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Severity, duration and frequency of drought in SE England from 1697 to 2011

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Abstract Severe droughts have affected much of Europe over the last 40 years. A limitation to current understanding of droughts is based around drought characteristics (e.g. frequency, severity and duration) as there are limited long series (>100 years) with well documented severe droughts. This is further complicated with future climate projections, and the potential implications that these will have on drought characteristics. This paper presents reconstructed drought series from 1697, 1726 and 1767 to 2011 for three sites in southeast England. Precipitation and temperature series are reconstructed to generate long drought series using the self-calibrated Palmer Drought Severity Index, enabling determination of drought characteristics. The reconstructions identify multiple drought-rich periods, 1730–1760 and 1890-present, with an increasing tendency towards more severe droughts during the latter period. Prolonged rainfall deficiencies are found to be the primary cause of severe droughts, with rising temperatures increasing soil moisture deficit, therefore intensifying drought conditions. Cycles at the 6–10 year period identify a sub-decadal to decadal signal during drought-rich periods. Analysis of the spatial variability of droughts finds that whilst severe events are predominantly regionally coherent, there are notable variations in severity and duration between sites, which are attributed to localised rainfall variability. This study extends the temporal range of previous drought studies and places recent drought events in a longer context improving upon existing 'benchmark' drought analyses in southeast England; with far-reaching implications for local, national and continental scale reduction of drought vulnerability and risk.

1 Introduction

Droughts are complex events that are a recurrent feature of the European climate, with severe droughts affecting large areas during the twentieth and twenty-first centuries, notably 1975–76 (Zaidman et al. 2001; Parry et al. 2012), 1991 (Mishra and Singh 2010) and 2003 (Fink et al. 2004). Recent droughts (e.g. 2004–06; 2010–12) highlight the UK's vulnerability, which

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appears greatest in south-eastern England where higher temperatures and lower rainfall, and high concentrations of industrial, agricultural and urban populations combine to create the greatest demand for water in the UK (Rodda 2006). Aquifers make a significant contribution to regional water supply and so long duration rainfall deficiencies (e.g. >18 months) are a considerable challenge, as groundwater resources are dependent upon winter replenishment (Marsh et al. 2007). Definitions of droughts commonly fall into one of five inter-related categories: meteorological, hydrological, agricultural and socio-economic (Wilhite and Glantz 1985; Heim 2002; Brazdil et al. 2008), with Mishra and Singh (2010) recommending the inclusion of groundwater droughts. Droughts usually begin following a prolonged period of widespread moisture deficiency (Palmer 1965; Van Lanen 2006) and propagate through the hydrological cycle, exhibiting differing spatial and temporal characteristics depending on a variety of factors e.g. duration of moisture deficiency and antecedent catchment conditions.

The United Kingdom's climate comprises of four distinct seasons; however, inter-seasonal variability is considerable. Future climate projections indicate the region will experience higher temperatures (IPCC 2007; Murphy et al. 2009) and enhanced rainfall seasonality with drier summers and wetter winters (Osborn et al. 2000; Huntington 2006; Burt and Ferranti 2012), leading to increased potential evapotranspiration (PET) and therefore greater soil moisture deficit, with an increased likelihood of frequent and severe droughts (Hisdal et al. 2001; Briffa et al. 2009). There are few long-term studies of drought in the UK (Wigley and Atkinson 1977; Jones and Lister 1998), with existing analyses focusing on single high-magnitude events (e.g. 1975/76, 1984, 1990, 2003: Ratcliffe et al. 1978; Marsh and Lees 1985; Marsh and Bryant 1990; Marsh 1995; Marsh 2004), seasonally specific droughts (Briffa et al. 2009), or clusters of drought years (e.g. 1988–1992: Bryant et al. 1994). These studies have often relied upon relatively short hydro-meteorological time series and were typically conducted from an impacts perspective, with particular studies focusing on water resources in southwest and northeast England (Phillips and McGregor 1998; Fowler and Kilsby 2002, 2004). As a result they are somewhat constrained in being derived predominantly from hydrological data, which negates consideration of climate variability and meteorological forcing (Marsh et al. 2007). Reconstructing long drought series that incorporate large numbers of events of differing magnitude, structure and impact permits a more robust analysis of the frequency, severity and duration of past droughts over longer timescales (~300 year).

This paper presents drought time series reconstructed for three sites located in southeast England, from 1697, 1726 and 1767 to 2011 (Online resource Figure S1). The self-calibrating Palmer Drought Severity Index (scPDSI) (Wells et al. 2004) was used to construct continuous records of past droughts from a meteorological perspective at both annual and monthly resolutions for all seasons. The temporal and spatial variability of droughts at the three sites is assessed, examining temporal pattern (Wavelet analysis), severity, duration and regional coherence. Physical mechanisms for the most severe droughts to have affected southeast England during the last 300 years are investigated.

2 Datasets

2.1 Identification of long rainfall and temperature data

This study capitalizes on the long history of observing and recording meteorological conditions in Europe (Brazdil et al. 2005). Rapid expansion of meteorological recording in the UK coincided with the period of scientific Enlightenment during the eighteenth century, and advances in communication technology during the nineteenth century leading to modern instrumental recording (Kington 1997). The longest precipitation series originates from Kew (1697, Wales-Smith 1971) and a number of other long homogenous regional meteorological series have been generated e.g. the Central England Temperature series (CET, 1659-present: Manley 1974; Parker et al. 1992). Three primary meteorological stations in southeast England were selected based on station longevity and continuity. Rainfall and temperature data for each site were collected from archival and digital repositories; additional original archival sources (Radcliffe Observation volumes, the UK Meteorological Office decadal yearbooks) were digitised and records to present day (end 2011) extracted from the British Atmospheric Data Centre's MIDAS Land Surface Station Dataset (Online resource Table S1).

2.2 Production of homogenous data series

Long-term homogenous rainfall (Kew, Oxford and Spalding) and temperature (Oxford) series were constructed using multiple original data sources (checked for duplicate entries, erroneous values and missing data), and linear regression analysis. Data bridging using adjacent stations was required to fill periods of missing data (Peterson et al. 1998) and generate site series based on a primary station (Tabony 1980). Construction of the rainfall series for Oxford required an additional methodological step to extend it back to 1767 (Wallace 1997), as no period of overlap for the two earliest data sources at Radcliffe Observatory exists: 1767–1814 and 1815–1852. Therefore, monthly rainfall totals from each series were compared (48 years), and all months with the exception of August, show no significant difference (Online resource Figure S2). These early records permit extension of the homogenous rainfall series for Oxford from 1767 to 2011.

Long climatological series can be influenced by inhomogeneities derived from climatic and environmental variability and human activities (Brazdil et al. 2005). Manual interrogation and homogeneity adjustments of the extended meteorological series (Fig. 1) ensured variations originate only from variations in weather and climate (Conrad and Pollack 1950; Peterson et al. 1998). Meta-data and previously published work for the chosen study sites are also available for consultation (Burt and Howden 2011), improving confidence in the reconstructed homogenous time series.

3 Drought identification

Several indices enable the identification of droughts from data series, reviewed in Heim Jr (2002); Keyantash and Dracup (2002); and Vicente-Serrano et al. (2010). Here we use an improved version of the Palmer Drought Severity Index (PDSI), which is more comparable across climatological regions (Wells et al. 2004), reviewed in Van der Schrier et al. (2006, 2007). The scPDSI is a widely used means of describing the spatial and temporal variability of moisture availability (Lloyd-Hughes and Saunders 2002; Heim 2002; Ntale and Gan 2003; Brazdil et al. 2008; Dai et al. 2004; Dai 2011; US Drought Monitor). The index incorporates historic records of precipitation and surface air temperature into a water balance, which considers the soil characteristics of the site being studied through the inclusion of a two-layer model for soil moisture. The model uses: (1) potential evapotranspiration, computed using the Thornthwaite method (1948); (2) recharge (field moisture capacity of the soil); (3) runoff; and (4) loss (soil moisture to evapotranspiration). Potential values for each of these four parameters are calculated within the model, which Palmer (1965) used to define "climatically appropriate

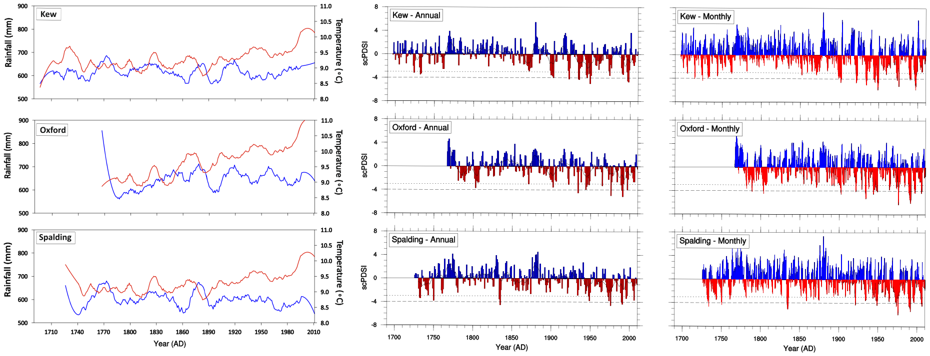

Fig. 1 Reconstructed annual rainfall (*blue line*) and temperature (*red line*) series using a 30-year Savitzky-Golay smoothing filter and 10-year moving average filter, for monthly fluctuations in scPDSI: Kew, 1697–2011, Oxford, 1767–2011 and Spalding, 1726–2011. *Small dashed line* shows severe drought and the *larger dashed line* extreme droughts

for existing conditions" (CAFEC) precipitation. The difference between this value and actual precipitation is central to the index and is an indirect measure of climatic moisture departure from normal. This is then multiplied by a weighting factor to be comparable in both space and time. The index involves the classification of relative moisture conditions within 11 categories as defined by Palmer (1965) (Online resource Table S2). Each category refers to a range of dimensionless index values over a typical scale of −4 (dry) to +4 (wet). Theoretically, normal precipitation and temperature conditions generate an index value of zero.

The simplicity of the (sc)PDSI has undoubtedly led to its popularity in global drought assessments since its inception in the USA; however, its simplistic treatment of potential evapotranspiration (PET) using the Thornthwaite (1948) method has been the subject of recent criticism (Sheffield et al. 2012). The empirical Thornthwaite equation considers temperature and latitude and not radiation, humidity and wind speed, which are other parameters considered in more physically-based PET methods such as Penman-Monteith types. Therefore, the scPDSI may be over-sensitive to temperature; as such increases in temperature since the early twentieth century may result in the over-estimation of drought severity, as discussed by Sheffield et al. (2012). Although Van der Schrier et al. (2011) and Dai (2011) identify differences in accumulated values of PET calculated using the Thornthwaite and Penman-Monteith methods, the scPDSI results are very similar in terms of correlation, regional averages and in classifying extreme events as wet or dry. The scPDSI is found to be insensitive to different methods for calculating PET because of the calculations in the water balance model central to the scPDSI; particularly how potential and actual evapotranspiration (loss) affect the drought index. The impact of PET on a scaling parameter in the precipitation equation (equations 1 and 2 in Van der Schrier et al. 2011) is very modest, with variations in the scPDSI largely controlled by precipitation rather than PET (Guttman 1991). Where appropriate the Thornthwaite method can be substituted by the Penman-Monteith method. Here the scPDSI was calculated using the original Thornthwaite approach since the additional variables required by the Penman-Montheith method are not readily available over the length of drought record being reconstructed (Burt and Shahgedanova 1998).

Further common criticisms of the (sc)PDSI relate to the imprecise treatment of precipitation. All precipitation is assumed to be in liquid phase; as such snow is poorly considered, though southeast England receives <20 days of snowfall per year (1971–2000) (UK Meteorological Office 2013). Changes in available water holding capacity (AWC) when soils are frozen are not considered within the calculation of the index (Alley 1984). For these reasons Van der Schrier et al. (2006) and Briffa et al. (2009) restrict their analyses of European droughts to the summer season, which will be unaffected by these factors. Here we present whole year droughts, since southeast England is most vulnerable to long rainfall deficiencies, especially in the winter half-year, reducing groundwater replenishment, which makes a significant contribution to water supply in the region (Marsh et al. 2007).

The scPDSI was run with an AWC value of 250 mm based on regional average rural soils data (National Soil Resources Institute) and held as a constant through the model runs (Van der Schrier et al. 2006). Sensitivity testing (not shown here) of the scPDSI values for Kew between 1911 and 2011 using AWC values ranging 125–1,000 mm (agricultural soils to wetland), similar to the ranges of AWC quoted for UK sites in Briffa et al. (2009), show little difference in annual average scPDSI. Runs were performed on a monthly time-step, enabling both monthly and annually averaged index time series to be constructed for the three sites. The coarse annual resolution shows broad overall patterns of longer duration events, whereas the finer monthly resolution identifies shorter term seasonal variability. Individual droughts were identified from the monthly scPDSI time series by determining quantitative thresholds for onset and termination. Droughts are defined as beginning with index values of ≤−0.50 and ending when values are next ≥−0.49 following Palmer (1965). This robust structure to delimiting droughts underpinned determination of characteristics such as: minimum event severity and duration and enables analyses of two drought severities (severe and extreme), whilst objectively identifying meteorological drought events. Analysis of temporal patterns in the monthly scPDSI series was undertaken using wavelet analysis (Torrence and Compo 1998).

4 Analysis of scPDSI series

4.1 Annual variability of droughts

Both annual and monthly series for Kew, Oxford and Spalding contain a number of droughts including well-documented severe drought years of the twentieth and twenty-first centuries: 2006; 1990–1992; and 1975–1976 (Cole and Marsh 2006; Marsh et al. 2007), and also less well-documented droughts of the nineteenth and eighteenth centuries: 1870–1872; 1833–1836; 1801–1808; 1783–1791; 1759–1763; 1730–1734 and 1722–1726 (Fig. 1). The dry extremes in the scPDSI (negative values) series show several distinct drought-rich periods occurring during 1730–1760 and 1890 onwards, with an increasing tendency towards more severe droughts in this latter period. The drought years of 1803 (Oxford), 1834 and 1835 (Spalding) are not part of these drought-rich periods and are discrete events that lack regional coherence restricted to the individual site series (Table 1).

Using the categorisation of drought events established by Palmer (1965), the scPDSI threshold of ≤−3.0 can be applied here to objectively identify severe to extreme drought years from the scPDSI time series. The monthly scPDSI values for each site were averaged and the resultant annual values ranked according to severity (Table 1). The most severe drought year at Kew occurred in 1949 (scPDSI −4.99), at Oxford in 1991 (−5.11) and in Spalding in 1976 (−4.57). A broad regional coherence of severe drought years is demonstrated, with the majority occurring during the last century.

4.2 Temporal variability in drought time series

Annual and monthly scPDSI values show significant inter-annual variability in wet/dry conditions, with extreme negative scPDSI values in the mid-eighteenth, twentieth and twenty-first

Table 1 Ranked annual scPDSI values according to severity and individual drought events ranked according to minimum event severity for all sites and record lengths (Kew: 1697–2011, Oxford: 1767–2011 and Spalding: 1726–2011)

Rank	Kew (1697–2011)					Oxford (1767–2011)					Spalding (1726–2011)				
	Year	scPDSI (average)	Event	scPDSI (min)	Duration (months)	Year	scPDSI (average)	Event	scPDSI (min)	Duration (months)	Year	scPDSI (average)	Event	scPDSI (min)	Duration (months)
1	1949	−4.99	04/1943–10/1950	−5.9	91	1991	−5.11	07/1975–11/1978	−6.3	41	1976	−4.57	05/1970–11/1978	−6.0	103
2	1998	−4.70	05/1995–03/2000	−5.8	59	1976	−4.94	10/1988–07/1992	−6.1	46	1835	−4.52	10/1988–06/1992	−5.4	45
3	1997	−4.53	07/1972–08/1976	−5.3	50	1934	−4.51	06/1933–03/1935	−5.3	22	1991	−4.33	09/1833–08/1836	−5.1	36
4	1935	−4.31	12/1932–09/1939	−5.1	82	1990	−4.04	11/1897–02/1903	−4.5	64	1990	−3.97	04/2009–12/2011	−4.7	33
5	1922	−4.20	09/1919–09/1923	−4.7	49	1997	−3.96	04/1943–09/1949	−4.5	78	1750	−3.79	12/1730–04/1734	−4.7	41
6	1934	−4.19	10/1897–02/1903	−4.7	65	1944	−3.92	04/1801–03/1808	−4.5	84	1974	−3.76	08/2003–04/2007	−4.5	45
7	1902	−4.00	11/1722–04/1725	−4.4	30	1803	−3.68	04/2003–08/2006	−4.4	41	1949	−3.76	07/1947–10/1950	−4.4	40
8	1945	−3.97	11/1988–04/1992	−4.1	42	1902	−3.54	06/1995–08/1998	−4.4	39	2006	−3.66	09/1748–12/1750	−4.3	28
9	1901	−3.70	01/1714–05/1715	−4.1	17	1945	−3.38	08/1783–09/1791	−4.2	98	1834	−3.54	11/1920–06/1922	−4.3	20
10	1950	−3.61	11/1730–04/1734	−3.9	42	1965	−3.26	02/1921–01/1923	−4.1	24	1733	−3.40	07/1994–02/1998	−3.9	44
11	1974	−3.58	01/1743–08/1744	−3.6	20	1948	−3.13	07/1964–03/1966	−3.8	21	1996	−3.36	05/1961–08/1965	−3.7	52
12	1899	−3.51	11/1867–05/1875	−3.4	91	1989	−3.13	05/1928–09/1929	−3.7	17	2011	−3.30	12/1857–08/1859	−3.6	21
13	1944	−3.48	12/1849–05/1852	−3.4	30	1922	−3.05	05/2010–12/2011	−3.7	20	1732	−3.28	12/1873–05/1875	−3.6	18
14	1732	−3.48	05/1959–02/1964	−3.3	58	1946	−3.04	07/1780–02/1782	−3.6	20	1973	−3.04	07/1933–08/1935	−3.6	26
15	1991	−3.41	08/1759–01/1763	−3.2	42	1871	−3.01	08/1937–11/1938	−3.6	16	1948	−2.99	08/1738–03/1744	−3.5	68
16	1946	−3.35	12/1857–08/1859	−3.0	21	1992	−2.94	08/1972–07/1974	−3.6	24	1743	−2.91	10/1759–01/1763	−3.4	40
17	1733	−3.31	12/1863–09/1865	−2.8	22	1806	−2.75	04/1870–02/1872	−3.4	23	1997	−2.89	09/1867–11/1868	−3.4	15
18	1948	−3.24	04/2003–08/2006	−2.8	41	1807	−2.71	07/1983–04/1985	−3.2	22	1934	−2.84	02/1779–02/1782	−3.2	37
19	1990	−3.20	07/1780–02/1782	−2.8	20	1901	−2.66	04/1893–05/1894	−3.1	14	1874	−2.61	03/1943–07/1946	−3.2	41
20	1724	−3.18	12/1883–08/1885	−2.7	21	1938	−2.65	12/1889–07/1891	−3.1	20	1761	−2.59	08/1869–05/1871	−3.0	22

centuries (Fig. 1). The scPDSI series for the three sites shows marked changes in pattern with high amplitude variations between dry/wet conditions during 1730–1760 and 1890–2011 with more subdued higher frequency oscillations during 1770–1890; this is particularly clear for Kew, but also present at other stations. To explore the localised variations in monthly scPDSI time series they were the subject of wavelet analysis. Continuous Morlet wavelet transforms were calculated based on Torrence and Compo (1998) for the monthly scPDSI data derived for each site. Concentrations of power in the power spectrum of scPDSI values (highlighted contour areas on Fig. 2b) are identified during 1720–1760 (Kew and Spalding) and 1890–2011 (all stations) with a 6–10 year periodicity. There is an additional concentration of power evident in the Spalding series during the 1830s, which is not as strong in the records for Kew and Oxford. This 6–10 year cyclicity suggests a decadal to sub-decadal signal during the 1720–1760 and 1890–2011 periods, and to a lesser extent the 1830s; phases of strong periodic behaviour containing the most severe droughts, with an absence of this signal from 1760 to 1890 (Kew and Oxford). The sub-decadal periodicity (6 to 10 years) for each time series is confirmed by Fig. 2c, which shows only one significant peak exceeding the 95 % confidence level for the integrated global wavelet spectrum (dashed red line).

The scale average wavelet power (Fig. 2d) is used to examine fluctuations in power over certain periods, in this case the 6–10, 10–16, and 16–50 year periods. This gives a measure of the average sub-decadal, decadal and multi-decadal variance of the signal against time

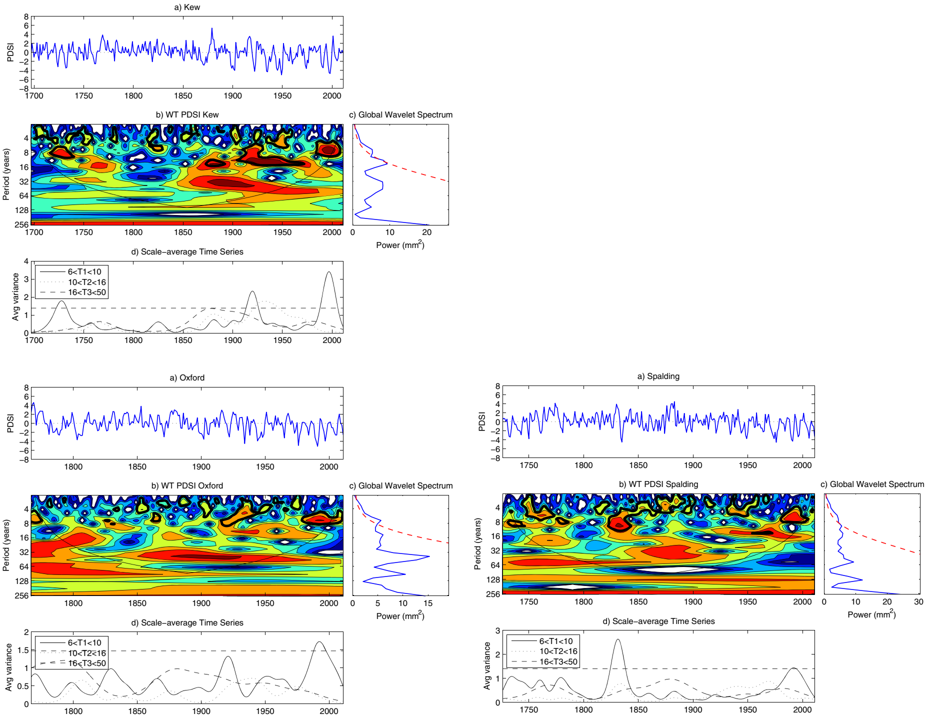

Fig. 2 **a** Annual scPDSI time series used for the wavelet analysis, **b** The wavelet power spectrum with thick contours showing the 95th confidence level and *black line* indicating the cone of influence where edge effects become important, **c** The global wavelet spectrum with *red dashed line* showing 95th confidence level, and **d** the scale-average time series showing variance during three periods with straight *dashed line* indicating the 95th confidence level

and can be used to examine the modulation of one periodicity by another within the same time series. Figure 2d (Kew) shows three distinct peaks for the 6–10 year period where variance was high and crosses the 95 % confidence level (straight dashed line): 1720–1740; 1910–1930 and 1980–2011. The peak during the late twentieth and early twenty-first centuries is evident and crosses the significance threshold for Oxford and Kew series. An additional peak during the 1830s for the 6–10 year period is present in the Spalding series. Fluctuations at the other periods (10–16 and 16–50) show low variance, with only one peak crossing the confidence threshold during 1930–1950 for the 10–16 year period at Kew. These data indicate that periods rich with severe droughts have a significant sub-decadal to decadal signal with a less significant multi-decadal signal. Therefore, when droughts become severe they are multi-year events that have a tendency to cluster in time creating drought-rich periods interspersed with drought-poor periods.

Droughts appear to be regionally coherent; appearing in at least two, or all, the scPDSI series; however, there are notable differences in the timing of onset and termination and therefore the duration of droughts, as well as differences in severity. For example, whilst the drought of the mid-1940s is identified in each of the three drought series: 1943–1950 (Kew); 1943–1949 (Oxford); and 1947–1950 (Spalding), both duration and severity differ between sites. There are also local, less regionally coherent severe to extreme droughts in individual scPDSI series e.g. 1801–1808 at Oxford and 1833–1836 at Spalding (Fig. 1 and Table 1).

To improve understanding of the causes, evolution and spatial variability of the severe droughts identified within drought-rich periods, drought structure (scPDSI series) alongside meteorological time series for two regionally coherent (1730–1734 and 1970–1978) and two spatially less coherent (1801–1808 and 1833–1836) severe droughts were examined. Rainfall departures from long term average, temperature and the scPDSI series were plotted for the 24 months preceding drought onset, for the duration, and for 6 months after drought termination for these four case studies (Fig. 3).

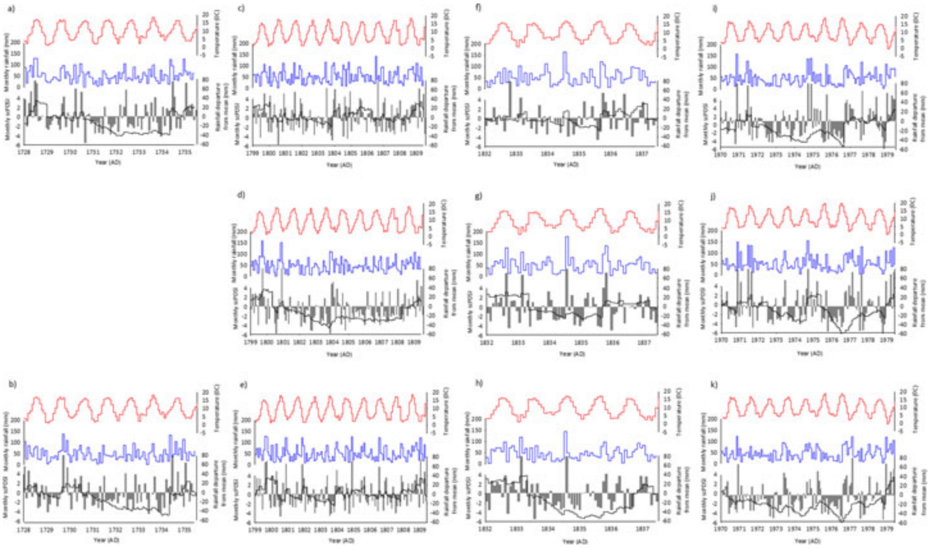

Fig. 3 Monthly rainfall (top left y-axis), temperature (top right y-axis), rainfall deficiencies from long term average (bottom right y-axis, record length for each site) and scPDSI time series (bottom left y-axis) during four key droughts: 1730 to 1734, **a**) Kew and **b**) Spalding; 1801–1808, **c**) Kew, **d**) Oxford and **e**) Spalding; 1834–1836, **f**) Kew, **g**) Oxford and **h**) Spalding; and 1970–1978, **i**) Kew, **j**) Oxford and **k**) Spalding

4.2.1 1730–1734

The overall structure of the 1730–34 drought (scPDSI) is similar, with only minor variations between sites. The drought began during November/December 1730 at Kew and Spalding respectively, with comparable rainfall deficits at both sites only interrupted by occasional months (<2 months) with above average rainfall across the seasons preceding drought onset (Fig. 3a, and b). The pattern of temperature variability follows the annual seasonal cycle with no obvious extremes. The drought ends in April 1734 at both Kew and Spalding, following several months of above average rainfall (>60 mm April, 1734).

4.2.2 1801–1808

The scPDSI series for 1799–1809 for Kew and Spalding present similar structures. The most severe drought conditions began in September/August 1802 at Kew and Spalding (Fig. 3c, d, and e), with small magnitude fluctuations between above average rainfall and deficit preceding drought onset. Rainfall deficits persist for the duration of the drought, with the event terminating in October 1803 at both sites. The onset of drought conditions at Oxford occurred in April 1801, with both high magnitude, above average rainfall and deficits spanning multiple months preceding drought onset. Sustained rainfall deficiencies over multiple seasons were experienced during the drought, punctuated by occasional months of above average rainfall. Temperature variability follows the annual seasonal cycle. Drought conditions terminate in March 1808 with several months of above average rainfall and smaller magnitude months of rainfall deficit (rainfall deficits: −60 mm in 1804).

4.2.3 1833–1836

The overall structure of the scPDSI series for 1832–1836 is much less comparable between the three sites than observed for the other case studies (Fig. 3f, g, and h). Drought conditions begin in October 1834, May 1833 and September 1833, at Kew, Oxford and Spalding, respectively. Above average rainfall and rainfall deficits spanning multiple months precede drought onset, with persistent rainfall deficiencies occurring during the drought at all sites (smallest magnitude at Kew). Temperature variability follows the annual cycle with no observable extremes. Drought conditions terminate in August 1836 at all sites, with consecutive months of above average rainfall at all sites.

4.2.4 1970–1978

The overall structure of the scPDSI series for 1970–1978 is comparable across sites, with minor variations between Kew and Oxford. Less variation between dry and wet conditions is evident in the Spalding series, indicating more persistent drought conditions throughout the 9 year period (Fig. 3i, j, and k). The onset of drought conditions occurs in May 1970 at Spalding, July 1972 at Kew and 1975 at Oxford. Fluctuations between wet and dry conditions were experienced prior to drought onset. Persistent rainfall deficiencies spanning multiple seasons occur throughout this drought, interrupted by short periods of above average rainfall. Above average rainfall months in the Kew and Oxford series which occur during winter 1974/75 are absent in the Spalding series, explaining the persistence of more severe drought conditions at this site. Drought conditions are terminated at all sites by successive months of above average rainfall (approximately 60 mm) commencing during winter 1978/79.

5 Discussion and conclusion

The scPDSI has been used to interrogate meteorological data from three sites distributed across southeast England to produce a continuous record of drought for AD 1697–2011 (315 years). This extends the temporal range of previous quantitative drought interpretations (Wigley and Atkinson 1977; Briffa et al. 2009) placing recent events in the longer historical context, using all seasons (summer only in Marsh et al. 2007) on monthly and annual bases. Previous quantitative drought reconstructions using meteorological data relied on single station data, whereas here they are derived from three sites, which is a significant extension to the existing 'benchmark' meteorological drought history for southeast England. The droughts identified (Table 1) are in broad agreement with those previously described (Wigley and Atkinson 1977; Jones et al. 1997; Fowler and Kilsby 2002; Marsh et al. 2007; Briffa et al. 2009), with additional severe events during the eighteenth century identified; 1722–1725, 1730–1734 and 1759–1763.

5.1 Temporal variability

The extended drought series show distinct periods, 1730–1760 and from 1890 onwards, where droughts exceeding a scPDSI threshold of ≤−3.0 occurred more frequently compared to other periods in the 315 year record. A wetter, drought-poor period occurs 1770–1890, comparable but longer than the 1770–1859 period described by Briffa et al. (2009); though several droughts are recorded at individual sites during this period, they lack the regional coherence identified in the drought-rich periods. The majority of severe droughts (Table 1) occur during the last century, indicating an increase towards more severe droughts previously identified in soil moisture deficits at Kew (1698–1976) (Wigley and Atkinson 1977). This increase in severe droughts is influenced by increasing temperatures since the early twentieth century; partly reflecting the sensitivity of the Thornthwaite (1948) method for calculating PET, a parameter in the scPDSI water balance model. Ranking of droughts by severity (Table 1) shows that the most severe are long-duration events spanning multiple seasons including multiple winters; for example, the most severe event on record for Kew starts April 1943 and lasts 91 months ending October 1950. The drought of the mid-1970s, often used as the benchmark against which subsequent droughts are compared, occurred between July 1972 and August 1976 at Kew. From a hydrological or agricultural perspective the negative impacts are perhaps much more easily perceived than the driving meteorological conditioning, with the drought of the mid-1970s often described as affecting spring 1975 and summer 1976 (for a full discussion see Rodda and Marsh 2011).

The longer duration droughts identified here compared to previous research (Marsh et al. 2007) in part reflects the thresholds for identifying drought onset, termination and therefore duration. High and consistent thresholds in the scPDSI were selected as a way of objectively identifying meteorological droughts, though a disconnection may exist with recorded hydrological droughts. Our aim was to examine meteorological conditions that give rise to severe-extreme droughts within the longer-overall drought periods depicted using this methodology. These severe-extreme droughts are often generated by an accumulation of moisture deficits over several months, exacerbated by an increasing temperature trend since the early twentieth century, which manifest within the environment as hydrological and agricultural impacts. This approach explicitly examines from a meteorological perspective, the relationship between the onset of drought conditions, development into severe-extreme droughts, and their termination and return to normal moisture conditions.

The scPDSI highlights how the duration and persistence of longer-term drought conditions over multiple years propagates through the hydrological cycle producing the most severe drought events, which can be identified in other drought classifications e.g. hydrological or agricultural. A challenge in future work will be calibration of the thresholds embedded in the scPDSI analysis presented here with other impact-focused series.

5.2 Regional variability

Droughts are well-documented as inherently regional phenomena, in contrast to other meteorologically-driven hazards e.g. floods, which often have more localised impacts. Using thresholds to discern onset and termination, comparison of drought duration and severity reveals that although they are mostly events with a degree of regional coherence (Table 1), variation in severity and duration between sites exists. Figure 3 illustrates that rainfall deficiency is the primary cause of droughts, rather than extremes of temperature, with the magnitude and duration of deficiencies controlling overall drought severity and duration. Where events lack regional coherence, 1801–1808 (Oxford) and 1834–1836 (Spalding), the rainfall series (Fig. 1) reveal an absence of rainfall not evident at the other sites. Thus localised variations in rainfall are important in determining the regional coherence of droughts; a finding consistent with observations made by Rahiz and New (2012) who note that intra-regional differences in the spatial coherence of droughts can be partly explained by spatial variability of precipitation.

5.3 Generating mechanisms

Prolonged rainfall deficiencies are the primary cause of severe droughts in southeast England (Fig. 3). The scPDSI uses rainfall and temperature as model inputs, highlighting the impact of temperature upon drought severity. Increases in air temperature since 1980 may have led to higher PET estimates in the PDSI water balance model, resulting in increased soil moisture deficit. During the drought-rich period of the mid-eighteenth century (1730–1760), high temperatures were observed during a period otherwise typified by cool and dry conditions (Jones and Briffa 2006). These higher temperatures may have led to increased rates of PET, intensifying drought conditions, causing them to become more severe and frequent during 1730–1760 and since 1890. This has important implications in the context of future climatic change; where a combination of higher temperatures and decreased summer precipitation (UKCP09) could lead to a higher probability of soil moisture deficit. However, Briffa et al. (2009) and Brazdil et al. (2008) have shown that, even if precipitation shows no changing trend, predicted higher temperatures will increase soil moisture deficit and drought severity.

Episodes considered as rich in severe droughts (≤ -3) have a significant sub-decadal to decadal signal; whereas, drought-poor periods do not. A concentration of power at 6–10 years suggests that large-scale atmospheric mechanisms causing modes of variability over this timescale may be driving these drought records alongside shorter-duration natural variability of the temperate oceanic NW European climate (Hurrell and Van Loon 1997). The North Atlantic Oscillation (NAO) is one prominent and recurrent pattern of atmospheric circulation that dictates climate variability over much of the northern hemisphere and is a possible driver of droughts in NW Europe (Vicente-Serrano and Cuadrat 2007; Hannaford et al. 2011; Parry et al. 2012). The annual drought series for Kew shows that several severe droughts coincide with phases of positive NAO; both in the winter, summer and over a longer periods, particularly during 1697–1760 and 1890–1992 (Fig. 4), but the relationship between drought and NAO appears non-stationary, as positive NAO phases, particularly in the nineteenth century, fail to relate to specific droughts. Since 1992 the relationship between NAO and droughts is less well

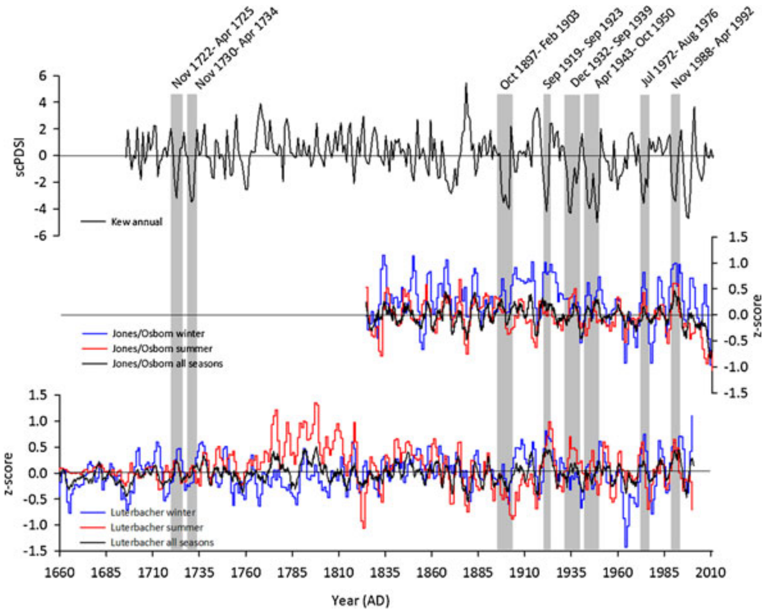

Fig. 4 Annual scPDSI series for Kew (1697–2011) compared with calculated seasonal time series of North Atlantic Oscillation using data from Luterbacher et al. (2002) and Jones et al. (2001) and Osborn (2012). NAO series were normalised over 1825–2000 common period and smoothed using a Savitky-Golay 11 year filter

defined and is perhaps a sign of a more unclear present and future. In terms of an association between scPDSI-defined droughts at Kew and NAO-related sea level pressure patterns linear regression projects fairly well onto the positive phase of the NAO in winter, but shows no clear relationship is shown for the summer season (Online resource Figure S4). Positive NAO is shown to be associated with warmer temperatures over northern and central Europe and colder over southern Europe in winter, with positive correlation of temperature and the NAO across southern England; though the relationship between positive NAO and rainfall is less clear in southeast England (Online resource Figure S5). As precipitation has previously been identified as the dominant driver in drought development, direct attribution of drought to NAO phases appears challenging (see Jones et al. 2001; Luterbacher et al. 2002 for discussion of uncertainties associated with the reconstructed NAO series).

6 Conclusions

Our analysis capitalises on the legacy of meteorological recording in the UK by constructing three long, continuous meteorological series (>245 years) for the analysis of droughts using the scPDSI for all seasons in southeast England. Previously documented events of the twentieth and twenty-first centuries, and new events in the eighteenth and nineteenth centuries are identified. The most severe events on record (1697–2011) occurred during: 1943–1950 (7.6 years) and 1970–1978 (8.6 years). Events with the greatest severity span multiple seasons, which pose considerable challenges when mitigating for future intensification of the hydrological cycle and associated changes in water supply and demand that may arise from predicted climate changes. Our identification of a 'build-up' period before many of the severest droughts (and their associated impacts) is significant, and should be incorporated into future drought management plans.

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