

LARGE SCALE PROBABILISTIC DROUGHT CHARACTERIZATION OVER EUROPE

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ABSTRACT

Probabilistic characterization of drought events can play a key role within a drought risk analysis, since it enables the evaluation of drought hazard over a region, which is a preliminary step to drought risk assessment. Besides, the reliable assessment of drought return periods is essential to help decision makers in setting effective drought preparedness and mitigation tools.

Generally, an inferential approach (i.e. fitting parametric distributions to observed drought characteristics) is unsuitable to model the marginal or joint probability distributions of drought characteristics, such as drought duration and accumulated deficit, due to the relatively limited number of drought events that can be observed from the historical records of hydrological variable of interest. As an alternative, the marginal and multivariate probability cdf's of drought characteristics can be derived as functions of the parameters of the cdf of the underlying variable (e.g. precipitation), whose sample series is usually long enough to get reliable results in a statistical sense.

In this study, the latter methodology is applied to investigate the space-time variability of drought occurrences over Europe by using the CRU TS3.1 precipitation dataset for the period 1901-2009, which is produced by the British Atmospheric Data Centre through a software provided by the Climate Research Unit (CRU) at the University of East Anglia. First, a spatial analysis of historical droughts at European level is carried out. Then, based on the cdf's of drought characteristics analytically derived, the return periods of both historical and design drought events are computed as the expected value of the interarrival time between consecutive critical droughts, and the corresponding spatial distribution are investigated. Results show that several heavy drought episodes have widely affected the continent. Among the most recent events, drought occurred during the period 1985-1995 was the worst in terms of extent of the regions characterized by drought return periods greater than 250 years. Besides, Euro-Mediterranean regions, North Western regions (e.g. from Southern England to Germany) and Central Eastern regions (e.g. countries close to the Black Sea) appear more drought prone than the rest of Europe, in terms of low values or return periods.

1 INTRODUCTION

An in depth knowledge of drought phenomena plays an important role for an appropriate planning and management of water resources (Yevjevich et al., 1983). Indeed,

severe and prolonged drought events have affected a large part of Europe during the last decades (Zaidman et al., 2001; Lloyd-Hughes and Saunders, 2002; Fink et al., 2004; Hannaford et al., 2011), with harmful impacts on public water supply, industrial and agricultural production, as well as on the environment, with special reference to the degradation of aquatic ecosystems.

According to the last report of the Intergovernmental Panel on Climate Change (IPCC) released in 2007, “drought is likely to intensify in both duration and severity”, with special reference to Southern Europe, as a consequence of the global warming. As a matter of fact, downward linear trends in drought indices time series over most of Europe have been documented in several studies carried out on reanalysis precipitation data sets (Bordi et al., 2009), gridded rain gauge data (Lloyd-Hughes and Saunders, 2002) and observations (Van der Schrier et al., 2006).

In light of lessons learnt from past experiences of coping with severe drought events, and of the potential intensification of such phenomena in the next future, a common awareness has risen about the need to develop and implement advanced drought risk management strategies. This requires on the one hand a better understanding and modelling of the natural phenomenon and of its impacts on economic activities, society and environment, and on the other hand the definition and implementation of adequate both long-term measures, oriented to significantly reduce vulnerability of water supply systems to drought events, and short term measures, oriented to minimize drought impacts (Wilhite et al., 1987; Rossi, 2000).

Pursue of the former objective requires a probabilistic characterization of historical drought events, properly identified on hydrometeorological series of interest, aimed at assessing drought hazard over a region, which combined with drought vulnerability yields to the corresponding drought risk. In particular, estimation of drought return periods can provide useful information for an appropriate water use planning under drought conditions.

Over the years, many approaches have been suggested for characterizing droughts. Yevjevich (1967) used the theory of runs to characterize droughts as a sequence of consecutive intervals where the water supply variable remains below a threshold level (somehow representative of water demand), preceded and succeeded by values above the threshold. Thus, each drought event can be characterized by two main properties, namely: drought duration, and accumulated deficit, defined as the sum of single deficits, i.e. the deviations of the variable from the threshold, over drought duration. Such characteristics are statistically dependent and therefore a multivariate approach is the most appropriate for their probabilistic analysis.

Generally, due to the relatively limited number of drought events that can be observed from the historical records, fitting parametric distributions to observed drought characteristics is unsuitable to model the marginal or joint probability distributions of drought characteristics, such as drought duration and accumulated deficit.

A traditional solution involve data generation by applying stochastic models (Millan and Yevjevich, 1971; Kendall and Dracup, 1992; Shiau and Shen, 2001).

An alternative approach (Downer et al. 1967; Llamas and Siddiqui, 1969; Sen, 1976; Sharma, 1995; Bonaccorso et al., 2003, Cancelliere and Salas, 2004, 2010) lies in deriving the marginal and multivariate probability cdf's of drought characteristics as functions of the parameters of the cdf of the underlying variable (e.g. precipitation), whose sample series is usually long enough to get reliable results in a statistical sense.

Once that such probability distributions are derived, return period of different type of drought events, with respect to one or more features (i.e. drought duration and/or accumulated deficit) can be assessed.

In general drought return period can be defined as the expected value of the interarrival time between consecutive critical droughts (Loaiciga and Marino, 1991; Fernandez and Salas, 1999; Shiau and Shen, 2001; Bonaccorso et al., 2003).

Since drought can span several years, it is not possible to identify a unique time unit (or trial) with respect to which, the exceedance probability $P[X_t > x_t]$ can be expressed, as one can usually make in flood frequency analysis, where the return period can be evaluated by the well known formula $T=1/P[X_t > x_t]$ (Fernandez and Salas, 1999).

In this regard, Shiau and Shen (2001) assuming independent and identically distributed events, developed a procedure for deriving the return period of accumulated deficit, as the expected value of the average interarrival time between two successive events with accumulated deficit greater than or equal to a fixed value. This procedure has been further extended to the case of drought events characterized by both drought duration and accumulated deficit or drought duration and intensity (Bonaccorso et al., 2003; Gonzales and Valdes, 2003; Cancelliere and Salas, 2004).

In the present study, the foregoing methodologies are applied to investigate space-time variability of meteorological drought occurrences over Europe, by using the annual precipitation series retrieved by the CRU TS3.1 gridded dataset for the period 1901-2009. Such dataset covers uniformly the globe and is freely accessible through the British Atmospheric Data Centre (BADC) website <http://badc.nerc.ac.uk>.

First, the goodness of fit of several probability distributions (normal, lognormal and gamma) to the considered precipitation dataset is examined cell by cell by the Lilliefors test, and the best distribution is chosen for each cell based on the lowest value of test statistic. Then, historical droughts at European level are identified through the theory of run and classified based on the probabilities of occurrence of annual deficit.

Finally, once that the marginal and bivariate cdf's of drought duration and accumulated deficit for each cell are analytically derived, based on the parameters of the probability distribution of annual precipitation series, the return periods of both historical and design critical droughts, with respect to drought duration and accumulated deficit, are computed and the corresponding spatial distributions are analyzed.

A brief description of the methodologies for the analytical derivation of the probability distributions of drought characteristics and for the assessment of drought return period are reported in Section 2. In Section 3, results of the application of the proposed methodology are illustrated. Conclusions are drawn in Section 4.

2 METHODOLOGY

2.1 Analytical derivation of probability distribution of drought characteristics

According to the theory of runs, a drought can be considered as a negative run, namely a sequence of consecutive intervals where the variable under investigation remains below a fixed threshold, preceded and succeeded by positive runs.

Let X_t , $t=1, 2, \dots, N$, be a time series of the hydrological variable of interest and x_0 the threshold water demand level. The drought duration L is defined as the number of consecutive intervals where $X_t < x_0$, followed and preceded by at least one interval where

$X_t \geq x_0$, whereas the accumulated deficit D is defined as the sum of single deficits $S_t = x_0 - X_t$ over the duration L . It follows that the accumulated deficit can be expressed as:

$$D = \sum_{t=1}^L S_t = \sum_{t=1}^L (x_0 - X_t) \quad \text{for } X_t < x_0 \quad (1)$$

In what follows the analytical derivations of the marginal and joint pdf's and cdf's of drought duration L and accumulated deficit D for stationary and independent series are briefly described.

2.1.1 Probability mass function of drought duration

Statistical properties of run length for stationary series have been far back derived in literature (Downer et al., 1967; Feller, 1968; Llamas and Siddiqui, 1969) and then applied to drought duration (Sen, 1976; Guven, 1983; Sharma, 1995).

In particular, for stationary and independent series, drought duration L is known to be geometric, i.e.:

$$f_L(l) = p_1(1 - p_1)^{l-1} \quad (2)$$

where $p_1 = P[X_t \geq x_0]$. Also, the first two moments of drought duration are given by:

$$E[L] = \frac{1}{p_1} \quad (3)$$

$$\text{Var}[L] = \frac{1 - p_1}{p_1^2} \quad (4)$$

2.1.2 Probability distribution of drought accumulated deficit

Analytical derivation of the probability distribution of accumulated deficit D and the joint distribution of accumulated deficit D and duration L are still unsolved problems, due to the mathematical difficulties that generally prevent closed form solutions (Millan and Yevjevich, 1971; Sen, 1976; Chung and Salas, 2000).

In order to overcome analytical difficulties, many authors fit a parametric distribution to empirical data of D or $D|L$ (e.g. Zelenhasic and Salvai, 1987; Mathier et al., 1992; Shiau and Shen, 2001).

An alternative approach consists in evaluating the parameters of the distributions of D and $D|L$, a priori selected, based on the parameters of the distribution of X_t , which, in turn, can be assessed with good approximation through the traditional inferential approach applied to common hydrometeorological sample series with length ≥ 30 data. In fact, the moments of D and $D|L$ can be expressed as functions of the moments of S_t and L , which in turn depend on the parameters of the variable X_t . In particular, under the assumption of serially independent X_t , the first two moments of D are given by:

$$E[D] = E[S_t] \cdot E[L] \quad (5)$$

$$\text{Var}[D] = E[L] \cdot \text{Var}[S_t] + \text{Var}[L] \cdot E[S_t]^2 \quad (6)$$

Previous studies (Shiau and Shen, 2001; Bonaccorso et al., 2003) assume D gamma distributed, namely:

$$f_D(d) = \frac{1}{\beta \Gamma(r)} \left(\frac{d}{\beta} \right)^{r-1} e^{-\frac{d}{\beta}} \quad (7)$$

with expected value and variance respectively:

$$E[D] = r \cdot \beta \quad (8)$$

$$\text{Var}[D] = r \cdot \beta^2 \quad (9)$$

Combining previous equations with Equations (5) and (6), the parameters r and β can be expressed as:

$$r = \frac{E[L]^2 E[S_t]^2}{E[L] \text{Var}[S_t] + E[S_t]^2 \text{Var}[L]} \quad (10)$$

$$\beta = \frac{E[L] \text{Var}[S_t] + E[S_t]^2 \text{Var}[L]}{E[L] E[S_t]} \quad (11)$$

As it can be shown, the pdf of S_t is equal to the truncated distribution of $X(t)$, i.e.:

$$f_{S_t}(s_t) = \frac{1}{p_0} \cdot f_{X(t)}(x_0 - s_t) \cdot I(s_t)_{(0,\infty)} \quad (12)$$

the k -th moment of S_t is given by:

$$E[S_t^k] = \frac{1}{p_0} \int_0^\infty s_t^k \cdot f_{X_t}(x_0 - s_t) \cdot ds_t \quad (13)$$

Therefore, substituting the first two moments of S_t and L into Equations (10) and (11) will yield the desired parameters r and β of the distribution of accumulated deficit D .

2.1.3 Joint probability distribution of drought duration and accumulated deficit

The joint probability distribution of drought accumulated deficit D and duration L can be derived as follows:

$$f_{D,L}(d,l) = f_{D|L=l}(d) \cdot f_L(l) \quad (14)$$

Under the assumption of serially independent events, the first two moments of $D|L$ are given by:

$$E[D|L] = E\left[\sum_{i=1}^L S_i \middle| L=l\right] = l E[S_t] \quad (15)$$

$$\text{Var}[D|L] = \text{Var}\left[\sum_{t=1}^L S_t \mid L = l\right] = l \text{Var}[S_t] \quad (16)$$

Again by assuming $D|L=l$ gamma distributed, the pdf is given by:

$$f_{D|L=l}(d) = \frac{l}{\beta \Gamma(r)} \left(\frac{d}{\beta}\right)^{r-l} e^{-\frac{d}{\beta}} \quad (17)$$

Thus, substituting Equation (17) and Equation (2) into Equation (14) and integrating, the joint cumulative distribution function of D and L is given by:

$$F_{D,L}(d, l) = \left[1 - G\left(r, \frac{d}{\beta}\right)\right] \cdot p_1 (1 - p_1)^{l-1} \quad (18)$$

For the case of $L \geq l$, the joint cdf is:

$$F_{D,L}(d, l) = \sum_{L=l}^{\infty} \left[1 - G\left(r, \frac{d}{\beta}\right)\right] \cdot p_1 (1 - p_1)^{L-1} \quad (19)$$

It is worth underlying that the parameters of $D|L$ can be derived in a similar fashion as D . In particular, the parameters can be expressed as:

$$r = l \cdot \frac{E[S_t]^2}{\text{Var}[S_t]} \quad (20)$$

$$\beta = \frac{\text{Var}[S_t]}{E[S_t]} \quad (21)$$

2.2 Assessment of drought return period

In general, the return period of a drought can be defined as the expected value of the average interarrival time T_E between two successive droughts, recognized “critical” with respect to one or more drought characteristics (Lloyd, 1970; Loaiciga and Marino, 1991; Fernandez and Salas, 1999; Shiau and Shen, 2001).

Let E be a critical drought, and $\bar{E}$ a non critical drought, by definition the return period of drought event E can be expressed as:

$$E[T_E] = E\left[L \mid \{E\} + L_n + \sum_{j=2}^{N_l} (L_j \mid \{\bar{E}\} + L_{n_j})\right] \quad (22)$$

where $L \mid \{E\}$ is the duration of the first critical drought E , L_n is the duration of the next non drought period, $L_j \mid \{\bar{E}\}$ and L_{nj} are the duration of j -th non critical drought event and the duration of the next j -th non drought period, and N is the number of drought and non drought events preceding the second critical drought.

Making use of well knows properties of conditional expected value, after few algebra,

Equation (22) simplifies as follows:

$$E[T_E] = \frac{E[L] + E[L_n]}{P[E]} \quad (23)$$

where $P[E]$ is the probability of occurrence of a critical drought E , which can be determined once that the pdf or cdf of event E are known.

In the present study, the methodology described at section 2.1 will be applied to derive the probability of occurrence of critical drought E with respect to accumulated deficit only and both drought duration and accumulated deficit jointly considered.

3 APPLICATIONS

3.1 Data

Data used for large scale drought analysis are annual precipitation series derived from the CRU TS3.1 dataset for the period 1901-2009 (<http://badc.nerc.ac.uk>). This dataset is produced by the British Atmospheric Data Centre through a software provided by the Climate Research Unit (CRU) at the University of East Anglia. It includes monthly values of several climate variables (e.g. cloud cover, daily mean temperature and wet day frequency, among others) computed on high-resolution grid (0.5x0.5 degree).

The gridded dataset is based on an archive of monthly climate observations from more than 4000 weather stations distributed around the world. The database is checked for inhomogeneities in the stations records using an automated method which includes the development of reference stations using neighbouring stations. For further details on the interpolation of the observed records onto the 0.5 latitude-longitude grid, readers may refer to Mitchell and Jones, (2005).

The study area is the European region 31.75-71.25°N and 33.75°E-15.25°W.

3.2 Goodness of fit of selected probability distributions to the data

The goodness of fit of normal, lognormal and gamma probability distributions to the considered annual precipitation dataset has been examined cell by cell through the Lilliefors statistic test (Crutcher, 1975). Such test is a modified version of the Kolmogorov Smirnov test, and is valid when the parameters of the underlying distribution are estimated from a sample.

First, the goodness of fit of each distribution was verified at the 5% significance level. Since test results did not clearly indicate a preference towards one distribution over all the investigated area, for each cell the distribution with the lowest Lilliefors test statistic value was selected. Table I reports for each distribution, the percentage of cells for which the null hypothesis H_0 (i.e. the probability distribution fits the data) is rejected at the 5% significance level, as well as the percentage of cells with the lowest test statistic value. Although, the gamma distribution shows a good fit for the most part of the cells, the normal distribution is the one to which correspond the greater number of cells characterized by the lowest test statistic. Figure 1 illustrates the spatial coverage of probability distribution identified for each cell. Such figure also includes a few scattered cells (about 2% out of the total) for which H_0 is rejected at the 5% significance level for all the considered distributions.

Table I. Comparison of the Lilliefors test results for the normal, lognormal and gamma probability distributions.

Probability distribution	Cells for which H_0 is rejected (%)	Cells with the lowest test statistic value (%)
Normal	10.72	48.41
Lognormal	13.84	26.61
Gamma	7.96	24.98

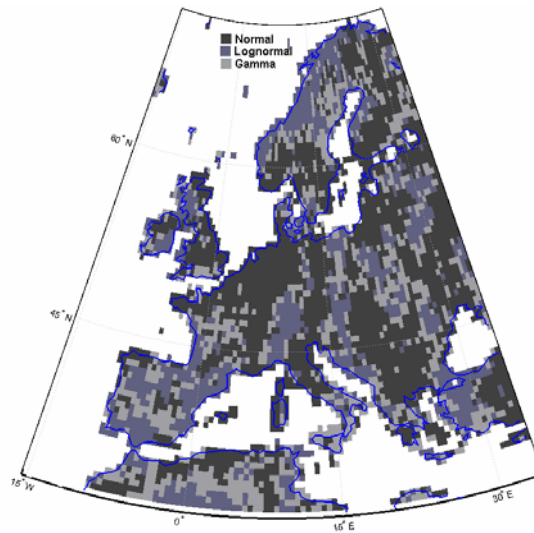


Figure 1. Spatial coverage of probability distributions, selected on the basis of the lowest Lilliefors test statistic value for each cell of CRU TS3.1 grid.

3.3 Drought identification and characterization

Drought conditions over Europe were identified by application of the theory of run on CRU TS3.1 annual precipitation gridded data, by considering a threshold level x_0 equal to the median computed from the fitted distribution.

Dry and wet conditions with respect to the k -th cell were classified based on the probabilities of occurrence of annual deficit and surplus. In particular, the time series of non exceedance probability of annual precipitation data were computed by making use of probability distributions previously determined for each cell. Then dry and wet conditions were identified according to the classification reported in Table II.

Table II. Wet and dry period classification based on the probability of occurrence of annual deficit

$P(x_i)$	Class
>0.40	Normal or wet
0.25-0.40	Moderately dry
0.10-0.25	Very dry
<0.10	Extremely dry

It is worth highlighting that, since the present work focuses on drought analysis, in what follows normal and wet conditions have been grouped into one class.

Figure 2 illustrates the spatial and temporal distribution of dry and wet periods from 1901 to 1956 (a) and from 1957 to 2009 (b), related to selected cells of the CRU TS3.1 grid including main cities in Europe. Although, the two images provide a partial picture of drought conditions, as limited to a few cells, they enable to identify at a glance the most severe dry periods, as well as the corresponding duration and affected areas.

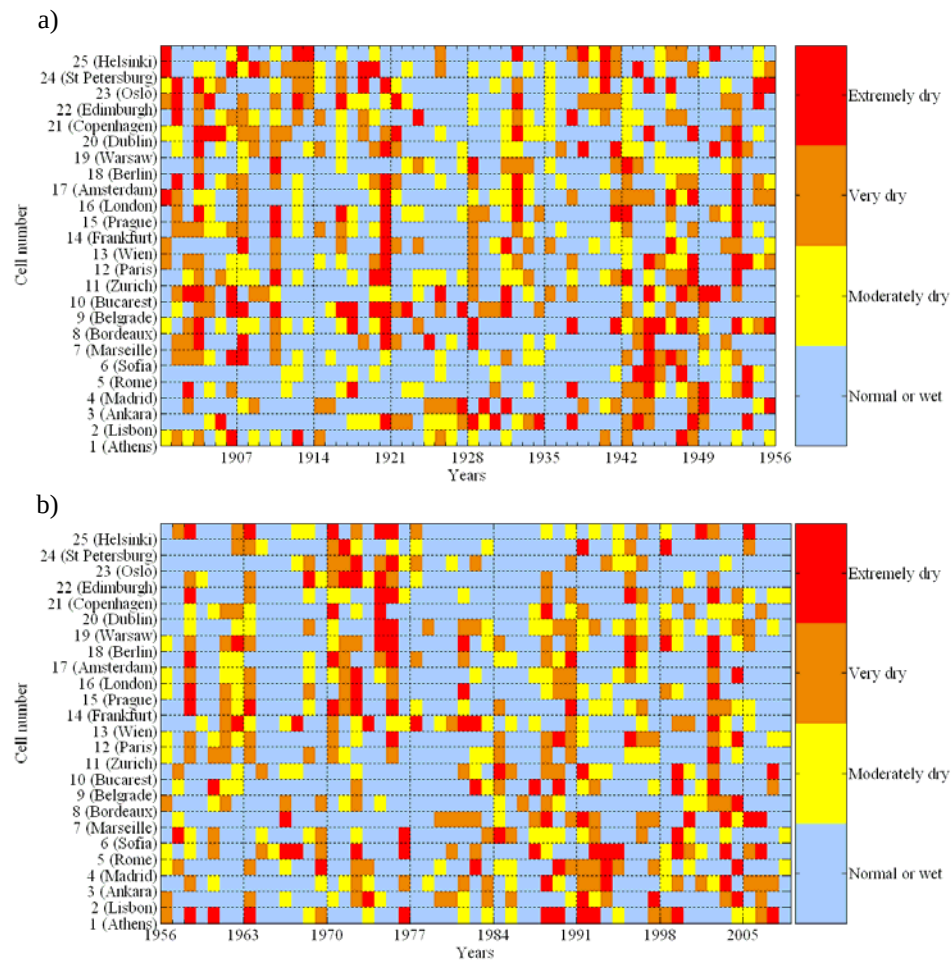


Figure 2. Dry and wet conditions over Europe from 1901 to 1956 (a) and from 1957 to 2009 (b).

In particular, with reference to Figure 2a, several dry periods have occurred during the first decade of the last century mainly in North Western and Central Europe. Shorter but drier periods have occurred at the beginning of the '20s in the same regions. During the '40s, long and severe dry periods have affected most part of Europe, with worse conditions in Southern Central Europe. Also, extremely dry conditions can be observed in 1953/1954 spread across the investigated area.

From the '60s onward (see Figure 2.b) the worst dry conditions seem to affect smaller area, with respect to the periods previously observed. For instance, one of the main dry periods, which has particularly affected North Western Europe, has been recorded during mid '70s. Between the end of the '80s and mid '90s, severe dry periods have occurred mainly in the South side. Finally, it is worth mentioning the 2003 event characterizing Central Europe, and those occurred in 2004 and 2005 in Southern Europe, which extended into 2007/2008 in South Eastern regions.

In order to complement such an analysis, Figure 3 illustrates the time series of the spatial coverage of dry conditions for the whole study area. In particular, Figure 3a represents the time variation of spatial extent of different dry conditions. It can be observed a general significant decreasing trend, particularly for very dry conditions depicted in Figure 3b.

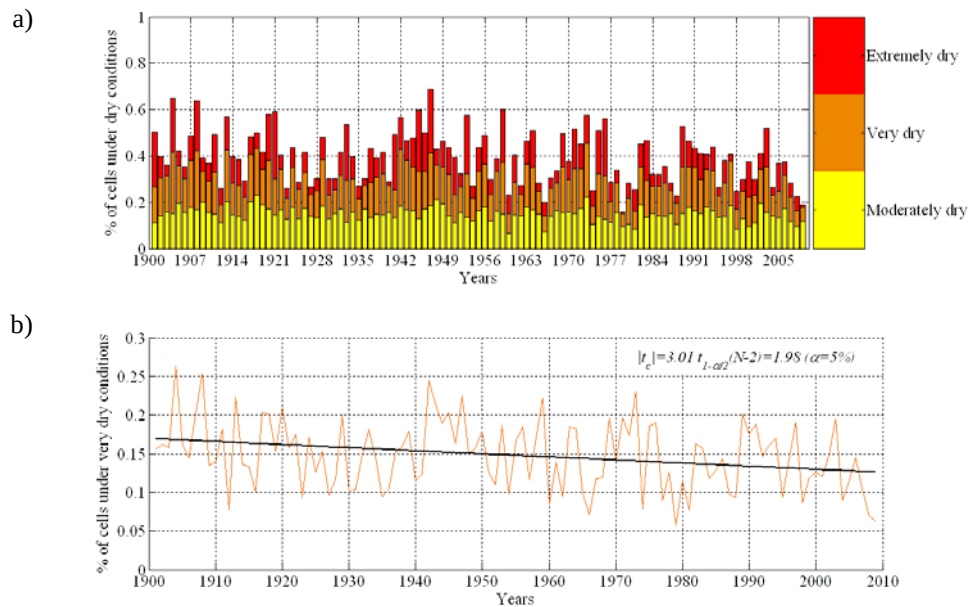


Figure 3. Time series of the percentage of cells under different dry conditions from 1901 to 2009 (a) and trend pattern in the percentage of cells under very dry conditions (b).

3.4 Return periods of historical critical droughts

Return periods of severe historical drought events have been computed, based on the methodology described in section 2.2, and then compared. In particular, well known and largely investigated drought events occurred in 1975-1976, 1989-1990 (Zaidman et al., 2001) and 2002-2003 (Fink et al. 2003), which affected a large part of the continent, as confirmed by previous results, have been selected.

In order to take into account the different durations of concurrent droughts, a time span of 11 years approximately centred around the above mentioned events was considered. To this end, the following periods have been analyzed: 1968-1978, 1985-1995 and 1999-2009. Figure 4 illustrates the spatial distribution of the bivariate return periods of drought

events characterized by $\{D > D_o, L \geq L_o\}$, where D_o and L_o are respectively the accumulated deficit and duration of historical drought identified in each cell for each period. In case that more than one event is identified in a cell in a given period, drought characterized by the largest accumulated deficit was selected for that cell.

According to the adopted chromatic scale, drought return period increases as cell colour ranges from white to dark brown, identifying from common ($T < 10$ years) to extremely rare events ($T > 1000$ years). As it can be observed, almost the whole case study area is under drought condition during the three considered periods. Nonetheless, the areas affected by the most extreme drought events ($T > 250$ years), change significantly from one period to another. In particular, the period 1985-1995 seems characterized by the broadest spread of extreme drought events, mainly localized on the Iberian peninsula, Central Europe, the Balkans and Western Turkey.

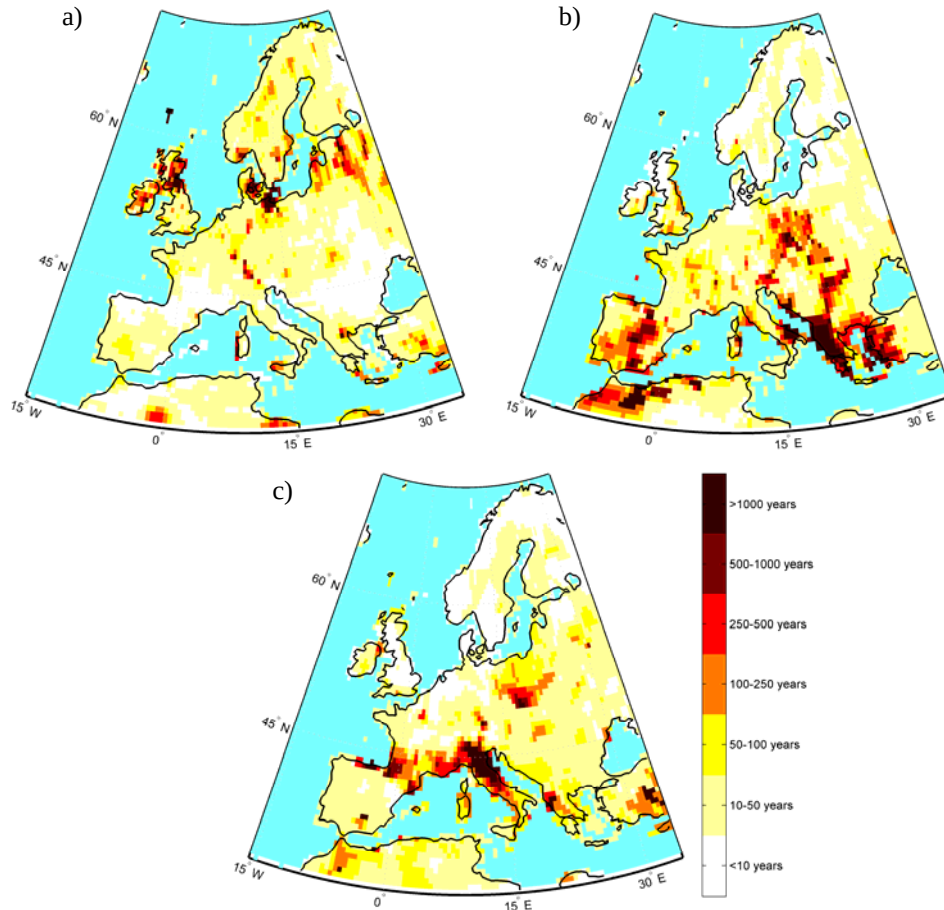


Figure 4. Spatial distributions of bivariate return periods of historical droughts occurred during 1968-1978 (a), 1985-1995 (b) and 1999-2009 (c).

For the sake of completeness, Table III reports the percentage of cells with corresponding return periods greater than 100 and 250 years and mean drought

characteristics. Results confirm that the period 1985-1995 has been the worst in terms of areal extent of extreme drought events occurred, as well as with respect to mean drought duration and accumulated deficit.

Table III. Percentage of cells with corresponding drought return periods greater than 100 and 250 years and mean drought characteristics for each selected period.

Period	Cells with $T > 100$ years (%)	Cells with $T > 250$ years (%)	Mean characteristics	
			L (years)	D/x_0
1968-1978	14.84	5.40	2.80	0.41
1985-1995	14.02	7.80	2.90	0.41
1999-2009	9.25	4.17	2.52	0.37

3.5 Return periods of design critical droughts

Previous results show that regions affected by extreme droughts (in terms of higher values of corresponding return periods) may significantly differ from one period to another. Thus, it could be interesting to analyze how the European regions respond to equal drought conditions, by fixing drought accumulated deficit and duration.

To this end, Figure 5 illustrate return periods of two design droughts: the first (Figure 5a) characterized by dimensionless accumulated deficit greater than 0.5 and duration greater than or equal to 3 years (a), the second (Figure 5b) with dimensionless accumulated deficit greater than 1 and duration greater than or equal to 5 years (b). In this case, the chromatic scale has been inverted in order to better highlight drought prone areas, characterized by the lowest values of return periods.

From both figures, it clearly appears that Euro-Mediterranean regions are more drought prone than the rest of the continent. However, with special reference to drought with moderate accumulated deficit and limited duration (Figure 5b) some North Western and Central Eastern regions also exhibit a marked tendency towards frequent events (i.e. return periods less than 50 years).

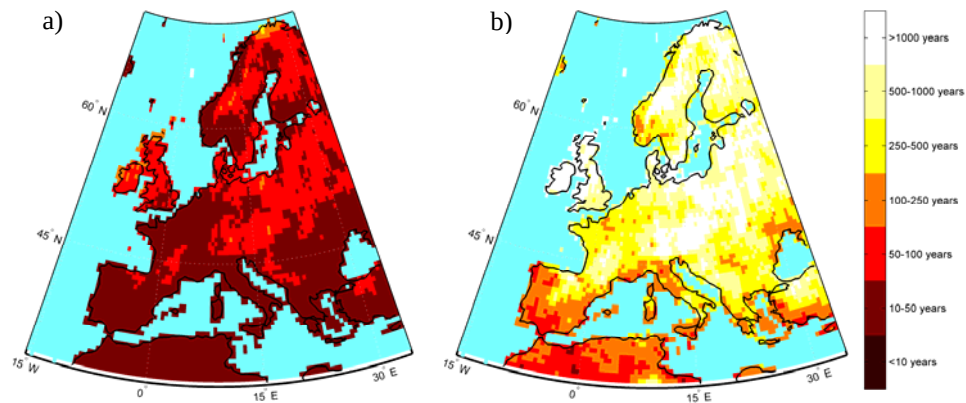


Figure 5. Spatial distributions of bivariate return periods of droughts with dimensionless accumulated deficit greater than 0.5 and duration greater than or equal to 3 years (a) and dimensionless accumulated deficit greater than 1 and duration greater than or equal to 5 years (b).

4 CONCLUSIONS

In this paper a methodology for drought characterization, proposed in previous studies (Bonaccorso et al., 2003, Cancelliere and Salas, 2004, 2010), is applied for deriving the probability distributions of drought events, considering both drought duration and accumulated deficit, and for estimating the ensuing return periods.

The proposed approach has been used for a large scale drought analysis at European level, based on annual precipitation series derived from the CRU TS3.1 gridded dataset for the period 1901-2009. A different probability distributions, among normal, lognormal and gamma, was fitted cell by cell to the data, based on the criteria of the lowest value of the Lilliefors test statistic. Historical dry and wet conditions have been identified through the theory of run with a threshold equal to the theoretical median, and then classified based on the probabilities of occurrence of annual deficit and surplus.

The analysis of spatial and temporal distribution of dry and wet periods, although limited to selected cells of the CRU TS3.1 grid, has revealed that quite a few severe dry periods, affecting a large part of the continent, have occurred during the period of observation, such as at the beginning of the '20s, during the '40s, in the mid '70s, at the end of the '80s and in 2002/2003.

The time behaviour of the spatial coverage of dry conditions for the whole study area has shown a general significant decreasing trend, which leads one to believe that recent severe droughts have a reduced extent with respect to those occurred in the first mid of the past century. On the other hand, the comparison of the spatial distribution of return periods of droughts occurred during 1968-1978, 1985-1995 and 1999-2009, has highlighted worst conditions during the second period, in terms of broader extent of the regions with a corresponding drought return periods greater than 250 years. Finally, the spatial distributions of return periods of droughts with fixed accumulated deficit and duration have revealed that, in addition to Euro-Mediterranean regions, some North Western regions (e.g. from Southern England to Germany) and Central Eastern regions (e.g. countries close to the Black Sea) are more drought prone.

Further investigations are ongoing to identify homogeneous regions for characterizing meteorological droughts at European level.

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