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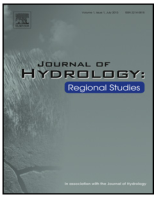

The biggest drought events in Europe from 1950 to 2012

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ABSTRACT

Study region: Europe, including European Russia, but excluding Greenland, the Canary Islands, the Azores, and Madeira.
Study focus: Drought is a complex climate-related phenomenon that can affect different sectors causing economic, social, and environmental impacts. We focus on meteorological and hydrological droughts, defined as shortage of precipitation over several months and we discuss the biggest drought events in 1950–2012. To define such drought events we computed three drought indicators, the Standardized Precipitation Index, the Standardized Precipitation Evapotranspiration Index, and the Reconnaissance Drought Index and we merged them into a combined indicator at 3-month scale for meteorological and 12-month for hydrological droughts. The indicators have been calculated using the E-OBS gridded data ($0.25^\circ \times 0.25^\circ$).
New hydrological insights for the region: Europe has been subdivided into thirteen regions and for each region we determined a list of drought events. The events have been characterized by the time, duration, severity, average area involved, peak month, and area involved at the peak month. We computed time series of the combined indicators for each region and country to determine the twenty-two biggest drought events in 1950–2012. Northern Europe and Russia show the highest drought frequency, duration, and severity in the 1950s and 1960s, where this is for the 1970s in Central Europe and the British Islands, and the 1990s and 2000s for the Mediterranean area and Baltic Republics.

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1. Introduction

In the context of current global warming (IPCC, 2014), drought is a hot topic in the scientific literature (Sheffield et al., 2012; Dai, 2013; Spinoni et al., 2014a; Trenberth et al., 2014). It is a weather and climate-related phenomenon of complex nature resulting in a variety of definitions (Smakhtin and Schipper, 2008) that makes it difficult to readily detect and evaluate its onset and evolution (Trenberth et al., 2004). Drought is typically classified into meteorological, agricultural, hydrological, ground-water, streamflow, and socio-economic drought (Mishra and Singh, 2010) and, depending on the type, drought monitoring is usually performed through a wide number of indicators (Heim, 2002; Mishra and Singh, 2011; Sharma and Panu, 2014). This study deals with meteorological drought, as it is based on meteorological input variables (precipitation and temperature), but the chosen accumulation scales of the drought indicators, i.e. 3-month and 12-month, are usually respectively referred to meteorological and hydrological droughts (Mishra and Singh, 2010).

In Europe, drought does not only affect semi-arid areas such as the Mediterranean region (Hoerling et al., 2012). Extended drought events have repeatedly affected also Western- and Central Europe (Rebetez et al., 2006), the British Islands (Perry, 1976), Scandinavia (Hisdal et al., 2006), Eastern Europe (Spinoni et al., 2013), and Russia (Arpe et al., 2012; Parry et al., 2010, 2012). There is much literature on single European drought events (see Bradford, 2000, for a collection), websites providing European drought bulletins, forecasting, or reports (e.g., the European Drought Observatory or EDO, see: http://edo.jrc.ec.europa.eu/; the Drought Management Centre for South-Eastern Europe or DMCSEE, see: http://www.dmcsee.org/), and global monitoring systems from which information about European droughts can be derived (e.g., the SPEI Global Drought Monitor, see: http://sac.csic.es/spei/; the Global Integrated Drought Monitoring and Prediction System, see: http://drought.eng.uci.edu/).

However, none of the cited online services provides a complete picture of the meteorological and hydrological drought events that occurred in Europe in the last decades. For example, the EDO reports on the current drought conditions, for some special cases using a combined drought indicator (CDI, Sepulcre-Canto et al., 2012), and is mainly focused on agricultural drought. The DMCSEE provides the user with valuable monitoring products, but focuses only on South-Eastern Europe. The SPEI Global Drought Monitor offers near real-time information about drought conditions at $0.5^\circ \times 0.5^\circ$ spatial resolution and contains time series of the SPEI from 1950 onwards, but does provide a historical dataset of past drought events.

An important step towards the construction of a detailed database of past drought events is represented by the European Drought Reference (EDR) database, hosted by the website of the virtual European Drought Centre (EDC, see: www.geo.uio.no/edc). However, so far this database uses the Standardized Precipitation Index (SPI) computed at 6-month accumulation period and daily temporal scale, as the sole drought indicator. The EDR classifies eleven major European drought events (Stagge et al., 2013), considering duration, area involved, and peak date as drought characteristics. The EDR is linked with the European Drought Impact Inventory (EDII; Stahl et al., 2012), an online database which collects documents dealing with drought impacts from various sources.

The main goal of our study is to compile a list of the biggest drought events which took place in Europe from 1950 to 2012, and analyze these events. Compared to the already existing drought datasets, we introduced some important novelties. Firstly, we based our analysis on quality-checked and homogenized data (see Section 2.1). Secondly, we set a multi-indicator approach to detect the drought events (see Section 2.2). Thirdly, we defined a list of characteristics for each drought event: start and end, duration, severity, intensity, area involved, peak month, and area involved at the peak month (see Section 2.3). Fourthly, we analyzed the drought events for the whole of Europe and also separately per region and country (see Section 3).

We aimed to create a robust list of the most relevant drought events through the use of homogenized data ensuring the reliability of the analysis and avoiding misleading anomalous data for drought events or outliers for extreme events. Three indicators are used instead of one in order to consider more complete information, and to take into account the effect of temperature and potential evapotranspiration (PET). The use of a wider set of descriptive characteristics based on an objective set of thresholds and definitions allows to obtain a better understanding of the different features of the drought events. The analysis performed per country and per region permits to compile a list of the longest and most severe events for each European country. The country and regional series of the combined drought indicator opens the way for further analysis of drought tendencies during the last decades at different spatial scales (Spinoni et al., 2015). This study preliminarily discusses the regional drought tendencies in terms of frequency, duration, and severity of the drought events in three different periods, i.e. 1951–70, 1971–90, and 1991–2010. Although all the analyses have been performed at both 3-month and 12-month accumulation scales, this paper focuses on the 12-month accumulation period, because this accumulation scale is most relevant for hydrological drought.

After the introduction, Section 2 presents the input data, the drought indicators selected, and the theoretical background of the drought variables. Section 3 presents the results: the drought time series per region and country, the evolution of the areas prone to drought conditions, and the list of the biggest European drought events from 1950 to 2012. Section 4 summarizes the main findings and introduces some possible follow-up studies and applications, in particular regarding the study of the possible links between drought events and impacts in different sectors.

2. Data and methods

2.1. Precipitation and temperature gridded data

To describe a drought event and compute the corresponding drought characteristics, we selected indicators based on precipitation (P) and PET. We retrieved daily mean temperature (T_M) and precipitation data for the period 1950–2012 from the E-OBS gridded data (version 10, spatial resolution: $0.25^\circ \times 0.25^\circ$) of the European Climate Assessment and Dataset (ECA&D; Haylock et al., 2008) of the Royal Netherlands Meteorological Institute (KNMI). We used T_M data to obtain PET at monthly scale, using an improved version of the Thornthwaite model (Van der Schrier et al., 2011; Thornthwaite, 1948). Such new version – still based on mean temperature and latitude as principal inputs – more carefully accounts for very low and very high temperatures through a refined parameterization. We also tested the FAO-56 Hargreaves equation (Allen et al., 1998), which is based on minimum and maximum temperature input data, but its use did not result in remarkable differences compared to the use of the Thorntwaite's model for the studied region.

It is important to underline that the choice of PET algorithms based on temperature inputs, as the Thornthwaite method, may influence the results (Trenberth et al., 2014). The Thornthwaite method can be considered a rather simplified model if compared with other formulations such as the one by Penman–Monteith (Allen et al., 1998). Sheffield et al. (2012) and Seneviratne (2012) pointed out that basing PET on temperature-driven models may exaggerate the effect of the current global warming, while on the other side Dai (2011) showed that the use of the Thornthwaite or the Penman–Monteith formulation does not remarkably affect the drought-related studies. However, such discussion is related to different drought indicators, i.e. the PDSI (Palmer, 1965) and the sc-PDSI (Wells et al., 2004) and, regarding Europe and the sc-PDSI, the use of the Thornthwaite model has proven to produce reliable results (Van der Schrier et al., 2013).

With regards to the input gridded data, we firstly performed a quality check on the daily data looking for outliers and spurious values. Secondly, we transformed the daily values of a given month into a monthly average (sum) if no more than three (one) temperature (precipitation) values were missing. Thirdly, we homogenized the monthly series with the Multiple Analysis of Series for Homogenization software (MASHv3.02; Szentimrey, 1999). The homogenization, based on the structure of MASH, can be summarized in eight steps: (1) conversion of daily incomplete series into monthly series, if necessary; (2) first estimation of inhomogeneities of monthly series; (3) smooth estimation of inhomogeneities of daily series using the parameters obtained in the previous steps; (4) automatic correction of daily series; (5) automatic quality check for the homogenized daily series; (6) automatic completion of missing daily data, if present; (7) computation of monthly series from quality-checked, completed, and homogenized daily series; (8) test of the homogeneity of the new monthly series. More details can be found in Spinoni et al. (2014b).

A few locations (<0.4%) in Northern Scotland, Central Italy, Albania, Macedonia, Southern Greece, and Central Turkey did not pass the homogeneity tests, which consequently have been excluded from the analysis. Whenever possible, we used the interpolated values taken from the surrounding grid cells to compute the drought indicators for these grid points. The most problematic situation involves Iceland: all the points did not pass the homogeneity tests for the period 2006–2012. Consequently, the Icelandic drought events were investigated until 2005 only.

2.2. Drought indicators: SPI, SPEI, RDI, and the combined indicator

Globally, droughts have been studied using many different indicators (see Heim, 2002; Hayes et al., 2011, for a review). In Europe, the most used indicators are the SPI (McKee et al., 1993) and the Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010). The SPI is based on precipitation and has been applied in almost every region in Europe (e.g. Lloyd-Hughes and Saunders, 2002), while the SPEI, based on the difference P-PET, is applied in particular in the Iberian Peninsula (Vicente-Serrano et al., 2011b), but its use throughout Europe is recently increasing (Beguería et al., 2014). Also the PDSI and the sc-PDSI have been successfully applied in European drought studies (e.g. Van der Schrier et al., 2006). However, they require many assumptions and variables that are hardly retrievable at high-resolution and at European scale. To obtain more complete information, we computed a third indicator, the Reconnaissance Drought Indicator (RDI; Tsakiris and Vangelis, 2005), based on the ratio P/PET, and applied it in particular in South-Eastern Europe (Vangelis et al., 2011).

We computed the indicators at monthly scale and for two accumulation periods: 3-month (SPI-3, SPEI-3, RDI-3) and 12-month (SPI-12, SPEI-12, RDI-12), using all the available data in the period 1950–2012 to fit the theoretical distributions. The distributions were taken equal to the ones initially proposed by the authors of the indicators. For the SPI, McKee et al. (1993) proposed the Gamma distribution for the cumulated precipitation (P), a choice that is further discussed by Guttman (1999). For the SPEI, Vicente-Serrano et al. (2010) suggested the use of the log-logistic distribution to the cumulated difference P-PET, as also further studied by Beguería et al. (2014). Tsakiris and Vangelis (2005) calibrated the RDI by using the lognormal distribution for the cumulated ratio P/PET, discussing also how this distribution helps solving the problems caused by very low to null PET values that may occur especially with short-term accumulation periods (e.g. for RDI-1 and RDI-3).

For a given grid point, we averaged the values of the SPI, the SPEI, and the RDI into a combined indicator called X (X-3 and X-12 depending on the accumulation period). If one of the described indicators showed missing values, we averaged the remaining ones. Firstly, we obtained a monthly series of X-3 and X-12 for the period 1950–2012 for every grid point. Secondly, we obtained the corresponding series for every European country by averaging the values within the national borders. Thirdly, we divided Europe into thirteen regions (Table 1) according to country borders, geographical, and climatic features, in order to derive regional series.

We separately analyzed the X-3 and the X-12 to evaluate meteorological drought events (X-3) and hydrological drought events (X-12) that may have consequences on agriculture (usually from 3 to

Table 1
List of countries belonging to the regions in which Europe has been subdivided.

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

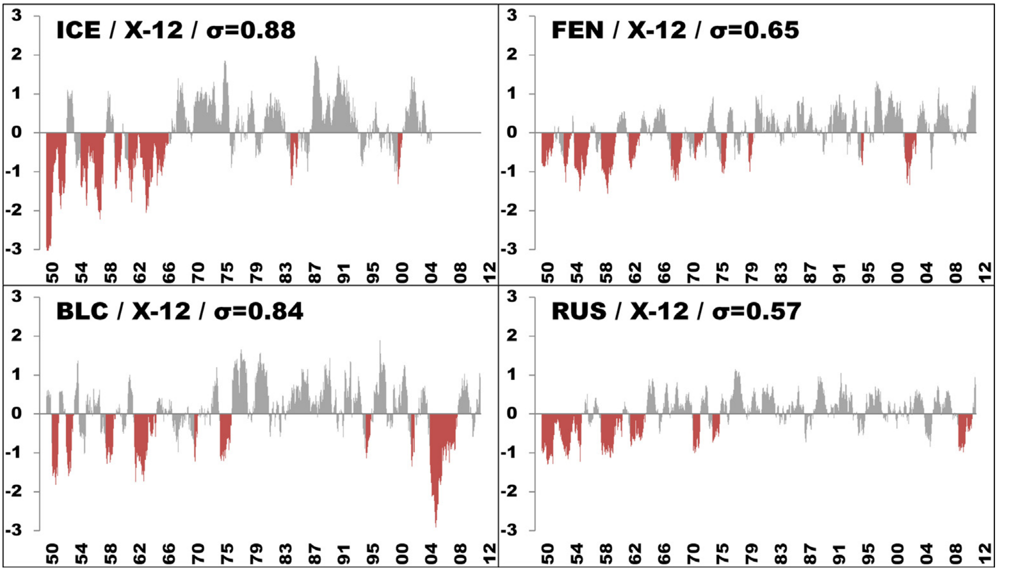

Fig. 1. Northern Latitudes regional drought series for the period 1950–2012 according to the indicator X-12. Drought events are marked in red.

6-month accumulation periods) and on the hydrological cycle (usually from 9 to 24-month periods; WMO, 2012). Though we show the results at a country or regional scale, the corresponding time series of the combined indicators have been also computed at the grid points. The latter results can be used to assess the evolution of drought conditions for every European location from March 1950 (December 1950 if the X-12 is used) to December 2012. As discussed in the introduction, we mostly show tables and figures regarding the X-12.

2.3. Drought events and their assigned parameters

According to McKee et al. (1993), a drought event starts when the SPI falls below −1 and ends when it turns positive. For a normalized quantity as the SPI (as well as for the SPEI and the RDI), the value 1 (−1) corresponds to one standard deviation above (below) the mean ($\bar{\text{SPI}} = 0$). The spatially averaged series of the combined indicator (X) for a country (or region) is no longer standardized, so we assume that a drought event starts when X falls below a certain threshold (X_τ) for at least three consecutive months and ends when it turns above the mean value of the series ($\bar{X}$). The threshold is no longer −1 as often used for the SPI, but it depends on the size of the country (region) under examination: the values of the averaged series for the country (region) are calibrated to a normal distribution and the mean and standard deviation calculated for each country (regional) series. The negative value of such standard deviation ($X_\tau = -1\sigma$), different for every country (region), is the threshold which determines the beginning of the drought event, while the corresponding mean of the series ($\bar{X}$) determines the ending. In Figs. 1–6 the mentioned threshold is indicated with σ and consequently the drought event "starts" whenever the combined indicator is below the negative value of the threshold ($-\sigma$) for the third consecutive month.

Whenever a drought event has been detected, it has been assigned a set of drought characteristics. These are: *start*, which is the first month with the indicator below the threshold; *end*, the last month with the indicator below the mean; *duration*, the number of months of the event; *severity score (dimensionless)*, 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); *peak month*, the month with the lowest value of the indicator during the drought event; *area involved (%)*, the percentage of the region (or country) with values below −1 (for the grid points −1 is always

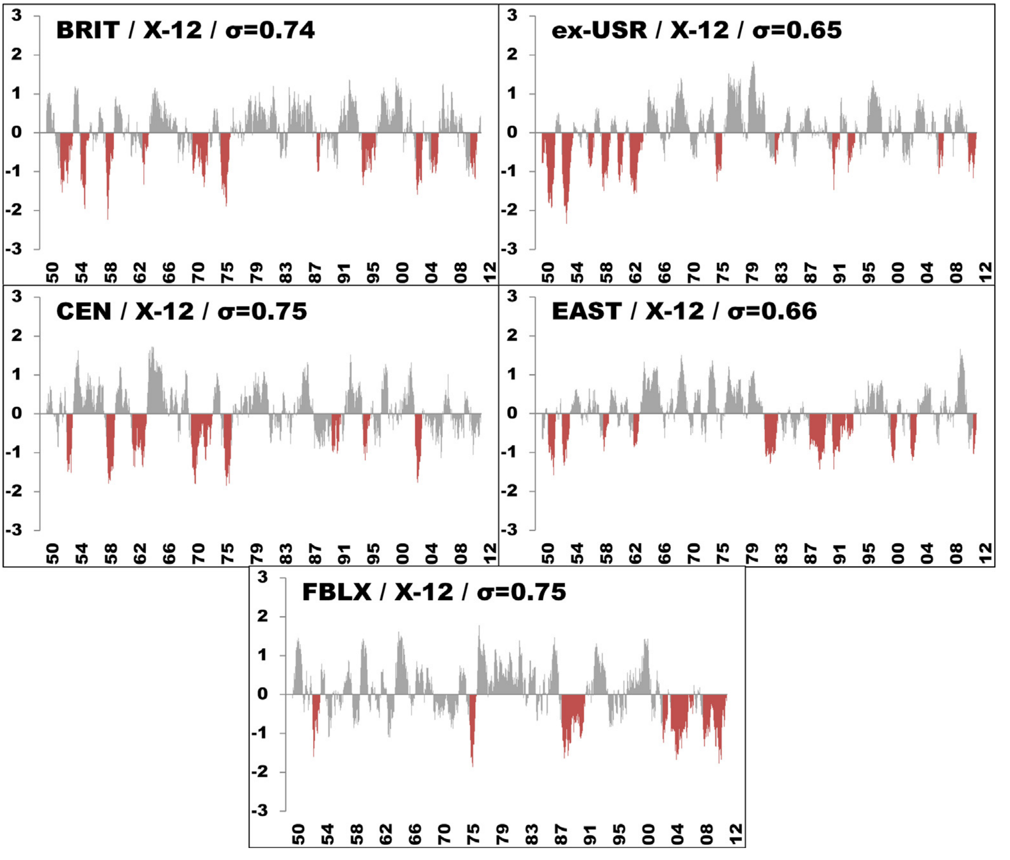

Fig. 2. Mid Latitudes regional drought series for the period 1950–2012 according to the indicator X-12. Drought events are marked in red.

Table 2
Regional drought characteristics for three periods according to X-12.

X-12	Events			Average duration *(months)*			Average severity *(score)*		
	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	**30**	26.3	1.3	5.7	**6.9**
BLK	**5**	3	4	9	8.3	**16.3**	2.7	3.6	**4.2**
EAST	**4**	2	3	11.8	**26**	19.7	2.4	**6.8**	3.2
RUS	**3**	2	1	**44**	12.5	24	**8.6**	1.7	3.5
FBLX	1	2	**3**	13	26	**33**	2.6	**7.8**	7
ex-USR	**6**	2	3	**17.2**	10.5	11.3	**7.2**	1.8	1.2
CEN	**3**	2	**3**	16.7	**25**	13.7	6	**8**	2.6
BRIT	**4**	3	3	15.8	**17**	16.3	**4.2**	4.1	3.3
FEN	**6**	3	2	**21.3**	12	12.5	**4.2**	0.9	1.8
BLC	**4**	2	3	20.3	13.5	**21.3**	5.9	1.6	**10**
ICE	**4**	1	1[a]	**39.8**	13	8	**15.4**	1	0.7

Bold is the highest value between the decades.
[a] The Icelands have no data in 2006–2010.

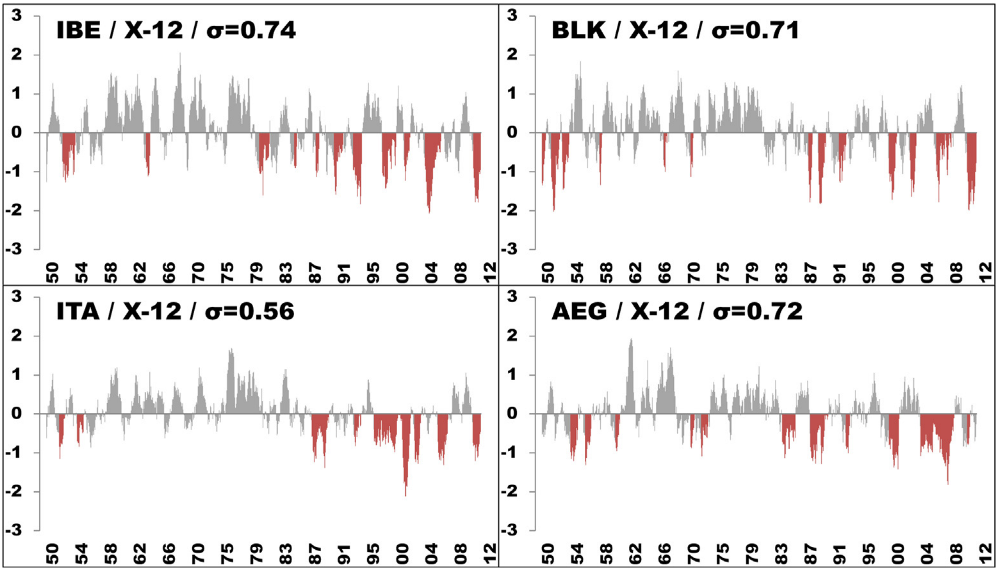

Fig. 3. Southern Latitudes regional drought series for the period 1950–2012 according to the indicator X-12. Drought events are marked in red.

set as unique threshold); *area involved at peak month (%)*, the widest area involved, but to the month with the lowest value of the indicator.

3. Results and discussion

3.1. Regional and country drought time series

For every region listed in Table 1 we computed the average monthly series for the X-3 (not shown here) and the X-12 (Figs. 1–3). Thereafter, we computed the time series of the X-3 and the X-12

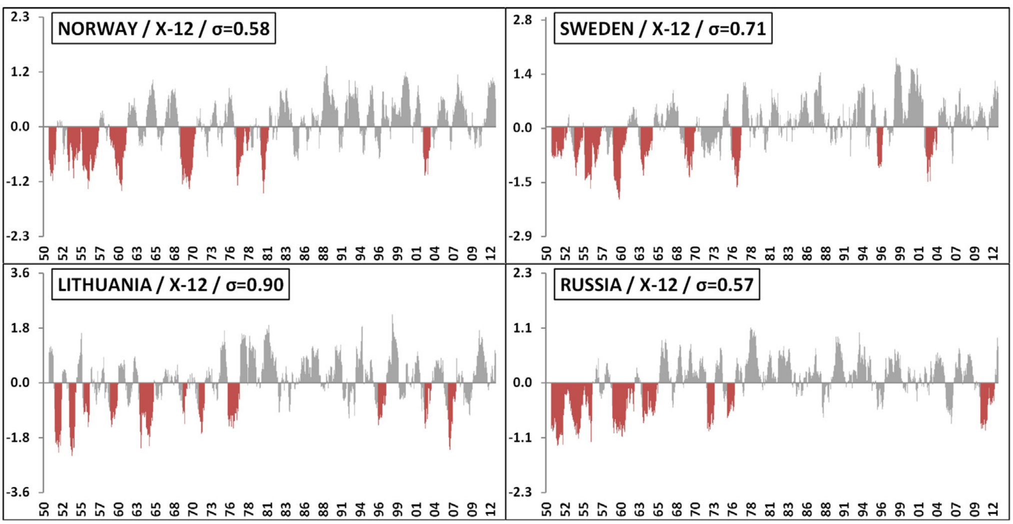

Fig. 4. Northern Europe country drought series for the period 1950–2012 according to the indicator X-12 for some selected countries. Drought events are marked in red.

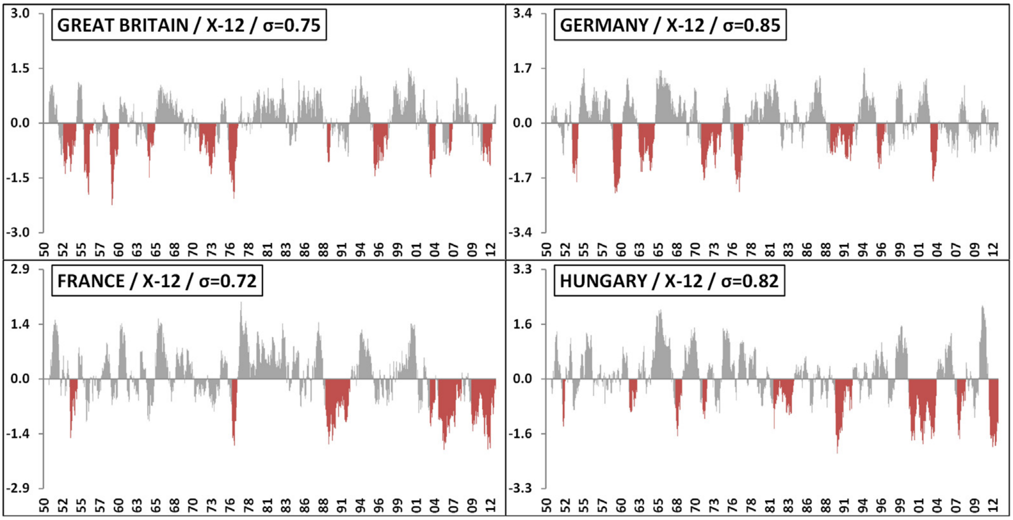

Fig. 5. Central Europe country drought series for the period 1950–2012 according to the indicator X-12 for some selected countries. Drought events are marked in red.

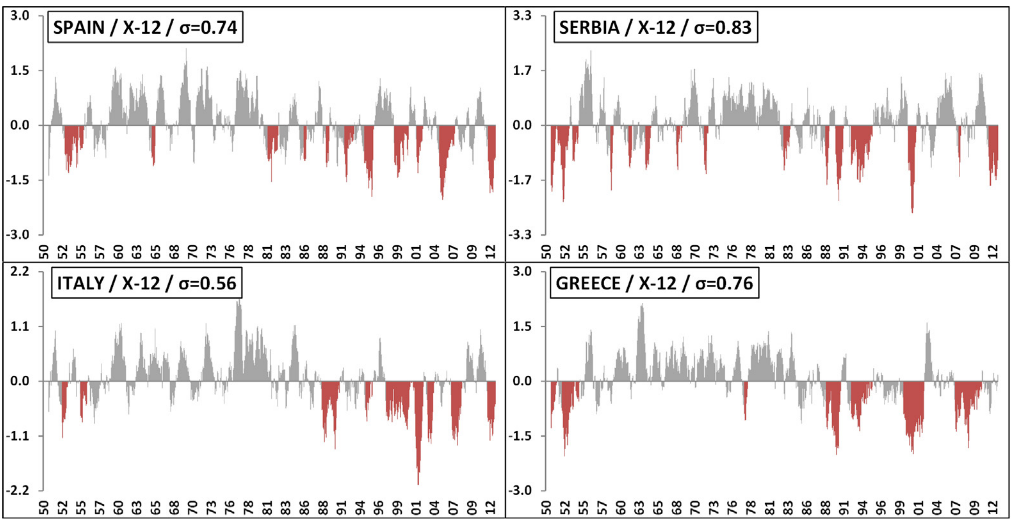

Fig. 6. Southern Europe country drought series for the period 1950–2012 according to the indicator X-12 for some selected countries. Drought events are marked in red.

for every European country and we show the corresponding X-12 series for some selected countries (Figs. 4–6). In Figs. 1–6, the drought events are marked in red. Fig. 7 provides a comprehensive view of all the drought events detected with the X-12, between 1950 and 2012. Though most of the grid points in Iceland, the Fær Øer islands, and the Svalbard islands passed the homogeneity tests, we handled with care the regional and country series of the northernmost European areas.

According to Figs. 1–3 and 7, Europe can be split into two macro areas: the North-Eastern regions have been hit by more drought events in the 1950s, the 1960s, and the 1970s, while for the South-Western countries this is the case in the 1980s, the 1990s, and the 2000s. Very similar findings have been obtained by computing the area affected by the droughts. In this study, a grid point is considered

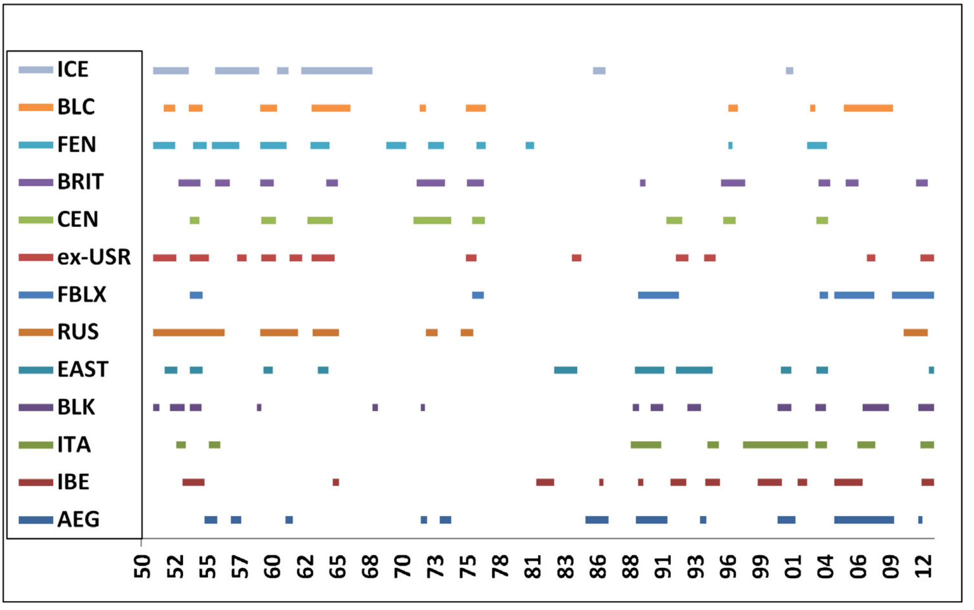

Fig. 7. Summary of drought events per region according to X-12.

"in drought" for a given month if the combined indicator X-12 is below −1. For every grid point, we counted how many months per year (in %) X-12 < −1 and we averaged such percentages for all the points within each region. Thus, we obtained annual series of areas in drought conditions (in %) per region (Fig. 8).

Europe experienced a decrease of such areas until the early 1980s, followed by a small but continuous increase in the last three decades. The North-Eastern regions (ICE, FEN, RUS, and ex-USR) show a decrease, the South-Western ones (IBE, ITA, BLK, and AEG) an increase, and Central and Eastern Europe (FBLX, CEN, EAST, and BLC) act like transition areas showing no clear tendencies. Similar

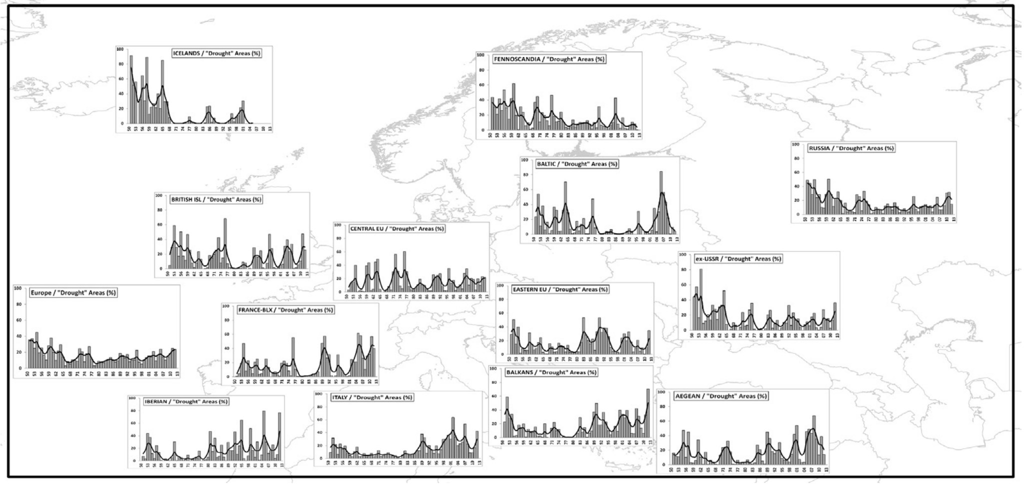

Fig. 8. Annual series of areas in drought conditions according to X-12. The bold lines represent the 5-year moving weighted averages.

Table 3
Longest (*number of months*), most severe (*drought score*), and widest (% of area involved in the peak month) drought event per region according to X-12.

X-12	Longest	Months	Most severe	Score	Widest	Area
AEG	2005–09	58	2005–09	10.4	ott-01	80.20%
IBE	2005–07	24	2005–07	11.8	ago-05	97.00%
ITA	1997–02	63	1997–02	16.3	apr-02	91.40%
BLK	2007–09	26	2011–12	12.5	mar-89	93.40%
EAST	1992–95	36	1989–91	7	ago-52	84.50%
RUS	1950–56	69	1950–56	16.7	giu-56	69.80%
FBLX	2009–12	41	1989–92	10	giu-76	87.00%
ex-USR	1963–65	24	1953–55	14.1	giu-64	95.80%
CEN	1971–74	37	1959–60	8.7	ago-76	93.80%
BRIT	1971–74	28	1975–76	8	set-59	96.00%
FEN	1955–57	27	1959–61	8.6	mag-60	76.40%
BLC	2005–09	48	2005–09	28	ago-06	99.00%
ICE	1962–68	69	1962–68	29.1	mar-51	100.00%

Table 4
Multi-region drought events detected by the X-3, the X-12, or both, the % of the entire European area involved by the drought event, and a few papers which mention such events.

Ind	Period	Drought macro-area	Regions involved	Area at peak (%)	Mentioned by
X-3; X-12	1950–52	Pan-European	ITA, BLK, EAST	10/1951 (50.1%)	Briffa et al. (1994)
			RUS, FBLX, ex-USR		Lloyd-Hughes and Saunders (2002)
			CEN, BLC, ICE		Cherenkova (2007) Sheffield et al. (2009)
X-3; X-12	1953–54	Pan-European	IBE, BLK, EAST, RUS, FBLX ex-USR, CEN, BRIT, FEN, BLC	12/1953 (54.3%)	Sheffield et al. (2009)
X-3; X-12	1955–56	Northern Europe	RUS, BRIT, FEN, ICE	09/1955 (41.2%)	Veryard (1956)
					Meshcherskaya and Blazhevich (1997) Santos et al. (2000)
X-3; X-12	1959–60	North-Central-Eastern Europe	EAST, RUS, ex-URS	04/1959 (26.6%)	Meshcherskaya and Blazhevich (1997)
			CEN, BRIT, FEN, BLC		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	EAST, RUS, ex-URS,	02/1964 (34.8%)	Hisdal et al. (2001)
			CEN, FEN, BLC, ICE		Zaidman et al. (2001) Hannaford et al. (2011) Parry et al. (2012)
X-3	1969	UK-Scandinavia	CEN, FEN, BRIT	10/1969 (15.9%)	Hannaford et al. (2011)
X-3; X-12	1972–74	pan-European	CEN, BRIT, FEN	03/1972 (54.1%)	Buchinsky (1976)
			BLK, RUS		Dronin and Bellinger (2005) Briffa et al. (2009) Stagge et al. (2013)

Table 4 (*Continued*)

Ind	Period	Drought macro-area	Regions involved	Area at peak (%)	Mentioned by
X-3; X-12	1976	Central Europe and British Islands	FBLX, ex-USR, FEN CEN, BRIT, BLC	05/1976 (23.7%)	Perry (1976) Shaw (1979) Doornkamp et al. (1980) Morren (1980) Parry et al. (2012) Stagge et al. (2013)
X-3	1983	Eastern Europe	EAST, ex-USR, CEN	10/1983 (16.0%)	–
X-3	1985	Southern Europe	AEG, IBE, ITA, FBLX, BLK	09/1985 (19.5%)	–
X-3; X-12	1989–91	Southern Europe, Mediterranean	AEG, IBE, ITA BLK, EAST, FBLX	03/1989 (32.2%)	Tselepidaki et al. (1992) Briffa et al. (1994) Zaidman et al. (2001) Tsakiris and Vangelis (2005)
X-12	1992	Central Europe	CEN, FBLX, EAST IBE, ex-USR	08/1992 (23.6%)	Szinell et al. (1998) Spinoni et al. (2013)
X-3	1994	North-Eastern Europe	EAST, FEN, ex-USR	09/1994 (29.5%)	–
X-12	1995	Southern Europe	AEG, IBE, ITA, EAST	12/1994 (13.8%)	Pal et al. (2004) Stagge et al. (2013)
X-12	1996–97	Central and Northern Europe	CEN, BRIT, FEN, BLC	08/1996 (24.1%)	Fleig et al. (2011) Parry et al. (2012) Stagge et al. (2013)
X-3; X-12	1999–2001	Southern//Eastern EU	AEG, IBE, ITA, BLK, EAST	12/2000 (33.5%)	Spinoni et al. (2013) Stagge et al. (2013)
X-3; X-12	2003	European heat-wave	ITA, BLK, EAST FBLX, CEN, BRIT, FEN	08/2003 (27.5%)	Fink et al. (2004) Ciais et al. (2005) Rebetez et al. (2006)
X-3; X-12	2004–05	Iberian Peninsula	AEG, IBE FBLX, BRIT, BLC	07/2005 (15.7%)	Garcia-Herrera et al. (2007) Santos et al. (2007) Ruiz-Sinoga and Martínez-Murillo (2009) Santos et al. (2010) Stagge et al. (2013)
X-3; X-12	2005–07	Baltic Republics	BLC, ex-USR, EAST, BLC	12/2006 (22.3%)	Tammets (2007) Briede and Lizuma (2010)
X-3; X-12	2007–08	Aegean countries	AEG, IBE, ITA, BLK ex-USR, BLC	07/2006 (34.3%)	August and Geiger (2008) Michaelides and Pashiardis (2008) Simsek and Cakmak (2010) Dimitrakopoulos et al. (2011)
X-3; X-12	2010	Russia	ex-USR, RUS, EAST	08/2010 (41.1%)	Mokhov (2011) Wegren (2011) Arpe et al. (2012)
X-3; X-12	2011	France, England, Central Europe	IBE, ITA, FBLX, BLK, RUS, BRIT, ex-USR	04/2011 (39.5%)	Kendon et al. (2013) Todd et al. (2013) Sepulcre-Canto et al. (2014)

trends have been reported by Dai (2013), Hoerling et al. (2012), Sheffield et al. (2012), Van der Schrier et al. (2013), and Spinoni et al. (2014a). These findings are consistent with the conclusions made by Willems (2013a,b) that precipitation extremes show oscillatory behaviour over multi-decadal time scales, and that the oscillation phases shift across Europe.

3.2. Compiling the list of the biggest past drought events in Europe

According to the monthly time series of X-3 and X-12, we compiled two corresponding lists of drought events for every region and country (period 1950–2012) and we assigned to every event the parameters described in Section 2.3. The complete lists, together with tables and interactive maps related to the drought events, are planned to become part of the European Drought Observatory (EDO, see the website: http://edo.jrc.ec.europa.eu/) of the European Commission's Joint Research Centre (JRC).

Table 2 reports the number of drought events, their average duration and severity for every region and for three 20-year periods, according to the X-12 indicator. Both the short-term (X-3, not shown here) and the long-term drought events (X-12, Table 2) show the highest frequency in the period 1951–1970 in most of the regions. An exception is the highest frequency in the period 1991–2010 in South-Western regions. In general, the drought events have been longest and most severe in North-Eastern Europe in the period 1951–70, in Central European regions in the period 1971–1990, and in Southern Europe (in particular in the Mediterranean area) in the period 1991–2010. Also this is consistent with the periods reported in Willems (2013a,b) as the periods with more/less and higher/lower precipitation extremes.

Table 3 lists the top events per region, according to the X-12 indicator. According to the X-3 (not shown here), the longest event occurred in the Baltic Republics and lasted about four years in the mid-2000s, while according to the X-12 the longest occurred in Iceland in the mid-1960s and in Russia in the early 1950s, both lasting more than five years. The most severe events (compared to the normal conditions of the region) occurred in Iceland (in 1950–51 for the X-3; in the mid 1960s for the X-12) and in the Baltic Republics (in the mid-2000s for both combined indicators).

In order to list the most relevant European drought events in the last six decades, we selected the events involving at least three macro regions simultaneously. Table 4 reports twenty-two multi-region events detected by the X-3, the X-12 or both: the temporal distribution of such events is uneven because most of the events occurred in the 1950s or in the 2000s (including 2011) and, according to X-12, the events in the 1950s involved about half of Europe. This is confirmed by literature: the 1950s are known as a dry period in Europe, characterized by low rainfall (Herweijer and Seager, 2008) and most of the driest months of the 20th century are related to the 1940s and the 1950s (Briffa et al., 1994; Lloyd-Hughes and Saunders, 2002; Van der Schrier et al., 2006). The 2000s have been characterized by rising temperature and more extreme precipitation events mixed with prolonged dry periods (IPCC, 2014), causing the increase in drought frequency and severity in Southern Europe and the Mediterranean area (Vicente-Serrano et al., 2011a; Hoerling et al., 2012), but also in Russia. Russia was hit by a devastating meteorological, agricultural, and hydrological drought in 2010 (Wegren, 2011; Arpe et al., 2012), which followed the heat-wave (Trenberth and Fasullo, 2012) and the wildfires (Konovalov et al., 2011).

Table 4 also reports some of the most important publications regarding the events being part of the list. In order to prove the effectiveness of our methodology to detect the most relevant drought events, we checked the scientific literature – where drought events are often sparsely discussed in single case studies – looking for papers or reports which confirm, directly or indirectly, the occurrence of the events listed in Table 4. Excluding a couple of cases that have been pointed out by the X-3 only, all the events reported in Table 4 have been documented. We underline that Table 4 refers only to multi-region drought events. Consequently, the events that hit one region or single countries are not reported there.

4. Conclusions

This study discussed the compiling of a pan-European list of past drought events for the period 1950–2012. To define such events at country, regional, and multi-region spatial scale, we computed three indicators (the SPI, the SPEI, and the RDI) at 3-month and 12-month accumulation scales. We averaged the indicators, to obtain a combined indicator for each accumulation period, i.e. the X-3 and the X-12. Using the country and regional monthly series of the X-3 and the X-12, we analyzed the related drought events with a set of drought-related characteristics (start, end, duration, severity, peak month, and area involved).

This new methodology proved to be valid to detect the most relevant European drought events, because it is based on homogenized input data, a multi-indicator approach and robust statistical background. However, there still are some drawbacks that need further analysis. First of all, the spatial resolution ($0.25^{\circ} \times 0.25^{\circ}$) does not allow at studying drought events at the local scale, e.g. to analyze droughts at the spatial scales of river basins or small hydrological catchments. Moreover, the choice to compute PET (and the use of PET instead of AET) with the temperature-based Thornthwaite model was motivated, but additional analysis with other parameterizations for PET may lead to more robust results in the hottest and driest regions, i.e. Southern Spain, Greece, Cyprus, and Southern Turkey. Another critical point lies in the choice of thresholds to define a drought events with a combined indicator that is not standardized. Although we discussed and motivated our choice, more tests about the uncertainties should be performed as well as comparisons with other combined indicators, e.g. the CDI included in the European Drought Observatory (Sepulcre-Canto et al., 2012).

According to the results presented in this study, Northern and Eastern Europe show the highest drought frequency and severity from the early 1950s to the mid-1970s. Considering entire Europe, the 1950s is the decade most hit by long, intense, and wide meteorological and hydrological droughts. Following the time series of the X-12, two of them (the 1951–52 and the 1953–54 events) involved about half of the whole of Europe. Southern and Western Europe (in particular the Mediterranean area) show the highest drought frequency and severity from the early 1990s onwards. In general, we found a small but continuous increase of the European areas prone to drought from the early 1980s to the early 2010s. These findings agree with recent scientific literature (Hoerling et al., 2012; Sheffield et al., 2012; Van der Schrier et al., 2013; Spinoni et al., 2014a; Vicente-Serrano et al., 2014).

The time series of the combined indicators (the X-3 and the X-12) allowed us to list twenty-two multi-region big drought events. To assess the validity of our methodology, we sifted the scientific literature and we looked for papers or technical reports that confirmed the occurrence of the drought events in our list. Only three events (detected by the X-3 only) could not be confirmed and, to our best knowledge, no documented multi-region drought event was missed by our methodology and consequently left out from the list. This preliminary dataset would be exploited more in further analysis. We plan ranking such events for duration, severity, and area involved. Moreover, we plan compiling similar charts of the most relevant drought events for each single European region and country. Finally, we will explore the possibility to extend the dataset back in time to the 1930s – for the late 1930s and the 1940s have been particularly dry in Europe (Briffa et al., 1994) – though the data availability and quality for many European areas before 1951 could prevent the realization of this plan.

This dataset can help researchers, stakeholders, and end-users handling the multitude of past drought events that are sparsely reported as single case studies in literature. Furthermore, as first possible application, we plan exploiting this dataset to correlate the severity and duration of each event with documented impacts in different sectors. In fact, drought events can have a wide variety of impacts, for example on primary production (Zhao and Running, 2010), crop yields (Li et al., 2009), vegetation (Vicente-Serrano et al., 2012), and water resources (Bond et al., 2008). We will therefore investigate the link between the meteorological and hydrological drought events in our lists and their possible impacts through dedicated damage functions, similarly to what has been recently done for floods and forest fires (Martinez et al., 2014). The preliminary tests, performed for single countries and using data related to hydropower generation and annual crop yields (wheat, vegetables, and fruits) are promising (Naumann et al., 2015), but more tests on other sectors are needed to derive conclusive results.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper, vol. 56. FAO, Rome, 15 pp.

Arpe, K., Leroy, S.A.G., Lahijani, H., Khan, V., 2012. Impact of the European Russia drought in 2010 on the Caspian Sea level. Hydrol. Earth Syst. Sci. 16 (1), 19–27.

August, D., Geiger, M., 2008, August. In: Durmaz, B.B., Antonelli, F., Dopke, M., Maragou, P., Gillet, S., Moroz, S., El Madani, M., Karivali, M., Is, G., Fernandez Lop, A., De Stefano, L. (Eds.), Drought in the Mediterranean. Recent Developments. Published by WWF Germany, Frankfurt am Main http://assets.wwf.es/downloads/drought_in_the_mediterranean_2008_1.pdf

Beguería, S., Vicente-Serrano, S.M., Reig, F., Latorre, B., 2014. Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. Int. J. Climatol. 34 (10), 3001–3023.

Bond, N.R., Lake, P.S., Arthington, A.H., 2008. The impacts of drought on freshwater ecosystems: an Australian perspective. Hydrobiologia 600 (1), 3–16.

Bradford, R.B., 2000. Drought events in Europe. In: Vogt, J.V., Somma, F. (Eds.), Drought and Drought Mitigation in Europe. Kluwer, Dordrecht, pp. 7–20.

Briede, A., Lizuma, L., 2010. Analysis of high temperature extremes and climatological drought long-term tendencies in Latvia. In: 10th EMS Annual Meeting, 10th European Conference on Applications of Meteorology (ECAM) Abstracts, EMS 2010-370, Zürich, Switzerland, September 13–17, 2010.

Briffa, K.R., Jones, P.D., Hulme, M., 1994. Summer moisture variability across Europe, 1892–1991: an analysis based on the Palmer drought severity index. Int. J. Climatol. 14 (5), 475–506.

Briffa, K.R., van Der Schrier, G., Jones, P.D., 2009. Wet and dry summers in Europe since 1750: evidence of increasing drought. Int. J. Climatol. 29 (13), 1894–1905.

Buchinsky, I.E., 1976. Droughts and dry winds. Gidrometeoizdat, 214 pp. (in Russian).

Cherenkova, E.A., 2007. Dynamics of severe atmospheric droughts in European Russia.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingestein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437 (7058), 529–533.

Martinez, C., Feyen, L., Soria Ramirez, A., Lavalle, C.S., Perry, M., Raes, F., Nemry, F., Demirel, H., Roszai, M., Dosio, A., Donatelli, M., Srivastava, A.K., Fumagalli, D., Niemeyer, S., Shrestha, S., Ciaian, P., Himics, M., van Doorslaer, B., Barrios, S., Ibanez Rivas, J.N., Forzieri, G., Rojas Mujica, R.F., Bianchi, A., Dowling, P., Camia, A., Liberta, G., San-Miguel-Ayanz, J., De Rigo, D., Caudullo, G., Barredo Cano, J.I., Paci, D., Pycroft, J., Saveyn, B., Revesz, T., Baranzelli, C., Vandecasteele, Batista, E., Silva, F., Ibarreta Ruiz, D., 2014. Climate Impacts in Europe. In: The JRC Peseta II Project. JRC-IPTS Working Paper JRC8701. Institute for Prospective and Technological Studies, Joint Research Centre, Ispra, Italy.

Dai, A., 2011. Characteristics and trends in various forms of the Palmer Drought Severity Index during 1900–2008. J. Geophys. Res.: Atmos. (1984–2012) 116 (June (D12)).

Dai, A., 2013. Increasing drought under global warming in observations and models. Nat. Clim. Change 3 (1), 52–58.

Dimitrakopoulos, A.P., Vlahou, M., Anagnostopoulou, C.G., Mitsopoulos, I.D., 2011. Impact of drought on wildland fires in Greece: implications of climatic change? Clim. Change 109 (3–4), 331–347.

Doornkamp, J.C., Gregory, K.J., Burn, A.S., 1980. Atlas of Drought in Britain 1975–76. Institute of British Geographers, London, 82 pp.

Dronin, N., Bellinger, E., 2005. Climate Dependence and Food Problems in Russia 1900–1990. The Interaction of Climate and Agricultural Policy and Their Effect on Food Problems. Central European University Press, Budapest/New York.

Fink, A.H., Brücher, T., Krüger, A., Leckebusch, G.C., Pinto, J.G., Ulbrich, U., 2004. The 2003 European summer heatwaves and drought – synoptic diagnosis and impacts. Weather 59 (8), 209–216.

Fleig, A.K., Tallaksen, L.M., Hisdal, H., Hannah, D.M., 2011. Regional hydrological drought in north-western Europe: linking a new Regional Drought Area Index with weather types. Hydrol. Process. 25 (7), 1163–1179.

Garcia-Herrera, R., Hernández, E., Barriopedro, D., Paredes, D., Trigo, R.M., Trigo, I.F., Mendes, M.A., 2007. The outstanding 2004/05 drought in the Iberian Peninsula: associated atmospheric circulation. J. Hydrometeorol. 8 (3), 483–498.

Golubev, G., Dronin, N., 2004. Geography of Droughts and Food Problems in Russia (1900–2000). Report A-0401. Center for Environmental Systems Research, University of Kassel, Kassel, Germany.

Guttman, N.B., 1999. Accepting the Standardized Precipitation Index: a calculation algorithm. JAWRA J. Am. Water Resour. Assoc. 35 (2), 311–322.

Hannaford, J., Lloyd-Hughes, B., Keef, C., Parry, S., Prudhomme, C., 2011. Examining the large-scale spatial coherence of European drought using regional indicators of precipitation and streamflow deficit. Hydrol. Process. 25 (7), 1146–1162.

Hayes, M., Svoboda, M., Wall, N., Widhalm, M., 2011. The Lincoln declaration on drought indices: universal meteorological drought index recommended. Bull. Am. Meteorol. Soc. 92 (4), 485–488.

Haylock, M.R., Hofstra, N., Klein Tank, A.M.G., Klok, E.J., Jones, P.D., New, M., 2008. A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006. J. Geophys. Res.: Atmos. (1984–2012) 113 (D20).

Heim Jr., R.R., 2002. A review of twentieth-century drought indices used in the United States. Bull. Am. Meteorol. Soc. 83 (8), 1149–1165.

Herweijer, C., Seager, R., 2008. The global footprint of persistent extra-tropical drought in the instrumental era. Int. J. Climatol. 28, 1761–1774.

Hisdal, H., Stahl, K., Tallaksen, L.M., Demuth, S., 2001. Have streamflow droughts in Europe become more severe or frequent? Int. J. Climatol. 21 (3), 317–333.

Hisdal, H., Roald, L.A., Beldring, S., Demuth, S., Gustard, A., Planos, E., Seatena, F., Servat, E., 2006. Past and Future Changes in Flood and Drought in the Nordic Countries. IAHS Publication 308. Climate Variability and Change: Hydrological Impacts., pp. 502–507, ISBN 978-1-90150278-7.

Hoerling, M., Eischeid, J., Perlwitz, J., Quan, X., Zhang, T., Pegion, P., 2012. On the increased frequency of Mediterranean drought. J. Clim. 25 (6), 2146–2161.

IPCC, 2014. Summary for policymakers. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L.

(Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom/New York, NY, USA, pp. 1–32.
Kendon, M., Marsh, T., Parry, S., 2013. The 2010–2012 drought in England and Wales. Weather 68 (4), 88–95.
Konovalov, I.B., Beekmann, M., Kuznetsova, I.N., Yurova, A., Zvyagintsev, A.M., 2011. Atmospheric impacts of the 2010 Russian wildfires: integrating modelling and measurements of an extreme air pollution episode in the Moscow region. Atmos. Chem. Phys. 11 (19), 10031–10056.
Li, Y., Ye, W., Wang, M., Yan, X., 2009. Climate change and drought: a risk assessment of crop-yield impacts. Clim. Res. 39 (1), 31–46.
Lloyd-Hughes, B., Saunders, M.A., 2002. A drought climatology for Europe. Int. J. Climatol. 22 (13), 1571–1592.
McKee, T.B., Doeskin, N.J., Kleist, J.,1993. The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th Conference on Applied Climatology. American Meteorological Society, Boston, MA, pp. 179–184.
Meshcherskaya, A.V., Blazhevich, V.G., 1997. The drought and excessive moisture indices in a historical perspective in the principal grain producing regions of the former Soviet Union. J. Clim. 10 (10), 2670–2682.
Michaelides, S., Pashiardis, S., 2008. Monitoring drought in Cyprus during the 2007–2008 hydrometeorological year by using the standardized precipitation index (SPI). Eur. Water 23 (24), 123–131.
Mishra, A.K., Singh, V.P., 2010. A review of drought concepts. J. Hydrol. 391 (1), 202–216.
Mishra, A.K., Singh, V.P., 2011. Drought modeling – a review. J. Hydrol. 403 (1), 157–175.
Mokhov, I.I., 2011. Specific features of the 2010 summer heat formation in the European territory of Russia in the context of general climate changes and climate anomalies. Izv. Atmos. Ocean. Phys. 47 (6), 653–660.
Morren Jr., G.E., 1980. The rural ecology of the British drought of 1975–1976. Hum. Ecol. 8 (1), 33–63.
Naumann, G., Spinoni, J., Vogt, J., Barbosa, P., 2015. Assessment of drought damage and their uncertainties in Europe. NHESS (in review).
Pal, J.S., Giorgi, F., Bi, X., 2004. Consistency of recent European summer precipitation trends and extremes with future regional climate projections. Geophys. Res. Lett. 31 (13).
Palmer, W.C., 1965. Meteorologic drought. U.S. Weather Bureau Research Paper, vol. 45, 58 pp.
Parry, S., Hannaford, J., Lloyd-Hughes, B., Prudhomme, C., Keef, C., 2010. Drought Summaries of Spatio-Temporal Evolution of Major European Droughts Since 1960. Environment Agency Science Report SC070079. Environment Agency, Bristol.
Parry, S., Hannaford, J., Lloyd-Hughes, B., Prudhomme, C., 2012. Multi-year droughts in Europe: analysis of development and causes. Hydrol. Res. 43 (5), 689–706.
Perry, A.H., 1976. The long drought of 1975–76. Weather 31 (10), 328–336.
Rebetez, M., Mayer, H., Dupont, O., Schindler, D., Gartner, K., Kropp, J.P., Menzel, A., 2006. Heat and drought 2003 in Europe: a climate synthesis. Ann. For. Sci. 63 (6), 569–577.
Ruiz-Sinoga, J.D., Martínez-Murillo, J.F., 2009. Eco-geomorphological system response variability to the 2004–06 drought along a climatic gradient of the Littoral Betic Range (southern Spain). Geomorphology 103 (3), 351–362.
Santos, J., Corte-Real, J., Leite, S., 2007. Atmospheric large-scale dynamics during the 2004/2005 winter drought in Portugal. Int. J. Climatol. 27 (5), 571–586.
Santos, J.F., Pulido-Calvo, I., Portela, M.M., 2010. Spatial and temporal variability of droughts in Portugal. Water Resour. Res. 46 (3), W03503.
Santos, M.J., Verissimo, R., Fernandes, S., Orlando, M., Rodrigues, R., 2000. Overview of meteorological drought analysis on Western Europe. ARIDE Technical Report 10. Water Institute, Lisbon, Portugal.
Seftigen, K., Linderholm, H.W., Drobyshev, I., Niklasson, M., 2013. Reconstructed drought variability in southeastern Sweden since the 1650. Int. J. Climatol. 33 (11), 2449–2458.
Seneviratne, S.I., 2012. Climate science: historical drought trends revisited. Nature 491 (7424), 338–339.
Sepulcre-Canto, G., Horion, S.M.A.F., Singleton, A., Carrao, H., Vogt, J.V., 2012. Development of a combined drought indicator to detect agricultural drought in Europe. Nat. Hazards Earth Syst. Sci. 12 (11), 3519–3531.
Sepulcre-Canto, G., Vogt, J.V., Arboleda, A., Antofie, T., 2014. Assessment of the EUMETSAT LSA-SAF evapotranspiration product for drought monitoring in Europe. Int. J. Appl. Earth Obs. Geoinf. 30, 190–202.
Sharma, T.C., Panu, U.S., 2014. Modeling of hydrological drought durations and magnitudes: experiences on Canadian streamflows. J. Hydrol.: Reg. Stud. 1, 92–106.
Shaw, E.M., 1979. The 1975–76 drought in England and Wales in perspective. Disasters 3 (1), 103–110.
Sheffield, J., Andreadis, K.M., Wood, E.F., Lettenmaier, D.P., 2009. Global and continental drought in the second half of the twentieth century: Severity-area-duration analysis and temporal variability of large-scale events. J. Climate 22 (8), 1962–1981.
Sheffield, J., Wood, E.F., Roderick, M.L., 2012. Little change in global drought over the past 60 years. Nature 491 (7424), 435–438.
Simsek, O., Cakmak, B., 2010. Drought analysis for 2007–2008 agricultural year of Turkey. J. Tekirdag Agric Fac. 7 (3), 99–109.
Smakhtin, V.U., Schipper, E.L., 2008. Droughts: the impact of semantics and perceptions. Water Policy 10, 131–143.
Spinoni, J., Antofie, T., Barbosa, P., Bihari, Z., Lakatos, M., Szalai, S., Szentimrey, T., Vogt, J.V., 2013. An overview of drought events in the Carpathian Region in 1961–2010. Adv. Sci. Res. 10 (1), 21–32.
Spinoni, J., Naumann, G., Carrao, H., Barbosa, P., Vogt, J.V., 2014a. World drought frequency, duration, and severity for 1951–2010. Int. J. Climatol. 34 (8), 2792–2804.
Spinoni, J., Szalai, S., Szentimrey, T., Lakatos, M., Bihari, Z., Nagy, A., Nemeth, A., Kovacs, T., Mihic, D., Petrovic, P., Krzic, A., Hiebl, J., Auer, I., Milkovic, J., Stepanek, P., Zahradnicek, P., Kilar, P., Limanowka, D., Pyrc, R., Cheval, S., Birsan, M.V., Dumitrescu, A., Deak, G., Matei, M., Antolovic, I., Nejedlik, P., Stastny, P., Kajaba, P., Bochnicek, O., Galo, D., Mikulova, K., Nabyvanets, Y., Skrynyk, O., Krakovska, S., Gnatiuk, N., Tolasz, R., Antofie, T., Vogt, J.V., 2014b. Climate of the Carpathian Region in the period 1961–2010: climatologies and trends of 10 variables. Int. J. Climatol., http://dx.doi.org/10.1002/joc.4059.
Spinoni, J., Naumann, G., Vogt, J., Barbosa, P., 2015. European drought climatologies and trends based on a multi-indicator approach. Global Planet. Change (in review).
Stagge, J.H., Tallaksen, L.M., Kohn, I., Stahl, K., van Loon, A.F., 2013. A European Drought Reference (EDR) Database: Design and Online Implementation. DROUGHT-R&SPI Deliverable D1.1. Technical Report No. 12, 42 pp. Available at: http://www.eu-drought.org/technicalreports (accessed 11.12.14).

Stahl, K., Blauhut, V., Kohn, I., Acácio, V., Assimacopoulos, D., Bifulco, C., De Stefano, L., Dias, S., Eilertz, D., Frielingsdorf, B., Hegdahl, T.J., Kampragou, E., Kourentzis, V., Melsen, L., van Lanen, H.A.J., van Loon, A.F., Massarutto, A., Musolino, D., de Paoli, L., Senn, L., Stagge, J.H., Tallaksen, L.M., Urquijo, J., 2012. A European Drought Impact Report Inventory (EDII): Design and Test for Selected Recent Droughts in Europe. DROUGHT-R&SPI Technical Report No. 3, 23 pp. Available at: www.eu-drought.org/technicalreports (accessed 11.12.14).
Szentimrey, T., 1999. Multiple analysis of series for homogenization (MASH). In: Proceedings of the Second Seminar for Homogenization of Surface Climatological Data, pp. 27–46.
Szinell, C.S., Bussay, A., Szentimrey, T., 1998. Drought tendencies in Hungary. Int. J. Climatol. 18 (13), 1479–1491.
Tammets, T., 2007. Distribution of extreme wet and dry days in Estonia in last 50 years. Proc. Est. Acad. Sci. 13, 252–259.
Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geogr. Rev., 55–94.
Todd, B., Macdonald, N., Chiverrell, R.C., Caminade, C., Hooke, J.M., 2013. Severity, duration and frequency of drought in SE England from 1697 to 2011. Clim. Change 121 (4), 673–687.
Trenberth, K.E., Fasullo, J.T., 2012. Climate extremes and climate change: the Russian heat wave and other climate extremes of 2010. J. Geophys. Res.: Atmos. (1984–2012) 117 (D17).
Trenberth, K.E., Dai, A., van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R., Sheffield, J., 2014. Global warming and changes in drought. Nat. Clim. Change 4 (1), 17–22.
Trenberth, K., Overpeck, J., Solomon, S., 2004. Exploring drought and its implications for the future. Eos Trans. Am. Geophys. Union 85 (3), 27.
Tsakiris, G., Vangelis, H., 2005. Establishing a drought index incorporating evapotranspiration. Eur. Water 9 (10), 3–11.
Tselepidaki, I., Zarifis, B., Asimakopoulos, D.N., 1992. Low precipitation over Greece during 1989–1990. Theor. Appl. Climatol. 46 (2–3), 115–121.
Van der Schrier, G., Briffa, K.R., Jones, P.D., Osborn, T.J., 2006. Summer moisture variability across Europe. J. Clim. 19 (12), 2818–2834.
Van der Schrier, G., Jones, P.D., Briffa, K.R., 2011. The sensitivity of the PDSI to the Thornthwaite and Penman–Monteith parameterizations for potential evapotranspiration. J. Geophys. Res.: Atmos. (1984–2012) 116 (D3).
Van der Schrier, G., Barichivich, J., Briffa, K.R., Jones, P.D., 2013. A scPDSI-based global dataset of dry and wet spells for 1901–2009. J. Geophys. Res. 118, 4025–4048.
Vangelis, H., Spiliotis, M., Tsakiris, G., 2011. Drought severity assessment based on bivariate probability analysis. Water Resour. Manage. 25 (1), 357–371.
Veryard, R.G., 1956. Looking back on 1955. Weather 11 (3), 83–88.
Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J. Clim. 23 (7), 1696–1718.
Vicente-Serrano, S.M., López-Moreno, J.I., Lorenzo-Lacruz, J., El Kenawy, A., Azorin-Molina, C., Morán-Tejeda, E., Pasho, E., Zabalza, J., Begueria, S., Angulo-Martinez, M., 2011a. The NAO impact on droughts in the Mediterranean region. Hydrological, Socioeconomic and Ecological Impacts of the North Atlantic Oscillation in the Mediterranean Region – Advances in Global Change Research, vol. 46. Springer, Netherlands, pp. 23–40.
Vicente-Serrano, S.M., Lopez-Moreno, J.I., Drummond, A., Gimeno, L., Nieto, R., Moran-Tejeda, E., Lorenzo-Lacruz, J., Begueria, S., Zabalza, J., 2011b. Effects of warming processes on droughts and water resources in the NW Iberian Peninsula (1930–2006). Clim. Res. 48, 203–212.
Vicente-Serrano, S.M., Zouber, A., Lasanta, T., Pueyo, Y., 2012. Dryness is accelerating degradation of vulnerable shrublands in semiarid Mediterranean environments. Ecol. Monogr. 82 (4), 407–428.
Vicente-Serrano, S.M., Lopez-Moreno, J.I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J.M., Azorin-Molina, C., Tejeda-Moran, E., revuelto, J., Trigo, R., Coelho, F., Espejo, F., 2014. Evidence of increasing drought severity caused by temperature rise in southern Europe. Environ. Res. Lett. 9 (4), 044001, http://dx.doi.org/10.1088/1748-9326/9/4/044001.
Wells, N., Goddard, S., Hayes, M.J., 2004. A self-calibrating Palmer drought severity index. J. Clim. 17 (12), 2335–2351.
Wegren, S.K., 2011. Food security and Russia's 2010 drought. Eurasian Geogr. Econ. 52 (1), 140–156.
Willems, P., 2013a. Multidecadal oscillatory behaviour of rainfall extremes in Europe. Clim. Change 120 (4), 931–944.
Willems, P., 2013b. Adjustment of extreme rainfall statistics accounting for multidecadal climate oscillations. J. Hydrol. 490, 126–133.
WMO, 2012. Standardized Precipitation Index. User Guide. World Meteorological Organization, Geneva, Switzerland, WMO-No. 01090. ISBN 978-92-63-11091-6.
Zaidman, M., Rees, G., Gustard, A., EU contract ENV4-CT-97-0553 2001. Drought Visualization. Assessment of the Regional Impact of Droughts in Europe. Final Report. Institute of Hydrology, University of Freiburg, Freiburg, Germany.
Zampieri, M., D'Andrea, F., Vautard, R., Ciais, P., de Noblet-Ducoudré, N., Yiou, P., 2009. Hot European summers and the role of soil moisture in the propagation of Mediterranean drought. J. Clim. 22 (18), 4747–4758.
Zhao, M., Running, S.W., 2010. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. Science 329, 940–943.