Somma, 2000), and there is currently no comprehensive European or global dataset of drought impacts. Our new database of past European drought events can be used as the basis on which to study the impacts of past drought events and to project the potential impacts of future events, and it can be best exploited in conjunction with a separate drought impacts database. This report also describes the creation of a preliminary database of drought impacts in Europe over different sectors. This impacts database has been used to construct a set of country-based damage functions for correlating the severity of drought events and their possible impacts. We project drought frequency, severity, intensity, and duration for the whole of Europe (excluding Iceland) for the periods 2041-2070 and 2071-2100 under a moderate emissions scenario (A1b; IPCC, 2000, 2013, 2014) and using an ensemble of realisations derived from the KNMI-RACMO2 model (van Meijgaard et al., 2008). Furthermore, we show how the projected variables that define **future drought events** would affect the resulting drought impacts on two sectors: cereal yields and hydropower production.

This report ends with a list of possible **improvements** of the presented methodologies and results, and suggestions for further research. The analysis of past meteorological drought events, trends, and impacts can be improved by including indicators based on shorter accumulation periods (including the seasonality patterns) and longer accumulation periods (including multi-annual cycles). The database of drought impacts can be enlarged by setting a stratified methodology which allows for the collection of data from more sources and by involving as many data providers as possible, in order to increase the quantity and quality of the drought-impact entries. Considering that the impact database is far from complete, this study should be considered somewhat pioneering, and not conclusive. However, starting from the database of past drought events and impacts described in this report, and including different indicators and entries, the methodology can be refined and adapted based on damage functions, and applied to different sectors. As regards future projections and impacts, other scenario families can be investigated, together with new analyses based on the projection of drought impacts on other relevant economic sectors. Given the current global warming situation and a foreseen warmer and drier future (Sherwood and Fu, 2014), a better quantitative evaluation of drought impacts at the European scale can play an important role in the development of frameworks for drought assessment, adaptation, and mitigation (European Commission, 2007a).

2. Constructing composite meteorological drought indicators

2.1 Input data and variables

The main goal of this study was the creation of a dataset of meteorological drought events, based on the two most important meteorological variables as input data. The analyses are based on daily **precipitation** (P), **minimum temperature** (T_N), and **maximum temperature** (T_X) data from the E-OBS grids (version 10) of the European Climate Assessment and Dataset project (http://eca.knmi.nl/; Haylock et al., 2008) of the Royal Netherlands Meteorological Institute (KNMI). This dataset encompasses the whole of Europe with a spatial resolution of 0.25°x0.25° (see Figure 1). The period analysed is 1950-2012.

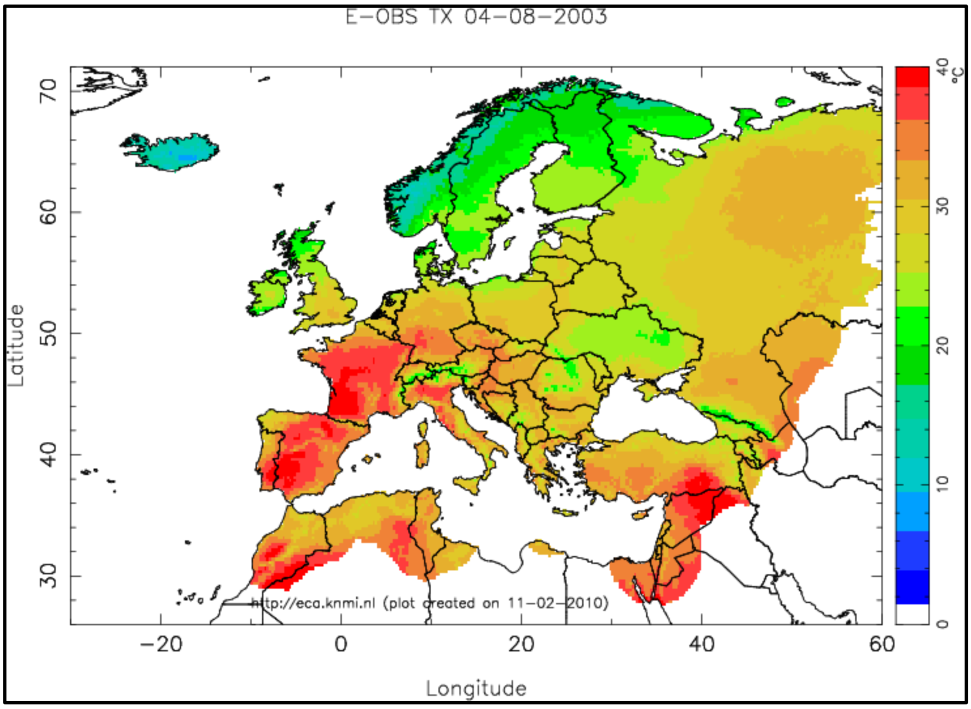

Figure 1 - Example E-OBS daily grid of a maximum temperature for 4th August 2003, showing the hottest European day since 1950. The original image is available at http://www.ecad.eu/images/TX_04082003_obs.png

After a first quality check, we computed **mean temperature** (T_M) as the arithmetic average of minimum and maximum temperatures. Daily temperature values of any given month were transformed into monthly averages if no more than three values were missing. **Precipitation** (P) was transformed from daily values into monthly sums if no more than one value was missing. The monthly series were subsequently quality-checked for a second time and tested for homogeneity with the latest version of the Multiple Analysis of Series for Homogenization software (MASHv3.02; Szentimrey, 1999). If a grid point failed the tests, a weighted combination of the surrounding grid points was used. A few points in Scotland, Italy, Albania, Macedonia, Greece, and Turkey had to be excluded from the analysis, because neither they nor the surrounding points passed the tests for certain intervals. They represent approximately the 1% of the total grid points.

Meteorological drought indicators are usually based on precipitation only or on precipitation and potential evapotranspiration (PET; Keyantash and Dracup, 2002). **Potential evapotranspiration** (PET) has been calculated from monthly T_M grids, using a new version (van der Schrier et al., 2011) of the Thornthwaite model (Thornthwaite, 1948). To avoid biases introduced by the computation methodology, tests for homogeneity were also performed for the monthly series of PET, and all of them passed the tests.

2.2 Meteorological drought indicators

Globally, two indicators were most frequently applied: the Palmer Drought Severity Index (**PDSI**: Palmer, 1965) and the Standardized Precipitation Index (**SPI**: McKee et al., 1993). We selected the SPI, for it requires only precipitation data as input, while the PDSI and its modified version, the self-calibrated PDSI (sc-PDSI: Wells et al., 2004), rely on many assumptions and variables that may complicate the analysis for extended regions like Europe. However, the SPI and the PDSI show similar results in Europe when the SPI is computed for 9- or 12-month accumulation periods (Lloyd-Hughes and Saunders, 2002).

Due to global warming (IPCC, 2014), we assume that it is important to consider at least one drought indicator that is directly or indirectly based on temperature inputs. We chose the Standardized Precipitation-Evapotranspiration Index (**SPEI**: Vicente-Serrano et al., 2010a) because it is frequently applied (Begueria et al., 2013) and based on the difference between P and PET. When computed for 6- to 12-month accumulation periods, it proved to be highly correlated with the sc-PDSI in Europe (Vicente-Serrano et al., 2010b).

In order to provide results based on a more robust methodology, we selected a third indicator, the Reconnaissance Drought Indicator (**RDI**: Tsakiris and Vangelis, 2005), that is based on the ratio between P and PET and is frequently applied in south-eastern Europe (Tsakiris et al., 2007). The three indicators have recently been applied simultaneously in China (Gao et al., 2012) and eastern Europe (Spinoni et al., 2013).

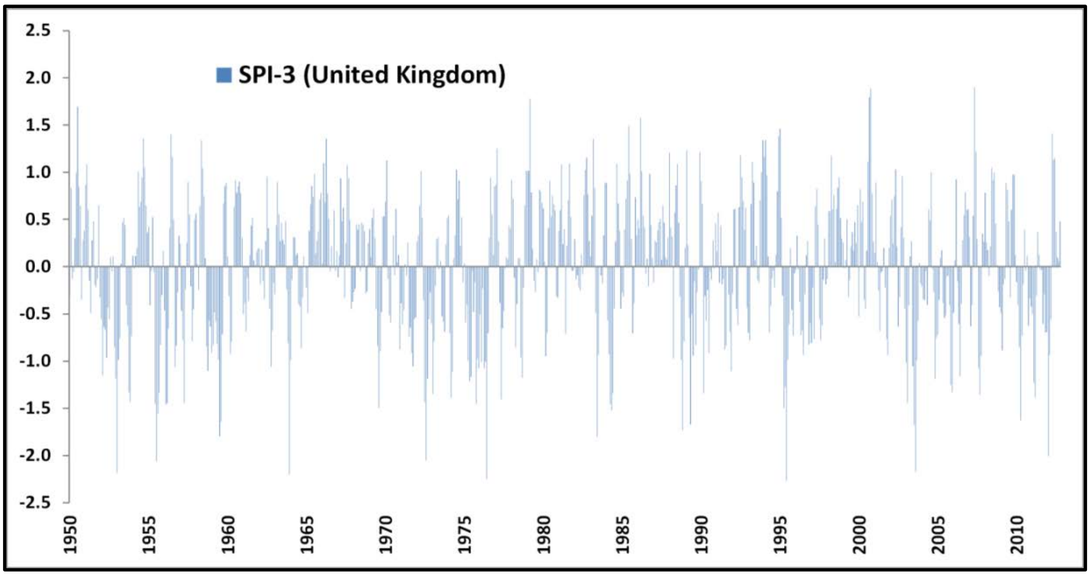

Figure 2 - Time series of the SPI-3 for the United Kingdom, averaged over the entire UK territories.

The mentioned indicators were computed for two different accumulation periods: **3-month** (related to ecosystem and agricultural impacts) and **12-month** (related to hydrological impacts) accumulation periods from 1950 to 2012 (see an example for the UK in Figure 2). The indicator calculations are based on different distributions providing for the best fit to the data in order to ensure that the results are not biased by the choice of a statistical distribution. We fitted the cumulated precipitation by the Gamma distribution (Thom, 1958) for the SPI, the cumulated difference P-PET by the log-logistic distribution (Shoukri et al., 1988) for the SPEI, and the cumulated ratio P/PET by the log-normal distribution (Heyde, 1963) for the RDI, following the approaches of the authors who originally presented these indicators, from which we also obtained the drought classes (Figure 3). All the available data in the period 1950-2012 have been used to fit the distributions.

SPI value	Class	CDF	Probab (%)
SPI > 2.0	Extreme Wet	0.977–1.000	2.3
1.5 < SPI ≤ 2.0	Severe Wet	0.933 – 0.977	4.4
1.0 ≤ SPI ≤ 1.5	Moderate Wet	0.841 – 0.933	9.2
-1.0 < SPI < 1.0	Normal Climate	0.159 – 0.841	68.2
-1.0 ≤ SPI ≤ -1.5	Moderate Dry	0.067 – 0.159	9.2
-2.0 ≤ SPI < -1.5	Severe Dry	0.023 – 0.067	4.4
SPI < -2.0	Extreme Dry	0.000 – 0.023	2.3

Figure 3 - Classification used for the SPI. This also applies to the SPEI and the RDI.

2.3 Composite drought indicators

Due to its intrinsic formalism, the SPI cannot always be computed for very dry regions that experience consecutive months without rainfall, while the SPEI may produce misleading results in hot and dry regions, and the RDI may result in unrealistically high values in very cold regions, where PET is close to zero in winter. Thus, it was decided to compute two special indicators based on the combined use of the three indicators mentioned above.

To construct the database of past drought events, we therefore calculated a fourth **composite indicator** (**X**) that is the arithmetic average of SPI, SPEI, and RDI. We distinguish X-3 (from SPI-3, SPEI-3, and RDI-3) from X-12 (from SPI-12, SPEI-12, and RDI-12). If only two indicators are available, the average is obtained from these two only; if only one indicator is available for a certain month, only this indicator is used. Every time an indicator showed unrealistic values (below -3.5 or above 3.5), it was discarded. The X-3 and the X-12 indicators were then used to compute monthly time series at each grid point, country, and regional level. A similar, but more simplified, approach can be found in Ziese et al. (2014).

For the drought climatologies and trends we opted for a different approach and defined a **fifth indicator** (**Z**), which focuses on drought conditions and is structured to favour the predominance of drought conditions (i.e. when more than one indicator, i.e. SPI, SPEI and/or RDI, shows values below -1) over the other possible classes. For any given month and grid point, Z-3 and Z-12 were calculated. Let us consider Z-12, keeping in mind that this methodology also applies to Z-3. **Z-12** is not a simple average: if two or more indicators (2+ in Table 1) suggest drought conditions, then the combined indicator also suggests drought conditions; conversely, if two or more indicators do not suggest drought, then the combined indicator also suggests that there is no drought. If only two indicators are available (<1.5% of cases), the **Z-12** results from the average. If only one indicator is available (<0.4% of the cases), that indicator becomes **Z-12**. We computed a monthly series of **Z-12** for the period 1950-2012 and for every grid point in Europe.

The assignment of drought conditions based on the combination of the individual indicators is detailed in Table 1.

Table 1 - Computational methodology for the composite indicator Z

Available Indicators	Values of the Indicators (SPI-12 ; SPEI-12 ; RDI-12)	New Z-12	Drought Conditions
3	2+ indicators ∈ [0,+∞)	1	wet/normal
	2+ indicators ∈ (-∞,0) // 2+ indicators ∈ (-1,0)	0	normal/dry
	// 2+ indicators ∈ (-2,-1]	-1	drought
	// 2+ indicators ∈ (-∞,-2]	-2	severe drought
	3 indicators ∈ (-∞,0) in different classes // average of 3 indicators ∈ (-1,0)	0	normal/dry
	// average of 3 indicators ∈ (-2,-1]	-1	drought
	// average of 3 indicators ∈ (-∞,-2]	-2	severe drought
2	2 indicators ∈ [0,+∞)	1	wet/normal
	2 indicators opposite in sign	0	normal/dry
	2 indicators ∈ (-∞,0) // 2 indicators ∈ (-1,0)	0	normal/dry
	// 2 indicators ∈ (-2,-1]	-1	drought
	// 2 indicators ∈ (-∞,-2]	-2	severe drought
	2 indicators ∈ (-∞,0) in different classes // average of 2 indicators ∈ (-1,0)	0	normal/dry
	// average of 2 indicators ∈ (-2,-1]	-1	drought
	// average of 2 indicators ∈ (-∞,-2]	-2	severe drought
1	indicator ∈ [0,+∞)	1	wet/normal
	indicator ∈ (-1,0)	0	normal/dry
	indicator ∈ (-2,-1]	-1	drought
	indicator ∈ (-∞,-2]	-2	severe drought
0	no indicator available	-999	no data

3. Database of past European meteorological drought events

3.1 How to define a drought event

According to McKee et al. (1993), a drought event starts when the SPI falls below -1 (which corresponds to one standard deviation from the mean) and ends when it turns positive (>0). We adapted this definition to our combined indicator **X**, by assuming that a **drought event** starts when the **X** falls below a certain threshold (X_{th}) for at least two consecutive months and ends when the mean value of the series ($\overline{X}$) turns positive. We separately analysed the two different accumulation periods (3 and 12 months), which resulted in two separate databases.

On a grid-point basis, the X_{th} can be approximated to -1 as this threshold holds for each of the single indicators. On the other hand, over a country or region the spatially averaged series of the combined indicator (X) is no longer standardised, so the threshold is no longer -1, but depends on the size of the country (region) under examination. The values of the averaged series for the country (region) must be fitted to a normal distribution (e.g. Lukacs, 1942) and a mean and standard deviation must be calculated for each **country (regional) series**. The negative value of one standard deviation (X_{th}=-1σ) is different for every country (region) and corresponds to the threshold that determines the beginning of the drought event, and the corresponding mean of the series determines the ending of the drought event. An example is given in Figure 4.

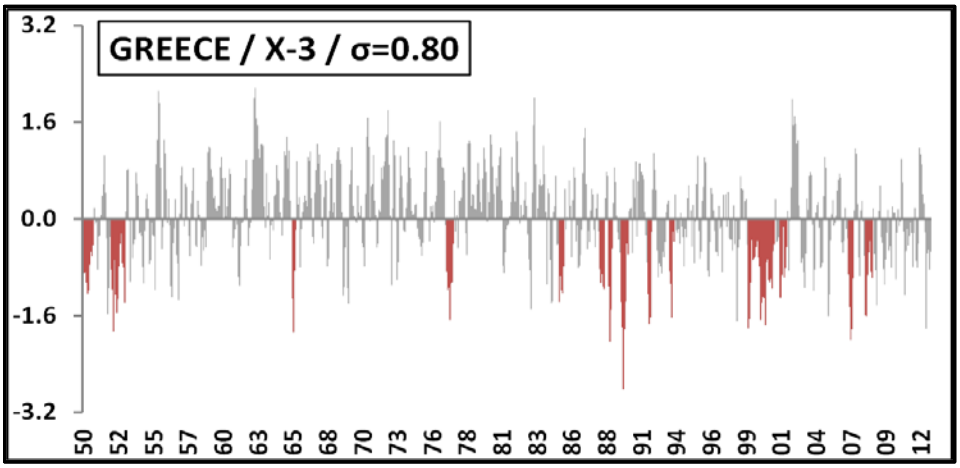

Figure 4 - The composite indicator X-3 computed for Greece. In this case, the specific threshold is -0.8.

3.2 Assigning a set of parameters to each drought event

Whenever a **meteorological drought event** is detected, it is assigned a set of **statistical parameters** and, for selected case studies, a few descriptive maps:

Start..............: first month for which the indicator is below the threshold;

End................: last month for which the indicator is below the mean;

Duration........: number of months of the event;

Severity.........: a severity score is computed as the sum of the differences, in absolute values, between the indicator values and the threshold (if the value is above the threshold but below the mean it is not counted);

Intensity ....: severity divided by duration;

Peak month...: month with the lowest value of the indicator during the drought event; this parameter is presented together with the severity value corresponding to that month;

Area involved : percentage of the region (or country) with values below -1 computed over the grid points. At grid-point level the value -1 is always set as the unique threshold.

Area involved in peak month: as the name suggests, this does not refer to the widest area affected, but to the affected area during the month with the lowest value of the indicator.

See Table 2 and Figure 5 for the example of the Iberian drought in 2005.

Table 2 - Statistical parameters for the Iberian drought in 2005.

Drought Event: Iberian Peninsula - 2005	
Indicator	X-3
Start // End	01/2005 // 09/2005
Duration	9 months
Severity	4.41
Intensity	0.49
Peak month	06/2005 (X-3 = -1.53)
Average area involved	66.4% (Spain 62.0%; Portugal 92.1%)
Area involved at peak month	79.6% (Spain 76.0%; Portugal 100.0%)

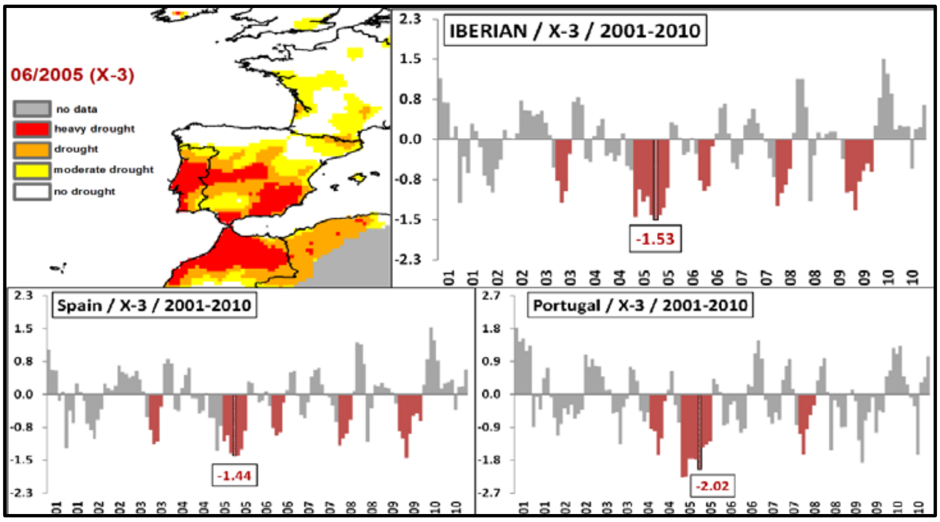

Figure 5 – Maps for a case study: the Iberian Peninsula drought in 2005. Indicated values correspond to June.

For the calculation of drought climatologies and trends, a supplementary list of **drought-related variables** was computed (see Yevjevich et al., 1967, and Spinoni et al., 2015b, for details):

Drought Frequency (DF): number of drought events during a certain interval. Usually, it is expressed in number of events *per decade* (10 years);

Total Drought Severity (TDS): sum of the severity of the drought events that occurred in a certain period. Though we often computed TDS over 20-year periods, the results are presented *per decade*;

Total Drought Duration (TDD): total number of months under drought during a certain period of time. This is usually expressed in number of months *per decade*.

3.3 Regional and country characteristics of drought events

Defining a drought event on the basis of spatial and temporal extent is not straightforward or univocal, for it may depend on the intensity, the area affected, the peak severity, the chosen thresholds, etc. To construct a European database of past drought events, we focused on two spatial scales: countries and regions. Monthly series of X-3 and X-12 for the period 1950-2012 were calculated for every grid point, and corresponding series for every European country were obtained by averaging the grid values within the national borders. Finally, in order to derive regional series, **Europe was divided into thirteen macro-regions** (Table 3) according to political borders, geographical features, and climatic patterns. These regions are more detailed than the regions used for the economic analysis carried out in the PESETA II study. While the PESETA II regions were defined on a purely economic basis, in this case the main factor is the homogeneity on a climatological basis. However, with a few exceptions of individual countries, the current macro-regions are sub-divisions of the economic regions identified in PESETA II. The correspondence is provided in the last column of Table 3. It should also be noted that the current study includes territories that were not considered in PESETA II (i.e. the Balkan countries, the European part of Russia and ex-USSR territories, as well as Iceland, Greenland and the Svalbard Islands).

Since impact data are generally provided per **country**, meteorological droughts were investigated at country level. On the other hand, we investigated the events at **regional level** to determine the biggest droughts that occurred in each part of Europe in the past six decades. Finally, we compiled a list of the overall most relevant European droughts that occurred in 1950-2012, by considering the events that involved more than one region (multi-regional events).

Table 3 – Thirteen macro-regions as defined for this study

Region	Code	Countries	PESETA II Regions
AEGEAN SEA	AEG	Cyprus, Greece, Turkey	Southern Europe
BALKANS	BLK	Albania, Bosnia and Herzegovina, Croatia, Montenegro, Rep. of Macedonia, Serbia, Slovenia	-- [+Slovenia]
BALTIC REPUBLICS	BLC	Estonia, Latvia, Lithuania	Northern Europe
BRITISH ISLANDS	BRIT	Faroe Islands, Great Britain, Ireland	UK & Ireland
CENTRAL EUROPE	CEN	Austria, Germany, Liechtenstein, Switzerland	Central Europe North
EASTERN EUROPE	EAST	Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovak Republic	Central Europe South [-Slovenia]
EUROPEAN RUSSIA	RUS	European Russia	--
EX-USSR	ex-USR	Belarus, Moldova, Ukraine	--
FENNOSCANDIA	FEN	Denmark, Finland, Norway, Sweden	Northern Europe
FRANCE-BENELUX	FBLX	Belgium, France, Luxembourg, Monaco, The Netherlands	Central Europe North [-Poland +France]
IBERIAN PENINSULA	IBE	Andorra, Portugal, Spain	Southern Europe
ICELANDS	ICE	Greenland, Iceland, Svalbard Islands	--
ITALY	ITA	Holy See, Italy, Malta, San Marino	Southern Europe

To trigger drought mitigation actions, different indicators and thresholds must be implemented. Since a drought onset is identified when the composite indicator falls below a given threshold for two or more consecutive months, a slight difference in the estimation of the threshold may lead to erroneous estimates of the drought onset and duration (Steinemann and Calvancanti, 2006; Carrao et al., 2014). This key issue is accounted for in this report by using adapted thresholds that are computed following the aggregation procedure for the country-averaged time series. Commonly and as described in previous sections, a drought event "starts" when the composite indicator falls below -1 for two or more consecutive months. However, this threshold is valid for single-grid-point series only. Due to the aggregation of several grid points, it needs to be recomputed by adjusting the threshold to the 15.87 percentile, which corresponds to one standard deviation for a normal distribution (Lukacs, 1942).

The importance of threshold definition is presented in Figures 6 and 7 where the differences between choosing a fixed threshold of -1 (Figure 6) or a threshold that reflects the distribution of the values for the averaged series (Figure 7) are shown. For the case of Central Europe, the new threshold detects eight meteorological drought events instead of the six that would result from a standard threshold of -1.

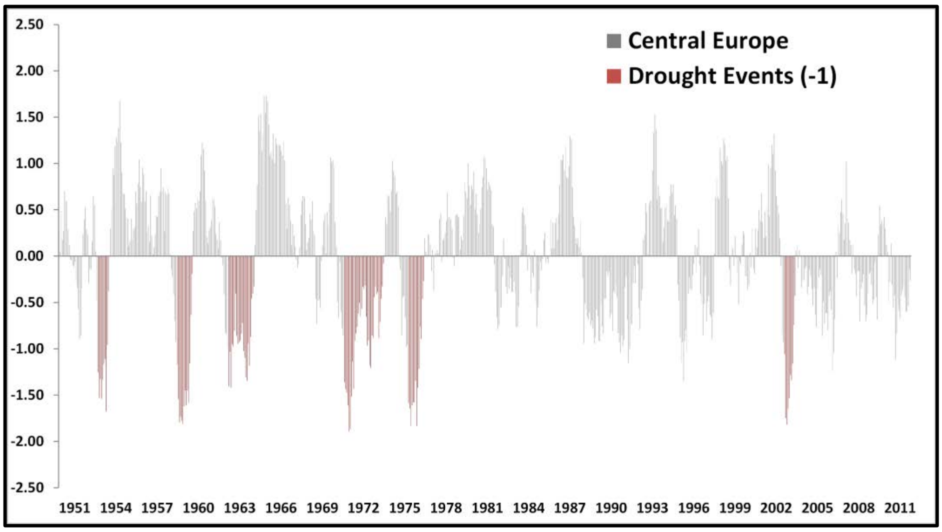

Figure 6 - Average monthly series of X-12 for Central Europe. Drought events in red (threshold is -1).

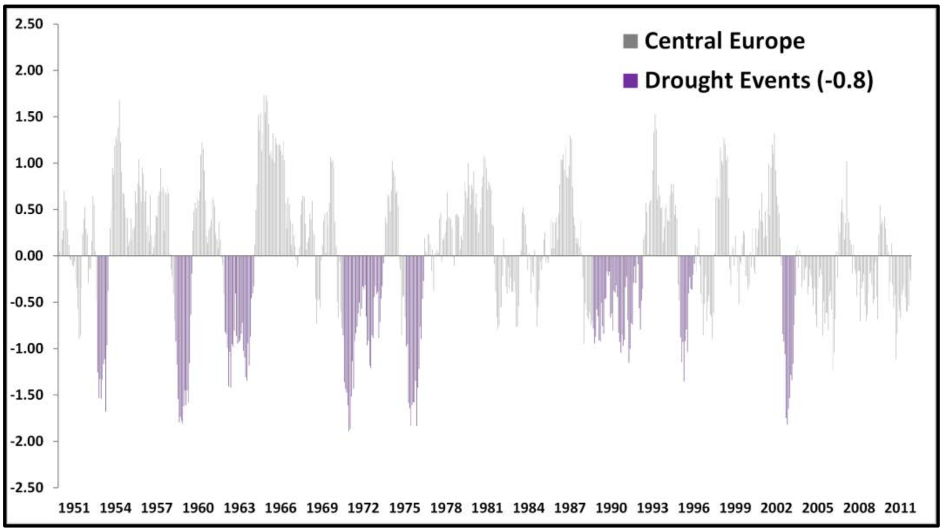

Figure 7 - Average monthly series of X-12 for Central Europe. Drought events in purple (threshold is -0.8).

For every country and region, a time series of X-3 and X-12 is available. In Figures 8 and 9 we show the regional series only.

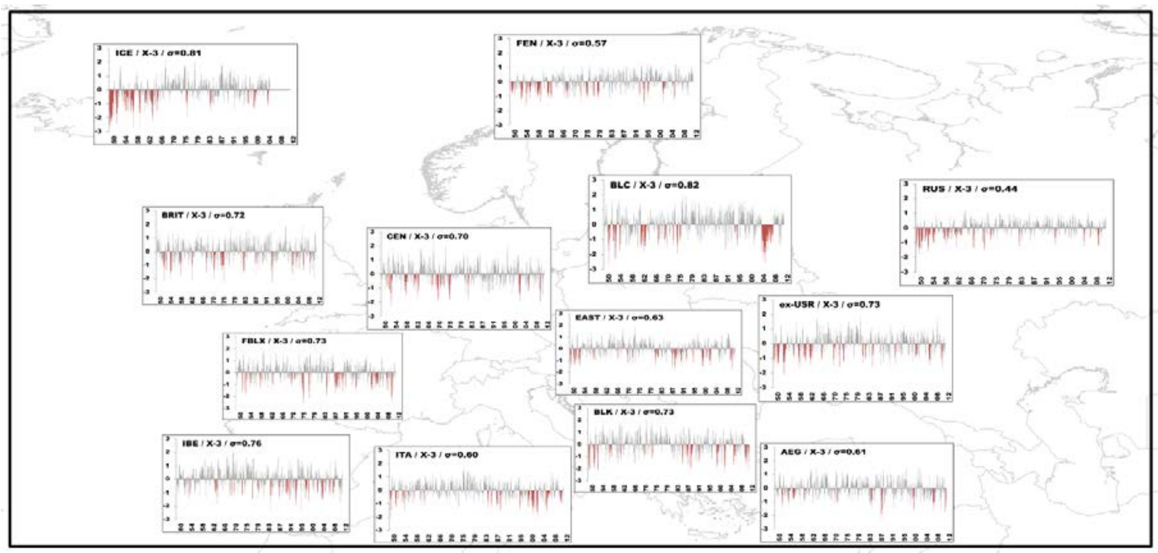

Figure 8 - Time series based on the composite indicator X-3. The drought events are shown in red.

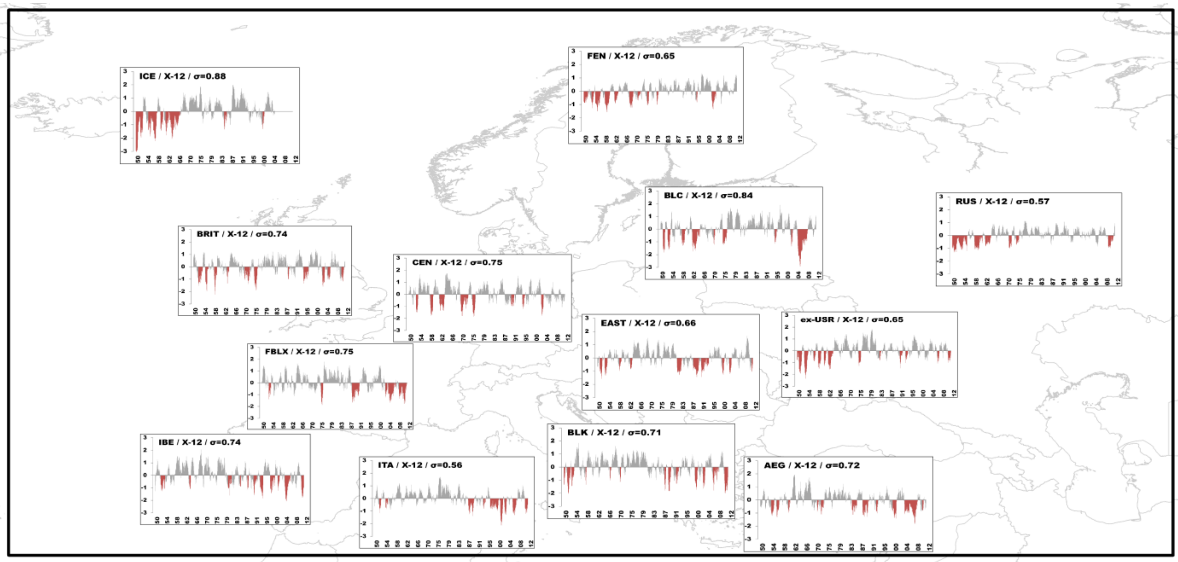

Figure 9 - Time series based on the composite indicator X-12. The drought events are shown in red.

According to Figures 8 and 9, Europe can be split into two big areas: the north-eastern regions that have been hit by more drought events in the 1950s, the 1960s, and the 1970s, and the south-western regions, which are characterised by more drought events in the 1980s, the 1990s, and the 2000s. For every region, the number, average duration and severity of the drought events for three 20-year periods (1951-70, 1971-90, and 1991-2010) have been computed (see Tables 4 and 5).

Table 4 - Regional drought characteristics (X-3). The highest values are in bold.

	Events			Average Duration (months)			Average Severity (score)		
X-3	51-70	71-90	91-10	51-70	71-90	91-10	51-70	71-90	91-10
AEG	**4**	3	2	**6.0**	5.7	**6.0**	1.2	3.0	**3.1**
IBE	4	6	**10**	4.0	4.2	**6.8**	1.3	1.4	**1.6**
ITA	5	4	**6**	4.0	4.8	**9.2**	1.1	1.9	**3.1**
BLK	4	**5**	4	5.8	7.0	**8.5**	2.5	1.9	**3.1**
EAST	5	**6**	5	4.6	**5.7**	5.4	1.4	1.4	**1.7**
RUS	**10**	3	4	**8.0**	3.7	5.0	**2.2**	1.8	1.5
FBLX	**6**	**6**	**6**	4.0	**6.5**	6.3	1.4	2.9	**1.8**
ex-USR	**8**	6	3	**7.5**	4.8	7.3	**1.9**	1.1	1.3
CEN	**8**	5	2	6.3	6.4	**7.5**	1.6	2.4	**2.7**
BRIT	**6**	4	5	4.5	**8.3**	4.2	2.1	**3.0**	1.8
FEN	**8**	4	5	**7.5**	5.3	4.8	**1.7**	1.5	1.4
BLC	**7**	4	2	7.3	4.5	**25.5**	2.7	1.1	**8.7**
ICE	**9**	2	3*	**10.2**	5.0	6.7	**5.1**	1.3	0.8

*Iceland: no valid data after 2005.

Table 5 - Regional drought characteristics (X-12). The highest values are in bold.

	Events			Average Duration (months)			Average Severity (score)		
X-12	51-70	71-90	91-10	51-70	71-90	91-10	51-70	71-90	91-10
AEG	3	**4**	3	10.7	18.3	**27.7**	1.7	1.8	**5.3**
IBE	2	3	**5**	14.5	9.7	**18.6**	2.5	1.3	**5.5**
ITA	2	1	**4**	11.0	**30.0**	26.3	1.3	5.7	**6.9**
BLK	**5**	3	4	9.0	8.3	**16.3**	2.7	3.6	**4.2**
EAST	**4**	2	3	11.8	**26.0**	19.7	2.4	**6.8**	3.2
RUS	**3**	2	1	**44.0**	12.5	24.0	**8.6**	1.7	3.5
FBLX	1	2	**3**	13.0	26.0	**33.0**	2.6	**7.8**	7.0
ex-USR	**6**	2	3	**17.2**	10.5	11.3	**7.2**	1.8	1.2
CEN	**3**	2	**3**	16.7	**25.0**	13.7	6.0	**8.0**	2.6
BRIT	**4**	3	3	15.8	**17.0**	16.3	**4.2**	4.1	3.3
FEN	**6**	3	2	**21.3**	12.0	12.5	**4.2**	0.9	1.8
BLC	**4**	2	3	20.3	13.5	**21.3**	5.9	1.6	**10.0**
ICE	**4**	1	1*	**39.8**	13	8.0	**15.4**	1.0	0.7

*Iceland: no valid data after 2005.

Both the short-term (X-3) and the long-term meteorological drought events (X-12) show the highest frequency in the period 1951-1970 in most regions. However, the highest frequency in the south-western regions was found in the period 1991-2010. In general, the drought events were longest and most severe in north-eastern Europe during the period 1951-1970, in Central European regions during the period 1971-1990, and in southern Europe during the period 1991-2010. The exact reasons for these temporal and spatial patterns are still unknown, and a detailed analysis of the physical and dynamic atmospheric processes behind them are beyond the scope of this study. However, besides the general climate variability, possible reasons are related to changes in the **atmospheric circulation patterns** as expressed in the North Atlantic Oscillation (NAO), or the Northern Annular Mode (NAM). Also, possible feedback mechanisms between the land surface and the atmosphere need to be better understood. All of these aspects are currently under scientific discussion and will be in the focus of scientific research in the coming years.

3.4 Biggest drought events from 1950 to 2012

We analysed the X-3 and the X-12 separately to evaluate meteorological drought events that may have impacts on agriculture (usually from 3- to 6-month accumulation periods) and on the hydrological cycle (usually from 9- to 24-month periods; WMO, 2012). We then compiled two separate **lists of meteorological drought events** for each region and assigned to every event the parameters shown in Table 2 and described in Section 3.2. In Tables 6 and 7 we show - for each region - the longest, the most intense, and the most extensive event in terms of area affected.

Table 6 - Most relevant meteorological drought events per region according to the composite indicator X-3

X-3	Longest	months	Most Severe	score	Widestarea	
AEG	1989	9	1989	5.5	Apr-89	97.7%
IBE	1991-92	12	2005	4.4	May-95	93.3%
ITA	2006-08	16	2001-02	6.0	Jul-03	94.0%
BLK	2000-01	12	1952	5.4	Feb-90	99.0%
EAST	1990	10	2000-01	2.9	Mar-89	92.8%
RUS	1955-56	12	1950-51	5.1	Feb-51	81.8%
FBLX	1989-90	16	1976	5.7	Nov-78	95.4%
ex-USR	1953-54	17	1953-54	5.0	Dec-53	93.0%
CEN	2003	11	2003	4.3	Dec-53	98.6%
BRIT	1975-76	16	1975-76	5.0	Aug-95	99.4%
FEN	1959-60	14	1959-60	2.9	May-60	82.0%
BLC	2005-08	47	2005-08	16.5	Jul-06	100.0%
ICE	1950-51	19	1950-51	17.6	Apr-50	100.0%

Table 7 - Most relevant meteorological drought events per region according to the composite indicator X-12

X-12	Longest	Months	Most Severe	Score	Widest Area	
AEG	2005-09	58	2005-09	10.4	Oct-01	80.2%
IBE	2005-07	24	2005-07	11.8	Aug-05	97.0%
ITA	1997-02	63	1997-02	16.3	Apr-02	91.4%
BLK	2007-09	26	2011-12	12.5	Mar-89	93.4%
EAST	1992-95	36	1989-91	7.0	Aug-52	84.5%
RUS	1950-56	69	1950-56	16.7	Jun-56	69.8%
FBLX	2009-12	41	1989-92	10	Jun-76	87.0%
ex-USR	1963-65	24	1953-55	14.1	Jun-64	95.8%
CEN	1971-74	37	1959-60	8.7	Aug-76	93.8%
BRIT	1971-74	28	1975-76	8.0	Sep-59	96.0%
FEN	1955-57	27	1959-61	8.6	May-60	76.4%
BLC	2005-09	48	2005-09	28	Aug-06	99.0%
ICE	1962-68	69	1962-68	29.1	Mar-51	100.0%

Based on all the events at regional scale, the events involving more than one region have been grouped together in a separate list. This list has been compiled in parallel with a detailed **bibliographical search** and, if possible, for each reported drought event a few related scientific publications have been reported (see Table 8, last column). Figure 10 shows a summary, per region, of the periods that experienced the most relevant drought events from 1950 to 2012.

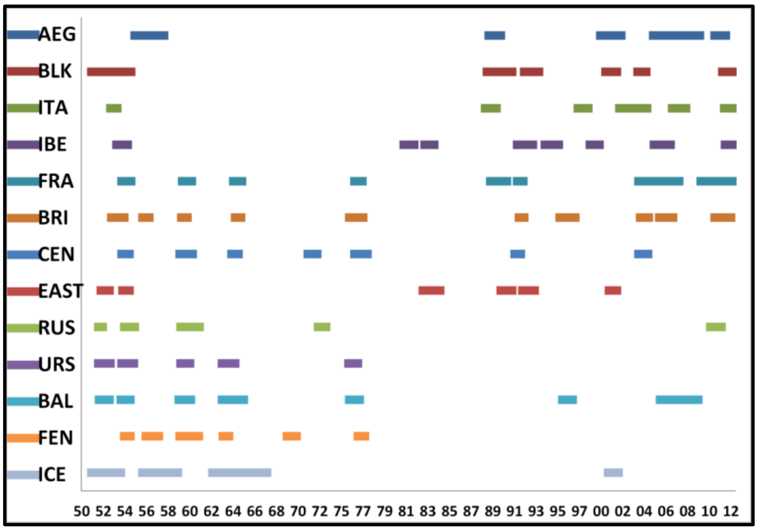

Figure 10 - Summary of the most relevant drought events, per country and region, from 1950 to 2012

Table 8 - List of the 21 most relevant inter-regional drought events that occurred in Europe in 1950-2012.

Indicator	Period	Drought Macro-Area	Mentioned (directly/indirectly) by
X-3 ; X-12	1950-52	Pan-European	Briffa et al., 1994 Lloyd-Hughes and Saunders, 2002 Cherenkova, 2007 Sheffield et al., 2009
X-3 ; X-12	1953-54	Pan-European	Sheffield et al., 2009
X-3 ; X-12	1955-56	Northern Europe	Veryard, 1956 Meshcherskaya and Blazevich, 1997 Santos et al., 2000
X-3 ; X-12	1959-60	North-Central-Eastern Europe	Meshcherskaya and Blazevich, 1997 Golubev and Dronin, 2004 Zampieri et al., 2009 Sheffield et al., 2009 Seftigen et al., 2013
X-3 ; X-12	1964	North-Central-Eastern Europe	Hisdal et al., 2001 Zaidman et al., 2001 Hannaford et al., 2011 Parry et al., 2012
X-3	1969	UK-Scandinavia	Hannaford et al., 2011
X-3 ; X-12	1972-74	pan-European	Buchinsky, 1976 Dronin and Bellinger, 2005 Briffa et al., 2009 Stagge et al., 2013
X-3 ; X-12	1976	Central Europe and British Isles	Perry, 1976 Shaw, 1979 Doornkamp et al., 1980 Morren Jr., 1980 Parry et al., 2012 Stagge et al., 2013
X-3	1983	Eastern Europe	-
X-3	1985	Southern Europe	-
X-3 ; X-12	1989-91	Southern Europe, Mediterranean	Tselepidaki et al., 1992 Briffa et al., 1994 Zaidman et al., 2001 Tsakiris and Vangelis, 2005

Table 8 continued

Indicator	Period	Drought Macro-Area	Mentioned (directly/indirectly) by
X-12	1992	Central Europe	Szinell et al., 1998 Spinoni et al., 2013
X-3	1994	North-Eastern Europe	-
X-12	1995	Southern Europe	Pal et al., 2004 Stagge et al., 2013
X-12	1996-97	Central and Northern Europe	Fleig et al., 2011 Parry et al., 2012 Stagge et al., 2013
X-3 ; X-12	1999-2001	Southern / Eastern EU	Spinoni et al., 2013 Stagge et al., 2013
X-3 ; X-12	2003	European heat wave	Fink et al., 2004 Ciais et al., 2005 Rebetez et al., 2006
X-3 ; X-12	2004-05	Iberian Peninsula	Garcia-Herrera et al., 2007 Santos et al., 2007 Ruiz-Sinoga and Martinez-Murillo, 2009 Santos et al., 2010 Stagge et al., 2013
X-3 ; X-12	2005-07	Baltic Republics	Tammets, 2007 Briede and Lizuma, 2010
X-3 ; X-12	2007-08	Aegean countries	August and Geiger, 2008 Michaelides and Pashiaridis, 2008 Simsek and Cakmak, 2010 Dimitrakopoulos et al., 2011
X-3 ; X-12	2011	France, England, Central Europe	Kendon et al., 2013 Todd et al., 2013 Sepulcre-Canto et al., 2014

4. European drought climatologies and trends

4.1 Drought hotspots in 1951-1970, 1971-1990, and 1991-2010

In order to identify **drought hotspots**, drought frequency (DF), total drought severity (TDS), and total drought duration (TDD) were computed for the whole of Europe and for three 20-year periods (Figure 11). All meteorological drought events lasting at least two months were considered, focusing on the long-term accumulation period (indicator **Z-12**).

In Figure 11, the drought frequency is expressed in number of events *per decade*, the total drought severity represents the sum *per decade* of the severity score of every event occurring in that period, and the total drought duration is given as number of months *per decade*. The maps refer to three different periods: 1951-70, 1991-90, and 1991-2010.

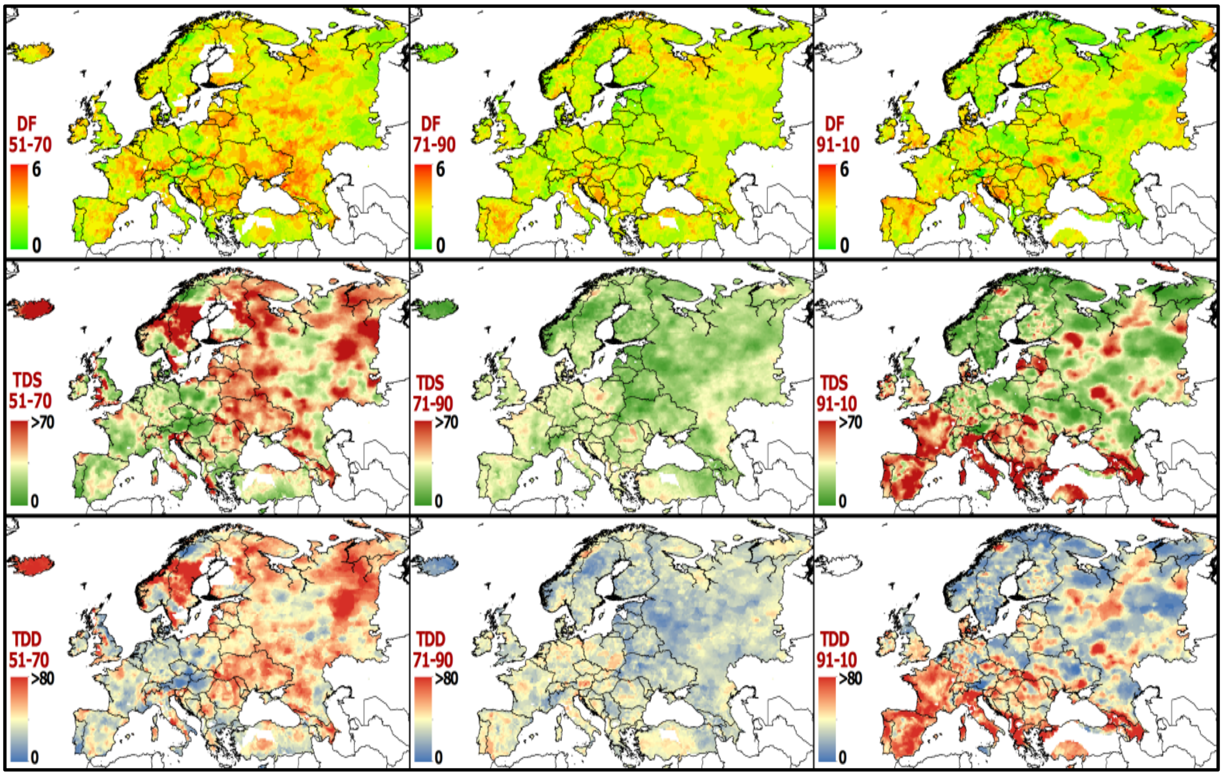

Figure 11 - European drought frequency (DF), total drought severity (TDS), and total drought duration (TDD) maps for 1951-70, 19971-90, and 1991-2010.

In the **period 1951-70**, the values for drought severity and duration were highest in Iceland, Scandinavia, the Baltic Republics, Belarus, Moldova, Ukraine, Western Russia, and the Urals. Frequent, but not severe, meteorological drought events occurred in eastern France and the Balkans. In the **period 1971-90**, no particular drought hotspot can be noticed. This does not mean that no events took place in Europe, but that the 1970s and the 1980s experienced fewer, shorter, and less severe drought events than the other decades. Frequent events, but which were neither intense nor long, occurred in

Central Spain and former Yugoslavia. In the **period 1991-2010**, values of drought severity and duration were highest in Latvia, the Caucasus, and southern Europe, in particular in the Mediterranean area (excluding Sicily). Frequent events occurred also in southern England, the Carpathians, and the Balkans. Iceland is excluded from the analysis regarding this period, because of the lack of valid precipitation data after 2005.

Comparing the results shown in Figure 11 to those presented in Spinoni et al. (2014a), which are based on a different dataset with lower resolution, and precipitation (SPI-12) only, no remarkable difference regarding the hotspots in the periods 1951-1970 and 1971-1990 can be seen compared to this study, except for a higher drought frequency in Scandinavia. The new results highlight more prominent drought conditions in southern Europe in the period 1991-2010. This is probably due to the **temperature rise** that particularly affected southern Europe in the past two decades (IPCC, 2014; Vicente-Serrano et al., 2014). As such an effect cannot be detected using drought indicators based on precipitation only, we recommend including at least one indicator based on temperature (or PET) in the analysis of meteorological droughts.

4.2 Drought trends for the period 1950-2012

To compute the **trends in drought variables** on grid point spatial scale, an approach similar to what has been discussed in Spinoni et al. (2014a) was adopted. Trends for drought frequency (DF), severity (TDS), and duration (TDD) for the period 1951-2012 were computed by splitting the entire period into nine intervals of seven years, computing DF, TDS, and TDD for the single periods, and then performing a linear trend analysis. The trends have been tested for significance with a Student's T-test (Wilks, 2011). In Figure 12, the dotted areas represent grid-points in which the linear trends are significant at 95% confidence level.

We further analysed droughts of different duration, by distinguishing between events lasting two or more months, and long drought events lasting at least six months. In Figure 12, the images on the left represent events lasting two or more months, those on the right represent events lasting six or more months (long events).

Drought frequency (Figure 12, top) shows an increase in the Iberian Peninsula, southern France, the British Isles, northern Germany, Austria, Hungary, the Czech Republic, Slovakia, the Urals, and Cyprus; a decrease can be seen in Iceland, Scandinavia, eastern Europe, and Russia. Regarding the long events, a more prominent increase can be seen in the Iberian Peninsula and Italy, and a more prominent decrease in Ukraine.

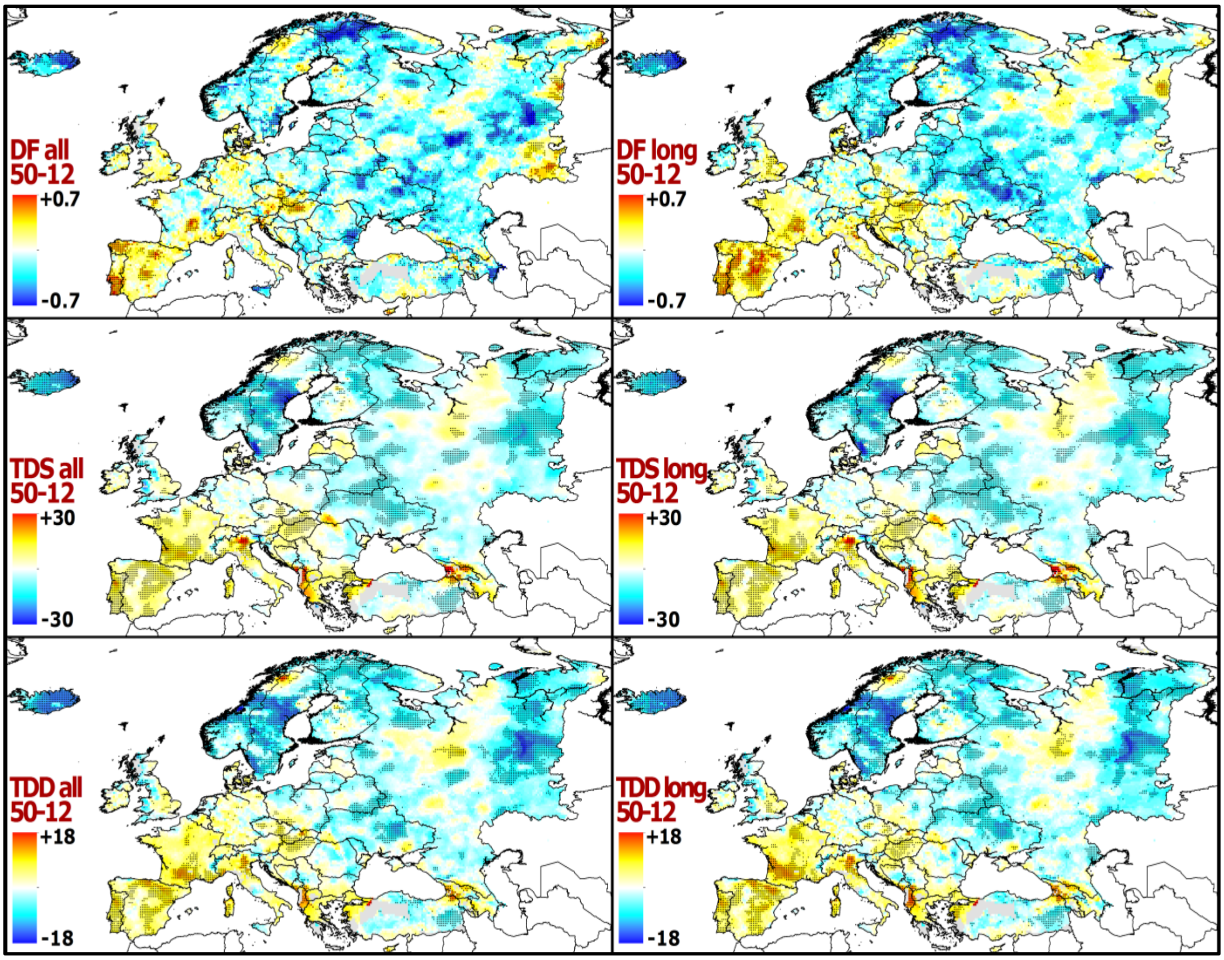

Figure 12 - European drought trends for the period 1951-2012

Drought severity (Figure 12, middle) and **duration** (Figure 12, bottom) show similar patterns: an increase in the Mediterranean region (in particular the Iberian Peninsula, southern France, and Albania), the Carpathian region (in particular Hungary and Slovakia), Ireland, the Black Sea coasts, and the Caucasus; conversely, a decrease is shown in Iceland, Scandinavia, Belarus, Ukraine and Russia. Regarding the long events, the only remarkable differences are a more prominent increase in drought duration in France and northern Italy, and a decrease in Ukraine and Belarus.

In summary, Europe can be split into two big areas: with a few exceptions, the southern and western regions show positive trends of drought frequency, duration, and severity, while the northern and eastern regions show a decrease. In Figure 13 this situation is even more evident: for every grid point we report how many drought variables show negative (less prone to droughts, light blue) or positive trends (more prone to droughts, yellow).

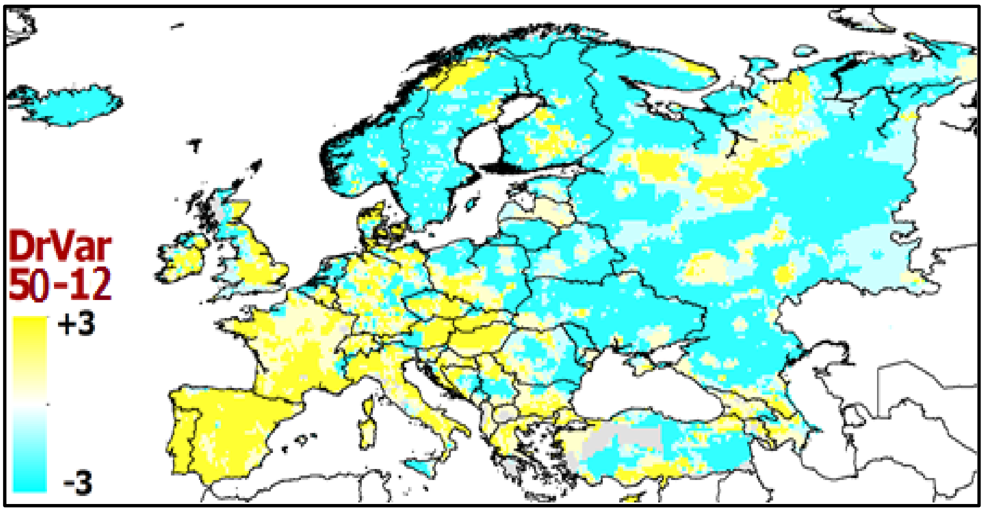

Figure 13 - Increase or decrease of drought variables for the period 1950-2012.

In particular, two hotspots with increasing drought patterns stand out: the Mediterranean region and the region west of the Carpathians. The Mediterranean is widely considered as the European region that is most vulnerable to climate change (Giorgi and Lionello, 2008) and water scarcity (Blinda et al., 2007), especially given the recent occurrence of hot summers that foster droughts (Zampieri et al., 2009). Hoerling et al. (2012) highlighted the recently increased drought frequency in the Mediterranean, and our results confirm such findings, showing that drought events also tend to be longer and more severe in this region. The same applies to the Iberian Peninsula (Vicente-Serrano et al., 2014). In the Carpathian region, many droughts occurred in the past three decades, as reported in Szinell et al. (1998) and Spinoni et al. (2013). In particular, the increase in drought severity and duration is statistically significant at 95% for almost the entire territory of Hungary.

This pattern is also evident in Figure 14, where we present the **trends** shown in Figure 12, but averaged **per country**. The images on the left relate to drought events which lasted at least two months, and the images on the right to drought events which lasted at least six months. With the exception of Iceland, whose average is based on the period 1951-2005, this analysis covers the period 1951-2010. In general, our main results - drought increase in south-western Europe and decrease in north-eastern Europe - agree with the results of recently published studies obtained using different methodologies, indicators, and/or datasets (e.g. Dai, 2011a, 2011b, 2013; Sheffield et al., 2012; van der Schrier et al., 2013).

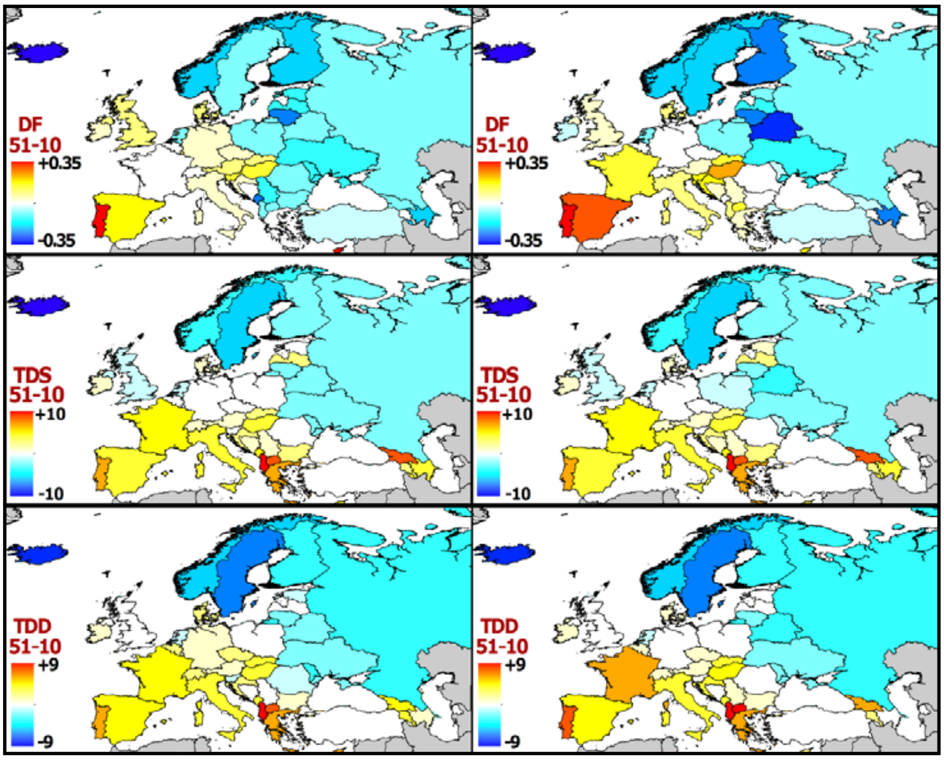

Figure 14 - Drought trends averaged per country for events lasting more than two months (left) and more than six months (right).

4.3 Temporal evolution of areas under drought conditions

The composite indicator Z-12 has also been used to compute, per year (and region), the percentage of **areas under drought condition**. In this study, a grid point is defined as being "under drought condition" in a given month if the composite indicator is below -1. For every grid point, the number of months per year during which Z-12 < -1 (in %), and an average of all the points within every country (or region), were calculated. In this way, we obtained annual series of areas under drought conditions per country (or region, see Figure 15), from 1950 to 2012.

As expected, we got similar results to those related to drought trends: in fact, according to Figure 14, Europe experienced a general decrease of areas under drought until the early 1980s, followed by a slight continuous increase in the past decades. The north-eastern regions (Iceland, Fennoscandia, European Russia, and former USSR countries) show a decrease, the south-western ones (Iberian Peninsula, Italy, the Balkans, and Aegean countries) an increase, and western, central and eastern Europe (France and Benelux, central Europe, eastern Europe, and Baltic Republics) act like transition zones showing no clear tendencies. This is also clear if we show the trends (in % *per decade*) of such values averaged per country (Figure 16).

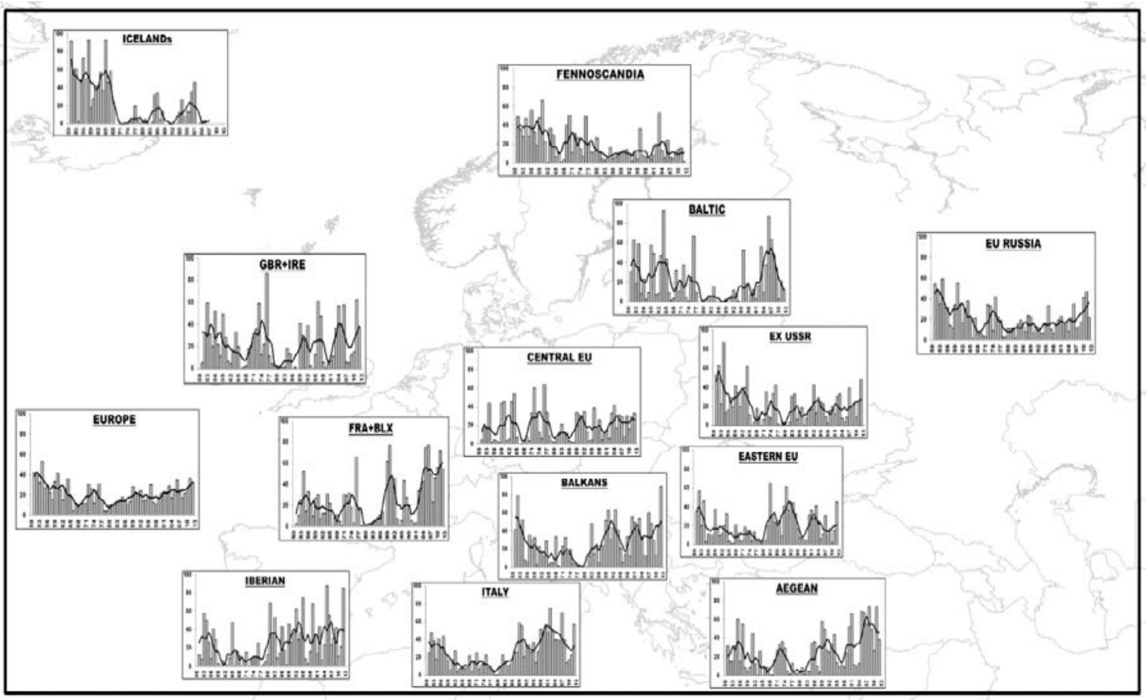

Figure 15 - Areas under drought conditions, averaged per year and region, for the period 1951-2012.

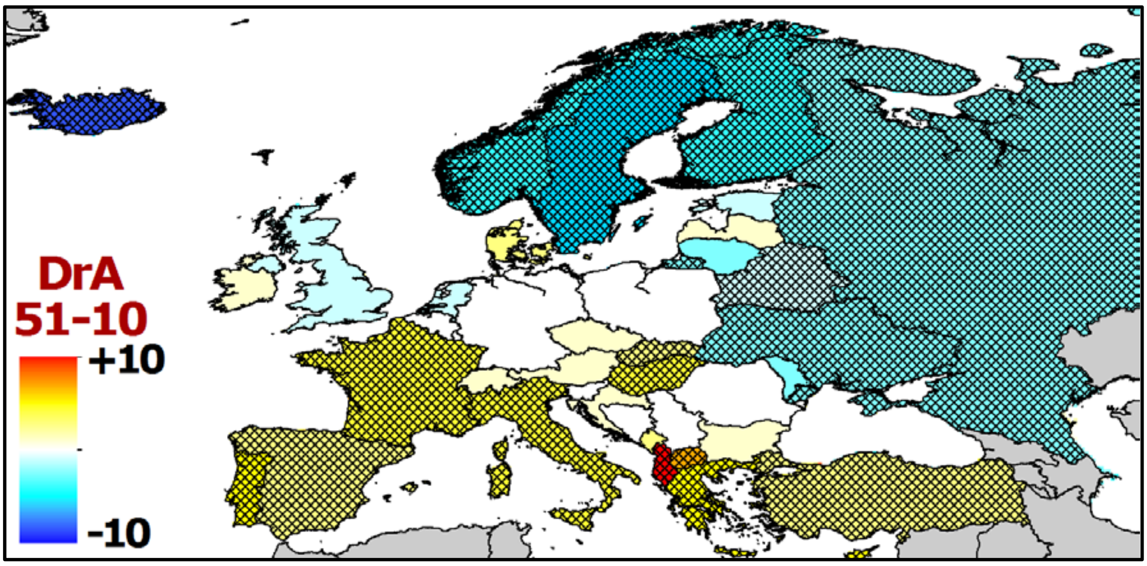

Figure 16 - Trends (% per decade) of areas under drought conditions (1951-2010). Significant trends are indicated by the hatched lines.

The main meteorological drivers for these trends (i.e. rainfall, temperature and evapotranspiration) are discussed in section 4.4 and summarised in Figure 17.

4.4 Have the drought trends been driven by rainfall or temperature?

The definition of meteorological drought usually refers to a prolonged lack of rainfall and a temporary decrease or deficit in natural water availability (Vogt and Somma, 2000). However, the potential consequences of an increase in temperature and/or evapotranspiration on droughts are still under debate (Trenberth et al., 2014). The dynamics of the soil-water balance are complex (Eagleson, 1978a, 1978b), but in climatology they can be synthesised within the climatic water balance (Milly, 1994). The available water in the soil is computed as the difference between rainfall and evapotranspiration. It follows that both prolonged high evapotranspiration rates as well as prolonged low precipitation rates may lead to meteorological drought. In this study, we used the potential evapotranspiration (PET), based on the Thornthwaite's model (PET_{Th}; Thornthwaite, 1948), which mainly depends on temperature. Consequently, a temperature increase is expected to lead to a higher PET and possibly to longer and more severe and frequent droughts.

In order to determine **which driver - precipitation, PET, or both - forced meteorological drought trends in Europe in the past six decades**, we analysed the relation between the linear trends in precipitation (P), potential evapotranspiration (PET), and drought severity (TDS) over the past 62 years. This analysis was carried out for each country by averaging all values of P, PET, and TDS within the country borders and then analysing the linear trend for each variable and country over the entire time period. The resulting trend can be positive, negative or show no direction at all. The combined interpretation of the slopes (positive, negative, neutral) of these trend lines provides some insight into the main drivers for drought occurrence in the different countries and regions of Europe. They are shown in Figure 17 and discussed below.

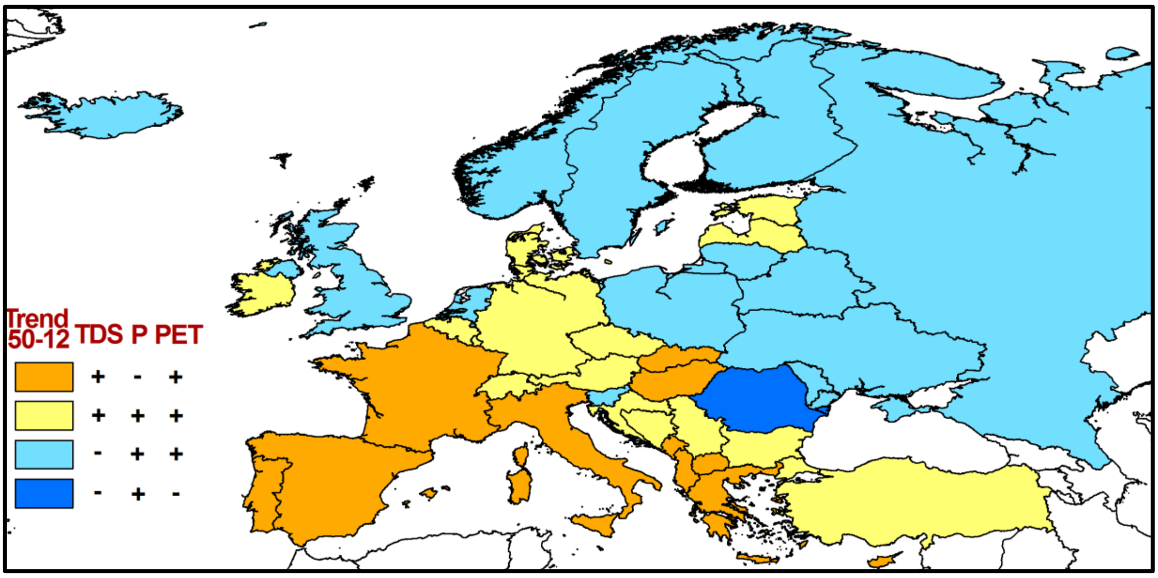

Figure 17 – Observed trends of the main drivers of meteorological droughts in Europe (TDS: Drought Severity, P: Precipitation, PET: Potential Evapotranspiration). The signs represent the direction (slope) of the changes and the colours the overall combinations of factors.

As shown in Figure 17, in the Mediterranean region, Hungary, and Slovakia, the increase in total drought severity (TDS) is driven by both a precipitation decrease and a temperature and corresponding PET increase. Though precipitation is the leading driver of drought in these areas, the evapotranspiration plays an important role. Van der Schrier et al. (2013) reported that PET is a fundamental driver of drought in the Mediterranean area, where the precipitation decrease is not universally significant. Also, Vicente-Serrano et al. (2014) reported the importance of increased temperature and PET regarding increased drought in southern Europe.

In Ireland, Central Europe, the Balkans, Turkey, Latvia, and Estonia, P, PET and TDS show a positive trend. However, the precipitation increase is not significant (at 95%, excluding Estonia), while the PET increase is always significant. It seems that PET is the leading driver of drought in Central Europe, as suggested by Teuling et al. (2013). However, although PET seems to be the key factor in the areas where precipitation trends are not significant (Central Europe and the Balkans), we emphasise that the inter-annual variability of precipitation can be more important for the occurrence of droughts than the annual trend. This is especially true in cases where the overall precipitation trend is not significant. In such cases, prolonged dry periods can be balanced by extreme rainfall events, resulting in an overall precipitation increase but also in more frequent and severe drought events at the local scale. This situation highlights the importance of continuous monitoring and the medium to long-range forecasting of droughts as a basis for adequate drought management.

In northern and eastern countries, drought severity shows a decrease linked to increased PET (excluding Romania) and precipitation. As both variables show significant trends (except in Poland and Slovenia), precipitation is the main driver in these regions.

On a spatial basis, three countries behave differently to their surrounding areas: Slovenia, Latvia, and Estonia. In Slovenia, the drought severity decrease is almost null, and in Estonia and Latvia the increase is relevant and is probably due to the striking drought events reported in the 2000s (e.g. Tammets, 2007; Briede and Lizuma, 2010). Due to their severity, the latter events will influence the slope of the regression over the 62 years analysed.

Table 9 summarises the **linear trends** (*per decade*) **per country** for mean temperature (TM, shown in °C and directly linked to evapotranspiration), precipitation (P, in mm), drought frequency (DF, events per decade), severity (TDS), duration (TDD), and areas under drought conditions (%). The colours, from red to blue, represent positive (red) and negative (blue) trends. The trends shown in bold - computed only for precipitation and temperature - are significant at ≥95% level.

Mean temperature increased everywhere but Romania, and once again precipitation shows distinct tendencies in northern (increase) and southern Europe (decrease).

Table 9 - Linear trends of the most important variables analysed per country and per decade

1951-2010	TM	P	DF	TDS	TDD	Areas
Cyprus	**0.22**	**-17.6**	0.33	5.48	6.96	6.2
Greece	**0.10**	**-21.0**	-0.02	8.61	5.85	5.9
Spain	**0.20**	-8.8	0.18	5.81	5.18	3.7
Turkey	**0.11**	4.3	-0.06	0.41	-0.40	3.6
Italy	**0.24**	-5.1	0.05	5.85	3.94	4.2
Portugal	**0.22**	-23.3	0.30	8.72	6.97	5.5
Albania	0.07	**-54.7**	-0.11	17.89	12.17	13.0
Macedonia	0.08	**-21.9**	-0.10	10.81	7.70	8.2
Georgia	**0.12**	**-33.8**	-0.09	10.71	5.56	6.7
Bulgaria	**0.13**	2.0	-0.12	2.87	1.43	2.2
Russia (Eu)	**0.26**	**14.6**	-0.12	-3.22	-3.18	-3.1
France	**0.25**	-4.7	0.03	6.78	5.69	4.5
Montenegro	**0.15**	**-23.5**	-0.22	6.23	3.55	3.8
Serbia	**0.14**	5.6	-0.10	1.53	0.31	-0.1
Bosnia H.	**0.22**	10.3	-0.02	1.45	0.75	0.3
Croatia	**0.17**	0.9	0.04	3.83	2.39	2.0
Romania	-0.02	2.1	-0.09	-0.20	-1.38	-0.3
Ukraine	**0.25**	**14.0**	-0.18	-3.46	-2.93	-3.3
Slovenia	**0.15**	16.2	0.16	-0.76	-1.12	-0.8
Moldova	**0.18**	**15.5**	-0.16	-3.16	-3.62	-3.4
Hungary	**0.14**	-3.6	0.15	5.76	4.42	4.2
Switzerland	**0.18**	3.7	0.02	2.59	2.66	1.1
Austria	**0.21**	0.4	0.11	1.94	2.11	1.2
Germany	**0.23**	7.2	0.04	0.29	1.83	0.4
Slovakia	**0.21**	-2.9	0.08	3.80	4.46	2.9
Czech Rep.	**0.20**	2.9	0.05	0.95	2.23	1.1
Poland	**0.24**	10.9	-0.09	-0.98	-0.64	-0.9
Belgium	**0.26**	11.8	-0.01	0.49	2.48	0.2
UK	**0.17**	**17.3**	0.08	-1.32	-0.46	-1.6
The Netherlands	**0.24**	**22.0**	-0.11	-2.06	-1.07	-1.3

Table 9 - continued

1951-2010	TM	P	DF	TDS	TDD	Areas
Belarus	**0.32**	**23.3**	-0.12	-4.51	-2.51	-3.3
Ireland	**0.15**	9.0	0.03	2.51	1.56	1.1
Denmark	**0.26**	5.0	0.11	1.95	2.56	2.8
Lithuania	**0.26**	**20.5**	-0.21	-3.22	-2.44	-3.0
Sweden	**0.15**	**23.6**	-0.12	-7.11	-6.00	-6.0
Latvia	**0.25**	1.6	-0.13	5.08	0.68	1.2
Estonia	**0.31**	**24.5**	-0.16	0.95	-1.55	-2.0
Norway	**0.17**	**28.7**	-0.17	-5.16	-5.35	-4.1
Finland	**0.24**	**18.7**	-0.19	-4.09	-3.69	-4.1
Iceland	**0.13**	**42.3**	-0.32	-12.22	-10.57	-9.7

To conclude this section, we focus on the fundamental question of whether findings based on the computation of PET with **Thornthwaite's model (PET_{Th})** are **reliable**. Contradictory opinions emerge from the literature. Sheffield et al. (2012) pointed out some drawbacks related to drought trends obtained with PET_{Th}: its estimation may depend too much on temperature without considering wind speed, solar radiation, and relative humidity, which are included in PET computed with the Penman-Monteith's approach (PET_{PM}; Allen et al., 1998). On the other hand, Dai (2011b) stressed the effects of global warming on drought and reinforced his opinion by showing that global trends of the sc-PDSI are correlated with precipitation trends, and that they are more prominent when the temperature rise is taken into account (Dai, 2013). Dai (2011a, 2011b) affirmed that the choice of PET_{Th} or PET_{PM} does not remarkably affect the drought trends, and van der Schrier et al. (2011) shared this opinion. Trenberth et al. (2014) suggested that the choice of the methodology to compute PET is just one of the key issues regarding the uncertainties of drought trends, i.e. climate forcing factors, local patterns, feedbacks, baseline period, input data reliability, natural climate variability, and so on. Trenberth et al. (2014) conclude by saying that drought indicators based on PET_{Th} can produce reliable outputs, provided that authors and users are aware of the limitations.

Based on this discussion and considering the availability of input data, we used the Thornthwaite method for the analysis of past trends and the **Penman-Monteith method** for analysing future trends. Note that for consistency in the latter case, PET for the reference period (1981 to 2010) was also calculated based on model outputs and using the Penman-Monteith algorithm. The use of PET_{PM} was feasible since the outputs of the climate models (in our case the RACMO 2 model) provide all the necessary data to calculate PET_{PM}. We consider that the Penman-Monteith method gives a more conservative estimate of PET as compared to the Thornthwaite method, which relies on temperature data only, and therefore more realistic results especially for projections into the far future which foresee significant temperature increases. This temperature increase could have a significant and maybe exaggerated impact when using the Thornthwaite method.

5. Database of drought impacts

Due the complexity of drought, it follows that **quantifying drought impacts** is not straightforward (Wilhite et al., 2007) and it is hard to find a comprehensive drought impacts database. However, many efforts have already been made in this direction at the global level (Eriyagama et al., 2009), and a wide variety of papers, reports, and technical notes regarding the impacts of selected drought events can be found in the scientific literature (e.g. Liverman, 1990; Asner and Alencar, 2010; Mallya et al., 2013; Kendon et al., 2013).

Regarding Europe, the most detailed **database of drought impacts** is currently the European Drought Impact Report Inventory (EDII; Stahl et al., 2012; Stagge et al., 2013; Kohn et al., 2014), which is being compiled together with the European Drought Reference database (EDR; the drought events are described using the SPI) in the framework of the Drought R&SPI Project (http://www.eu-drought.org/). This project has been running since 2011, and the EDII contained more than 4 000 impact entries at the end of 2014, organised per country and event. Such impacts are often descriptive reports and documents with little quantitative information regarding the key aspects of meteorological droughts. However, we assumed that constructing a similar drought impact database would have added little information given the time and human resources to hand. Consequently, the EDII should be considered as a relevant external resource for our study that is free to use after registration.

Complementary to this database, we decided to **collect geo-referenced spatial data** which can be **related to drought impacts**, such as cereal yields, hydropower generation, livestock production, etc. These data, usually available per country and on an annual basis, can help to quantify the impacts of relevant drought events selected according to statistical parameters. In this section, after a synthetic review of the nature of drought impacts for various sectors, we report the most important online drought impact databases. We then describe the provisional structure of a new impact database, structured over drought events detected using our multi-indicator methodology, and finally we report on the first preliminary search for the data that might be used to assess drought impacts in Europe.

5.1 Review of drought impacts by sector (synthesis of the literature)

Drought impacts affect almost all parts of the environment and communities. Unlike other natural hazard such as floods, earthquakes or hurricanes that result in clear damages, droughts develop slowly, and drought conditions often remain unnoticed until water shortages become severe and serious impacts begin to occur. The slow nature and long duration of drought typically makes the task of quantifying drought impacts difficult (Wilhite, 2005).

On the other hand, of all extreme weather types, **droughts have one of the largest impacts on society**. Economic damages from drought events can also be catastrophic, with a single drought event capable of causing damages to the tune of billions of Euros.

In a previous assessment published by the European Commission's DG Environment, it is reported that, on average, drought and water scarcity over the past 30 years have affected at least 11% of the European population per year, with economic losses estimated at a total of €100 billion over this period (European Commission, 2007b).

Impacts of natural hazards can be classified as direct or indirect (Montz and Tobin, 2011). Examples of direct impacts are the physical destruction of buildings, infrastructures, crops or other natural resources. In this context, drought can cause loss of life, reduce crop yields and limit public water supply (Liverman, 1990). Indirect impacts are related to the indirect consequences of the destruction of natural resources. These include temporary rural unemployment or business interruption. In extreme cases, droughts may result in malnutrition, starvation and disease in the more vulnerable countries (Greene, 1974; Prospero and Nees, 1986; Hillier and Dempsey, 2012). Figure 18 schematically shows the propagation of a meteorological drought through the hydrological cycle, resulting in possible direct and indirect social, economic, and environmental impacts. Because of their very nature, most of the drought impacts are indirect due to the dependence of many industrial sectors on water for production and the importance of water for providing services and recreation. These indirect damages can propagate quickly through the economic system, affecting regions far from the origin (Wilhite, 2002).

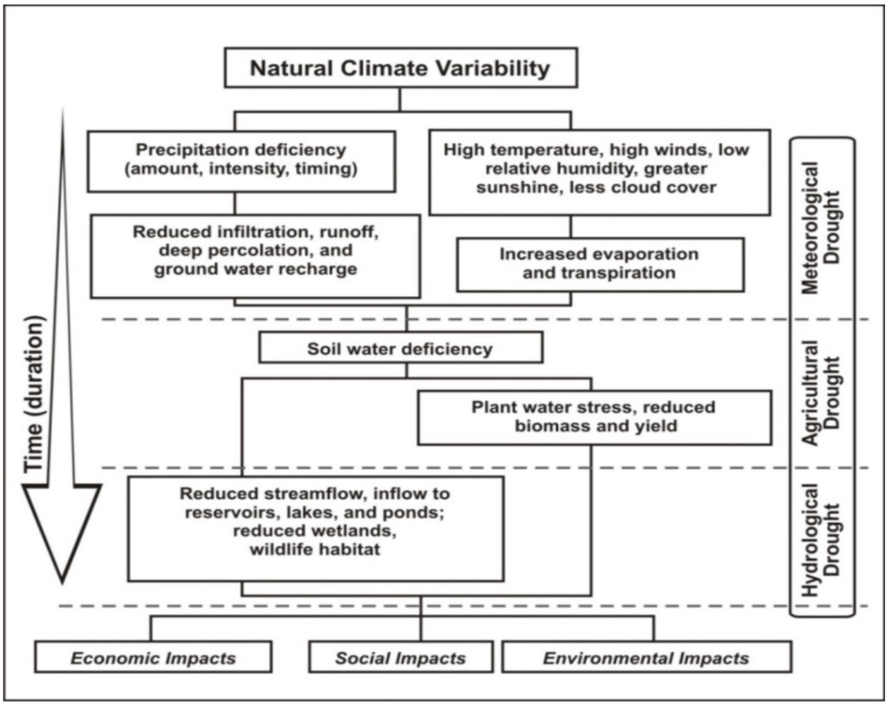

Figure 18 - Sequence of drought occurrence and resulting impacts for commonly accepted drought types. All droughts originate from a precipitation deficiency. Other drought types and impacts cascade from this deficiency. (Source: National Drought Mitigation Center, Univ. of Nebraska-Lincoln, U.S.A.)

According to the European Commission (2007b), the information provided by Member States made it possible to identify severe events that on an annual basis affected more than 800 000 km² of the European Union's territory (approximately 37%) and 100 million inhabitants (approximately 20%) in 1989, 1990, 1991, and 2003. The results show that the **annual average impact** has doubled between the 1976-1990 period and the 1991-2006 period, and has reached an average cost of €6.2 billion/year in the most recent years, with an exceptional cost of €8.7 billion in 2003. These estimations only cover economic costs. They do not include social and environmental costs due to the absence of data.

In the scientific and non-scientific literature, the wide spectrum of different drought impacts is often roughly sub-categorised into economic, environmental, and social impacts (Wilhite and Glantz, 1985; see Figures 18-19). Below, we build on these **categories**, providing brief definitions and, where possible, examples of related scientific publications. When not explicitly indicated, the numbers come from the European Commission's report on Water Scarcity and Drought (2007b) or from single entries of the EDII (http://www.geo.uio.no/edc/droughtdb/).

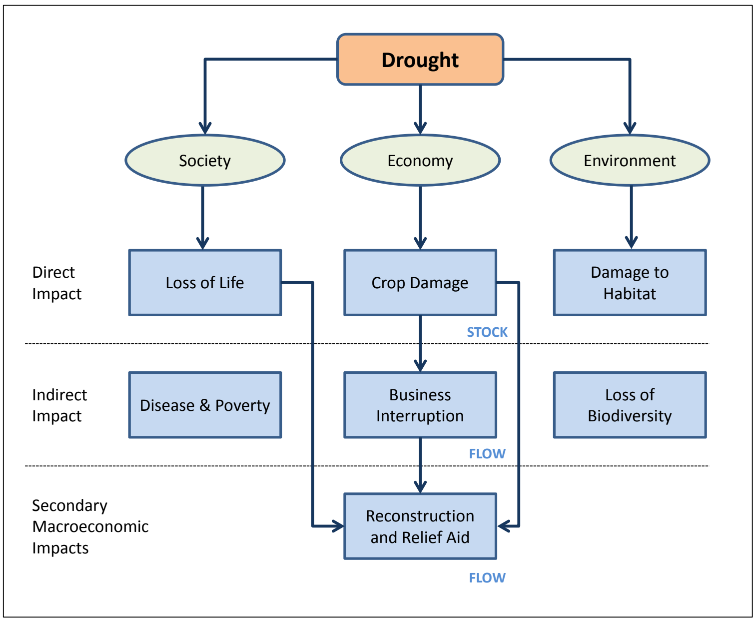

Figure 19 - Schematic presentation of drought impact categories and examples of related drought impacts (Source: Jenkins, 2011)

Economic impacts

A water deficit induced by droughts affects production, sales and business in a variety of sectors. See also: Benson and Clay (1998), Ward et al. (2006), Harou et al. (2010), etc.

Socioeconomic impacts

Welfare changes experienced by human beings should be accounted for in the measures of the socioeconomic impacts of drought. The social impacts of drought can affect people's health and safety, cause conflicts between people when water restrictions are required, and may result in changes in lifestyle. In 2002-2003, Finland experienced water quality problems in 42 waterworks and in many private water wells. In 1995, Spain estimated the number of inhabitants suffering from water restrictions at 12 million, with acute problems in Seville, Cadiz and Palma de Mallorca. From 1992 to 1996, the Spanish Jucar basin experienced a decrease in employment, at a cost of €70 million in lost wages. In England (the South East and Thames river basin districts), about two hundred job losses were attributed in part to restrictions on the use of hosepipes. Regarding the social impacts of drought events, see also Rossi (2000), Alston and Kent (2004), Bithas (2008) and Simelton et al. (2009). During August 2003, the extreme heat wave and drought led to almost 15,000 deaths in France, an excess of 60% over expected mortality for the period (Poumadere et al. 2005).

Impacts on environmental, forestry, wildfires, and biodiversity

Drought affects the environment in many different ways. Plants and animals depend on water, and under drought conditions their food supply can shrink and their habitat can be damaged. Sometimes the damage is only temporary and their habitat and food supply return to normal when the drought is over. But sometimes drought impacts on the environment can last a long time, or may lead to permanent land degradation. In general, the local and regional biodiversity may be highly affected by drought events. Droughts may for instance lead to desiccation of wetlands, disappearance of species and/or fires. In the Netherlands, loss of nature value may be noted, as it is influenced by the amount of water, the seepage level, the quantity of salt in groundwater and surface water as well as features of the water coming from outside the area.

In recent years, large areas of forest have been destroyed by fires and led to enhanced soil erosion and deficiency in water retention. On the other hand, it should be further considered that some forests, such as forests of eucalyptus, do not appropriately ensure the preservation of biodiversity and sustainable water management. In Portugal, the droughts of 2004-2006 led to costs of 8.8 million € linked to forest fires. In Spain, fires on 28,822 ha during the 1994-95 droughts gave rise to expenditures of €36 million. In France, a significant increase in fired areas has been noticed from 1976 to 2003 (+ 17,000 ha). The average cost for a fired hectare is estimated to 8,550 €. The average cost due to fires in years with outstanding drought can be estimated to €145 million. The exceptional features of the 2003 drought led to a total cost of €370 million. In 2002-03, drought enhanced the presence of dead wood in Finland, more than doubling the number of forest fires, compared to average years.

An extensive list of scientific papers, reports, and books accounting for drought impacts on plants, wildlife, forests, biodiversity, and natural environment can be found. We cite only a few examples regarding drought and wildlife (Roe et al., 2011; Seabrook et al., 2011), biodiversity (Archaux and Wolters, 2006; Feehan et al., 2009), and forests (Leuzinger et al., 2005; Bréda et al., 2006; Rouault et al., 2006; Lindner et al., 2010; Jactel et al., 2012).

Impacts on farming and livestock

Farmers may lose money if a drought destroys their crops. If a farmer's water supply is too low, the farmer may have to spend more money on irrigation or to drill new wells. Ranchers may have to spend more money on feed and water for their animals. Businesses that depend on farming, such as companies that make tractors and food, may lose business when drought damages crops or livestock. The cost of the 2003 drought to French farms has been estimated at €590 million (€240 million in 2004, €250 million in 2005; European Commission, 2007b). See also: Thornton et al. (2009) and Campbell et al. (2011).

The first impact of drought on agriculture is a decrease in productivity. In Portugal, the drought of 2004-06 resulted in a cost of €39 million for the farming sector. In France, the impacts of droughts slightly vary from one region to another, and also depend on the type of crop. For cereals, the yields and quality of crops in 2005 were not too far from the average. For autumn crops, an average decrease of about 10% of the yield was observed. For maize, yields fell by an estimated 20% in 2005 compared to 2004. In 2003, 83 departments received subsidies. In 2005, 17 departments received money from the “calamity fund” from the Ministry of Agriculture. From 1989, drought impacts on agriculture have cost France an average of €110 million per year, compared to the impacts on fishery, which have been estimated at €3 million a year. In Lithuania, losses in agricultural production amounted to €12 million in 2002, and €180 million in 2006 (European Commission, 2007b). For further examples, see Ciais et al. (2005), Lehner et al. (2006), Hlavinka et al. (2009), and Falloon and Betts (2010).

Impacts on public water supply

Drought conditions impact water supplies by decreasing supply and increasing demand for various usages (industrial, agriculture or residential use). According to the European Commission’s technical report (European Commission, 2007b) the European population affected by water use restrictions is 50 million in the most sensitive years, which represents a substantial increase since the 1970s. On the basis of recent examples, restrictions have led to a reduction in water consumption by an average of 10%. Belgium assessed that if a 1976 drought event were to occur under the current water demand situation, the country would face a shortage in infiltration capacity for drinking water production for 44 days, with an associated cost of €1.87 million. In Finland, 10 000 private houses (equivalent to 40 000 inhabitants) that usually get their water from private wells, suffered from insufficient water for household consumption during the drought of 2002-2003. Approximately 200 000 m^3 of water were carried by canisters or brought by tank trucks, at an estimated cost of €5.5 million. Due to the 2004-2006 drought, Portugal spent €23.2 million on urban water supply. In 66 municipalities (100 500 inhabitants), urban water supply was supplemented by 22 850 water tank operations. For further examples, see Shih and Revelle (1995), Cancelliere et al. (1998), Estrela and Vargas (2012), and Hrdinka et al. (2012).

Impacts on surface and groundwater

Direct impacts of droughts on surface waters include reduced river flows and reservoir levels. Significant decreases in aquifer levels are the main expression of drought impacts on groundwater. These decreases can also be accompanied by an increased risk of sea intrusion and eutrophication. In Portugal, reservoir levels fell significantly during the 2004-06 droughts, as did the level of some major aquifers, and algal blooms occurred. In the southern province of the Algarve, two major reservoirs – Funcho and Arade – were totally depleted. Decreasing flows in rivers gave rise to problems for migrating species (such as the lamprey in the Minho river) and for water abstractions (e.g. Morris et al., 2010). The average flow in Finland is usually about 3 200 m^3/s per year. In 2003, the flow dropped to 2 100 m^3/s. Due to the low oxygen concentration in shallow rivers and lakes which experienced eutrophication, fish mortality increased. In Belgium, the lowest water levels for the period 1970-1985 were observed in phreatic wells in 1976. In 2001-03, water levels severely dropped in most phreatic wells. In Finland, at the beginning of 2003, estimates report a reduction of 30 km^3 of water in groundwater aquifers and 30 km^3 in lakes and soil moisture, compared to the average situation. In the UK (the South East and Thames river basin districts), some groundwater levels reached historic lows during the 2005-06 drought (see Marsh et al., 2007).

Impacts on industry

Belgium estimated that if a 1976 drought event were to occur under the current water demand situation, two important companies would stop their production for 80 to 100 days. The associated cost was estimated at € 350 million. Finland reports that during the drought of 2002-03, pulp and paper industries suffered from deficiencies due to drought conditions. Financial losses were estimated at €1 million. Portugal reports thatthe fertiliser industry and the pulp and paper industry faced an additional cost of €32.25 million in 2004-2006 (European Commission, 2007b). Other relevant information on drought impacts on industry production in the European territories can be found in Lise and Bakker (2005), Bose (2010), Wada et al. (2013), for example.

Impacts on power generation: hydropower, thermal, and nuclear

Several Member States have reported a reduction in hydroelectricity production due to drought events (Finland, France, Portugal and Spain). As hydroelectricity production is related to the amount of water stored in the upper reservoirs, the production level can be lower during a drought. Peak demands for electricity then need to be satisfied by other means available in the short term (e.g. gas turbines). The amount of losses depends on hydroelectricity infrastructures and drought severity: €50 million in Finland in 2002-03, €210 million in Spain in 1990-95, €182 million in Portugal in 2004-06. France has reported the impacts of the 2003 summer drought and heat wave on the national French utility EDF due to low flow regimes that have a lower cooling power leading to a reduction in the potential of electricity production (Poumadere et al., 2005). During the 2003 drought, several thermal power plants reported a reduction in the energy production of up to 50% for several days. This reduction can be due to low flow problems or excessive temperature of the water used for cooling, and usually a combination of both. As reported in the EDII database, a reduction in energy production is usually foreseen if a critical value of river water temperature of 25°C is exceeded. According to reports compiled in the EDII, high water temperatures of the river Rhine in August 2003 at the site of the Biblis nuclear power plant led to the operation of additional cooling towers for several weeks. On 7 August 2003, the cooling towers of the Block A (which was not operating at that time) were also activated in order to reduce the heat of the discharge into the Rhine. A precautionary emergency exemption from environmental legislation was granted to be able to continue energy production (if the critical water temperature were exceeded). Despite these measures, energy production had to be reduced by 50% between 8 and 12 August. On 3 August, the Obrigheim nuclear power plant was forced to shut down. The energy supplier therefore decided to carry out the annual revision works 10 days earlier than planned. During August, the power production was reduced by 100%. Because of the high water temperatures of the river Rhine at the site of the Philippsburg nuclear power plant, the German Ministry for Environment gave the order to reduce production by 20%; the energy supplier (EnBW) proved that Block II could continue to operate at higher river water temperatures (without safety concerns). Until 19 August 2003, the use of river water was permitted only if it did not exceed a temperature of 25°C. During August, power production was reduced by about 30%. Also on 3 August 2003, low flow problems led to a reduction in the power production of the Brokdorf nuclear power plant by 3%, the Krümmel nuclear power plant by 40%, the Stade nuclear power plant by 30%, and the Unterweser nuclear power plant by 70%.

Further examples and information can be found in Lagadec (2004), Kopytko and Perkins (2011), Linnerud et al. (2011), Rübbelke and Vögele, (2011), van Vliet et al. (2012), etc.

Impacts on commercial shipping

During low-flow conditions, barges and ships may have difficulty in navigating streams, rivers, and canals because of low water levels, affecting businesses that depend on water transportation for receiving or delivering goods and materials. People might have to pay more for food as a result. Belgium reports that if a 1976 drought event were to occur under the current water demand situation, navigation would be made impossible on the canal system for 115 days, resulting in an estimated cost of €123 million (see the EDII impact database). The estimated damage is only based on the direct damage experienced by the sector itself and thus does not include the sizable economic damages borne by all the industries that depend on this mode of transport. In 2003, navigation on the canal system was hindered for 22 days, with an associated cost of €0.05 million. In the UK (the South East and Thames river basin districts), the low flow of rivers gave rise to navigation problems, and locks could not operate normally due to insufficient water levels (Marsh and Harvey, 2012).

Impacts on tourism and recreation

Since many activities in the tourism sector are water-related, droughts can bring critical losses. Droughts have impacts on both summer and winter activities. In Europe, little data has so far been available on this issue. France reports losses of €144 million during the winter of 2006-07 in the French Alps (Savoie and Haute-Savoie). Portugal had to mitigate the negative effects on urban water supply during the 2004-05 drought by investing some €23 million to perform 22 850 water tank operations in 66 municipalities (100 500 inhabitants) (European Commission, 2007b). While it proved difficult to retrieve scientific publications in this field, there are many non-scientific publications (e.g. newspaper articles) on the impacts of drought on tourism. However, the latter usually lack quantitative information and provide more qualitative estimates.

5.2 Present databases of drought impacts

Here we briefly list the most relevant drought impact databases that can be accessed online. Unfortunately, the current situation shows that only a few structured databases exist, most of them regarding single U.S. States or regions.

European Drought Reference (EDR) / European Drought Impact Report Inventory (EDII) - The European Drought Reference (EDR) database and the European Drought Impact Report Inventory (EDII) have both been compiled as part of the EU-funded Drought R&SPI Project (Stahl et al., 2012). The database is designed to provide a single, publicly available site to disseminate detailed information about historical drought events in Europe. See the official reports (http://www.eu-drought.org/technicalreports) for further information. The EDII is organised per country and event. While it provides very useful documentation of past drought events in Europe, the reported impacts are based on descriptive reports, documents and publications with often limited and quantitative information that has not been standardised. The geo-referencing of the impact data also has limitations. We therefore decided to complement the EDII with a more quantitative database for specific impact categories for which quality-controlled data can be retrieved from official data sources, such as statistical offices, international organisations or the insurance industry.

Website (EDR): http://www.geo.uio.no/edc/

Website (EDII): http://www.geo.uio.no/edc/droughtdb/ (Figure 20).

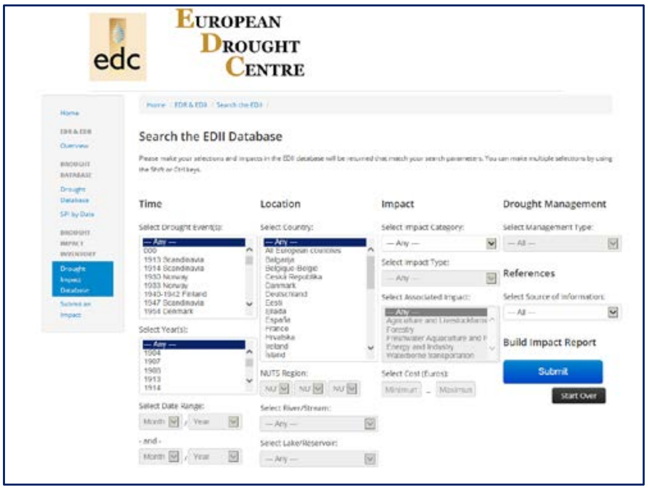

Figure 20 - The interface of the EDII database: the impacts of droughts can be searched according to different criteria.

European Drought Observatory (EDO) - The European Drought Observatory (EDO) makes use of the European Media Monitor (EMM) to retrieve information on droughts and related topics from news portals worldwide in many languages. During exceptional droughts, EDO also provides drought reports or bulletins. EDO is maintained by the Joint Research Centre (JRC) of the European Commission, and will host the database of past meteorological drought events described in this report. EDO is available at http://edo.jrc.ec.europa.eu (Figure 21).

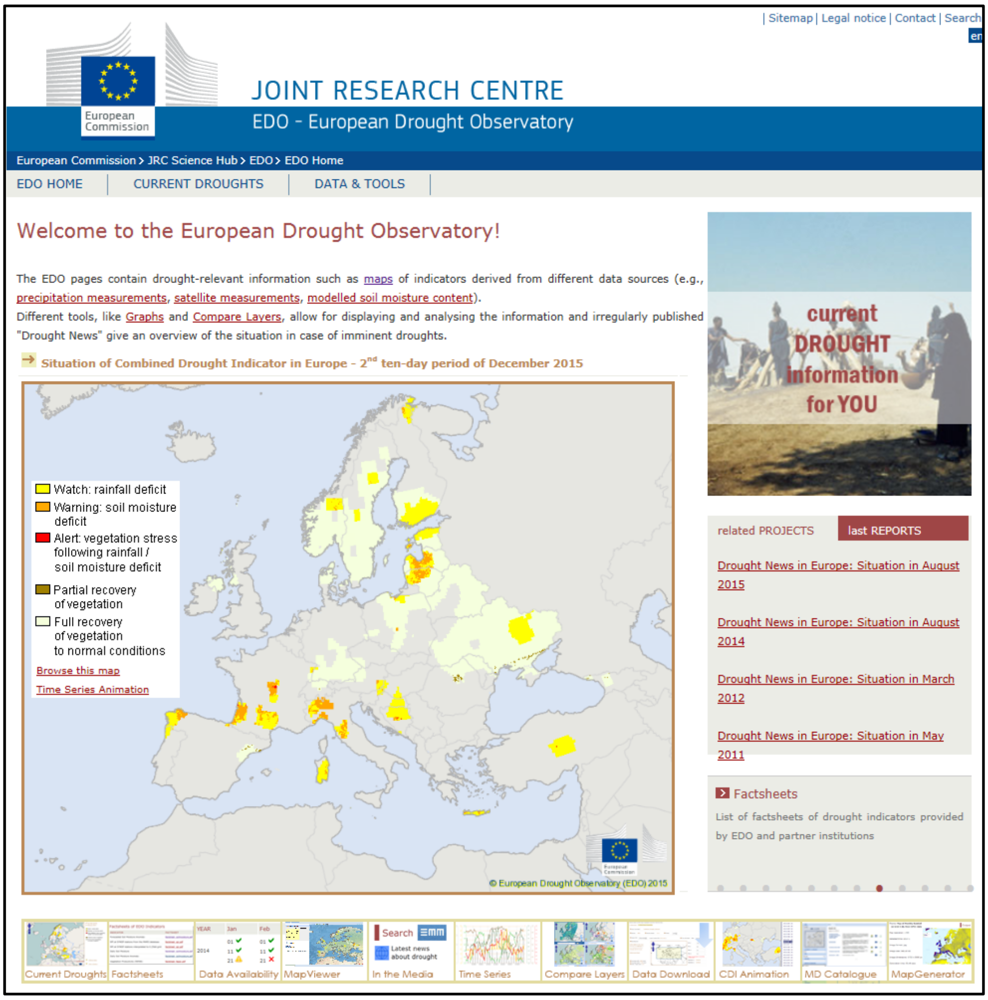

Figure 21 - Homepage of the European Drought Observatory.

Drought Impact Reporter / Drought Management Database (U.S.A.) - The National Drought Mitigation Centre of the University of Nebraska-Lincoln launched the Drought Impact Reporter on their website in 2005. Through continuous updates, it collects and displays several types of impact information. All the information available in the Drought Impact Reporter is based on user and media reports; consequently not all the information included is peer-reviewed. The Drought Management Database (DMB) divides the impacts into eight categories: farming, livestock production, water supply and quality, energy, recreation and tourism, fires, plants and wildlife, and society and public health.

Website of the Drought Impact Reporter: http://droughtreporter.unl.edu/ (Figure 22)

Website of the DMB: http://drought.unl.edu/droughtmanagement/Home.aspx

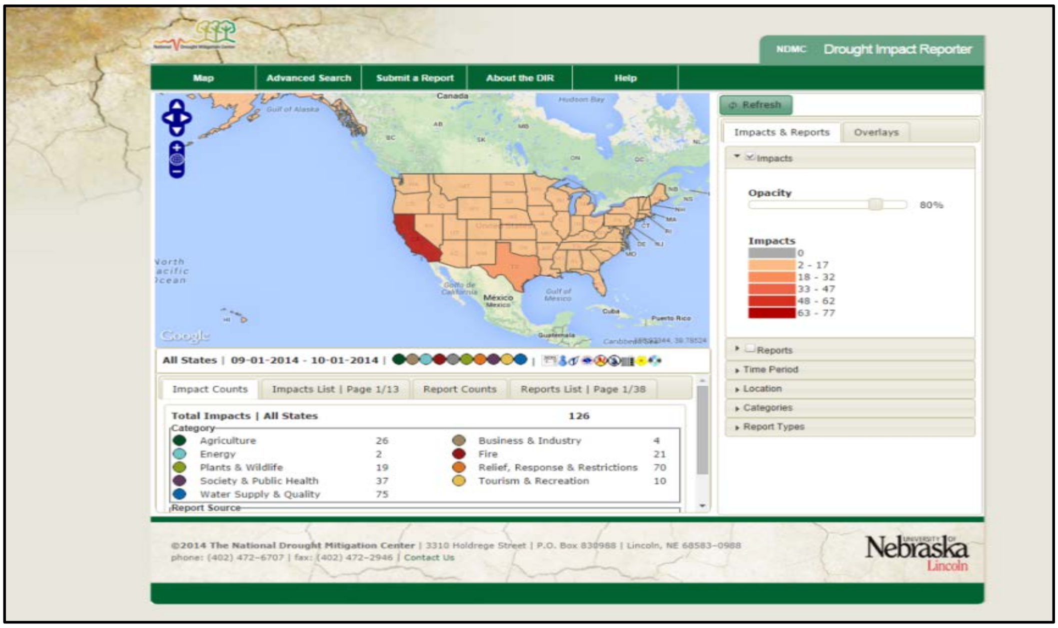

Figure 22 - Map of drought impacts of the National Drought Mitigation Centre, U.S.A.

Western Water Assessment's Socioeconomic Climate Impacts database (U.S.A.) - The Western Water Assessment's (WWA's) Socioeconomic Climate Impacts database is a publicly accessible and searchable collection of peer- and non-peer-reviewed articles, reports, websites, and presentations about the socioeconomic impacts of and adaptations to climate variability and change, focused on the WWA region (Colorado, Utah and Wyoming). The entries are limited to three sectors: agriculture, outdoor recreation, and water.

Website: http://www.socioeconimpacts.org/

EM-DAT Emergency Disaster Database - The United Nations Development Program (UNDP) and the Centre for Research on the Epidemiology of Disasters (CRED; University of Louvain, Belgium) have undertaken a review of existing available historical disaster databases, which summarises the content, presentation, and accessibility of international, national, regional, and event-specific disaster loss databases. Many different types of natural disasters are reported, including droughts, earthquakes, epidemics, extreme temperatures, floods, insect infestation, landslides, volcanic eruptions, wildfires, windstorms, industrial accidents, transport accidents, and so on. Unfortunately, only a few entries regarding drought impacts are available, particularly regarding drought events in Europe.

Website: http://www.emdat.be/

5.3 Quantifying the impacts of drought by sector

The degree of social **risk from droughts** is determined not only by the degree of exposure to or frequency of the natural hazard, but also by the vulnerability of society at the moment of a severe event (Wilhite et al., 2007). Understanding and quantifying drought impacts can help the development and the implementation of well-formulated policies and mitigation actions that would lead to a reduction in the risk associated with the forthcoming events. This section describes the main steps followed to construct a **preliminary version of the drought impact database**. The database of past meteorological drought events for the period 1950-2012 is complete, and a first related database quantifying drought impacts is available. The latter should be further developed over the coming years.

Figure 23 shows a summary of the proposed methodological framework for the construction of the drought events and impact database.

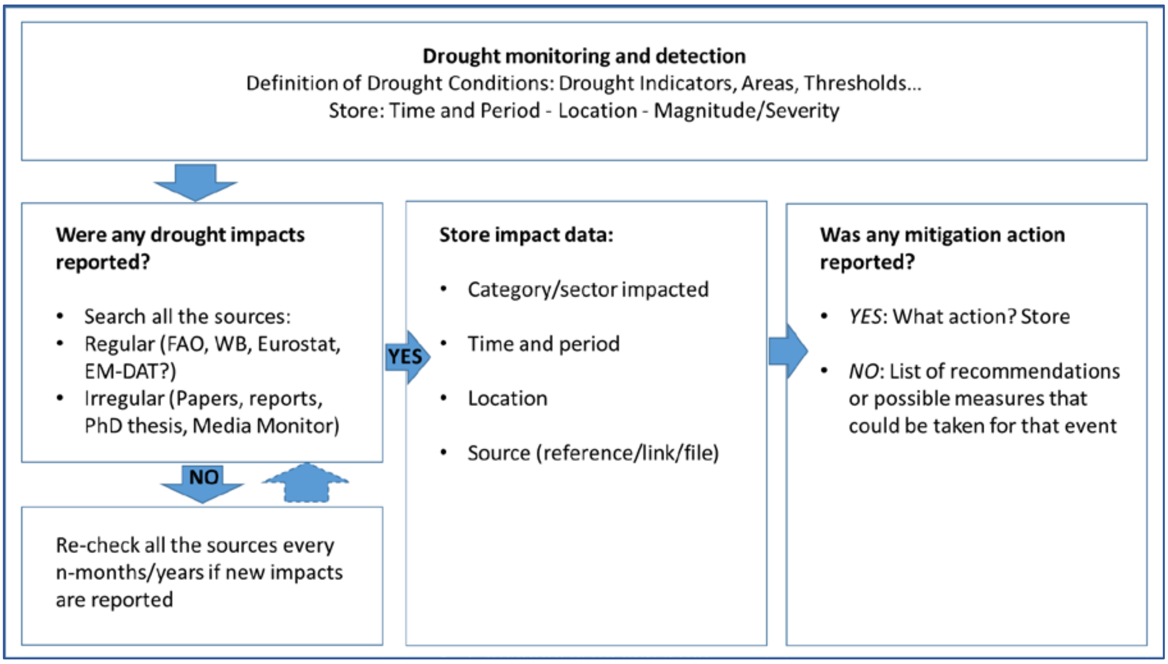

Figure 23 - Schematic representation of the database organisation

Firstly, to structure the database it is necessary to develop a clear and precise **definition of drought conditions** through selected indicators, statistical analysis, and a robust methodology. Once an event is detected (see Sections 2 and 3), each drought event should have associated an ID, a list of parameters, and possibly some maps that show its spatial extent. Each drought event should therefore be given the associated information:

- Location (country, region, macro-region, NUTS region or other);
- Period (year(s) and months of drought occurrence);
- Precise period (start and end date): the format should be MM/YYYY, because we use monthly data to assess the drought event occurrence; however, the information on impacts can be in a different temporal resolution;

- Drought category: based on duration, severity, intensity, area involved, peak intensity, etc.;
- Drought-related information: Identification and definition of variables used to define any single drought event. Definition of possible impacts (meteorological, agricultural, hydrological, etc.) according to the statistical parameters and the accumulation period. Description of the evolution of drought indicators. Characterisation of the events that occurred simultaneously in different and non-bordering countries;
- Time series: the time series or maps of the different variables could be retrieved via a hyperlink. They could be static or computed by underlying software, as currently implemented in the EDO portal.

Secondly, **drought impact information** should be inserted. Each reported impact (*YY*) should have an ID that will be associated with their corresponding drought event (*XX.YY*):

- Location of the reported impact: This can be different from the defined drought event: if the drought event is detected at country level, the impact report can be for a greater (e.g. Central Europe) or smaller spatial scale (NUTS, river basin, a dam or nuclear power plant, etc.);
- Time period (not mandatory): if provided, this can be different from the drought event;
- Type or category of the impact: agricultural, energy production reduction, biodiversity, etc. Such categories of impacts could be the same as the EDII or the DMB of the NDMC, because some kind of standardisation is desirable to make the databases intercomparable;
- Data Source(s): We should discriminate between two principal categories of impact data sources:
  - o periodic reports that are updated regularly (e.g. quarterly, yearly) such as FAO, World Bank, and Eurostat data or the JRC Media Monitor (updated continuously);
  - o irregular sources that usually appear with some delay (e.g. scientific publications, PhD theses, official reports) but often include some kind of quantitative information.

We highlight that some **issues** might arise when the impact reports are added to the database. Usually, the official reports are in their original language, so for example the EDII database takes advantage of research and project partners from different countries that regularly check the official reports for their respective country. Moreover, there could be impacts that cannot be classified in any category. Finally, a simple but effective methodology to check the quality of incoming information needs to be defined. For regular contributors this could be an automatic process. For irregular contributors (e.g. stakeholders, or the general public), however, a verification process needs to be in place.

Thirdly, the database could contain information on related **policies**, adaptation and (proactive) prevention measures before the event, and (reactive) mitigation measures after the event. It follows that in the database an optional field can be included to quantify when and where effective or ineffective measures have been taken.

For each reported impact the following **questions** can be formulated: did the impact demand management? Private or public and at which level? If management was necessary, further questions should be formulated: has any response measure been taken and if yes, which one? If no management was needed, or no measure was taken or reported, a list of recommendations and/or possible measures could be added. However, we understand that the interaction with stakeholders and end-users from different levels and sectors would probably be time-demanding and requires considerable human resources and expertise.

Given the fact that the structure of the EDII dataset could be used as the reference structure to further develop, we suggest building an online interface structured over an entry system based on standard Microsoft Access™ spreadsheets and tables. The preliminary tests are promising and such a system could become part of the European Drought Observatory (EDO), thus helping to link ongoing monitoring and forecasting with possible impacts.

5.4 First collection of data to be used to assess the impacts of drought events

The dataset of past drought events has to be connected to a dataset of drought impacts. Since drought impacts are mostly reported without a common methodology (e.g. media reports, bulletins of environmental agencies, case studies regarding a reduction in agricultural production, peer-reviewed papers discussing case studies, etc.), more quantitative datasets that describe drought impacts have been sought for in this pilot study.

Firstly, we checked global datasets with sparse and sometimes non-continuous drought impact updates. Unfortunately, the majority of the global datasets dealing with climate-related impacts focus on extreme events with immediate (structural) damages, such as floods, wildfires, volcanic eruptions, earthquakes, tornadoes, etc. Moreover, the global datasets contain far more entries regarding less developed countries (where the extreme events cause more severe damage due to a lack of adequate prevention and adaptation strategies) than developed countries. As a consequence, these databases usually contain only a limited number of entries for Europe.

Below, we therefore briefly discuss the most relevant databases that could be used as **sources for a European drought impacts database,** keeping in mind that the EDII dataset should be considered - to our best present knowledge – as the reference source.

The **EDII impact database** (www.geo.uio.no/edc/droughtdb) implemented by the European Drought Centre in the framework of the Drought R&SPI Project provides a list of reported impacts for each selected drought event, categorised by country and impact type. We recommend including part or all of the impacts reported in this database through a scientific collaboration with the EDII developers.

The **EM-DAT international disaster database** (www.emdat.be) is provided by the Centre for Research on the Epidemiology of Disasters (CRED) and reports a wide variety of natural and technologicalnatural disasters of the past century. While only a few drought entries regarding Europe are included in EM-DAT, some quantified economic information is available.

The **Global Disaster Identifier Number dataset** (GLIDE; www.gripweb.org) does not provide quantitative information regarding past European drought events, but a short description of some events.

The **DesInventar** inventory system of the impact of disasters (www.desinventar.org) currently does not include European drought events.

Private reinsurance companies such as **Munich-RE** (www.munichre.com) or **Swiss RE** (www.swissre.com) only provide general statistics to external users. However, public institutions may access more detailed data under special agreements.

In order to add different, more quantitative information layers to the existing impact databases, we studied the relationships between detected meteorological drought events and related impacts in different economic sectors that are reported regularly by the World Bank, Eurostat and the FAO. Examples are reductions in crop yields, livestock losses, or changes in hydropower generation and demand. Correlations between the reported changes in the mentioned variables and the characteristics of the drought events as described in the first part of this report can be quantified through dedicated **damage functions** that may be used to estimate possible damages of drought events when no impact data is available, and to project possible damages to future drought events. To do so, annual data related to different sectors possibly correlated with drought impacts were collected from the following sources:

- The **FAOSTAT** dataset (http://faostat.fao.org)

Downloaded data: crop production and yields, processed crop production, primary and processed livestock, values of agricultural production (VAP), water withdrawal for agriculture, producer and consumer prices, land areas and percentages, and emissions from agricultural soils. Similarly, data about basic goods and foods such as milk, meat, and cheese have been stored.

- The **Eurostat** dataset (http://epp.eurostat.ec.europa.eu)

Downloaded data: crop production (cereals), land areas, primary energy consumption, round wood production and utilised agricultural area.

- The **World Bank** dataset (http://www.worldbank.org/)

Downloaded data: various indicators related to land areas, cereal yields, energy production and use (in particular electricity and hydropower), livestock production, forest cover, emissions, and GDP per capita from agricultural activities.

Depending on the need and availability, other databases with similar features may be searched in the future.

6. Linking past drought events with their impacts

6.1 How to exploit the drought events and impacts databases

As we previously discussed, to construct a **database of past meteorological drought events for the period 1950-2012**, we selected version 10 of the high-resolution (0.25°x0.25°) E-OBS gridded daily temperature and precipitation data (version 10; Haylock et al., 2008). Using these data, we computed the SPI, the SPEI, the RDI, and composite indicators based on the predominance of drought or non-drought conditions. The composite indicators have been used to define meteorological drought events for the period 1950-2012 and a corresponding set of parameters: start, end, duration, intensity, severity, peak, and area involved. Subsequently, we constructed a database (split into 3- and 12-month accumulation periods) per country and region, depending on geographical, political and climatic barriers. A detailed analysis of the final database also resulted in a robust evaluation of the European drought hotspots and trends for the period 1950-2012. We also compiled a list of the most severe and widespread drought events that occurred in Europe from 1950 to 2012 and, for each event, we searched for one or more related documents in the scientific literature (see section 3.4).

Compared to the construction of a drought events database, the construction of a **drought impacts database** is more difficult, due to the complexity of drought and the difficulties in quantifying drought impacts (Wilhite et al., 2007). In the literature, a huge variety of scientific papers, reports, newspaper articles, media reportages, and technical notes about the impacts of selected drought events can be found (e.g. Liverman, 1990; Asner and Alencar, 2010; Mallya et al., 2013; Kendon et al., 2013). However, regarding Europe, there is no universally accepted common drought impacts database.

To overcome this deficiency, the European Drought Impact Report Inventory (EDII; Stahl et al., 2012; Stagge et al., 2013; Kohn et al., 2014) was compiled together with the European Drought Reference Database (EDR; the drought events are described using the SPI) in the framework of the Drought R&SPI Project. However, due to the nature of the information sources, the EDII information is often descriptive and deals with qualitative data that in some cases have not been verified by independent sources. Consequently, EDII served as an important source of drought impact information, which we extended with complementary, especially quantitative, information from other data sources. To do so, we collected **scientific publications** that deal with drought impacts in different sectors, namely the economy (e.g. Ward et al., 2006), farming and livestock production (e.g. Thornton et al., 2009), agriculture (e.g. Lehner et al., 2006 and EC, 2007a), water supply (e.g. Hrdinka et al., 2012), groundwater resources (e.g. Marsh et al., 2007), industry (e.g. Bose, 2010), energy production (e.g. Linnerud et al., 2011), commercial shipping (e.g. Marsh and Harvey, 2012), social systems (e.g. Alston and Kent, 2004), tourism and recreation (e.g. EC, 2007), and forests and biodiversity (e.g. Leuzinger et al., 2005; Feehan et al., 2009; Seabrook et al., 2011). We also **collected data** from the EM-DAT Emergency Disaster Database, the Global Disaster Identifier Number dataset, and publicly available information from private reinsurance companies as Munich-RE and Swiss RE.

Finally, in order to add new quantitative data to the impacts database, we collected **annual data per country**, related to different sectors that are possibly correlated with drought impacts. The annual data were used to calibrate **damage functions**, which correlate drought events and their related impacts. Data were taken from three main data sources: the FAOSTAT dataset, the World Bank dataset, and the Eurostat dataset. In particular, we collected data about crop production and yields, processed crop production, primary and processed livestock, values of agricultural production (VAP), water withdrawal for agriculture, producer and consumer prices, land areas and percentages, and emissions from agricultural soils, harvested land areas, primary energy consumption, round wood production, utilised agricultural area, forest cover, emissions, GDP per capita, gross and net income, and production costs. Due to time constraints and the sometimes incomplete time series of the data, only a few relations could be explored within the frame of this pilot study.

Table 10 shows a small **sample** of the entire dataset, i.e. annual total cereal yields (in kilogrammes/hectare) for three European countries (Sweden, Turkey and the United Kingdom). The data were collected for the period 1961-2013, but some quantity or country data is missing, especially from before the 1980s or the 1990s. We highlight the fact that some countries show data only from a certain year onwards, due to the fact that many European countries came into being in the 1990s after the breaking-up of the U.S.S.R. and Yugoslavia. The data are organised in columns - which can be easily exported by the end users – and follow an order that can be based on the countries, on data sources, on the quantities or the year under examination. The user can switch to the preferred order and, in the final version of the online database, should be able to visualise simple graphics of time series, trends, and the possible connections with documented drought events. We also plan to give the user the possibility to suggest the uploading of new data or sources, as can be done in the EDII.

Other data sources - newspapers, media reports, bulletins, technical documents, interactive maps, and peer-reviewed publications – were also collected. However, in this study we limit ourselves to discuss the derivation of the damage functions, apply them to the data, validate the methodology with independent data, and show the potential of the new database with case studies that deal with two different sectors.

Table 10 – Total annual cereal yields for three European countries, from 1981 to 2012.

Database	World Bank	World Bank	World Bank
Country	Sweden	Turkey	UK
Quantity	Cereals	Cereals	Cereals
Unit	Yield (kg/ha)	Yield (kg/ha)	Yield (kg/ha)
1981	3 827.00	1 855.10	4 933.15
1982	3 923.94	1 871.71	5 438.96
1983	3 653.48	1 978.74	5 377.49
1984	4 492.15	1 838.40	6 590.89
1985	3 779.12	1 971.10	5 592.14
1986	3 907.69	1 931.04	6 083.15
1987	3 820.78	2 135.53	5 506.13
1988	3 681.52	2 137.44	5 399.39
1989	4 325.08	2 250.24	5 866.66
1990	4 963.74	1 742.11	6 170.95
1991	4 492.61	2 214.16	6 467.70
1992	3 359.40	2 239.45	6 324.50
1993	4 758.94	2 123.45	6 424.44
1994	3 891.37	2 255.02	6 555.52
1995	4 358.62	1 911.52	6 872.74
1996	4 893.63	2 037.86	7 320.39
1997	4 718.29	2 105.75	6 695.03
1998	4 379.75	2 131.47	6 661.57
1999	4 276.34	2 359.48	7 043.55
2000	4 560.26	2 075.20	7 164.75
2001	4 583.34	2 311.05	6 291.74
2002	4 780.43	2 127.17	7 075.61
2003	4 584.49	2 237.68	7 029.43
2004	4 892.90	2 297.99	7 030.51
2005	4 932.34	2 466.71	7 196.10
2006	4 292.19	2 626.11	7 277.44
2007	5 150.83	2 656.74	6 633.44
2008	4 820.45	2 359.47	7 420.19
2009	5 078.87	2 443.59	7 030.57
2010	4 508.59	2 783.14	6 953.03
2011	4 715.99	2 708.78	6 984.56
2012	5 096.67	2 957.59	6 212.99

6.2 Definition of damage functions to relate drought events to impacts

Following the detection of meteorological drought events, the next step is to **relate the events to reported impacts**., While incipient efforts to link natural hazards with their impacts are described in recent literature, these studies mostly focused on global and long-term changes of climate features such as the increase in temperature (Nordhaus and Boyer, 2000). Little attention has been given to the impacts of extreme weather events, particularly with regard to droughts. This can be explained by several issues linked to the characterisation of extreme weather and climate events that complicate the issue.

As discussed in the previous chapters, the availability and quality of data on drought impacts in different sectors is one of the main constraints in constructing a convincing database that quantifies the losses from droughts. While different sources of drought impact data do exist (e.g. EM-DAT, EDII), they are far from complete and no consistent methodology to record drought losses is yet available. Recently, the JRC formulated technical recommendations for a European approach to standardise loss data (De Groeve et al., 2013), which propose a **conceptual framework for collecting loss data** that allows for a cost-benefit analysis of different scenarios. The framework considers loss accounting, disaster forensics and risk modelling as key applications. Unfortunately, this structure cannot directly fit the drought impacts because, at the moment, they are still sparsely reported by EU Member States, and are mainly linked to requests for solidarity funds.

Extreme weather and climatic events are - by definition - atypical and usually very rare events. This makes it hard to get a sample size that is big enough to derive a robust linkage between hazards and impacts. Moreover, drought losses include direct and indirect non-market effects that are difficult to represent using single indicators, and relationships between different sectors need to be explained. While Input-Output (IO) models are generally able to represent the relationship between different sectors, they are still not well suited for the analysis of extreme climate events (Okuyama, 2007).

Table 11 briefly presents the main **methodologies** applied **to link climate hazards with their impacts**. The methodologies presented show different levels of complexity and a number of drawbacks that determine the level of confidence achievable in the loss or damage estimation. Before choosing the damage functions as our approach to quantify the link between drought events and impacts, we analysed the published scientific literature about similar methods.

Table 11 – Different methodologies commonly used to link hazards and impacts.

Method	Description
Climate analogues	Based on historical data of weather extremes that serve as analogue for conditions and losses that may occur in the future (Carter, 2007). Remarks: case-study dependent. Some applications: STARS model (PIK, Germany). Hoffmann et al., 2014; Gerstengarbe et al., 2013; Lutz et al., 2013; Orlowsky et al., 2010
Damage functions	Reduced formal relationship that links market and non-market impacts to climate indicators (Jenkins, 2012). Remarks: Calibrated using data from a limited number of events. Availability and quality of quantitative impact data is usually low. Some applications: Nordhaus and Boyer, 2000; Jenkins, 2012
Input-Output (I-O) models	Industries consume goods from other industries/sectors to produce their own goods (Okuyama, 2007). Remarks: Good for indirect impacts. Widely used in natural disaster studies. Assumption of linearity. Use of economic theories but not well suited for weather extremes such as droughts. Some applications: Jenkins, 2013; Wiedmann et al., 2007
Integrated Assessment Models (IAMs)	Based on a multidisciplinary analysis, can integrate multiple dimensions of climatic and economic models (Stern, 2007). Remarks: as IAMs rely on several type of models (GCM and socioeconomic), the level of uncertainty increases with model complexity. Highly developed for GCMs and RCMs, but less so for impact modelling (Vasiliades et al., 2009, van Vuuren et al., 2011). Some applications: Warren et al., 2008; Füssel, 2010; Hulme et al., 1995

The scope of analysing **damage functions** is to ultimately measure the risk of certain drought events under present and future climate scenarios: this information can be used to inform early warning systems in the short term and to develop mitigation plans for different future scenarios. The damage functions can provide a method to evaluate past impacts and project future impacts in the context of climate change. Damage functions are usually based on historical data of both drought events (physical aspects) and impacts (losses). In combination with future projections of extreme drought events, the damage functions can be useful tools for estimating future economic implications.

However, numerous **issues** in the construction of damage functions have been reported. In order to project losses under the assumption of climate change, a very good knowledge of the past impacts is needed. Usually, the data related to drought impacts are not comprehensive, they are not quantitative but just qualitative, and they are frequently biased in countries or regions that do not report every single event but only a few special cases. It follows that the damage functions can provide simplified estimations that are rarely fully calibrated against empirical evidence of past damages (Mastrandrea and Schneider, 2004). Therefore, damage functions usually do not provide definitive estimations, and they might be replaced with more accurate functions as new information and knowledge become available.

In this study, we applied damage functions to link drought events and possible impacts and damages, taking advantage of global datasets that usually report annual data for a diversity of sectors. We focused on cereal **crop production** and **hydropower generation**, assuming that they are directly or indirectly impacted by extreme droughts and can be represented by univariate functions. However, the suitability of different methodologies needs to be explored in order to address more complex relations such as indirect or non-market losses.

The effect of a natural hazard on the objects, goods or population of a particular area depends on complex interrelationships and emerging domino effects. The UN (1991) and the UNDP (2004) define a conceptual framework for risk (R) assessment, which assesses the capacity of a society or system to cope, resist and recover from certain impacts (exposure and vulnerability). Here, the hazard is related to an external factor that will be defined by the intensity of the natural phenomena that threaten the social system (Bohle, 2001). The risk and the hazard are therefore two of the basic quantities that were taken into account to construct the damage functions.

The **hazard** can be defined as the expected number of events of a certain severity in a region and period (N). The drought **risk** can then be considered as the expected damage (D) caused by an event of a certain severity for a given region and time interval (Hergarten 2004; Merz et al., 2009).

$$Risk = ND \tag{1}$$

N=expected mean number of drought events; D=expected Damage

This relation is not a universal statement, and it can only determine the risk of a drought of a certain severity. Considering all possible events, N can be represented by its cumulative density function P(s), where s represents the magnitude of a drought with a severity (s). The magnitude (s) in this context can either be the drought severity (sum of scores during dry conditions in a year), the area affected by a drought of a certain magnitude, or even follow a bivariate density function (the 'copulas', as described in Lee et al., 2013).

Following the formulation in Hergarten, (2004), let p(s) be the probability density of an event of size "s"

$$p(s) = -\frac{P(s)}{ds} \tag{2}$$

and D(s) the expected damage. The expected overall damage ($\bar{D}$) is then

$$\bar{D} = \int p(s)D(s)ds \tag{3}$$

and, the total drought risk can be determined by:

$$R = N\bar{D} = N\int p(s)D(s)ds \tag{4}$$

According to the previous definitions, the risk assessment relies on two main processes: the identification of a suitable distribution that can represent the drought events (**hazard**) and the assessment of the **damage** for a certain sector as a function of the drought severity.

Regarding the drought characterisation and modelling, considerable research has recently been carried out to model and define the **thresholds** that can be suitable for drought representation (e.g. Steinemann and Cavalcanti, 2006; Mishra and Singh, 2011; Carrao et al., 2014). On the other hand, little research is available regarding the link between damages and droughts (e.g. Jenkins, 2012; Jenkins, 2013), and no uniform methodology is universally accepted.

To estimate the damage functions, we therefore propose to link droughts to damages by simple and flexible **power-law dependence**:

$$D(s) = \alpha s^{\beta} \tag{5}$$

Here, α is the parameter that scales the function and represents the expected drought damage for a severity of 1. The exponent β can be unitary in some cases, representing a linear relation. However, as depicted in Table 12, the exponent β can also be greater than 1 (exponential growth) or smaller than 1 (limited growth relation). The shape of this relationship conditions the type of drought risk that is expected for each sector. The relationship between drought severity and damage depends on the sector type, the interrelations with other sectors, the diversification of the sector, the mitigation measurements taken to cope with droughts, and other predictable or unpredictable forcing factors.

Table 12 – Types of relations between drought severity and damages according to β.

Exponent β	Type of relation
β = 1	Linear relation
β < 1	Limited growth relation
β > 1	Exponential growth
β ≈ 0	No relation
β << 0	Possible positive effects of droughts

Figure 24 presents the shape of some ideal damage functions according to the value of the β parameter.

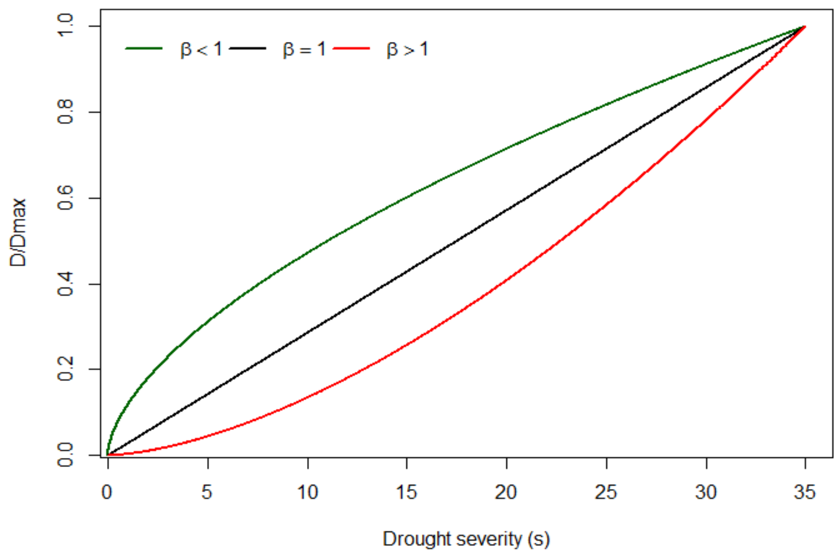

Figure 24 - Theoretical damage functions for different β values.

In most cases, the damage can be a **linear function** of the drought severity. For instance, a reduction in hydroelectric power generation or a reduction in inland waterways transportation may be determined as being proportional to the reduction in flows for a certain river basin. However, other factors can be present and may lead to changes in other sectors that cannot be taken into account using this methodology, as natural or even technological factors other than droughts can influence the sectors analysed.

Other fundamental questions need to be answered: which drought Indicator should be chosen? Which is the best aggregation or accumulation period? Are there universal thresholds or should we calibrate them depending on the case study? In the next section, we show that, unfortunately, the answers are not univocal.

6.3 Applying the damage functions to cereal yields and hydropower

Before testing the damage functions, we need to decide which **drought indicator** could best represent the drought hazard. Unfortunately, there is no univocal answer. Different drought indicators can be used to define drought events. In this research three meteorological drought indicators, as well as the aggregated indicator defined in previous sections, have been tested and selected in order to describe past European drought events (Spinoni et al., 2015a). These indicators are the Standardized Precipitation Index (SPI; McKee et al., 1993), the Standardized Precipitation Evapotranspiration index (SPEI; Vicente Serrano et al., 2010a, 2010b), and the Reconnaissance Drought Index (RDI; Tsakiris and Vangelis, 2005). All the indicators have been computed for 3-month and 12-month accumulation periods. As we will see in the following sections, the choice of the best indicator depends on the quantity (or quantities) under investigation.

We therefore propose the construction of damage functions at country level based on **power-law functions** (Hergarten, 2004) for two sectors where the impacts of droughts are direct and relevant, and for which quantitative and quality-checked data are available. The European countries analysed are those that did not change their borders during the past 50 years (e.g. we excluded the Czech Republic and Slovakia), to avoid data disaggregation issues. The sectors analysed are cereal **crop production** (kg/ha) and **hydroelectric power generation** (kWh) for which data were obtained from FAOSTAT and the World Bank Database. Also, inland water transportation of goods was preliminarily analysed using the Eurostat database, but it turned out that the data availability and quality are not of high enough quality to perform statistical analyses and draw conclusive results.

Cereal yields, measured as kilogrammes per hectare of harvested land, include wheat, rice, maize, barley, oats, rye, millet, sorghum, buckwheat, and mixed grains. Production data on cereals relate to crops harvested for dry grains only. Cereal crops harvested for hay or harvested greens for food, feed, or silage and those used for grazing were excluded. The FAO allocates production data to the calendar year in which the bulk of the harvest took place. **Hydroelectric power** generation refers to electricity produced by hydroelectric power plants in a country.

Differentiation and **detrend strategies** were tested for both sectors (Box and Jenkins, 1970). For the trend removal, a first order polynomial was fitted and then subtracted from the data, for the differencing procedure each value was subtracted from the previous one. This is equivalent to discrete-time differentiation. Also, the tri-annual differentiation was tested to avoid short term fluctuations. Finally, the degree of correlation between the detrended series and the drought indicators used in this study was assessed. In the future, the statistics dealing with the other tests could also be reported. Here we show the most relevant examples. A correlation analysis was firstly performed using the drought severity as an independent variable, but also using other drought-related characteristics, such as the total area affected by drought, the mean indicator per year, and the absolute minimum (Table 13).

Table 13 – Drought-related characteristics used to quantify annual drought magnitude. In particular, severity is computed as the sum, in absolute values, of monthly values below zero of the selected indicator.

Drought annual characteristic	Definition
Severity	$\sum Indicator < 0$
Mean	$\frac{1}{12}\sum Indicator$
Area affected	$\#\, pixel\ with\ Indicator < -1$
Absolute Minimum	$\min(Indicator)$

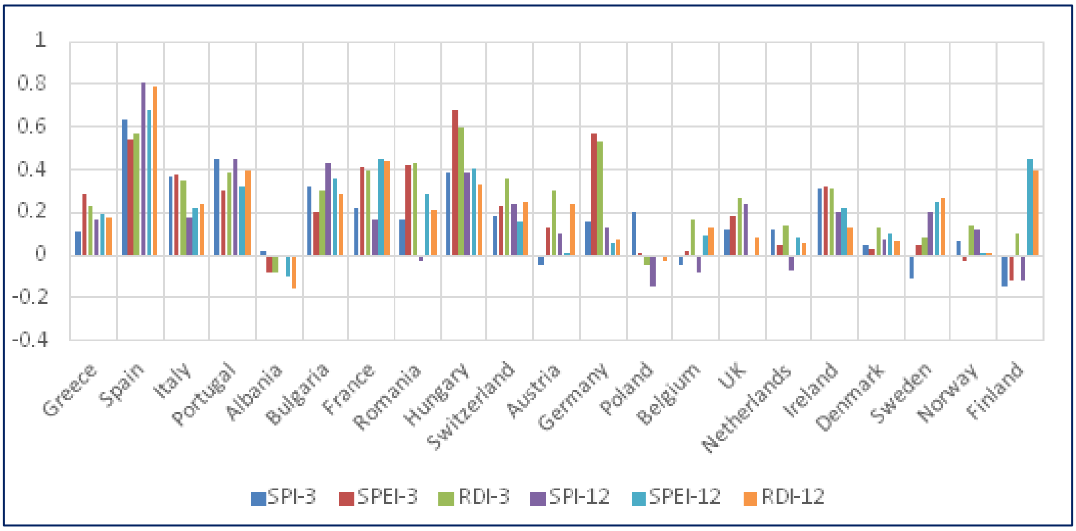

Figure 25 – Detrended cereal production compared to drought severity as reflected in six drought indicators.

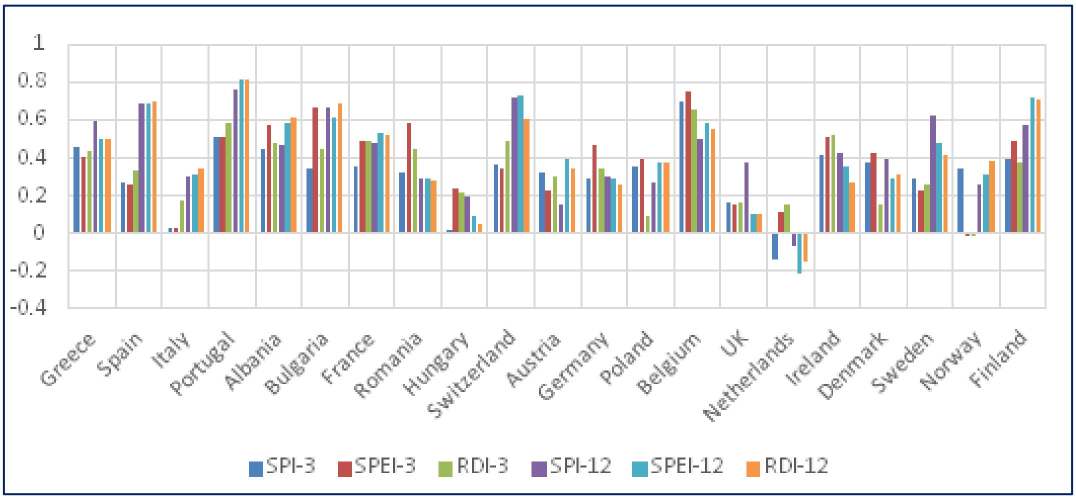

Figure 26 – Detrended hydropower generation compared to drought severity as reflected in six drought indicators.

Figure 25 and Figure 26 show the **correlation** results on a country basis. Overall, the highest correlations for **crop production** are achieved by using the **SPEI-3**. On a physical basis, the SPEI, with a seasonal aggregation period, seems to be able to effectively represent the seasonal water requirements needed for the different stages of crop growth. Usually, meteorological drought indicators such as the SPEI can also be satisfactorily applied to agricultural drought at medium-term accumulation periods (three or six months, see Mishra and Singh, 2010). Moreover, the best correlation is found for Spain and Hungary (Table 6). In some cases, such as for Spain or France, greater accumulation periods also produce good correlations (see Table 14).

Table 14 – Correlation Coefficients between detrended cereal crop production and drought severity

	SPI-3	SPEI-3	RDI-3	SPI-12	SPEI-12	RDI-12
Greece	0.11	0.28	0.23	0.17	0.19	0.17
Spain	0.64	0.54	0.57	0.81	0.68	0.79
Italy	0.36	0.38	0.35	0.17	0.22	0.24
Portugal	0.45	0.30	0.39	0.45	0.32	0.39
Albania	0.02	-0.08	-0.08	-0.01	-0.10	-0.16
Bulgaria	0.32	0.20	0.31	0.43	0.36	0.29
France	0.22	0.41	0.39	0.17	0.45	0.44
Romania	0.16	0.42	0.43	-0.03	0.28	0.21
Hungary	0.39	0.68	0.60	0.39	0.41	0.33
Switzerland	0.18	0.23	0.36	0.24	0.16	0.25
Austria	-0.04	0.13	0.30	0.10	0.01	0.24
Germany	0.16	0.57	0.54	0.13	0.05	0.07
Poland	0.21	0.01	-0.04	-0.14	0.00	-0.03
Belgium	-0.05	0.02	0.17	-0.08	0.10	0.13
UK	0.12	0.18	0.26	0.24	-0.01	0.08
Netherlands	0.12	0.05	0.14	-0.07	0.08	0.05
Ireland	0.31	0.32	0.32	0.20	0.22	0.13
Denmark	0.04	0.03	0.12	0.07	0.10	0.07
Sweden	-0.11	0.04	0.08	0.21	0.25	0.26
Norway	0.07	-0.03	0.14	0.12	0.00	0.01
Finland	-0.15	-0.12	0.10	-0.12	0.45	0.40

Hydroelectric power generation is best modelled with the **SPEI-12** in line with usual reservoir management timescales and the common timescale used to assess hydrological drought events. Best correlations were reported for Portugal and Belgium (Table 15).

Table 15 – Correlation Coefficients between detrended hydroelectric power and drought severity

	SPI-3	SPEI-3	RDI-3	SPI-12	SPEI-12	RDI-12
Greece	0.46	0.40	0.44	0.59	0.50	0.50
Spain	0.27	0.26	0.34	0.69	0.69	0.70
Italy	0.03	0.02	0.17	0.30	0.31	0.34
Portugal	0.51	0.51	0.59	0.77	0.82	0.81
Albania	0.45	0.57	0.47	0.47	0.58	0.62
Bulgaria	0.35	0.66	0.45	0.67	0.62	0.69
France	0.36	0.49	0.49	0.47	0.53	0.52
Romania	0.32	0.58	0.45	0.29	0.29	0.28
Hungary	0.01	0.23	0.22	0.20	0.09	0.05
Switzerland	0.37	0.34	0.49	0.72	0.73	0.60
Austria	0.32	0.23	0.30	0.15	0.40	0.35
Germany	0.29	0.46	0.35	0.30	0.29	0.26
Poland	0.35	0.39	0.09	0.27	0.37	0.37
Belgium	0.70	0.75	0.66	0.50	0.59	0.55
UK	0.16	0.15	0.16	0.38	0.10	0.10
Netherlands	-0.14	0.11	0.16	-0.07	-0.22	-0.15
Ireland	0.42	0.51	0.52	0.42	0.35	0.27
Denmark	0.38	0.42	0.16	0.40	0.29	0.31
Sweden	0.29	0.23	0.26	0.62	0.48	0.42
Norway	0.35	-0.01	0.00	0.26	0.31	0.39
Finland	0.39	0.49	0.38	0.58	0.72	0.70

Drought damage functions were then computed using the detrended quantities and the drought severity derived from the SPEI-3 for the cereal production and the SPEI-12 for the hydropower generation. In Figures 27 and 28, we show the **best fit functions** together with the β parameter for the countries where a significant relation was found. The lack of significant relations for some countries can be due to different factors: The lack of data is the most important obstacle to obtaining robust estimations when analysing weather/climate extremes. By definition, as extremes represent the very tail of the distribution with few data points, long-term time series are needed to obtain sufficient data for robust statistics.

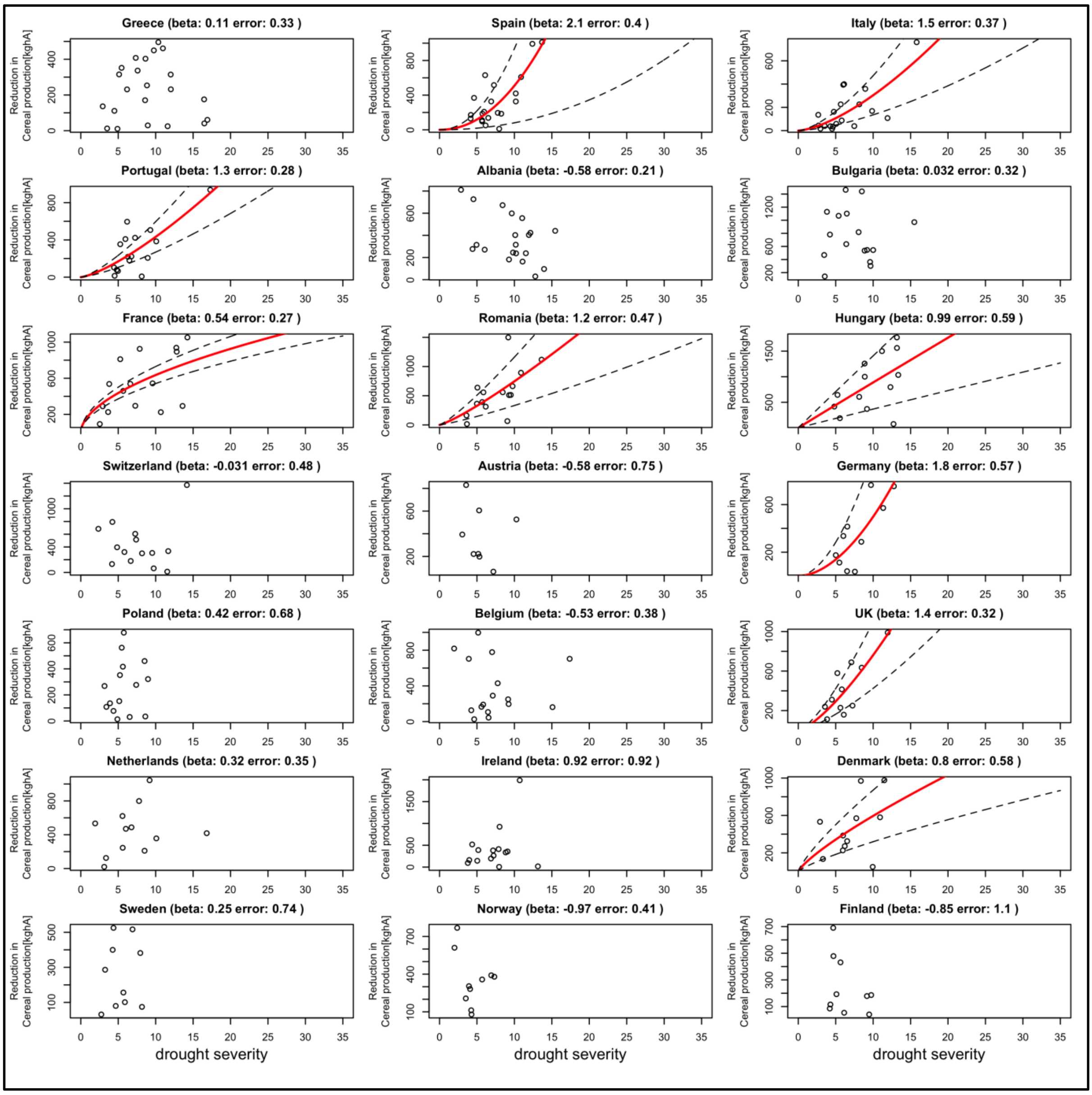

Figure 27 - Drought-damage functions depicting the relationship between reduction in cereal crop production and magnitude of the drought severity. Red lines are presented only for relevant correlations: only nine out of twenty-one countries show a statistically robust correlation.

Moreover, as we discuss later, drought is not the only factor affecting the analysed sectors. The implementation of new technologies, irrigation schemes, the artificial management of water flow in European rivers or changes in policies, for example, can override the relationship between drought severity and its impacts. In order to be able to separate the impacts resulting from various **external factors** from the drought impact, other methodologies such as I/O functions could be explored. However, I/O functions are not yet suited for the analysis of extreme events such as droughts, while damage functions are widely used and their relative simplicity makes it easy to communicate statistically significant and therefore robust results to decision makers.

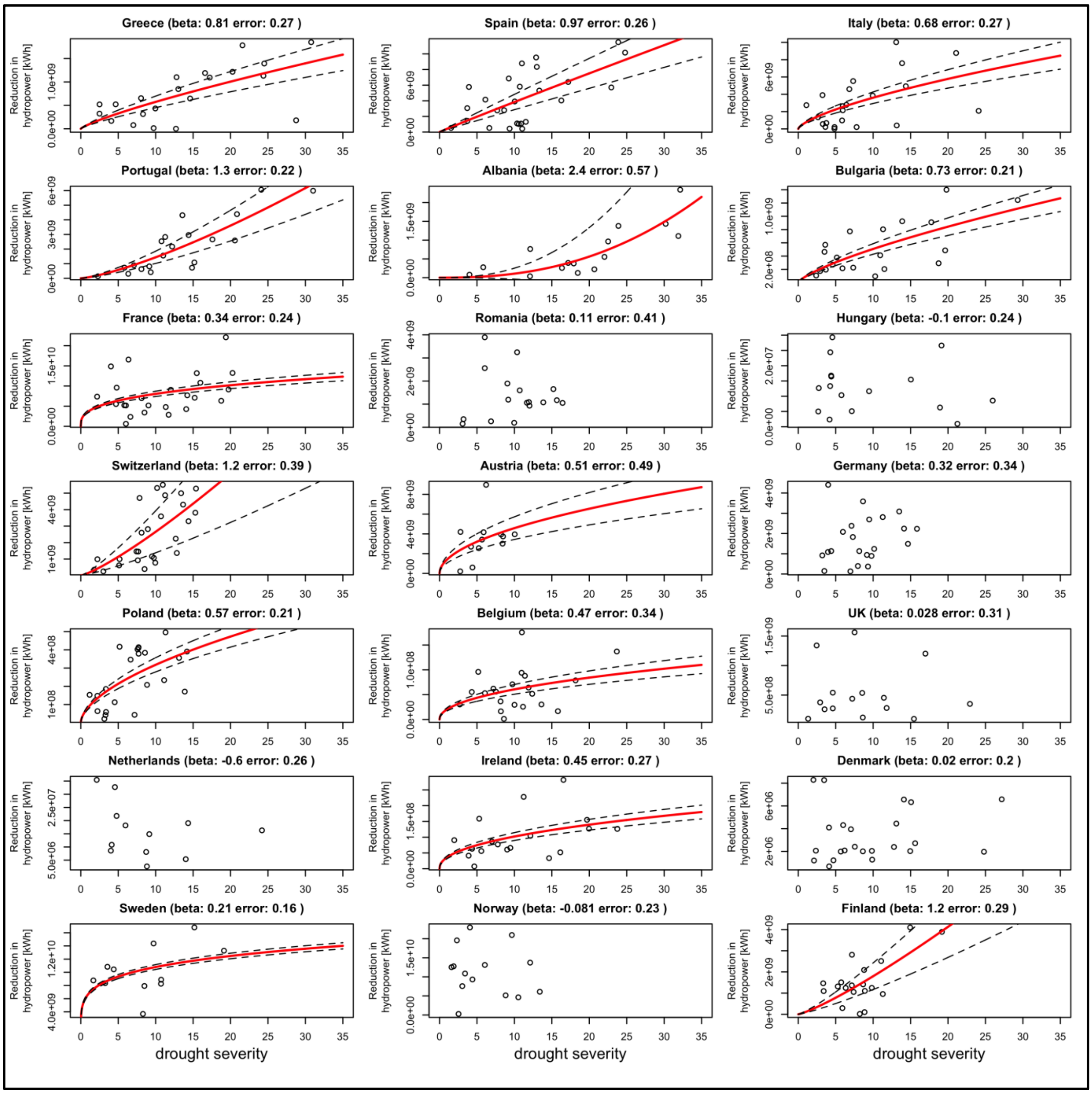

Figure 28 – The same as Figure 27 but for hydropower generation.

In Figures 27 and 28, the uncertainties are represented with dashed lines. They have been calculated using an error propagation analysis that can be summarised in a few steps.

The damage function is defined as:

$$D(s) = \alpha s^{\beta} \tag{5}$$

The partial derivative of D with respect to s is then:

$$\frac{\partial \mathrm{D}}{\partial \mathrm{s}} = \pm \alpha \beta \mathrm{s}^{\pm(\beta-1)} \tag{6}$$

Multiplying the previous equation by $\frac{D}{\alpha s^{\beta}} = 1$, we obtain:

$$\frac{\partial \mathrm{D}}{\partial \mathrm{s}} = \frac{\pm \mathrm{D} \alpha \beta \mathrm{s}^{\pm(\beta-1)}}{\alpha \mathrm{s}^{\beta}} \tag{7}$$

That can be reduced to:

$$\frac{\partial \mathrm{D}}{\partial s} = \pm \frac{\beta \mathrm{s}}{\mathrm{s}} \tag{8}$$

And, finally, we obtain the uncertainties as:

$$\sigma_{\mathrm{D}} = \left(\frac{\pm \beta \mathrm{s}}{\mathrm{s}}\right) \sigma_{\mathrm{s}} \tag{9}$$

Though mathematically these uncertainties give an idea of the spread of values of the damages, other physical sources of **uncertainties** should also be taken into account. For example, one should take into account the uncertainties related to the selection of the drought indicator: those related to the computation of the indicator, those regarding the selection and the quantification of the events used to compute the functions, and those related to the quality and accuracy of the impact data.

Regarding **cereal yields** (Figure 27), an exponential relation (β>1) is observed for most of the Mediterranean countries. This reflects the high vulnerability of these countries where water scarcity is a tangible constraint, in particular during hot and dry summers, which have increased significantly over the past decades (IPCC, 2014). The United Kingdom, Romania and Germany also show an exponential relation with β>1, but in lower proportions; in some cases the relation is almost linear. On the other hand, Norway and Finland are characterised by a negative β, suggesting a possible beneficial relationship between crop yields and drought. This might be related to the longer sunlight periods during such events in the northern regions. Similar findings have been discussed by Olesen and Bindi (2002), Maracchi et al. (2005), Alcamo et al. (2007), and Olesen et al. (2011), where climate-related increases in crop yields during drought conditions are expected in northern Europe, while the largest reductions are expected in the Mediterranean region, in the south-western Balkans, and in southern European Russia.

On a **country basis**, the plot of the β parameter for the selected countries (Figure 29) shows notable regional differences between northern and southern countries. These differences can be explained by the different limitations to crop growth in northern and southern regions. Cold temperatures and short growing seasons are the biggest limitations in northern Europe, whereas high temperatures and persistent dry periods during summer usually limit the crop production in southern Europe (Olesen et al., 2011).

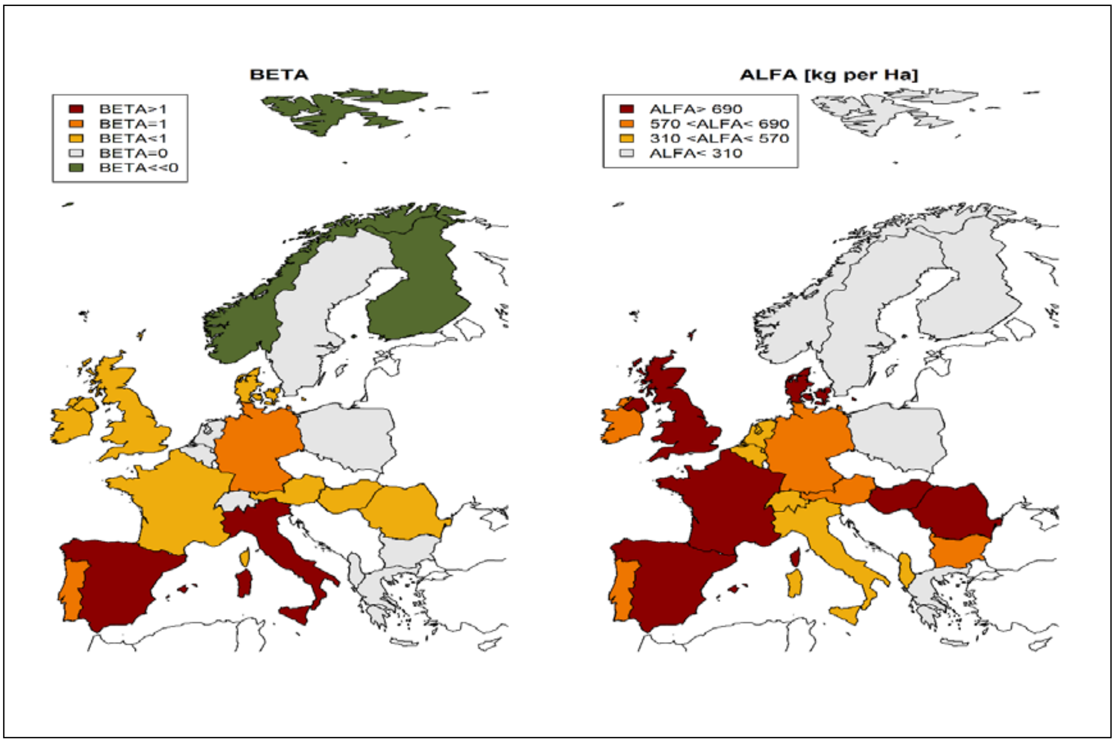

Figure 29 - Parameters α and β obtained for the relation between drought severity and reduction in cereal crop production.

With respect to **hydroelectric power generation** (Figures 28 and 30), a consistent relation is observed for most of the countries except for the Netherlands, the United Kingdom, Germany, Denmark and Norway. The countries that are most vulnerable (β>1) are Albania, Portugal and Switzerland. These countries rely heavily on electricity production from hydroelectric sources: 100% in Albania, 55% in Switzerland, and 22% in Portugal. The absence of a relationship between droughts and hydropower generation in Norway can be due to the smooth development of their market since the deregulation that started in 1990. As depicted in Amundsen et al. (2006), this allowed the Norwegian market to deal with the 2002-03 winter drought (Finon et al., 2004; Doorman and Botterud, 2008) thanks to good management practices.

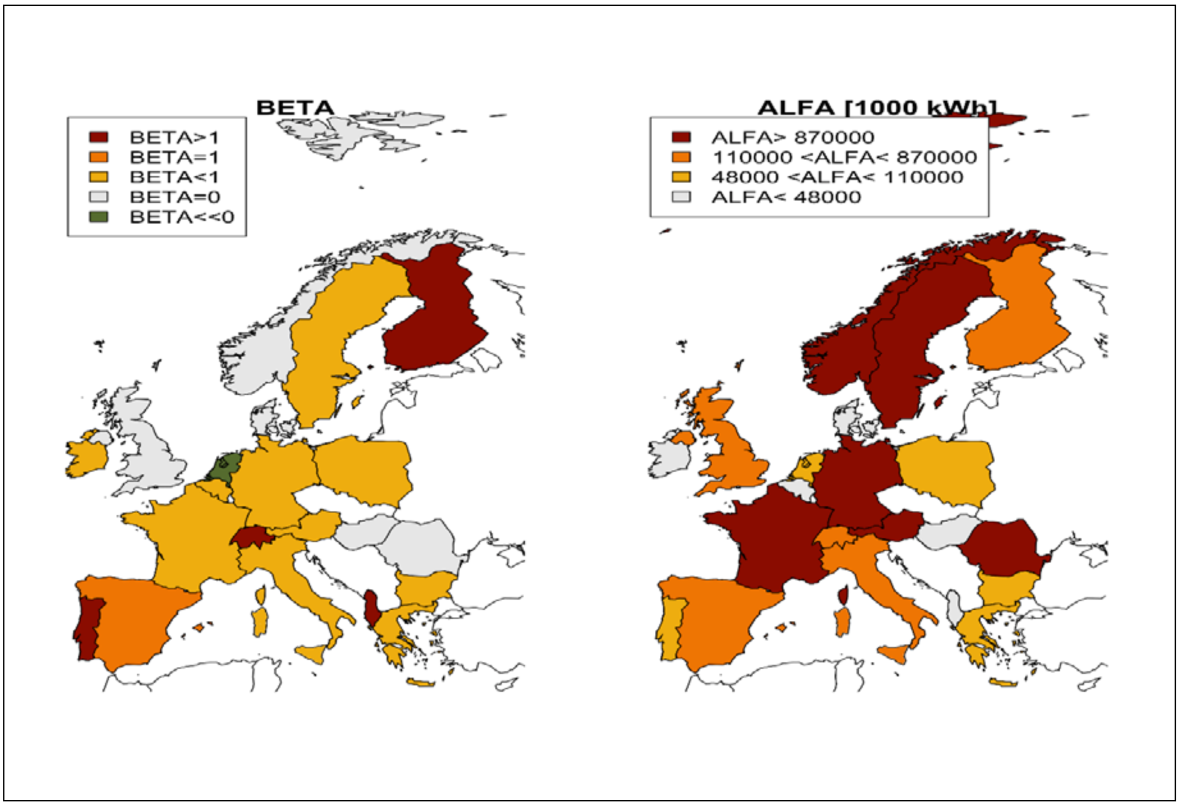

Figure 30 – The same as in Figure 29, but for hydroelectric power production.

The contribution of large and small events to the annual damage of a sector can help to understand how a sector is affected by a certain natural hazard and how the risk is perceived. Typically, more attention is given to the most severe events that are associated with high damages but also with a low probability of occurrence. On the other hand, less severe but more frequent events can lead to similar damages if compared with extreme events. Figure 31 shows the **contribution** of drought events of a certain severity on the total reduction in cereal and hydroelectric power production: both sectors have different damage behaviours. The cereal production sector is characterised by greater losses resulting from the less severe but more frequent drought events, while the hydropower sector is mainly affected by the most severe events. Further investigations should be carried out to detail this behaviour.

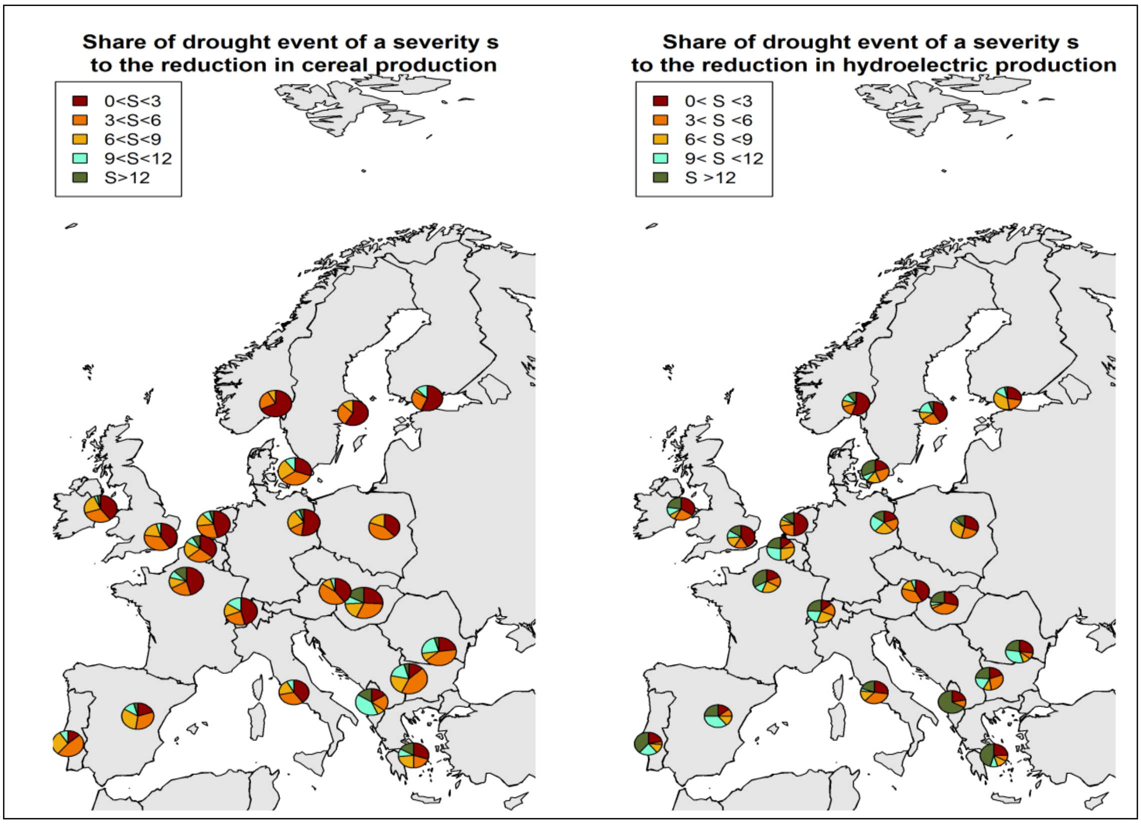

Figure 31 – Contribution of drought events of a given severity to the total reduction in cereal production (left) and hydroelectric power (right).

6.4 Sensitivity analysis and model validation

As already stressed, the damage functions presented should be considered as preliminary results. A **sensitivity analysis** and model validation is, therefore, important. To preliminarily assess the robustness of the damage functions, we studied how the uncertainties in the input factors (methodology used, selection of samples, etc.) can propagate through the overall estimation of the damage functions. To do so, different Monte Carlo simulations (e.g. Binder, 1987) were performed in order to assess the contribution of the individual sources of uncertainty to the output variance. This methodology is based on multiple evaluations of the model with different samples that generate different probabilistic density functions (the 'pdf', see for example Parzen, 1962) of the model outputs.

The analysis of extreme events is directly linked to the **sample size**. By definition, droughts are events with a low (but not extremely low) probability of occurrence. Combined with the limited availability of impact data, this makes the estimation of damage functions unstable or even unpredictable. With decreasing sample size, the uncertainties associated with the estimation could sharply increase. An example is provided in Figure 32: the estimation of the drought damage function for inland water transportation in Germany, considering all samples (n=7) and the estimation without the year 2009 (n=6). During 2009, no severe droughts were observed in Germany, but the transport performance of European inland waterways declined between 15% and 25%.

This was due to the economic and financial crisis that hit the steel industry and led to a severe reduction in transport demand for coal, iron, and metal products, but also for port-hinterland transport of containers (UNECE, 2014). As shown in Figure 32, the estimation for the year 2009 shows high uncertainties (i.e. wide confidence intervals) and low correlation coefficients. The estimation performed without the 2009 data (that can be roughly considered an outlier) shows a closer relationship between drought severity and inland water transport, as depicted by the estimation of the coefficients of determination (r^2=0.85 for exponential relation and r^2=0.93 for linear fit) and the narrower confidence intervals.

This example shows the need to **cross-check the information** on losses within different sectors and their relationship with the analysed hazard, in order to avoid introducing effects that are not related to the specific hazard. In most cases, the damage can be a linear function of the drought severity. For instance, the reduction in hydroelectric power generation or a reduction in inland waterways transportation may be determined as proportional to the reduction in river flows in a certain river basin. However, there are other factors that can lead to changes in each sector that cannot be taken into account using this methodology, as there are other natural or even technological factors apart from droughts that influence the sectors analysed.

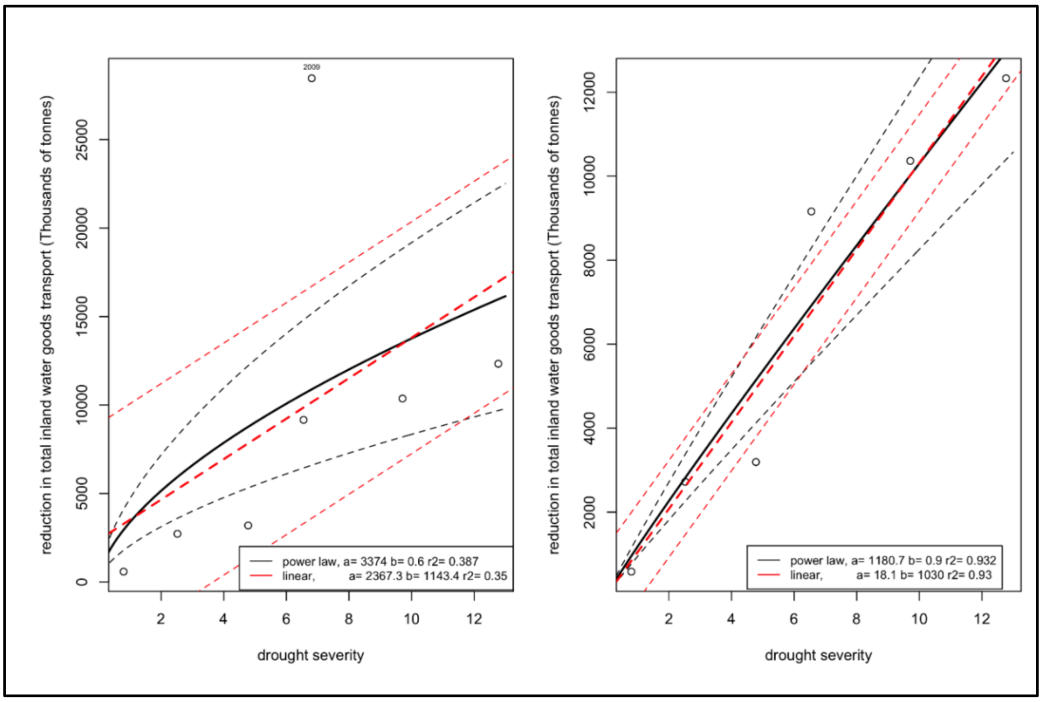

Figure 32 - Country-specific damage functions depicting the relationship between Inland Water Transportation and drought magnitude in Germany. Left: all cases with relevant reduction of goods transported; right: Same sample but without year 2009.

The **complexity** of this model increases when more sectors are considered. In a recent publication, Jenkins (2013) highlighted that modified **Input-Output** models are suitable to assess the propagation of economic losses across multiple sectors. An indirect loss assessment can provide more comprehensive estimations of drought losses for current or projected climate scenarios. However, the methodology is still not satisfactorily calibrated to consider extreme events (Okuyama, 2007) and further research is therefore needed.

The uncertainties due to the sample size and definition can be evaluated through a sensitivity analysis of the model. As described in Naumann et al. (2012), a non-parametric **bootstrap** method was applied to assess the uncertainties. The initial idea behind resampling tests is to perform a collection of artificial data batches of the same size as the actual data, and then to compute the test statistics for each artificial batch. The results provide a number of values of the test statistics corresponding to the number of artificially generated data batches (Wilks, 2011).

Let us assume that a random sample of observations (X={X1, X2,..., Xn}) is used to obtain a sample estimate (θs) of a parameter of interest (θ), which can be the shape or scale parameter that defines the gamma distribution for X. The purpose of bootstrap simulation is to estimate the uncertainty (bias and variance) associated with the sample estimate (θs). According to Efron and Tibshirani (1993), a random sample size of size *n* is drawn with replacement from the original sample.

Using the k^{th} bootstrap sample of a given number of *b* bootstrap simulations we have:

$$X^*(k) = \{X^*1, X^*2, \ldots, X^*n\} \qquad k=1,2,\ldots,b \tag{10}$$

A new bootstrap estimate θk* of θs can be obtained. The set of θ*= {θ*1,βθ*2,...,βθ*b} constitutes the sampling distribution of θs. The bootstrap estimate of the bias is then:

$$\text{Bias} = (\theta^*m - \theta s) \tag{11}$$

Where *θ*m* represents the average of all bootstrap estimates θ*. This leads to the bias-corrected estimator of parameter θ, which is:

$$\theta = \theta s - \text{Bias} = 2\theta s - \theta^*m \tag{12}$$

And the variance of θs is estimated by:

$$\text{Variance} = 1/(b-1)^*\text{sum}\{k=1 \text{ to } b\}(\theta^*k - \theta^*m) \tag{13}$$

Figure 33 shows the country-specific damage functions that depict the relationship between a reduction in crop production and drought severity for France, and between a reduction in hydropower generation and drought severity for Spain. This function was fitted for the original parameters of an exponential function by using the parameters obtained after the bootstrap technique (see the equations above). Figure 33 also shows the estimation and the family of functions associated with the **bootstrap resampling**. Though members of this family could vary widely, in this case they are all between the error bands.

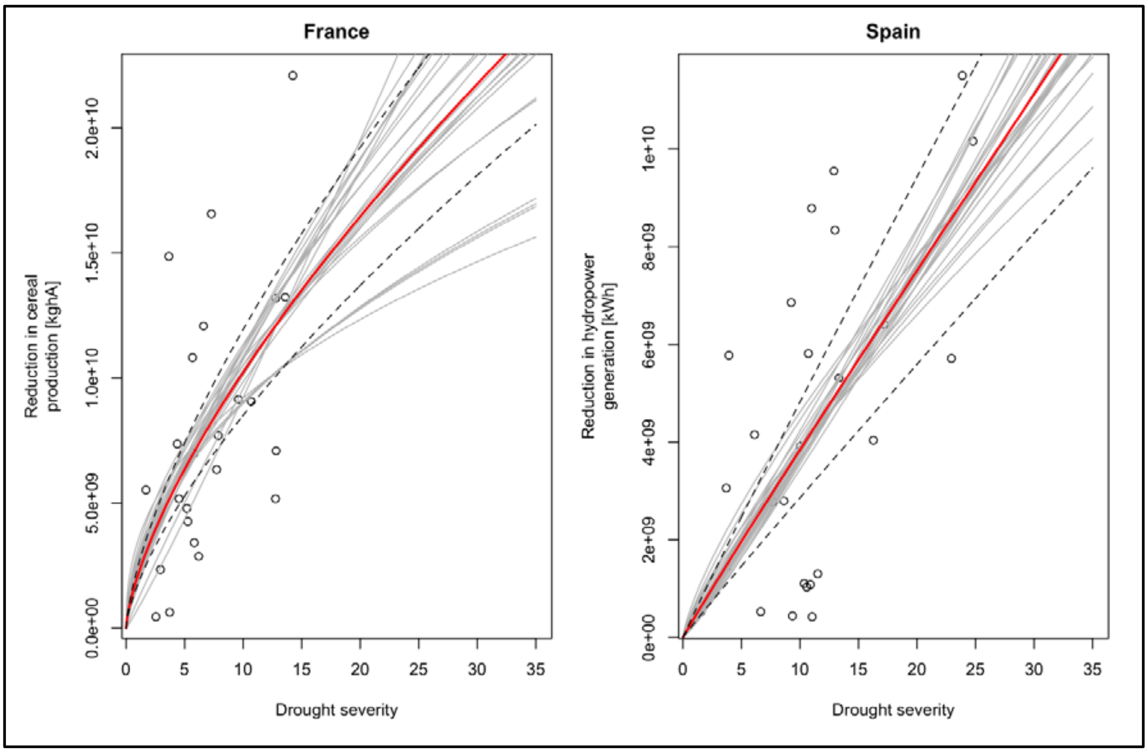

Figure 33 – Country-specific damage functions depicting the relationship between a reduction in crop production and drought severity for France (left) and between hydropower generation and drought severity for Spain (right).

This approach could be used to assess and communicate uncertainties to **decision makers**. The uncertainties are intrinsically associated with the datasets, and can help better understand for which situations (and also sectors, countries, spatial resolutions) this tool is more reliable than others. Moreover, this approach could allow for the quantification of the uncertainties when the damage functions are used to assess future projections. For instance, it is possible to use the distribution information for each member of the bootstrap as initial conditions to develop drought damage scenarios. These types of scenario could also prepare decision makers and local stakeholders to take the appropriate action in high- or low-risk situations. Figures 34 and 35 show other examples of damage functions and sensitivity analyses regarding crop reduction and hydropower generation in Romania and Germany.

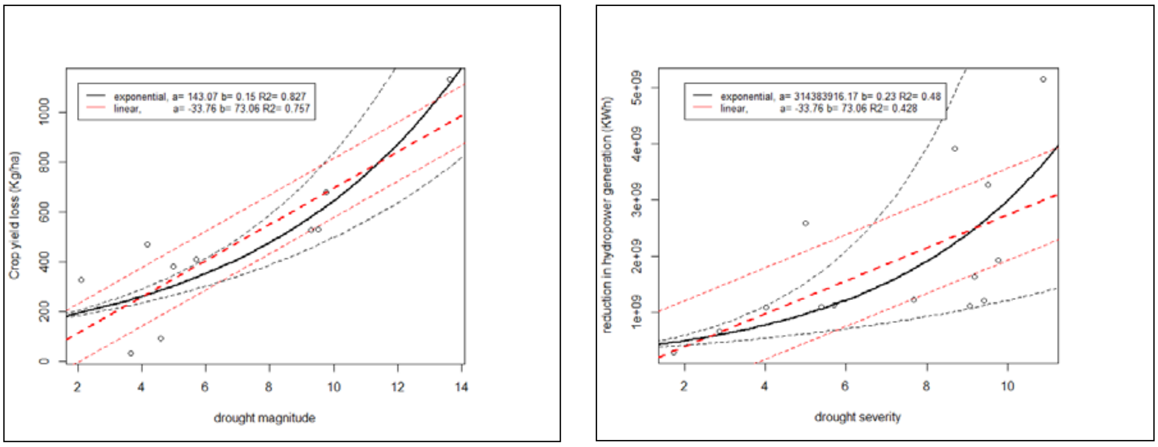

Figure 34 - Country-specific damage functions depicting the relationship between crop yield losses (left) and hydropower generation (right) and drought magnitude in Romania.

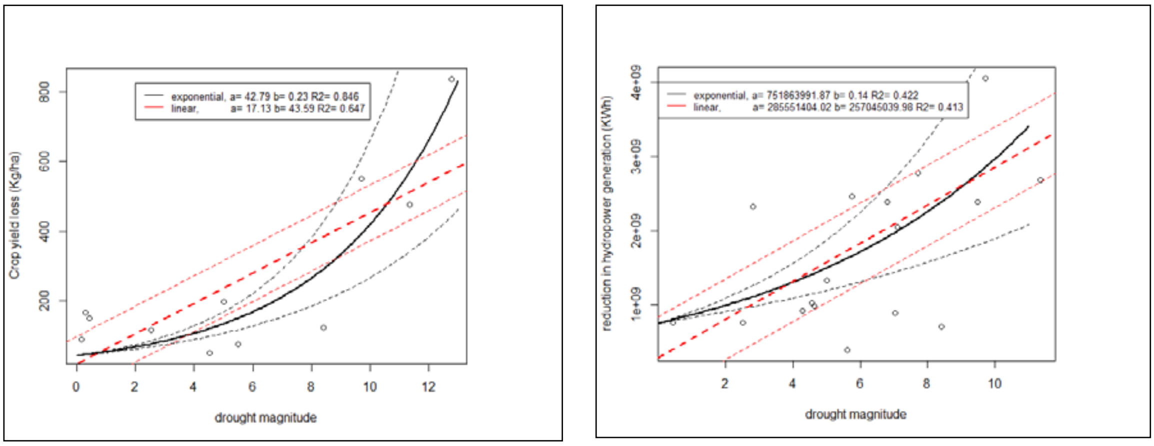

Figure 35 - Country-specific damage functions depicting the relationship between crop yield losses (left) and hydropower generation (right) and drought magnitude in Germany.

7. Projecting drought events towards 2100

In the context of **climate change**, characterised by rising temperatures and more extreme precipitation regimes, drought is considered to be one of the most relevant natural disasters, and it is generally assumed that the situation will get worse in the coming decades, with southern Europe as a hotspot for drought (Sheffield and Wood, 2008; Forzieri et al., 2014). However, due to the intrinsic nature of drought and its multiple definitions, the evaluation of **future drought patterns** should be generally handled with care due to the various sources of uncertainties (Burke and Brown, 2008).

This section describes a methodology based on the **projections of meteorological variables**, i.e. precipitation, and potential evapotranspiration, according to the moderate emissions scenario A1b until 2100 (e.g. see IPCC, 2000, for details on climate scenarios). Potential evapotranspiration has been calculated following the Penman-Monteith methodology, which takes into account several meteorological variables as well as the aerodynamic resistance of the land surface. The projected variables formed the basis to compute two indicators, i.e. the **SPI** and the **SPEI** (at 3- and 12-month accumulation scales) over the period **1950-2100**. A set of drought variables – frequency, duration, severity, and intensity – was then derived for the whole of Europe (excluding Iceland) both at grid-point (0.25°x0.25°) and country scale.

The approach focuses on the **characteristics of the events**: namely, we discuss how the average duration, severity, and intensity of the meteorological drought events are projected to change in the near future (**period 2041-2070**) and in the far future (**period 2071-2100**) as compared to the past three decades (period 1981-2010). The last part of this section provides an overview of the European drought tendencies for future decades, based only on the comparisons of the drought indicators. Although there are possible **drawbacks** of our methodology, which we address in this report, the choice of an event-based approach greatly reduces the shortcomings compared to an approach based on the cumulated drought variables.

The projected drought variables, in particular the average drought severity of an event at country level, have been used as input in order to project drought impacts through the damage functions. As we discuss in next chapters, we applied the parameters derived from past drought events and impacts to possible **drought events in the future**, in order to account for the **projected** increase or decrease of **drought impacts** in Europe for the sectors already discussed in Section 2 (cereal crop production and hydropower electricity generation).

7.1 Projecting the input variables according to the scenario A1b

In 2000, the Intergovernmental Panel on Climate Change published a special report on **emission scenarios**, the SRES (IPCC, 2000). Four main categories (or scenario families) were defined: A1, A2, B1, and B2. The A1 scenario family describes a future world of very rapid economic growth, global population that peaks in the 2050s and declines thereafter, and the rapid introduction of new and more efficient technologies. The A2 scenario family describes a very heterogeneous world: economic development is mainly regionally oriented, the economic growth and technological change are slower than in other scenarios, and population will continuously increase, although the process will be slow. The B1 scenario describes a convergent world with the same global population, which peaks in the mid-century and declines thereafter, but with rapid changes in economic structures toward reductions in material intensity and the introduction of clean and resource-efficient technologies, improved equity, but no additional climate initiatives. The B2 scenario describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability: the population will continuously increase in a world that has intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1 scenarios (IPCC, 2000, 2001).

The **A1 scenario** category can be divided into three subcategories which correspond to different directions of technological change in the energy system. They refer to the fossil-intensive energy sources (A1FI), to the non-fossil energy sources (A1T), and to a balance across all sources (A1B). 'Balance' indicates similar improvement rates which apply to all energy supply and end-use technologies (IPCC, 2000). As we can see from Figure 36, the A1B scenario is the most balanced and foresees moderate but increasing emissions of carbon dioxide (CO_2) and methane (CH_4) until the mid-century, followed by a slow but remarkable decrease thereafter. Nitrous oxide (N_2O) emissions are projected to be stable through the whole of the century, and the sulphur dioxide (SO_2) emissions are projected to increase until the 2030s and to decrease thereafter.

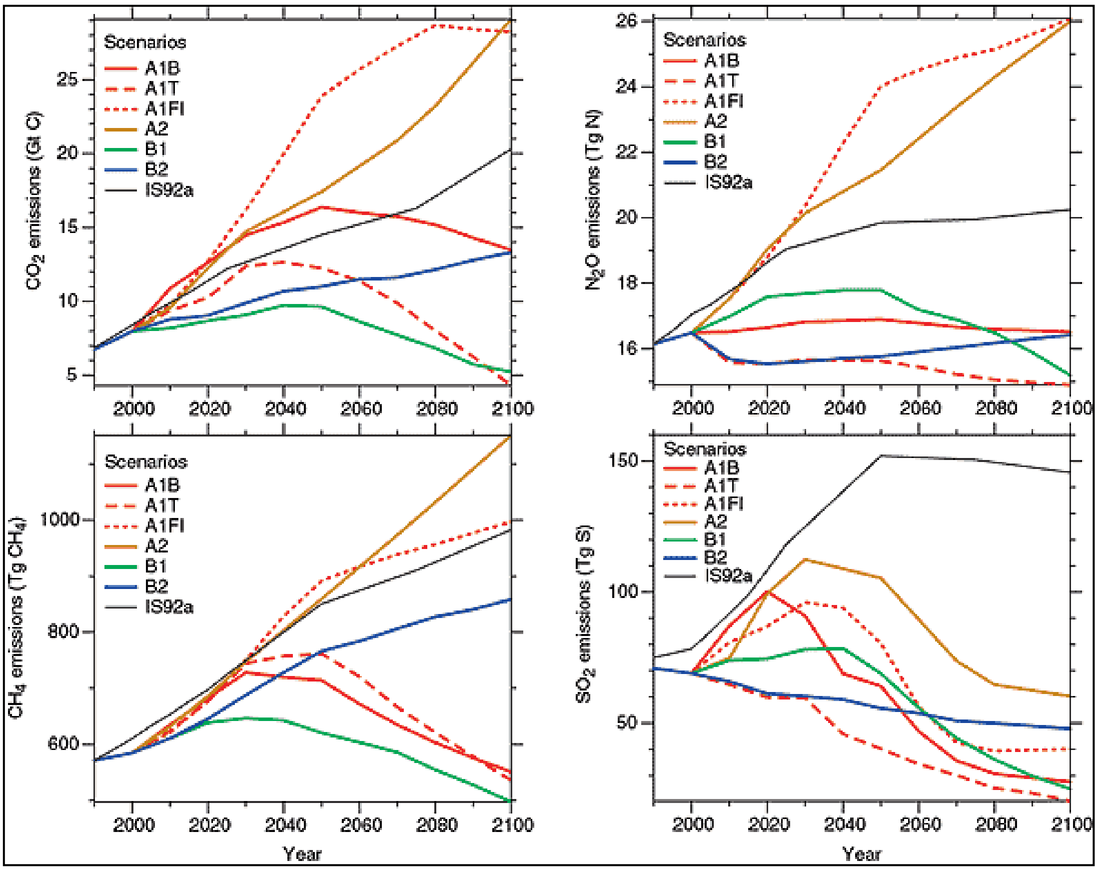

Figure 36 - Global anthropogenic emissions of CO_2, CH_4, N_2O and SO_2 for the six illustrative SRES scenarios (A1B, A2, B1 and B2, A1FI and A1T). The IS92a scenario is also shown for comparison (IPCC, 2000, 2001).

The **four scenario families** are expected to lead to different consequences for the climate, agricultural, and socio-economic systems. In the fifth, and latest, assessment report (IPCC AR5, 2014), it was discussed how much the various scenario models have been able to represent what effectively happened in the past decades, and it emerged that the four scenario families, and in particular the A1 class, are able to provide an effective picture of the actual global change (see Figure 37), only slightly overestimating the emissions and, more remarkably, the temperature rise.

For this reason, we selected the **A1b family** to make drought event projections towards the end of the century. Our choice was also based on two other important reasons: firstly, the climate-related analyses in the framework of the PESETA II project were performed using the moderate A1b scenario family for future projections (Ciscar et al., 2014); secondly, the fifth IPCC assessment report – with its new or refined scenario models – was not officially published when the choice of the methodologies to use regarding this report were made, i.e. at the end of 2013.

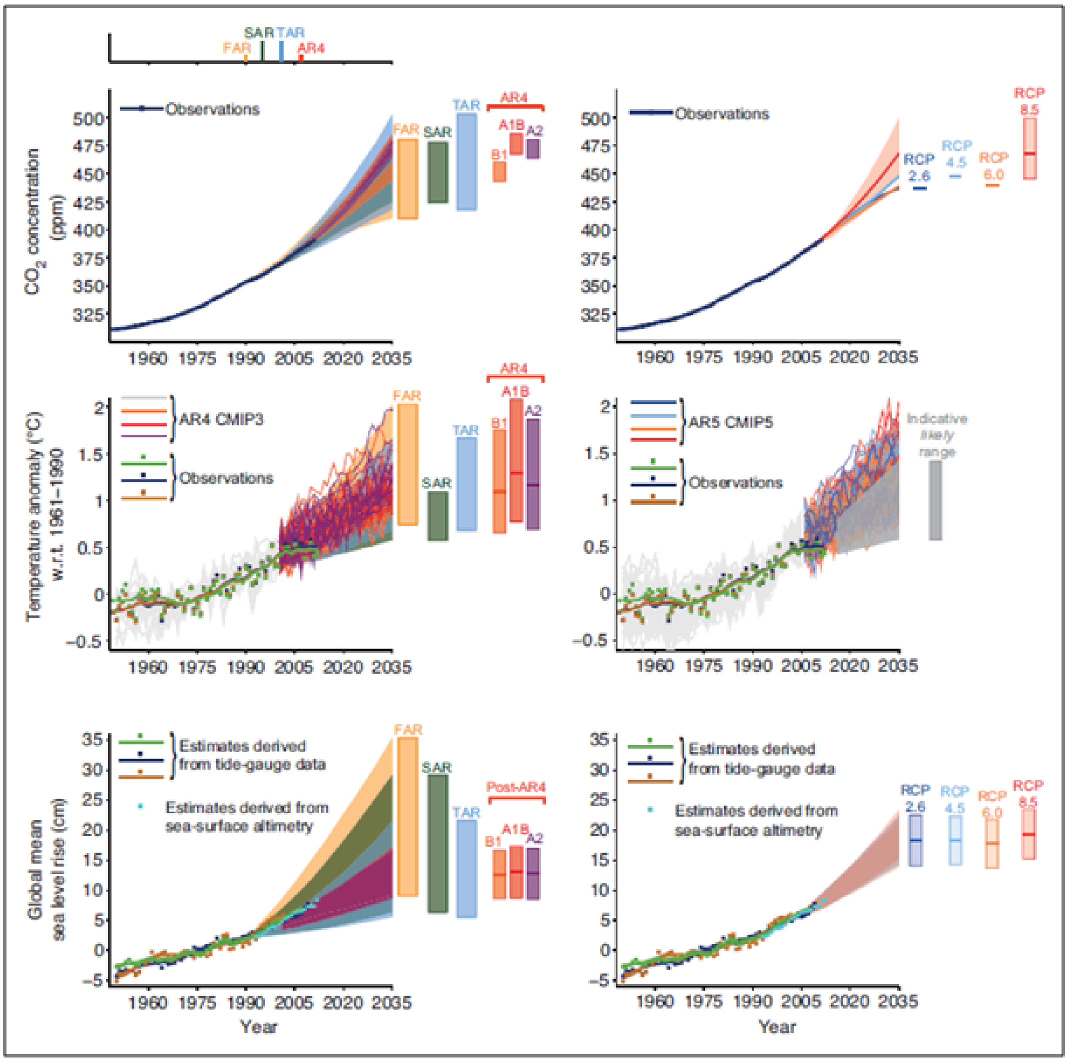

Figure 37 – Global carbon dioxide emissions, temperature, and sea level rise comparisons between scenario predictions of the five assessment reports (FAR: IPCC, 1990; SAR: IPCC, 1996; TAR: IPCC, 2001; AR4: IPCC, 2000 and 2007; and AR5 CMIP5: IPCC, 2013) and the observations (IPCC, 2014).

During the past years, many different simulations in the scenario family A1b have been created and applied to a wide range of different sectors. To name a few examples, they have been used to study the climate feedbacks between atmosphere and ocean (Soden and Held, 2006), the shift of the Arctic and Antarctic ice areas (Bracegirdle et al., 2008), the sea level rise (Horton et al., 2008), the more frequent precipitation extremes (O'Gorman and Schneider, 2009), socio-economic impacts (Arnell, 2004), tourism (Hamilton et al., 2005), health issues (Selin et al., 2009), and agriculture (Lavalle et al., 2009).

However, though some studies deal with drought projections (e.g., Burke et al., 2006; Hirabayashi et al., 2008; Sheffield and Wood, 2008; Dai, 2011a), only few studies deal with **drought projections** in Europe (Lehner et al., 2006). To overcome such lack, we we selected the KNMI regional atmospheric climate model **RACMO** (version 2.1: van Meijgaard et al., 2008), provided by the Royal Meteorological Institute of the Netherlands, and its output variables (precipitation and potential evapotranspiration) modelled from 1950 to 2100. The spatial resolution is the same as the E-OBS grids provided by the KNMI ECA&D (Haylock et al., 2008), that is: 0.25°x0.25°. The data are provided with monthly temporal resolution. Iceland was excluded from the analyses, for its data failed the homogenization tests in the 2000s.

7.2 Computing the drought indicators over the period 1950-2100

Gridded series of monthly temperature and potential evapotranspiration, modelled and projected from 1950 to 2100, have been used to compute two selected drought indicators, the Standardized Precipitation Index (SPI: McKee et al., 1993) and the Standardized Precipitation-Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010). Monthly series of SPI-3, SPI-12, SPEI-3 and SPEI-12 have been computed for every grid point (0.25°x0.25°), as have the corresponding averaged series at country level. Figures 38-43 show, as examples, the averaged **SPI-3 and the SPEI-3 series for Germany** for each of the three analysed 30-year periods that represent the recent past, future and far future.

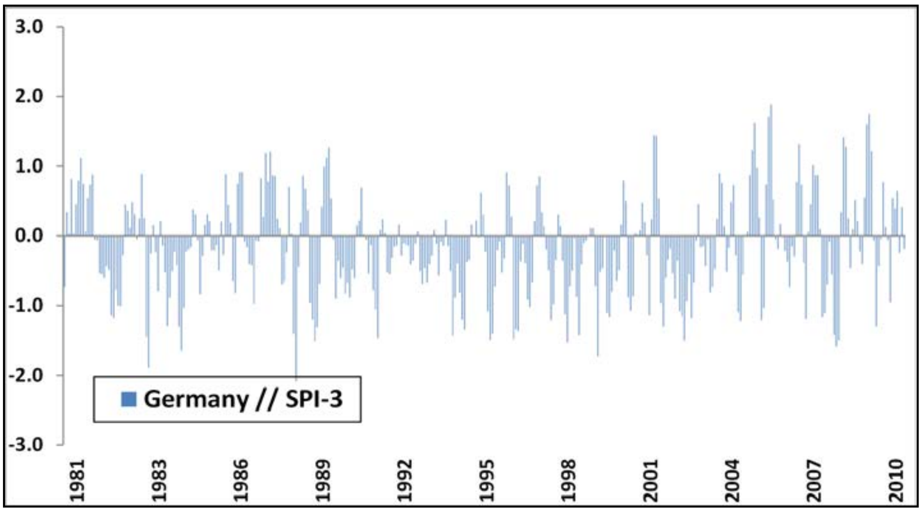

Figure 38 – Average SPI-3 series for Germany for the recent past (1981-2010).

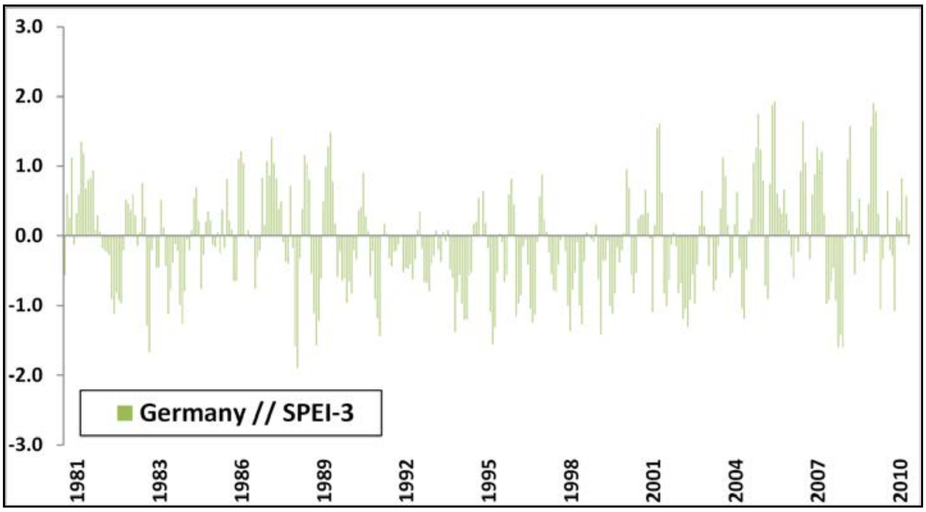

Figure 39 – Average SPEI-3 series for Germany for the recent past (1981-2010).

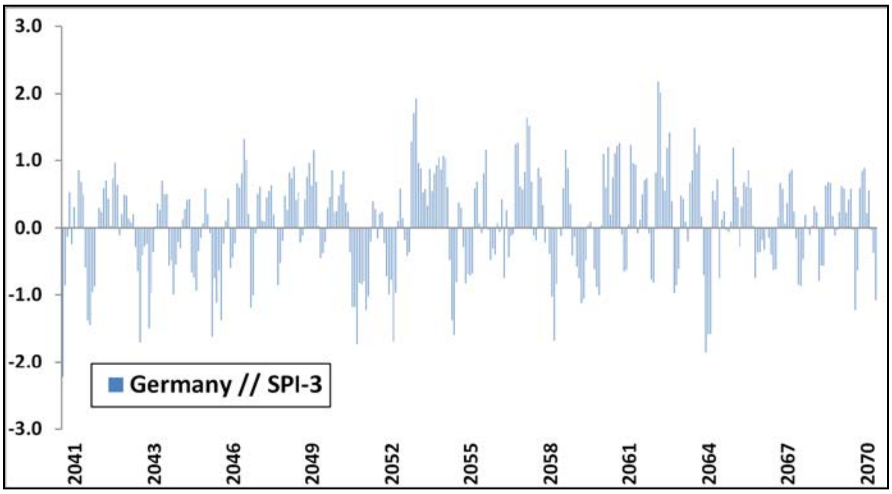

Figure 40 – Average SPI-3 series for Germany for the near future (2041-2070).

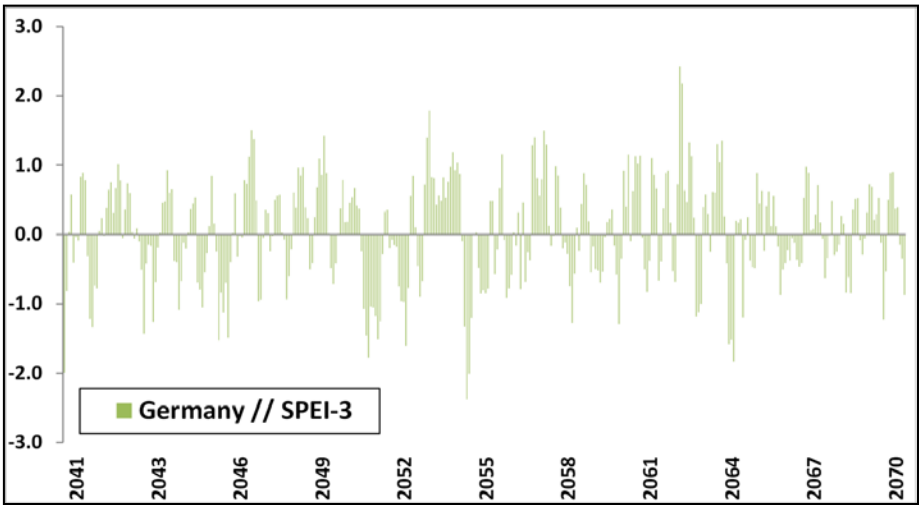

Figure 41 – Average SPEI-3 series for Germany for the near future (2041-2070).

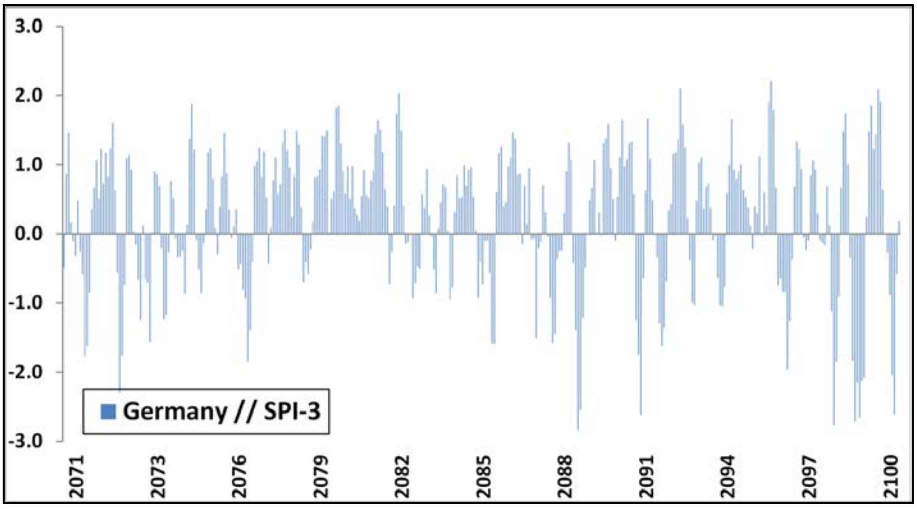

Figure 42 – Average SPI-3 series for Germany for the far future (2071-2100).

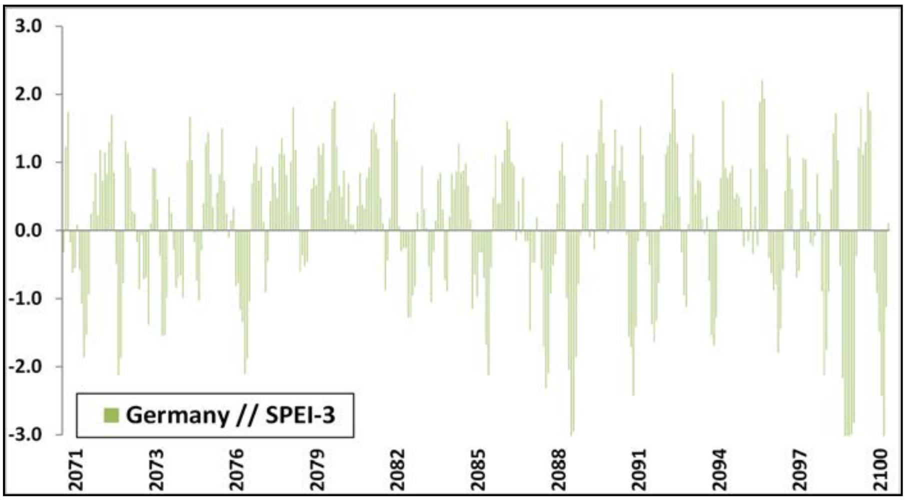

Figure 43 – Average SPEI-3 series for Germany for the far future (2071-2100).

Dealing with standardised indicators, two important issues must be carefully addressed: the length of the record used (Wu et al., 2005) and the choice of the **baseline period** (Guttman, 1999). In particular, the baseline period plays a key role in the study of past and future drought events. Let us suppose that a 30-year period is chosen as the baseline: every other period will be computed as a sort of comparison to this period, e.g. 1961-90. Consequently, if the selected period has been characterised by frequent and severe drought events, this will influence the computation of the standardised indicator, and the other periods are likely to be characterised by less frequent and severe drought events. On the other hand, if we select the entire period as the baseline, this shortcoming is avoided, but it may happen that an underlying trend would bias the absolute number of events of a certain period. Figure 44 highlights the differences between the same indicator (the SPI-12) computed over two different baselines: while most of the drought events are detected by both of the series, some of them are identified in one series only.

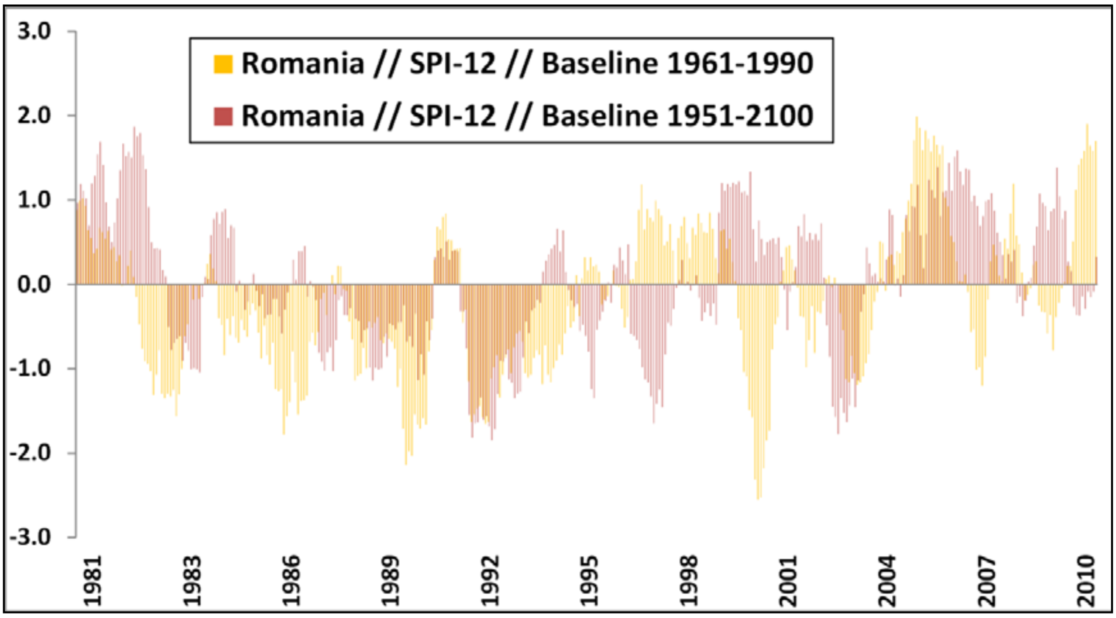

Figure 44 – Average SPI-12 series for Romania for the recent past computed according to different baselines.

In this study, the second approach (baseline calculated over the entire period studied) was chosen, because we are not interested in the evaluation of past events for which a database has been constructed from measured data. Instead, we aimed to study the **drought tendencies** towards a drier or less dry Europe in the coming decades, and the second approach is well suited for comparisons between different periods.

For our analyses, we focused on three 30-year periods: the present or **recent past** (**1981-2010**), the **mid-term future** (**2041-2070**), and the **far future** (**2071-2100**). We performed separate analyses according to each indicator (the SPI and the SPEI) and accumulation period (3-month or 12-month periods). As the SPI is based only on precipitation as input data, and the SPEI on precipitation and PET data, the drought projections based on the SPEI are expected to be influenced by global warming, as the potential evapotranspiration is computed using temperature as one input variable (e.g. van der Schrier et al., 2013).

Using the monthly series of the indicators at grid-point level, we followed Guerrero-Salazar and Yevjevich (1975), McKee et al. (1993), and Spinoni et al. (2014a) to define the occurrence and the characteristics of meteorological drought events. A **drought event** takes place every time the drought indicator under examination goes below -1 for at least two consecutive months, and it ends every time the indicators turns positive. In a given period, the **drought frequency** is therefore defined as the number of drought events, usually reported in the maps as events *per decade*.

Once a drought event has been detected, it is assigned three fundamental properties: **duration**, **severity**, and **intensity**. Duration refers to the number of months the event lasts, severity refers to the integral area of the event (the sum of the indicator values, in absolute values, during the occurrence of the drought event), and intensity refers to the ratio between severity and duration. It follows that our analyses are based on the **characteristics of the individual events**, not on the total number of months spent in drought condition, and the total severity. Consequently, our analyses were carried out to answer the questions: will drought events be more frequent in Europe, compared to the recent past? Will they be longer, more severe, and more intense?

Although the analyses were performed for both accumulation periods, we show only the results obtained by means of the **SPI-12** and the **SPEI-12**, because longer accumulation periods lead to more stable outputs that are less sensitive to monthly or seasonal variability, which can be a critical drawback of projections based on scenarios (Burke et al., 2006).

7.3 Drought frequency, duration, severity, and intensity in the near future (2041-2070)

As discussed in previous chapters, we decided to base our analysis on **comparisons between different periods**. So, the drought patterns of the mid-term (or near) future, i.e. the period **2041-2070**, have been evaluated against the reference period 1981-2010. We used the averaged output data from twelve runs of the RACMO2 model with the A1b scenario for the entire period under investigation, i.e. the period 1950-2100. There was another possible choice, that is using the drought variables for the period 1981-2010 already obtained from the E-OBS (version 10) European grids as reference (Spinoni et al, 2015b). We discarded this possibility after some tests, because the combined use of data derived from the interpolation of measured in situ data for the past and data obtained as the average of multiple runs of a model for the future, caused relevant biases (even though the models have been calibrated and bias-corrected, see Haylock et al., 2008). This is particularly true for regions where the station density is low, for example Russia and Turkey.

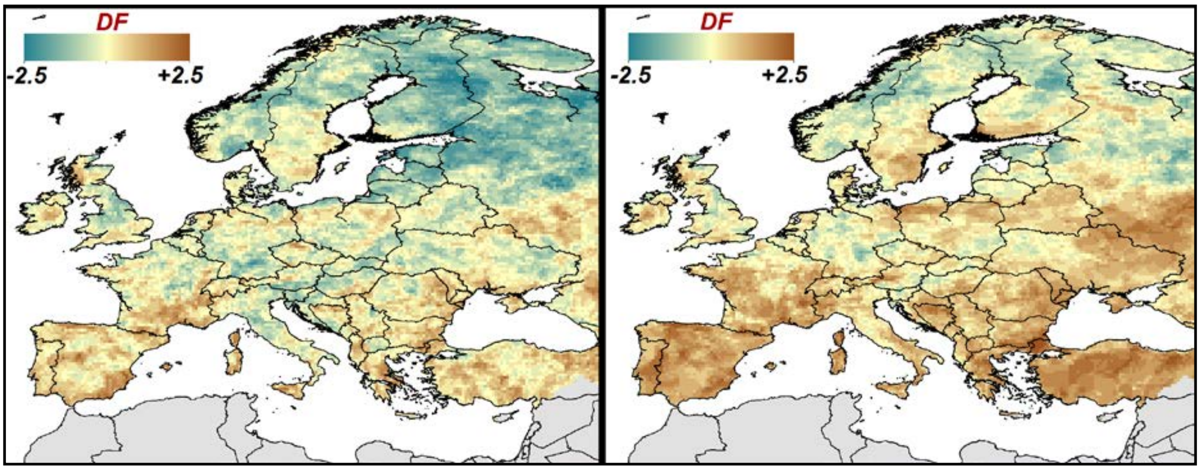

Figure 45 **– Drought Frequency (DF)**: near future compared to recent past. Based on SPI-12 (left) and SPEI-12 (right).

According to the SPI-12 (Figure 46, left), drought events are projected to be more frequent in the near future (2041-2070) than in the recent past (1981-2010) in the Mediterranean region, the Balkans, along the Black Sea coast and in general in southern

Europe. On the contrary, Scandinavia and the Baltic Republics are projected to experience fewer drought events. According to the SPEI-12 (Figure 46, right), the gradient between northern and southern Europe is more evident, but the European mid-latitudes are also projected to experience more frequent droughts in the near future (up to 2.5 more events per decade).

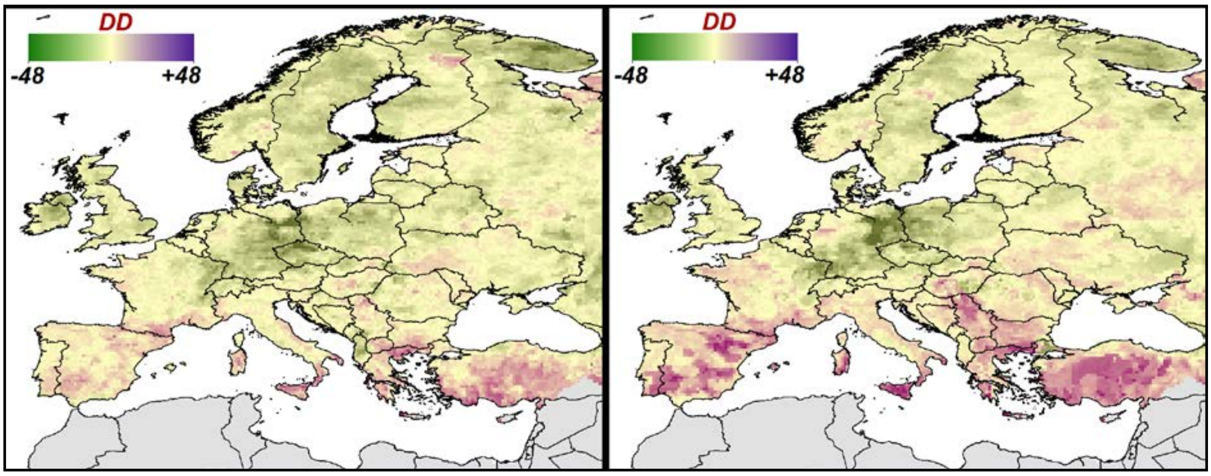

Figure 46 – **Drought event Duration (DD)**: near future compared to recent past. Based on SPI-12 (left) and SPEI-12 (right).

According to the SPI-12 (Figure 46, left), drought events are projected to be, on average, longer in the near future than in the recent past in Spain, along the French Riviera, and in Sicily, Sardinia, Greece and Turkey; they are projected to be shorter in Northern Ireland, central Europe, and Scandinavia. According to the SPEI-12 (Figure 46, right), they will be longer (and longer than projected by the SPI-12) in the entire Mediterranean region and the Balkans, and shorter in the same regions and with the same order of magnitude as highlighted by the SPI-12. It therefore seems that the temperature increase will make the drought events more frequent, but not necessarily longer everywhere.

According to both indicators, drought events are projected to follow, on average, the same spatial patterns regarding severity and duration. In Figure 47, drought severity is expressed on a dimensionless score (per decade, i.e. 10 years), while in Figure 46 the duration is expressed in months per decade. The spatial patterns seen in Figure 47 are similar to those described for drought frequency and duration.

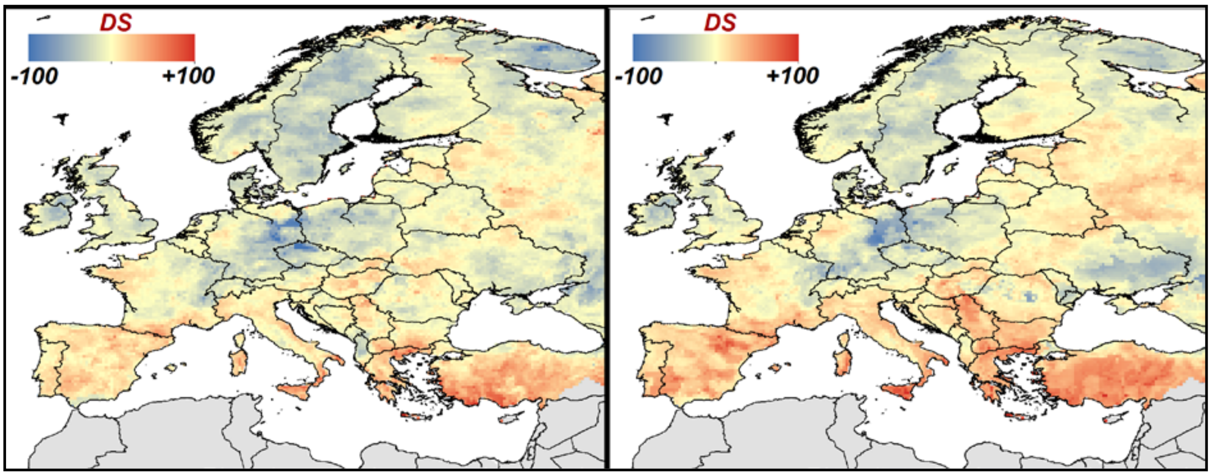

Figure 47– **Drought event Severity (DS)**: near future compared to recent past. Based on SPI-12 (left) and SPEI-12 (right).

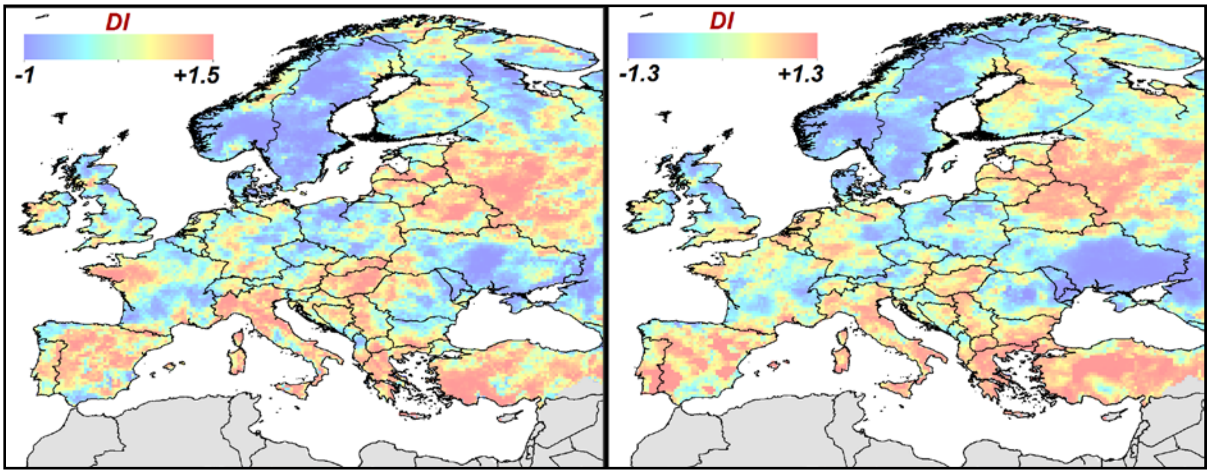

Figure 48 – **Drought event Intensity (DI)**: near future compared to recent past. Based on SPI-12 (left) and SPEI-12 (right).

Regarding the intensity of the drought events (Figure 48), the spatial patterns are less homogeneous than for the other variables. The average intensity is projected to be higher in central Spain, north-eastern France, northern Italy, the Carpathian region, the Balkans, Belarus, Greece and Turkey. By contrast, it is projected to be lower especially in Scandinavia and Ukraine. In general, it seems that the projected temperature increase will not affect the average intensity of meteorological drought events in Europe in the near future, but the differences could be related to the different precipitation variability.

7.4 Drought frequency, duration, severity, and intensity in the far future (2071-2100)

We repeated the analyses discussed in Chapter 7.3 for the **far future** (**2071-2100**). This time we compared the far future with the recent past (1981-2010), and also with the near future (2041-2070), in order to evaluate whether global climate change simulated for the A1b scenario will project countinuous trends for drought events, or the partial emission decrease after the 2050s will introduce new feedbacks to drought events and their spatial patterns in Europe.

Figures 49 and 50 show the **comparisons between the far future and the recent past, and between the far future and the near future**. We can see that, according to the SPI-12, southern Europe is expected to experience more frequent meteorological drought events in the far future than in the recent past.

This higher drought frequency will be even more remarkable according to the SPEI-12, according to which only Scandinavia will see a decrease. Drought events will be more frequent in the far future than the near future at mid-European latitudes, in particular in central and eastern Europe. To summarise, it seems that the increase in temperature and potential evapotranspiration will be important drivers of the increase in drought frequency in the far future as well as in the near future for most of Europe, excluding Scandinavia and northern Russia, while the Mediterranean region could be considered a hotspot.

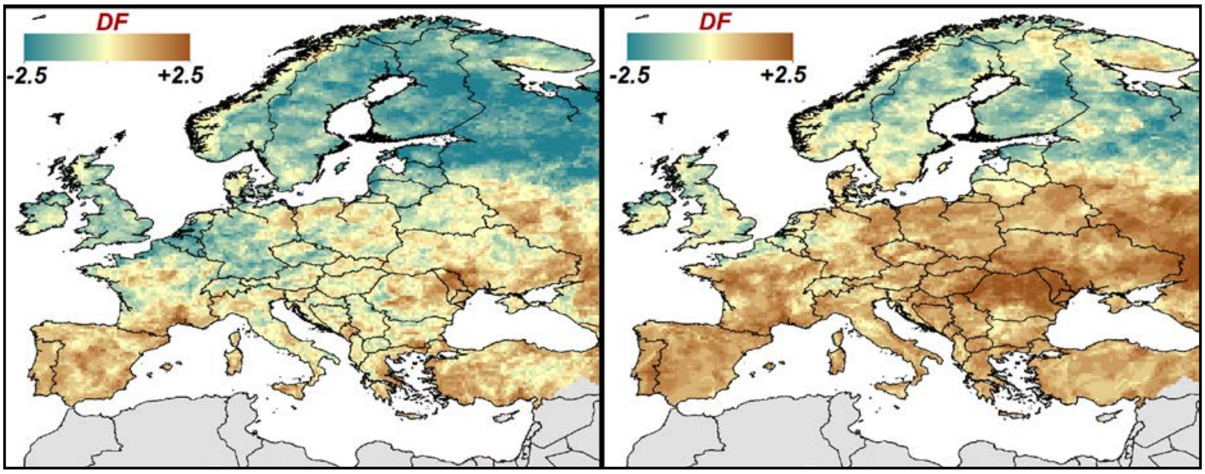

Figure 49 – **Drought Frequency (DF)**: far future compared to recent past. Based on SPI-12 (left) and SPEI-12 (right).

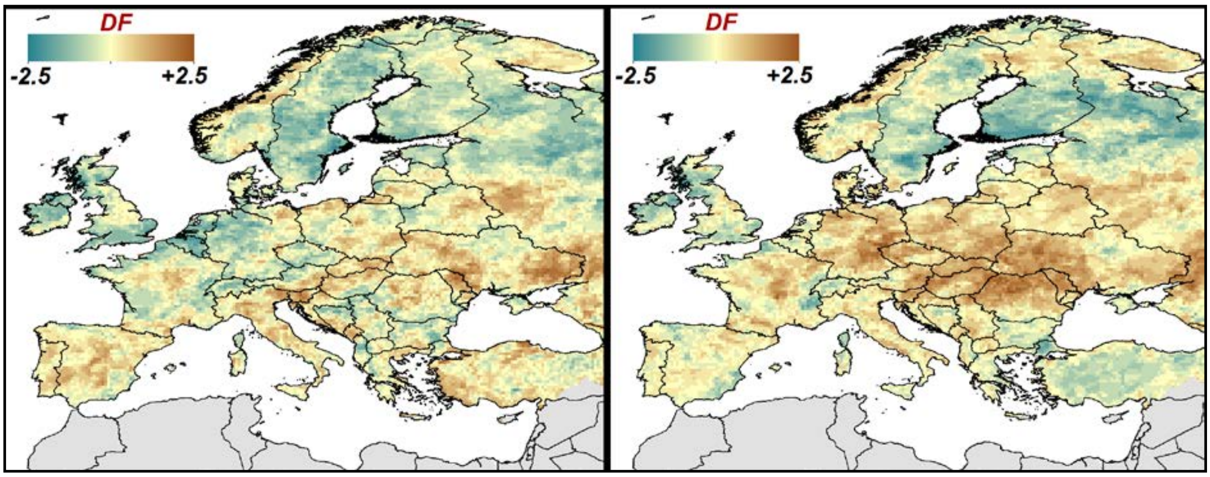

Figure 50 – **Drought Frequency (DF)**: far future compared to near future. Based on SPI-12 (left) and SPEI-12 (right).

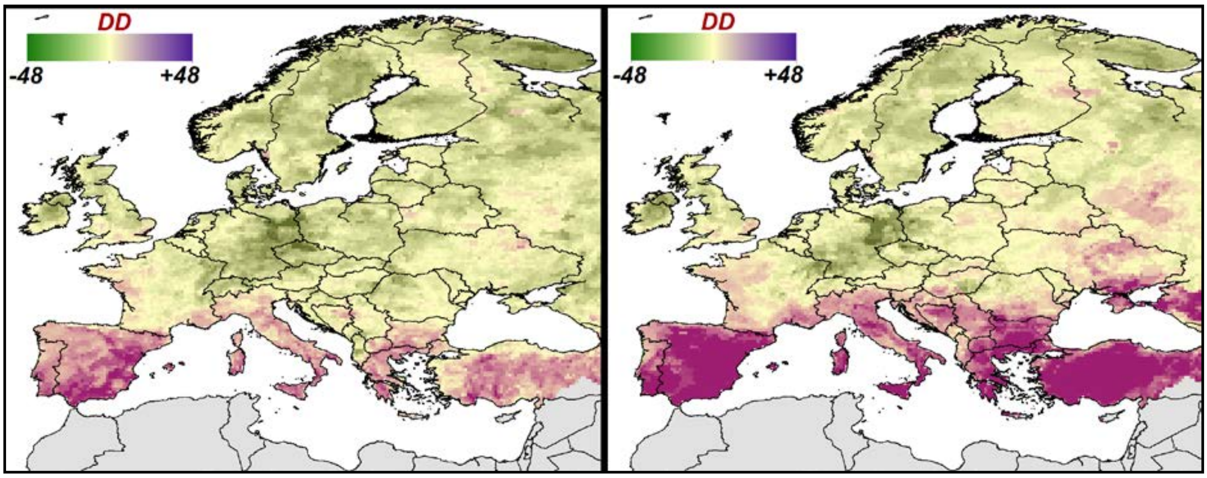

Figure 51 – **Drought event Duration (DD)**: far future compared to recent past. Based on SPI-12 (left) and SPEI-12 (right).

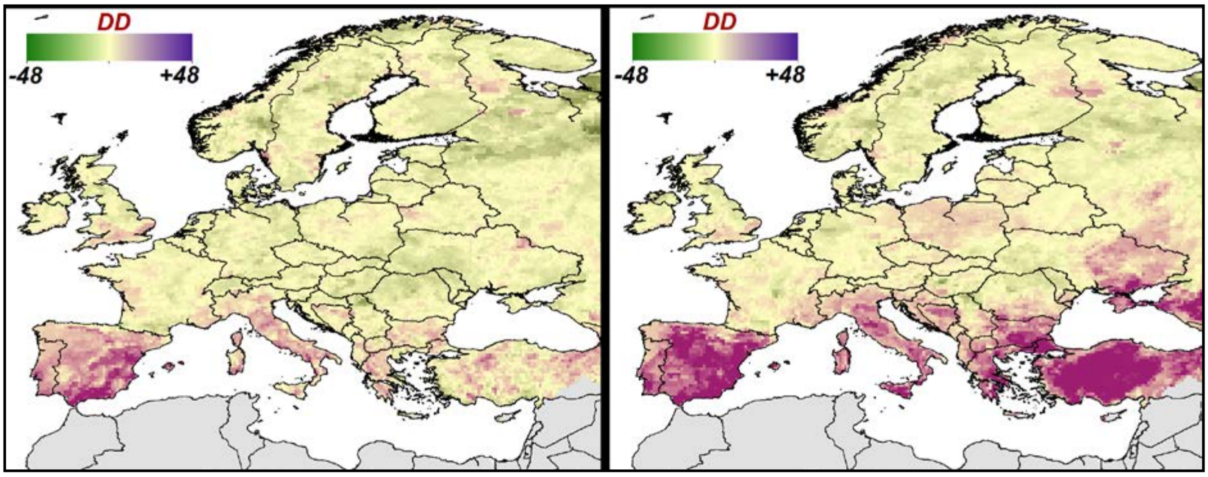

Figure 52 – **Drought event Duration (DD)**: far future compared to near future. Based on SPI-12 (left) and SPEI-12 (right).

From figures 51 and 52 we notice that, according to the SPI-12, the Mediterranean region - and southern Europe in general - is expected to be involved by longer meteorological drought events in the far future than in the recent past: this is evident from the SPI-12-based map, but it is even more remarkable from the SPEI-12-based map.

On the other hand, the decrease in northern European regions is lower in absolute values. According to the SPI-12, the increase in drought duration in the far future compared to the near future is only relevant in Spain, while according to the SPEI-12 it is relevant in every part of Europe below 45°N latitude. It seems that the global warming tendency may produce longer drought events (and possibly the consequent impacts) at the end of the century, even under a moderate scenario such as the RACMO2, based on the A1b family.

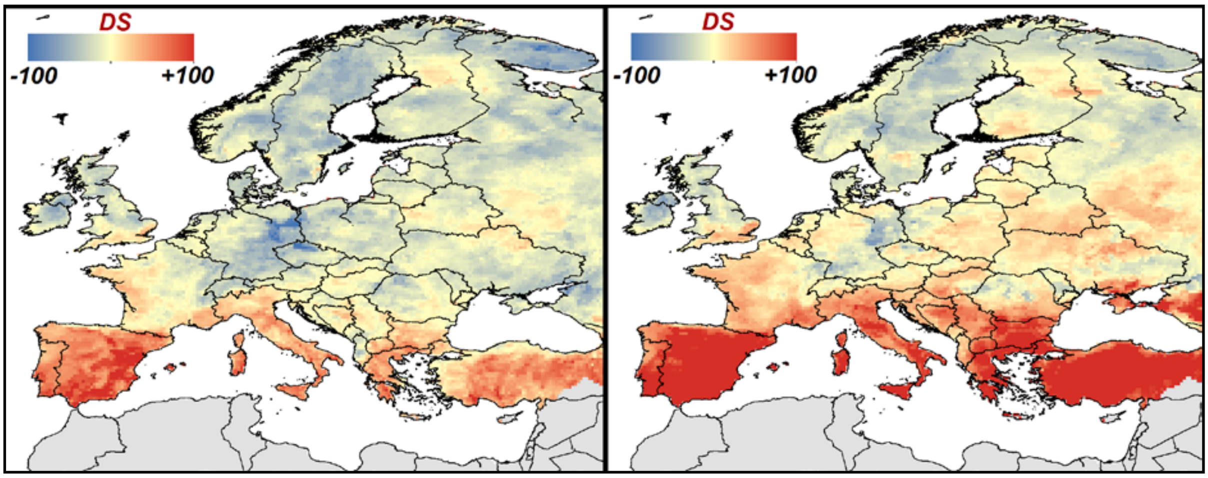

Figure 53 – **Drought event Severity (DS)**: far future compared to recent past. Based on SPI-12 (left) and SPEI-12 (right).

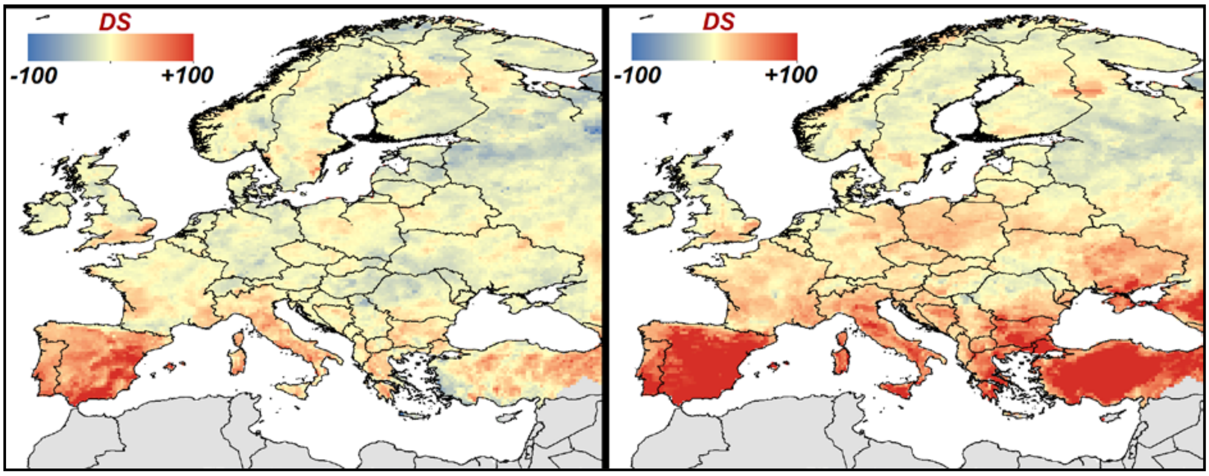

Figure 54 – **Drought event Severity (DS)**: far future compared to near future. Based on SPI-12 (left) and SPEI-12 (right).

Drought event duration shows very close spatial patterns to drought event severity. Southern Europe is also projected to experience more severe events in the far future than in the recent past and, according to the SPEI-12, the increase will be higher than according to the SPI-12, as the temperature increase is a leading factor for drought severity, in particular for Spain, Greece, and Turkey, the hottest and driest European countries (Hoerling et al., 2012). In general, no region, except for north-western Russia, is projected to experience less intense meteorological drought events in the far future compared to the near future (Figure 56). Instead, less severe events will occur in the far future, compared to the recent past, at latitudes greater than 45°N, according to the SPI-12 and only in Ireland, Northern Ireland, Scotland, western Germany, Norway, and Sweden, according to the SPEI-12.

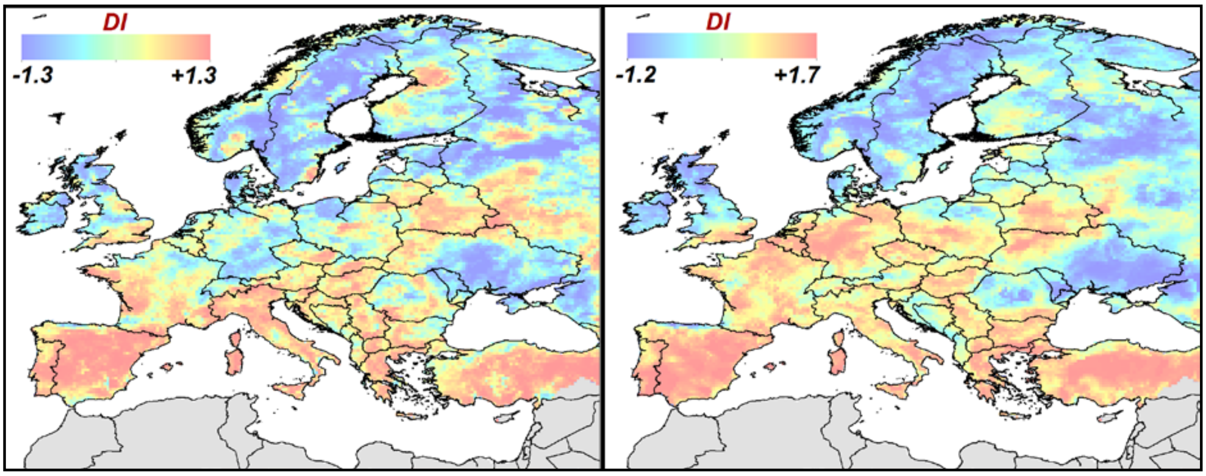

Figure 55 – **Drought event Intensity (DI)**: far future compared to recent past. Based on SPI-12 (left) and SPEI-12 (right).

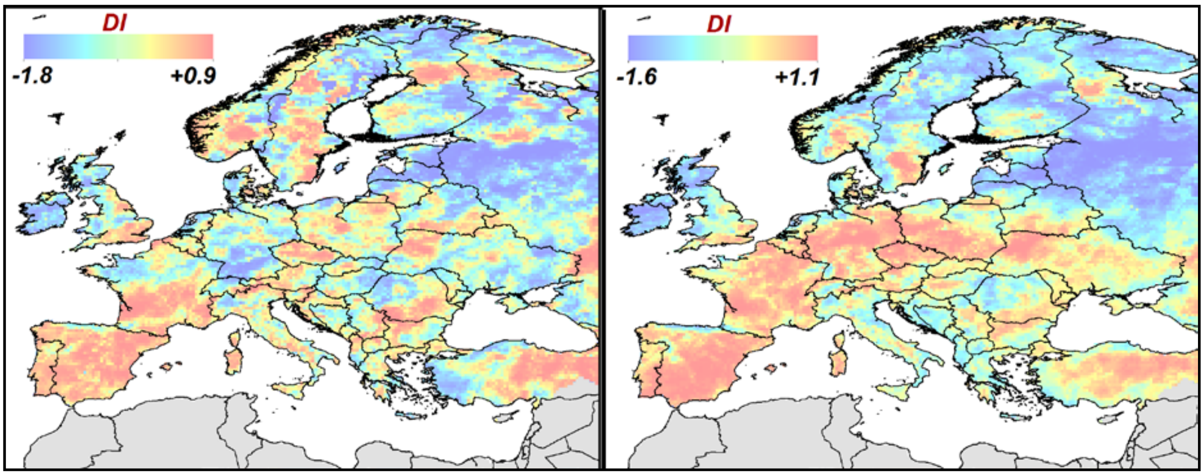

Figure 56 – **Drought event Intensity (DI)**: far future compared to near future. Based on SPI-12 (left) and SPEI-12 (right).

Figures 55 to 56 show different spatial patterns in the comparisons between the far and near futures based on the SPI-12 and the SPEI-12 regarding the average intensity of drought events. The drought event intensity is projected to increase in the far future - compared to recent past - in southern Europe, the Balkans, and Belarus according to the SPI-12, but also in France and Central Europe according to the SPEI-12. On the other hand, both indicators foresee a decrease for Scandinavia and Ukraine.

To summarise, the drought variables most influenced by a temperature increase are severity and duration, while intensity seems to depend more on precipitation variability and trends as well as the frequency of meteorological drought events.

7.5 Overview of future European drought tendencies

In order to provide with a **summary of the future European drought tendencies**, the complete monthly records of four indicators (SPI-3, SPI-12, SPEI-3, and SPEI-12) from 1950 to 2100 have been analysed. These indicators were averaged at country level and compared for the three periods already investigated in the previous chapters, i.e. the recent past (1981-2010), the near future (2041-2070), and the far future (2071-2100).

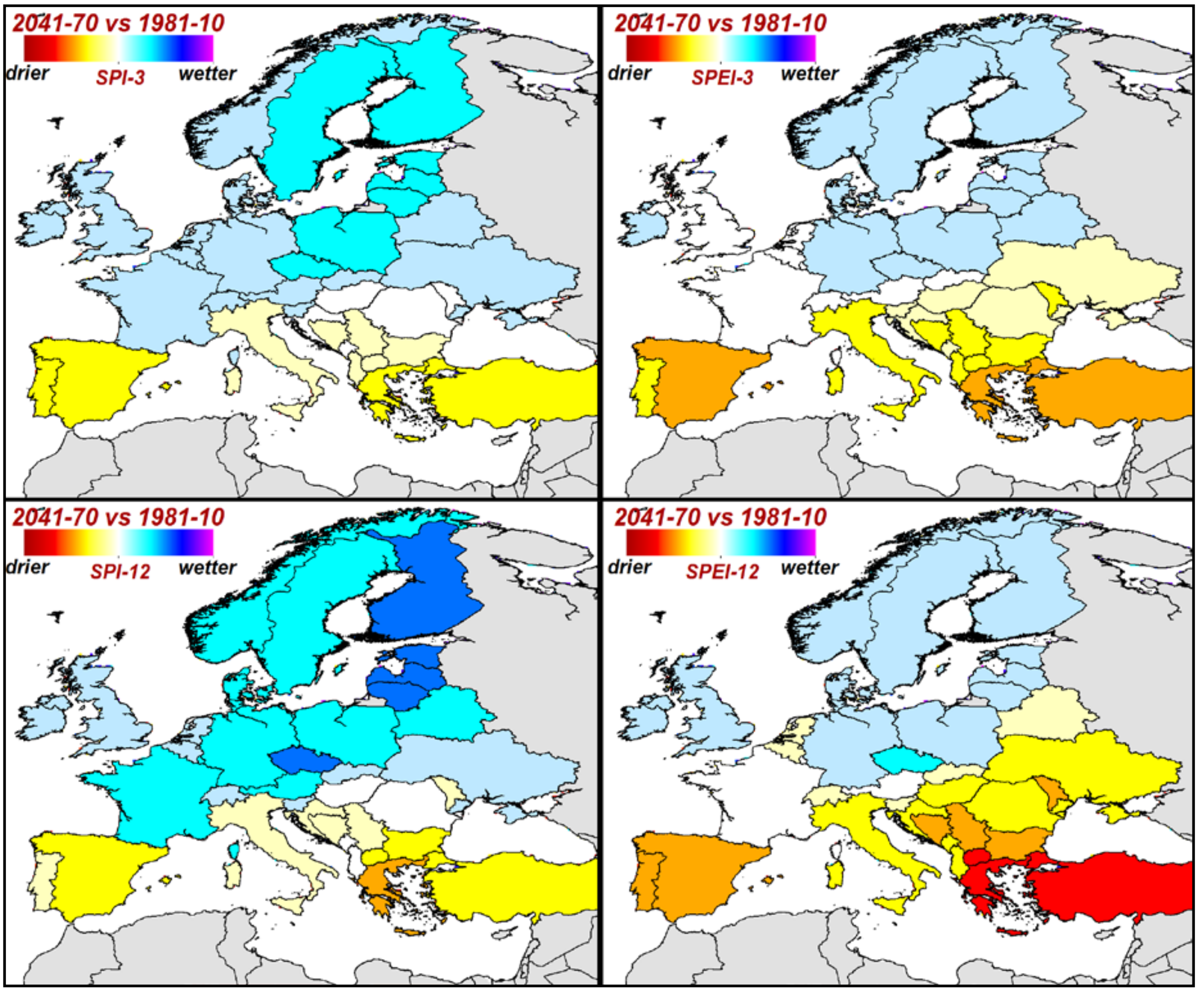

Figure 57 – European drought tendencies in the near future compared to the recent past.

According to the four indicators shown in Figure 57, the southern European countries are projected to be drier in the near future than in the recent past. In particular, the two SPEI indicators project even drier conditions than the SPI indicators for the Mediterranean countries, the Balkans, and Turkey. According to the SPI (and consequently due to precipitation variability and trends), the central and northern European countries are projected to be wetter, in particular the Baltic Republics and Finland.

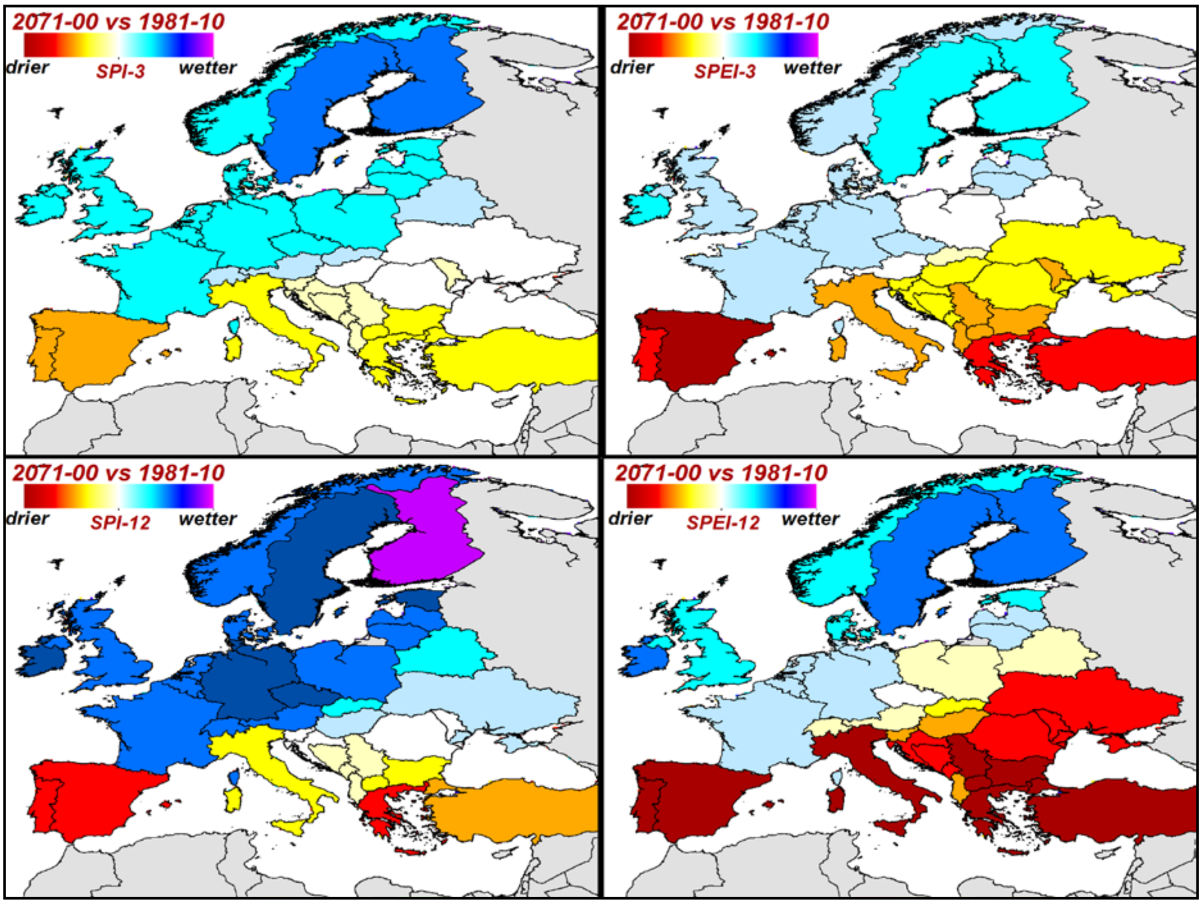

Figure 58 – European drought tendencies in the far future compared to the recent past.

The comparisons between the far future and the recent past shown in Figure 58 highlight more extreme shifts toward drier conditions for southern Europe, in particular the Iberian Peninsula, Greece, the Balkans and Turkey. On the other hand, more extreme shifts towards a wetter northern Europe can be seen, involving in particular Finland but also central Europe. In the last decades of the current century, such shifts are also projected to be extreme by the SPI, especially regarding the shifts towards wetter conditions, but also towards drier conditions for the Iberian Peninsula and Greece.

The Mediterranean region and the Balkans will experience longer and more severe meteorological events as the century progresses (Figure 59), leading to drier (and hotter) climate conditions that will potentially be coupled with devastating drought events and impacts. By contrast, wetter conditions are projected to increase in the British Isles and Scandinavia as the century progresses and this, coupled with less severe and intense droughts, can be seen as a positive tendency. Unfortunately, a continuous tendency towards wetter conditions could potentially cause extreme rainfall events and floods, as discussed in the latest IPCC report (IPCC, 2013, 2014).

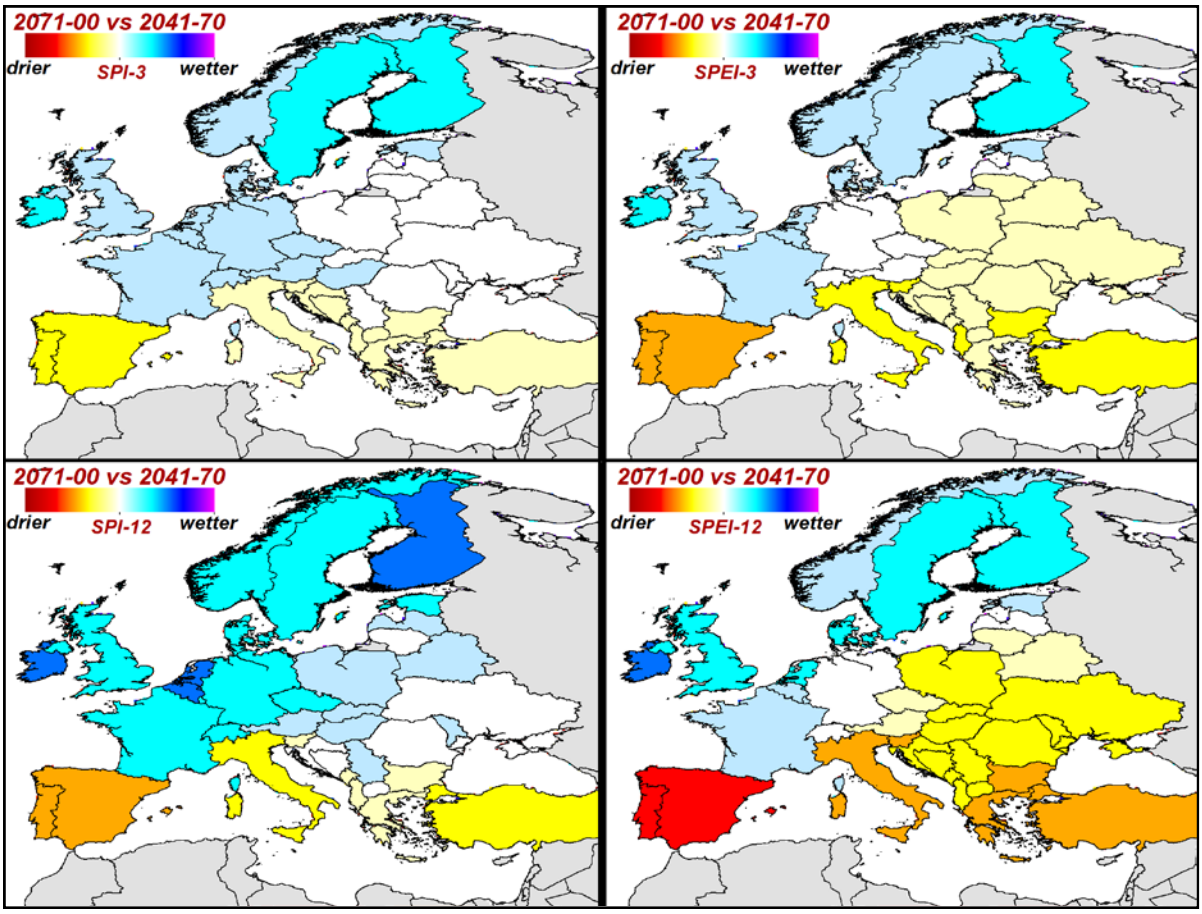

Figure 59 – European drought tendencies in the far future compared to the near future.

These findings reinforce the general idea of the observed climate change in Europe: from the 1950s to 2010s, **southern Europe** faced a **drying tendency** and **northern Europe** a **wetting tendency** (Lloyd-Hughes and Saunders, 2002; IPCC, 2007, 2014; Briffa et al., 2009; Bordi et al., 2009; Sheffield et al., 2009; Hannaford et al., 2011; Hoerling et al., 2012; Spinoni et al., 2014a).

This spatial pattern is projected to continue, and to increase in magnitude, until the end of the century: in southern Europe the dry regions will become drier, and in northen Europe the wet regions will become wetter, as discussed by Greve et al. (2014), Sherwood and Fu (2014), and Trenberth et al. (2014), to cite a few relevant and recent studies.

8. Projecting drought impacts

8.1 Use of damage functions to project drought impacts at country level

As discussed in Chapter 6, **damage functions** were derived to link meteorological drought events to their impacts. The gridded E-OBS temperature and precipitation data were used to compute three drought indicators, namely the SPI, the SPEI, and RDI. It emerged that the SPEI, calculated for a 3-month accumulation period (SPEI-3) was the best choice to apply the damage functions to cereal yield reduction on an annual basis and at a country level in Europe. Regarding hydropower energy production, the best indicator proved to be SPEI-12. From the monthly series of these indicators we derived a set of parameters, and the annual cumulated drought severity was selected as the independent variable in the damage functions. Let us briefly recall the basic equations.

The damage function D(s) directly depends on the drought severity s:

$$D(s) = \alpha s^{\beta} \tag{5}$$

Using drought impacts derived from the World Bank database and drought events detected using the discussed methodology, for each country and sector analysed we obtained two parameters: α and β. These parameters were calculated using past data, but they can be applied to different data and periods, provided that their statistical errors are taken into account, i.e. σ_α and σ_β (see Chapter 6).

Thus, if we consider the recent past (1981-2010, period 1), we can obtain modelled impacts $D_1(s_1)$ just using the parameters α and β and the drought severity (s_1) calculated from the modelled data obtained with the A1b scenario family RACMO2.

$$D_1(s_1) = \alpha s_1^{\beta} \tag{14}$$

Similarly, we can **apply the damage function methodology to the near future** (2041-2070, period 2) and to the far future (2071-2100, period 3) and obtain modelled impacts for both the periods ($D_2(s_2)$ and $D_3(s_3)$).

$$D_2(s_2) = \alpha s_2^{\beta} \tag{15}$$

$$D_3(s_3) = \alpha s_3^{\beta} \tag{16}$$

Consequently, if we want to evaluate the decrease or the increase of the drought impacts for a given country, we need to compute the difference between two periods, e.g. the far and the near future.

$$\Delta_{(2,3)} = D_3(s_3) - D_2(s_2) \tag{17}$$

Of course, the difference could be provided with its error, σ_Δ, which depends on σ_{D2} and σ_{D1}, which in turn depend on σ_{s1}, σ_{s2}, σ_α, and σ_β. The theoretical background and the computation of the errors are not included in this report. For the time being we present only the maps with differences per country. Maps with the errors per country and related to different sectors and impacts could be drawn up in the future.

In order to avoid biases introduced by the use of different data sources, we decided to **calibrate the damage functions** on recorded impacts and variables, and then to apply them to the modelled RACMO2 outputs. The other option was to apply the damage functions only to modelled data regarding the near and far future, and compare the outputs with the recorded past impacts. We did not aim to obtain future drought impacts in terms of absolute values such as kg/ha or income in euros, as such values will depend on future socioeconomic and technological developments that are not considered in the damage functions. We, therefore, are mainly interested in the increasing or decreasing tendencies which were derived by applying the damage functions to the modelled data for the past, near future, and far future resulting from the runs of the RACMO2 with the A1b scenario. Based on the results we discuss whether the drought impact will increase or decrease per country, without providing the actual projected drought impacts.

8.2 Example of projected impacts: cereal yields

By means of the damage functions, we studied whether meteorological drought events will cause less or more frequent cereal yield reductions and whether the total reduction occurring in the future is projected to be lower or higher than the total reduction that occurred in the reference period 1981-2010. The base drought indicator used is the SPEI-3.

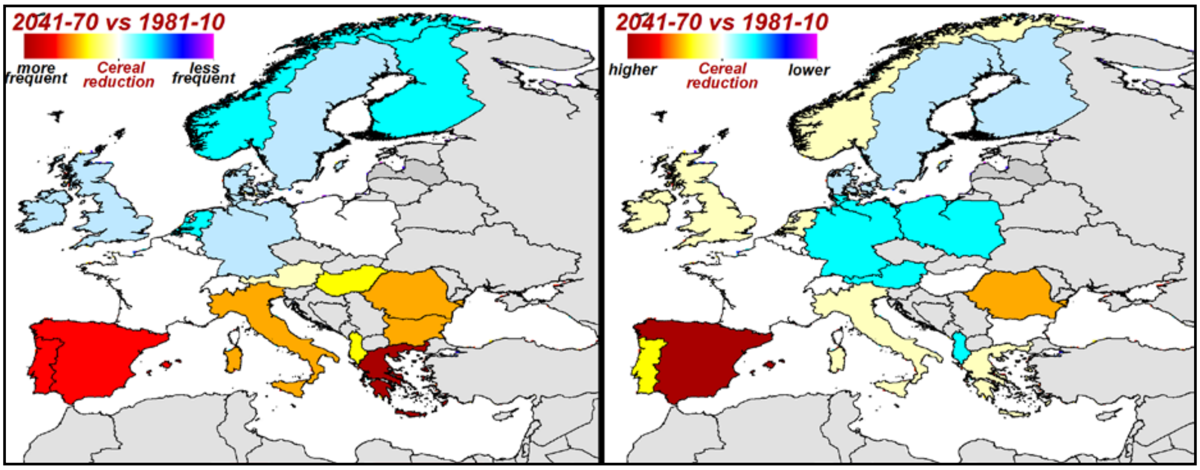

Figure 60 – Cereal reduction frequency (left) and total value (right): near future versus recent past.

Figure 60 shows that, compared to the recent past (1981-2010), the near future (2041-2070) will see more frequent **reductions in cereal yields** in the Iberian Peninsula, the Mediterranean region and eastern Europe, and that the total reduction will be higher in the Iberian Peninsula and Romania. Scandinavia and central Europe, on the other hand, will experience less frequent reductions and lower total reductions. The British Isles and Norway will be characterised by less frequent but more severe reductions.

Compared to the recent past (1981-2010), the far future (2071-2100) will see the same spatial patterns regarding the frequency of reductions in cereal yields (Figure 61, left), however, with more pronounced increases and decreases in cereal yields than those found when comparing the near future and the recent past. Regarding the total reduction (Figure 61, right), the situation is more complex and there is no spatial homogeneity.

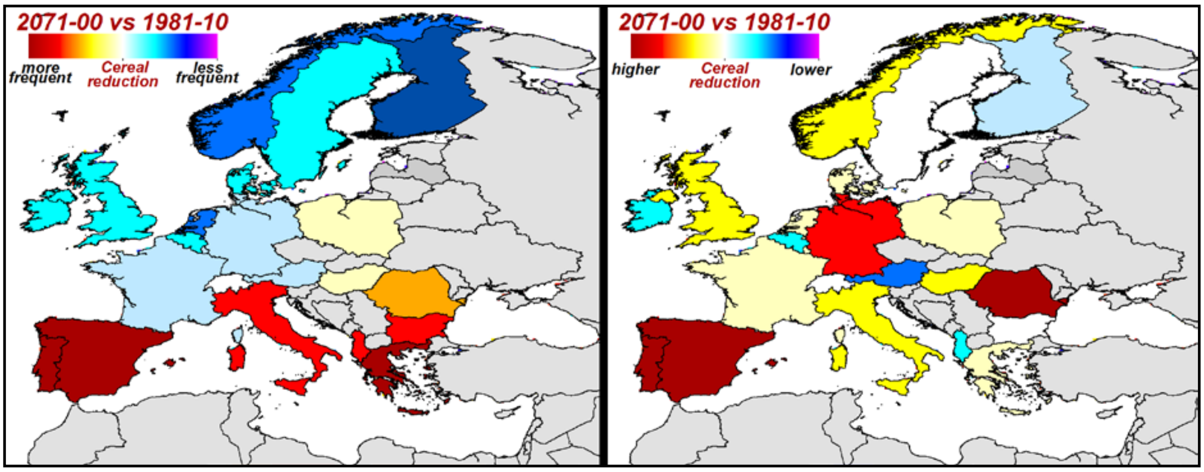

Figure 61 – Cereal reduction frequency (left) and total value (right): far future versus recent past.

Compared to the near future (2041-2070), meteorological drought events in the far future (2071-2100) will cause more frequent cereal yield reductions in southern Europe and less frequent reductions in parts of western and northern Europe (Figure 62). The increase in the severity of such reductions will be highest in Spain and Germany and lowest in Austria. The observed **spatial heterogeneity** suggests that projections of drought impacts should be handled with care, even though the methodology is statistically robust. Different climate and social feedbacks may influence the relationships in the future, resulting in very unstable predictions. Also the power-law function tends to overshoot, with increasing values for beta.

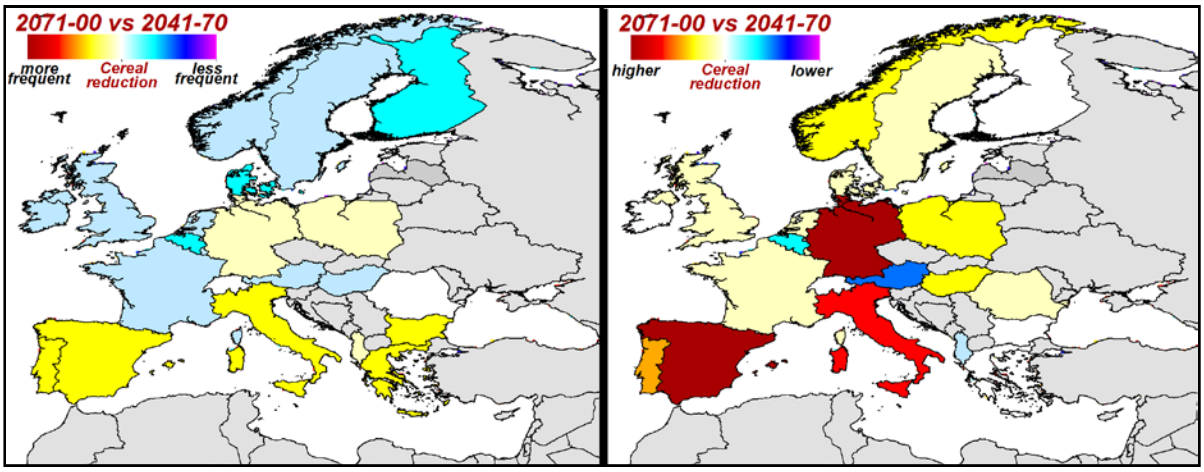

Figure 62 – Cereal reduction frequency (left) and total value (right): far future versus recent past.

8.3 Example of projected impacts: hydropower production

The analyses of the meteorological drought impacts on hydropower production (i.e. the annual reductions at a country level) are based on the same methodology as described in Chapter 6.3. The base indicator, however, is the SPEI-12.

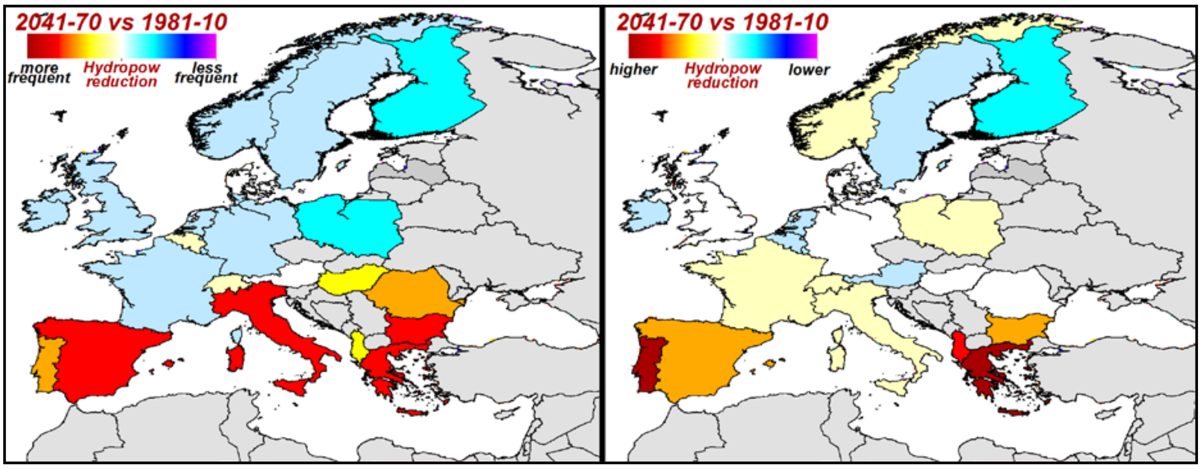

Figure 63 – Hydropower reduction frequency (left) and total value (right): near future versus recent past.

As shown in Figure 63, southern Europe will be more frequently hit by **hydropower reduction** due to drought events in the near future than in the recent past, but the increase in the total magnitude of such reductions will be particularly relevant in the Iberian Peninsula and south-eastern Europe only. On the other hand, a slight decrease in both frequency and total magnitude is projected for Scandinavia, excluding Norway.

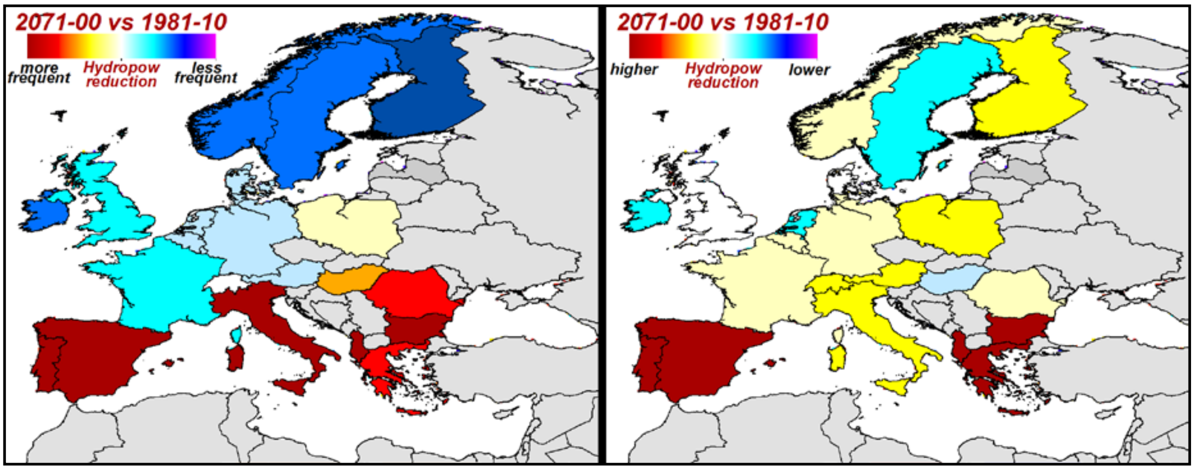

Figure 64 – Hydropower reduction frequency (left) and total value (right): far future versus recent past.

The latitudinal gradient (less drought impacts in northern Europe and more in southern Europe) is more evident if we compare the far future with the recent past (Figure 64). This is true for both the frequency and the total magnitude of the impacts on hydropower generation, with the exception of Poland and Finland which show opposite effects in terms of frequency (decrease) and total magnitude (increase).

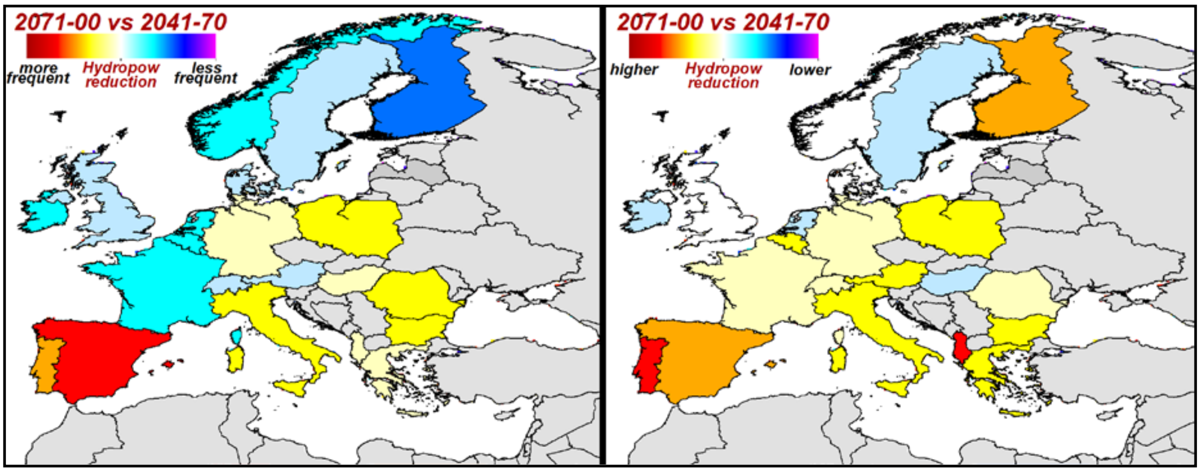

Figure 65 – Hydropower reduction frequency (left) and total value (right): far future versus near future.

More frequent reductions in hydropower caused by drought events are projected to occur in the far future than in the near future in the Iberian Peninsula, Italy, and eastern Europe, while France, the British Isles and Scandinavia will behave oppositely (Figure 65, left). A possible reason for this behaviour is that stronger climate change impacts on drought frequency and severity are expected for the former countries, while the latter countries will be less impacted. As regards the total magnitude, lower impacts are projected only for Ireland, the Netherlands, Sweden, and Hungary (Figure 65, right). This can possibly be explained by the fact that either a limited growth relationship or no clear relationship has been detected for these countries, which can reflect the relatively limited level of dependency on hydropower production and/or advanced management and mitigation practices.

9. Directions for future research

The methodologies and the outputs described in this report should be considered as the basis for enlarging the spectrum of the analyses regarding the links between drought events and impacts. Here, we report a list of the most important **aspects** that should be **further analysed** in order to improve the methodology and results. These have been grouped into five categories: the database of drought events and impacts, damage functions or similar methods, drought projections, feedbacks between drought and other climate-related disasters, and the spatial and temporal resolution of the inputs and the outputs. In the following, we give a bullet-point list of suggestions for possible improvements for each category.

9.1 Improving the database of past drought events and impacts

To construct the database of past drought events, we used the gridded E-OBS (version 10) as input data, the SPI, the SPEI, and the RDI as drought indicators, and a set of statistical parameters to define the events (frequency, duration, severity, peak month, area involved, etc.). This **database** could be improved according to the following suggestions:

- Use different gridded databases for precipitation (e.g. the GPCC: Rudolf et al., 2005; Schneider et al., 2014) and temperature (e.g. CRU TS3.10: Harris et al., 2014);
- Use modelled input data such as reanalysis datasets (e.g. ERA-40: Uppala et al., 2005; EURO4M: Soci et al., 2011);
- Test the data quality and homogeneity with other models (see Peterson et al., 1998; Costa and Soares, 2009; Venema et al., 2012);
- Add new meteorological drought indicators (e.g. the PDSI: Palmer, 1965; Alley, 1984; the sc-PDSI: Wells et al., 2004);
- Create a dataset of agricultural drought events (Boken et al., 2005; Wang, 2005; Rhee et al., 2010), hydrological drought events (Shiau and Shen, 2001; Tallaksen and Van Lanen, 2004; Nalbantis and Tsakiris, 2009; Fleig et al., 2011), groundwater drought events (Van Lanen and Peters, 2000; Tallaksen and Van Lanen, 2004; Peters et al., 2005), and socioeconomic drought events (Arnell, 2004; Alcamo et al., 2007; Simelton et al., 2009);
- Search for other scientific and non-scientific drought event reports to confirm the events detected with our multi-indicator approach;
- Search for other scientific and non-scientific drought impact reports and drought impact datasets such as the EDII (Stahl et al., 2012; Stagge et al., 2013; Kohn et al., 2014).

9.2 Testing new damage functions/methodologies for different sectors

As discussed in Chapter 2, we chose **damage functions** to study the possible links between drought events and drought impacts. We tested this methodology on two sectors, cereal yield production and hydropower energy generation, and the results are promising. However, to provide users with more detailed analyses, different approaches should be tested and new sectors should be investigated.

- Test different approaches to correlate drought events and impacts, such as climate analogues (Orlowsky et al., 2010; Lutz et al., 2013), Input-Output models (Weidmann et al., 2010; Jenkins, 2013), Integrated Assessment Models (Warren et al., 2008; Füssel, 2010), etc.;
- Test more complex mathematical models for deriving damage functions;
- Complete a robust theoretical background concerning the errors of the damage functions and other models;
- Apply the selected methodology to evaluate drought impacts over other sectors such as crop production (Kulshreshtha and Klein, 1989; Blum, 1996; Rojas et al., 2011), livestock mortality (Nkedianye et al., 2011; Cruz et al., 2014), energy supply (Hsiao, 1993; Michelsen and Young, 1993; Omer, 2010), technology (Liverman, 1990; Wilhite, 2005), forestry (Kloeppel et al., 2003; Phillips et al., 2009; Allen et al., 2010; Asner and Alencar, 2010), etc.
- Search for feedbacks between droughts and other human-induced disasters in order to suggest more effective mitigation strategies.

9.3 Refining drought projections with an ensemble of models and scenarios

In order to project the possible increase or decrease in drought impacts, we first had to evaluate the **projections of drought variables** until the end of the 21st century. To do so, we based our study on the outputs of the RACMO2 model: the average values of twelve runs were used as monthly series for the whole of Europe from January 1950 to December 2100. We assume that new models should be coupled to the A1b family in order to also provide information regarding worst-case scenarios.

- Add new runs with different initial conditions to the RACMO2 outputs;
- Compare the RACMO2 outputs with other models belonging to the A1b scenario (see Meehl et al., 2005, for a summary);
- Include model outputs from different scenario families, i.e. the A2 (e.g. Jiang et al., 2004; Lu et al., 2007; Williams et al., 2007), the B1 (Meehl et al., 2005; Ohlemüller et al., 2006; Van Lanen et al., 2013; Ashraf Vaghefi et al., 2014), and the B2 (Warren et al., 2012; Djamel and Didier, 2013; Fraser et al., 2013);
- Include the newest versions of the scenario models (IPCC, 2013, 2014);
- Perform test statistics to compute the error intervals of the climate projections.

9.4 Coupling drought information with other climate extremes

The PESETA II Project (Ciscar et al., 2014) set the basis for an integrated study of the climate-related impacts of many different disasters on various economic sectors. This report accounts for **drought impacts** only. However, drought is a slowly developing and often long-lasting natural phenomenon (Vogt and Somma, 2000) that may be influenced by the simultaneous occurrence of **other climate- or weather-related disasters**. It might, therefore, be useful to

- Apply similar damage functions to the impacts caused by floods (Brujin, 2004; Lehner et al., 2006), earthquakes (Newmark, 1965; Guha-Sapir et al., 2011), forest fires (Flannigan et al., 2000; Lindner et al., 2010; Zumbrunnen et al., 2011), and heat and cold waves (Meehl and Tebaldi, 2004; Poumadere et al., 2005; Tan et al., 2007);
- Couple drought events and impacts with permanent land degradation (Agnew and Warren, 1996) and desertification (Thomas, 1997; Spinoni et al., 2014b);
- Study the possible link between droughts and heat waves (Beniston, 2004; Fischer et al., 2007), droughts and wildfires (Balling Jr. et al., 1992; Dimitrakopoulos et al., 2011; Sarris et al., 2014; Stagge et al., 2014), and droughts and other climate-related or weather-driven extremes;
- Evaluate the effect of adopted strategies to mitigate or cope with drought (Wilhite, 1993; Rossi et al., 2005; Lehner et al., 2006; Rossi et al., 2007; Iglesias et al., 2009; Mechler et al., 2010; Estrela and Vargas, 2012)

9.5 Increase the spatial resolution (local/small-scale) and involve more experts

This study was performed at a satisfactorily high **resolution** (0.25°x0.25°) for a large area such as Europe. However, this may not be enough to assess regional- or local-**scale** drought impacts. Moreover, we have not included Iceland and the European Atlantic Islands because of a lack of valid data. Enlarging the research network through collaborations and the acquisition or sharing of new data and models, could strongly improve the quality of our results.

- Increase the spatial resolution by also using remote sensing data;
- Create a more comprehensive network in the framework of the European Drought Observatory (http://edo.jrc.ec.europa.eu);
- Ask for the continuous support of recognised experts in drought modelling and management from different European countries;
- Establish an operational system that can compute possible drought impacts in near-real time from weekly updated online drought maps;
- Disseminate the results to the scientific community and create strict connections with politicians and stakeholders.

10. Conclusions and highlights

In the past decades, **drought** has been a recurrent feature of the European climate, with striking drought events in both high- and low-rainfall areas and in any season (Lloyd-Hughes and Saunders, 2002). Historically, water shortage is a well-known problem of many south-European countries, especially Spain, southern Italy, and Greece, but in the past 30 years almost the whole of Europe has been repeatedly affected by drought, especially in the past decade (IPCC, 2014).

From 2006 to 2010, 15% of the territory and 17% of the EU population was affected by drought on an annual basis, causing considerable damages and economic losses. In the past 30 years, the costs of drought were estimated to be more than €100 billion (European Commission, 2007b). While in the past the Mediterranean area was an area of major concern in Europe, central and eastern Europe (Lloyd-Hughes, 2012) and the Carpathian region have become additional drought hotspots in the past decades (Spinoni et al., 2013). Due to climate change and increased human water needs, **drought impacts** are likely to get worse in the future (IPCC, 2014), and will therefore require constant monitoring and assessment.

Though a few recent papers deal with global drought patterns (Dai, 2011a; Sheffield et al., 2012; van der Schrier et al.; 2013, Spinoni et al., 2014a; Trenberth et al., 2014), no similar studies - updated to 2012 and based on high-quality and high-resolution datasets - exist for Europe. To overcome this lack of data, we developed a **multi-indicator approach to investigate the occurrence, frequency, duration, intensity, and severity of meteorological drought events across Europe for the period 1950-2012**. We then investigated the hotspots and trends and constructed a database of drought events at different spatial scales (grid, country, region, macro-region).

In the 1950s and 1960s, the **drought hotspots** were Scandinavia and Russia, in the 1970s and 1980s no particular drought hotspot emerged, and in the 1990s and 2000s the drought hotspots were the Mediterranean area and the Carpathian Region. A **linear trend analysis** shows that Europe can be roughly split into two large areas: the north-eastern regions, which have been experiencing a decreasing drought trend over the past six decades, and the south-western regions, which have experienced an opposite increasing trend. Such results confirm what has been reported by Hoerling et al. (2012), Sheffield et al. (2012), Dai (2013), and van der Schrier et al. (2013), following different approaches.

With the exception of the European Drought Reference (EDR) database and the European Drought Impact Report Inventory (EDII), no databases for drought events and impacts exist for Europe. Nevertheless, the EDR is based only on one indicator (the SPI) and very few drought events are quantitatively described in the EDII. We therefore constructed a **new database of meteorological drought events based on a composite indicator** (based on SPI, SPEI, and RDI) and focused on two different accumulation periods (3 and 12 months). This database also reports the twenty-one major droughts that hit Europe from 1950 to 2012, six of which occurred after 2000. This database will be included in the European Drought Observatory (EDO) in 2016 as a complete list of drought events, including a set of statistical parameters for each event detected.

Another objective of this study was the construction of a **parallel drought impacts dataset**. Starting from the structure of the EDII, we developed a preliminary version of such a database (including journal articles, peer-reviewed papers, and books) related to the drought events detected, and collected data that qualitatively and (especially) quantitatively report drought impacts in various sectors. We exploited the combination of the database of past drought events and the drought impacts, mostly arranged by country and on an annual basis, in order to develop dedicated **damage functions** that correlate the severity of the events with documented impacts or data that may have been indirectly affected by the drought events. The damage functions were calibrated by country and tested on two sectors: cereal yield production and hydropower energy generation.

After several tests, it emerged that damage functions that follow an exponential model best fit the annual **reduction in cereal yield and hydropower production**. Furthermore, the best indicators to be used as input for the damage functions proved to be the SPEI-3 for cereal yields and the SPEI-12 for hydropower production. This is physically reasonable, as 3-month accumulation periods for drought indicators are usually associated with agricultural impacts, and 12-month accumulation periods with hydrological impacts.

One of the main goals of this study was to develop a methodology that permits the **projection of drought impacts** into future decades. To do that, we decided to firstly project the meteorological variables (precipitation, PET, and temperature) from the 1950s to 2100, and thereafter computed the selected indicators (the SPI and the SPEI) on a monthly basis for the period 1950-2010. According to the PESETA II Project (Ciscar et al., 2014), we chose the scenario model RACMO2 (van Meijgaard et al., 2008), which belongs to the moderate emissions A1b family (IPCC, 2000, 2007, 2014). The data we used came from the average of twelve ensemble runs of the RACMO2 model.

Using the modelled drought series both at country level and grid-point level (spatial resolution: 0.25°x0.25°), we evaluated the **future drought tendencies** for the entire European area (excluding Iceland, due to the lack of valid data over the past). We focused our analyses on different characteristics of the drought events (i.e. frequency, average duration, severity and intensity) and compared the average properties of the meteorological drought events over three different periods: the **recent past** (1981-2010), the **near future** (2041-2070), and the **far future** (2071-2100).

We looked for the answers to a few fundamental **questions**: are the drought events likely to become more frequent in future decades? Will they be longer? Will they be more severe and intense? The answers to these questions are in the affirmative regarding most of southern Europe – in particular the Mediterranean area, but also the Balkans - which is projected to experience more frequent, longer and more severe and intense drought events. This tendency is more evident if a drought indicator based also on temperature inputs is used (i.e. the SPEI), proving that the projected **global warming** will be a key factor regarding the more extreme aspects of drought events in Europe, in particular in the last decades of the 21st century. On the other hand, northern Europe – in particular the Scandinavian countries – is projected to experience less frequent, shorter, and less severe and intense drought events. In this case, the precipitation variability is more significant than the temperature trend.

This spatial gradient, a **projected tendency** towards a drier future for southern Europe and wetter future for northern Europe (see also Russo et al., 2013), causes an opposite behaviour regarding possible drought impacts. The damage functions, calibrated over the past recorded events and applied over the entire range of the scenario outputs, show that **cereal yield** reductions due to drought events are projected to increase in southern Europe and decrease in northern Europe. Similarly, reductions in **hydropower production** are projected to increase in southern Europe and decrease in northern Europe. However, the spatial gradient for hydropower is not as homogeneous as for cereal production.

The results shown in these deliverables were presented at the annual meeting of the European Geosciences Union 2014 in Vienna (Spinoni et al., 2014b) and at the 14th meeting of the European Meteorological Society 2014 in Prague (Spinoni et al., 2014c; Spinoni et al., 2014d). They are part of four scientific papers on the analysis of past drought trends (Spinoni et al., 2015a), the construction of the database of past drought events (Spinoni et al., 2015b), the construction and the validation of the damage functions (Naumann et al. 2015), and the projections of drought event characteristics in Europe (Spinoni et al., 2015c). Moreover, it is planned to apply the described methodologies to past and future drought trends on a seasonal basis, different climate scenarios, and more sectors which are likely to be directly or indirectly affected by drought events.

Because the methodologies described in this report are somewhat new to drought concepts, or have been rarely applied (Stahl et al., 2012; Bachmair et al., 2015), we recommend that they be handled with care. In particular, we strongly recommend that robust statistical validation tests be performed on any possible input dataset and the outputs of the projected impacts be carefully checked.

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List of acronyms

CRU:	Climate Research Unit
CRED:	Centre for Research on the Epidemiology and Disaster
DF:	Drought Frequency
DMCSEE:	Drought Management Centre for South-Eastern Europe
EC:	European Commission
EDC:	European Drought Centre
EDII:	European Drought Impact inventory
EDR:	European Drought Reference Database
EDO:	European Drought Observatory
EMM:	European Media Monitor
GPCC:	Global Precipitation Climatology Centre
IPCC:	Intergovernmental Panel on Climate Change
JRC:	Joint Research Centre
KNMI:	Royal Netherland Meteorological Institute
MASH:	Multiple Analysis of Series for Homogenization (software)
NAM:	Northern Annular Mode
NAO:	North Atlantic Oscillation
NUTS:	Nomenclature of Units for Territorial Statistics
PDSI:	Palmer Drought Severity Index
PESETA:	Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis.
PET:	Potential Evapo-Transpiration
RACMO2:	Regional Atmospheric Climate Model version 2
RDI:	Reconnaissance Drought Indicator
SPEI:	Standardized Precipitation-Evaporation Index
SPI:	Standardized Precipitation Index
TDS:	Total Drought Severity
TDD:	Total Drought Duration

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As the Commission's in-house science service, the Joint Research Centre's mission is to provide EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle.

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