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Wet and dry summers in Europe since 1750: evidence of increasing drought

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ABSTRACT: Moisture availability across Europe is calculated based on 22 stations that have long instrumental records for precipitation and temperature. The metric used is the self-calibrating Palmer Drought Severity Index (scPDSI) which is based on soil moisture content. This quantity is calculated using a simplified water budget model, forced by historic records of precipitation and temperature data, where the latter are used in a simple parameterization for potential evaporation. The precipitation and temperature records are updated to include the 2003 summer and all records, except for one, span at least 200 years, with the record for Kew going back to 1697.

The Kew record shows a significant clustering of dry summers in the most recent decade. When all the records are considered together, recent widespread drying is clearly apparent and highly significant in this long-term context.

By substituting the 1961–1990 climatological monthly mean temperatures for the actual monthly means in the parameterization for potential evaporation, an estimate is made of the direct effect of temperature on drought. This analysis shows that a major influence on the trend toward drier summer conditions is the observed increase in temperatures. This effect is particularly strong in central Europe.

Based on the 22 scPDSI records, a gridded scPDSI dataset covering a large part of Europe has been constructed and compared to a recent high-resolution scPDSI dataset spanning the twentieth century only. We again observe that a major cause for the large areal extent of summer drought in the last two decades is high temperatures. Temperatures in the 12 months preceding and including the summer of 2003 explain an increase in the areas experiencing slightly dry (or worse) conditions of 11.1%.

KEY WORDS drought; Europe; instrumental data; Palmer Drought Severity Index

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1. Introduction

Most global climate model simulations of future enhanced greenhouse gas climates indicate expected summer desiccation in the Northern Hemisphere mid-latitudes (Meehl *et al*., 2007). With an increased evaporative demand and higher temperatures outweighing a possible increase in precipitation, soil moisture levels are likely to go down. The combination of dry soils and high levels of potential evapotranspiration may lead to stunted growth or even wilting of crop plants. The potential for a major impact on global food supply is why this can be considered to be among the gravest aspects of the global warming phenomenon (Robock *et al*., 2005). Indeed, Wigley and Atkinson (1977) argued, some 30 years ago, that in southeast England the first signs of a trend towards more persistently occurring droughts could already be discerned. Their study showed that the final 50 years of their 279-year-long record, running from 1698 up to 1976, contained the three most severe droughts which occurred over this period. Against this background, and prompted largely by the apparently extensive nature of dry conditions affecting Europe in recent years (especially 2003), we investigate if the trend discerned by Wigley and Atkinson (1977) for south-east England has persisted since the 1976 drought. Additionally, we investigate if a trend towards more frequent summer drought occurs on a larger spatial scale within Europe, in the near 300-year context afforded by a number of long instrumental climate records. This study, therefore, represents a temporally extended though necessarily less spatially comprehensive extension of the European analysis of van der Schrier *et al*. (2006a) which spanned the period 1901–2002. With this study, it is possible to check whether the (multi-) decadal scale variability seen in the 103-year-long records of van der Schrier *et al*. (2006a) is related to any long-term trend.

The metric we use to identify dry and wet spells is the self-calibrating Palmer Drought Severity Index (scPDSI) (Wells *et al*., 2004), a recent improvement of the Palmer Drought Severity Index (PDSI). The PDSI is a measure of regional moisture availability that has been used extensively to study droughts and wet spells in the contiguous USA, particularly as the primary indication of the severity and extent of recent droughts (Palmer, 1965; Heim, 2002;

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Table I. Classification of dry and wet conditions as defined by Palmer (1965) for the PDSI.

PDSI	Class
≥4.0	Extremely wet
3.0 : 4.0	Severely wet
2.0 : 3.0	Moderately wet
1.0 : 2.0	Slightly wet
0.5 : 1.0	Incipient wet spell
−0.5 : 0.5	Near-normal
−0.5 : −1.0	Incipient dry spell
−1.0 : −2.0	Slightly dry
−2.0 : −3.0	Moderately dry
−3.0 : −4.0	Severely dry
≤−4.0	Extremely dry

van der Schrier *et al*., 2006b) with applications to other parts of the world emerging in the past decade (Briffa *et al*., 1994; Dai *et al*., 2004; van der Schrier *et al*., 2006a, 2007). The computation of the PDSI involves a classification of relative soil moisture conditions within 11 categories as defined by Palmer (1965) (Table 1), which range from −4 (extremely dry) to +4 (extremely wet). The index is based on the balance between water supply and demand, which is calculated using a rather complex water-budget system based on historical records of precipitation and temperature, with the soil characteristics of the site being taken into account.

The PDSI (as formulated by Palmer, 1965) has been criticized for a variety of reasons of which the most significant is perhaps that it is not comparable between diverse climatological regions, and that it produces values which are ≥4 or ≤−4 up to 15% or more of the time (Wells *et al*., 2004): hardly corresponding to the classification 'extreme'. Moreover, the PDSI tends to have a slightly bimodal distribution (Wells *et al*., 2004, their Fig. 8), with maxima in the distribution outside the 'near-normal' category.

The scPDSI as proposed by Wells *et al*. (2004) represents an improvement over the 'traditional' PDSI with respect to these points. Due to a lack of computational resources, Palmer calculated a set of empirical weighting factors, which are used in the PDSI algorithm, by averaging the values from only a few locations, mainly in the American mid-west. These averaged values for the weighting factors have since become an integral part of the PDSI computation, regardless of the climate for which it is applied (Wells *et al*., 2004). Wells *et al*. (2004) improve the performance of the PDSI by automating the calculations that produce the weighting factors which are uniquely appropriate to their location.

A detailed description of how the PDSI is computed can be found in Alley (1984) and Karl (1986). A detailed description of the modifications to this algorithm to obtain the scPDSI is given by Wells *et al*. (2004) and, more concisely, by van der Schrier *et al*. (2006a).

Inputs to the scPDSI calculations are monthly precipitation and temperature values. The latter are used in a simple parameterization for evapotranspiration. From these data, together with information on the potential soil moisture storage capacity, the drought index is determined. A selection of long instrumental records for precipitation and temperature, 22 in total from western and central Europe, are the basis for the scPDSI calculations in this study.

The longest record used is the Kew precipitation record, starting in 1697 and terminating after 1999. The shortest record is that of Berlin, starting in 1848 and continuing up to the present.

Note that the influence of large-scale changes in water usage associated with reservoir development, urbanization, or changes in irrigation are ignored in the index. Neither does the calculation of the index account for precipitation in the form of snow, but assumes all precipitation to be in the liquid phase, and the calculation takes no account of changes in the potential water-holding capacity (WHC) of the soils when the ground freezes. For these reasons, we restrict this analysis to exploring changes in summer scPDSI only, which is largely unaffected by these factors (van der Schrier *et al*., 2007).

The current paper is organized as follows: Section 2 describes the sources of data used to calculate the scPDSI. Section 3 gives an analysis of the long scPDSI records and examines the specific influence of changing temperatures. Section 4 is concerned with a gridded scPDSI dataset, and Section 5 draws brief conclusions about the trends in moisture availability over the last 250 years.

2. Temperature, precipitation and soil moisture data

This analysis is based on a selection of 22 long European precipitation records, for which the spatial and temporal distributions of the data are shown in Figures 1 and 2 respectively. These data were extracted from the Climatic Research Unit archives. All but two of these stations are located between 43 °N and 56 °N and 5 °W–20 °E, with the greatest concentration falling within a 1000-km-diameter circle centred on central Austria. There are no

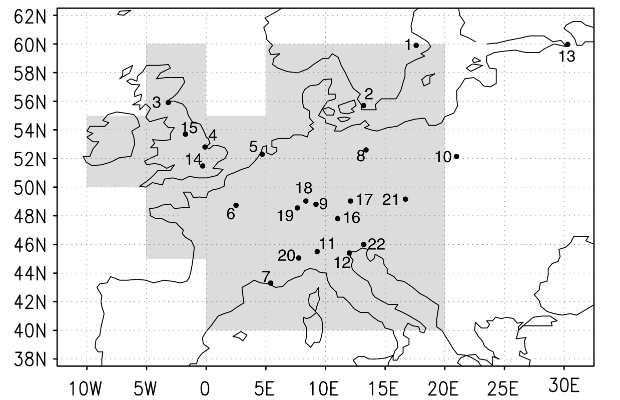

Figure 1. The area covered by the gridded scPDSI maps (in grey), and the network of instrumental records. The numbers refer to the station numbers in Table 2.

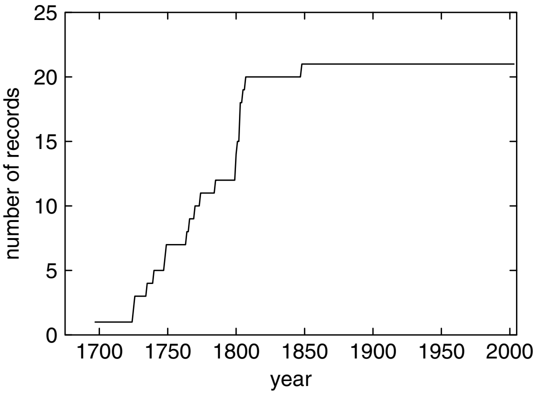

Figure 2. Temporal changes in the number of available long precipitation records since 1697.

stations in southwest or southeast Europe long enough to be included in this analysis. Though the longest record, for Kew, extends back to the beginning of the seventeenth century, only half reach back before 1800, and only five before 1750. These are mostly located in the northwest.

The records are updated with data from the original station or they are updated with a blend of data from nearby stations. In some cases, the records were updated by using synoptic data [i.e. daily data distributed via the global telecommunications system, (GTS)].

Besides monthly mean precipitation data, input to the scPDSI algorithm includes (monthly) temperature and the latitude of the station, to enable an estimate of the potential evaporation to be calculated using the Thornthwaite (1948) formula. In many cases, it was not possible to find a temperature record of equivalent length from the same location as the precipitation record. To overcome this problem, the nearest long temperature record was substituted for the *in situ* temperature data. This is justified by noting that temperature variability on monthly timescales is spatially very homogeneous (New *et al*., 1999, 2000). The pairs of long precipitation and temperature records used in this analysis are shown in Table 2.

Some precipitation and temperature records also had data gaps. Table 3 shows, for each precipitation record and its paired temperature record, the percentage of summer months for which data were missing. This table shows that the stations which are affected most by missing precipitation data are St. Petersburg, and to a lesser degree, Stuttgart. The scPDSI algorithm cannot deal with missing data. These were replaced by the appropriate monthly mean values, calculated over the 1961–1990 period. Those temperature records that did not cover the same time span as their associated precipitation record were also 'padded' with the appropriate monthly mean temperature values (again for the 1961–1990 period). PDSI values for the months with missing precipitation data are flagged as 'missing' and not used in the analysis described here, but this is not done for the months with missing temperature data. The calculation of the drought index with monthly mean temperatures replacing missing data is justified by noting that the variability

Table II. The time spans and locations of instrumental data series used in this analysis. The water-holding capacity (WHC) values used for each location are also shown. The records for some stations have been updated with a blend of data from surrounding stations.

	Precipitation record	Time span	Temperature record	Time span	Latitude (°N)	Longitude (°E)	WHC (mm)
1.	Uppsala	1774–2001	Uppsala	1722–2001	59.90	17.60	175
2.	Lund	1748–2005	Kopenhaven	1768–2004	55.70	13.20	175
3.	Edinburgh	1785–2004	CET	1659–2004	55.91	−3.18	195
4.	Podehole	1726–2005	CET	1659–2004	52.80	−0.10	1000
5.	Hoofddorp	1735–2004	De Bilt	1706–2004	52.30	4.70	1000
6.	Paris	1770–2004	Paris	1764–2004	48.73	2.50	175
7.	Marseille	1749–2004	Milan	1763–2003	43.30	5.40	175
8.	Berlin	1848–2004	Berlin	1701–2004	52.60	13.40	175
9.	Stuttgart	1807–2004	Basel	1755–2005	48.80	9.20	175
10.	Warsaw	1803–2004	Warsaw	1779–2004	52.15	20.98	125
11.	Milan	1764–2003	Milan	1763–2003	45.50	9.30	175
12.	Padua	1725–2002	Padua	1774–2003	45.40	12.00	175
13.	St. Petersburg	1740–2004	St. Petersburg	1743–2004	59.97	30.30	175
14.	Kew	1697–1999	CET	1659–2004	51.48	−0.30	1000
15.	England-Wales	1766–2004	CET	1659–2004	≈51.50	≈−1.74	175
16.	Hohenpeissenberg	1800–2004	Hohenpeissenberg	1781–2004	47.80	11.02	80
17.	Regensburg	1800–2004	Basel	1755–2005	49.03	12.10	40
18.	Karlsruhe	1801–2004	Basel	1755–2005	49.03	8.35	1000
19.	Strassbourg	1803–2004	Basel	1755–2005	48.55	7.64	175
20.	Turin	1803–2004	Milan	1763–2003	45.05	7.75	175
21.	Brno	1805–2004	Vienna	1775–2004	49.16	16.70	175
22.	Udine	1803–2004	Padua	1774–2003	46.00	13.20	175

Table III. Percentage of data missing in the precipitation record, accumulated over the summer (JJA) months only, and the percentage of data missing in the corresponding temperature record overlapping with the precipitation record.

Precipitation record	Percentage of precipitation data missing	Percentage of temperature data missing
Uppsala	0.00	0.00
Lund	0.00	5.45
Edinburgh	0.00	0.00
Podehole	0.00	0.00
Hoofddorp	0.00	0.00
Paris	0.57	0.00
Marseille	0.65	0.00
Berlin	0.00	0.21
Stuttgart	6.73	1.35
Warsaw	0.50	0.00
Milan	0.00	0.00
Padua	1.08	2.28
St. Petersburg	31.19	4.53
Kew	0.00	0.00
England-Wales	0.00	0.00
Hohenpreissenberg	0.49	0.00
Regensburg	0.49	1.30
Karlsruhe	0.49	1.31
Strassbourg	0.50	1.32
Turin	0.50	0.00
Brno	0.50	0.00
Udine	0.50	3.30

in the PDSI is only weakly related to the variability in local temperature (*ca* 10%) (Hu and Willson, 2000).

The potential soil moisture storage capacity dataset used here is taken from the Food and Agriculture Organization's digital soil map of the world (Food and Agriculture Organization, 2003). This dataset has a spatial resolution of $5' \times 5'$, and the WHC in a gridbox is taken to be that of the most dominant soil type in that gridbox. The WHC of the soils is subdivided in nine classes, ranging from wetlands, which are given a WHC of 1000 mm/m, to soils with a WHC of <20 mm/m. The reason for choosing this WHC dataset, rather than the one used earlier in van der Schrier *et al*. (2006a), is that the higher resolution of the current dataset is better suited to an analysis where the focus is on station rather than gridded data.

3. Analysis of long scPDSI records

Figure 3 shows the probability distribution of the monthly values of the 22 scPDSI records, calculated from the instrumental precipitation and temperature records (Table 2). It shows that the scPDSI does not exhibit the non-normality of the 'original' PDSI data. The probability distributions are near-normal with the most common values lying in the 'near-normal' category. The calibration of the scPDSI is intended to produce ca 2% of values in the extremely dry category and 2% in the extremely wet category.

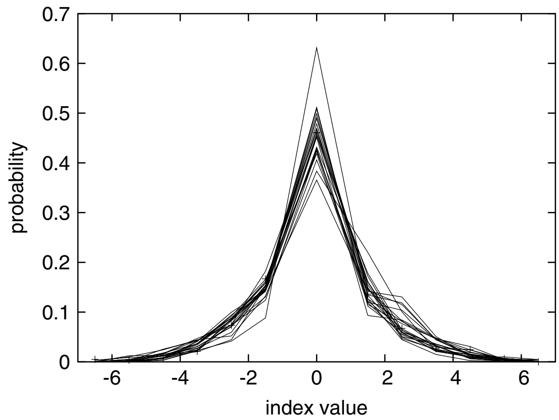

Figure 3. Probability distribution of monthly scPDSI for all stations.

The probability distribution of mean summer values of the Kew scPDSI record is shown alongside the growing season soil moisture deficit record calculated by Wigley and Atkinson (1977) in Figure 4. The latter distribution is strongly skewed to the larger soil moisture deficit values, whereas the scPDSI record has a near-normal distribution.

Figure 5 shows 22 timeseries of the mean summer (JJA) scPDSI values. The correlation between the summer scPDSI values for the Kew precipitation record and the Wigley and Atkinson growing season soil moisture deficit values for Kew is fairly strong at −0.68. The high value of this correlation indicates the underlying similarity in the calculation of both quantities. A negative correlation is to be expected, since higher values of soil moisture deficit are associated with more negative values of the scPDSI.

A simple average over the available records from 1750 onwards (Figure 6) suggests a trend toward more widespread summer drought in Europe in recent times. The three driest summers which stand out in this simple average are 1976, with an average summer scPDSI of −2.8, 1990 (−2.1) and 1921 (−1.9). The summer of 2003 does not stand out as particularly dry in this simple average: the summer scPDSI is −0.9. The wettest summers occurred in 1941 (with an average summer scPDSI of 1.9) and 1879 (2.2).

3.1. Frequency of the occurrence of wet and dry summers

3.1.1. Kew

The Kew record, the longest analysed here (Figure 5) displays a trend towards wetter summer conditions from the end of the seventeenth century to the beginning of the nineteenth century, which is followed by a trend toward drier conditions with record dry summers in the latter part of the twentieth century.

Figure 7 shows the number of occurrences of moderately wet and dry summers (or worse) in the Kew record, grouped per decade. The most noticeable features of this

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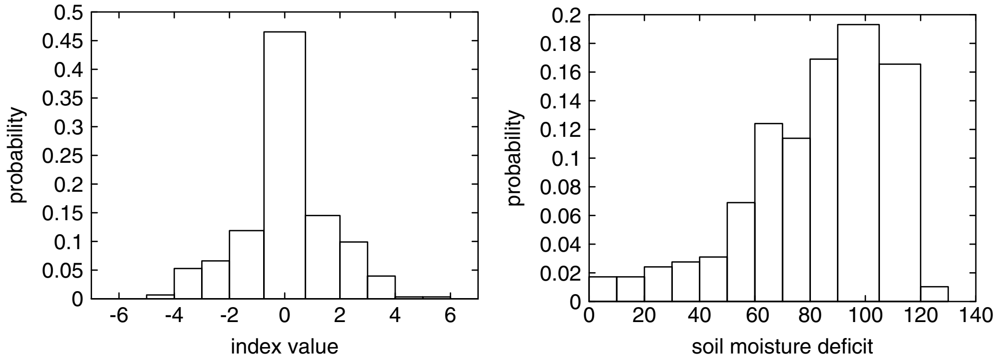

Figure 4. Probability distribution of summer scPDSI for the Kew record, evaluated over the 1698–1999 period (left) and growing season soil moisture deficit (mm) values for Kew as calculated by Wigley and Atkinson (1977), evaluated over the 1698–1976 period (right).

Figure are the wet drought-free period, 1770–1859, and the persistent dry summers that occur in the latter part of the record. The reverse picture is seen in the case of wet summers. This confirms the earlier findings of Wigley and Atkinson (1977) who calculated values of soil moisture deficit rather than the scPDSI as a metric for drought. Their soil moisture model is similar to the one used in the scPDSI algorithm, but it has a slightly more complex parameterization for potential evapotranspiration (Penman, 1949).

The statistical significance of these observations may be established by constructing a set of surrogate data using a Monte Carlo approach (Theiler *et al.*, 1992). Each surrogate dataset is derived from the summer scPDSI timeseries by a Fourier transformation followed by the randomization of the phase spectrum. The spectra are then transformed back to the time-domain. This produces surrogate data which share the power spectrum of the original data, and in particular, the auto-correlation structure, but have randomized phase relations. The rationale behind this approach is similar to that of Osborn and Briffa (2006) who assessed the precedence of recent warmth in a number of Northern Hemisphere proxy temperature series. In our analysis, changes in the occurrence of dry or wet periods can be considered non-significant if it is shown that they can occur reasonably frequently in the surrogate records. In that case, all the structure in the scPDSI record is given by its Fourier spectrum and a change in climate is not likely to have played a role in the increase in extreme droughts observed in the recent part of the record. This null-hypothesis can be rejected if it is unlikely that the clustering of droughts in the most recent part of the record is reproduced by the surrogate data.

To test the null-hypothesis, 10 000 different surrogate timeseries of the Kew summer scPDSI record were produced, and for each decade, the number of summers classed as moderately dry or worse (scPDSI values ≤ -2) and the number of summers that are moderately wet or worse (scPDSI values ≥ 2) are counted, starting with the 1700–1709 decade. The ensemble of surrogate datasets provides a probability distribution so that for each decade, the upper and lower 1st, 5th and 10th percentiles can be calculated. These are plotted in Figure 7 as black lines. This figure shows that the high number of droughts in the most recent decade in southeast England are significant at the 95% level, but fail to pass the 99% confidence level.

3.1.2. *Europe*

In order to establish whether the trend toward more frequently occurring dry summers during the latter part of the twentieth century apparent in the Kew record is shared by other records on the European continent, the following test was performed. The yearly fraction of the total number of records with values exceeding a specified dryness threshold was calculated. If the persistence of dry summers occurring on a Europe-wide scale is shifting, then this should be reflected in the timeseries of this fraction. The threshold value used here is scPDSI ≤ -2, corresponding to a moderately dry summer or worse, and is similar to the threshold used in Section 3.1.1. To monitor the frequency of occurrence of wet summers, we also calculate the equivalent fraction of records that exceed the scPDSI = 2 threshold. Figure 8 shows the results of these calculations. This figure clearly shows more frequently occurring dry summers in the more recent part of the record, with wet summers occurring less frequently. Similar conclusions are reached when the scPDSI ≤ -3 (scPDSI ≥ 3) thresholds are taken, relating to severely dry (wet) conditions or worse (not shown).

To test the null-hypothesis that the clustering of widespread droughts in Europe can be explained by the auto-correlation structure of the scPDSI records and that the evidence of increased drought frequency is, therefore, not significant, 10 000 different surrogate timeseries of each summer scPDSI record were produced. The exceedences of these records were recalculated for the surrogate datasets so as to build up a distribution of possible values. The 90th, 95th and 99th percentiles of this distribution were calculated for each year and are shown in Figure 8 as the black lines. The fraction of observed records that exhibit dry summers in the latter part of the record far exceeds even the 99th percentile of the surrogate data, clearly showing that the

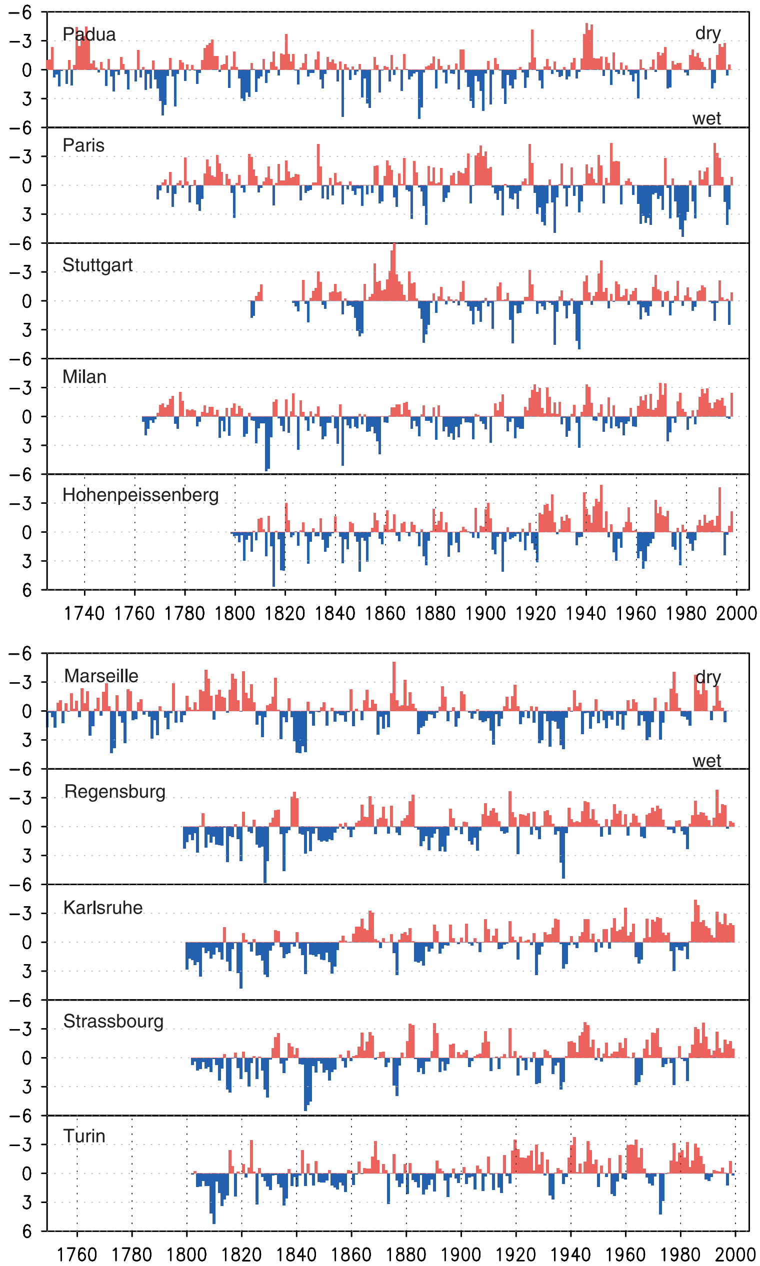

Figure 5. Summer values of the self-calibrating PDSI for the 22 locations considered in this study. See also Table 2 and Figure 1. Note the inverted vertical scale. This figure is available in colour online at www.interscience.wiley.com/ijoc

expansive recent dryness across Europe is statistically highly unusual.

3.2. An estimate of the influence of temperature on recent summer drought

The soil moisture model which is the basis of the (sc)PDSI, is a simple water balance calculation. One of the terms in this balance is an estimate of the potential evapotranspiration, which is based on the Thornthwaite (1948) parameterization (Karl, 1986). The Thornthwaite formula gives a crude measure of the evaporation, dependent solely on temperature and latitude. It is, therefore, possible to estimate the impact of the high temperatures in recent decades on the severity of summer drought by substituting climatological monthly mean temperatures for the actual observed monthly mean temperatures in the Thornthwaite parameterization. The algorithm of the scPDSI then computes new scPDSI records where the year-to-year variability is related uniquely to that in the precipitation record, rather than a combination of variability in precipitation and temperature. The algorithm also calculates a new set of calibration constants. The climatological mean temperatures are based on the 1961–1990 period.

Figure 9 summarizes the results of such an exercise and can be compared directly with Figure 8. Figure 9 shows that of the dry summers in the last decade of the twentieth century, only the 1991 summer stands out above the 99% confidence level. The

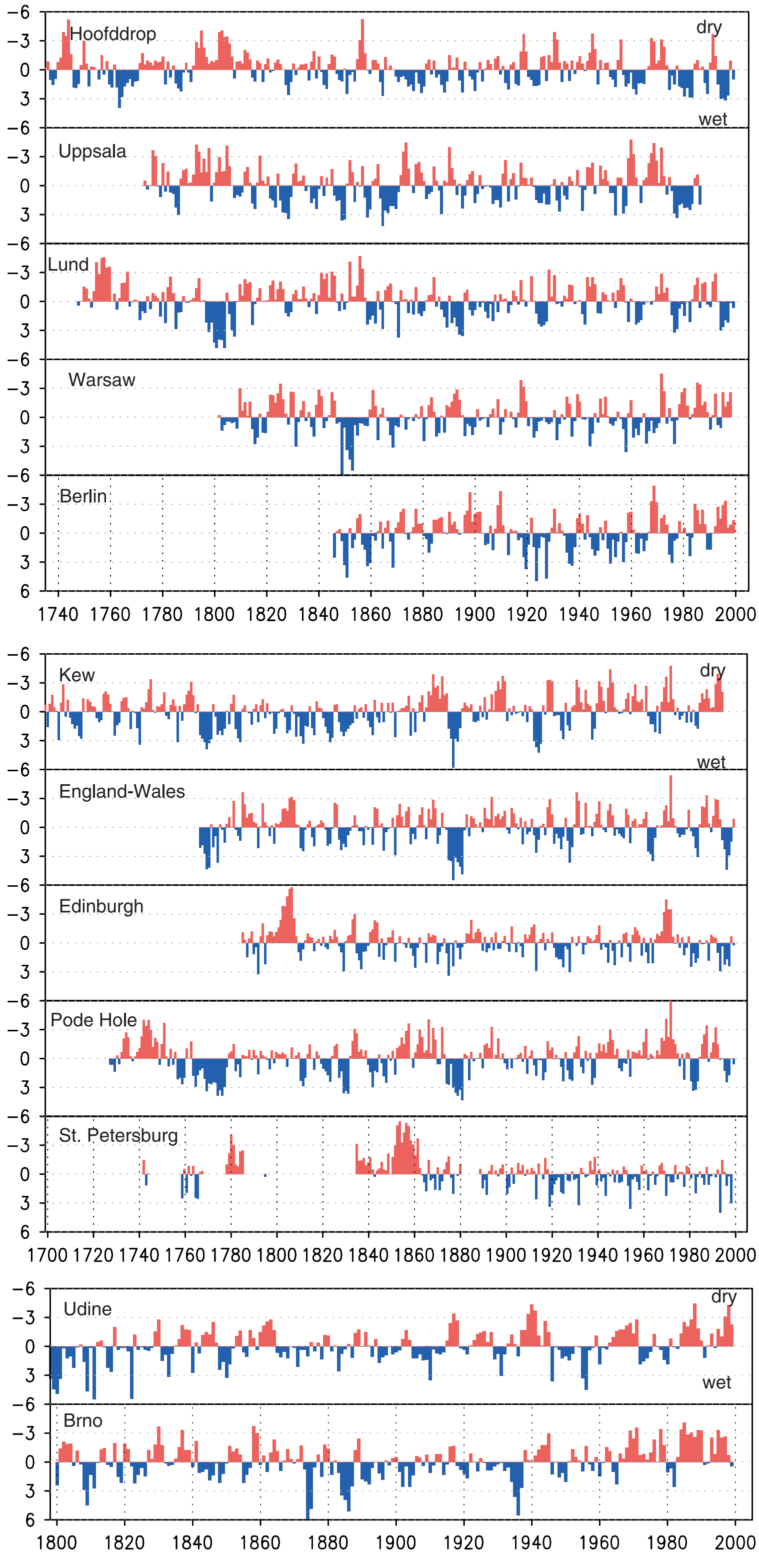

Figure 5. (*Continued*).

fraction of records which show moderately dry conditions (or worse) for this year is 0.36, a decrease of 0.09 (the equivalent of two records) from the value shown in Figure 8. The summers of 1990, 1992 and 1998 fail to pass the 99% significance level when the variability in temperature does not contribute to variations in the scPDSI metric. Other dry years, like 1974 and 1976, still indicate that a large fraction of the records show dry conditions, but the fraction is much lower.

Interestingly, the third quarter of the nineteenth century (the years 1858, 1859, 1865, 1870 and 1874) shows the opposite effect, with cool summers making dry conditions in Europe less widespread.

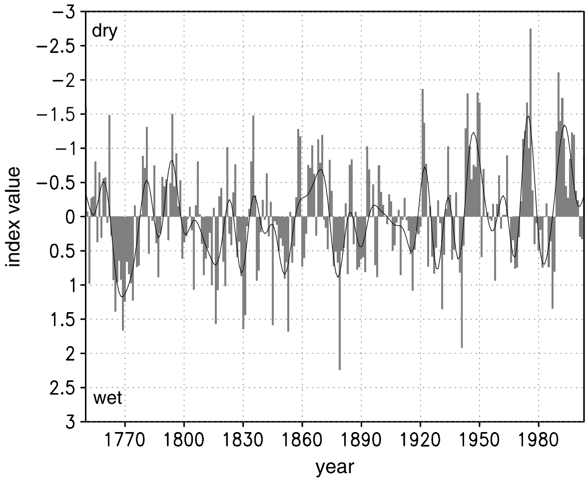

Figure 6. Summer mean values of scPDSI from 1750 onwards, averaged over the available records. The smooth black line represents 10-year low-pass filtered values. Note the inverted vertical scale.

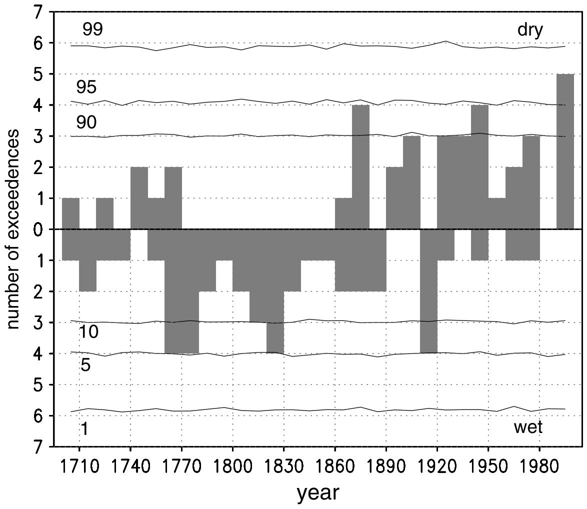

Figure 7. The number of times that the summer scPDSI value at Kew was at or below the −2 threshold (upper part) or at or above the +2 threshold (lower part) in 10-year intervals. The black lines indicate the 1st, 5th, 10th, 90th, 95th and 99th percentiles of the individual distributions, produced by repeating the analysis 10 000 times using surrogate data.

Figure 10 shows the change in the number of moderately dry summers (or worse) since 1950 for each record when variability in the temperature record is removed from the scPDSI calculations, making it dependent on precipitation only. This figure indicates that in central Europe a large fraction of the dry summers since 1950 can be related to variability in temperature. The stations that stand out in this respect are Karlsruhe and Brno. This analysis suggests that for Karlsruhe since 1950, 12 (1950, 1974, 1975, 1976, 1977, 1989, 1990, 1992, 1993, 1998, 1999, 2001) and for Borr 13 (1950, 1974, 1975, 1981, 1983, 1989, 1990, 1994, 1995, 1998, 2000, 2001, 2002) dry summers, are related to anomalously high temperatures.

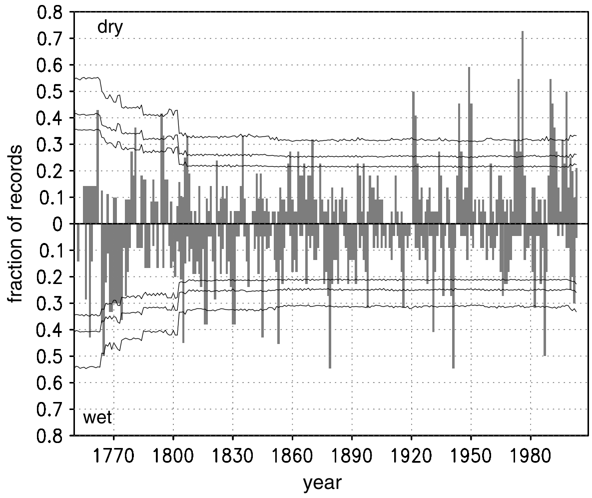

Figure 8. The fraction of the records available each year that show a moderately dry summer or worse (scPDSI ≤ -2, (upper part)) and the fraction of the records available each year that show a moderately wet summer or worse (scPDSI ≥ 2, (lower part)). The black lines show the 1st, 5th, 10th, 90th, 95th and 99th percentiles of the distributions produced by repeating the analysis 10 000 times using surrogate data.

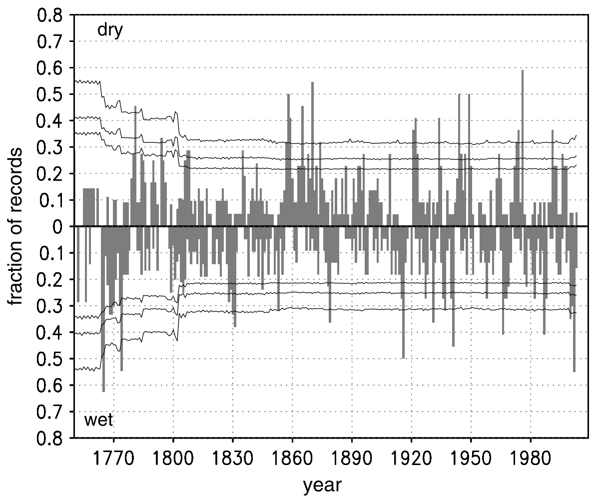

Figure 9. As for Figure 8, but the scPDSI is now calculated using fixed climatological temperatures rather than actual varying temperatures.

4. Construction of a gridded scPDSI dataset

To investigate if the spatial extent of droughts has changed since 1750, we construct a gridded scPDSI dataset on the basis of the 22 records studied here. Given the scarcity of long precipitation records, a rather coarse gridding resolution of $5° \times 5°$ is adopted. Figure 1 shows the network of scPDSI records and the area over which the gridding is achieved.

4.1. The interpolation technique

The gridding scheme follows the approach used by Efthymiadis *et al.* (2006). The interpolation technique used is based on the angular-distance-weighted averaging of neighbouring timeseries, where the weight $w(k)$ with which timeseries k determines the scPDSI value of a

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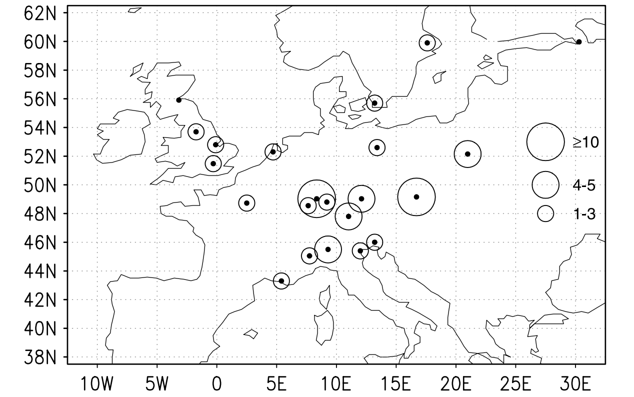

Figure 10. The network of instrumental records (thick black dots) with an indication of the number of at least moderately dry summers (scPDSI ≤ -2) since 1950 which may be related to variations in temperature alone shown as circles.

gridbox, is determined by

$$w(k) = w_{\text{rad}}(k)w_{\text{ang}}(k). \quad (1)$$

The radial term w_{rad} is a function of radial distance from the gridbox. This term is 1 if the radial distance between timeseries and gridbox is 0, and has an e-folding scale of 100 km. The angular term w_{ang} is a function of the angular separation of other timeseries which determine the value for the gridbox:

$$w_{\text{ang}}(k) = 1 + \frac{\sum_{l=1}^{n} w_{\text{rad}}(l)[1 - \cos\theta_j(k,l)]}{\sum_{l=1}^{n} w_{\text{rad}}(l)} \quad \text{with } l \neq k. \quad (2)$$

Here $\theta_j(k,l)$ is the angular separation of data stations k and l at the grid point j.

The procedure used to construct the monthly gridded dataset is as follows. For every gridbox in the domain (Figure 1) and for every month between January 1750 and December 2003, three stations, S_1, S_2, S_3, are located which have data for that month and are the nearest stations to the centre of the gridbox. If the temporal correlation between one of these stations and any of the others is less than or equal to zero, then the value for the gridbox is flagged as 'absent'. If the correlation between the three nearest stations is positive, the weights associated with each station are calculated, using Equation (1).

The scPDSI value for month t and gridbox j is now calculated by the summation:

$$\sum_{k=1}^{3} w(k)S_k(t). \quad (3)$$

To test the gridded dataset, we compare it to a recent gridded scPDSI dataset for Europe (van der Schrier *et al.*, 2006a). The latter dataset is re-gridded from the original

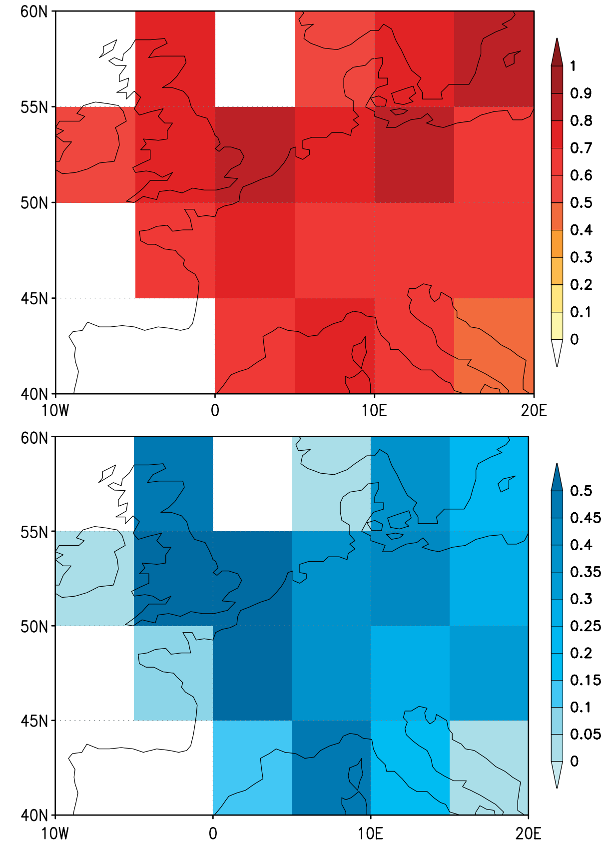

Figure 11. Correlation maps showing the similarity between the reconstructed summer scPDSI values and re-gridded summer scPDSI values of van der Schrier *et al.* (2006). The correlations are shown in (the upper map), the explained variance for the reconstructed scPDSI dataset, calculated using formula 1, is shown in (the lower map). These values are calculated over the summer period from 1901 to 2002. This figure is available in colour online at www.interscience.wiley.com/ijoc

$0.5^\circ \times 0.5^\circ$ to the current $5^\circ \times 5^\circ$ grid. The test involved two aspects. One is the calculation of the correlation coefficient for each gridbox over the common period of the datasets (January 1901–December 2002). Figure 11 shows that, the correlation between the reconstructed scPDSI values and the reference dataset is fairly high, with an average correlation of 0.67. The highest value is found over east England and the Netherlands at 0.9. The lowest value is found in the southeastern corner of the region at 0.3.

The other aspect is the calculation of the 'variance explained' score,

$$\text{Variance explained} = \left(1 - \frac{\text{Variance } (P(j) - P_{\text{ref}}(j))}{\text{Variance}(P_{\text{ref}}(j))}\right), \quad (4)$$

over the common period. Here $P_{\text{ref}}(j)$ is the reference timeseries and $P(j)$ is the timeseries from the reconstructed gridded dataset for gridbox j. Figure 11 shows that the variance explained is rather low, with an average value of 0.30, which is not surprising given the few records from which the gridded scPDSI reconstruction

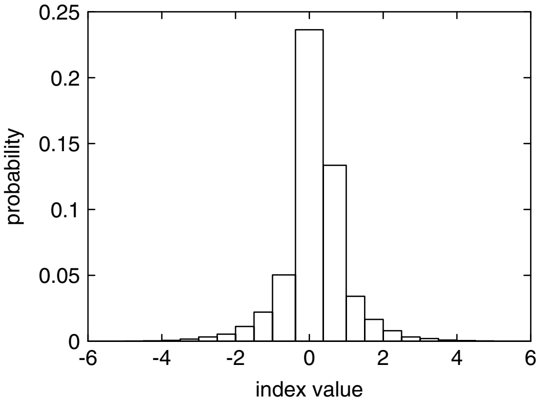

Figure 12. Probability distribution as an average over all available gridboxes in the gridded dataset.

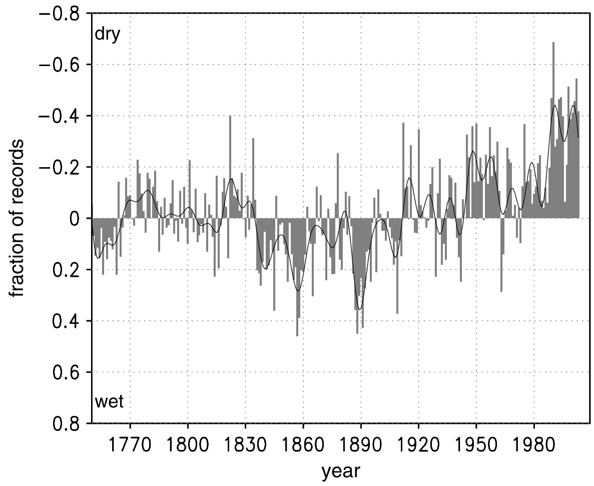

Figure 13. The difference in mean European summer self-calibrating PDSI as calculated using actual varying monthly temperatures and as calculated using fixed climatological monthly mean temperatures. The values represent a spatial average of all gridboxes, weighted by the cosine of the latitude. The smooth line shows 10-year low-pass filtered values.

is produced. Highest values are found over England, the Netherlands and central France.

The low levels of explained variance have their impact on the probability distribution of the scPDSI values of the gridded dataset. This is summarized in Figure 12, where the probability distribution of summer scPDSI values is shown as an average over the gridboxes. This figure shows a probability distribution which is much narrower than the probability distributions of the timeseries used to construct the gridded dataset (Figure 3).

Two different datasets are constructed using this interpolation technique. One is based on the scPDSI records as introduced in Section 3.1. For the other dataset, we use the alternative scPDSI records, which have their temporal variability related to variations in precipitation only, rather than a combination of precipitation and temperature. These records are calculated using climatological monthly mean data as described in Section 3.2.

4.2. The effect of temperature on dry conditions since 1750

Figure 13 shows the difference in summer scPDSI, averaged over Europe, between the two gridded datasets. This figure shows strong decadal-scale variability and trend towards overall drier conditions since *ca* 1890. The 1990 summer stands out in this respect, with a value of −0.68 scPDSI unit related to anomalous high temperatures. Averaged over the period 1990–2003, European summer scPDSI values were 0.40 lower due to anomalous high temperatures.

Figure 14 shows the percentage of the total reconstructed drought area and area with moisture excess. The upper part of the figure shows the percentage area where the scPDSI ≤ -1 threshold (in grey) or the scPDSI ≤ -3 threshold (in black). In the terminology introduced in Table 1, these indicate a slight or severe drought, respectively. However, due to the loss of variance inherent in gridding and interpolation discussed above, these qualifications have lost some of their aptness. The lower part of the figure shows the percentage area where the scPDSI ≥ 1 threshold (grey) or the scPDSI ≥ 3 threshold (black) is exceeded.

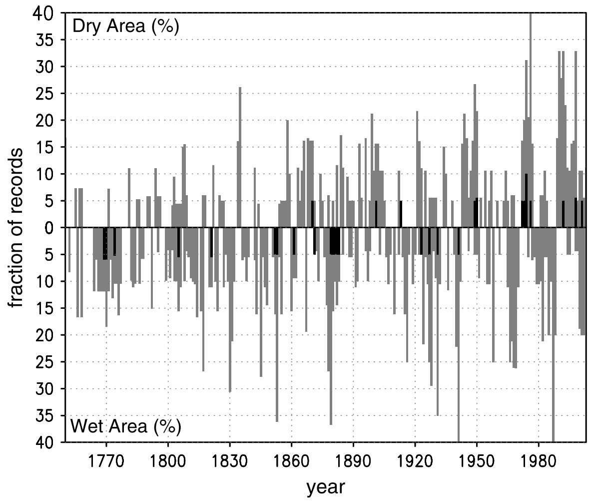

Figure 14. Indices of the changing area of European drought and moisture excess. The areas of slight (|scPDSI| > 1.0: grey shading) or severe (|scPDSI| > 3.0: black shading) moisture deficiency (upper bars) or excess (lower bars) are shown as percentages of the overall area.

Nevertheless, the trend toward more widespread dry conditions, both for slightly dry and severely dry conditions is still apparent. The summer of 1976, previously highlighted in the earlier analysis by Wigley and Atkinson (1977) for southern England, stands out with over *ca*. 42% of the gridded area showing moderate drought and *ca*. 5% experiencing severe drought. However, there are three summers in the 1990s (1990, 1992, 1998) with over 30% of the area affected by scPDSI values ≤ -1.

Figure 15 compares the spatial extent of slight (scPDSI ≤ -1) and severe (scPDSI ≤ -3) drought, averaged over the complete reconstructed area, including and excluding variability in temperature. This figure shows that over the last two decades, the data show a general trend

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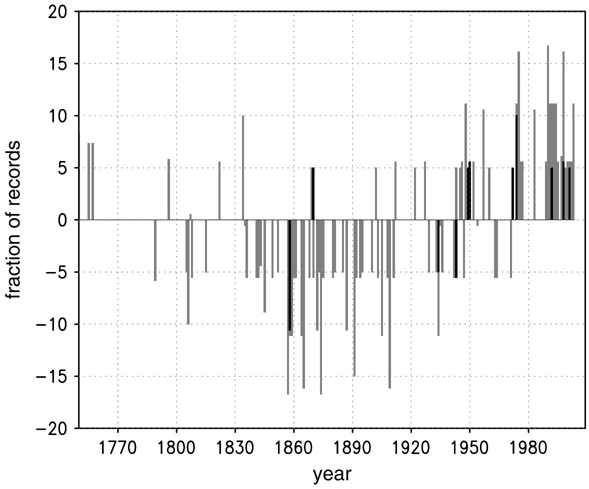

Figure 15. The difference in percentage area of drought between the scPDSI maps calculated using actual monthly temperatures and scPDSI maps based on the use of fixed climatological monthly mean temperatures. The difference in areas of slight (scPDSI ≤ -1.0) or severe (scPDSI ≤ -3.0) moisture deficiency are shown as percentages of the overall area in grey and black, respectively.

towards more widespread dry conditions due only to this 'temperature-related' effect.

Since 1980, the deviation of temperatures from the climatological mean increased the areal extent of slight (or worse) droughts, with 5% or more for 14 summers (1983, 1989–1995, 1997, 1990–2003). For 7 summers in the 1980–2003 period, this was 10% or more (1983, 1990–1994, 2003), and for 2 summers the increase in areal extent due to the 'temperature effect' was >15% (1990, 1998). High temperatures preceding and including the summer of 2003 explain an increase in the area percentage with slightly dry (or worse) conditions of 11.1%.

5. Discussion and conclusions

We have described variations in summer moisture availability based on the scPDSI calculated using 22 long European instrumental records of precipitation and temperature.

The longest record used, Kew, dates back to 1697, and the shortest, Berlin, starts in 1848; the average length of the records is 220 years. These records have enabled an analysis of changes in the recurrence of wet and dry summers in Europe over the period 1750–2003.

The most important conclusions of this study are that the Kew record, the longest analysed here, displays a trend towards wetter summer conditions from the end of the seventeenth century up until the beginning of the nineteenth century, followed by a continuing trend toward drier conditions. Record dry summers are apparent in the latter part of the twentieth century. The trend towards more frequently occurring dryness, observed in a previous analysis of the Kew record by Wigley and Atkinson (1977), is shown in the current analysis to have persisted during the period after the extremely dry conditions in 1976 that were the motivation for their study. A significance test indicates that the high number of occurrences of dry summers in the latter part of the twentieth century is significant at the 95% confidence level, though it fails to reach significance at the 99% confidence level.

The trend toward more frequently occurring dry summers observed at Kew in the recent part of the record, is also apparent in a wider European context. The fraction of the total number of records showing at least moderate summer droughts is anomalously high for the more recent part of the record. This expansive recent dryness in Europe is shown to be highly statistically significant.

In order to estimate the impact of high temperatures in recent decades on the severity of summer drought, climatological monthly mean temperatures were substituted for the actual observed monthly mean temperatures in the parameterization for potential evapotranspiration. This enabled scPDSI records to be calculated where the variability in the drought index is related uniquely to that in the precipitation record, rather than a combination of variability in precipitation and temperature. This analysis shows that recent anomalously high temperatures are a major contribution to the severity of recent dryness. The impact of high temperatures on summer drought is particularly strong in central Europe.

Finally, a gridded scPDSI dataset covering a large part of Europe has been constructed. Again, high summer temperatures are seen to be a major cause for the large areal extent of summer drought in the last two decades. This conclusion is consistent with the results of an earlier study of drought in the Greater Alpine Region (van der Schrier *et al.*, 2007). That study also revealed that a trend towards more widespread dry conditions experienced over the Greater Alpine Region during the most recent two decades was also related to increasing temperatures in that area.

The scarcity of 200-year-long precipitation and temperature records precludes the calculation of scPDSI data with a more satisfactory coverage over Europe. The southwestern, northern and eastern regions were either not represented or have very few of these long records.

The earlier analysis of van der Schrier *et al.* (2006a), was based on a more dense and spatially extensive network of self-calibrating PDSI values, but spanned only the 1901–2002 period. The coverage of the 22 long PDSI records used in this study coincides roughly with one of the dominant modes of variability identified in the higher-resolution dataset, i.e. the third Empirical Orthogonal Teleconnection (EOT) pattern shown in Fig. 7c of van der Schrier *et al.* (2006a). This mode, describes moisture variability over most of Sweden, England, France, and the low countries . The pattern weakens towards Poland. The correlation of summer scPDSI variability associated with this third EOT and that represented by the average of the longer station-based PDSI records (Figure 6) over the 1901–2002 period is high at 0.82.

In the earlier analysis of van der Schrier *et al.* (2006a), trends in summer desiccation since 1950 could not be distinguished from the strong (multi-) decadal variability. The longer records in the current study, however, provide a different viewpoint.

The current analysis indicates a robust trend toward more frequently occurring dry summers in England. Allowing for the admittedly 'patchy' spatial coverage of the data over Europe, the same conclusion can be drawn regarding drying in the larger context of west and central Europe. The data described in this paper can be accessed at: WWW.cru.uea.ac.uk/cru/data.

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