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**Technical Report No. 33**

**OBJECTIVE DROUGHT AND HIGH FLOW  
CATALOGUES FOR EUROPE**



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Date: 24<sup>th</sup> August 2011



WATCH is an Integrated Project Funded by the European Commission under the Sixth Framework Programme, Global Change and Ecosystems Thematic Priority Area (contract number: 036946). The WACH project started 01/02/2007 and will continue for 4 years.

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Submission date:	24 <sup>th</sup> August 2011
Function:	This report is an output from Work Block 4; task 4.1.2
Deliverable	WATCH deliverable 4.1.6a and 4.1.6b

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## 1. Introduction

Drought is a large-scale phenomenon that simultaneously affects wide areas, often causing damaging socio-economic, agricultural and environmental impacts. The significant spatial and temporal scales over which drought has an impact are predominantly driven by meteorological conditions; large, stable anticyclonic systems are often highly persistent, and it is the propagation of precipitation deficiencies through the hydrological cycle that is the cause of streamflow, agricultural and water resources drought. Since drought is an inherently large-scale phenomenon, it is appropriate to investigate it at a regional scale. This may also prove most useful for water resource planners and policymakers, as well as being an approach which may potentially underpin monitoring or predictive forecasting tools.

Whilst localised high flow events centred on a single river are often those which are most widely reported in the media, spatially coherent high flows can also occur simultaneously over wide areas, such as the flooding witnessed in central England in summer 2007 (Marsh and Hannaford, 2007), and that which affected Central Europe in 2002 (Ulbrich *et al.* 2003). Since high flow occurrence is predominantly driven by precipitation, frontal systems can generate persistent rainfall over a given region for a prolonged period of time, prompting streamflow response across a wide area. As such, regional studies of high flow occurrence are pertinent in assessing the spatial extent of risk posed by high flow events.

In order to assess large-scale drought and high flow characteristics across a continent such as Europe which has a variable hydroclimatology, it is desirable to employ methods that allows the intercomparison of streamflow regimes across a range of locations and seasons. The Regional Deficiency Index (RDI; Stahl, 2001) is one such methodology, expressing regional drought relative to a particular time of year and location. Conceptually similar to the RDI, the methodology employed in this study to assess high flows occurrence is the Regional High Flow Index (RHFI; after the RFI of Parry *et al.* 2010).

## 2. Data

### 2.1 River Flow Data

This study utilises daily river flow records from 11 countries in Europe, from the European Water Archive (EWA) and updated by Stahl *et al.* (2010). The records are sourced from catchments that are known to have flow regimes that are not impacted by artificial influences, gauged by stations with good hydrometric performance. Catchment areas are generally less than 1000 km<sup>2</sup> in order to reduce the likelihood of artificial influences, although this maximum has been exceeded in instances in which there is good knowledge of minimal disturbance.

Additional river flow data were sourced from Banque Hydro in France (Prudhomme and Sauquet, 2006) and the UK National River Flow Archive (Hannaford *et al.* 2011), generating a dataset of 579 daily river flow records in total spanning the period 1961 to 2005. The catchments are unevenly distributed across Europe owing to the lack of data availability in some regions, or the prevalence of artificial influences in others (e.g. the Benelux countries, the Seine basin, etc.).

### 2.2 Precipitation Data

Precipitation data are used in this study to provide an indication the correspondence between meteorological and hydrological drought, and to extend the analysis of drought back to the beginning of the twentieth century. Data are sourced from the British Atmospheric Data Centre (BADDC), using the Climatic Research Unit (CRU) TS 3.0 dataset (Mitchell and Jones, 2005). These data are available at a

0.5 degree grid cell resolution and on a monthly time step, and data for the period 1901-2005 are utilised in this study.

### 3. Methodology for River Flow Indices

Deriving the Regional Deficiency Index (RDI; Stahl, 2001) and the Regional High Flow Index (RHFI; Parry *et al.* 2010) requires three stages of processing, which are outlined below. Since the two methods are conceptually identical but for their application to low flows and high flows, respectively, the derivation of the RDI is explained in full, whilst the RHFI method is given in parentheses.

#### 3.1 Deficiency Index (DI) and Exceedence Index (EI)

The initial stage of the RDI (RHFI) is to produce a DI (EI) index time series for each daily river flow record. A daily-varying Q90 (Q10) threshold is used to allow flows to be expressed in relation to the particular location and time of the year. The daily-varying nature of the threshold necessitates the derivation of a Q90 (Q10) value for each individual day of the year, calculated by ranking all of the flows recorded on the given day throughout the period of record with all those flows on the preceding 15 days and succeeding 15 days throughout the period of record. For example, the Q90 (Q10) value on 16 January is calculated from all daily flow values on 16 January in the period of record, along with all flow values on days 1-15 January and days 17-31 January. For a 30-year daily river flow record, this would give  $30 \times 31 = 930$  observations. This moving 31-day window approach increases the sample size, generating a more robust value for Q90 (Q10). For each day in the year, the observations captured by the 31-day moving window are ranked, to produce a Q90 (Q10) value for that day.

Once the daily-varying Q90 (Q10) threshold has been derived for every daily river flow record, the streamflow data are compared to the threshold to produce the DI (EI). If the river flow is below (above) the Q90 (Q10) threshold, DI (EI) takes a value of 1, signifying that the flow on that day is amongst the lowest (highest) 10% in the period of record *relative to normal conditions for the location and time of year*. Otherwise, DI (EI) takes a value of 0. This derivation is expressed below for DI:

$$DI(t) = 1 \quad \text{if } Q(t) \leq Q90(t)$$

$$DI(t) = 0 \quad \text{if } Q(t) > Q90(t)$$

and for EI:

$$EI(t) = 1 \quad \text{if } Q(t) \geq Q10(t)$$

$$EI(t) = 0 \quad \text{if } Q(t) < Q10(t)$$

Therefore, the DI (EI) time series for each river flow record comprises a binary series of ones and zeros, indicating whether or not the river is under drought (high flow) conditions.

#### 3.2 Clustering

The second stage of the derivation of the regional drought and high flow indices is to group together those river flow records that respond homogeneously to drought and high flows. Since large-scale droughts and high flows are investigated in this study, considering regional-scale hydrological extremes is appropriate, and is achieved through performing a cluster analysis to group individual flow records into homogeneous regions. Within this methodology, clustering has been performed on the binary DI time series derived previously, grouping together into regions those catchments which experience a deficiency at the same time.



A cluster analysis was originally performed on these binary time series for Europe by Stahl and Demuth (2001). In this study, the original regions have been assessed for homogeneity and subsequently modified by Prudhomme and Sauquet (2006) and Hannaford *et al.* (2011). In total, 23 homogeneous regions have been defined for Europe, within which catchments respond similarly in their expression of drought. The 23 regions are illustrated in Figure 1.

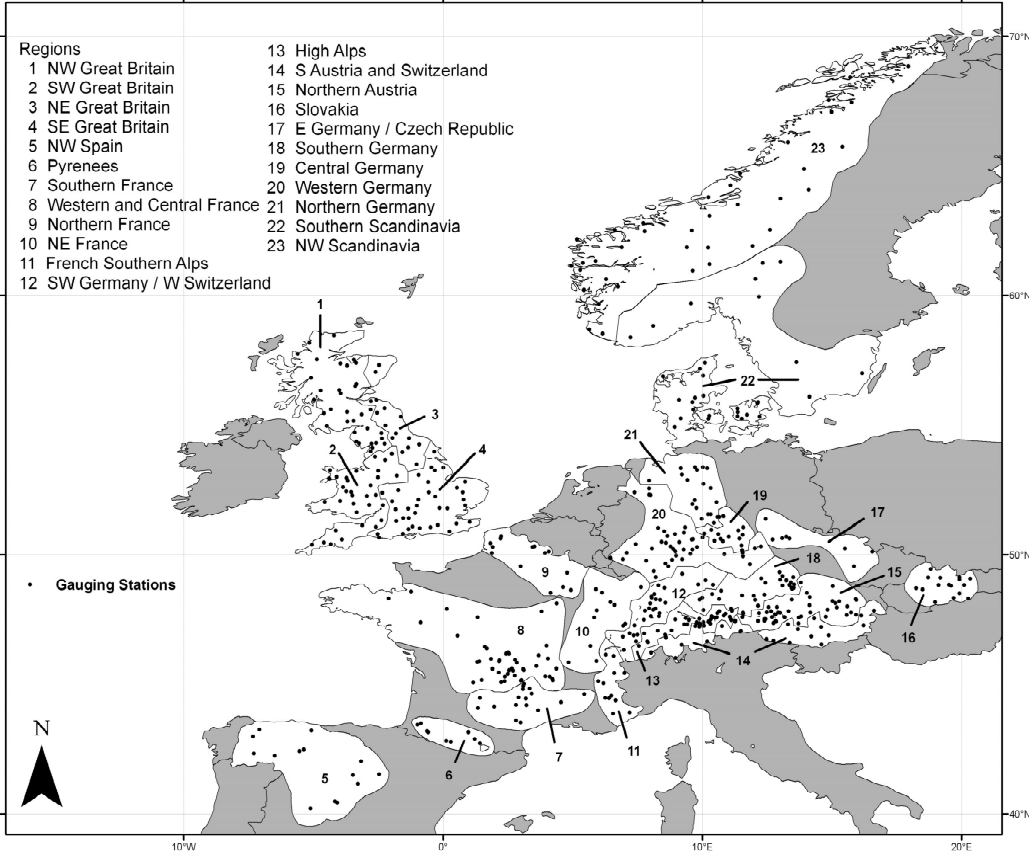


Figure 1 Homogeneous regions for Europe (Stahl and Demuth, 2001; Prudhomme and Sauquet, 2006; Hannaford *et al.* 2011).

These regions were defined based on homogeneous low flow response through a cluster analysis of the DI time series for each catchment. For practical purposes and to enable consistent comparisons to be made, the same regions have been utilised for both the RDI and RHF1 in this study. It may be expected that different regions would be formed if clustering were performed separately for high flows and low flows, but an alternative test clustering on the basis of high flow occurrence using the EI time series (reported in Parry *et al.* 2010) produced similar groupings of catchments, and so the regions shown in Figure 1 have been taken for the derivation of both the RDI and the RHF1, for the sake of consistency.

### 3.3 Regional Deficiency Index (RDI) and Regional High Flow Index (RHF1)

The final procedure in deriving the RDI (RHF1) is to average the binary DI (EI) time series within the 23 homogeneous regions shown in Figure 1. For each of the homogeneous regions, the arithmetic mean is taken of the DI (EI) time series of the catchments which fall within its boundaries. For the RDI, this can be written as:

$$RDI(t) = \frac{1}{M} \sum_{i=1}^M DI_i(t)$$

and for the RHF1:

$$RHF\text{I}(t) = \frac{1}{M} \sum_{i=1}^M EI_i(t)$$

where M is the number of catchments with a DI (EI) value for a given day.

The daily RDI (RHF\text{I}) time series for each region therefore represents the proportion of the region that is under drought (high flow) conditions on that day. Since the RDI (RHF\text{I}) averages a number of binary time series, its values lies between 0 and 1. RDI (RHF\text{I}) values of 0 indicate none of the catchments in a region are being affected by drought (high flows), whereas values of 1 signify the entire region is under drought (high flow) conditions.

## 4. Methodology for Precipitation Indices

The Regional Standardised Precipitation Index (RSP\text{I}) is an extension of the widely used Standardised Precipitation Index (SP\text{I}), and is an objective classification of meteorological drought that is conceptually similar to the RDI. A meteorological index has only been utilised in this study to assess regional drought because analysis of monthly precipitation data is of limited utility for the investigation of high flows, which tend to be generated by short-term excess precipitation.

### 4.1 Standardised Precipitation Index (SP\text{I})

The SP\text{I} (McKee *et al.* 1993) is used in this study as an objective proxy for meteorological drought. It is the unit normal transformation of the time averaged precipitation time series climatologically appropriate to the particular location and time of year. Figure 2 illustrates the concept which underpins the SP\text{I}, allowing very different rainfall regimes to be expressed in relative terms.

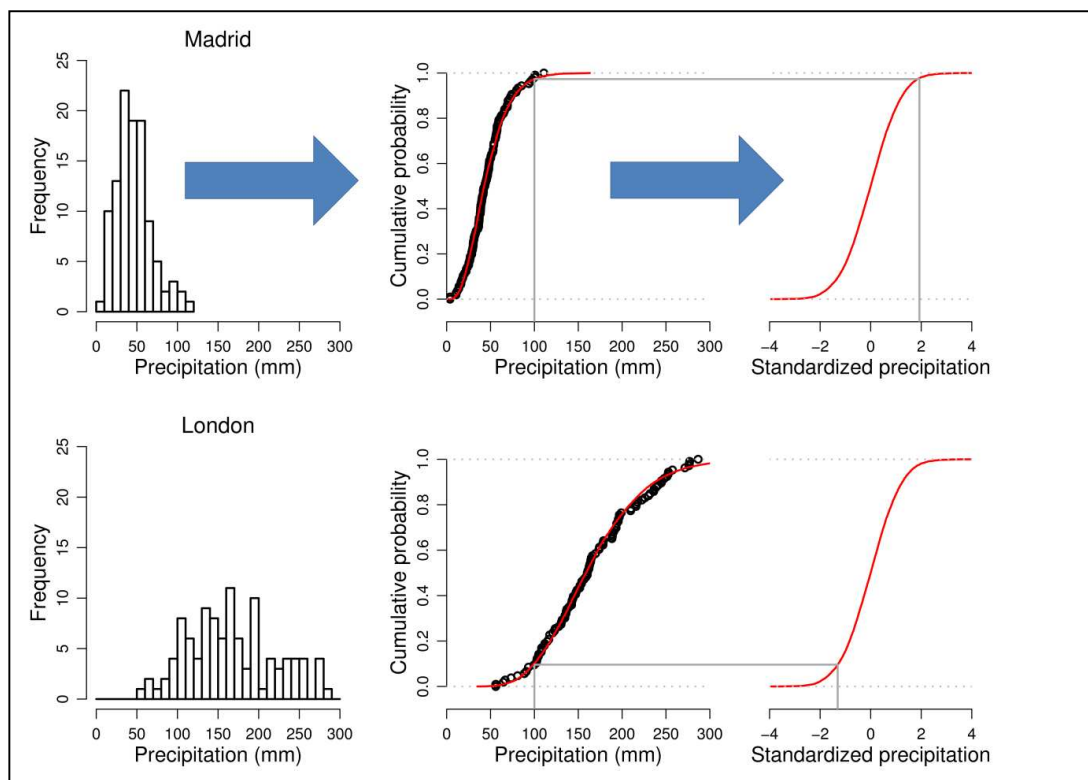


Figure 2 Standardised Precipitation Index applied to summer three-month accumulations (JJA) for Madrid and London, 1901-2005.

The SPI allows different magnitudes of precipitation to be expressed relative to the time of year and the location considered. For example, as illustrated in Figure 2, 100 mm of precipitation in Madrid for JJA is unusually wet (SPI of +2), whereas for London, 100 mm is relatively little (SPI of -1.3). The SPI values exemplified here would be denoted as August SPI3, i.e. the three-month accumulation ending in August.

In this study, the SPI was calculated for each grid cell, with the length of accumulation (i.e. SPI $n$ ) determined by the maximum rank correlation between the meteorological index and the RDI.

## **4.2 Regional Standardised Precipitation Index (RSPI)**

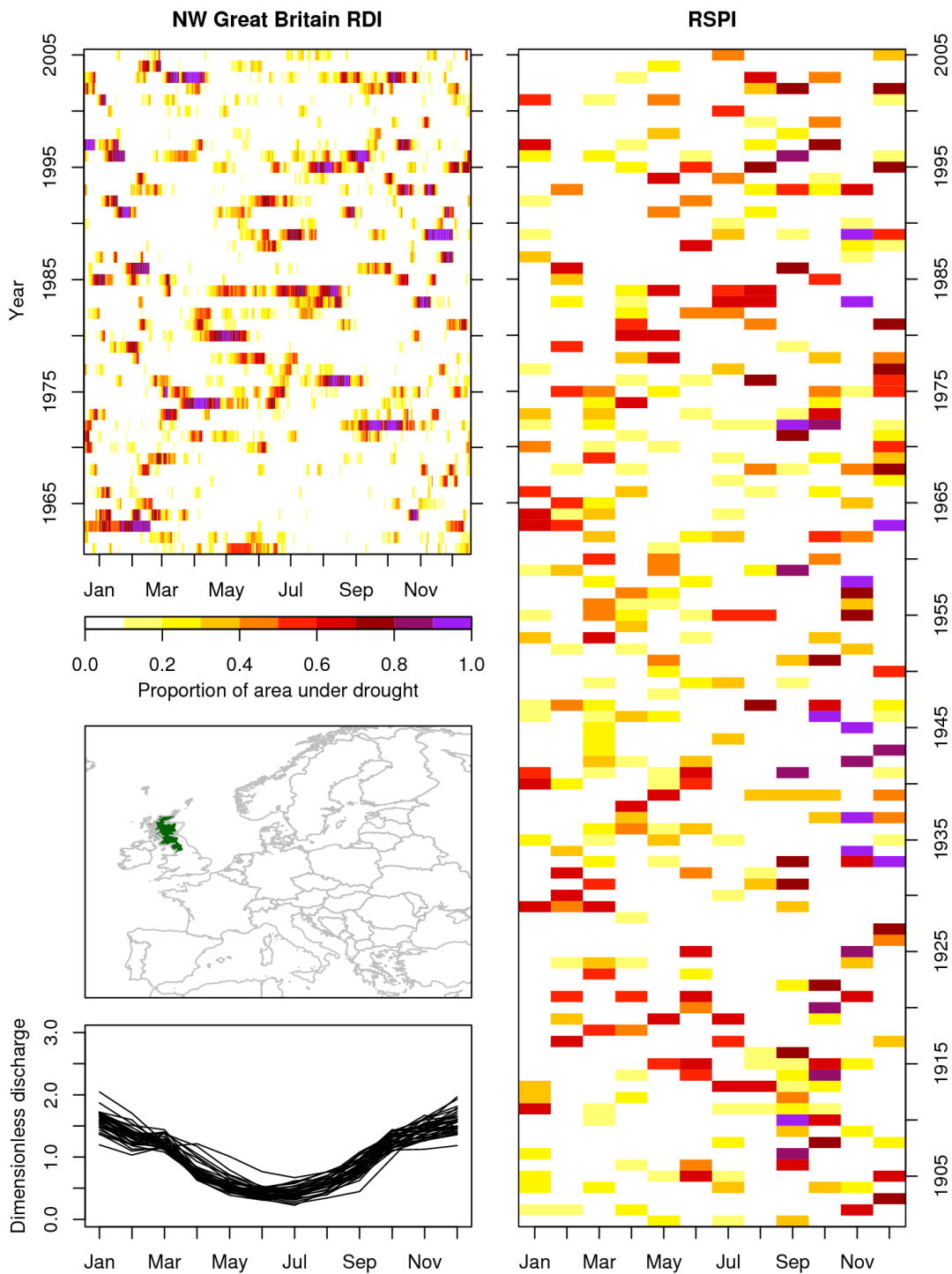
The RSPI implements the SPI within the regions defined on homogeneous hydrological response in the river flow data, to enable a comparison to be made between the two regional indicators. For each region, the RSPI is calculated as the proportion of grid cells within the region that are experiencing 'moderate' drought, with SPI < -1. The RSPI takes values between 0 and 1, with 0 representing no grid cells under moderate drought, and 1 signifying that all cells are experiencing meteorological drought.

## 5. Drought Catalogues

Data for each of the 23 homogenous regions are presented as a single page in the catalogue, which provides a direct comparison of regional streamflow drought for the period 1961-2005 with the meteorological indicator spanning 1901-2005. The RSPIn plot (where  $n$  is the number of months over which precipitation totals are accumulated before they are standardised) that is presented for each region in the drought catalogue is the one which is most closely correlated with the RDI. Periods of coherent drought are easily picked out by blocks of colour. The darker the colouration, the more coherent the drought across the region. Any potential lag between the meteorological input and the hydrological response is evident by a shift in the position of the coloured blocks. A map indicates the location of the region and a plot illustrates the flow regimes at each gauging station within the regional network.

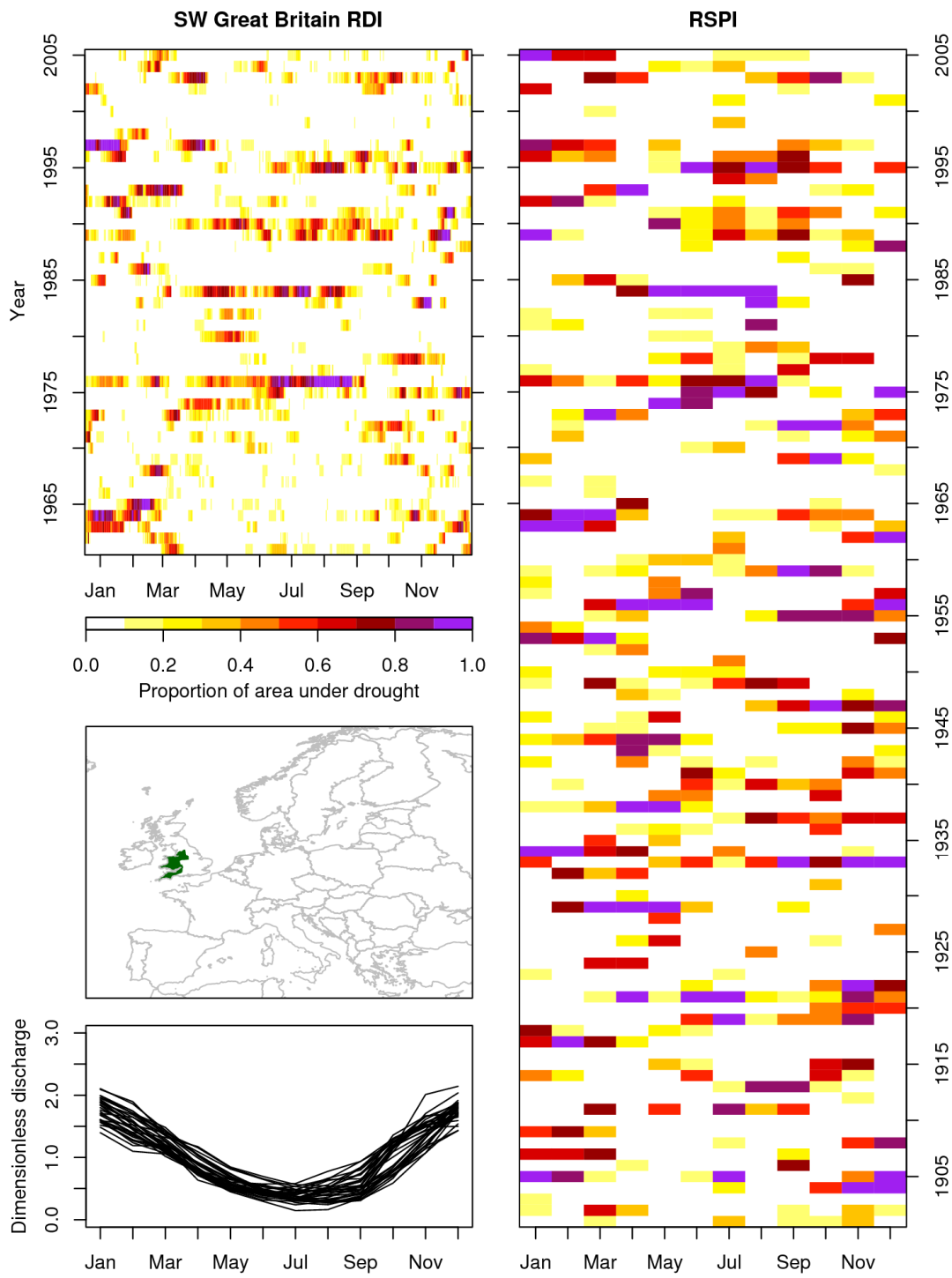
The catalogue entry is completed by a description of the predominant characteristics of hydrological and meteorological drought in the region, such as particularly strong or weak correspondence between streamflow and precipitation deficiencies, and regional characteristics in drought duration, seasonality and spatial coherence.

As part of the analysis conducted by Hannaford *et al.* (2011) into the homogeneity of regions, it was decided that a subset of groundwater-dominated catchments from the SE Great Britain region should be considered separately for droughts, since their hydrological response to meteorological inputs is significantly different to those catchments in which groundwater is not influential. As such, the groundwater-dominated catchments are not a geographic entity which can be illustrated as a separate region, but can be considered to lie within the boundary of the SE Great Britain region in Figure 1. In addition to the 23 homogeneous regions presented in Figure 1, there is a drought catalogue page dedicated to the SE Great Britain groundwater-dominated 'region'. Analysis of the distinct drought characteristics of this subset of catchments will allow a broader understanding of drought expression in different geological settings.

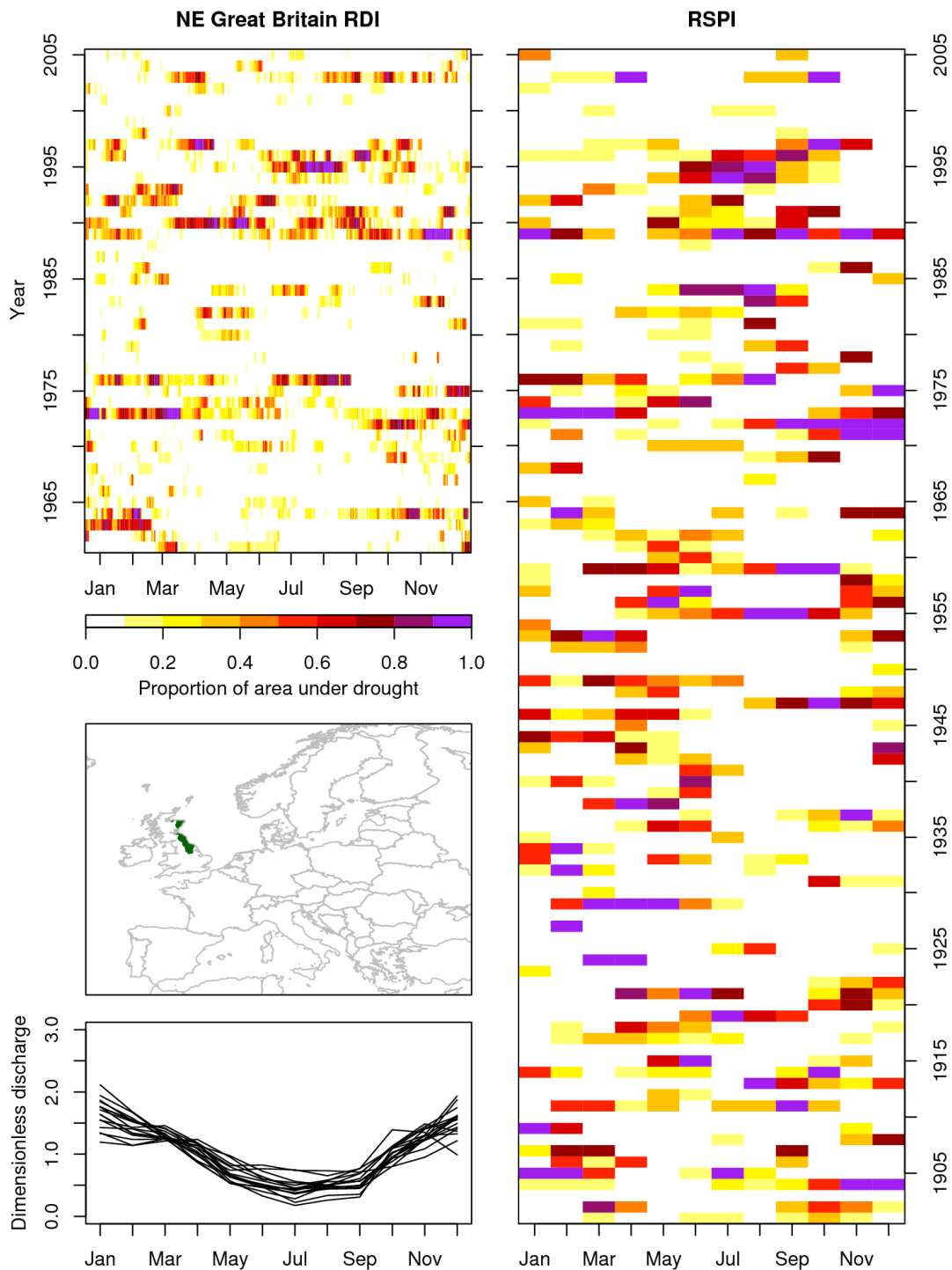


The NW Great Britain region is characterised by a wet climate and responsive catchments. Whilst hydrological drought episodes can show significant spatial coherence, they tend to be of short duration. There is some evidence of a shift in seasonality of hydrological drought, with summer and autumn droughts becoming more common towards the end of the 1961-2005 period. The short duration of hydrological drought in the NW Great Britain region is largely a function of high precipitation variability (owing to the prevalence of frontal weather from the north Atlantic), which results in few lengthy precipitation deficits, and the responsive nature of the catchments, hence the highest correlation with RSPI1. There appears to be a consistent pattern in seasonality throughout the 1901-2005 period, with the most severe (albeit short) meteorological deficits occurring in the autumn and early winter.

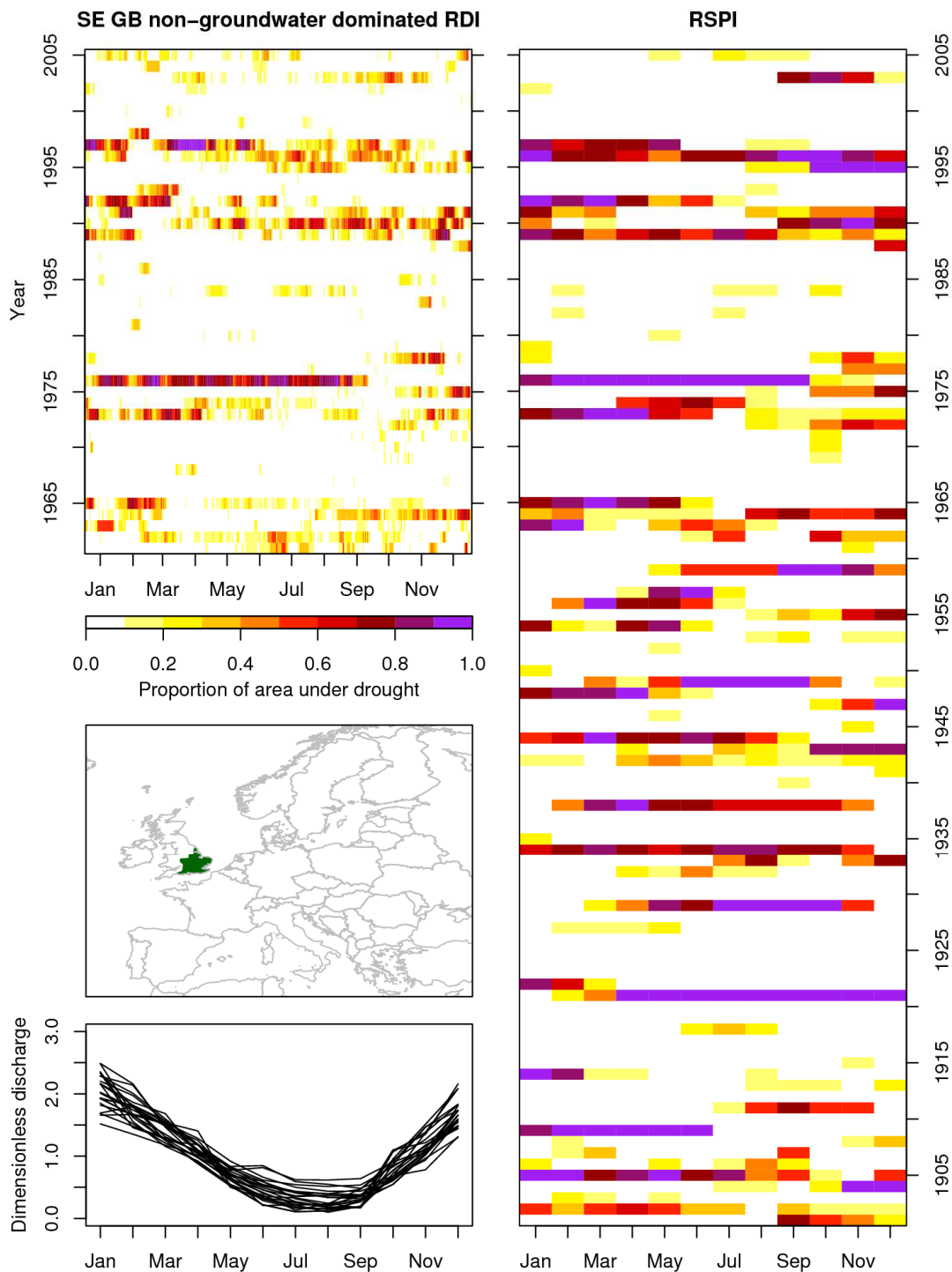




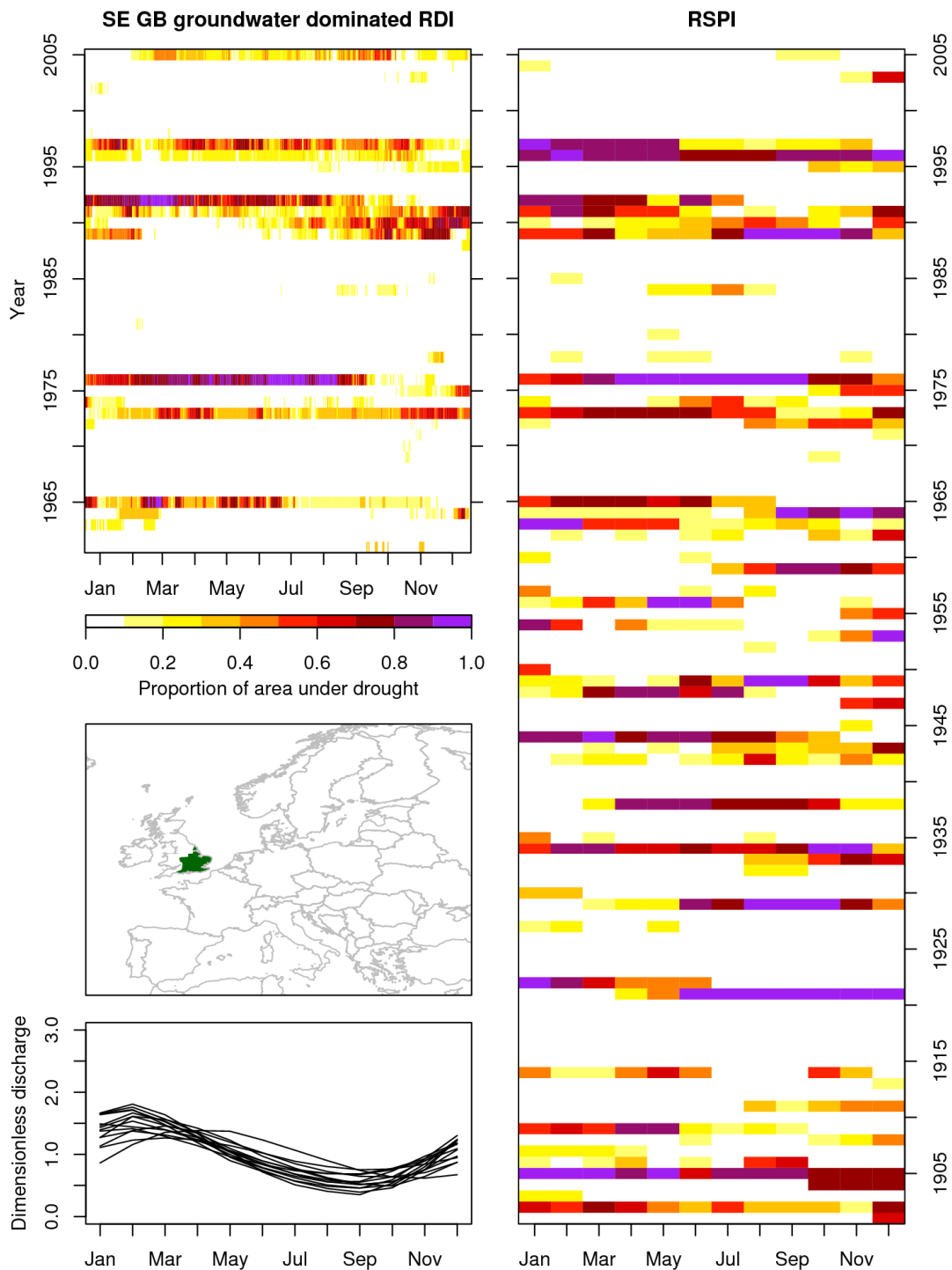
The predominant characteristic of hydrological drought in the SW Great Britain region is the occurrence of some prolonged episodes. Hydrological drought events exist as protracted periods in the summer (e.g. 1976, 1984) or as short but intense deficiencies in the winter. Multi-year droughts (albeit with interruptions) occur in the 1990s. The early record (up to the mid-1970s) is characterised by a general lack of deficiencies except for the notable winter droughts of the early 1960s. The period since 1997 is also relatively unaffected by hydrological drought conditions, except for the drought of 2003 (which was not particularly coherent in this region). Meteorological drought characteristics in this region according to RSPI3 exhibit relatively little structure, although accumulated deficits over multiple seasons or years can be significant, and generally conform to periods of hydrological drought.



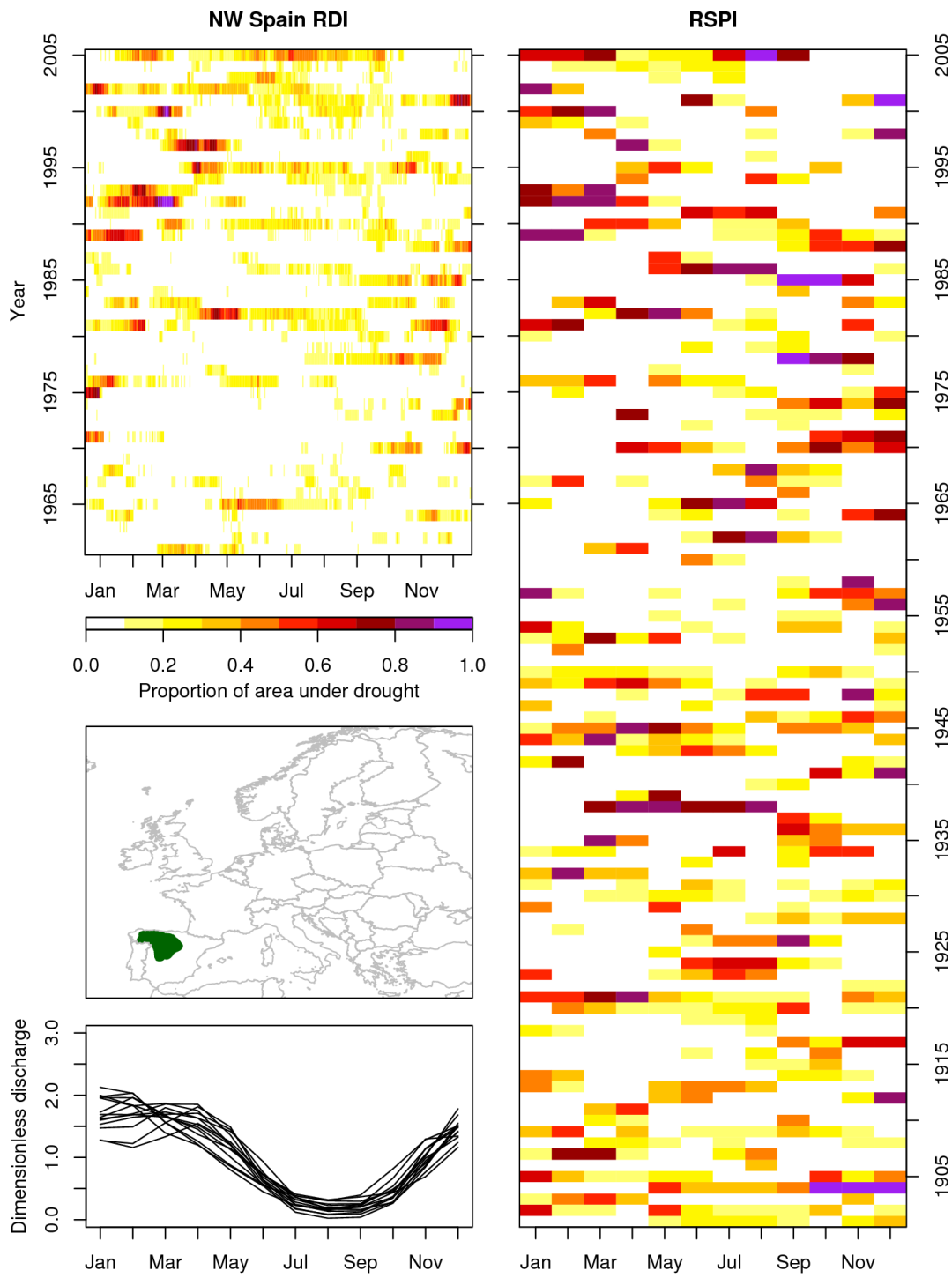
The NE Great Britain region is notable for having pronounced “drought rich” (e.g. the 1990s) or “drought poor” (1977 – 1987) periods. This suggests that the catchments within the region are homogeneous in their response to precipitation inputs (or lack thereof). Hydrological drought can occur at any point throughout the year, although deficits often occur in multi-season or multi-year events, although these tend to be long successions of minor deficit periods, which incorporate short periods of very coherent drought (e.g. 1988 – 1992, with peak RDI occurring autumn 1989 and early summer 1990). The occurrence of hydrological drought in this region is predominantly in agreement with the timing of meteorological drought, as shown by RSPI3.



Although there are relatively few droughts which affect the non-groundwater dominated SE Great Britain catchments, those which do occur are significant in both length and peak spatial coherence. There are distinct multi-year periods in which hydrological drought is prevalent (especially in the first half of the 1970s and through the 1990s), contrasting with other periods characterised by a lack of deficit conditions (the late 1970s and 1980s especially). The onset of the majority of hydrological droughts in this region is in winter (e.g. 1975 – 76), when precipitation deficits cause depletion of surface and groundwater stores (whilst not “groundwater dominated”, this region still has many catchments with relatively high groundwater storage). The catchments in this region thus respond primarily to highly coherent and sustained meteorological droughts, illustrated by RSPI9.

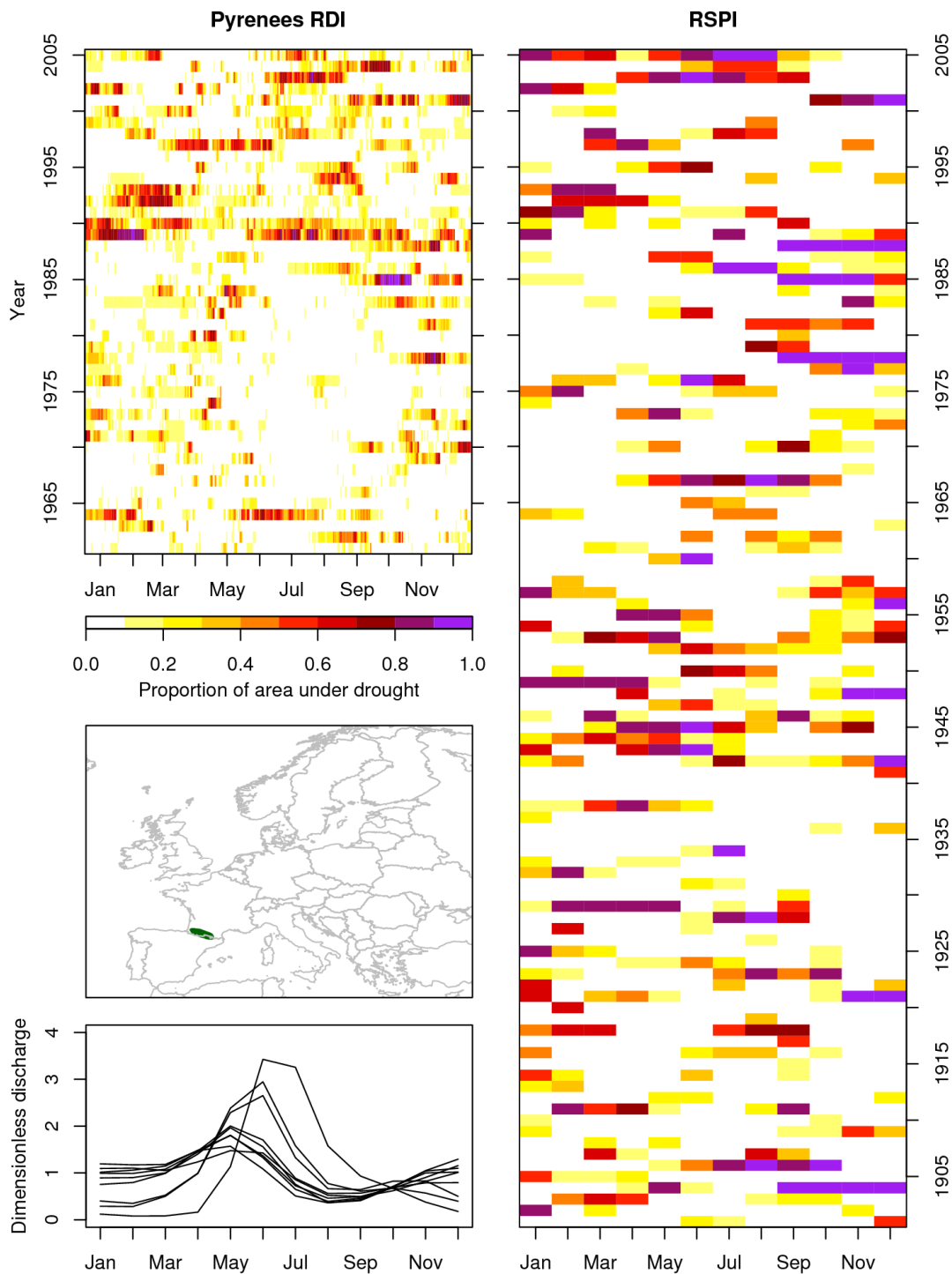


The groundwater-dominated catchments of SE Great Britain experience prolonged multi-year drought events episodically throughout the 1961-2005 period. Such events are highly coherent, reflecting homogeneous response amongst the catchments, which are all developed on the Chalk aquifer of the southeast. The relatively small number, but lengthy duration, of hydrological droughts in this region is determined by this characteristic: the permeable geology allows significant baseflow to sustain river flows during short periods of meteorological drought; conversely, the slow response means that droughts tend to persist, sometimes after meteorological deficiencies have ended. Such systems are only stressed if meteorological droughts are sustained throughout consecutive seasons or years. Hydrological droughts in this region only result from long-term precipitation deficiencies, as indicated by RSPI12, and these show distinct periods of multi-year clustering.

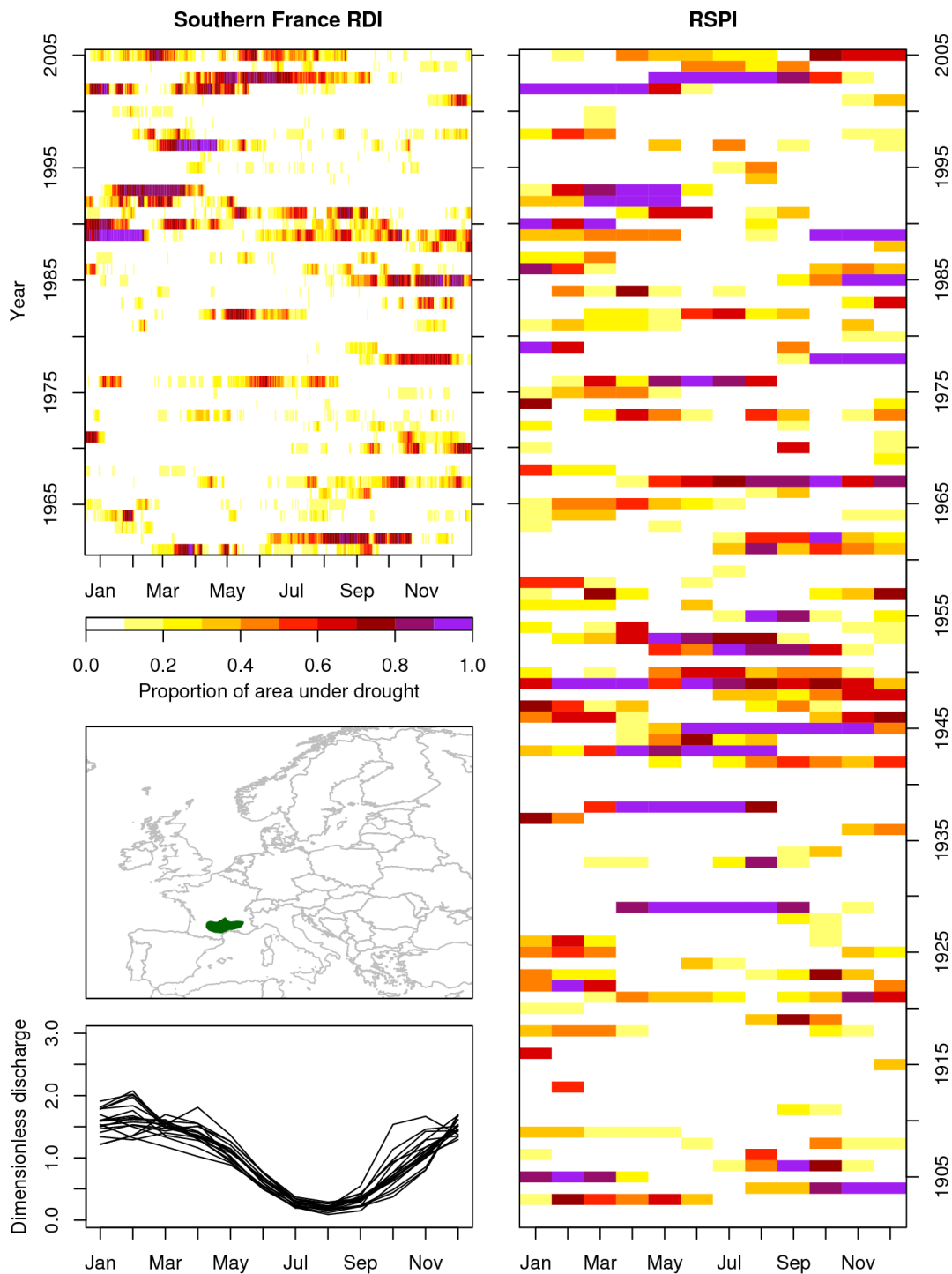


The NW Spain region exhibits many deficiencies but very few regionally coherent hydrological drought events, although it should be noted this region exhibits relatively low homogeneity in its hydrological response due to the large size of the region containing relatively few stations. The most severe droughts have occurred in winter and spring in recent years, and it appears that (albeit minor) deficiencies have become more common in general, whilst there is a lack of deficit conditions throughout most of the year in the early part of the 1961-2005 record. Coherent meteorological drought conditions are relatively prevalent according to RSPI3; the reduced homogeneity of the region mitigates the observation of concurrent deficiencies in the hydrological data. It appears that meteorological deficits are becoming more spatially coherent within the region over the twentieth century, although the duration and seasonality remain largely unaffected.

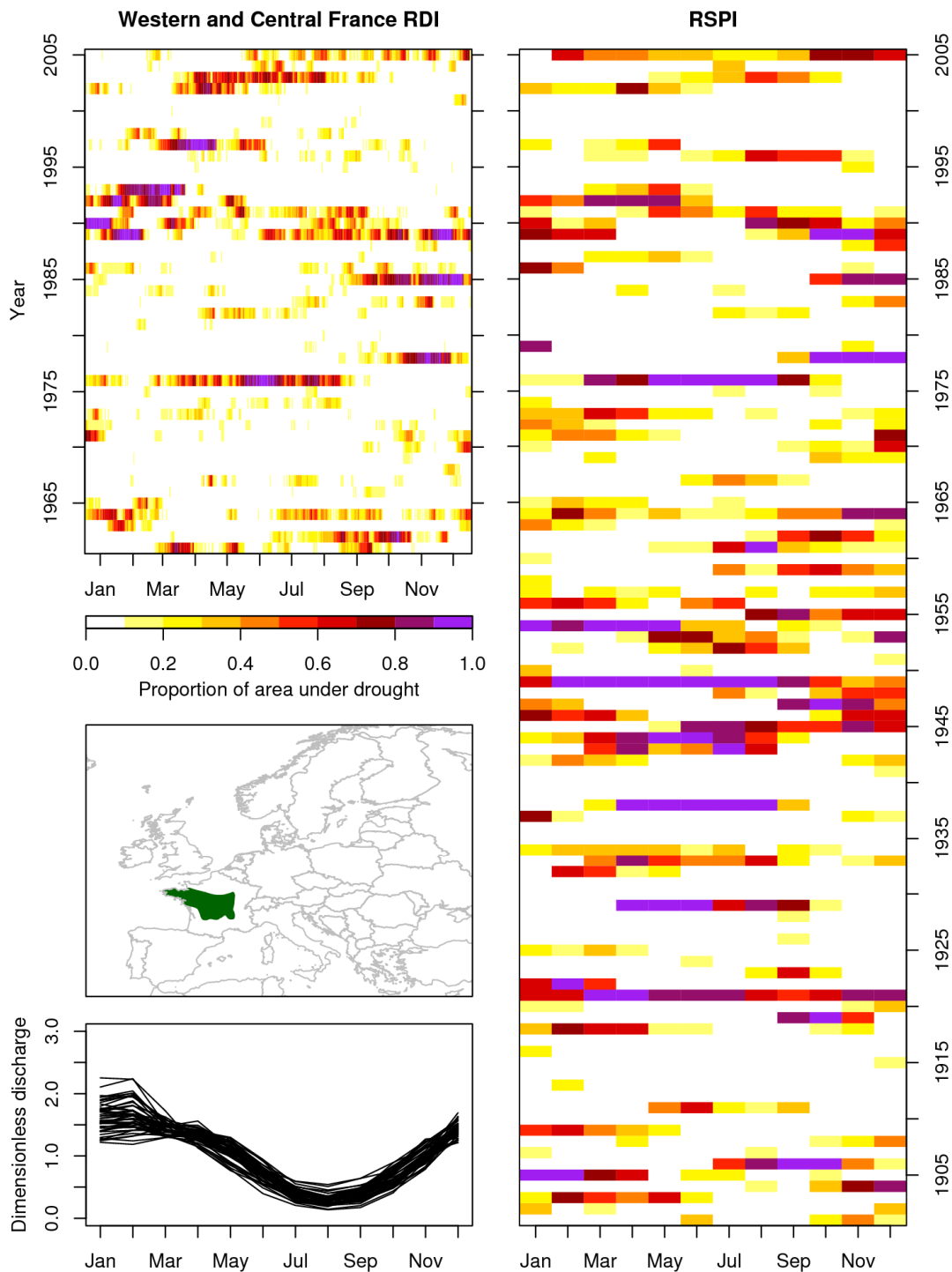




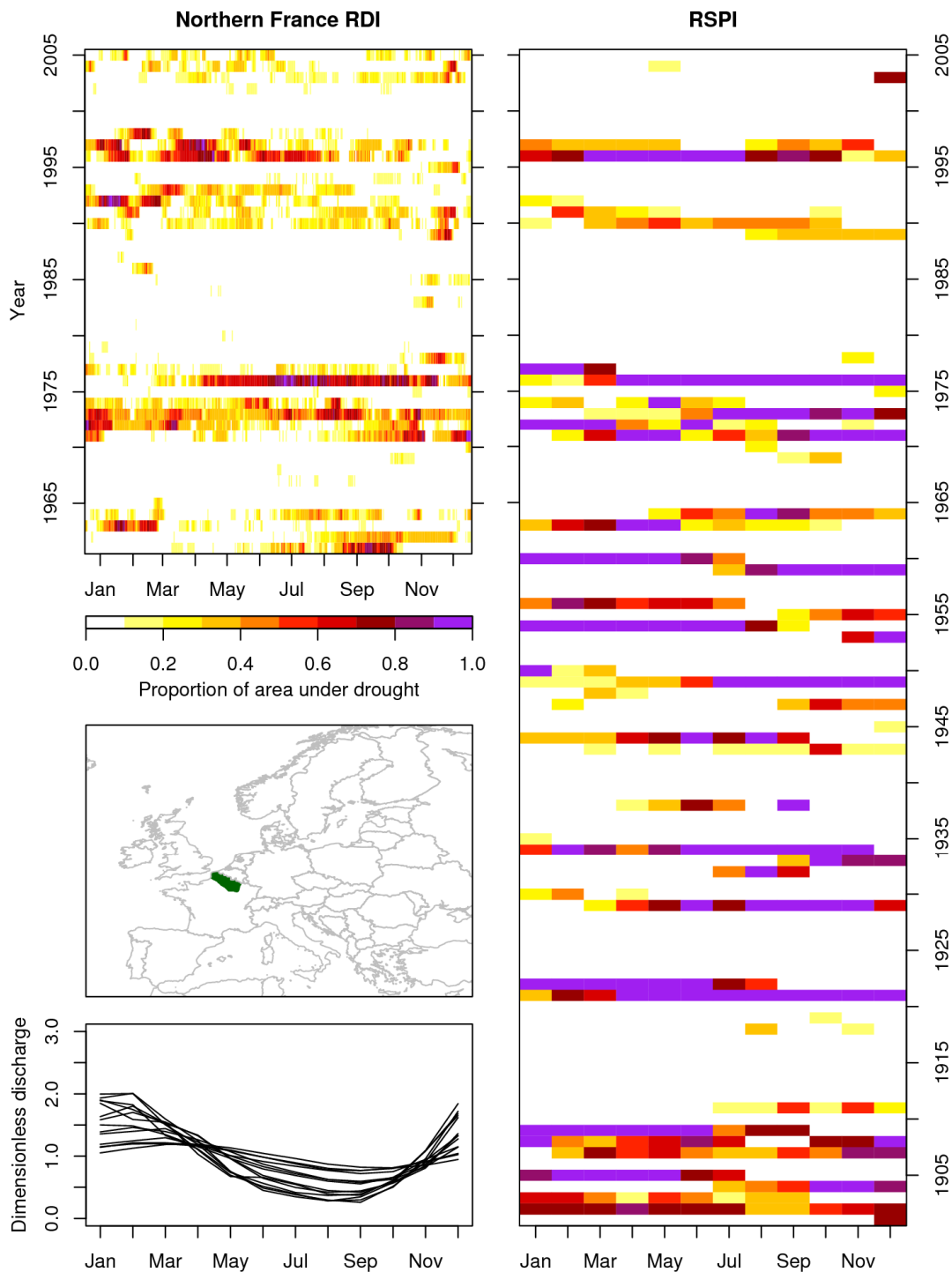
The most notable characteristic of hydrological drought in the Pyrenees region is the relative absence of drought conditions prior to 1985, and the prevalence of episodes after this date. The breakpoint is very apparent, with the most spatially coherent events occurring since this time, and a near-complete absence of summer droughts in the earlier part of the record. Catchments in this region are all snowmelt-influenced (as shown by the regime plots), so changing snowmelt patterns (perhaps towards earlier melt) may explain the occurrence of summer deficiencies more recently, compared to the earlier record. The spring melting period often corresponds to a break in drought conditions, but can also be associated with short deficiencies. Whilst temperature-driven snowmelt dynamics are undoubtedly important, overall the main hydrological droughts confirm to meteorological droughts, which often show strong spatial coherence as illustrated by RSPI3.



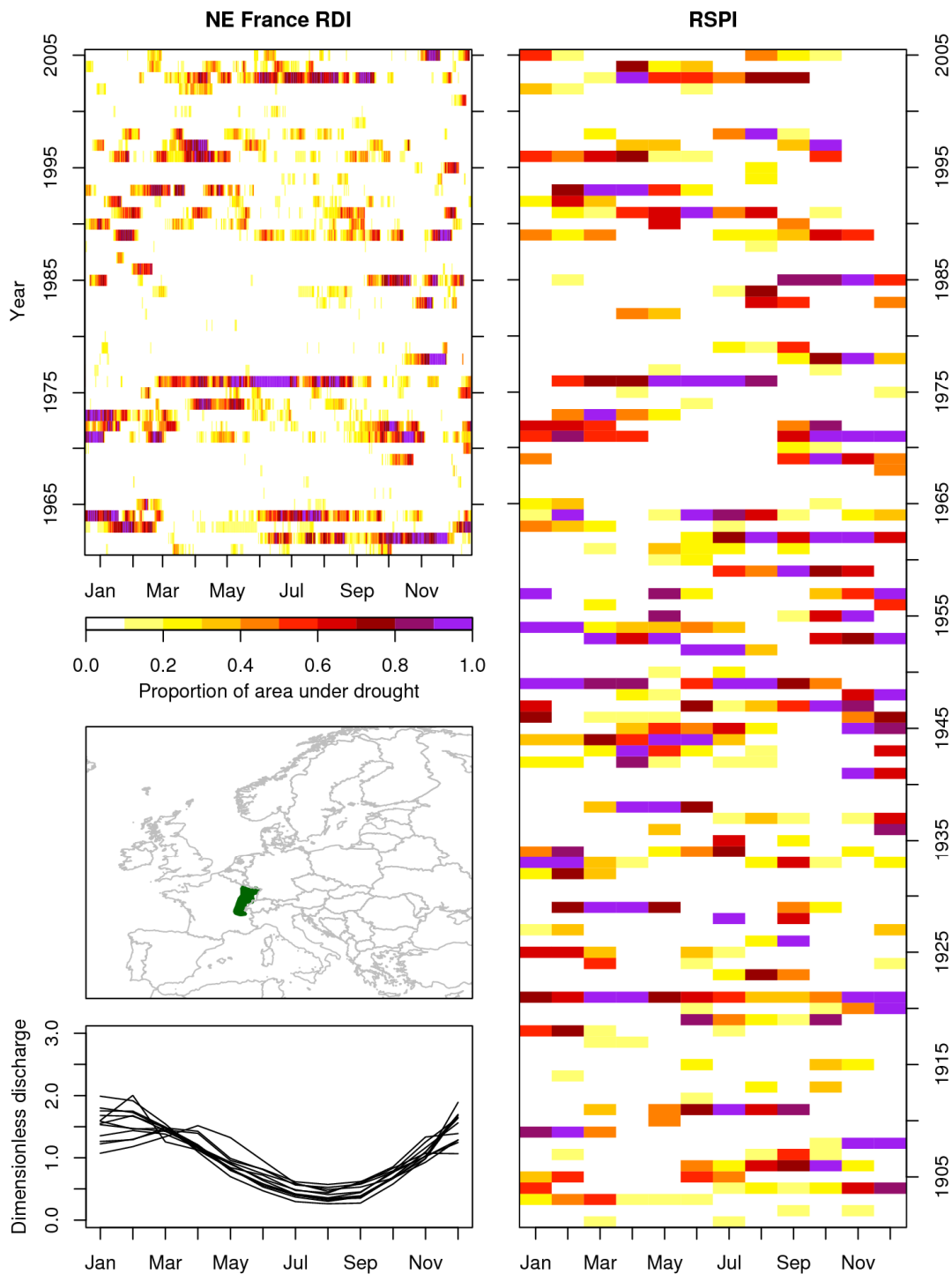
The Southern France region exhibits distinct hydrological drought-rich and drought-poor periods, although these have varied in their characteristics throughout the 1961-2005 record. Before 1985 there are relatively few significant hydrological droughts, and they tend to be of short (3-4 month) duration and of limited spatial coherence. However, since 1989 there has been a tendency toward longer, multi-year hydrological droughts (with a particular cluster 1989 – 1993) with most coherent deficits witnessed in the winter and spring especially, although with the 2003 summer drought being a notable exception. Patterns observed in hydrological drought appear to correspond fairly well with meteorological drought occurrence (RSPI6), although there are some periods in which there are periods of meteorological drought with no corresponding hydrological drought expression. The early part of the 20<sup>th</sup> century was relatively drought-poor, and the 1940s and early 1950s was particularly drought-rich.



The Western and Central France region exhibits similar drought characteristics to Southern France and, to a lesser extent, the Pyrenees; 1985 again appears to mark a breakpoint for increased prevalence of hydrological drought. The period prior to this is relatively drought-poor (although droughts in 1976 and 1978 are notable), but since 1985 there has been a tendency for spatially coherent deficits of moderate duration to occur in winter and spring – as part of a multi-year period of less coherent deficiencies in 1989 – 1993, and as a single short event in 1997. The 2002 – 2005 period also features long (but less coherent) deficiencies, including the summer 2003 drought and developing drought conditions in 2005 (also seen in SE England). There is good agreement between meteorological and hydrological drought indices, and the region is relatively homogeneous in its drought response, in spite of its large area. The 1940s and 1950s exhibit the most significant period of drought for this region as shown by RSPI6.

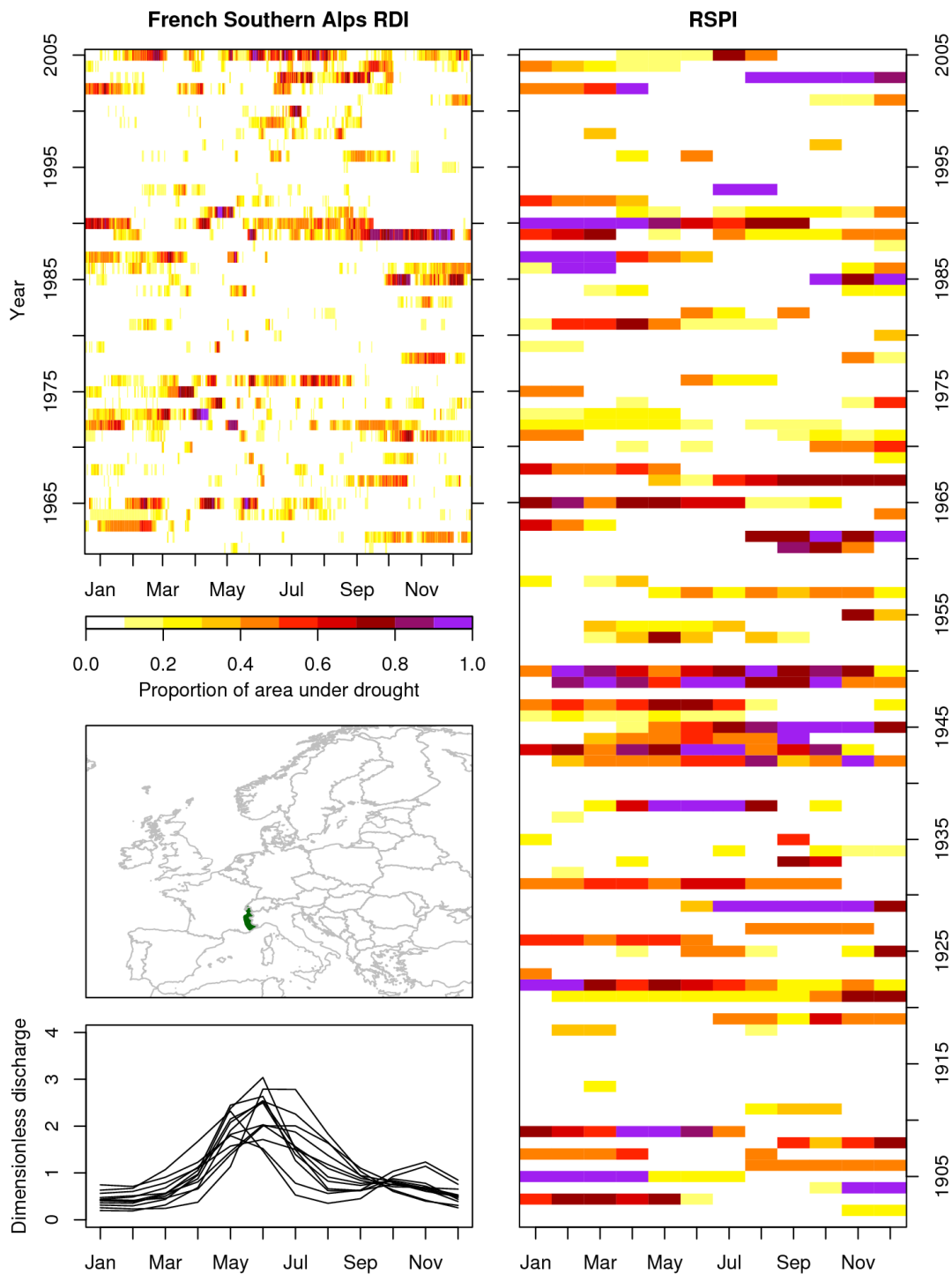


The hydrological drought characteristics exhibited by the Northern France region are similar to those in the SE Great Britain region, reflecting the similar geological settings. The influence of groundwater in this region is apparent from the duration and infrequency of the significant drought events, with very distinct drought-rich (e.g. early 1970s) and drought-poor periods (1980s). However, despite the long, multi-year droughts, the spatial coherence rarely reaches its maximum, suggesting that the catchments do not necessarily respond entirely homogeneously to precipitation. Nevertheless, there is a good correspondence between meteorological and hydrological drought. The RSPI12 index suggests that this region has become less affected by drought over the course of the 20<sup>th</sup> century, and meteorological droughts have been more severe (in RSPI terms) but not as sustained as those in SE Great Britain. The 1901 – 1910 period is a particularly strong cluster of long, severe droughts.

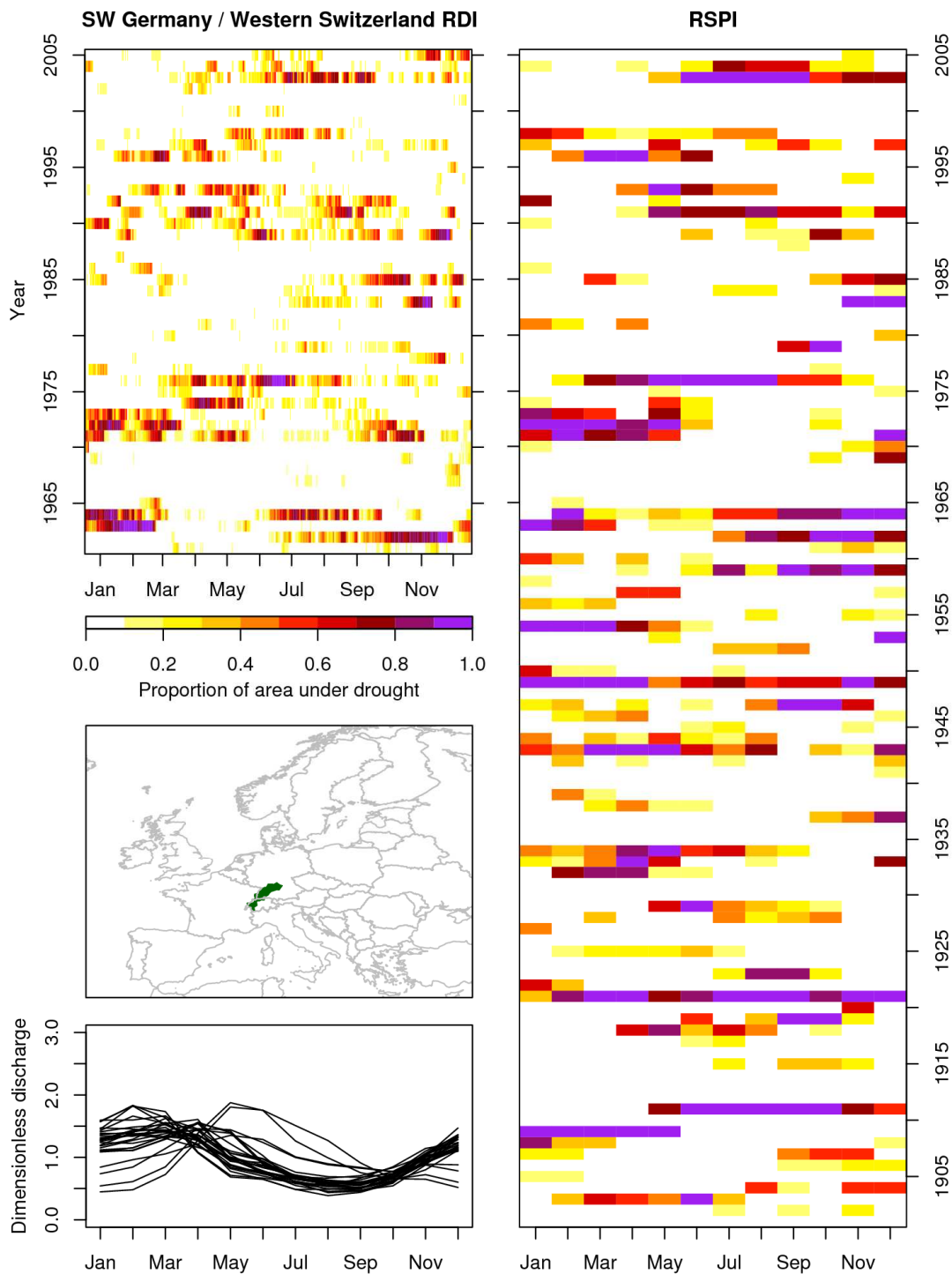


The hydrological drought chronology suggests that NE France is susceptible to a variety of drought types. There are numerous short-duration (1 – 2 months) events occurring at different times throughout the year, which display fairly high (but rarely maximum) spatial coherence, and are part of longer runs interrupted by periods of no deficiency (e.g. 1971 – 1974, 1988 – 1992); longer droughts are therefore more regularly “broken” than in other regions in northern France. In contrast, there are distinct periods in which there are very few drought episodes, and there are some longer events in the early 1960s, 1976 and 2003. Meteorological deficiencies given by RSPI3 are more prevalent towards the end of the calendar year, but this does not show a concurrent response in the hydrological drought index.

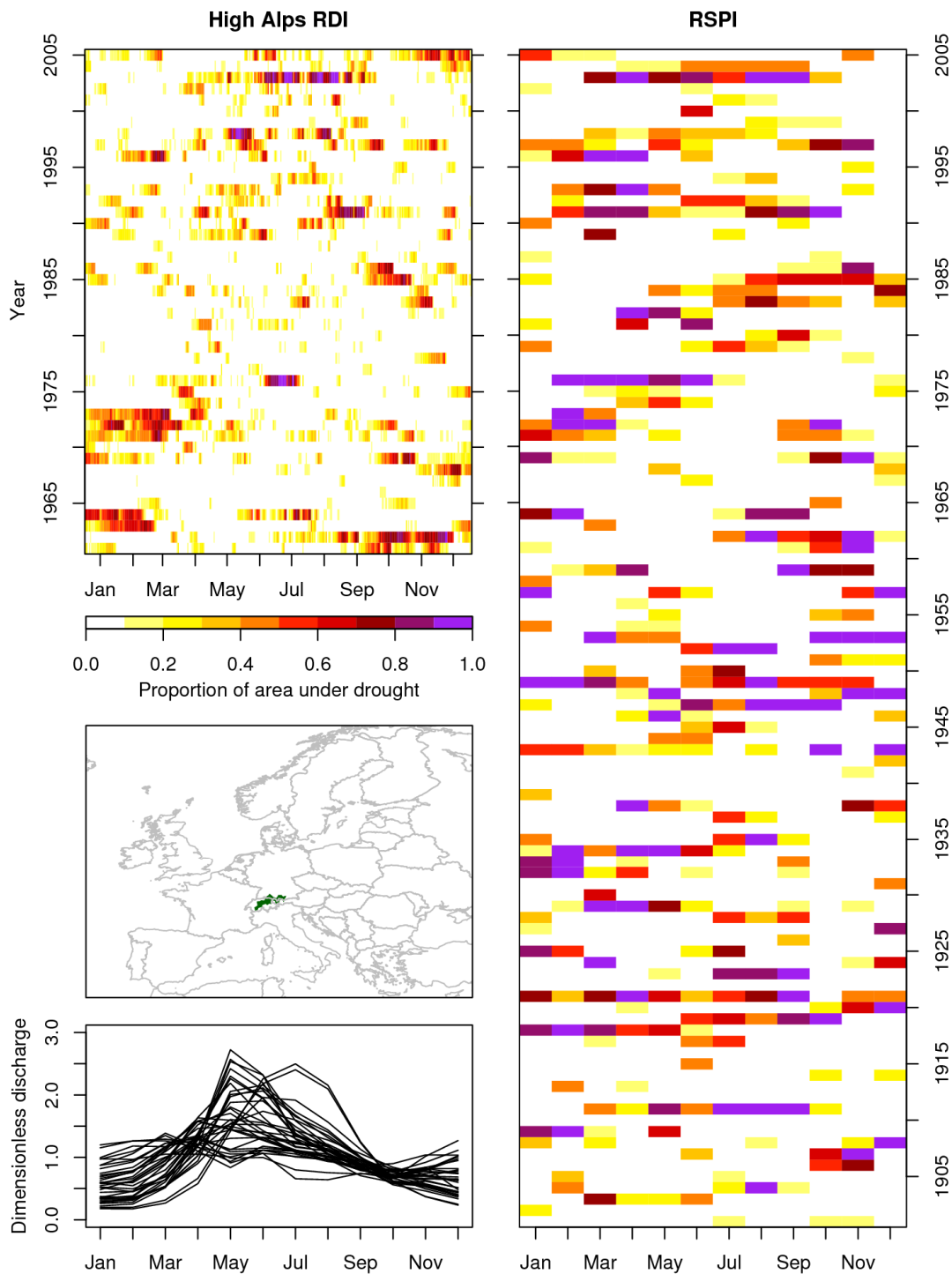




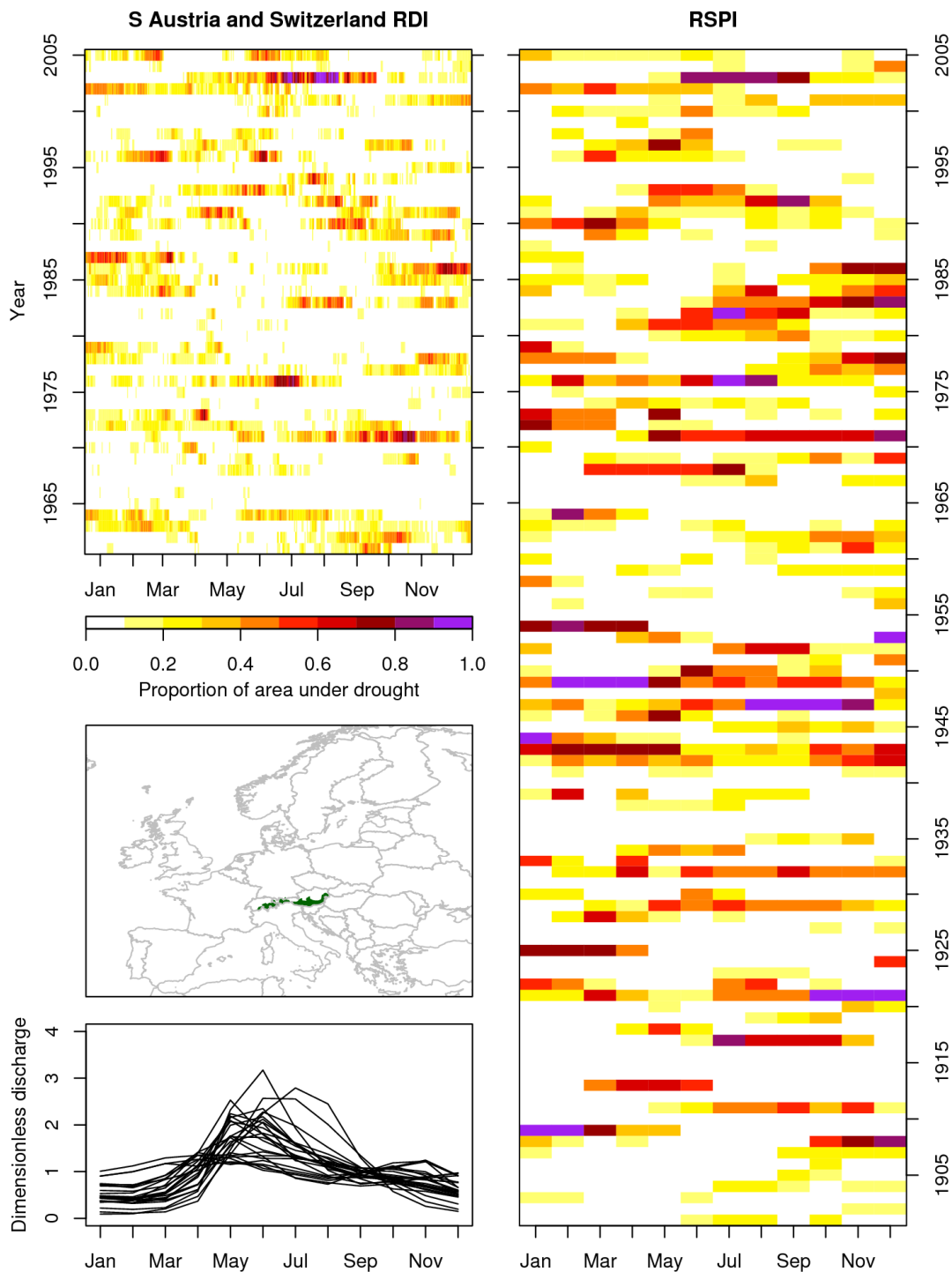
The regimes of the French Southern Alps region are influenced by melting snow and ice. The expression of hydrological drought is relatively limited; there are a few years which exhibit prolonged streamflow deficits, but these rarely reach high values of spatial coherence. Such episodes predominantly occur in the summer and autumn, and summer droughts have become more apparent since the late 1980s, perhaps suggesting earlier snowmelt and warm, dry spring/summer periods. Furthermore, winter deficits were more common earlier in the record, but almost absent in the 1990s. As with the Pyrenees region, there appears to be a minor deficit in the spring in some years, although in others there is often a consistent break in deficit conditions at this time. Meteorological droughts (RSP19) tally with some hydrological events, but there are notable exceptions which may underline the role of temperature of a driver of drought.



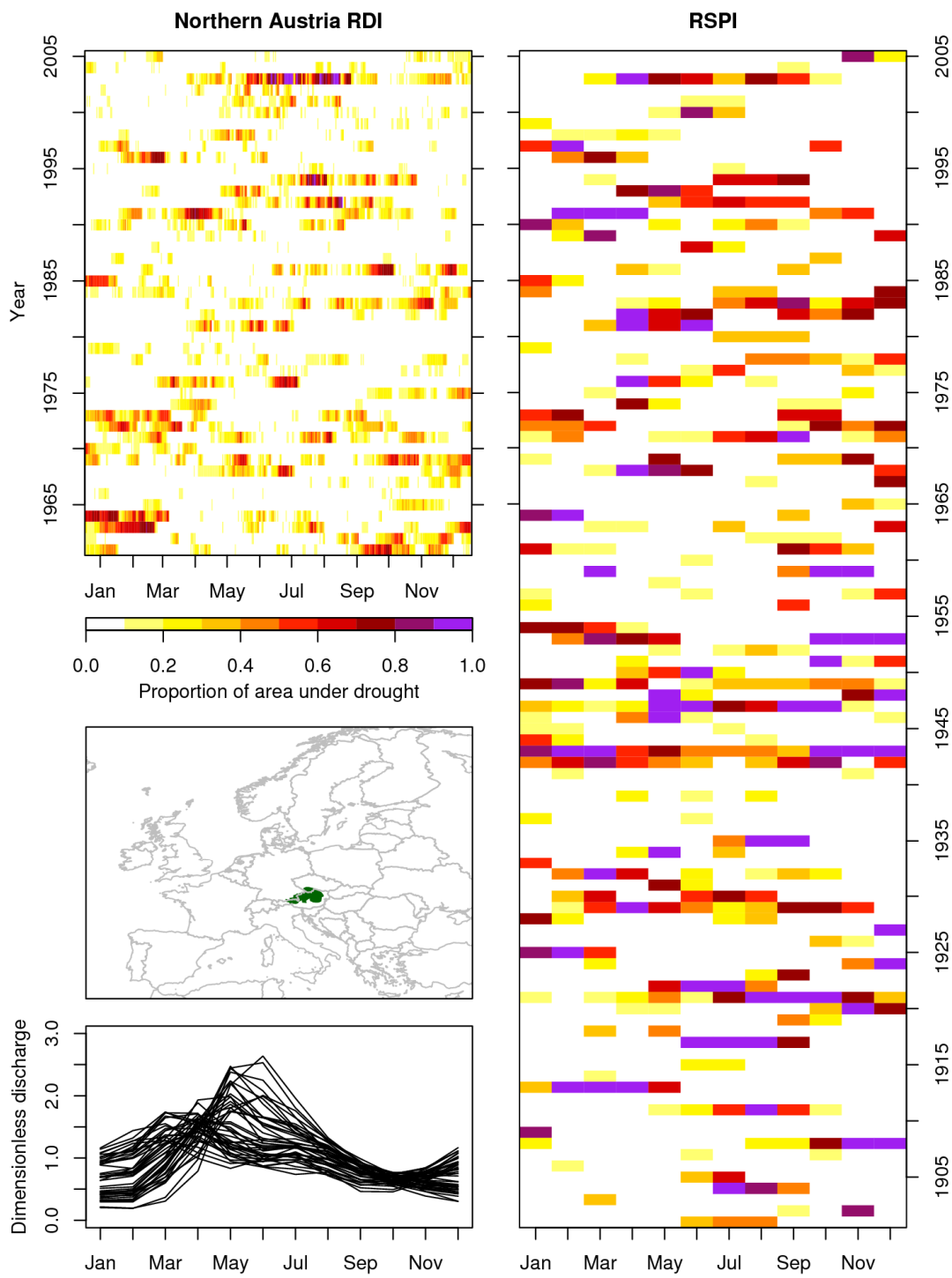
For the SW Germany and Western Switzerland region, deficiency periods exhibit a variety of durations, timings of onset, and spatial coherence. This is likely influenced by the different types of catchments within the region, as can be witnessed in the hydrological regime plot, featuring a combination of rainfall-dominated regimes and high altitude snowmelt-dominated regimes. Nevertheless, the drought characteristics are broadly similar to the neighbouring NE France region, albeit with less spatial coherence: drought episodes typified by short deficiencies interspersed with wetter interludes, and the occasional longer drought. The early 1960s and early 1970s feature successive winter droughts. Meteorological drought (RSPI6) experienced in this region exhibits more spatial coherence than for hydrological drought.



For the High Alps region, the timing of onset of hydrological drought appears to have shifted over the 1961-2005 period. In the 1960s and 1970s, hydrological drought predominantly occurred in the autumn and winter months, with very few deficit periods in the summer (except for short-but-intense drought in 1976). This probably reflects catchments which were largely frozen in the winter months in such high altitude areas, with abundant runoff in the spring/summer peaks. More recently, there has been a shift towards clusters of deficiency periods in the summer months, perhaps suggesting that winters are now milder (mitigating winter droughts) and that recent hot, dry summers have been influential (e.g. summer 2003), likely causing earlier melting and low runoff in the summer. There is relatively little structure in the meteorological drought characteristics of this region, with durations short, seasonality variable, and spatial coherence sometimes significant illustrated by RSPI3.

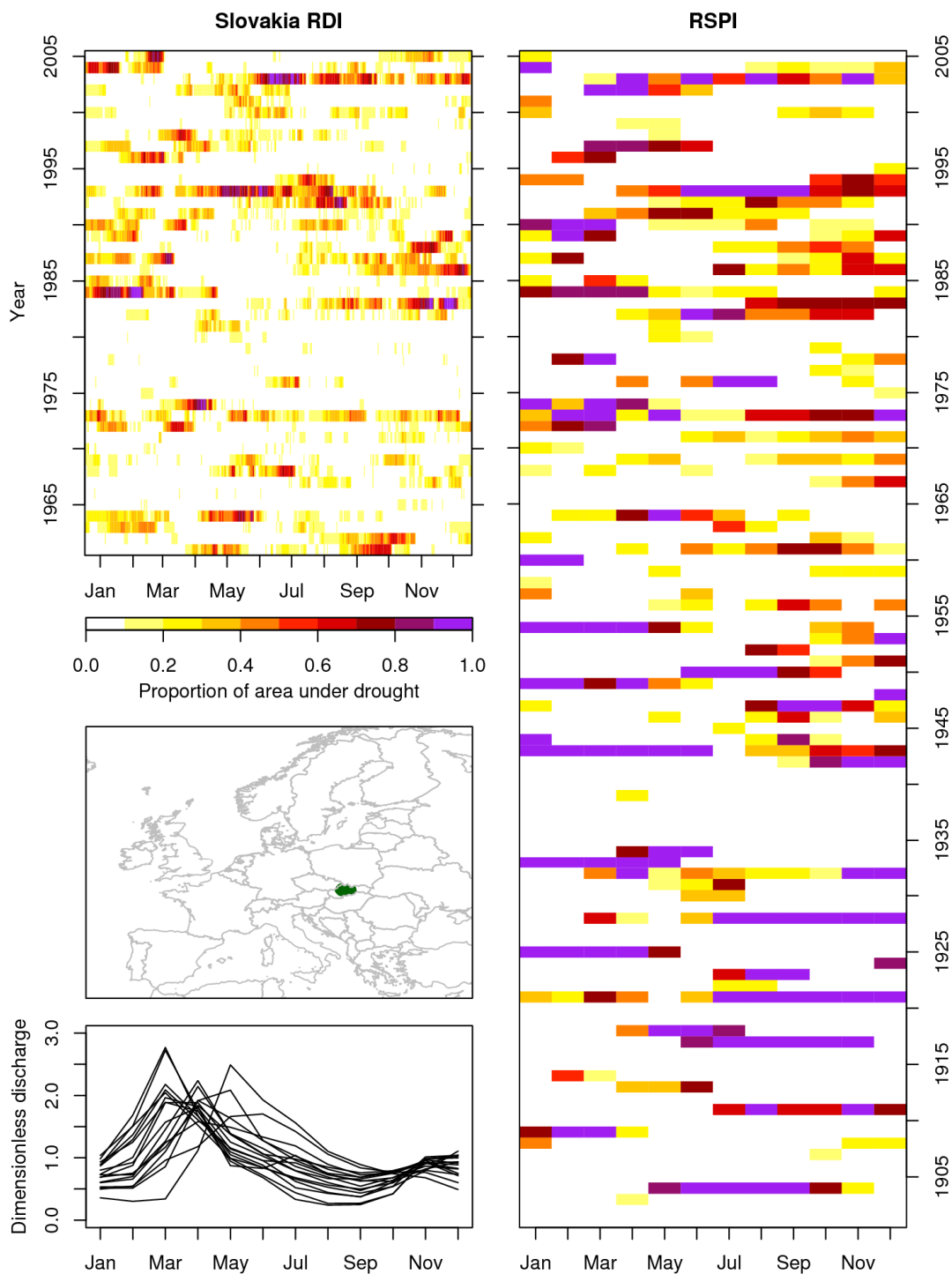


Hydrological drought events in the Southern Austria and Switzerland region occur frequently, although they rarely exhibit significant spatial coherence (RDI values are predominantly  $<0.5$ ). This is likely influenced by the lack of homogeneity: this region has the lowest in this study. Periods of more pronounced deficiency tend to be of short duration and there is no consistent seasonal pattern of drought timing. There is some evidence of an increasing prevalence of summer events, as in other alpine regions, but winter droughts have remained broadly similar, generally being of low spatial coherence. There is evidence of a spring cessation of droughts in many years, as well as minor deficits, and some indication that the timing of this has changed over the 1961-2005 period. The limited correspondence between meteorological (RSPI6) and hydrological drought expression is likely influenced by the low homogeneity of the region, and storage of precipitation in snow and ice within catchments.

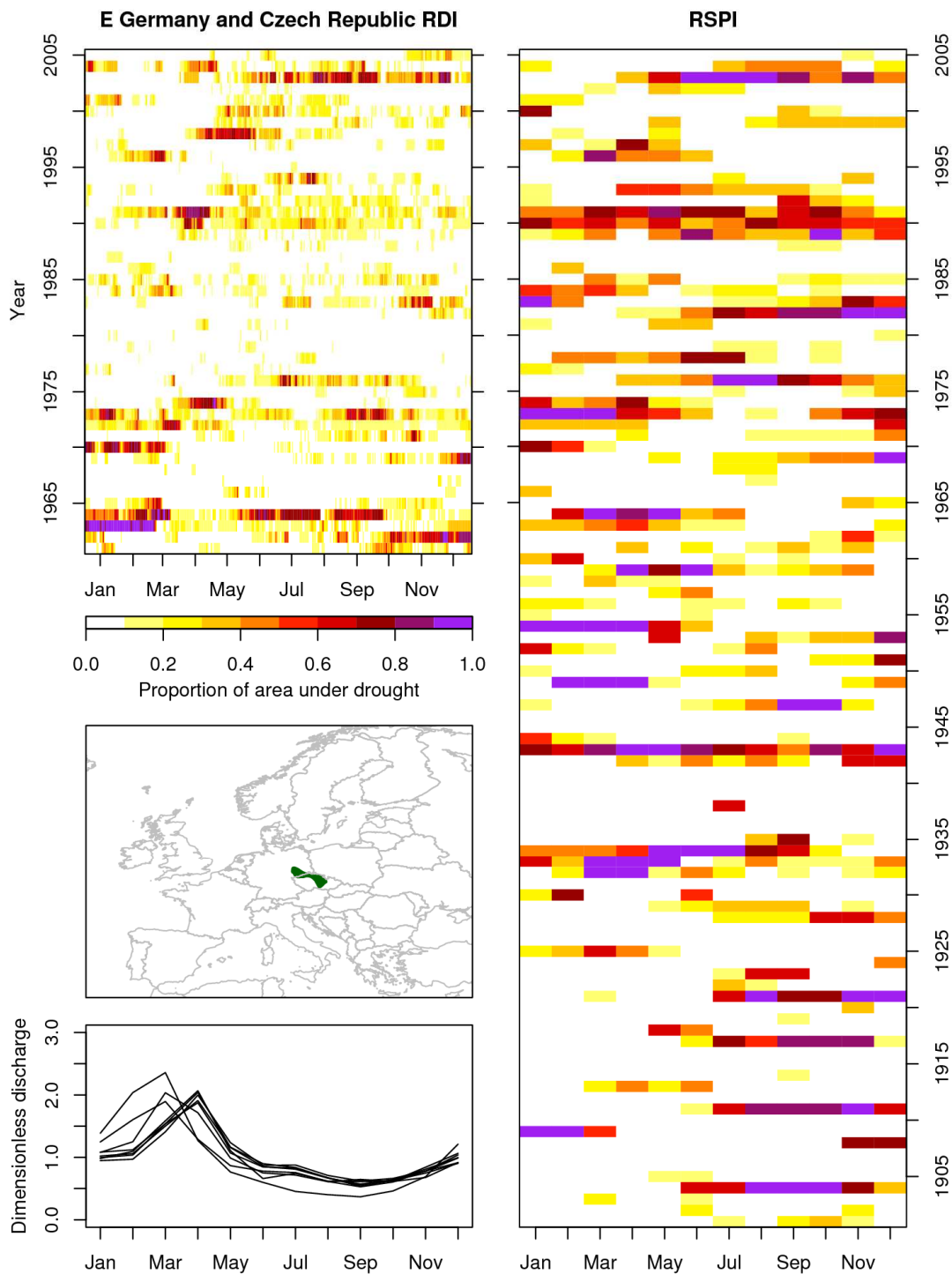


The Northern Austria region experiences predominantly short duration hydrological drought events, with moderate spatial coherence. There is no consistent pattern in terms of the seasonality of deficits (likely to be a consequence of the differing hydrological regimes of the catchments within this region; see regime plots), although broadly similar patterns to S. Austria/Switzerland occur, with winter droughts in the 1960s and 1970s, which are less common later relative to summer droughts. Spring and summer seasonal snowmelt terminates winter and spring deficit periods at varying times. As is witnessed in other snowmelt-dominated regions, there is limited correspondence between meteorological and hydrological drought; meteorological deficits (shown as RSPI3) often do not manifest themselves in runoff due to the slow response time and persistence of snow and ice storage within catchments.

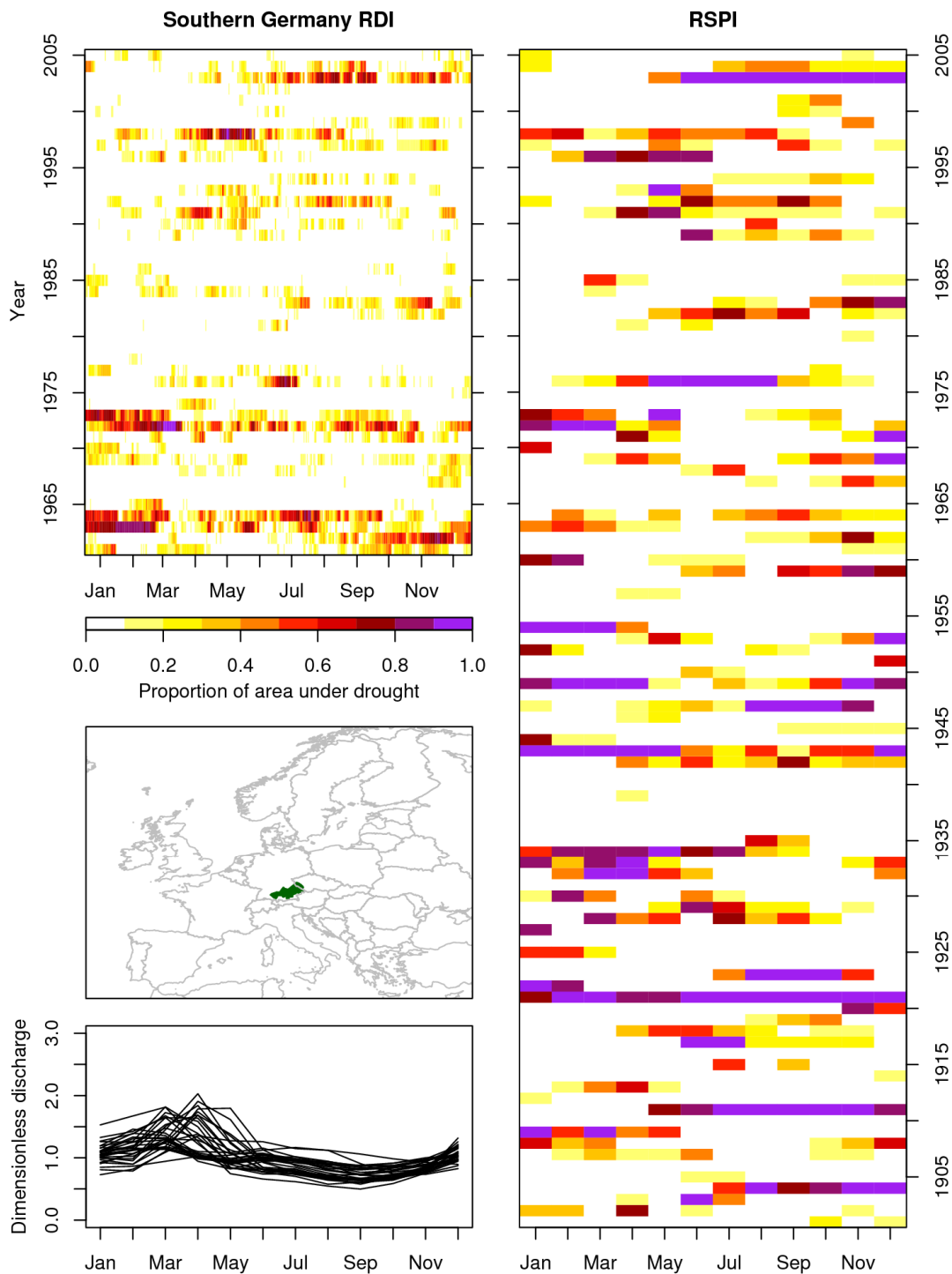




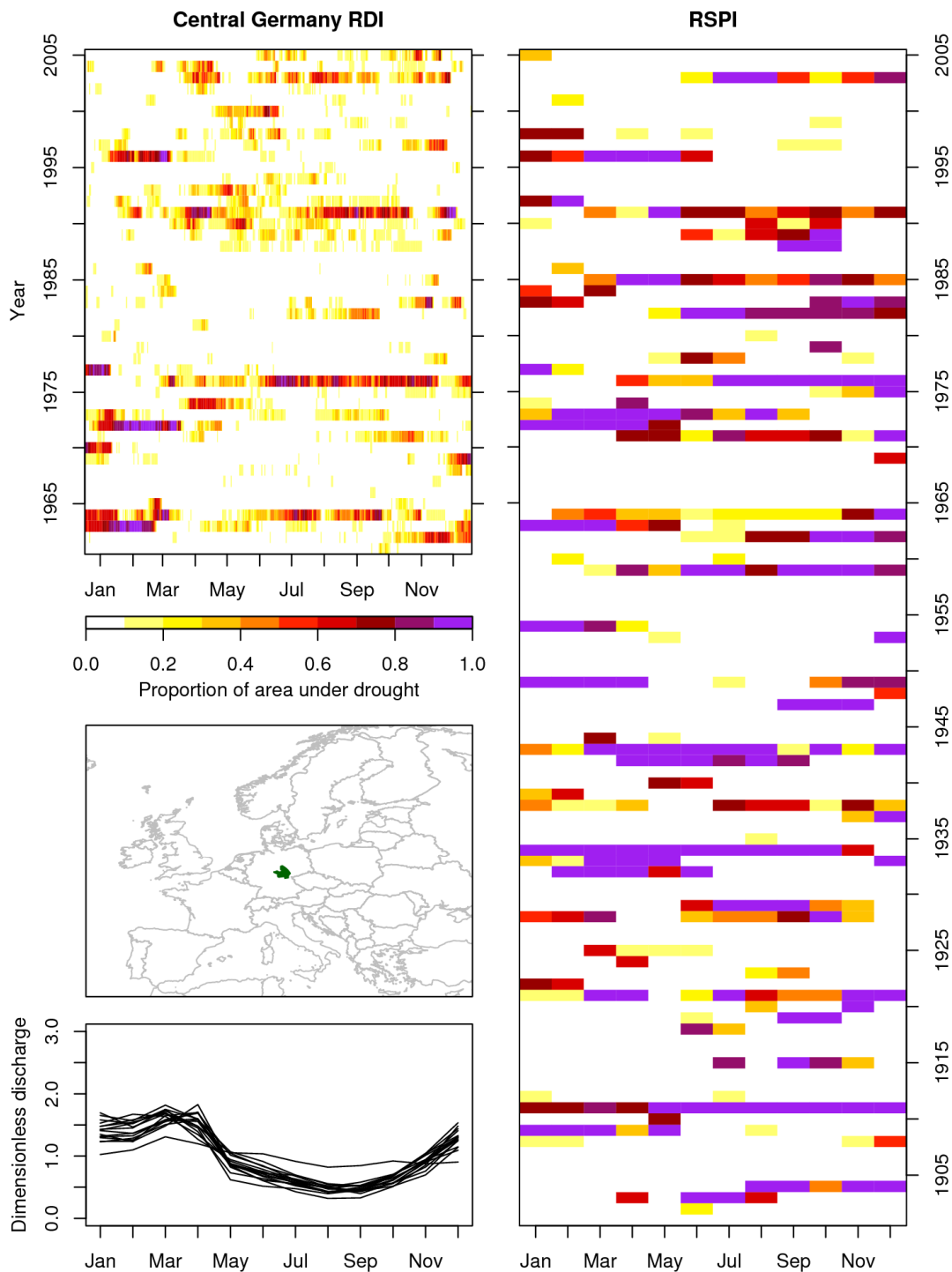
The Slovakia region exhibits some protracted periods of streamflow deficiency, over multiple seasons or years, and on some occasions attaining high levels of spatial coherence (e.g. 1984/1985; 1993; 2003). The most severe events do not show a seasonal pattern, with deficits common in both summer and winter. Droughts are less notable in the earlier record, and there is a distinct drought-poor period from 1975 – 1982. After this, droughts are much more frequent and prolonged. The short- and long-term meteorological droughts (RSPI6) also show clustering which is broadly similar to the hydrological droughts, although there are some significant meteorological droughts prior to 1982 that are not represented as streamflow deficiencies. There are also differences between the earlier RSPI record, where there are coherent droughts interspersed with drought-poor gaps, and post-1955 where less coherent deficits become more prevalent.



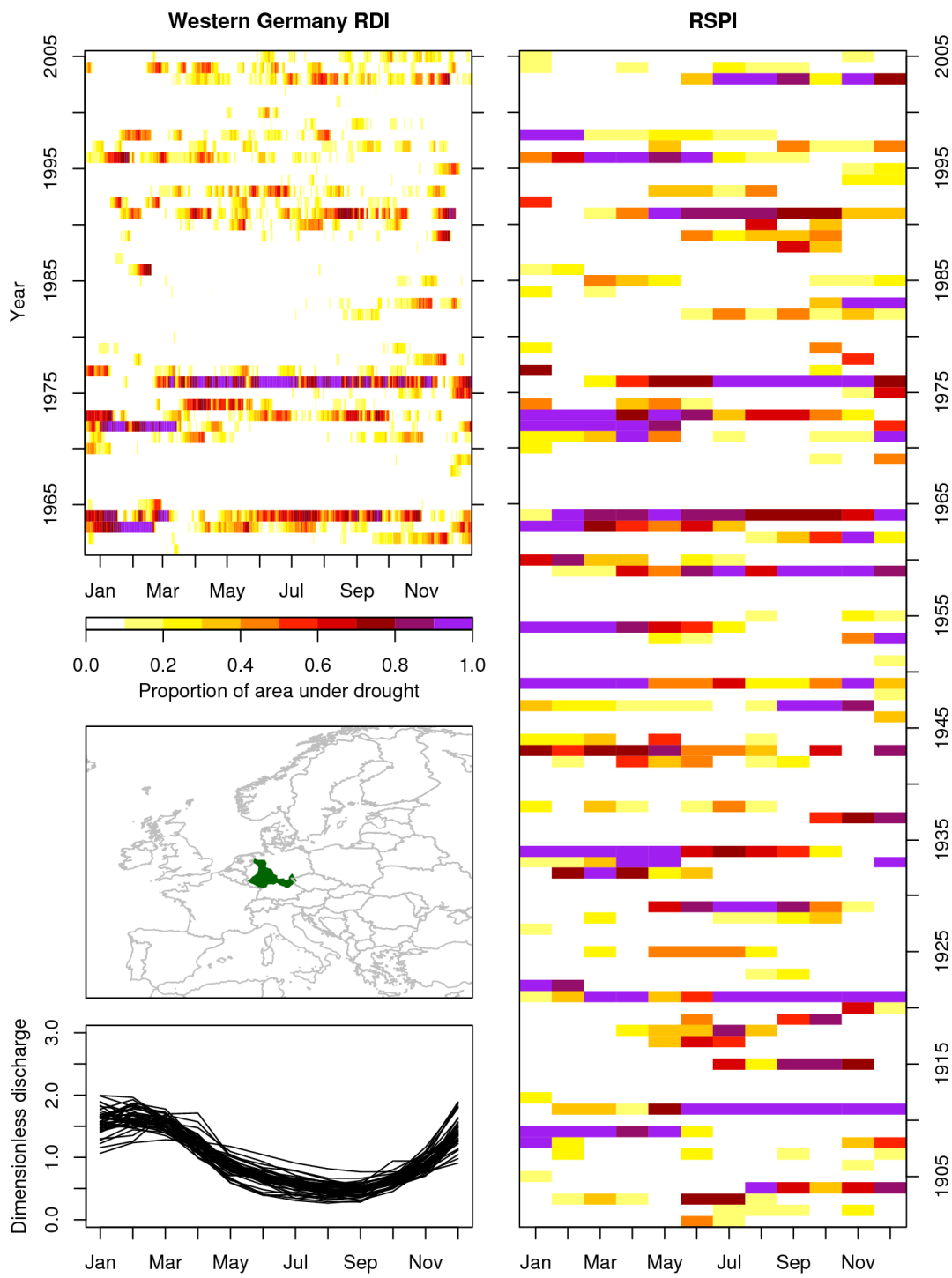
The most severe hydrological droughts witnessed in the East Germany and Czech Republic region occur at the beginning and end of the 1961-2005 period. Clusters of multi-season drought occur in the early 1960s and early 1970s, including successive dry winters and summer drought in 1964. Between 1975 and 1990, hydrological drought occurrence is limited; after this, significant streamflow deficits occur in spring/summer (e.g. 1990, 1997), often within incorporated within minor multi-season episodes. Despite their protracted nature, the longest hydrological droughts rarely achieve maximum spatial coherence (e.g. in 2003). Whilst the major hydrological deficiency periods do correspond with precipitation deficits (shown by RSPI6), the most protracted meteorological drought in 1989-1991 has very little hydrological expression, and similarly significant precipitation deficiencies during the 1975-1990 period have little hydrological impact.



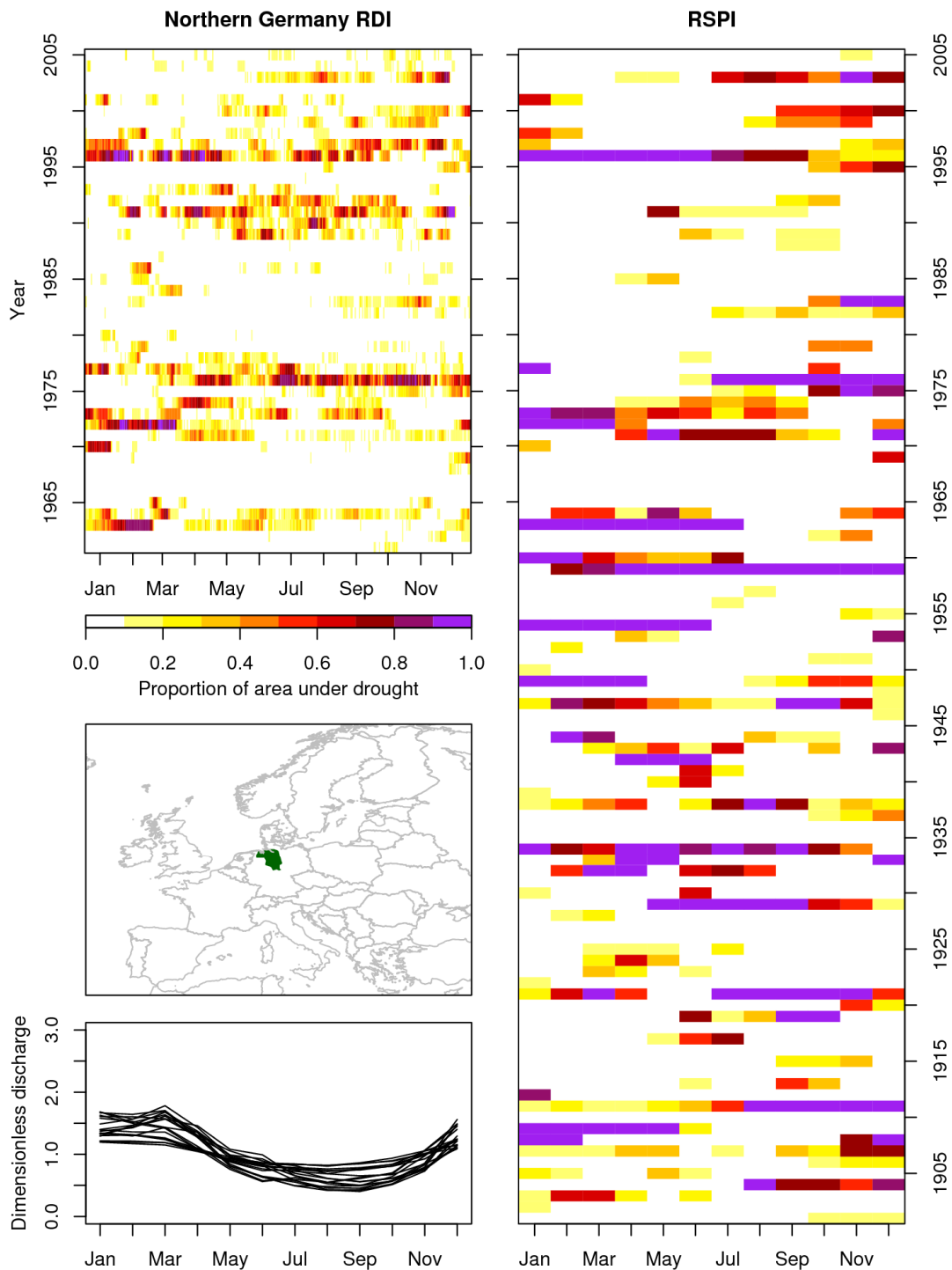
The Southern Germany region exhibits similar hydrological drought characteristics to those of the East Germany/Czech Republic region. The two most severe episodes occur prior to 1974, both multi-year episodes with successive dry winters. There is limited hydrological drought expression up to the mid-1990s, with long (but broken) summer events afterwards. Whilst multi-year hydrological droughts are apparent, streamflow deficiencies rarely achieve maximum values of spatial coherence; events can be prolonged but are broken up by wetter interludes. There is also a shift in seasonality of hydrological drought events, with winter droughts common early in the record but absent later; summer droughts occur throughout and can be protracted (e.g. 1964, 1972, 2003). There is generally a good correspondence between meteorological (RSPI6) and hydrological drought, although there are significant precipitation deficiencies that have little hydrological expression.



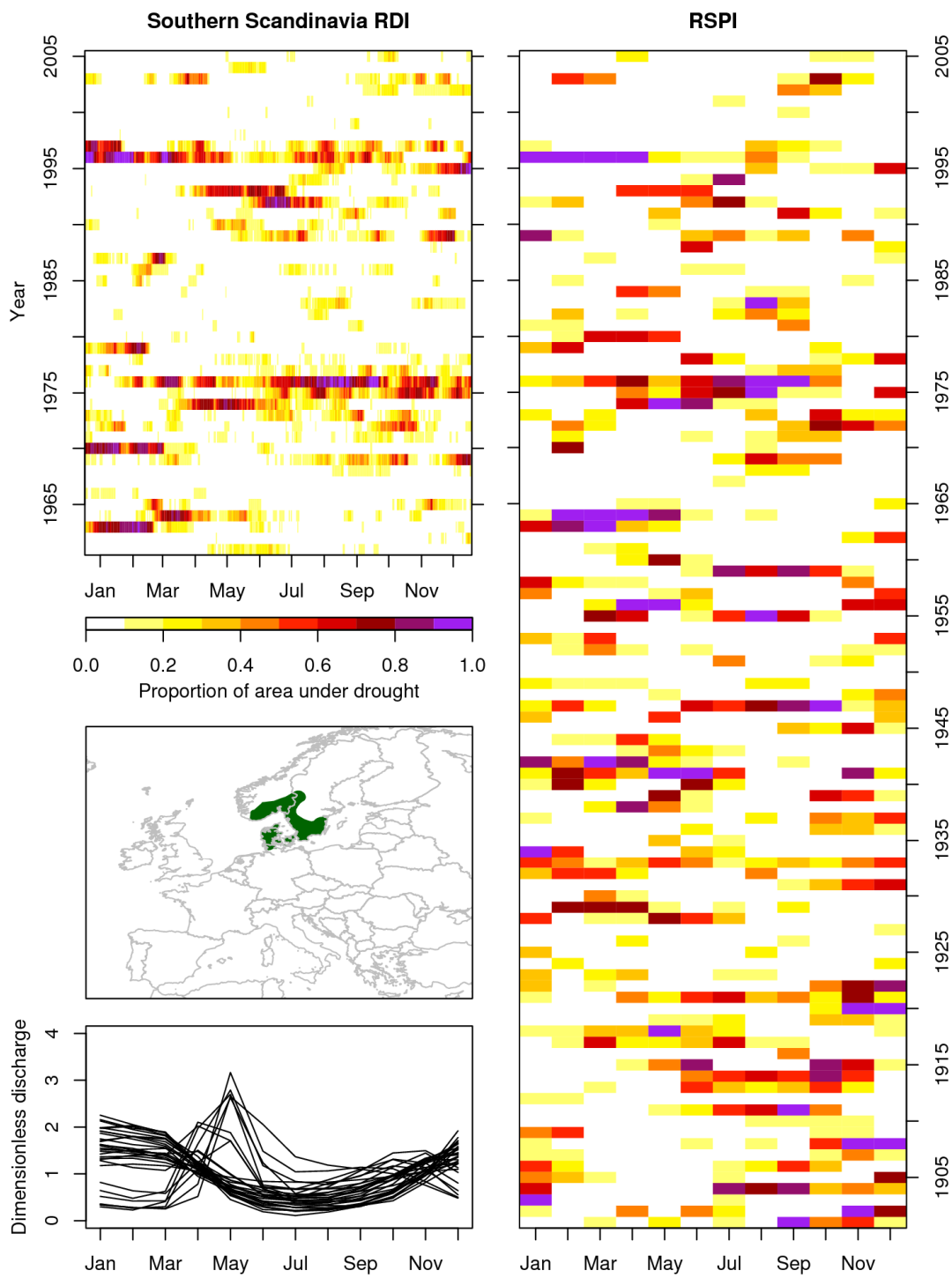
Central Germany exhibits relatively few hydrological droughts, although those which do occur tend to attain high peak coherence - particularly winter droughts in 1962 and 1972, with summer/autumn events rarely achieving the same extent of spatial coherence. Whilst prolonged periods of moderate RDI occur, generally in summer/autumn (e.g. 1976, 1991), there are few truly multi-season or multi-year events. The major hydrological events are separated at fairly regular intervals by periods of little or no drought occurrence. Meteorological drought is much more prevalent than hydrological drought in this region, with many instances of highly spatially coherent precipitation deficits (RSPI6). However, some of the most severe meteorological deficiencies have little corresponding hydrological expression.



Western Germany exhibits many of the characteristics common to other German regions, with the two most significant hydrological droughts occurring during the initial 15 years of the 1961-2005 period. Thereafter, there is little hydrological drought expression, and virtually none between 1978 and 1988. The two early multi-year drought periods are the only events which exhibit long durations and high spatial coherence, and they incorporate both winter (1963/64 and 1972/73) and summer (1964, 1976) deficiencies. The expression of hydrological drought in recent years is muted, and much less pronounced than witnessed in other German regions. There is correspondence between meteorological (RSPI6) and hydrological drought for the two most significant events in the 1961-2005 period; the spatial coherence and duration of the precipitation deficiencies for these two episodes suggest that they among the most severe drought periods in the twentieth century. Other meteorological droughts appear less efficacious in causing a hydrological response.

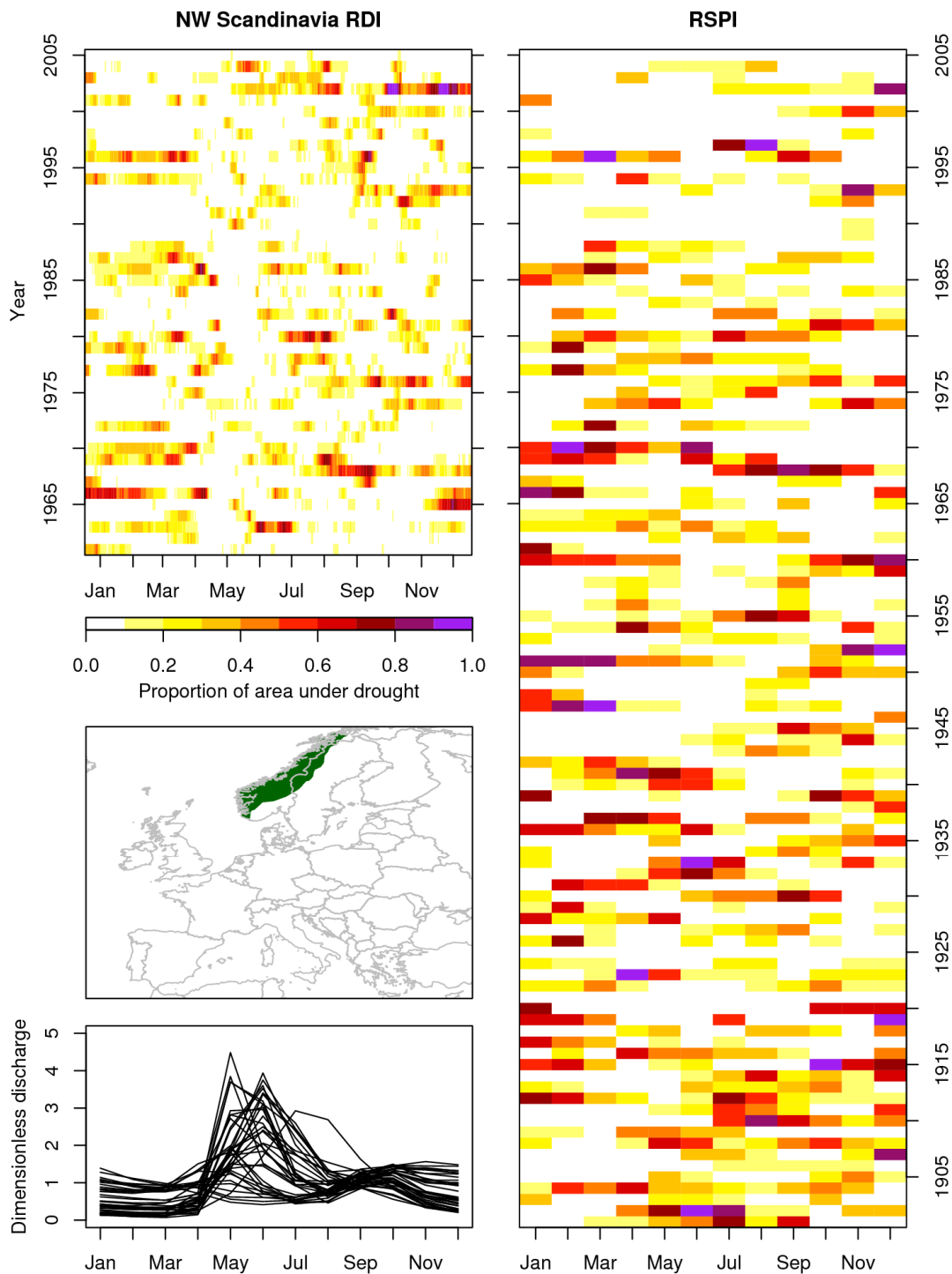


The Northern Germany region can be characterised by a series of distinct drought-rich and drought-poor periods, with little hydrological expression during the intervening years. In common with many of the other German regions, there is an absence of hydrological drought from the late 1970s to the late 1980s. Patterns are broadly similar to W. Germany, but earlier droughts are less severe in this region. Whilst there is evidence of prolonged periods of streamflow deficiency (e.g. 1976, 1996), there is a failure to maintain high values of spatial coherence. Meteorological droughts given by RSPI6 frequently achieve high values of spatial coherence, sometimes for protracted durations, but such significant deficiencies do not correspond always trigger hydrological drought; conversely, 1989- 1993 is characterised by hydrological deficits in spring – autumn (which are of limited spatial coherence and are not sustained), which are not associated with major precipitation deficiencies.



Southern Scandinavia can be characterised by infrequent hydrological droughts which often achieve very high values of spatial coherence. The region is relatively homogeneous in its drought response, although this is somewhat surprising as the region is comprised of catchments with two very different hydrological regimes. The most coherent hydrological droughts that occur in this region are predominantly of short – moderate length (2 – 4 months), particularly the early winter droughts, although longer episodes of coherent deficiencies occur as part of multi-year episodes (e.g. 1975/76, 1995 – 1997). Meteorological drought illustrated by RSPI3 corresponds well with expression of hydrological drought in this region, although it is rare for high values of spatial coherence to be exhibited for even moderate durations.





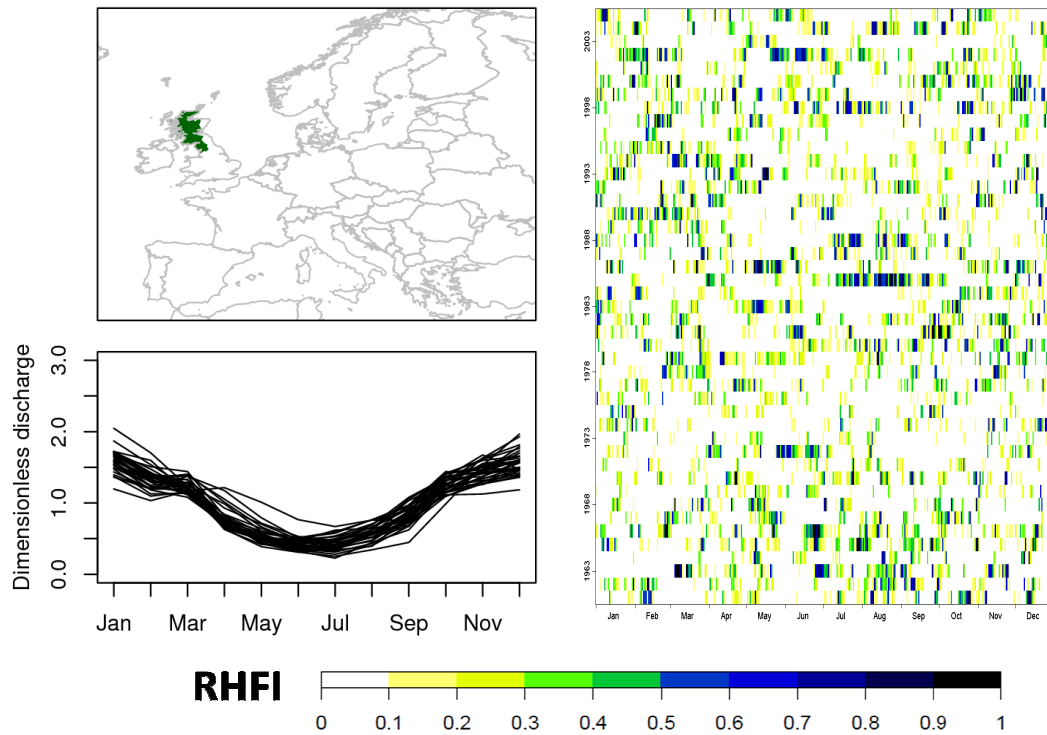
In the Northwest Scandinavia region, whilst hydrological droughts occur frequently, they are predominantly short duration events which demonstrate little spatial coherence. There is a tendency for the longer episodes to occur in the winter half-year, and these sometimes attain moderate coherence (notably 1965/66, 2002). This is likely due to unusually cold winters inhibiting meltwater or precipitation inputs to the hydrological system. In most years with winter drought, deficits are terminated by the spring/summer snowmelt season (April – June), when RDI is typically zero. Summer half-year deficits are generally short and weak, although there are exceptions (e.g. 1980). Meteorological drought shown through RSPI3 agrees with the hydrological pattern on a broad scale, with short and generally less spatially coherent deficits, but a lack of agreement in some droughts (e.g. 2002) may reflect the importance of cold temperatures in driving winter droughts. It appears meteorological droughts have become less frequent and less severe over the course of the twentieth century.

## 6. High Flow Catalogues

The regional high flow catalogues for the 23 European regions are presented over the following pages, with one region per page. For each catalogue, each year is represented as a horizontal row, from January on the left to December on the right, with years arranged vertically, from 1961 at the bottom to 2005 at the top. White and yellow colours indicate low RHF1 values (insignificant regional high flows) whilst blue and black colours represent regionally significant, spatially coherent high flow events.

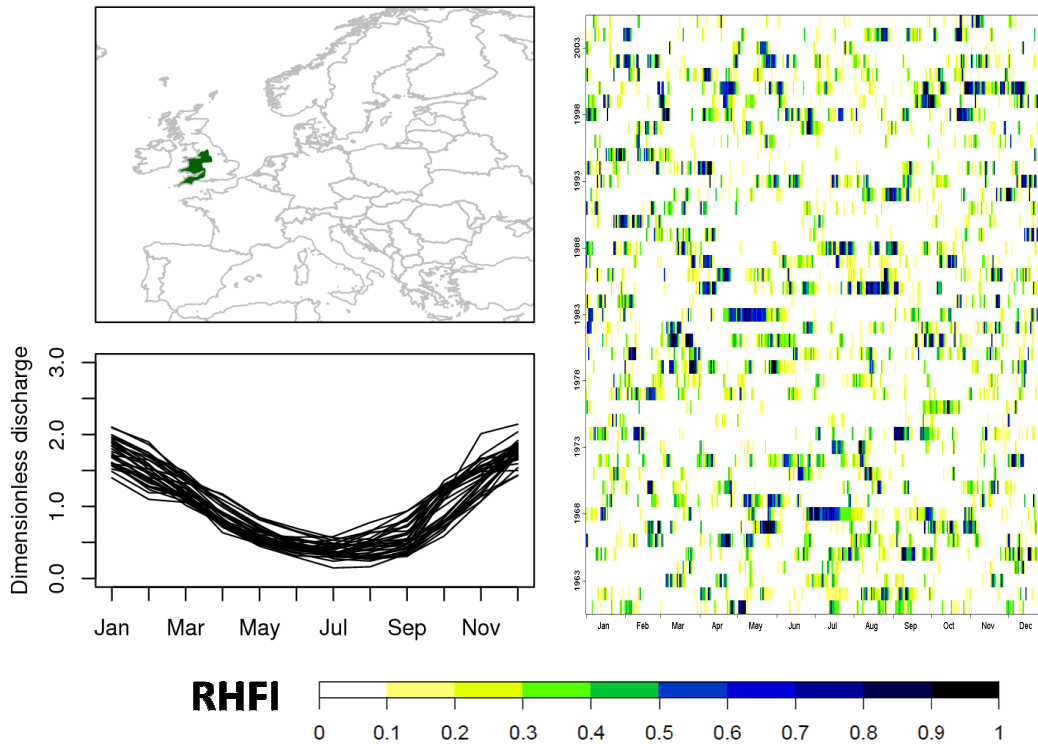
The catalogue entry is completed by a description of the predominant hydrological characteristics of the region.

## NW Great Britain



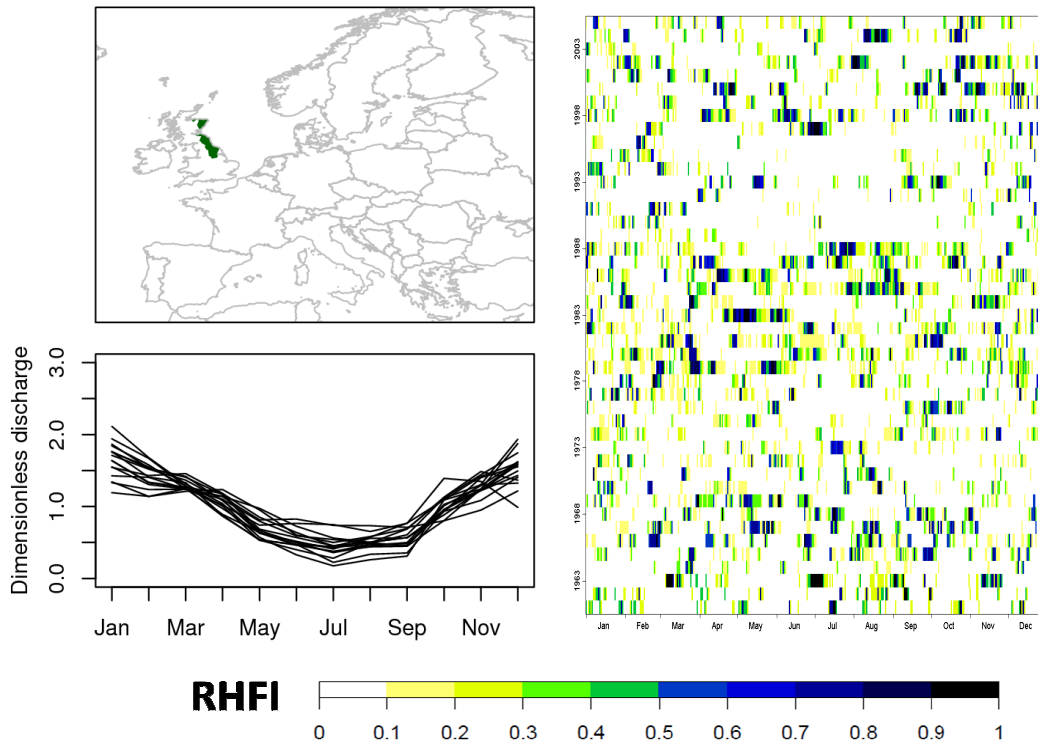
There is very little structure in the regional high flow characteristics of Northwest Great Britain, with frequent, short-duration events throughout the 1961-2005 period showing no seasonality. This is a reflection of the significant rainfall received and limited storage capacity in catchments within the region. Highly coherent episodes are also predominantly of short duration, although the most spatially coherent regional high flow events occur in the summer, between May and August.

## SW Great Britain



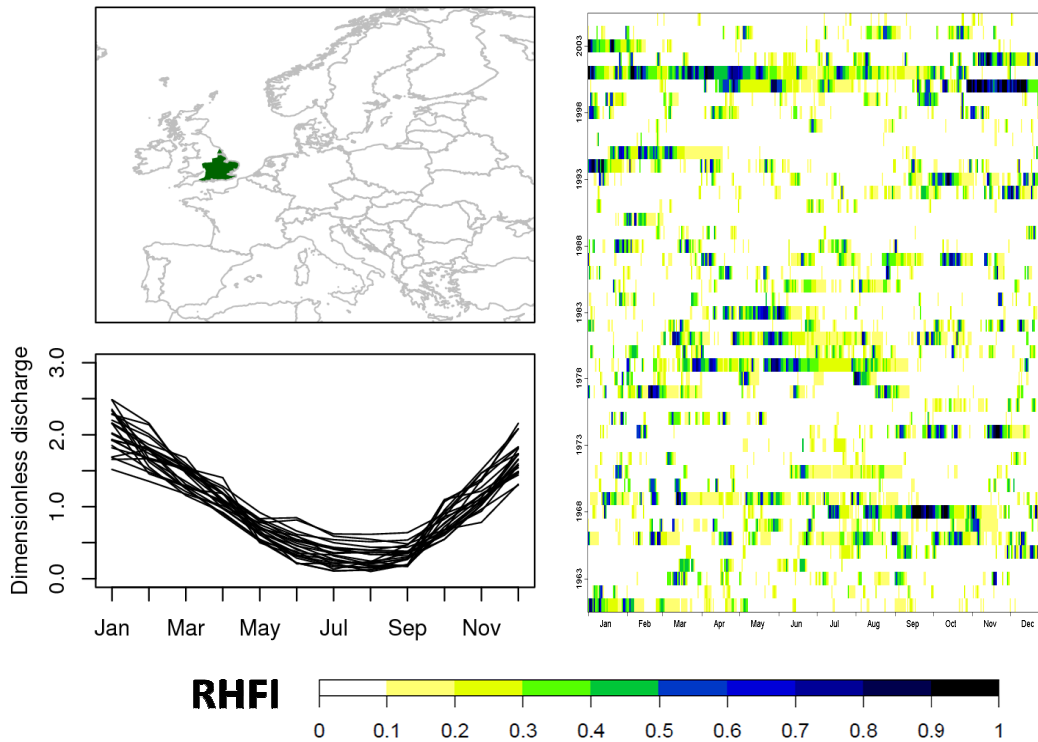
Short-duration, high frequency regional high flow events are the predominant characteristic of Southwest Great Britain, reflecting the relatively wet climate, although more persistent regional high flows occur occasionally in the summer months. The most coherent episodes are distributed across the year and throughout the period of record, although these tend to be of longer duration in the summer. There is no evidence that regional high flow characteristics have changed through the period of record.

## NE Great Britain



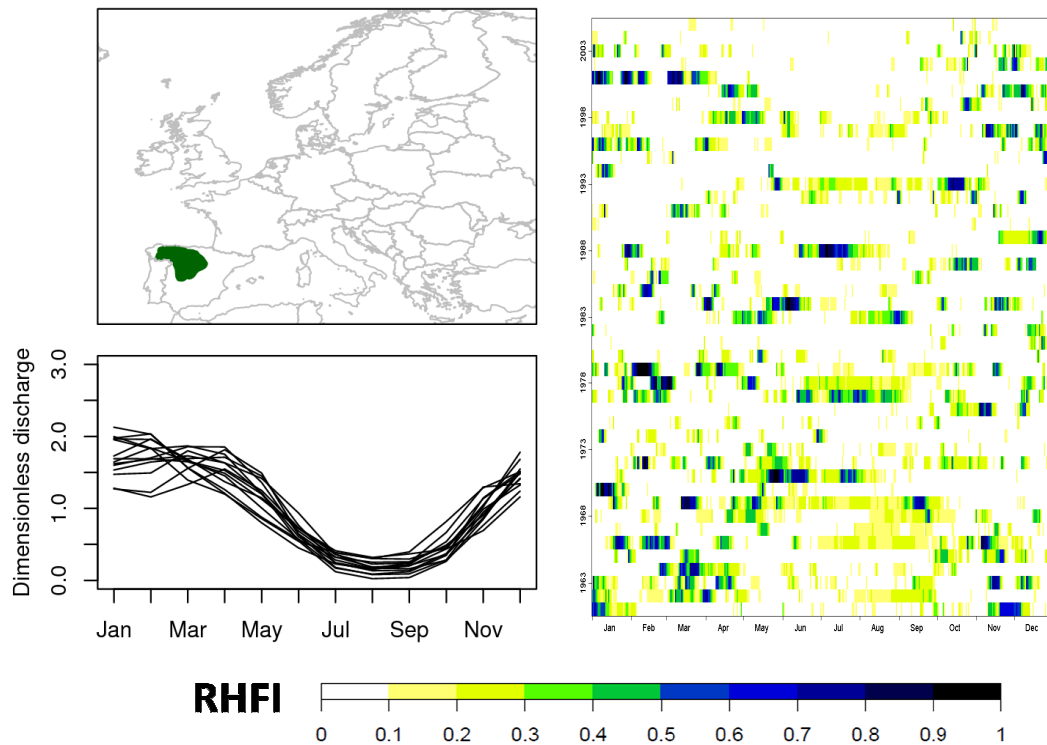
In Northeast Great Britain, regional high flows in winter tend to occur with greater frequency but are of shorter durations, whereas the opposite is true for summer events, which are less numerous but persist for longer. Whilst the most coherent regional high flows occur throughout the year, they are of longer duration in the summer months. There is no evidence of distinct periods of prevalent or absent regional high flows over the 1961-2005 period, and no suggestion that regional high flow characteristics have changed. Note however the late 1980s and early 1990s periods is associated with a relative absence of regional high flow events in the summer.

## SE Great Britain



The regional high flow characteristics of Southeast Great Britain are an amalgamation of those of two distinct subsets of catchments, the groundwater dominated and non-groundwater dominated catchments of lowland England. Whilst both groups of catchments exhibit some regional high flow events of a protracted nature, the groundwater dominated catchments experience infrequent and long duration episodes, whilst this signal is less apparent in non-groundwater dominated basins. Periods of prevalent and absent regional high flows are identifiable throughout the 1961-2005 period, although again this is more apparent in the groundwater-dominated catchments. Event durations in these catchments can be multi-season or multi-year, whereas episodes in non-groundwater dominated areas are more likely to be of the order of months. The somewhat contrasting regional high flow characteristics of these two subsets of catchments are obscured by considering them in a single Southeast Great Britain region.

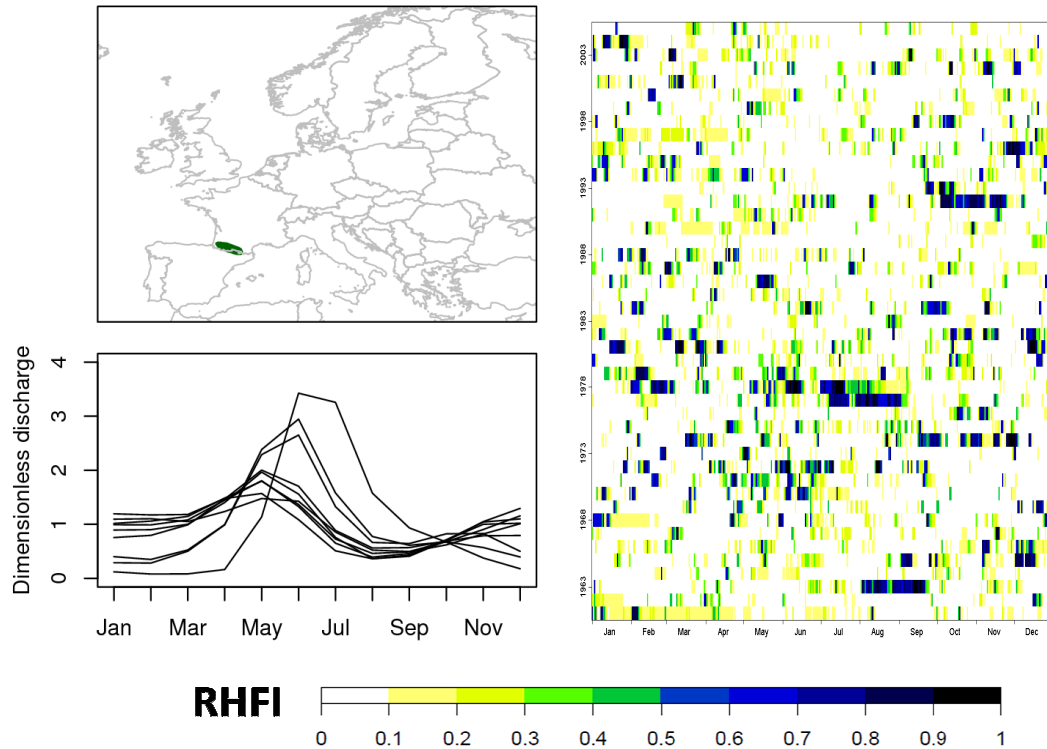
## NW Spain



The regional high flow characteristics of NW Spain vary seasonally. Regional high flows in the winter half-year (Nov-Apr) tend to show high spatial coherence (high RHF values), although such events are typically abrupt with short durations. Conversely, during the summer half-year (May-Oct), regional high flow periods are much less severe and extensive (low RHF values), but they persist for longer durations. There is a notable absence of regional high flow events during the summer in the post-1998 record for NW Spain, suggesting that regional high flow events which help to mitigate drought development may not be occurring with such regularity.

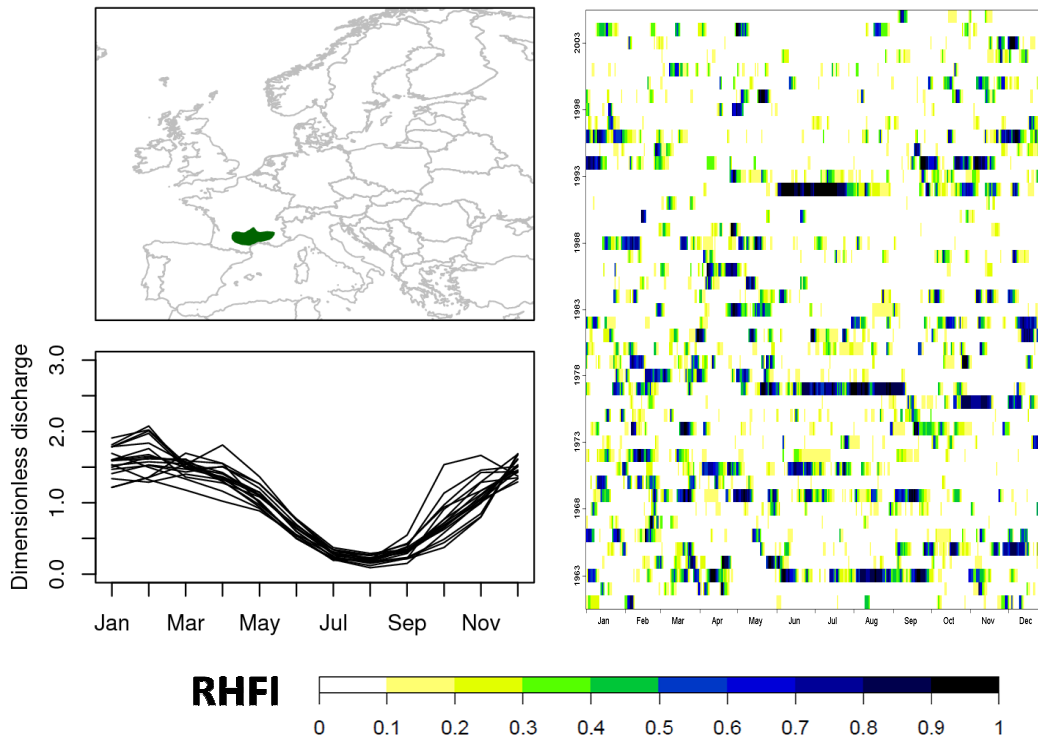


## Pyrenees



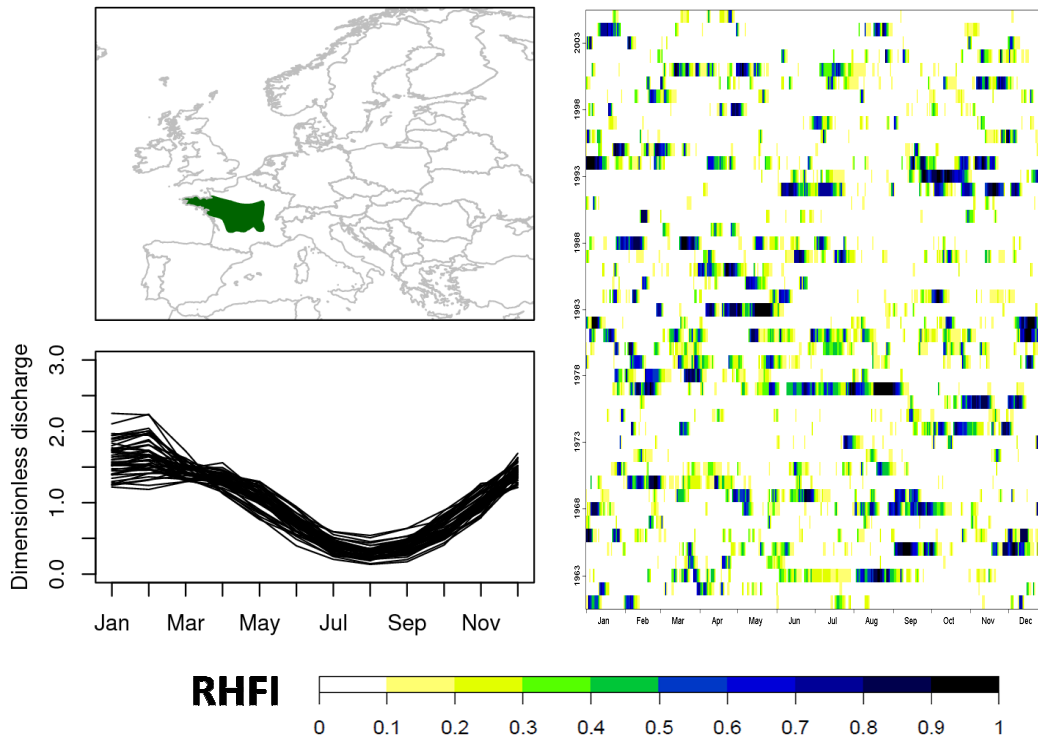
In general, regional high flow characteristics of the Pyrenees exhibit a flashy response typical of smaller responsive headwater catchments. The first six months of the year are characterised by shorter, intense regional high flow events, although often with high spatial coherence. In contrast, the second half of the year is predominantly composed of more protracted periods of severe regional high flows, with relatively fewer abrupt episodes. Regional high flow characteristics in the Pyrenees region tend to reflect the onset of the melting of the snow and ice packs in the spring or summer. As such, individual years tend to be characterised by a series of short, abrupt regional high flow events throughout the spring and summer, or when the onset of seasonal melting is delayed, limited regional high flow occurrence throughout the beginning of a year, followed by a significant protracted period of regional high flows.

## Southern France



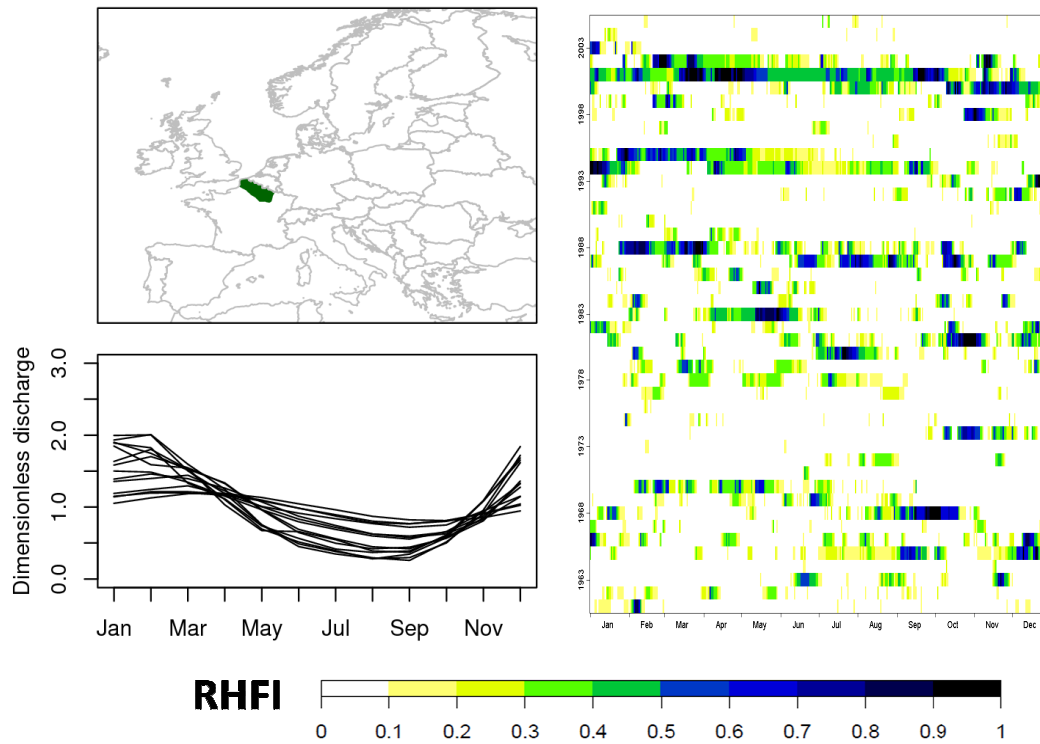
Southern France exhibits a marked change in regional high flow occurrence over the 1961-2005 period. Prior to 1983, regional high flows frequently occur throughout the year, with both short and long duration and a range of extents of spatial coherence. However, since 1983 there has been a noticeable decline in the number of regional high flow episodes throughout the year, suggesting that the impact extreme rainfall and streamflow in this region has declined substantially. There is also a notable seasonal variation in regional high flow characteristics for this region, with shorter events in the winter half-year and longer, more protracted regional high flows in the summer.

## Western and Central France



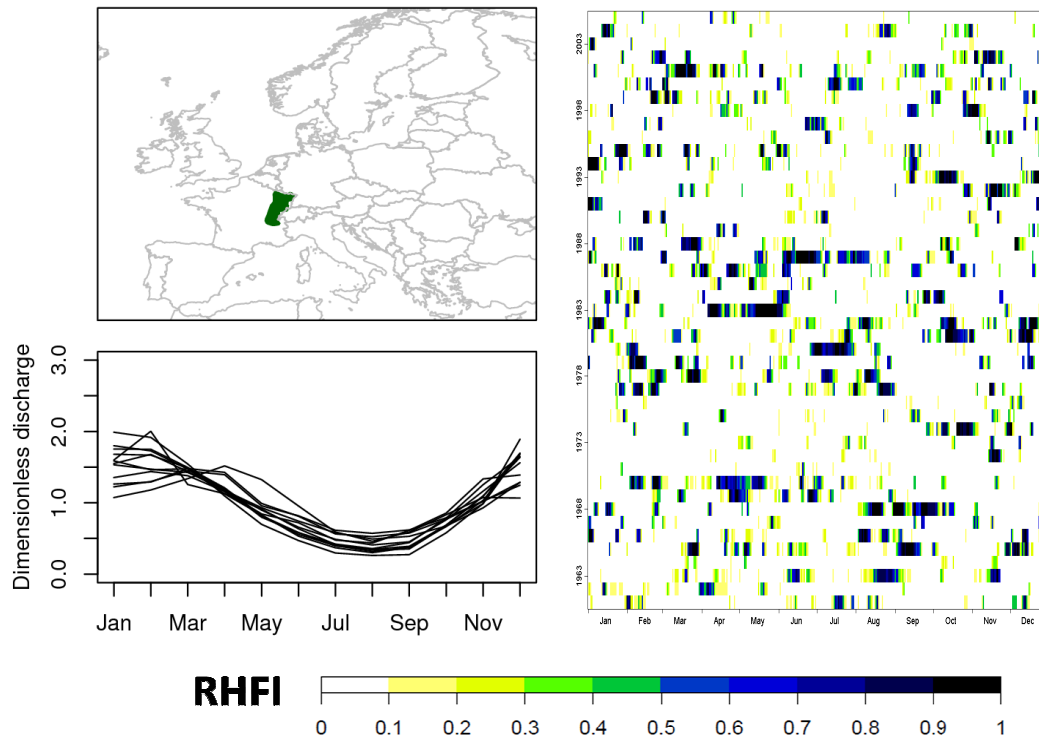
Western and Central France has a fairly consistent regional high flow chronology throughout the 1961-2005 period, with events spanning a range of durations distributed relatively evenly throughout the year. There are no notable periods with diminished or excessive regional high flow occurrence, and no patterns of increasing or decreasing regional high flows. Regional high flow response for the region appears to be less flashy than that for other regions, perhaps owing to groundwater influence in the region allowing limited responsiveness of catchments to precipitation inputs.

## Northern France



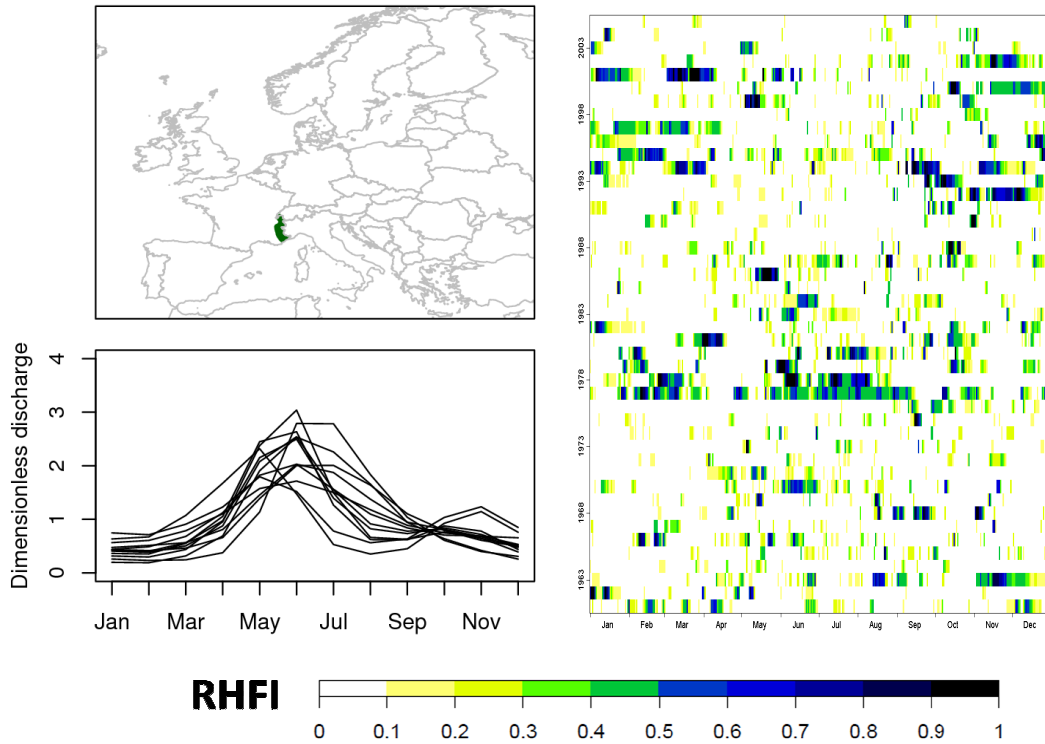
Northern France exhibits regional high flows characteristics representative of a region with significant groundwater influence. The majority of events affect wide areas (high RHF values) for protracted durations, with relatively fewer abrupt regional high flows. The dampening effect of groundwater storage in catchments acts as a buffer against rapid hydrological response, requiring prolonged excess precipitation before streamflow increases follow. It can also be observed that regional high flow episodes have significantly increased in frequency, duration and magnitude over the 1961-2005 period, the most notable expression of which is the recent emergence of protracted multi-year events.

## NE France



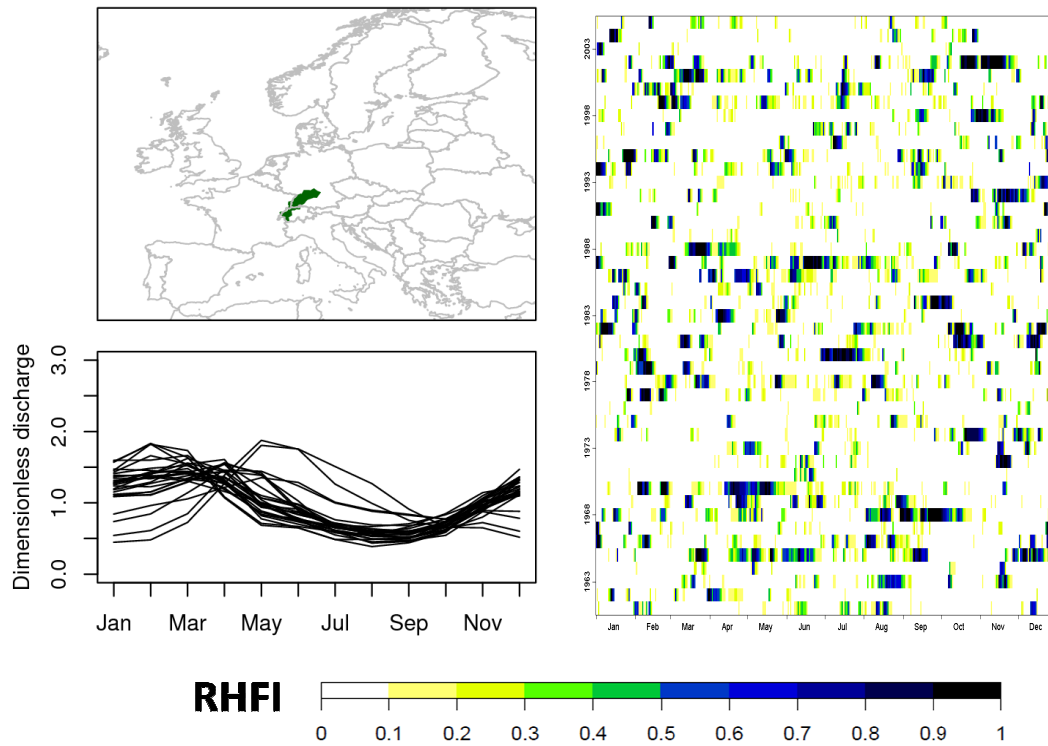
Northeast France is notable for its very spatially coherent regional high flow events, with the majority of catchments within the region responding homogeneously to precipitation inputs. High RHFI values characterise the majority of regional high flow episodes, regardless of duration, although such events rarely persist for longer durations than a few months. There are no noticeable periods of regional high flow prevalence or absence, and no patterns of increasing or decreasing occurrence.

## French Southern Alps



Whilst the French Southern Alps region is mountainous, the regional high flow characteristics suggest that the melting of snow and ice has a limited role in determining the flood chronology; neither the flashy hydrological response nor potential delayed onset of melting are observed in the regional high flow catalogue for this region. Conversely, the most spatially coherent episodes tend to be protracted, single season events. Regional high flows tend to be restricted to the winter half-year, whilst summers rarely witness extreme discharges, with one notable exception. There appear to be periods of the 1961-2005 record in which regional high flows are either frequent or absent.

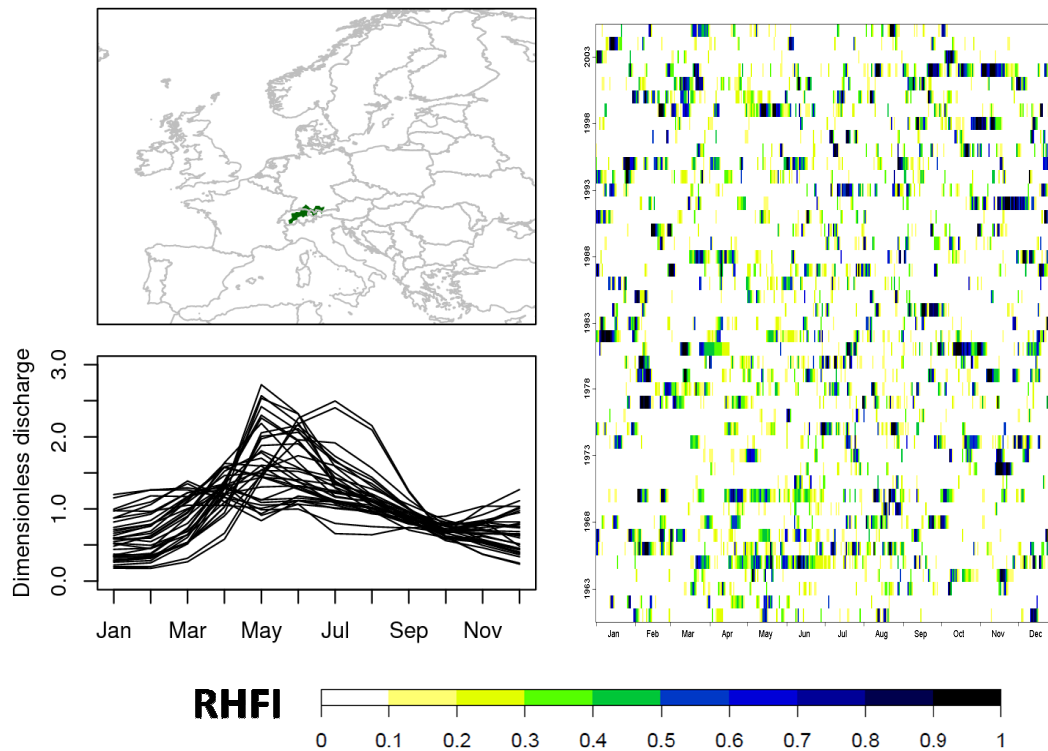
## SW Germany and Western Switzerland



The regional high flow chronology for Southwest Germany and Western Switzerland can be characterised as predominantly spatially coherent, with catchments exhibiting homogeneous response throughout the year. Regional high flow episodes tend to be short, rarely longer than a couple of months in duration, and are not more prevalent at any one time of year. Similarly, there are no patterns relating to the increasing or decreasing occurrence of such events throughout the 1961-2005 period.

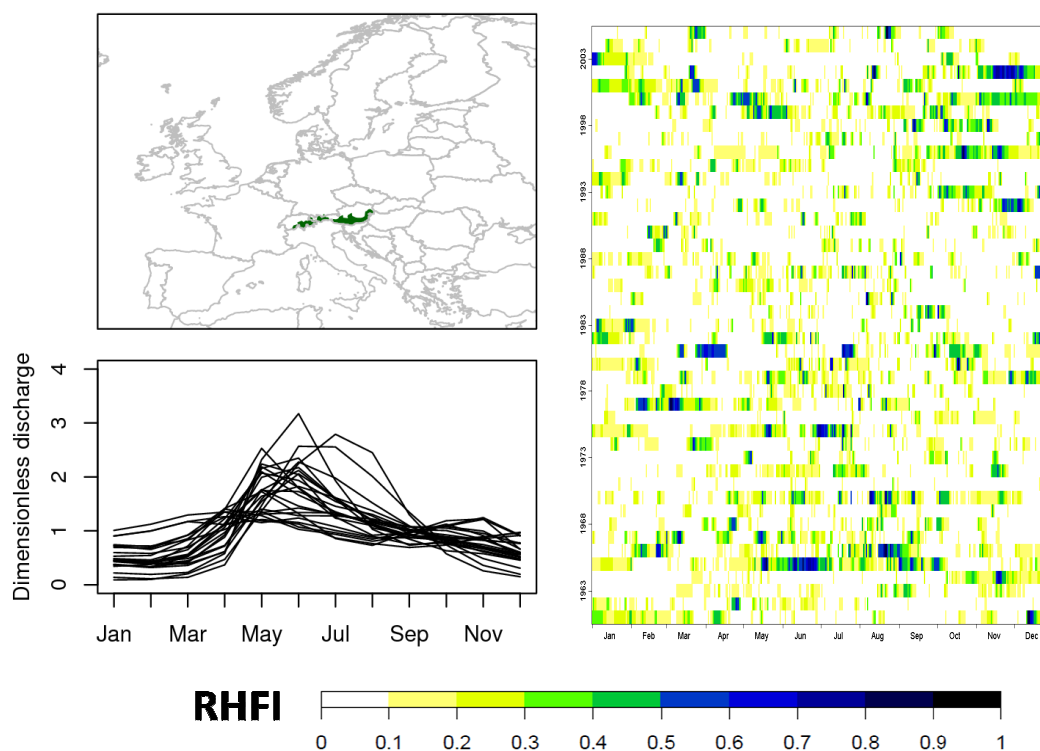


## High Alps



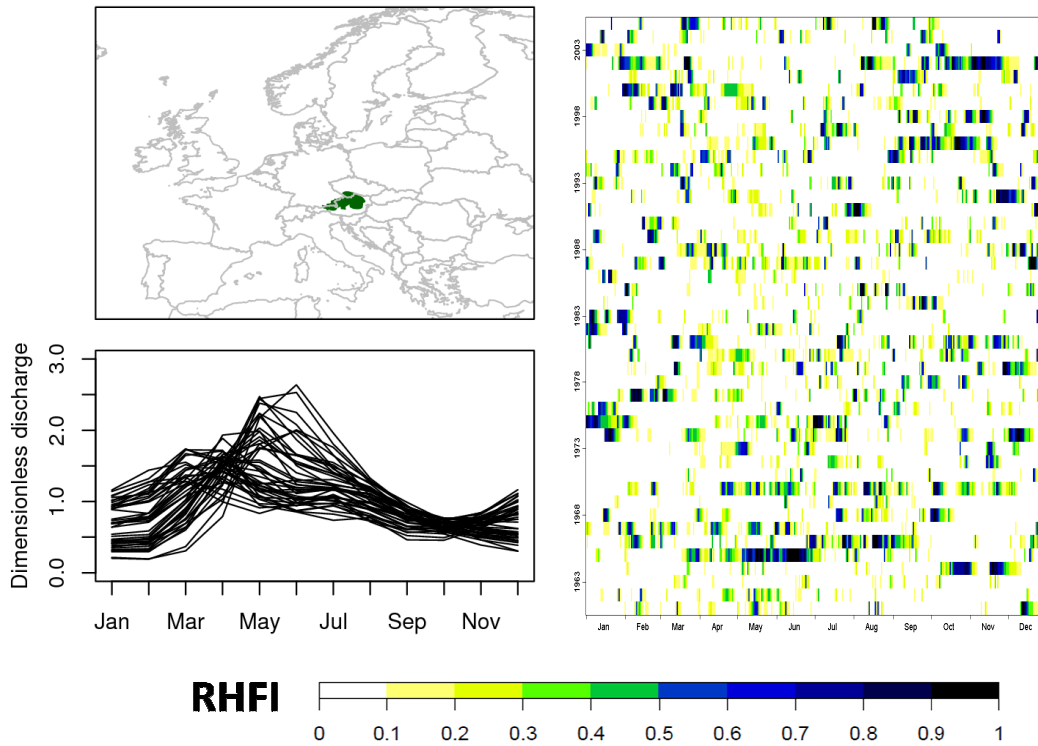
The High Alps region experiences very short regional high flow events, the majority of which are shorter than a month in duration. There is some evidence to suggest that longer durations occur during the winter half-year, with the most spatially coherent events between October and January, although these long periods rarely exceed a month. Shorter events on the order of days are a frequent feature of the summer. There is no evidence of regional high flows related to the delayed onset of seasonal melting.

## Southern Austria and Switzerland



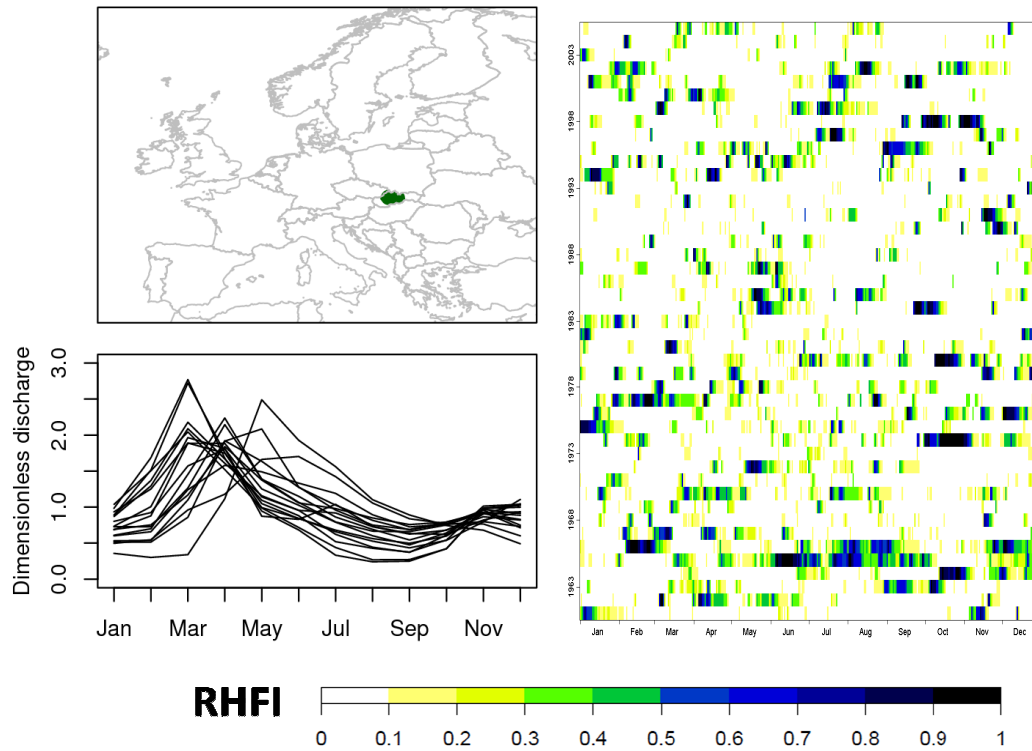
The regional high flow characteristics of Southern Austria and Switzerland are difficult to define because there is not much structure to their pattern. Regional high flows tend to show little spatial coherence within the region, perhaps representing a group of highly responsive catchments receiving variable climatic inputs. The frequency of episodes is consistently high throughout the 1961-2005 record, with no evidence of changing characteristics, other than a recent prevalence of wet Oct-Dec periods. Whilst the most severe and spatially coherent regional high flow events are of the longest duration, their occurrence is overwhelmed by frequent, short-duration, minor episodes as the predominant regional high flow characteristic of the region.

## Northern Austria



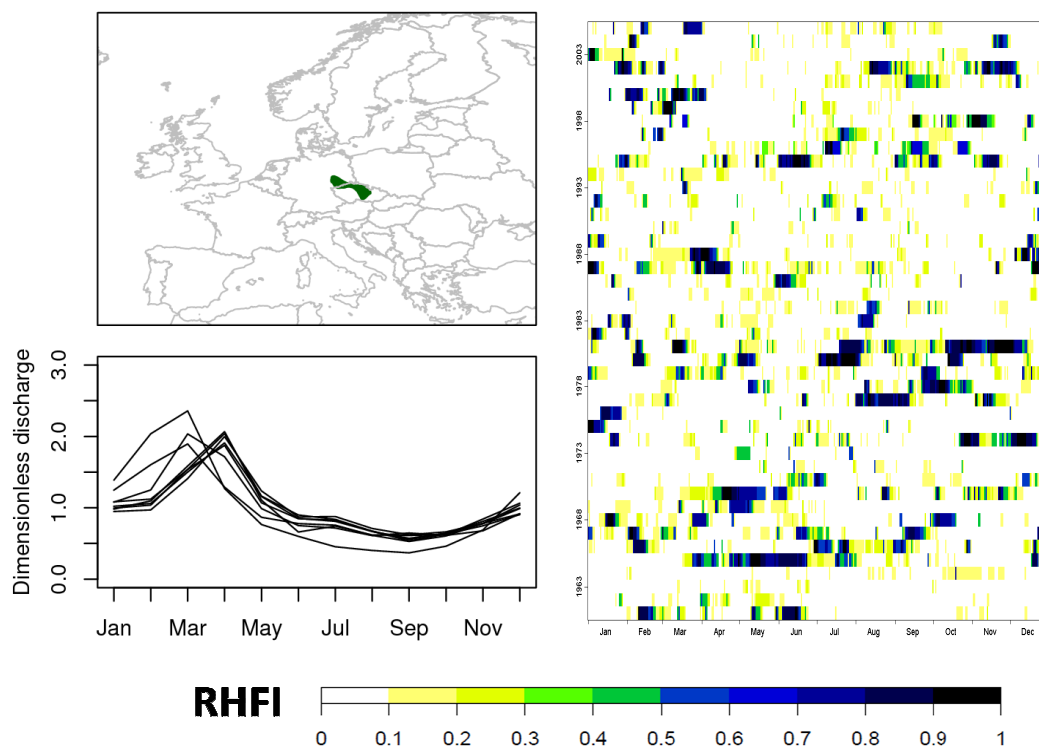
The majority of regional high flow events in Northern Austria are spatially coherent, across the range of durations. The shorter duration episodes, predominantly occurring in the summer half-year, are less spatially coherent, although this is perhaps to be expected given the oscillatory nature of regional high flows. There are a couple of instances of potential examples of delayed onset of snowmelt, although these longer durations are greater than two months. There is perhaps some evidence for later melting of the snow and ice pack from 1961 to the mid-1980s, and possibly a transition back towards earlier melting from the early 1990s to 2005.

## Slovakia



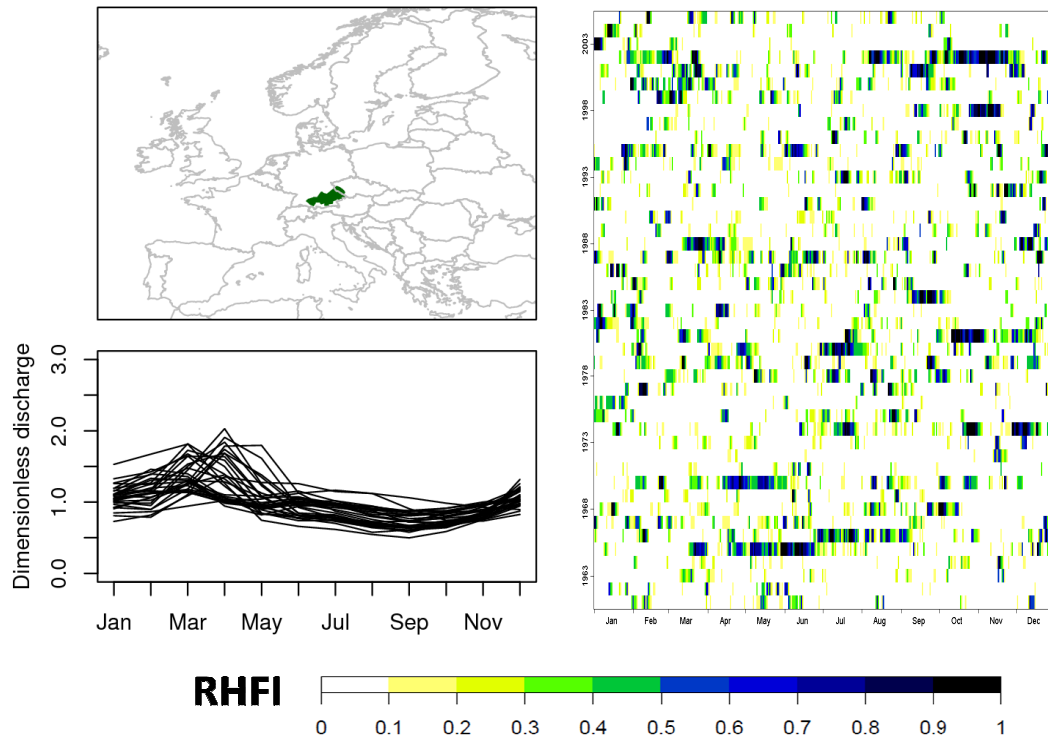
The regional high flow response of Slovakia tends to be protracted in nature, owing to the important groundwater influence in this region. The longer duration events exhibit the greatest within-region spatial coherence, although catchments may also respond homogeneously to short episodes. The longer duration and most spatially coherent episodes predominantly occur in the second half of the calendar year. There is no evidence of changing regional high flow characteristics over the 1961-2005 period.

## Eastern Germany and Czech Republic



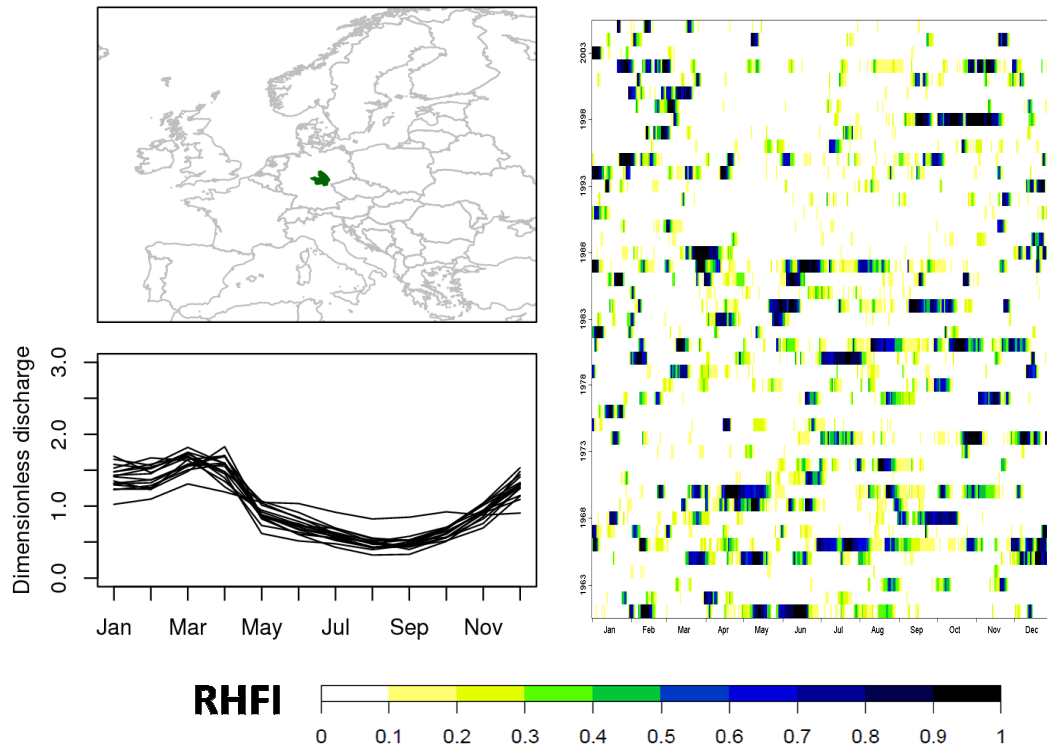
The Eastern Germany and Czech Republic region exhibits two contrasting regional high flow characteristics. The most obvious feature of the regional high flow catalogue for this region is the proliferation of very spatially coherent, predominantly longer duration higher flow events. However, these significant episodes overlay noisy background behaviour, with many short duration, insignificantly coherent regional high flows. It is notable that RHF values are restricted to the extreme ends of the range, with events affecting all catchments simultaneously, or only affecting a few. The most severe episodes are distributed evenly throughout the year and across the 1961-2005 period; although there is perhaps evidence that regional high flow duration has decreased from 1961 to 2005.

## Southern Germany



There is very little structure to the pattern of regional high flow characteristics exhibited by Southern Germany. Throughout the 1961-2005 period, the spatial coherence of events is highly variable, although there is an increased likelihood of greater coherence later in the year. Episodes tend to be shorter in duration and where they are longer, high values of within-region coherence are not sustained. There is no evidence of distinct periods of prevalent or absent regional high flows, and the characteristics do not appear to change over the 1961-2005 period.

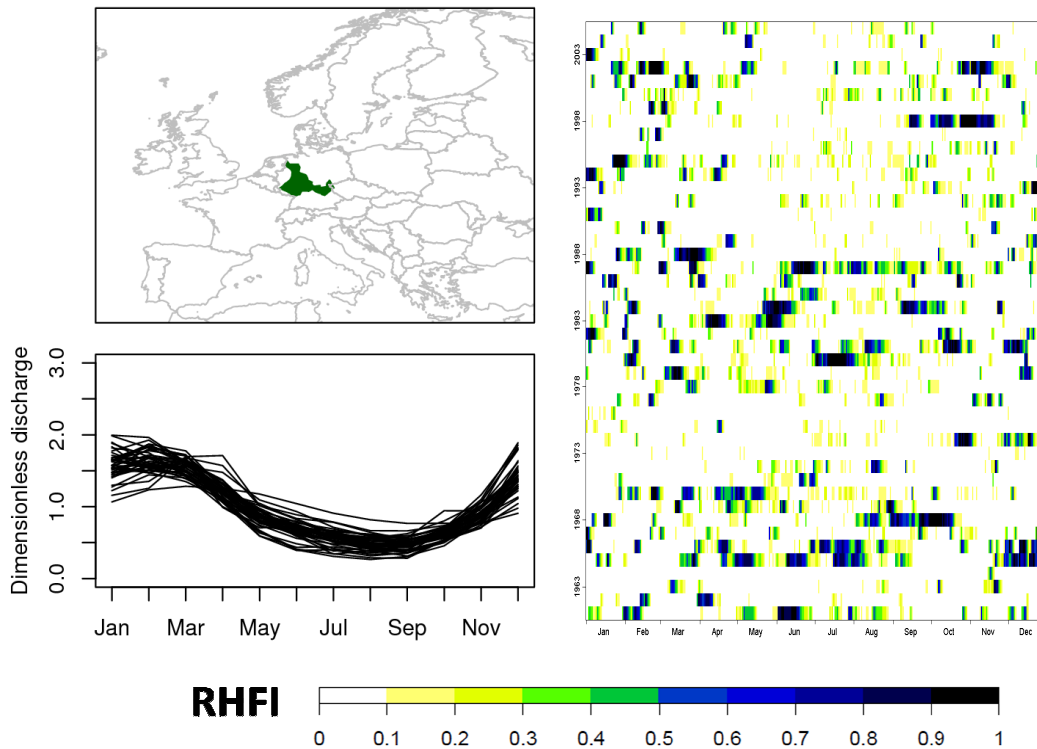
## Central Germany



Regional high flow characteristics in Central Germany tend to be strongly coherent, with catchments predominantly homogeneous in their hydrological response. The longest events are rarely longer than two months, whilst the shortest and least coherent episodes are clustered in the summer months (Jun-Aug). It is notable that there is an abrupt change in the prevalence of regional high flows in 1988. Following this date, episodes are far less frequent, shorter and less spatially coherent, with one exception. This is particularly apparent in the summer half-year, which witnessed many significant regional high flow events prior to 1988, but since then they are essentially absent. This is a pattern which is mirrored in Western Germany.

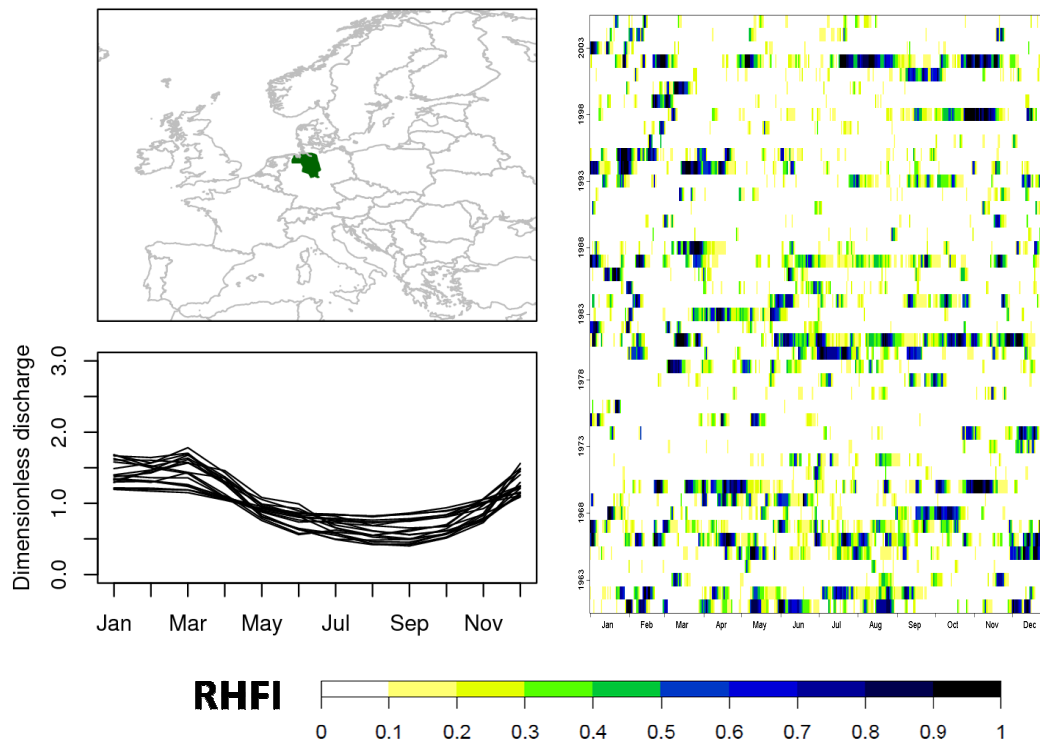


## Western Germany



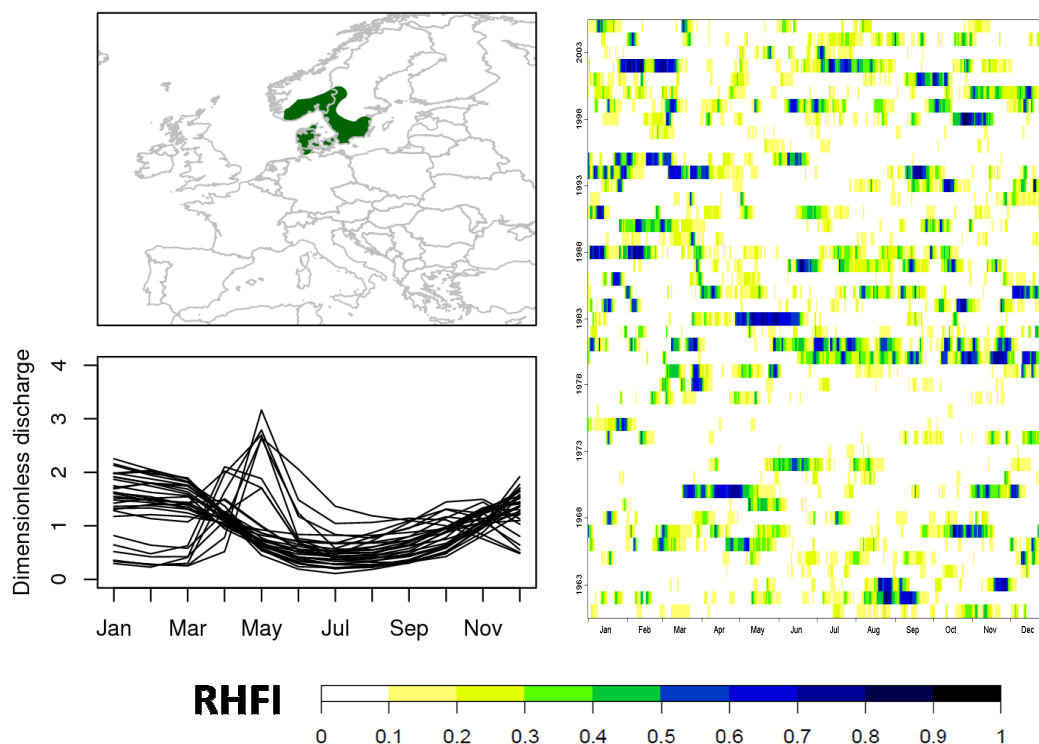
Regional high flows in Western Germany can achieve significant degrees of spatial coherence, even over relatively short periods. During quiescent phases, regional high flow events are distributed relatively evenly over the year, with longer durations more likely in the second half of the calendar year. Short events with low spatial coherence tend to be cluster in the summer months. It is notable that there are distinct periods of the 1961-2005 in which regional high flows are predominantly present (e.g. 1961-70, 1979-88) or absent (e.g. 1971-78, 1989-2005); the distinct breakpoint in 1988, after which regional high flows become much less frequent and less significant, is also observed in the regional high flow catalogue for Central Germany.

## Northern Germany



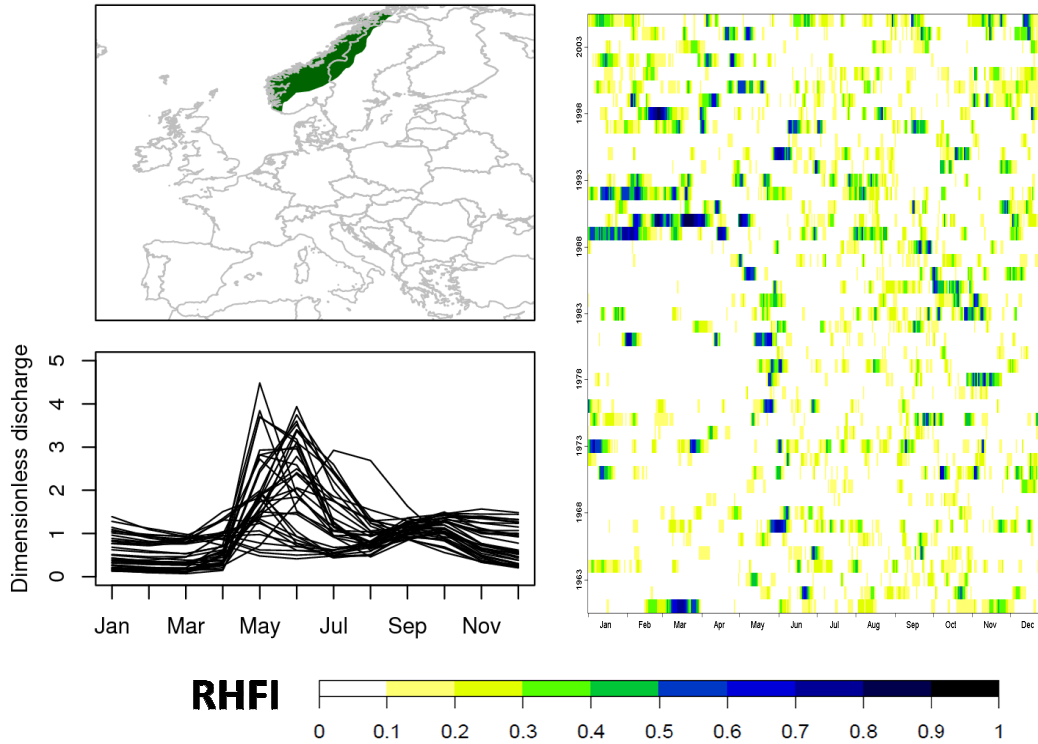
Northern Germany exhibits a certain degree of hydrological responsiveness, reflected in the shorter periods of spatially coherent regional high flows. Whilst longer durations do occur in this region, they do not maintain the high spatial coherence over sustained periods witnessed in other regions in Europe. Significant spatial coherence is exhibited for very short hydrological events, which are distributed evenly throughout the year, with a slight tendency for longer durations towards the end of the calendar year. Within the 1961-2005 period, there are distinct periods characterised by the high frequency or absence of regional high flows; a similar chronology is also exhibited by Western Germany. Although apparent, the breakpoint between the quiescent pre-1988 period and the regional high flow deficient post-1988 period is partially obscured by recent regional high flow occurrence.

## Southern Scandinavia



Southern Scandinavia has a regional high flow chronology that can predominantly be characterised by only moderate spatial coherence. This is perhaps unsurprising given the large geographical area of the region. Regional high flow events tend to be short and frequent; where they are longer in duration, even moderate values of spatial coherence are not sustained. Episodes are evenly distributed throughout the year, although the more prolonged period of moderate spatial coherence are more likely in the first six months. There is a distinct breakpoint in regional high flow characteristics evident in 1980; before this date regional high flows are relatively infrequent or absent, whereas the post-1980 period exhibits increasingly prevalent episodes.

## NW Scandinavia



The majority of regional high flow events in Northwest Scandinavia show relatively little spatial coherence, although this is perhaps a consequence of the large geographical area of the region; given that climatic input is the predominant driver of regional high flows, it is unsurprising that such a large area does not necessarily respond homogeneously. A notable aspect is the characteristics of the Jan-Apr period. Prior to 1988, regional high flows are essentially absent between January and April, potentially driven by cold Scandinavian winters inhibiting snowmelt and precipitation as rainfall. The moderately coherent regional high flow episodes which mark the end of this Jan-Apr in many of the years prior to 1988 are the onset of snowmelt; there is perhaps evidence that the timing of this onset gradually becomes earlier between 1961 and 1988. However, from 1988 onwards, particularly in the immediate years following 1988, there is a proliferation of regional high flow events in winter. It is possible winters have become milder, allowing precipitation through rainfall.

## References

- Hannaford, J., Lloyd-Hughes, B., Keef, C., Parry, S. and Prudhomme, C.: 2011, 'Examining the large-scale spatial coherence of European drought using regional indicators of precipitation and streamflow deficit', *Hydrological Processes* 25, 1146-1162.
- Marsh, T.J. and Hannaford, J.: 2007, 'The summer 2007 floods in England and Wales - a hydrological appraisal', Wallingford, Centre for Ecology and Hydrology, 30pp.
- McKee, T.B., Doeksen, N.J. and Kliest, J.: 1993, 'The relationship of drought frequency and duration to time scales', *Proceedings of the 8<sup>th</sup> Conference on Applied Climatology*, 17-22 January. American Meteorological Society: Anaheim, CA.
- Mitchell, T.D. and Jones, P.D.: 2005, 'An improved method of constructing a database of monthly climate observations and associated high resolution grids', *International Journal of Climatology* 25, 693-712.
- Parry, S., Prudhomme, C., Hannaford, J. and Lloyd-Hughes, B.: 2010, 'High and low flow catalogues for Europe: regional indicators as tools to characterise spatially-coherent hydrological extremes', in *Global change: facing risks and threats to water resources. Sixth World FRIEND Conference*, IAHS Press, Fez (Morocco), pp. 653-660.
- Prudhomme, C. and Sauquet, E.: 2006, 'Modelling a regional drought Index in France', CEH/Cemagref report, p. 42.
- Stahl, K.: 2001, 'Hydrological drought - a study across Europe', Albert-Ludwigs Universität Freiburg: Geowissenschaftlichen Fakultät. Freiburg.
- Stahl, K. and Demuth, S.: 2001, 'Atmospheric circulation and drought', in *ARIDE - Assessment of the Regional Impact of Droughts in Europe*. Institute of Hydrology, University of Freiburg, Freiburg, Germany.
- Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L.M., van Lanen, H.A.J., Sauquet, E., Demuth, S., Fendekova, M. and Jódar, J.: 2010, 'Streamflow trends in Europe: evidence from a dataset of near-natural catchments', *Hydrol. Earth Syst. Sci.* 14, 2367-2382.
- Ulbrich, U., Brucher, T., Fink, A.H., Leckebusch, G.C., Kruger, A. and Pinto, J.G.: 2003, 'The central European floods of August 2002: Part 1 - Rainfall periods and flood development', *Weather* 58(10), 371-377.