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Multi-year droughts in Europe: Analysis of development and causes

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Abstract

Whilst hydrological systems can show resilience to short-term streamflow deficiencies during within-year droughts, prolonged deficits during multi-year droughts are a significant threat to water resources security in Europe. This study uses a threshold-based objective classification of regional hydrological drought to qualitatively examine the characteristics, spatio-temporal evolution and synoptic climatic drivers of multi-year drought events in 1962-64, 1975-76 and 1995-97, on a European scale but with particular focus on the UK. Whilst all three events are multi-year, pan-European phenomena, their development and causes are contrasting. The critical factor in explaining the unprecedented severity of the 1975-76 event is the consecutive occurrence of winter and summer drought. In contrast, 1962-64 was a succession of dry winters, mitigated by quiescent summers, whilst 1995-97 lacked spatial coherence and was interrupted by wet interludes. Synoptic climatic conditions vary within and between multi-year droughts, suggesting that regional factors modulate the climate signal in streamflow drought occurrence. Despite being underpinned by qualitatively similar climatic conditions and commonalities in evolution and characteristics, each of the three droughts has a unique spatio-temporal signature. An improved understanding of the spatio-temporal evolution and characteristics of multi-year droughts has much to contribute to monitoring and forecasting capability, and to improved mitigation strategies.

Keywords

Drought; drought catalogue; Regional Deficiency Index; spatial coherence; spatio-temporal evolution; Standardised Precipitation Index.

Introduction

Drought is a complex phenomenon that varies in its expression, both spatially and temporally, and its wide range of impacts. Drought events refer to the limited availability of water, although the most notorious episodes are also associated with high temperatures during prolonged heatwaves. The environmental consequences of terrestrial water shortages during droughts include: the contraction of the river network and associated loss of aquatic habitat and subsequent fish kills; forest and heathland fires as a consequence of reduced soil moisture; and water quality issues since there is less flow for dilution. Socio-economic impacts of drought can include damage to forestry and agriculture by wildfires and restricted use of irrigation.

In recent years, the hydrological extreme that has most commonly impacted the UK has been flooding, with significant events in 2007, 2008 and 2009. As a result, the vulnerability to drought in the UK has perhaps diminished from public perception, and it has taken arid phases in 2010 and 2011 to awaken the media and the public to the risk posed by major drought, as was witnessed to a significant extent by droughts in 2003 (Fink *et al*. 2004, Marsh 2004) and 2004-06 (EC 2006, Marsh *et al*. 2007, Demuth 2009).

In the UK, the second half of the 20th century witnessed a number of significant and widespread drought events, including those in 1962-64, 1975-76, 1988-92 and 1995-97 (Marsh *et al.* 2007*)*. Droughts tend to evolve slowly and affect large areas simultaneously. Therefore, in examining the development of droughts in the UK, there is significant merit in also considering the expression of drought elsewhere in Europe.

Research has been conducted on UK regional drought, but such studies have rarely examined drought in a wider European context. Burke and Brown (2010) present regional indicators of drought deficit and drought area for nine spatially coherent precipitation regions, but the varying regional patterns are considered only with respect to the ability of the climate model in reproducing event characteristics. Fleig *et al*. (2010) use a regional index to identify droughts, before discussing the variations between regions in the context of weather types, although the study is limited in its scope across Europe, only considering six regions in the UK and Denmark. Fowler and Kilsby (2002) also investigate the potential of a weather-type approach in regional drought research, but the focus of the study was predominantly on the use of weather typing in facilitating estimation of return periods.

Previous authors have examined spatio-temporal evolution of droughts. Zaidman *et al*. (2002) investigate the contrasting evolution of the 1975-76 and 1989-90 droughts. Van der Schrier *et al*. (2006) focus on meteorological drought and on summer drought only, but for water resources applications particularly it is necessary to investigate the occurrence of drought in all seasons. Precipitation deficiencies in winter are often as serious as heatwave-dominated summer droughts, if not more so, in many regions of Europe, as the winter season is an important time for the replenishment of soil moisture and groundwater stores and reservoirs (van Loon *et al*. 2010). Furthermore, in high-latitude or alpine areas, river flow deficiencies may be caused by increased storage in ice and snow following the winter accumulation period.

However, there are still major gaps in our understanding of the spatio-temporal dynamics and causative factors of historical droughts in Europe and, from the perspective of the UK, of the extent to which droughts in the UK are linked with those on the continent. The significant spatial and seasonal variability in both climate and river flow regime throughout Europe further complicates direct comparison of flow magnitude. To allow for this variability, a methodology which defines flow regimes relative to a particular location and a specific time within the annual hydrological cycle is most appropriate. Such an approach facilitates the intercomparison of major drought events across temporal and spatial scales. The Regional Deficiency Index (RDI) (Stahl and Demuth 2001) has been used previously to provide an objective definition of drought for the production of a drought catalogue, which underpinned an analysis of the spatial coherence of European droughts (Hannaford *et al*. 2011). Whilst some droughts were found to be spatially coherent, with some relationships developed which could potentially improve drought forecasting, the spatio-temporal evolution of droughts was not considered.

This paper contains qualitative evaluations of the drought catalogues, as a companion to the quantitative analyses in Hannaford *et al*. (2011). A qualitative investigation is particularly important for highlighting commonalities between the spatio-temporal development of different pan-European droughts of the last 50 years and may help identify causative mechanisms and refine the creation of drought forecasting tools.

After explaining the data and methodology used, the approach used to select the droughts analysed in this study is outlined. The section that follows summarises the spatio-temporal evolution of three droughts, before exploring some potential explanatory factors such as temperature and pressure anomalies and synoptic climatic conditions. A discussion section compares and contrasts the three droughts in terms of their development and underlying causes, before conclusions are drawn.

Data

To characterise hydrological drought, daily river flow data from 579 gauging stations spanning 11 European countries from the European Water Archive (EWA) are used, covering the period 1961-2005; the core of the dataset was collated and updated by Stahl *et al*. (2010). This was supplemented by additional stations sourced from Banque Hydro (France) and the

National River Flow Archive (NRFA) (UK). The dataset comprises catchments with minimal artificial influences, considered to be ‘near-natural’, and the associated gauging stations have good hydrometric performance. The distribution of the selected gauging stations across the continent is highly variable (Fig. 1), owing predominantly to the necessity for minimally influenced catchments.

For meteorological drought definition, 0.5° × 0.5° gridded monthly precipitation data (TS3.0) from the Climate Research Unit (CRU) (Mitchell and Jones 2005) are used. The resolution was considered appropriate for comparison with regional streamflow drought, although the methodology described below is suitably flexible that it could be applied to other, higher-resolution datasets in future research.

Methodology

The drought catalogues and the subsequent analyses presented here use a parallel classification of hydrological and meteorological drought indices. Hydrological drought was measured using the RDI (Stahl and Demuth 2001) as a method for characterising drought within homogeneous regions. Daily river flow time series were converted into binary series based on whether the flow falls below a daily-varying threshold; ‘1’ if the flow is below the threshold, and ‘0’ otherwise. The Q90 threshold was chosen, which represents the flow that is exceeded 90 per cent of the time. The homogeneous regions (Fig. 1) were then produced through a cluster analysis on these binary time series, grouping catchments with similar drought occurrence. The regions used in this paper were originally derived by Stahl and Demuth (2001), and have been subsequently modified by Prudhomme and Sauquet (2006) and Hannaford *et al*. (2011). Further details of the clustering procedure are given in Hannaford *et al*. (2011). Finally, the arithmetic mean of the binary deficit indices within each homogeneous region was taken, producing a daily time series of values between 0 and 1 reflecting the measure of spatial coherence, and by proxy the severity, of drought on a regional basis.

Meteorological drought was expressed through the Regional Standardised Precipitation Index (RSPI), a modification of the Standardised Precipitation Index (SPI) (McKee *et al*. 1993). The RSPI facilitates comparison of meteorological drought occurrence across the spectrum of rainfall regimes, and was derived by calculating the proportion of cells that are 'in drought' (SPI < -1, moderate drought or worse) within the homogeneous regions.

It should be noted that although the RDI is a daily index of drought occurrence, it has been aggregated to the monthly time step to facilitate intercomparison with the monthly RSPI. Further information on the methodologies employed can be found in Hannaford *et al*. (2011).

A number of approaches have been utilised in analysing the droughts presented in this paper. Qualitative narratives of spatio-temporal development were summarised from drought matrices and monthly evolution maps. The drought matrices display monthly-averaged RDI values for all 24 European regions. These matrices help to summarise a vast amount of information into a succinct table for each episode, providing an overview of the spatio-temporal evolution of the major drought events. A number of monthly maps of RDI and RSPI have been selected for each of the events that best represent the defining spatio-temporal characteristics of the episode. The parallel presentation of both the RSPI and RDI allows for analysis of potential time lags between the relative onset of meteorological and hydrological drought. The RSPI evolution maps represent the RSPI-3 values, which are the regional average SPI for three-month accumulations.

Qualitative patterns in pressure and temperature anomalies prior to and during drought events were considered in assessing possible drivers for spatially coherent episodes on a European scale. Extreme temperature anomalies, influenced by the synoptic climatic conditions and associated pressure anomalies, can have the effect of reducing the amount of precipitation which enters the hydrological network through enhanced evaporation (although such anomalies can also be associated with convective activity) or through frozen storage.

Selection of major drought events

There are a number of distinct ‘drought rich’ and ‘drought poor’ periods on a European scale; 1962-64, 1975-76, 1988-92, 1995-97 and 2003 were identified by Hannaford *et al*. (2011) as major, spatially coherent pan-European droughts. Since these droughts have been identified as the most important events on a continental scale, they warrant further research on their causes and evolution. Although the 1962-64 and the 1995-97 episodes were not the most severe hydrological droughts witnessed in the last 50 years, they are two events with complex spatio-temporal evolution on which there has been comparatively little focus in the drought literature. The 1975-76 event, on the other hand, has been extensively studied and is widely regarded as the most severe drought on record in Europe. The 1975-76 drought provides a useful benchmark against which to compare the lesser studied episodes, to elucidate potential differences in explaining their varying extents and outcomes. All three of these events are identified as major hydrological droughts in England and Wales by Marsh *et al*. (2007), and correspond to major UK regional meteorological droughts identified by Burke and Brown (2010).

Spatio-temporal evolution

The 1962-64 drought

The 1962-64 drought can be characterised as a succession of winter droughts across Europe punctuated by dry summers on the continent, although not in the UK (Fig. 2). Streamflow drought developed gradually beginning in summer 1962 across France and Alpine Europe, increasing in severity through the autumn and extending across central Europe. Deficits further intensified throughout winter 1962/63 affecting the majority of central Europe and encompassing parts of northern Europe and Scandinavia, peaking in severity in January and February during which month Germany experienced RSPI values up to 1.0 and RDI values in excess of 0.9 (Fig. 3f). In the UK and Europe, the winter of 1962/63 was extremely cold, with frozen catchments generating historically low winter runoff rates, particularly in northern areas of the UK.

A second successive winter drought followed in 1963/64 across western and central Europe (Fig. 2), with Germany once again witnessing some of the most spatially coherent within-region deficits. In the UK, the worst of the winter deficits were confined to southwest areas, and although the drought was less spatially coherent than the previous winter throughout the British Isles, it was longer. Akin to the winter 1962/63 phase, drought conditions in winter 1963/64 also receded rapidly in the spring, on this occasion into northern Germany and Scandinavia. The abrupt termination of winter droughts in both 1962/63 and 1963/64 can be attributed to a switch from continental to maritime influence in early March in both years in the UK. However, European streamflow deficiencies did not abate for long; a moderately spatially coherent late summer drought affected France, Germany and Alpine areas in 1964 (Fig. 3n), although this was not persistent through the autumn. Although the winter of 1964/65 was relatively dry, deficits were not coherent; a third consecutive winter drought predominantly affected the UK, developing during the autumn in eastern regions and intensifying toward winter 1964/65. Despite experiencing winter drought in three successive years, a challenging scenario for water resource managers, the wet springs which followed in each year ensured that the 1962-64 drought had limited hydrological expression in the UK (Cole and Marsh 2006). Nevertheless, the winters of 1963/64 and 1962/63 rank as the first and second driest on record, respectively, since 1914 for England and Wales.

The 1975-76 drought

Although comparatively short in duration relative to the other major droughts featured in this paper, the 1975-76 drought is widely acknowledged as the benchmark drought of the last 50 years in the UK – with no other historical drought matching the degree of spatial coherence, geographic extent or hydrological intensity exhibited in 1975-76 (Marsh *et al.* 2007) – and many regions of Europe. Streamflow minima established during summer 1976 remain the lowest flows on record for more than half of the UK gauging stations held on the NRFA (Marsh *et al*. 2007).

The 1975-76 drought commenced in May 1975 and terminated in late autumn 1976, with the hydrological drought lagging behind rainfall deficiencies over this 16-month period. The event initially developed slowly throughout the winter of 1975/76 as a winter drought in the UK, before extending throughout the continent into a summer drought (Fig. 4). This successive occurrence of both winter and summer droughts in 1975-76 caused severe depletion of surface and groundwater resources.

The winter drought underpinning the 1975-76 episode predominantly affected the UK, particularly the vulnerable southeast, and to a lesser extent southern Scandinavia (Fig. 5d), with increasing spatial coherence in most regions throughout winter. In the UK, the winter drought initially affected western regions from October-December 1975, before extending east where the focus would remain until the whole of the UK experienced severe drought in summer 1976. By January 1976, the most serious deficiencies were affecting the southeast regions of the UK; the lag in drought occurrence in these regions can be explained by the greater groundwater component within the southeast regions providing resilience to short-term precipitation deficits. Such groundwater storage was particularly influential during the development of the 1975-76 drought, since this resilience was increased by high groundwater levels in spring 1975. However, groundwater-dominated catchments are more vulnerable to longer duration rainfall deficiencies, a situation that was borne out as winter turned to spring.

Whilst the UK continued to be impacted by drought conditions into spring 1976, mainland Europe also became affected to a similar extent. In France and western Germany, streamflow deficits increased rapidly, peaking at highly coherent RSPI values of up to 1.0 and RDI values of up to 0.9 in both May and June (Fig. 4), some of the highest values in the 1961-2005 time series for these regions, signifying the high spatial coherence of streamflow drought. In France, RDI values actually declined slowly through the remainder of the summer, although persistence was the most significant characteristic, with RDI values above 0.6 (Fig. 4) driven by RSPI values of 1.0 until November for northern regions. However, in general throughout Europe, heatwave conditions in summer only served to exacerbate streamflow deficiencies and increase demand for water. As resources dwindled, measures to reduce water demand were introduced in the UK; 136 Drought Orders were imposed, and rationing and standpipes were introduced (Cole and Marsh 2006). RDI values peaked in July and August 1976 in most regions (only peripheral European regions were not impacted by the 1975-76 drought); 14 of the 24 European regions had RDI values greater than 0.5 in July 1976 (Fig. 4), with the groundwater-dominated southeast UK region peaking at an RDI value of 0.95, reflecting drought conditions over almost the entire area. In August 1976, 11 of the 24 European regions had RSPI values of 1.0, almost half of the regions experiencing severe and coherent meteorological drought in all of their grid cells. In addition to the severity of the 1975-76 event, the durations over which deficit conditions were experienced were particularly notable. Although the UK was perhaps most severely affected by the 1975-76 drought and for the longest duration, the episode also had profound impacts for mainland Europe, particularly northern and western areas. The river network diminished in extent across much of Europe with the associated loss of aquatic habitat, and there are many examples in the literature of environmental impacts and water quality problems, e.g. Davies 1978 and Doornkamp *et al*. 1980. Drought occurrence in German regions lagged slightly behind that of UK and French regions; although July and August 1976 were once again the most coherent months of drought, Germany experienced drought conditions into the late autumn and early winter, in contrast to the abrupt cessation of deficits in the UK and France following September 1976.

The 1995-97 drought

Whilst the majority of deficiencies during the 1995-97 drought were of limited spatial expression and coherence on a regional basis, there were some periods of severe continental-scale drought (Fig. 6). The hydrological drought lagged behind the meteorological drought, which developed in western Europe during early/mid 1995, although streamflow deficiencies did not appear until the late summer and were restricted to the UK, with most regions registering coherent drought (RSPI up to 1,0; RDI > 0.7) in August 1995 and little concurrent response on the continent (Fig. 7b). The lack of spatial coherence on a European scale can be attributed to the relatively localised impact of heatwave-dominated drought over the UK. The short-duration summer phase in 1995 had important adverse effects on those areas of the UK dependent on surface water resources, such as the South West, North West, Yorkshire and Midlands regions. The use of mitigation measures was widespread in these locations, with 53 drought orders imposed and hosepipe bans common (Cole and Marsh 2006).

A relatively coherent phase of the drought, characterised by modest streamflow deficits (RDI = 0.5-0.6) expanded through Denmark, northern Germany and northern France during winter 1995/96, culminating in moderate spatial coherence across much of north-central Europe in April 1996 (Fig. 6). This phase of the 1995-97 drought weakened through central Europe into the summer and the remainder of 1996 can be characterised by the prevalence of a comparatively wet interlude, although September saw some abrupt and shortlived deficiencies in Scandinavia and the UK (Fig. 7j), the latter of which had witnessed gradual drought development from eastern regions throughout the summer. Whilst the winter of 1996/97 was dry, only January 1997 was affected by moderately coherent drought, and only then in the UK and Scandinavia once more (Fig. 7l). Following a brief cessation in February and March, a spatially-extensive drought phase emerged in April with RSPI > 0.8 and RDI > 0.5 across Spain, France and parts of the UK (Fig. 7n), although this began to diminish and weaken into central Europe through spring. The remainder of 1997 is characterised by spatially-extensive drought but which lacked regional coherence (RDI values generally < 0.5); deficits were diffuse and highly variable in their distribution, although in the UK drought conditions persisted throughout 1997. High RDI values remained during summer and autumn in the southeast regions, with the deficiencies in groundwater-dominated catchments again exhibiting greater persistence (Fig. 6). There was a significant regional component to the event in the UK, to some degree dependent on the existence of aquifer systems. Responsive areas in the northwest of the UK experienced low reservoir levels in autumn 1995, whilst the English lowlands exhibited severe hydrological drought in 1997 when groundwater levels had been sufficiently depressed by precipitation deficits throughout the 1995-97 period.

The 1995-97 drought had many severe environmental and socio-economic impacts in the UK. Ecologically significant fish kills, such as 20,000 in the River Trent, and agricultural losses were among the myriad of environmental impacts (Cole and Marsh 2006), the latter amounting to £180 million, with concurrent losses in the retail sector of £380 million and the cost of additional provision of water totalling £96 million (Palutikof *et al*. 1997).

Explaining drought characteristics and evolution

Pressure and temperature anomalies

The 1975-76 drought can be distinguished from the 1962-64 and 1995-97 events by the relative simplicity of climatic conditions underpinning its onset and spatio-temporal evolution. Whereas the three-year episodes were underlain by variable pressure and temperature anomalies, mirrored correspondingly in their complex expression of streamflow drought, the 1975-76 drought is easier to characterise in that it resulted from a succession of stationary high pressure centres. Their predominant development over the North Sea meant northern and western regions of Europe were most seriously affected by the drought, although the resulting outflow of air from notable high pressure anomalies in August 1975, October 1975, February / March 1976 (Fig. 8c) and particularly August 1976 (Fig. 8d) suppressed precipitation across large swathes of Europe. Anticyclonic conditions over northern Europe were responsible for widespread heatwave conditions in summer 1976, with the UK, northern France and the Netherlands experiencing exceptionally warm temperatures (Fig. 9d). Higher temperatures would have increased evaporative demand and subsequently soil moisture deficits, intensifying streamflow drought. However, the pan-European average temperature for the 1975-76 drought was in line with the long-term average, as prevailing anticyclonic conditions brought reduced temperatures to the continent in winter 1975/76 (Fig. 9c), and to eastern Europe even in summer 1976. Nevertheless, whilst temperature anomalies may have offset between winter and summer, the most notable characteristic of both seasons (as well as spring) was persistent high pressure suppressing precipitation over an extended period.

The multi-year droughts of 1962-64 and 1995-97 exhibit much more complex patterns of anomalies than those of the multi-season 1975-76 event. The 1962-64 episode began with significant rainfall deficiencies during one of the coldest and driest winters in the 1961-2005 period, and which was caused by blocking highs (Fig. 8a) that brought exceptionally low temperatures (Fig. 9a). Anticyclonic conditions over the northern Atlantic Ocean predominated for the next two years (Fig. 8b), although hydrological drought would have been more severe had it not been for the periodic influence of rain-bearing circulation systems. This alternation between extremes of pressure over 1962-64 is reflected in the fragmentary nature of spatially coherent drought. The dominant high pressure centre moved eastward over Europe towards the end of the drought (Fig. 9b), perhaps responsible for the summer drought of 1964 occurring in central and eastern Europe whilst the UK and Scandinavia were unaffected.

The 1995-97 drought was initiated by a high pressure centre which caused severe summer drought in parts of the UK (Fig. 8e). Summer 1995 registered as the third warmest on record (Fig. 9e), and the driest since the unprecedented 1975-76 drought. The resilience of surface water resources was further tested by the winter drought of 1995/96, caused by anticyclonic conditions over Scandinavia forcing cold air across Europe (Fig. 8f) and bringing negative temperature anomalies (Fig. 9f). As was the case in 1962-64, Europe experienced consecutive winter droughts as high pressure developed over the North Sea in winter 1996/97, synoptic conditions which are akin to those that underpinned the 1975/76 drought. The complex and variable migration of the high pressure systems inhibited the development of spatially coherent deficit conditions in both 1962-64 and 1995-97.

Synoptic climatic conditions

The relationships between the RDI and large-scale atmospheric circulation indices were investigated in Hannaford *et al*. (2011), in order to potentially explain the large-scale spatial coherence of major droughts in Europe. It was found that there are no significant correlations between the RDI and the eleven climatic indices considered, although the North Atlantic Oscillation (NAO) and the East Atlantic / West Russia (EA/WR) Pattern were found to show similarities with the most significant groupings resulting from a principal component analysis of regional streamflow drought (Hannaford *et al*. 2011). These findings perhaps suggest that the NAO and the EA/WR Pattern show most potential in explaining the spatio-temporal evolution and characteristics of large-scale drought in Europe, so the patterns of these teleconnections prior to and during the drought events are presented in Fig. 10 and discussed below.

North Atlantic Oscillation

The signal of the NAO is important in determining the track of storm systems crossing the Atlantic, in turn controlling precipitation patterns particularly for maritime western Europe which is predominantly influenced by prevailing westerly winds. The NAO is strongest in the winter season and therefore can play a significant role in the generation of streamflow deficiencies, since winter drought is perhaps the most important cause of prolonged multi-year droughts (van Loon *et al*. 2010). Hannaford *et al.* (2011) found the NAO to influence winter drought in a dipole-like manner, with negative correlation in northern Europe and positive correlation in the south. This reflects the fact that a negative phase of the NAO occurs when anticyclonic conditions are dominant over Iceland and low pressure exists over the Azores. In this case, the track of rain-bearing Atlantic storms is diverted south into the Mediterranean, suppressing precipitation totals in northern and western regions of Europe. The 1962-64 drought is a good example of an event which was significantly influenced by the NAO, in which a sustained two-year negative phase (Fig. 10a) prevented Atlantic storms from depositing significant precipitation across northern Europe.

Given the influence of winter precipitation deficits in the 1975-76 drought, it is surprising that the synoptic climatic conditions underpinning the episode do not suggest a significant role for the NAO in accounting for its unprecedented severity. Late 1975 and early

1976 are characterised by neutral NAO values, after which a moderately positive phase emerged spanning the remainder of 1976 (Fig. 10c).

In contrast, the 1995-97 drought exhibited a third type of behaviour of the NAO leading to sustained streamflow deficiencies. At the beginning of 1996, an abrupt switch in the NAO occurred from positive to negative (Fig. 10e), a reversal which is likely to have influenced winter deficit conditions in regions of northern Europe. This is a strong indication that the 1995-97 drought was an amalgamation of at least two smaller events.

East Atlantic / West Russia pattern

The EA/WR Pattern contains four circulation centres across Eurasia in the mid-latitudes, the most important of which for European drought development are the low pressure cell over the central North Atlantic and the anticyclonic cell over central Europe. An intensified high pressure cell over central Europe has the effect of suppressing precipitation in these regions. A positive EA/WR Pattern was found to correlate with high RDI across much of central and western Europe in the winter half-year (Hannaford *et al*. 2011).

Of the three droughts covered in this paper, the 1975-76 event featured the most significant departures from neutral values of the EA/WR Pattern. However, these departures could only be described as moderate, although the EA/WR Pattern remained in a positive phase throughout the episode (Fig. 10d). Positive phases of the EA/WR Pattern are associated with increased pressure anomalies across northwest Europe, conditions which were prevalent during the 1975-76 drought.

Conversely, the 1962-64 drought featured a consistent slightly negative phase of the EA/WR Pattern (Fig. 10b), the opposite of which would have been expected for a multi-year period of streamflow deficiency. The negative signal would have had the effect of reducing the severity of winter precipitation deficits, hindering the potential development of severe water resource drought over this multi-year event. It is possible that the EA/WR signal inhibited the development of the drought, since the 1962-64 event was not spatially coherent. Nevertheless, the 1962-64 drought can be characterised as a succession of two or three consecutive dry winters; had the EA/WR Pattern been in a positive phase, streamflow deficiencies may have been considerably worse and the episode more severe as a result.

The 1995-97 drought also developed in a predominantly negative phase of the EA/WR Pattern, although there is some evidence for a switch in the signal (Fig. 10f), albeit less apparent than that which occurred for the NAO.

Discussion

The complex variations in the onset, development and termination of multi-year drought episodes in Europe have been demonstrated through the presentation of three contrasting multi-year droughts. Despite their longer duration, the 1962-64 and 1995-97 droughts did not herald deficiencies as severe as those witnessed in 1975-76. The 1962-64 drought can be predominantly characterised as a fairly straightforward succession of dry winters, which were generally coherent across the UK and Europe, although the winter deficits varied in severity. Conversely, the 1995-97 drought was a more complex amalgam of both summer and winter periods of deficiency, which varied spatially and in terms of their extent, duration and spatial coherence. In the UK, this variability was not only the result of different synoptic climatic conditions, but also regional heterogeneity in catchment characteristics, with groundwater storage in particular influencing the onset and development of streamflow drought occurrence.

It would appear that the relative distribution of summer droughts and winter droughts within a multi-year episode is the most important factor in determining severity of drought events. The 1975-76 drought featured a sustained winter drought through the winter of 1975/76 followed by an intense heatwave-dominated summer drought in summer 1976. The role that winter droughts play in initiating severe drought episodes is to ‘prime’ regions and catchments for significant streamflow deficiencies by restricting the replenishment of surface, soil moisture and groundwater reservoirs, impacting the hydrological regime of the following year. Once catchments and regions are primed, the occurrence of a heatwave-dominated summer phase will cause severe streamflow drought to occur. However, the 1962-64 drought is an example of successive winter droughts which primed catchments and regions for severe drought, but in each spring a shift toward maritime influences mitigated further drought development. Consecutive winter and summer droughts have not occurred in the UK to the same extent as for 1975-76 at any other time throughout the period of analysis (or, other work has suggested, in the entire England and Wales rainfall series from 1766; Marsh *et al*. 2007), suggesting that it is this sequence which is responsible for the unprecedented severity of the 1975-76 drought.

In comparing and contrasting the three droughts analysed in this paper, it is apparent that there are characteristics and developmental stages that are common to many droughts. For example, although not always the case, there appears to be a tendency for drought conditions to progress from west to east across Europe (e.g. 1962-63, 1975-76), with the UK experiencing deficit conditions prior to their onset in mainland Europe. This is potentially explained by the predominant westerly direction from which the UK and Europe receive weather systems. However, there are as many instances when there is little evidence for spatial coherence in drought response. Deficits can occur in the UK with no corresponding expression on mainland Europe (e.g. summer 1995; Fig. 6), and *vice versa* (e.g. summer 1964; Fig. 2). Similarly, the extent to which the UK and Europe are ‘in-phase’ or ‘out-of-phase’ within multi-year droughts (such as those investigated in this paper) also varies throughout the course of the episode and between events. As such, each major drought episode has its own unique spatio-temporal signature, despite being driven by qualitatively similar conditions. The uniqueness of large-scale droughts was also reported by

Lloyd-Hughes (in press) who, using the SPI within a new three-dimensional framework for analysing spatio-temporal development of meteorological droughts, found that all drought episodes which occurred in the much longer 1901 and 2006 period are significantly dissimilar to each other, even when comparing the most similar events.

When considering the climatic conditions driving the pressure and temperature anomalies which underpin drought occurrence, similar conclusions on the uniqueness of events can be drawn. Precipitation deficits are predominantly associated with stable and persistent anticyclonic conditions occurring over the affected region; these dominant high pressure centres have the effect of 'blocking' frontal precipitation (e.g. 1975-76) and whilst they persist rainfall totals will be significantly reduced. However, the exact location of the high pressure centre varies both between and within drought events, suggesting each episode has a set of driving synoptic climatic conditions with a distinct spatio-temporal signature, partly responsible for the unique streamflow drought response. In addition to the absence of a common set of forcing conditions, the development of similar synoptic climatic conditions may not result in an identical expression of hydrological drought or even meteorological drought. Local conditions, such as catchment characteristics, groundwater influence, and storage in snow or ice packs, may complicate the relationship between synoptic conditions and drought response. The existence of complex land-surface feedbacks may also propagate and exacerbate drought conditions (e.g. Pal and Eltahir 2003; Schar *et al*. 1999) demonstrating the significance of antecedent soil moisture conditions for rainfall occurrence, or lack thereof. Lloyd-Hughes *et al*. (submitted) have shown that it is possible to use soil moisture to underpin predictions on the likelihood of drought continuing once it has been initiated; drought is 50% more likely to continue under deficient soil moisture conditions.

The influence of the NAO and the EA/WR Pattern on drought occurrence and spatio-temporal evolution has been investigated for the 1962-64, 1975-76 and 1995-97 droughts.

Whilst negative phases of the NAO can be associated with winter deficiencies in particular, it is not the overriding explanatory factor for drought onset and development. The links between the NAO and European drought are well documented in the literature (e.g. Lopez-Moreno and Vicente-Serrano 2008), but it is clear that there are more factors involved than simply the NAO. Associations between the EA/WR Pattern and streamflow deficiencies are perhaps more complex than those which have been found for the NAO and, moreover, the interaction between the two patterns would undoubtedly be influential. This has not been explored in this paper but remains an avenue for further work. In addition, other work has shown that potential relationships between weather types and streamflow drought are modulated by catchment characteristics (Fleig *et al*. 2010), and it may be expected that the relationship between larger-scale modes of variability and river flow deficiencies would be similarly confounded by catchment properties, as found for the NAO and seasonal river flows by Laizé and Hannah (2010).

Descriptions of drought development are clearly dependant on data availability. Owing to the prevalence of relatively short river flow time series on digital archives across Europe, with reliable information restricted to the period since 1960, only a few large-scale droughts can be studied in terms of their pan-European spatio-temporal development, which perhaps limits the extent to which common patterns can be detected across events. Furthermore, the lack of any data from south-eastern Europe is undoubtedly an obstacle to how well these large-scale events are captured, and may confound the analysis of drought indices related to large-scale teleconnections. However, the lack of data in north-western Europe, and in particular in the Benelux countres, is probably less important as the spatial coverage in northern and western Europe is relatively good.

There are a number of different avenues of future research that are currently being pursued, expanding upon the work presented here. The RDI has been applied to gridded runoff data produced by global hydrological models and land surface schemes, in order to assess the performance of these models in reproducing hydrological extremes in the historical record through comparison with observed drought catalogues. In such analyses, it appears that models reproduce drought duration and spatial coherence reasonably well (Prudhomme *et al*. in press). Once the reproducibility of historical hydrological droughts has been verified, an advantage of using modelled runoff data is that it can be used to explore drought characteristics in the early 20th century (as climate forcing data is generally available for much longer periods than the streamflow records used herein). This would potentially increase the sample size of large-scale droughts for a more rigorous analysis. Modelled runoff could also be used to infer drought characteristics in parts of Europe which are not currently represented in the streamflow dataset. Further work will aim to project potentially changing drought characteristics and spatio-temporal evolution under 21st century climate change scenarios. Most future projections for Europe are for meteorological drought (e.g. Blenkinsop and Fowler 2007), so an assessment of future changes in the spatio-temporal characteristics of hydrological drought would be highly beneficial for water managers in Europe.

Conclusion

In summary, the RDI methodology has been shown to be useful in elucidating commonalities and differences between the three major droughts presented in this paper. The 1962-64, 1975-76 and 1995-97 droughts each have unique spatio-temporal signatures, despite being underpinned by qualitatively similar synoptic climatic conditions; this is due to a combination of antecedent soil moisture conditions, catchment characteristics, and the occurrence of sequences of winter and summer drought phases, amongst others. The factor which appears to differentiate the 1975-76 drought from the other two multi-year events presented here is the occurrence of a heatwave-dominated summer drought across regions that were primed for severe streamflow deficiencies by a winter drought phase immediately beforehand. The NAO and EA/WR Pattern, driving pressure and temperature anomalies, are also important determinants of drought, although the varying magnitude and sign of these indices within and between the major drought episodes presented here demonstrates the complexity of the climate system in driving streamflow deficits. Further research on the spatio-temporal evolution of multi-year droughts may lead to an improved understanding of the dynamics of these events and the development of monitoring and forecasting tools to help mitigate against the most serious impacts.

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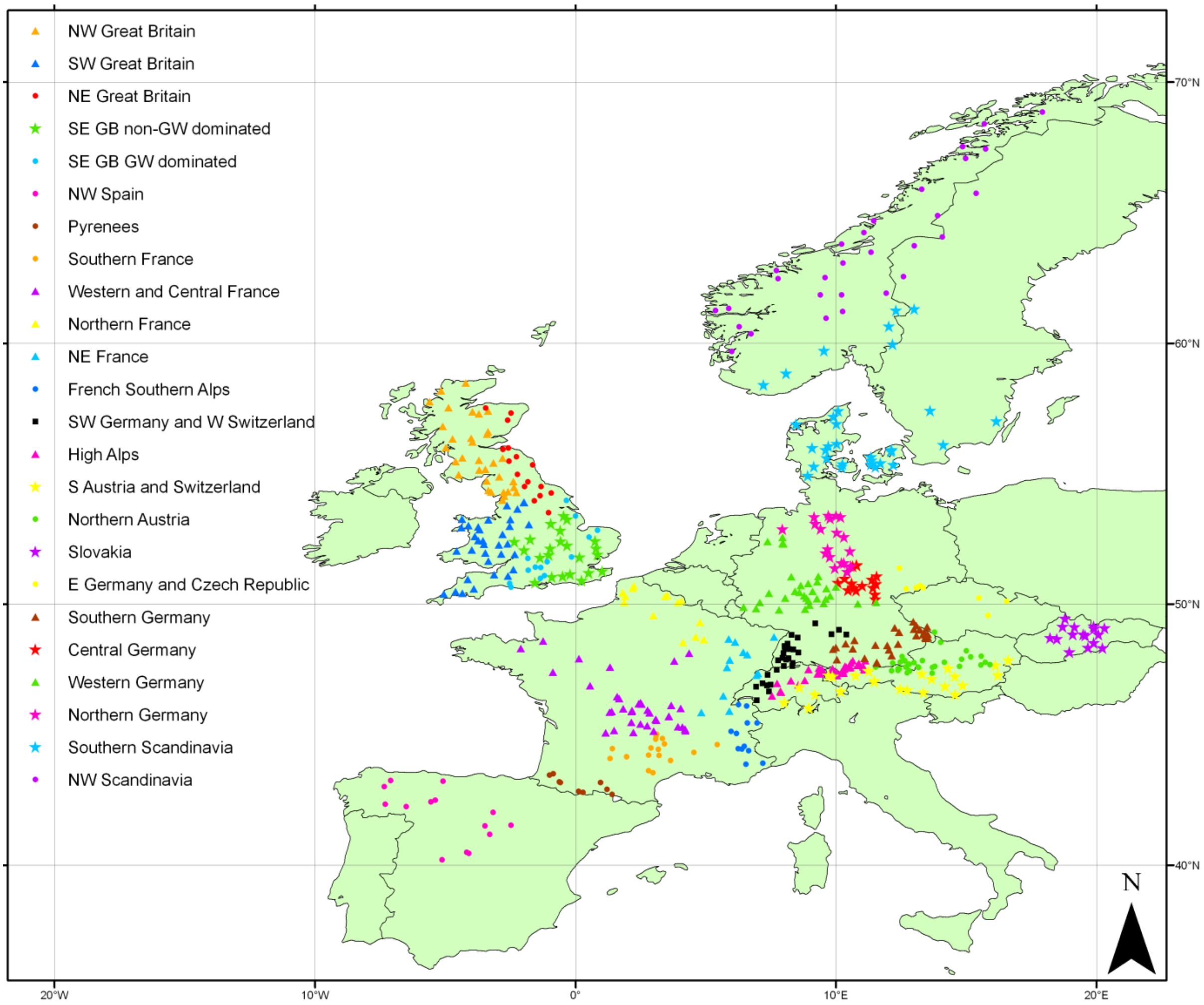
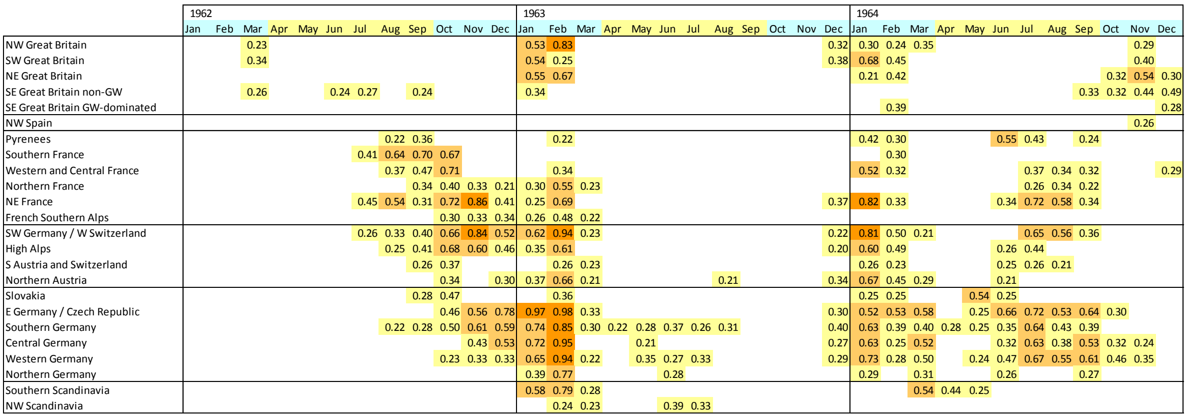


Figure 1 Homogeneous drought regions for Europe (Stahl and Demuth 2001, Prudhomme and Sauquet 2006, Hannaford *et al*. 2011). Symbols represent gauging stations within each region.



	1962												1963												1964											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NW Great Britain			0.23										0.53	0.83										0.32	0.30	0.24	0.35								0.29	
SW Great Britain			0.34										0.54	0.25										0.38	0.68	0.45									0.40	
NE Great Britain													0.55	0.67											0.21	0.42								0.32	0.54	0.30
SE Great Britain non-GW			0.26			0.24	0.27		0.24				0.34																				0.33	0.32	0.44	0.49
SE Great Britain GW-dominated																										0.39										0.28
NW Spain																																			0.26	
Pyrenees								0.22	0.36					0.22											0.42	0.30				0.55	0.43		0.24			
Southern France							0.41	0.64	0.70	0.67																0.30										
Western and Central France								0.37	0.47	0.71				0.34											0.52	0.32					0.37	0.34	0.32			0.29
Northern France									0.34	0.40	0.33	0.21	0.30	0.55	0.23																0.26	0.34	0.22			
NE France							0.45	0.54	0.31	0.72	0.86	0.41	0.25	0.69										0.37	0.82	0.33				0.34	0.72	0.58	0.34			
French Southern Alps										0.30	0.33	0.34	0.26	0.48	0.22																					
SW Germany / W Switzerland							0.26	0.33	0.40	0.66	0.84	0.52	0.62	0.94	0.23									0.22	0.81	0.50	0.21				0.65	0.56	0.36			
High Alps								0.25	0.41	0.68	0.60	0.46	0.35	0.61										0.20	0.60	0.49				0.26	0.44					
S Austria and Switzerland									0.26	0.37				0.26	0.23										0.26	0.23				0.25	0.26	0.21				
Northern Austria										0.34		0.30	0.37	0.66	0.21					0.21				0.34	0.67	0.45	0.29			0.21						
Slovakia									0.28	0.47				0.36											0.25	0.25			0.54	0.25						
E Germany / Czech Republic										0.46	0.56	0.78	0.97	0.98	0.33									0.30	0.52	0.53	0.58		0.25	0.66	0.72	0.53	0.64	0.30		
Southern Germany								0.22	0.28	0.50	0.61	0.59	0.74	0.85	0.30	0.22	0.28	0.37	0.26	0.31				0.40	0.63	0.39	0.40	0.28	0.25	0.35	0.64	0.43	0.39			
Central Germany											0.43	0.53	0.72	0.95			0.21							0.27	0.63	0.25	0.52			0.32	0.63	0.38	0.53	0.32	0.24	
Western Germany										0.23	0.33	0.33	0.65	0.94	0.22		0.35	0.27	0.33					0.29	0.73	0.28	0.50		0.24	0.47	0.67	0.55	0.61	0.46	0.35	
Northern Germany													0.39	0.77				0.28							0.29		0.31			0.26			0.27			
Southern Scandinavia													0.58	0.79	0.28												0.54	0.44	0.25							
NW Scandinavia														0.24	0.23			0.39	0.33																	

Figure 2 Drought matrix of monthly-averaged Regional Deficiency Index (RDI) values for the 1962-64 drought. Yellow cells represent RDI > 0.2; light orange cells represent RDI > 0.5; dark orange cells represent RDI > 0.8. Remaining white cells represent no significant drought (RDI < 0.2).

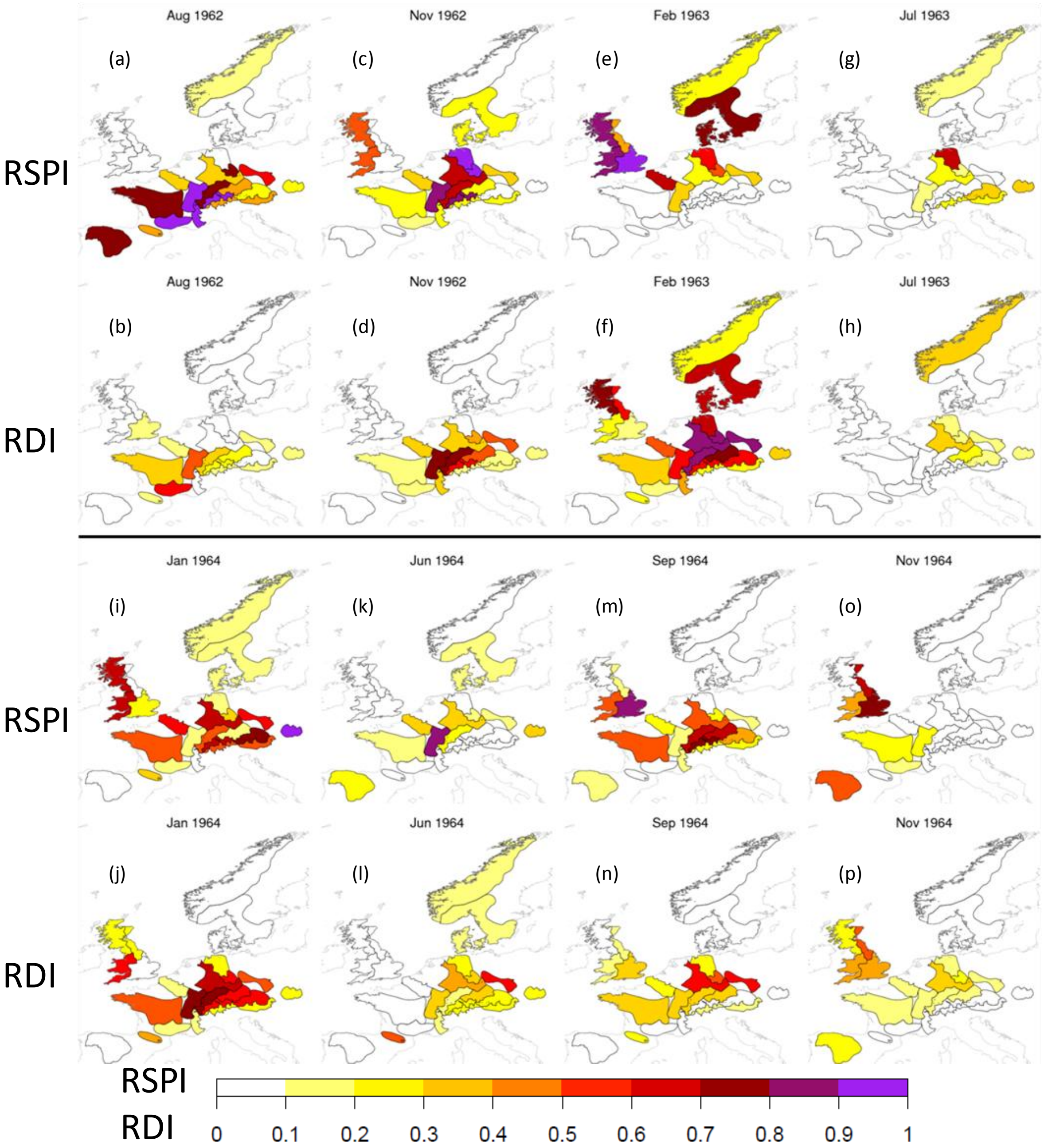
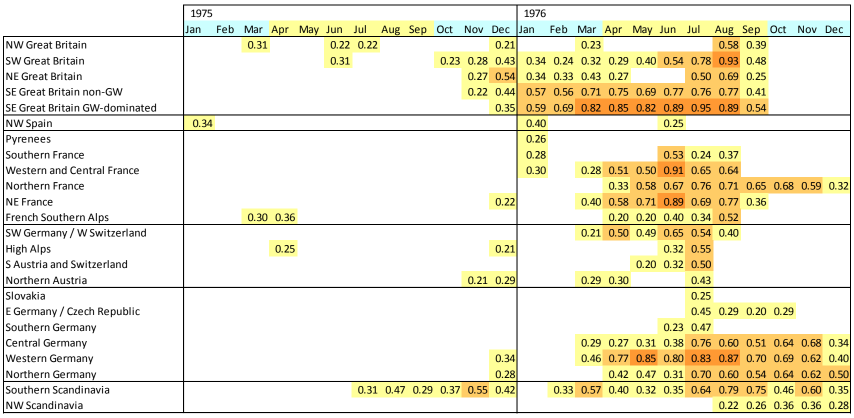


Figure 3 Spatio-temporal evolution maps of Regional Standardised Precipitation Index (RSPI-3 = 3 month SPI averaging interval) values and monthly-averaged Regional Deficiency Index (RDI) values for the 1962-64 drought.



	1975												1976											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NW Great Britain			0.31			0.22	0.22					0.21			0.23					0.58	0.39			
SW Great Britain						0.31				0.23	0.28	0.43	0.34	0.24	0.32	0.29	0.40	0.54	0.78	0.93	0.48			
NE Great Britain											0.27	0.54	0.34	0.33	0.43	0.27			0.50	0.69	0.25			
SE Great Britain non-GW											0.22	0.44	0.57	0.56	0.71	0.75	0.69	0.77	0.76	0.77	0.41			
SE Great Britain GW-dominated												0.35	0.59	0.69	0.82	0.85	0.82	0.89	0.95	0.89	0.54			
NW Spain	0.34												0.40					0.25						
Pyrenees													0.26											
Southern France													0.28					0.53	0.24	0.37				
Western and Central France													0.30		0.28	0.51	0.50	0.91	0.65	0.64				
Northern France																0.33	0.58	0.67	0.76	0.71	0.65	0.68	0.59	0.32
NE France												0.22			0.40	0.58	0.71	0.89	0.69	0.77	0.36			
French Southern Alps			0.30	0.36												0.20	0.20	0.40	0.34	0.52				
SW Germany / W Switzerland															0.21	0.50	0.49	0.65	0.54	0.40				
High Alps				0.25								0.21						0.32	0.55					
S Austria and Switzerland																	0.20	0.32	0.50					
Northern Austria											0.21	0.29			0.29	0.30			0.43					
Slovakia																			0.25					
E Germany / Czech Republic																			0.45	0.29	0.20	0.29		
Southern Germany																		0.23	0.47					
Central Germany															0.29	0.27	0.31	0.38	0.76	0.60	0.51	0.64	0.68	0.34
Western Germany												0.34			0.46	0.77	0.85	0.80	0.83	0.87	0.70	0.69	0.62	0.40
Northern Germany												0.28				0.42	0.47	0.31	0.70	0.60	0.54	0.64	0.62	0.50
Southern Scandinavia							0.31	0.47	0.29	0.37	0.55	0.42		0.33	0.57	0.40	0.32	0.35	0.64	0.79	0.75	0.46	0.60	0.35
NW Scandinavia																				0.22	0.26	0.36	0.36	0.28

Figure 4 Drought matrix of monthly-averaged Regional Deficiency Index (RDI) values for the 1975-76 drought. Yellow cells represent RDI > 0.2; light orange cells represent RDI > 0.5; dark orange cells represent RDI > 0.8. Remaining white cells represent no significant drought (RDI < 0.2).

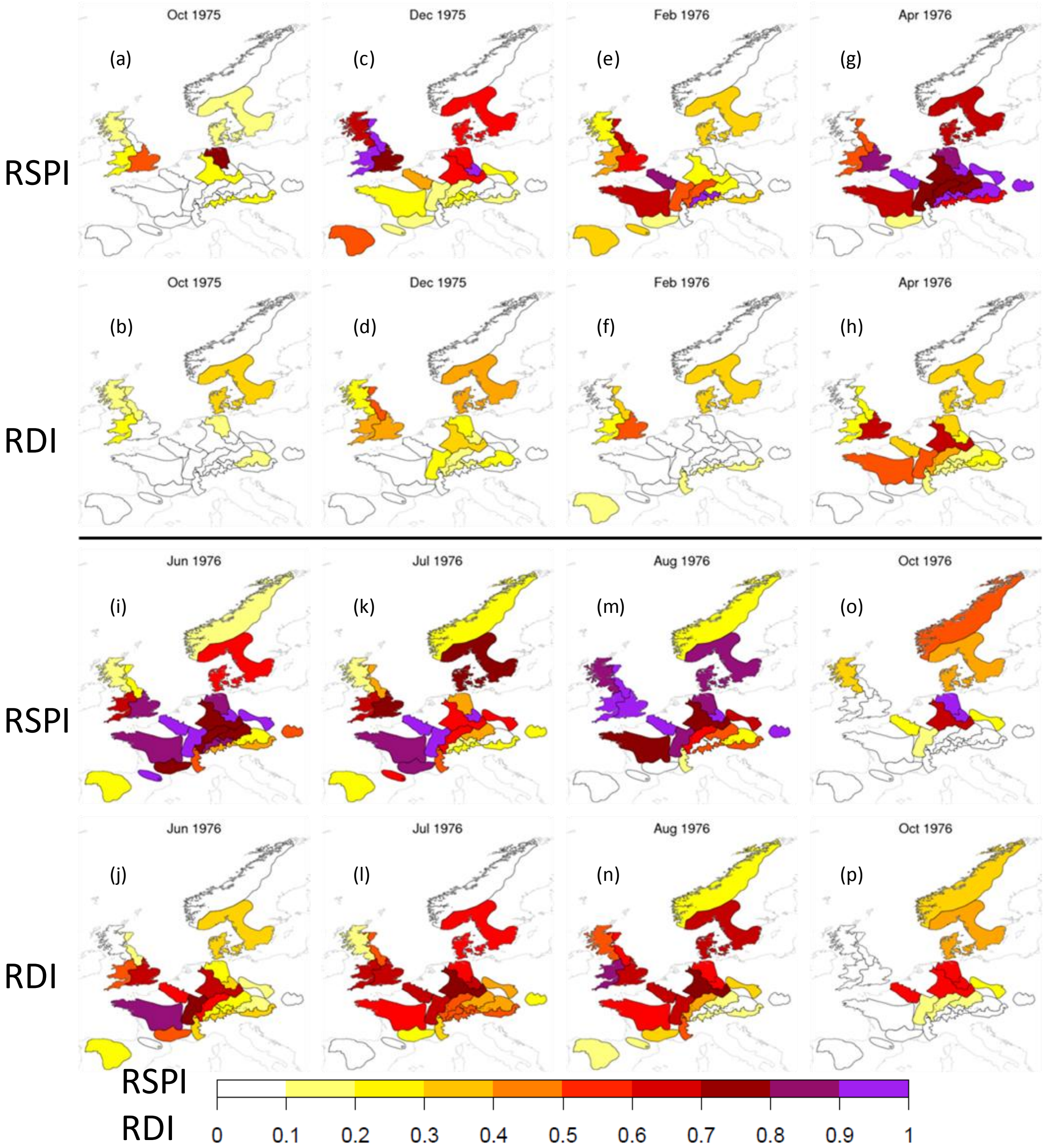
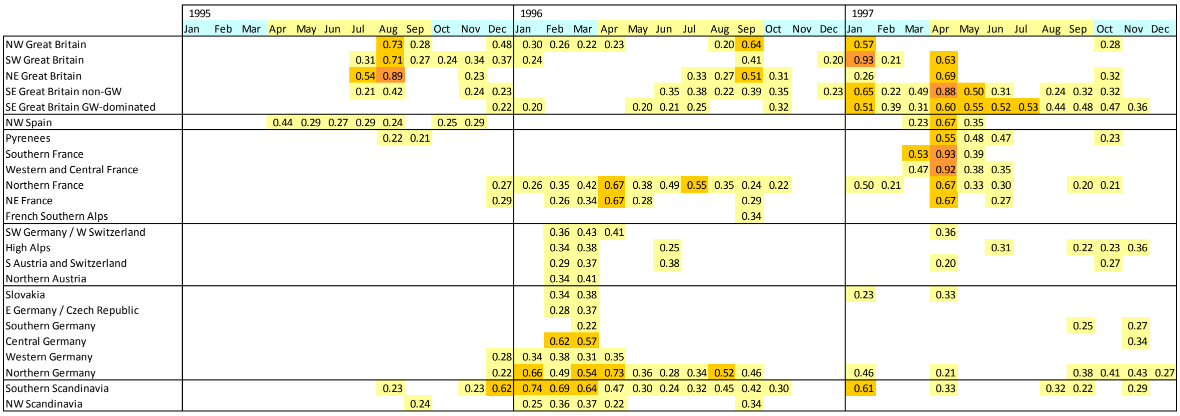


Figure 5 Spatio-temporal evolution maps of Regional Standardised Precipitation Index (RSPI-3 = 3 month SPI averaging interval) values and monthly-averaged Regional Deficiency Index (RDI) values for the 1975-76 drought.



	1995											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NW Great Britain								0.73	0.28			0.48
SW Great Britain							0.31	0.71	0.27	0.24	0.34	0.37
NE Great Britain							0.54	0.89			0.23	
SE Great Britain non-GW							0.21	0.42			0.24	0.23
SE Great Britain GW-dominated												0.22
NW Spain				0.44	0.29	0.27	0.29	0.24		0.25	0.29	
Pyrenees								0.22	0.21			
Southern France												
Western and Central France												
Northern France												0.27
NE France												0.29
French Southern Alps												
SW Germany / W Switzerland												
High Alps												
S Austria and Switzerland												
Northern Austria												
Slovakia												
E Germany / Czech Republic												
Southern Germany												
Central Germany												
Western Germany												0.28
Northern Germany												0.22
Southern Scandinavia								0.23			0.23	0.62
NW Scandinavia									0.24			

	1996											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NW Great Britain	0.30	0.26	0.22	0.23				0.20	0.64			
SW Great Britain	0.24								0.41			0.20
NE Great Britain							0.33	0.27	0.51	0.31		
SE Great Britain non-GW						0.35	0.38	0.22	0.39	0.35		0.23
SE Great Britain GW-dominated	0.20				0.20	0.21	0.25			0.32		
NW Spain												
Pyrenees												
Southern France												
Western and Central France												
Northern France	0.26	0.35	0.42	0.67	0.38	0.49	0.55	0.35	0.24	0.22		
NE France		0.26	0.34	0.67	0.28				0.29			
French Southern Alps									0.34			
SW Germany / W Switzerland		0.36	0.43	0.41								
High Alps		0.34	0.38			0.25						
S Austria and Switzerland		0.29	0.37			0.38						
Northern Austria		0.34	0.41									
Slovakia		0.34	0.38									
E Germany / Czech Republic		0.28	0.37									
Southern Germany			0.22									
Central Germany		0.62	0.57									
Western Germany	0.34	0.38	0.31	0.35								
Northern Germany	0.66	0.49	0.54	0.73	0.36	0.28	0.34	0.52	0.46			
Southern Scandinavia	0.74	0.69	0.64	0.47	0.30	0.24	0.32	0.45	0.42	0.30		
NW Scandinavia	0.25	0.36	0.37	0.22					0.34			

	1997											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NW Great Britain	0.57									0.28		
SW Great Britain	0.93	0.21		0.63								
NE Great Britain	0.26			0.69						0.32		
SE Great Britain non-GW	0.65	0.22	0.49	0.88	0.50	0.31		0.24	0.32	0.32		
SE Great Britain GW-dominated	0.51	0.39	0.31	0.60	0.55	0.52	0.53	0.44	0.48	0.47	0.36	
NW Spain			0.23	0.67	0.35							
Pyrenees				0.55	0.48	0.47				0.23		
Southern France			0.53	0.93	0.39							
Western and Central France			0.47	0.92	0.38	0.35						
Northern France	0.50	0.21		0.67	0.33	0.30			0.20	0.21		
NE France				0.67		0.27						
French Southern Alps												
SW Germany / W Switzerland				0.36								
High Alps						0.31			0.22	0.23	0.36	
S Austria and Switzerland				0.20						0.27		
Northern Austria												
Slovakia	0.23			0.33								
E Germany / Czech Republic												
Southern Germany									0.25		0.27	
Central Germany											0.34	
Western Germany												
Northern Germany	0.46			0.21					0.38	0.41	0.43	0.27
Southern Scandinavia	0.61			0.33				0.32	0.22		0.29	
NW Scandinavia												

Figure 6 Drought matrix of monthly-averaged Regional Deficiency Index (RDI) values for the 1995-97 drought. Yellow cells represent RDI > 0.2; light orange cells represent RDI > 0.5; dark orange cells represent RDI > 0.8. Remaining white cells represent no significant drought (RDI < 0.2).

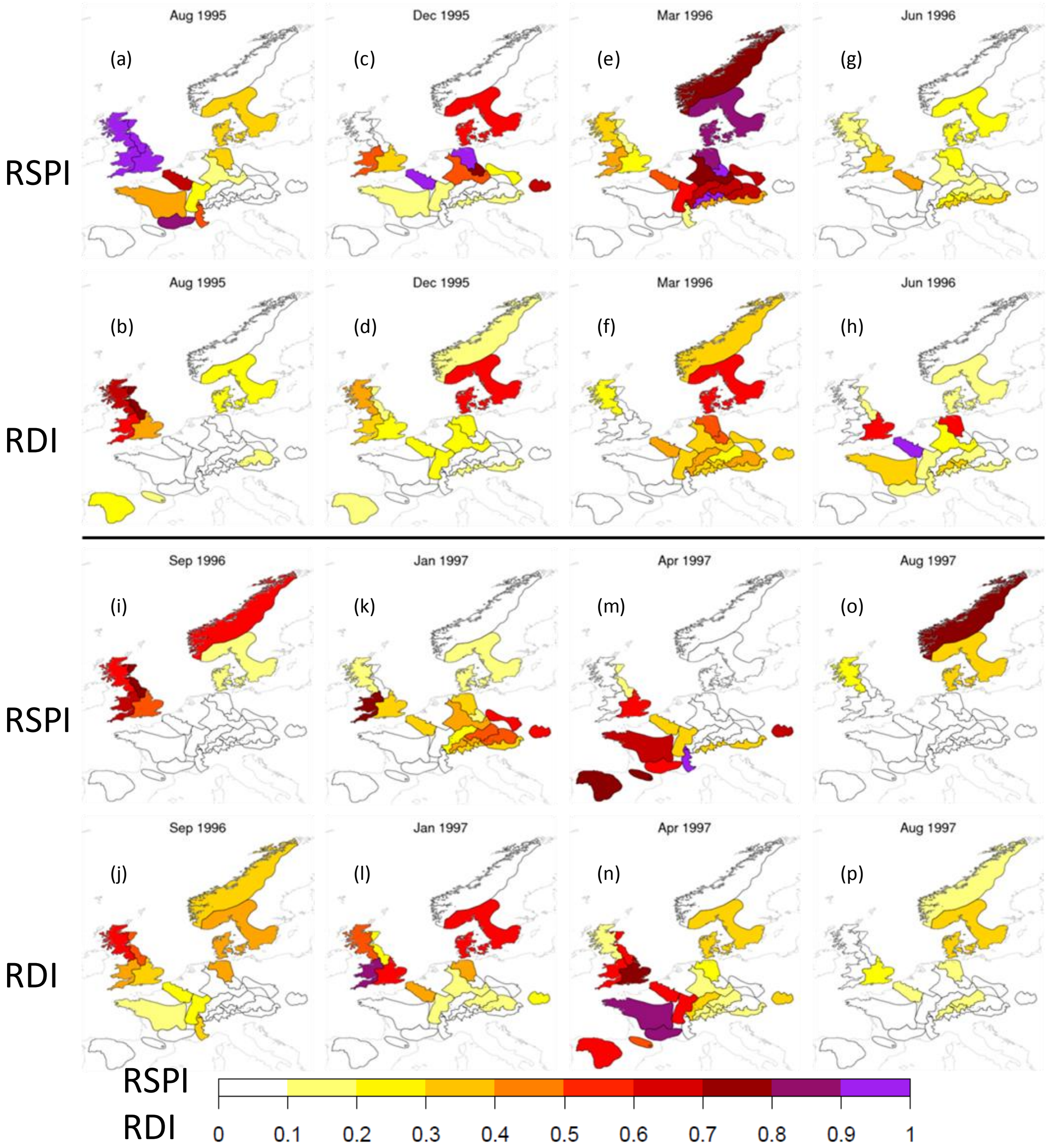


Figure 7 Spatio-temporal evolution maps of Regional Standardised Precipitation Index (RSPI-3 = 3 month SPI averaging interval) values and monthly-averaged Regional Deficiency Index (RDI) values for the 1995-97 drought.

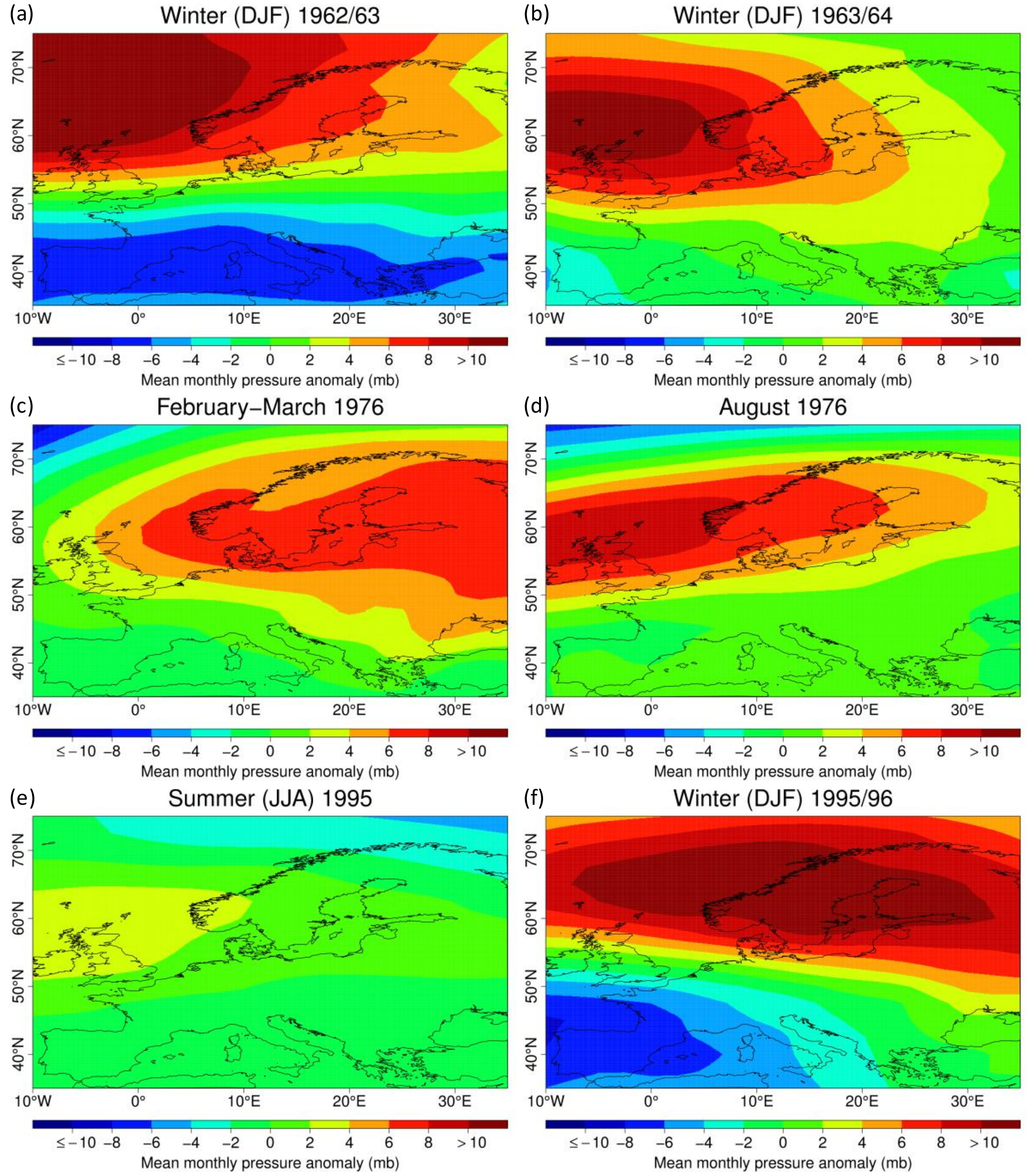


Figure 8 Mean monthly pressure anomalies (mb) with respect to the 1971-2000 climatology for the 1962-64, 1975-76 and 1995-97 droughts. Derived from gridded National Centers for Environmental Prediction (NCEP) / National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay *et al*. 1996).

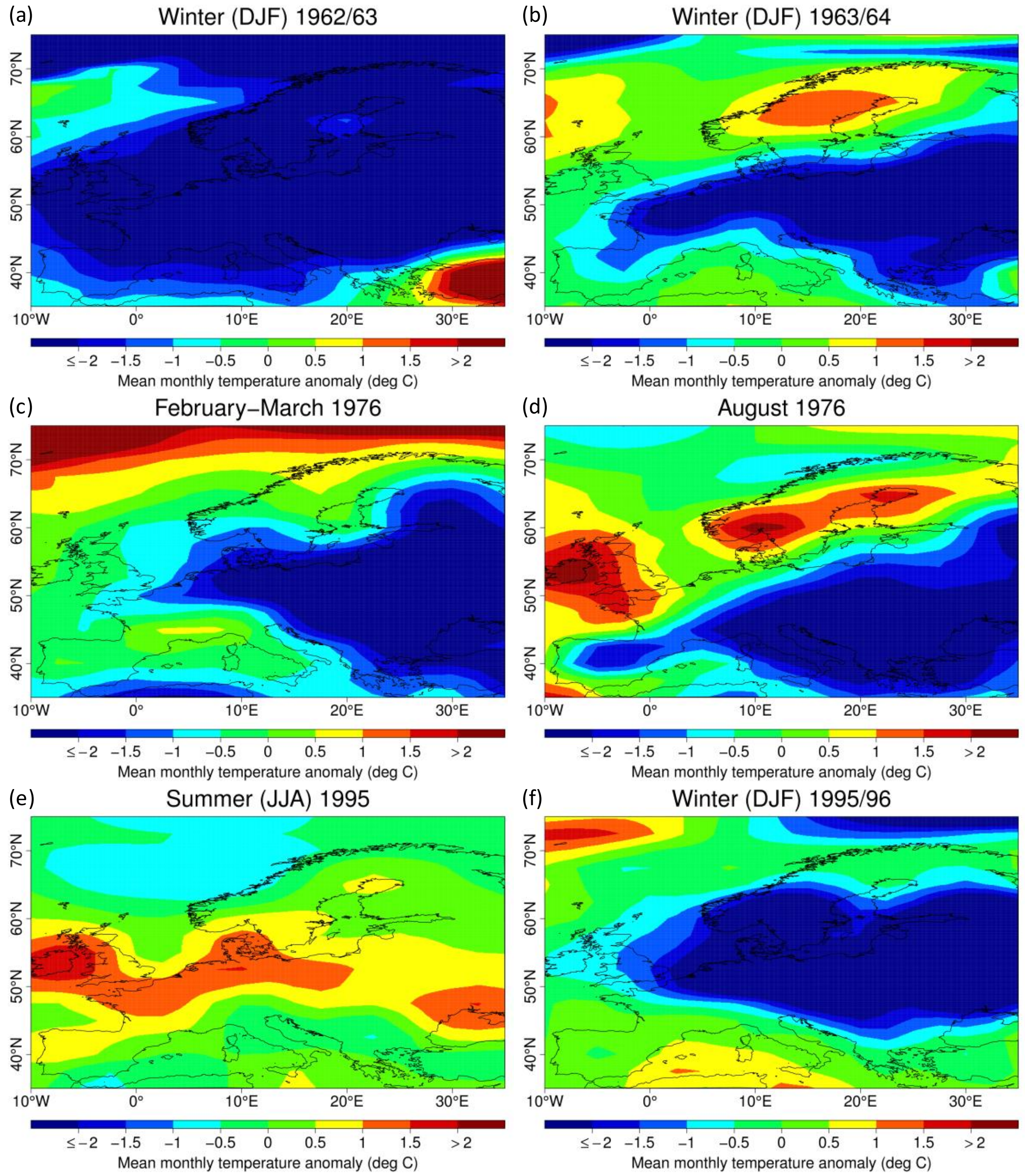


Figure 9 Mean monthly temperature anomalies (deg C) with respect to the 1971-2000 climatology for the 1962-64, 1975-76 and 1995-97 droughts. Derived from gridded National Centers for Environmental Prediction (NCEP) / National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay *et al*. 1996).

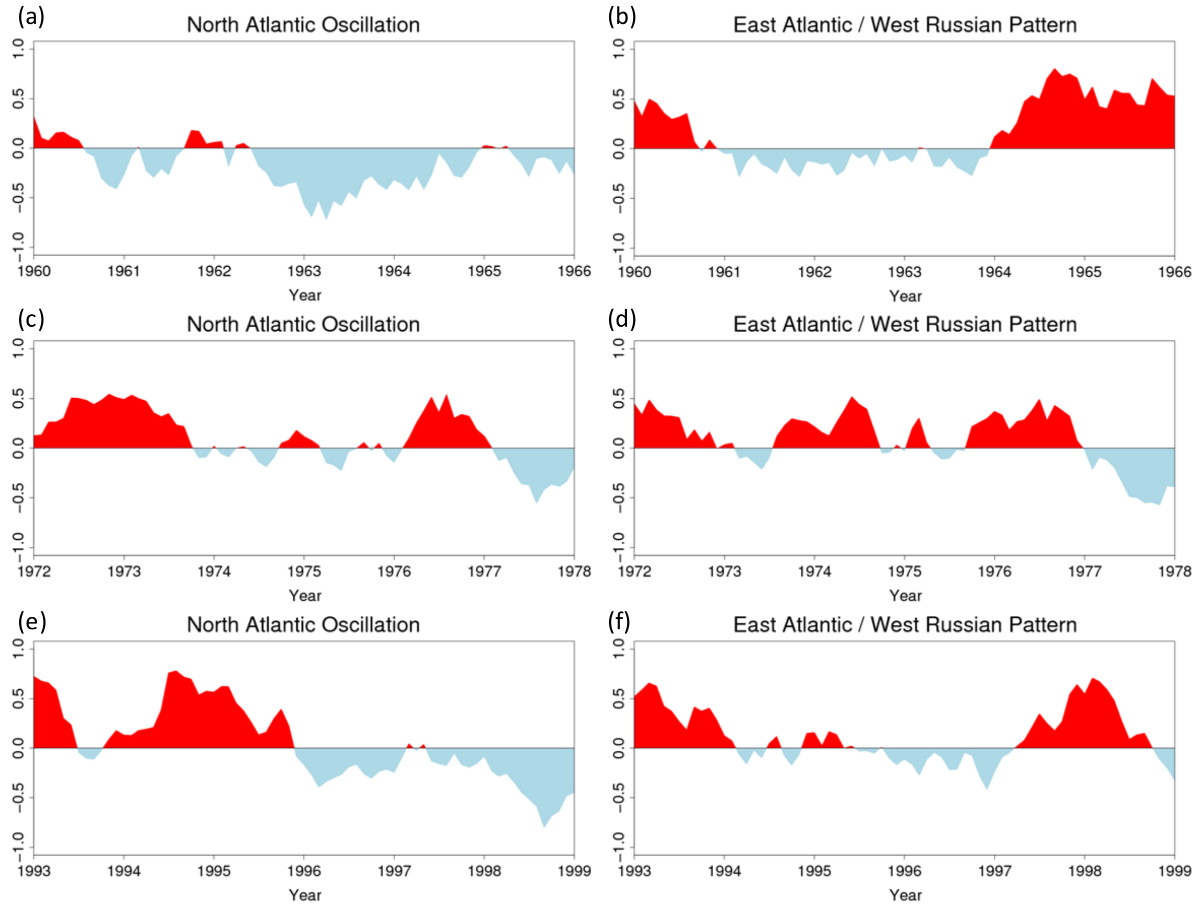


Figure 10 North Atlantic Oscillation (NAO) and East Atlantic / West Russian (EA/WR) Pattern anomaly plots for the 1962-64, 1975-76 and 1995-97 droughts. Derived from NOAA (2009) data.