The Spatial Coherence of European Droughts – UK and European Drought catalogues

Science Report – SC070079/SR1

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Steve Killeen

Head of Science

Executive summary

The project, 'The Spatial Coherence of UK and European Droughts', investigates potential relationships in the occurrence, development and extent of droughts in mainland Europe with view to assessing whether UK drought forecasting can be improved. This report describes the methodology developed and applied to generate European and UK drought catalogues from 1901 to 2005.

Two complementary drought definitions are considered: hydrological, relating to unusually low streamflows; and meteorological, relating to less-than-usual monthly rainfall totals. Building on previous research, objective drought definition criteria were implemented on 579 streamflow records across Europe and 0.5^{o} gridded rainfall data covering the European land-surface. A Regional Drought Index (RDI) describes the extent and severity of hydrological drought in a given region by calculating the proportion of the region where the observed streamflow is lower than a daily varying low flow (90^{th} percentile) threshold. A Regionalised Standardised Precipitation Index (RSPI) describes the extent and severity of rainfall deficiency in a given region, using a concept similar to that of the RDI.

Twenty-three regions showing the same timing of hydrological drought were identified across Europe. These include four distinct zones within the United Kingdom. A two page summary is presented for each identified region which graphically displays the spatial extent, duration, and seasonality of major hydrological droughts for the period 1961-2005 and from 1901-2005, for meteorological droughts.

The catalogue reveals a wealth of interesting detail such as the drought-rich period of 1975-76 in Great Britain and the drought-poor period of the 1980s in Eastern Europe. Only the 1975/1976 drought is coherent on a pan-European scale for a persistent period. Some major UK droughts do not appear to have had any equivalent impact in Europe – for example, the summer droughts in 1984 and 1995. In contrast, there are some droughts which manifest themselves over a wide area in continental Europe, but are not expressed in the UK – for example in late 1971/1972. Some long droughts (1962 – 1964; 1995 – 1997; 1988 – 1992) result from a combination of both winter and summer deficiencies.

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1 Introduction on the UK and European Drought Catalogues 1901-2005

A drought usually begins with a period of reduced precipitation over a wide area that can eventually propagate to the entire hydrological cycle. Different types of drought manifest at different temporal and spatial scales, depending on the physical processes involved, and the antecedent conditions (Zaidman et al., 2002). A meteorological drought is defined as a rainfall deficiency, and can develop into an agricultural drought after a few weeks as crops suffer from lack of soil moisture, whereas an hydrological drought develops over longer timescales, as river flows gradually deplete from shortfalls in catchment runoff or aquifer recharge (Marsh et al., 2007).

There are many ways to define droughts, but definitions almost always refer to a period of time when there is a decrease in water availability compared to what would normally be expected at a given location (Tallaksen and Van Lanen, 2004).

The project, 'The Spatial Coherence of UK and European Droughts', investigates potential relationships in the occurrence, development and extent of droughts in mainland Europe with view to assessing whether UK drought forecasting can be improved. It examines both the hydrological droughts (based on river discharge measurements) and the meteorological droughts (based on rainfall measurements).

This report describes the Stage 1 of the project. Section 2 presents the methodology used to identify droughts and define regions experiencing abnormally low flow at the same time. The regions are presented in Section 3. Section 4 provides the drought catalogues for all identified regions of the UK and Europe.

2 Methodology

Two European drought catalogues – one describing hydrological, the other meteorological droughts – were derived exploiting a method developed in the EU-funded project ARIDE (ENV4-CT97-0553) (Demuth and Stahl, 2001). A modification of the ARIDE approach was introduced in this study whereby meteorological droughts, which were not included originally, were defined using the Standardised Precipitation Index (McKee et al., 1993). A description of the steps involved in deriving the catalogues is given below.

2.1 Deficiency Index

The first step requires the calculation of a Deficiency Index time series for each time series of daily flow data. In order to account for the inter-annual characteristics of river flow regimes, in which similar flow variations may be expected during typical years, the approach involves evaluation whether the flow on any given day falls below a daily varying (moving) low flow threshold – this is a flow deficiency. In this study, the flow exceeded 90% of the time (the Q90 flow) was used as the threshold, such that a different Q90 threshold value was calculated for every day of the year (i.e. 365 Q90 values). The daily "moving Q90" value is calculated by ranking all observed flows on the "day of interest" together with those 15 days either side of the day of interest. For example, the moving Q90 value for 16 January (the day of interest) would be calculated from all flow vales recorded 1-15 January (15 days previous), 16 January (day of interest) and 17-31 January (15 days after) from every year of the data record. For a complete daily record of, say, 20 years' duration, the moving Q90 for any day would thus be based on a sample of 620 (31x 20) observations.

The moving threshold approach is illustrated in Figure 2.1 for two catchments having contrasting river flow regimes: a snow-melt dominated regime (left); and a rainfall-dominated regime (right). The figure shows the discharge in cumecs (y-axis) associated with different flow exceedence percentiles (coloured lines) calculated for each day of the year (x-axis), from Q25 flow (black lines) to Q95 (red line). As can be seen, the orange (Q90) line does not remain constant throughout the year and is higher during high-flow seasons than in low flow seasons. A single, constant, value clearly would not capture such inter-annual variation and would be misleading, as regards real periods of deficiency. The figures also illustrate the variability of the moving Q90 between one catchment and another.

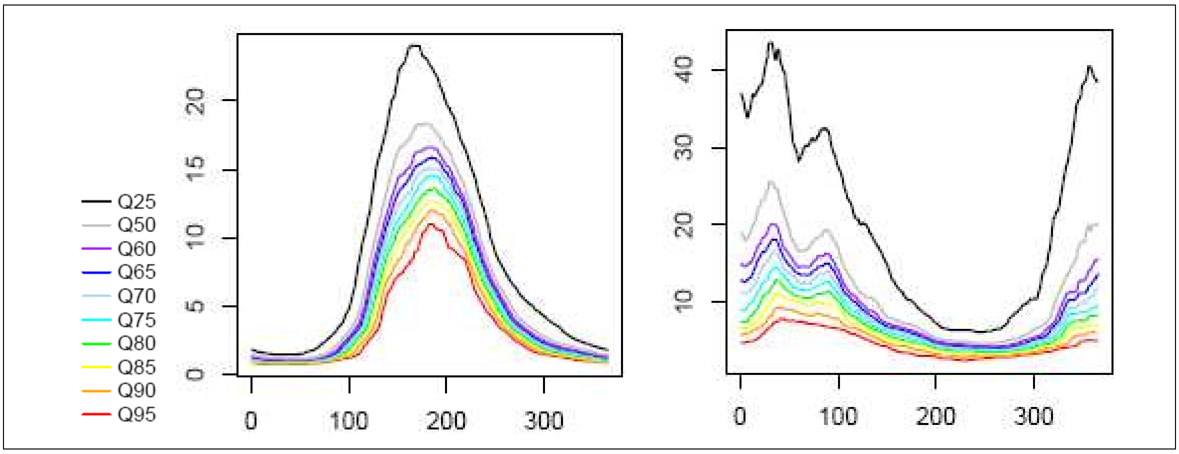


Figure 2.1 Definition of moving Q90 for a snow-driven catchment (left) and pluvial catchment (right)

The Deficiency Index of a particular streamflow daily time series is determined according to whether each daily streamflow value is equal to or lower than the corresponding daily threshold (Q90) value. If the flow is less than the threshold, then the conditions experienced during that day are amongst the 10% driest for that day and potentially represents a period of extreme low flow, or drought.

The *Deficiency Index* time series simply reduces the streamflow series to a binary time series populated with values of 0, when the flow is greater than the moving Q90 for that day, or 1, if lower, as given by the following equation:

$$DI(t) = 1 \qquad if\ Q(t) \leq Q90(D)$$
$$DI(t) = 0 \qquad if\ Q(t) > Q90(D)$$

2.2 Clustering

The second step groups catchments that experience an abnormal low flow at the same time into homogeneous regions. The clustering is based on the premise that droughts are generated over large swaths of territory and, thus, affect many catchments simultaneously. In order to delineate regions that behave similarly according to a large-scale circulation conditions, and might experience a drought together, the Deficiency Index series of all catchments are compared. Clustering aims to put together all gauging stations (catchments) which have Deficiency Index equal to 1 on the same days, and in different groups from catchments that have a Deficiency Index equal to 0 that day.

There are many clustering methods, which are generally time consuming to apply. Running a new cluster analysis would be time-consuming and would duplicate previous work. The decision was made, therefore, to build upon earlier work in Western Europe (Demuth and Stahl, 2001) and France (Prudhomme and Sauquet, 2007) in which a total of 22 homogeneous regions were defined using river flow data from 10 countries, as shown in Figure 2.2.

This study benefited, however, from an updated set of river flow data, comprising more recent data up to 2005, which allowed a review and redefinition of the original regions. This activity is described more fully in Section 3.

Note that such construction of homogeneous regions applies to hydrological droughts only.

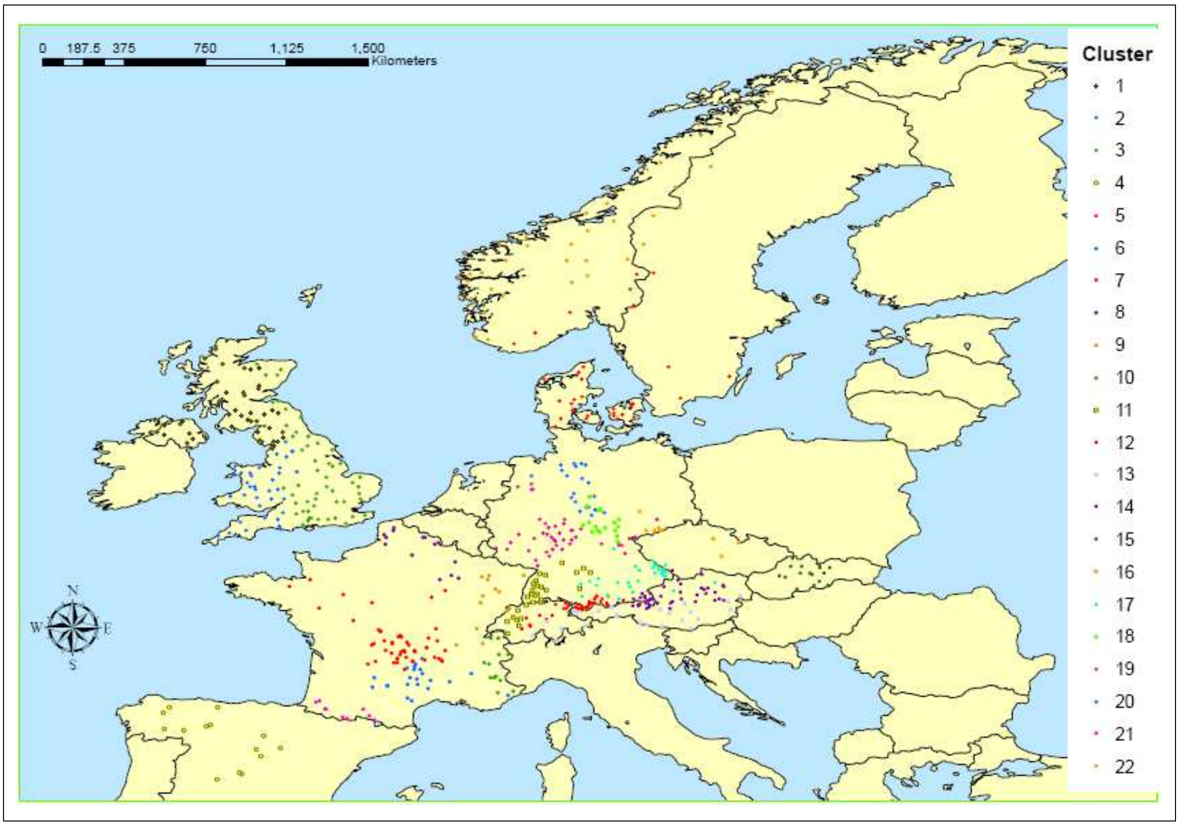


Figure 2.2 The 22 original Drought European regions defined by Demuth and Stahl (2001) and Prudhomme and Sauquet (2007)

2.3 Regional Deficiency Index (RDI)

The final step in the establishment of the drought catalogue is to derive the Regional Deficiency Index (RDI). For each of the regions found to experience exceptional low flows at the same time (i.e. the clusters defined in 2.2), the proportion of the region experiencing such abnormal low discharge is derived by calculating, for each day of the catalogue, the arithmetic mean of the Deficiency Index series of all catchments within the region, as described in the following equation:

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

with M the number of catchments with available data and derived DI series in the region. This represents the proportion of catchments in the region that experience abnormal low flows at that time.

By construction, the RDI series has value between 0 and 1. A value of 0 reflects that none of the gauging stations (catchments) where data was available had exceptionally low flow, and thus, the region is not in a drought condition. In contrast, a value of 1 occurs when all catchments with data had extremely low discharge for the day (i.e. DI equals to 1). This situation is exceptional and defines a very severe drought. Values ranging between 0 and 1 define an event with very few catchments experiencing low flows conditions (RDI towards 0) to an event when the majority of the region experienced low flows (RDI towards 1). An RDI of 0.3 is recommended as a minimum to define the existence of a severe drought, corresponding to 30% of the region showing a streamflow deficit (Stahl, 2001). An illustration of RDI series is given in

Figure 2.3 for the region of North East France. Coloured bars show the periods where RDI is greater than 0.1. Contiguous bars of colour represent prolonged droughts, the darker the colour, the more severe the drought (higher RDI), and the greater the drought severity. Drought-poor periods are easily identified by the periods in white.

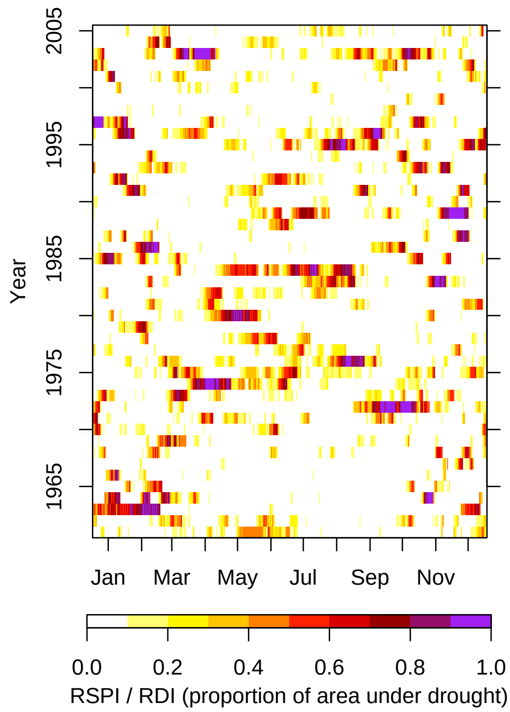


Figure 2.3 Example of RDI series, for the North East region of France

2.4 Standardised Precipitation Index

In order to extend the spatial coverage and historical extent of the drought record beyond that possible from the hydrological gauge network, we use the Standardized Precipitation Index (SPI) (McKee et al., 1993) as a meteorological proxy for drought. The SPI is the unit normal transformation of the time averaged precipitation time series climatologically appropriate to the particular location and time of year. This is illustrated in Figure 2.4 which shows the transformation of precipitation accumulated over a 3 month period (June-July-August) for two contrasting regions, namely, London and Madrid.

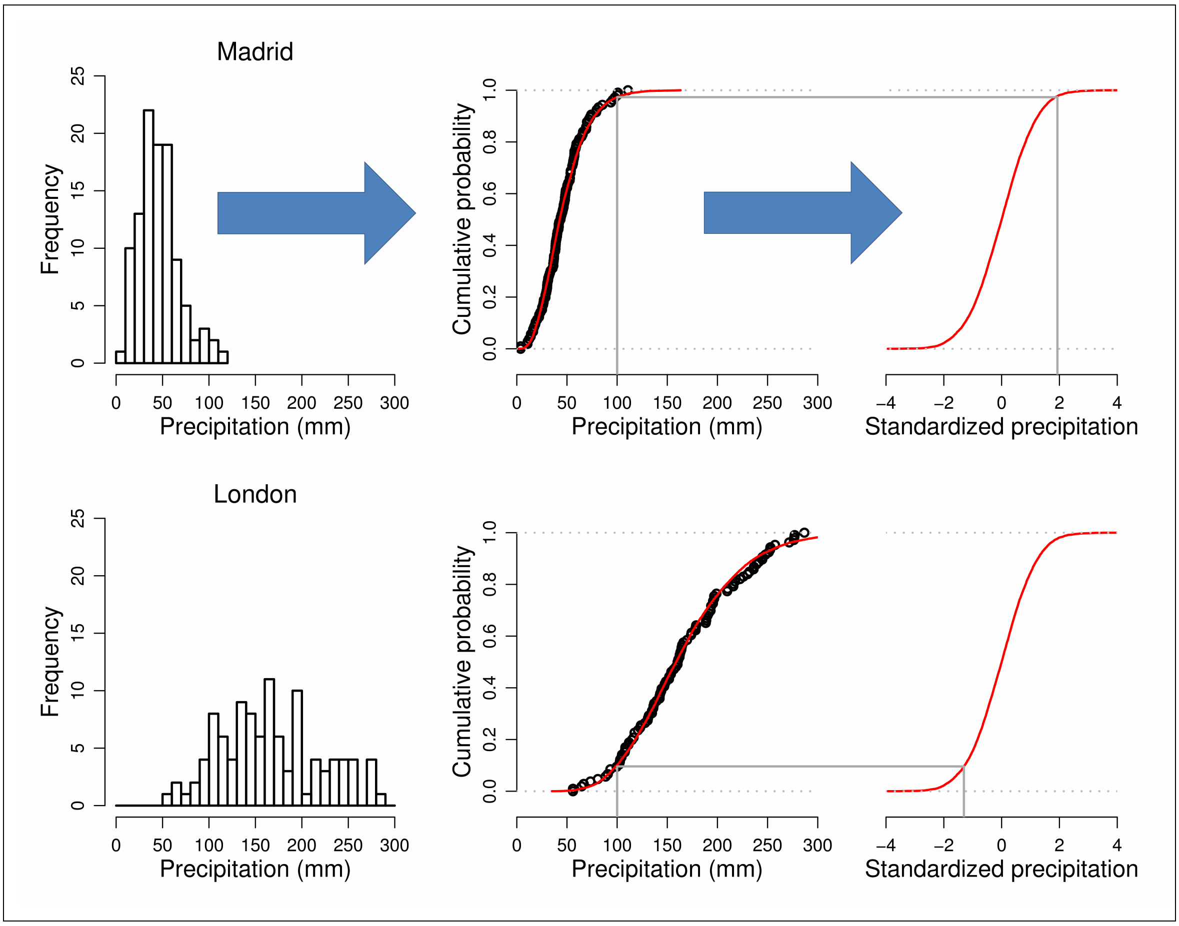


Figure 2.4 Standardised precipitations for Madrid and London June-July-August 1901-2005

The relative importance of a given amount of rainfall accumulated over a particular time period varies from place to place and from time to time in the year. The SPI value allows us to compare say e.g. 100mm over the summer in Madrid (+2 i.e. very wet) with 100mm over the summer in London (-1.3 i.e. quite dry). The example illustrates August SPI3. A similar comparison for precipitation accumulated in the six months from July to December would be described as December SPI6. The month always refers to the end of the accumulation period and SPI *n* to the *n*-month total that is being standardized.

Since the SPI is by definition normally distributed we can assign return periods to droughts of a given severity: Moderate < -1 (5 years) Severe < 1.5 (15 years) Extreme < -2 (40 years).

The precipitation data used to compute the SPI are taken from the CRU 0.5° x 0.5° gridded analysis 1901-2006 (Mitchell and Jones, 2005). Gridded precipitation data are preferred over raw raingauge observations because they reduce biases arising from the irregular distribution of the raingauge network (Jones and Hulme, 1996, Dai et al., 1997).

2.5 Regional Standardised Precipitation Index

Since our aim is to provide a direct mapping of the meteorological description to the hydrological, the Regional Standardized Precipitation Index (RSPI) follows directly from the homogeneous reporting units identified during the hydrological classification. It is defined as the proportion of the grid cells under the region boundary experiencing moderate drought i.e. with SPI < -1. A representative timescale for the SPI (e.g. 3, 6, or 12 months) was determined for each region by the maximum rank correlation between the index and the RDI. Storage effects were allowed for by the consideration of lagged correlations of up to 12 months.

3 Validation of original regions

3.1 Indicators of regions

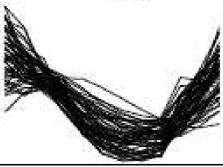
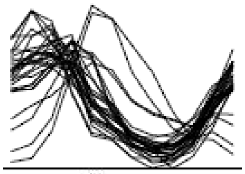
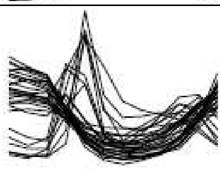
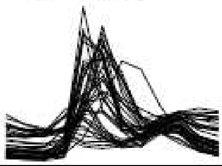
For each region, some metrics have been derived that provide some summary of the characteristics of the region in terms of hydrology and droughts. These indicators are described in the next paragraphs, and given in Table 3.1. They will be used to evaluate whether the original regions, derived from two different studies and using different hydrometric records lengths, should be further refined. For each region, the following is provided:

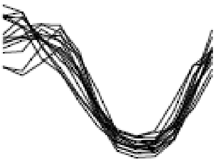
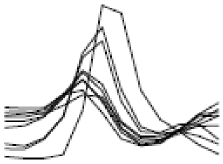
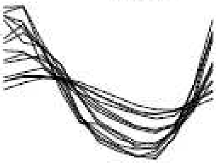
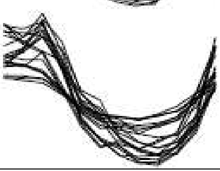
- **Number of gauging stations**. The total number of streamflow records in a given region. A greater number of time series increases the significance of a larger RDI value for a given cluster, because more of the records have to be in deficit conditions to generate such a value;
- **Intergauge distance**. This is the median distance between all the gauges located in a region, given in km. Dense, small regions will have a smaller inter-gauge distance than larger areas;
- **Mean monthly hydrograph**. Derived for each station using the mean monthly discharge standardised by the mean annual discharge. The seasons of high and low flows provide a visual indicator of the dominant streamflow regime (e.g. rainfall-dominated, snow-melt dominated or mixed). The clusters have been derived using purely statistical techniques aiming to maximise the simultaneous occurrence of Drought Index. The streamflow regime is an independent measure of the hydrological homogeneity of the clusters;
- **Clusters Homogeneity**. Based on the definition of the Q90 and the derived DI series, the RDI of gauging stations within a “perfect” region (where a region is defined as a cluster of stations that experience drought at exactly the same time), will be 0 for 90% of the time, and equal to 1 for 10% of the time. The Cluster Homogeneity is the distance between the cumulative distribution function of the regional RDI and the ideal cumulative distribution. The Cluster Homogeneity measure can have values of 0 to 1 (or 0% to 100%), with a perfect region having a value of 0.
- **Relative proportion of severe droughts**. This measures how likely a small number of gauges in the region experience a drought: the larger the number of stations experiencing a drought at the same time, the more coherent the region is in terms of its response to drought conditions. This is calculated using:

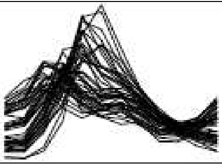
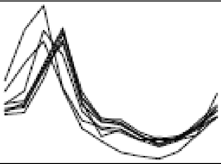
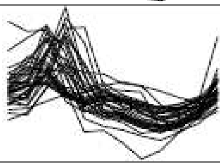
  $$P_c = \frac{P(RDI > 0.5)}{P(RDI > 0)}.$$

  A totally coherent region (all stations have DI=1 at the same time) has a P_c equal to one, while P_c equals zero if the probability of more than half the gauging stations in that cluster experiencing a drought at the same time is zero.
- **Correlation between RDI and RSPI** (on monthly series). This provides an indication of how well the regional meteorological drought series (RSPI) matches the hydrological drought series (RDI). This will be useful to extend the analysis prior to 1961, when most of the gauging stations records start.

Table 3.1 Analysis of regions drought coherence

	Region	Number of gauging stations	Inter-gauge distance (km)	Mean Hydrograph	Cluster homogeneity (%)	P_C	Correlation RDI and SPI
UK	1	43	197.7		7.5	0.146	0.13
	2	37	155.6		8.1	0.124	0.29
	3	57	207.1		9.1	0.079	0.14
Alps	11	28	119.5		7.7	0.152	0.62
	12	35	78.7		8.8	0.085	0.53
	13	25	215.3		11.4	0.021	0.50
Scandinavia	21	31	241.9		8.6	0.099	0.44
	22	39	385.8		10.9	0.024	0.05

	Region	Number of gauging stations	Inter-gauge distance (km)	Mean Hydrograph	Cluster homogeneity (%)	P_C	Correlation RDI and SPI
Western Europe	4	14	226.5		10.8	0.036	0.58
	5	9	90.5		8.1	0.160	0.33
	6	18	108.5		7.3	0.163	0.58
	7	48	132.7		7.5	0.128	0.65
	8	14	139.2		9.5	0.096	0.61
	9	12	134.5		7.0	0.214	0.59
	10	12	97.3		8.6	0.099	0.50
	18	16	72.3		7.9	0.109	0.50
	19	47	143.5		7.8	0.116	0.68
	20	19	111.3		8.5	0.111	0.58

	Region	Number of gauging stations	Inter-gauge distance (km)	Mean Hydrograph	Cluster homogeneity (%)	P_C	Correlation RDI and SPI
Eastern Europe	14	49	113.2		9.8	0.055	0.50
	15	17	81.6		9.7	0.081	0.55
	16	8	162.5		8.2	0.132	0.50
	17	30	115.8		9.3	0.086	0.61

In order to investigate possible relationships between drought occurrences of different regions, it is important that drought behaviour within individual regions is as homogeneous as possible, as it is unlikely to obtain sensible correlations between non-homogeneous regions. The reason for this is that if stations (or catchments) within a region have a low level of coherence, they are unlikely to simultaneously experience drought conditions. In RDI terms, such a region would never experience severe droughts and establishing statistically significant relationships with any other regions would be unlikely.

From Table 3.1, two areas were considered for cluster refinement: Region 3 (in the UK) and Region 22 (in Scandinavia):

Region 22, primarily located in Norway, is the least coherent in terms of P_C, the relative proportion of severe droughts, and has the smallest correlation between RDI and RSPI. It covers the largest geographical area and has the largest inter-gauge distance. It also contains gauges that measure flows for inland rivers with a predominantly snowmelt regime and those on the coast with a more rainfall-dominated regime. Re-arranging this region with the adjacent Region 21 could lead to more coherent sub-regions.

Region 3, covering most of the eastern side of Britain, although not the least coherent of all remaining regions, has he 4^{th} lowest P_C value and is the least coherent British region.   As one of the primary aims of Stage 2 of the project is to examine correlations between UK droughts and European droughts, a special effort was made into obtaining coherent UK regions. The large geographical area of Region 3, the high precipitation gradient from north east Scotland (where average annual rainfall can be >1000mm) and south east England (where average annual rainfall can be < 500mm), and its grouping of catchments having widely varying flow regimes, from slowly responding chalk catchments to quickly responding upland catchments, are considered to be the main reasons for the region's low coherence.

3.2 Modified regions

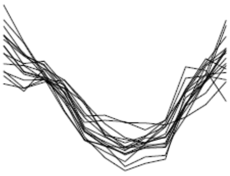
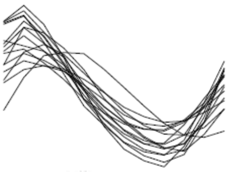
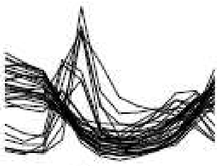
Investigation into the homogeneity of the Scandinavian clusters focused on attempting to revise the regions based on flow regimes. Table 3.1 shows that Region 21 and 22 have a mix of snowmelt- and rainfall-dominated regimes, so re-clustering attempted to separate out regions based on the two dominant processes. However, this did not yield any improvement in cluster homogeneity, so the original two regions were retained. However, some stations in the far north of Norway were omitted because they are a long distance away from the remainder of the region, making the area very large, with by-far the highest inter-gauge distance, and covering an extensive climatological gradient.

Revision of the UK cluster focused on separating the large Eastern cluster. Firstly, this was separated into a North East and South East cluster, broadly following a distinction between previously-defined North East and Central homogeneous rainfall regions (a widely used scheme for classifying regional rainfall (e.g. Jones and Conway, 1997). The two clusters thus derived were more homogeneous than the original cluster (both with a Cluster Homogeneity value of < 8%).

It was further decided to split the South Eastern Great Britain region into two subgroups on the basis of flow regimes. The rationale for this is that a high number of catchments in SE England are groundwater-dominated, and it likely these may respond differently to precipitation deficiencies, as compared to impermeable catchments. It would be expected that droughts would be slower-developing and longer. If the regimes are mixed, it is less likely that they will respond synchronously, resulting in lower RDI values and poorer cluster homogeneity. The region was therefore split into two based on the Base Flow Index (BFI, Gustard et al., 1992) of catchments. An investigation was made into an appropriate BFI threshold, examining the distribution of BFI across the catchments. A threshold of 0.8 was chosen, to separate out those catchments which are generally dominated by baseflow; these catchments are all chalk catchments in southern and eastern England, which so it is likely the regional response would be homogeneous. A lower BFI threshold would introduce catchments from other aquifers, and would also then require catchments from other clusters to be separated out. It should be noted that within the BFI < 0.8 group, baseflow may still contribute a substantial component of the regime of any catchment – this should not be thought of as a group of ‘flashy’ catchments (average BFI = 0.43).

The results in Table 3.2 show that the two South Eastern Great Britain (groundwater dominated and non-groundwater dominated) regions are homogeneous, with the homogeneity of the high baseflow region being particularly good (the lowest across all clusters). Although two distinct sub-regions are defined, this is still viewed as a single geographical region (South Eastern Great Britain) – the BFI-based split cannot be used to create distinct geographical regions.

Table 3.2 Table of metrics for revised UK and Scandinavian regions

	Region	Number of gauging stations	Inter-gauge distance (km)	Mean Hydrograph	Cluster homogeneity (%)	P_c	Correlation RDI and SPI
UK	NW Great Britain	33	159.8		7.3	0.162	0.52
UK	SW Great Britain	34	146.7		7.9	0.139	0.58
UK	NE Great Britain	16	151.9		7.6	0.157	0.58
UK	SE Great Britain non-groundwater dominated	23	132.3		7.7	0.132	0.63
UK	SE Great Britain groundwater dominated	14	130.4		6.8	0.230	0.69
Scandinavia	Southern Scandinavia	31	241.9		8.6	0.099	0.63
Scandinavia	NW Scandinavia	37	347.5		10.7	0.030	0.65

3.3 Final regions

Without a uniformly dense network of river gauges, establishing the boundaries of homogeneous Drought Regions is a difficult and somewhat arbitrary exercise. In a very strict sense, the RDI only provides information for the 579 European catchments considered, and for any location outside these catchment boundaries. However, for any practical use, a wider definition of the regions is necessary. This procedure is explained in the next paragraphs.

The approach taken here is a compromise between objective criteria and manual correction. From the statistical clustering of the 579 DI series, 23 distinct groups emerged (with an additional 'groundwater-dominated' sub-region, for one region of the UK). All regions show distinct geographical features that provided the basis for the final region boundaries.

Thiessen polygons were used to create boundaries between adjacent river gauges locations, and drawn around all 579 gauging stations. With no digital catchment boundaries available for the majority of the European river basins, this technique was considered to provide acceptable alternative to the use of hydrometric boundaries. Merging these polygons according to the homogeneous regions provided geographic extent of each drought region. A fixed buffer zone around each station insured the majority of the regions showed unbroken areas. Where no data was available for some countries, it was decided to exclude that country from any of the final drought region. Despite providing artificial boundaries, following administrative limits rather than being-processed-based, this technique was preferred to avoid including some areas where the droughts regime could not been analysed within the framework of this project. Note that for some regions, the administrative boundaries also coincide with some hydrological boundaries (e.g Southern limit of Region 14, South Austria and Switzerland). Final manual re-adjustment was necessary where the adjacent gauging stations were far apart.

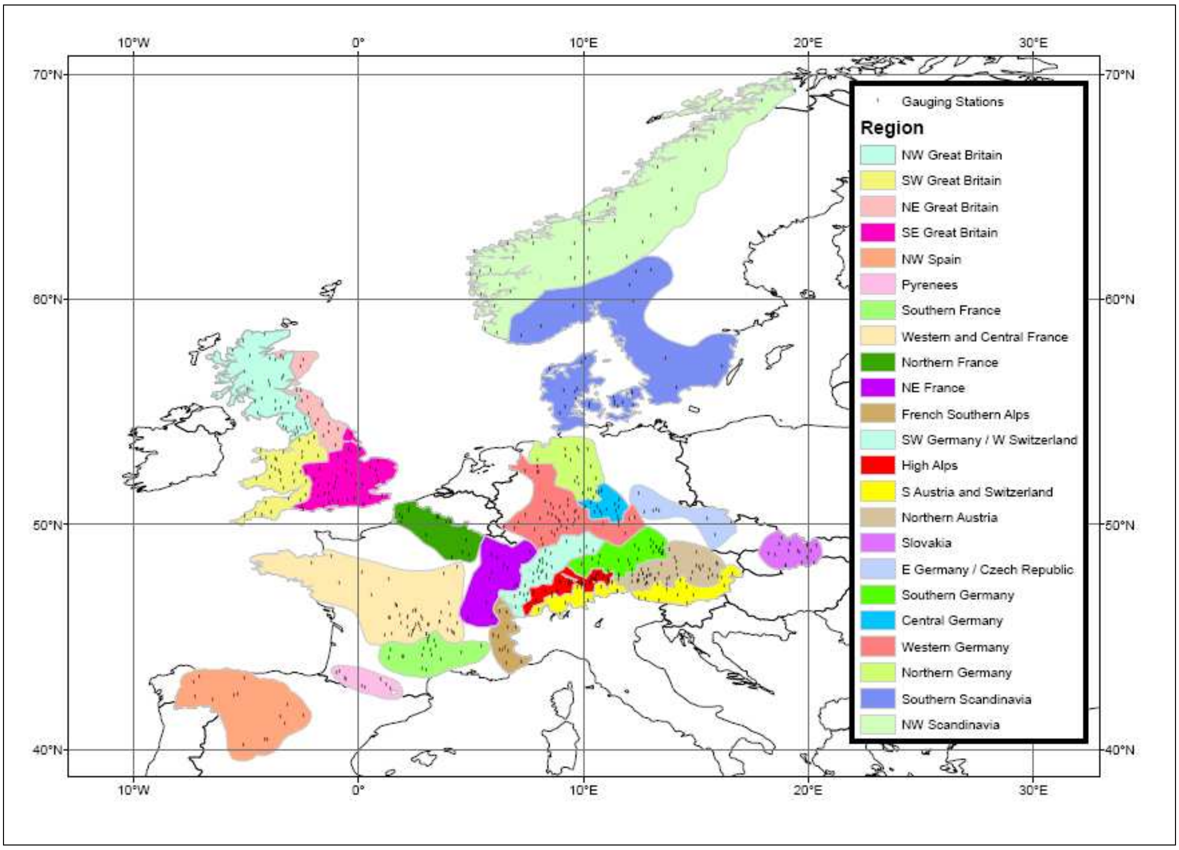


Figure 3.1 Final European Drought regions

Figure 3.1 shows the final regions and their spatial extent. Note that these geographical regions only impact on the RSPI series, derived by superposing the 0.5º grids of the monthly rainfall on these region boundaries. The RDI series remained defined from the 579 hydrological series.

4 Drought Catalogues

4.1 Description of the catalogues

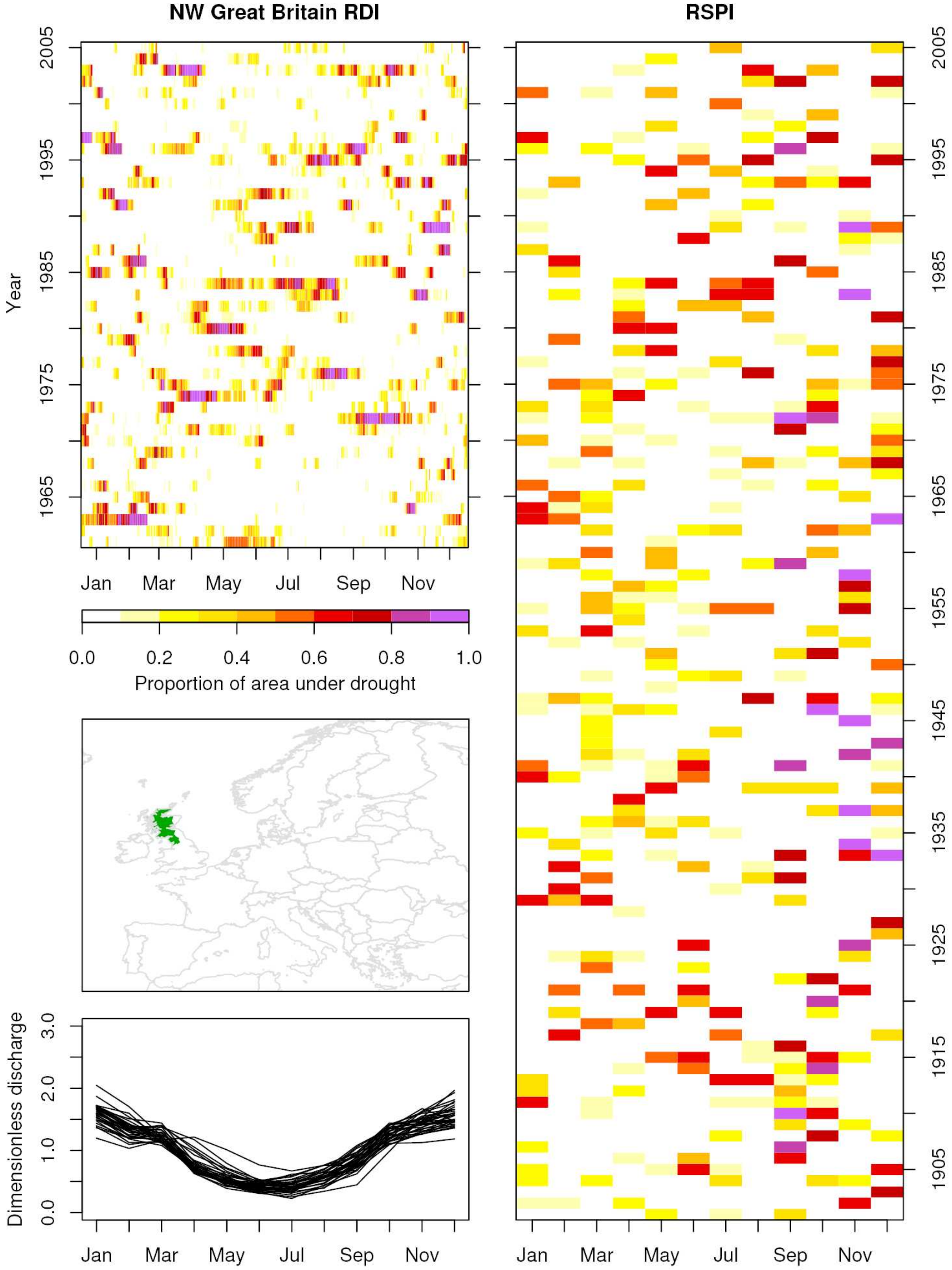
Data for each homogenous drought region are described over two pages in the catalogue. The first page provides a direct comparison of regional stream flow drought for the period 1961 to 2005 and the longer record meteorological indicator 1901-2005. Periods of coherent drought are easily picked out by blocks of colour. The darker the colouration the more coherent is the drought across the region. Any potential lag between the hydrological response and the meteorological input is evident by a shift in the horizontal position of the coloured blocks. A map indicates the location of the region and a spaghetti plot illustrates the flow regimes at each gauging station within the regional network.

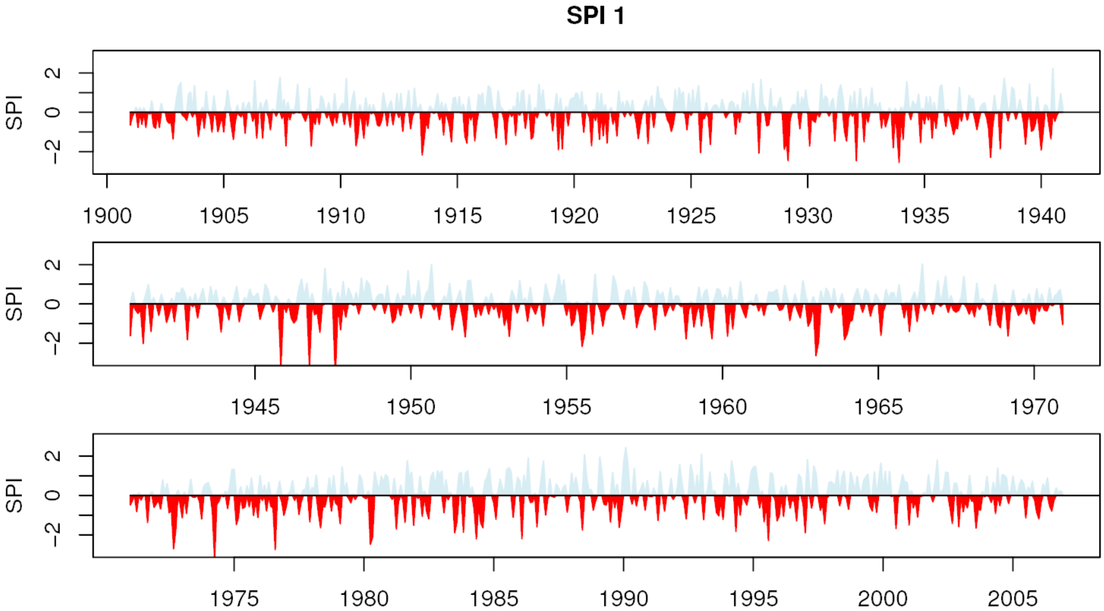
The second page provides times series of the area averaged Deficiency Index and Standardized Precipitation Index. These compliment the regional plots by providing information on the severity of any spatially coherent events. Seasonality of the onset, duration, and spatial coherency of droughts within the region can be explored using circular plots at the bottom of the page. A drought beginning in February is represented as a line pointing to that month on the circle. The length of the radius indicates the coherency of the event where a radius of one, i.e. a line extending to the edge of the circle means that the whole of the region is affected. The colour of the line represents the duration of the event in months.

The catalogue entry is completed by a brief description of any special characteristics of this region such as particularly strong or weak correlations between stream flow and precipitation, suspected inhomogeneities, lack of data, etc.

4.2 Catalogues

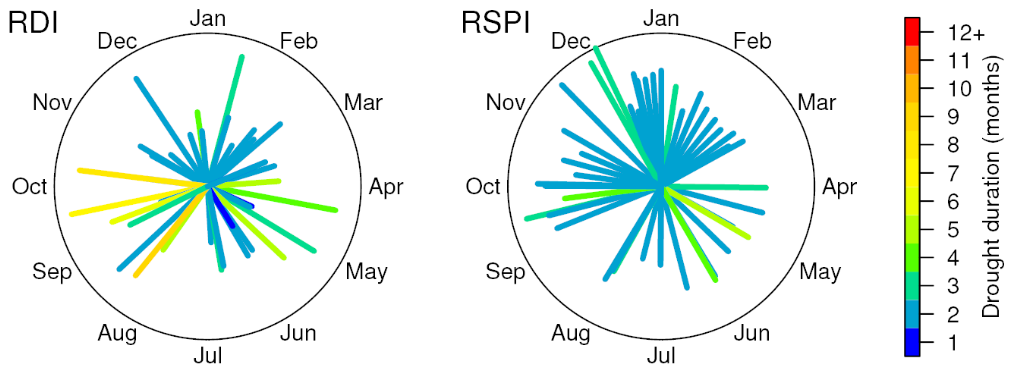
4.2.1 North West Great Britain





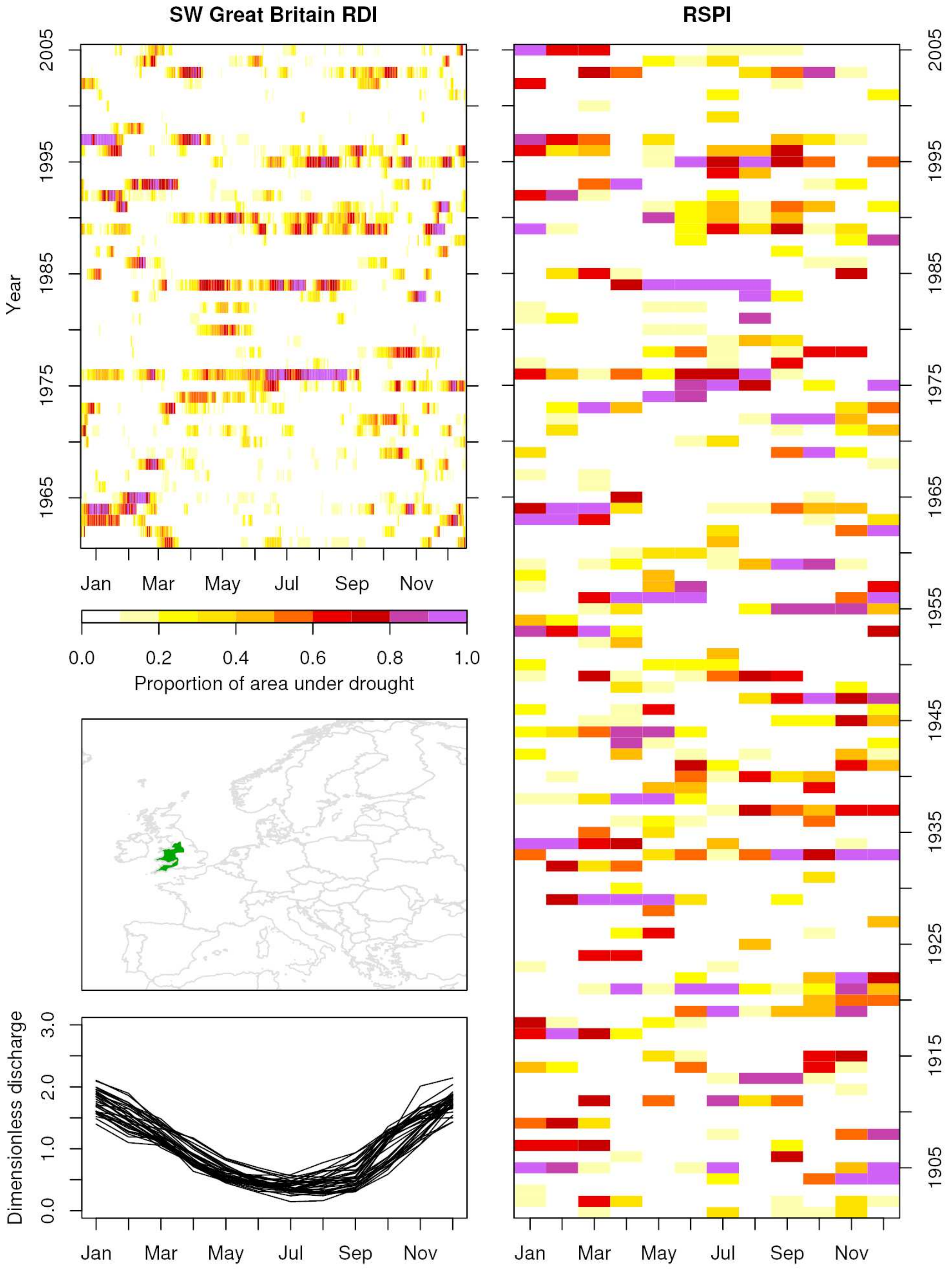
Notes

Regime: Precipitation–dominated, high flows in winter, low flows in summer.
The optimal meteorological proxy for streamflow drought is SPI 1 at a lag of 0 months with a rank correlation of 0.52.
Majority of hydrological droughts are of short duration.
Multi–month hydrological droughts generally start late summer/autumn with shorter droughts originating in winter/spring.

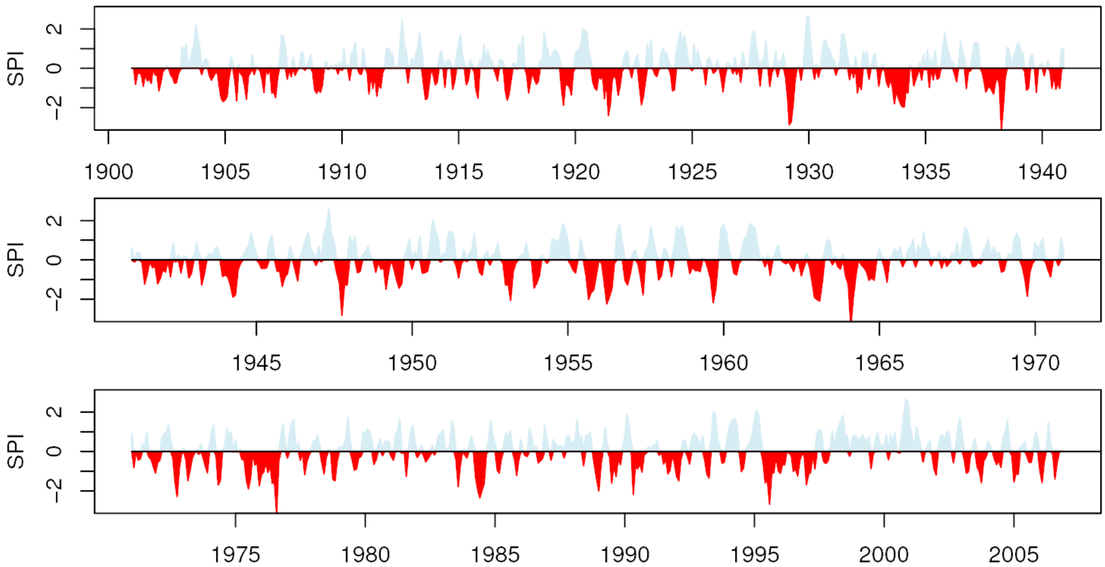


Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

4.2.2 South West Great Britain



SPI 3



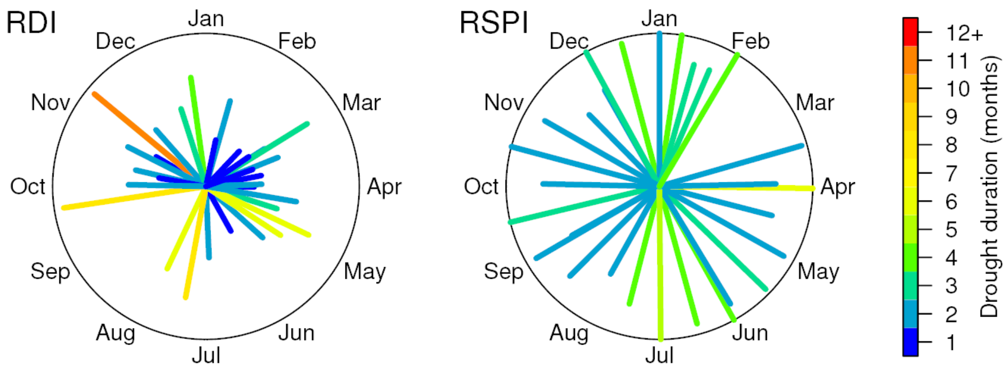
Notes

Regime: Precipitation–dominated, high flows in winter, low flows in summer.

The optimal meteorological proxy for streamflow drought is SPI 3 at a lag of 0 months with a rank correlation of 0.58.

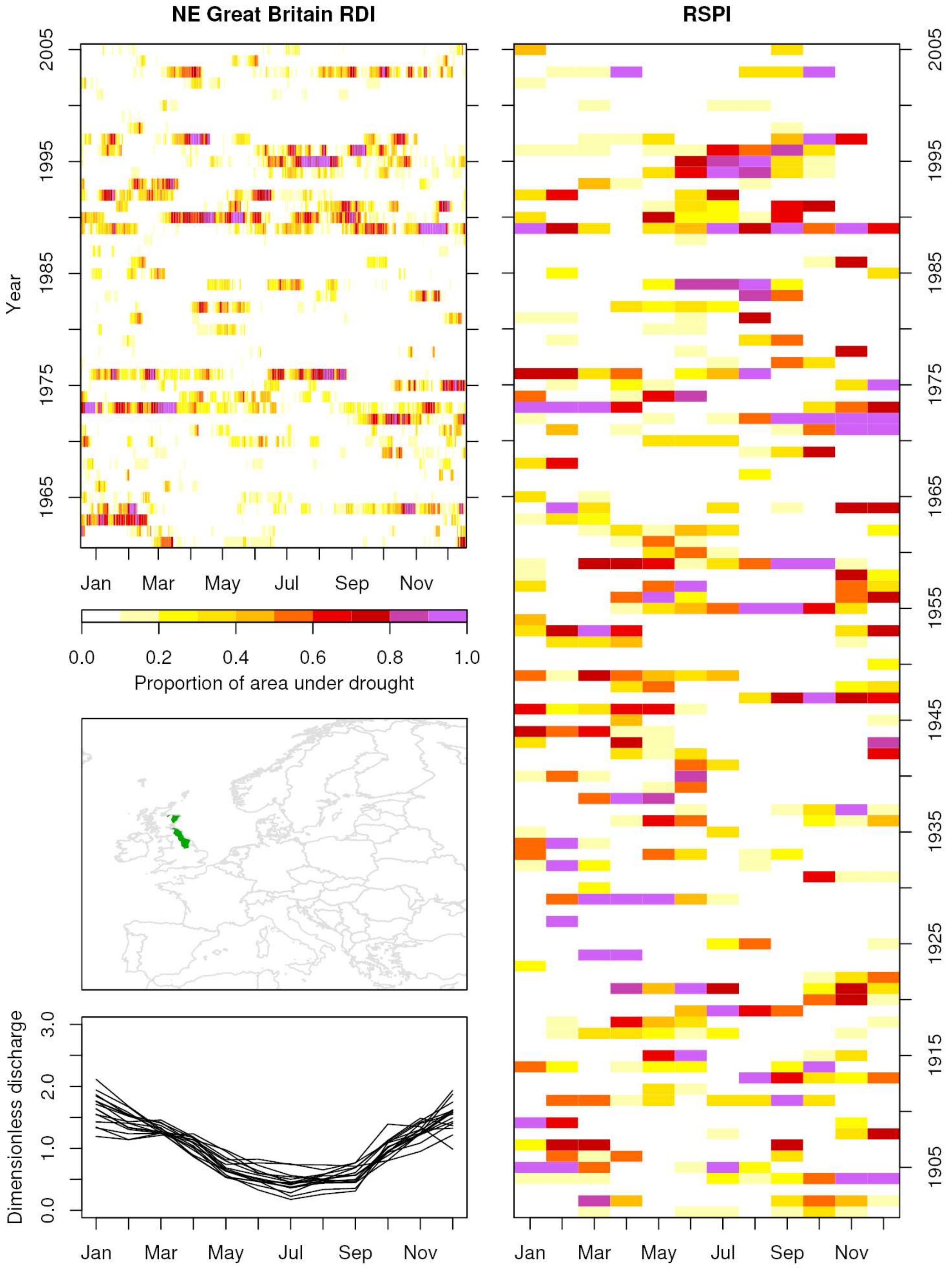
Some long coherent hydrological droughts but the majority are less coherent and of shorter duration.

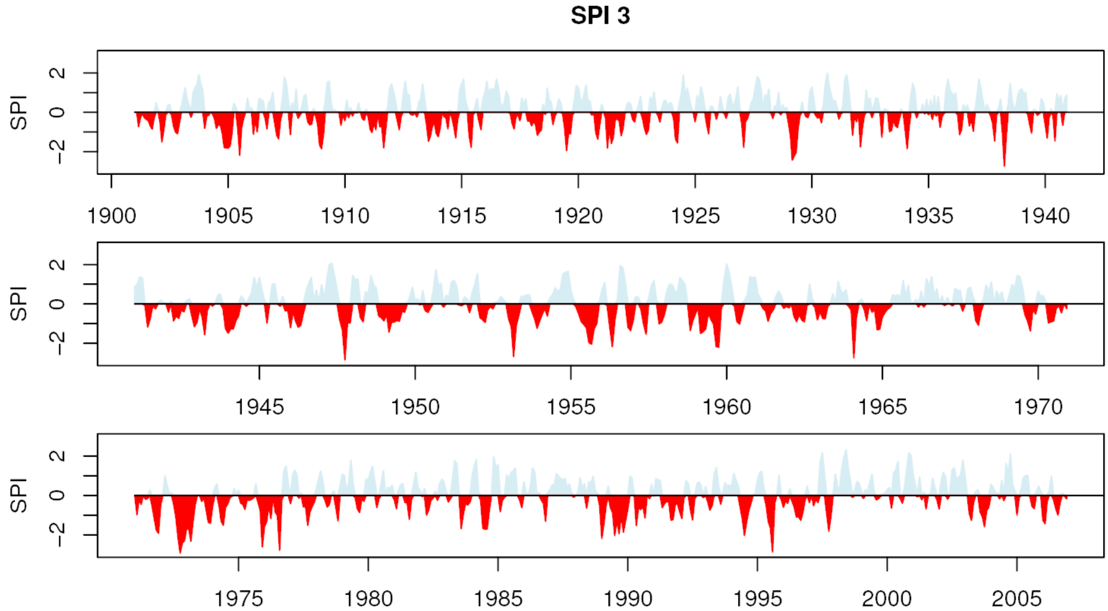
Multi–month hydrological droughts generally start from May to November.



Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

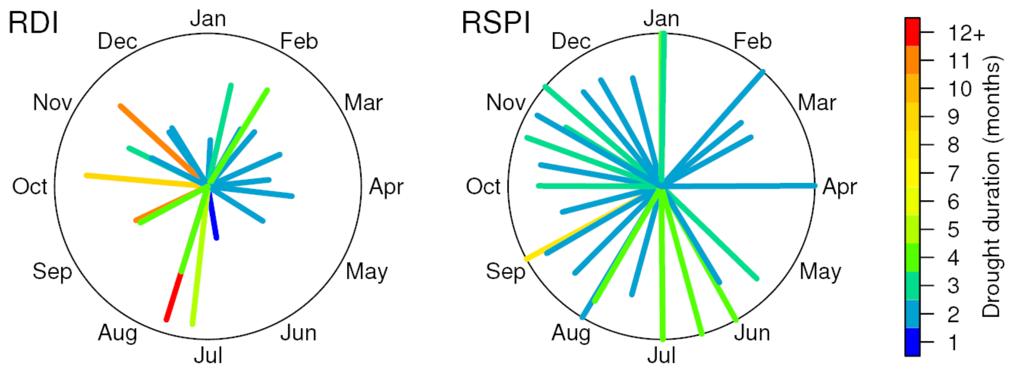
4.2.3 North East Great Britain





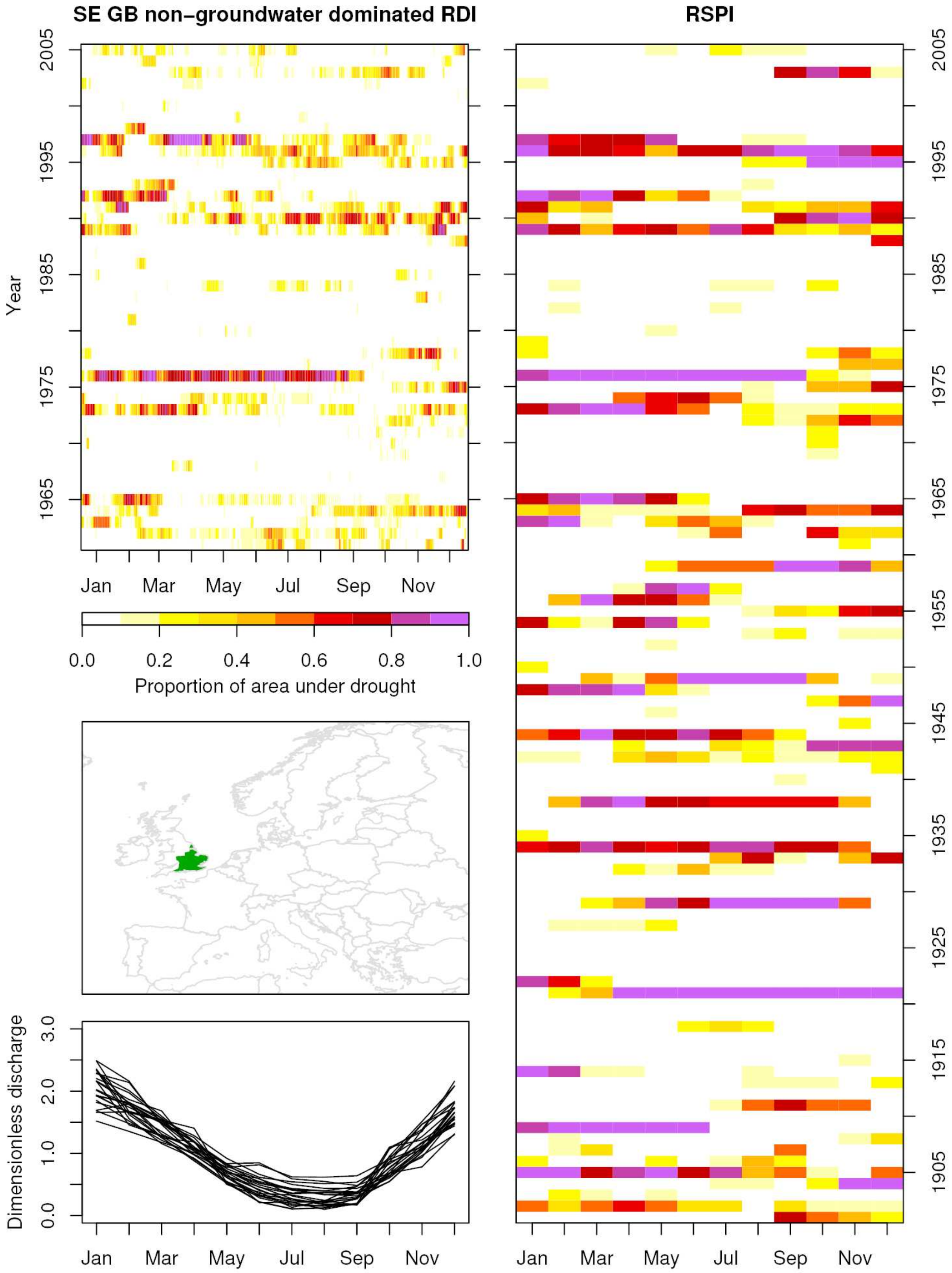
Notes

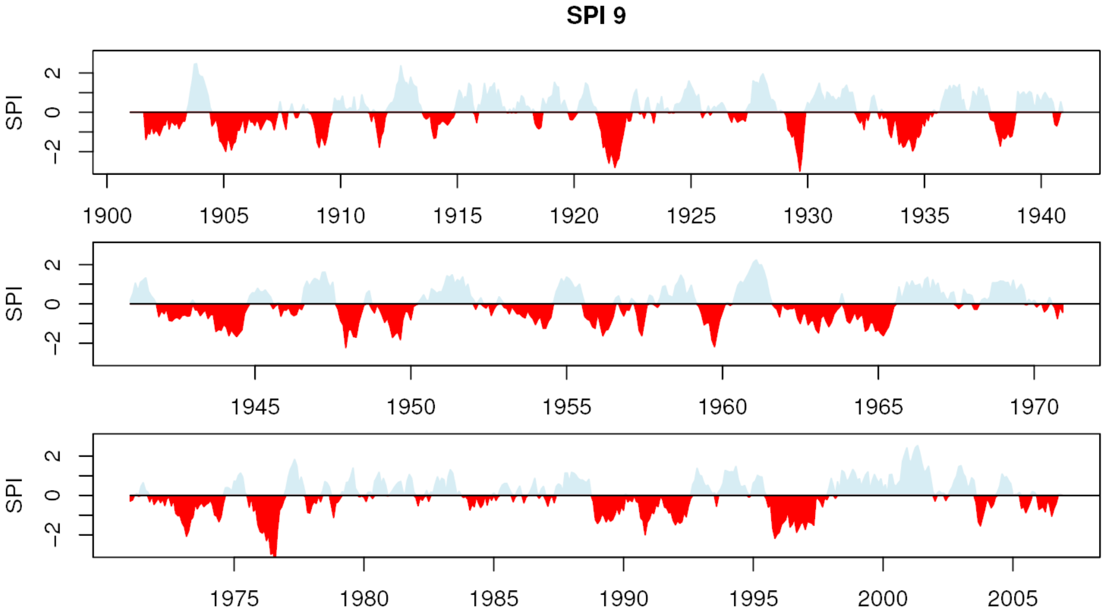
Regime: Precipitation–dominated, high flows in winter, low flows in summer.
The optimal meteorological proxy for streamflow drought is SPI 3 at a lag of 0 months with a rank correlation of 0.58.
Some long coherent hydrological droughts but the majority are less coherent and of short duration.
Multi–month hydrological droughts generally start from July to November.
Spring/summer droughts dominated by short duration low coherency.



Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

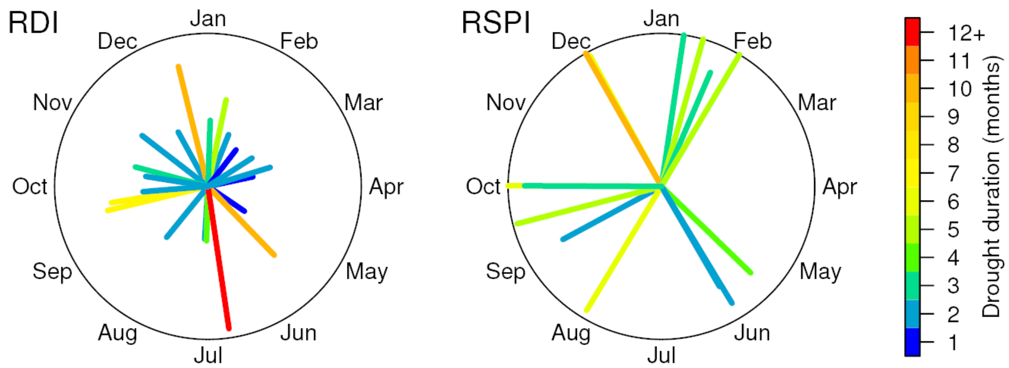
4.2.4 South East Great Britain (non groundwater dominated)





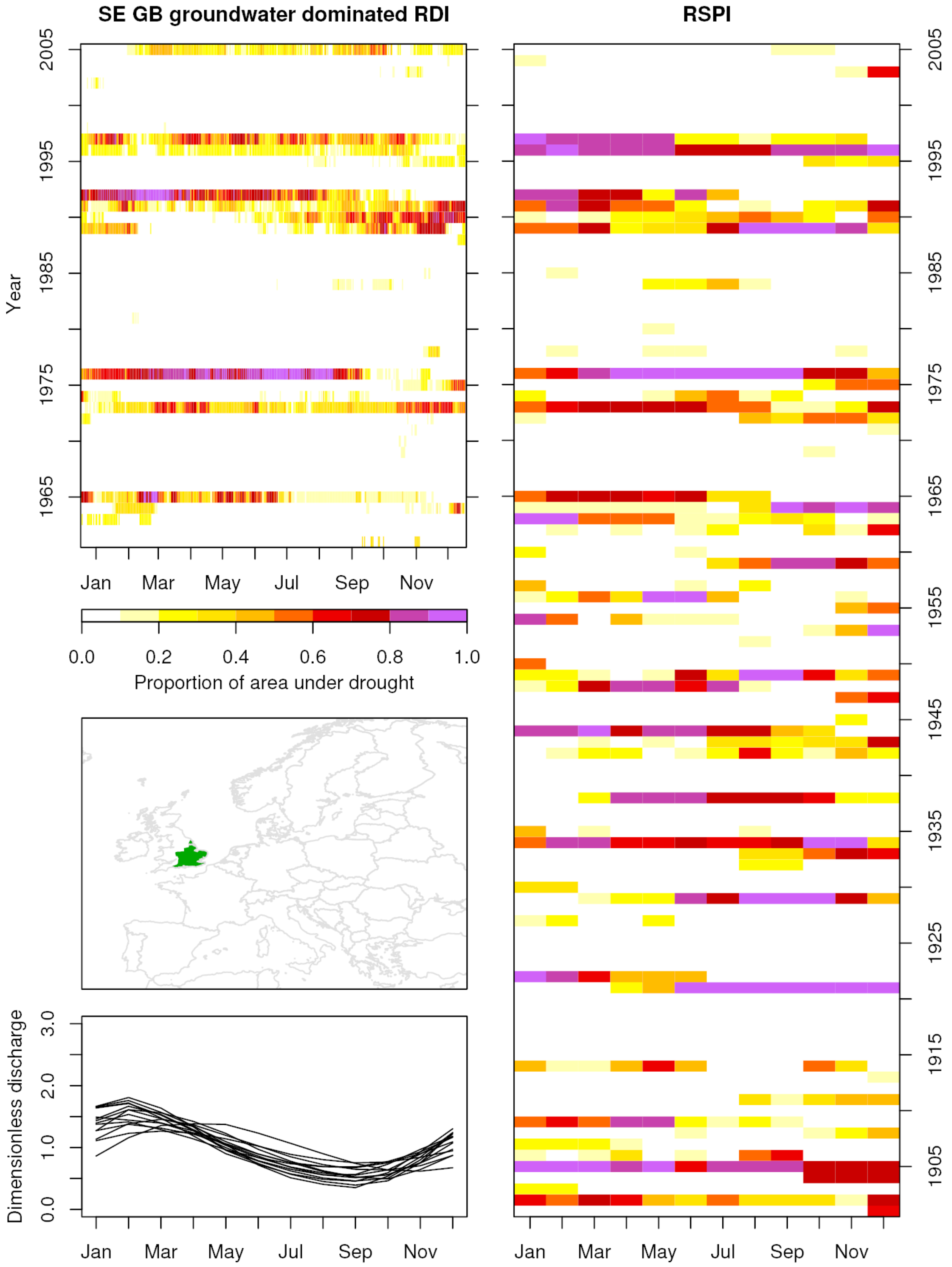
Notes

Regime: Precipitation–dominated, high flows in winter, low flows in summer.
The optimal meteorological proxy for streamflow drought is SPI 9 at a lag of 0 months with a rank correlation of 0.63.
Few coherent short hydrological droughts, some long hydrological droughts.
No clear seasonality in hydrological drought occurrence.

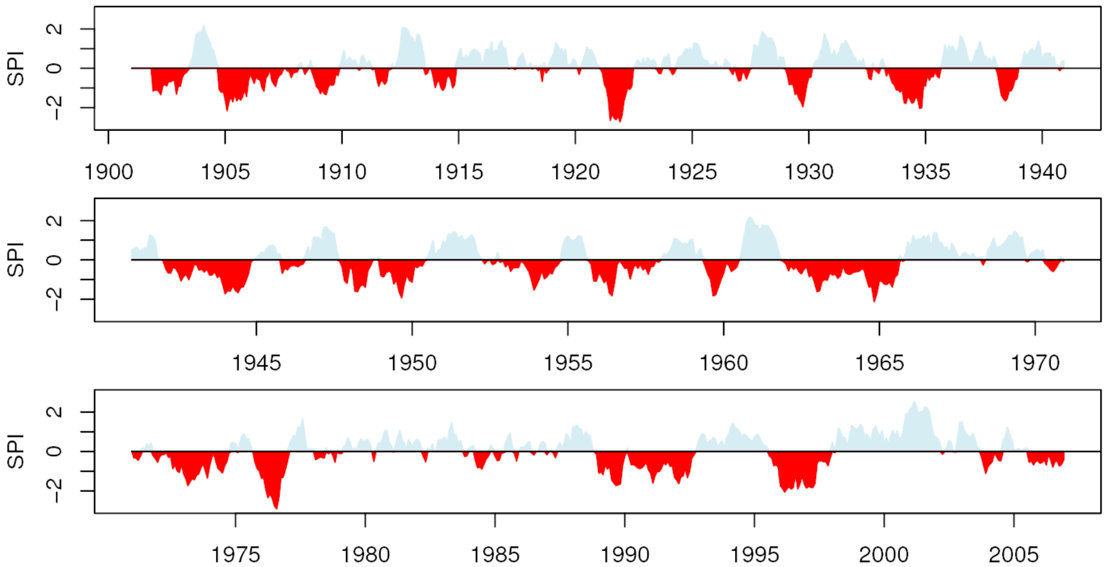


Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

4.2.5 South East Great Britain (groundwater dominated)



SPI 12



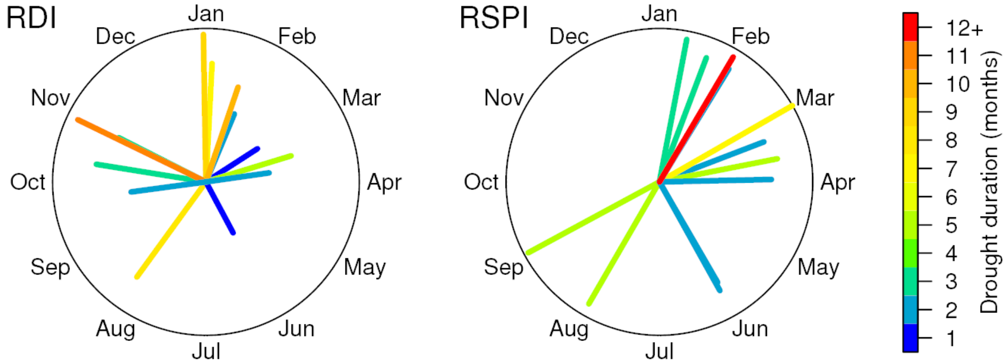
Notes

Regime: High flows winter to spring, low flows late summer to autumn.

The optimal meteorological proxy for streamflow drought is SPI 12 at a lag of 0 months with a rank correlation of 0.69.

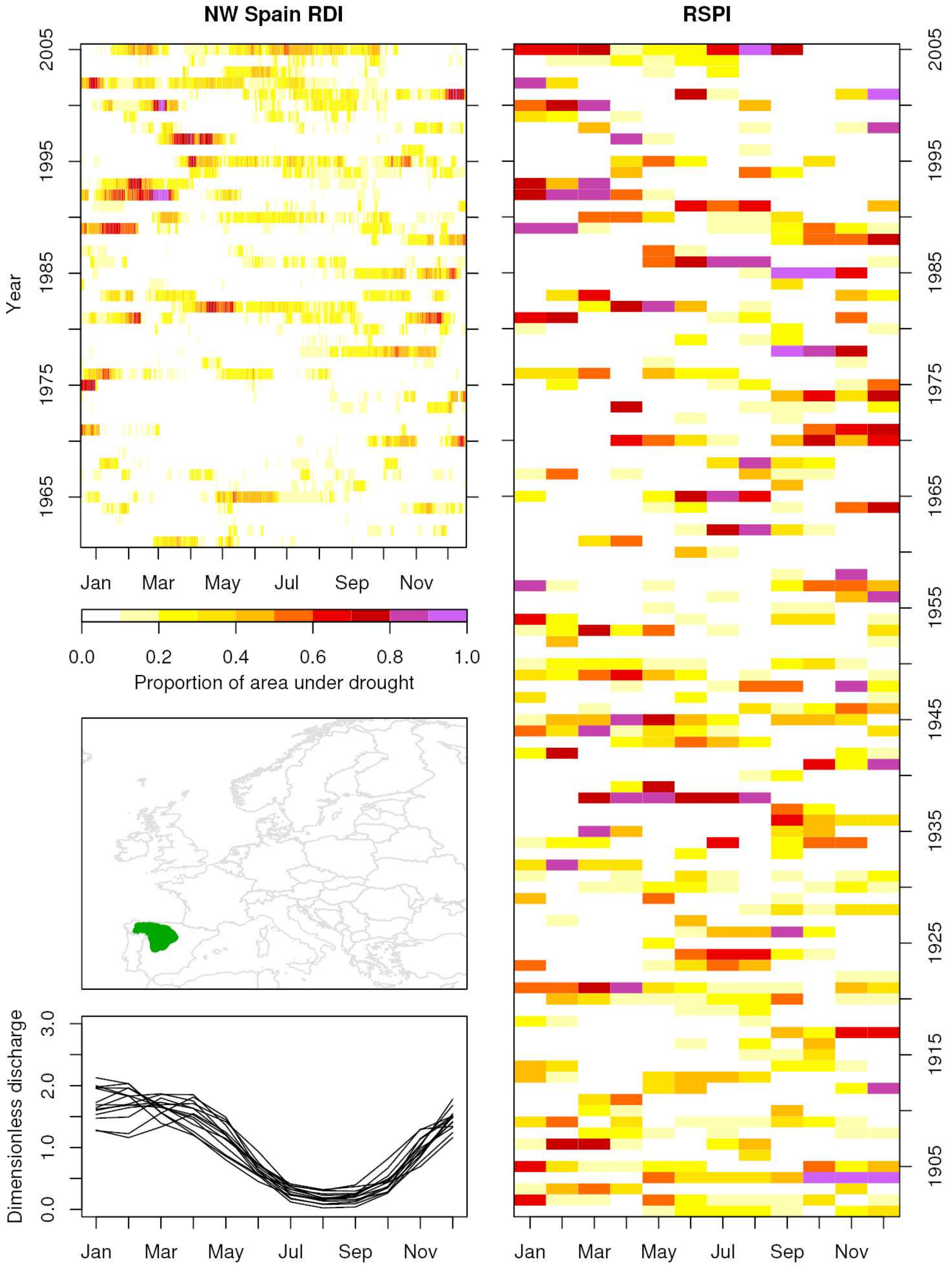
Most hydrological droughts develop to affect a high proportion of the region and tend to be long lasting, in particular 1975–1976.

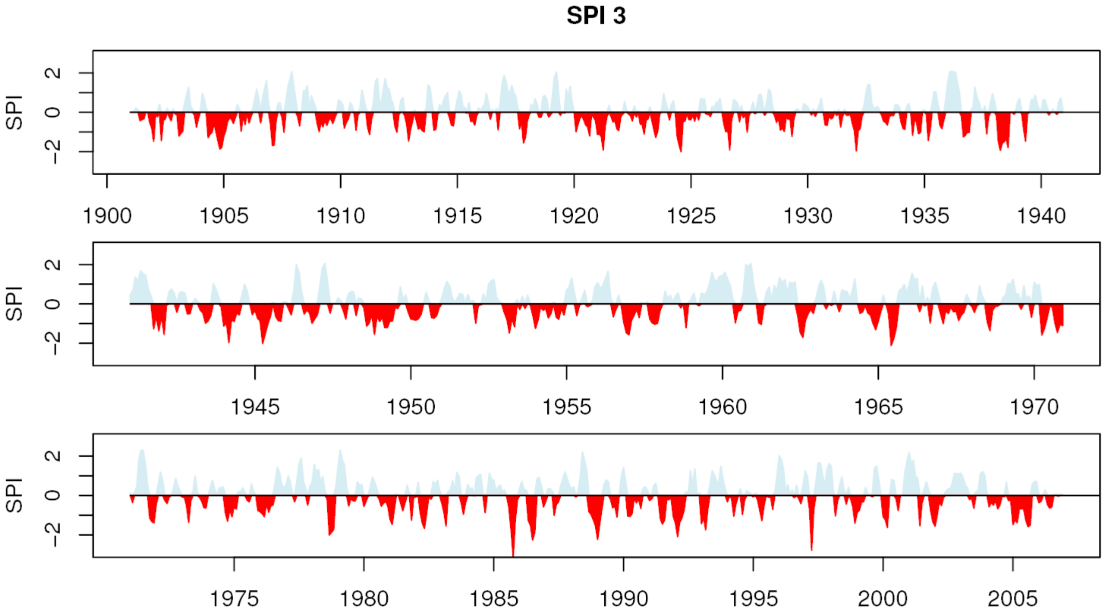
The longest droughts start in winter.



Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

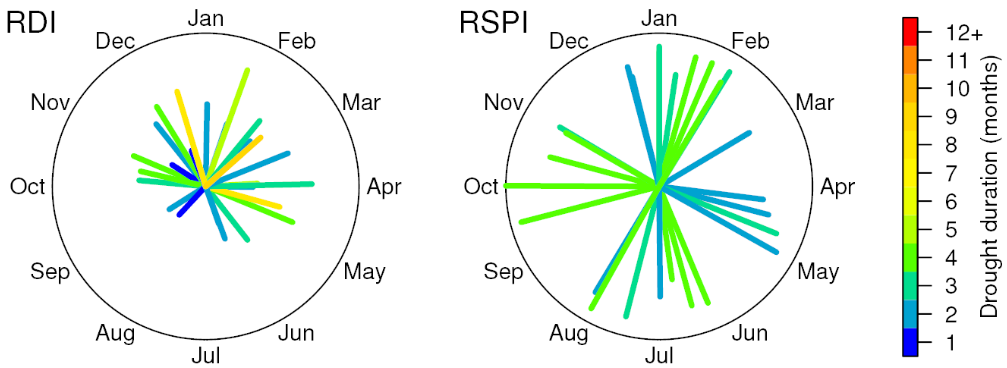
4.2.6 North West Spain





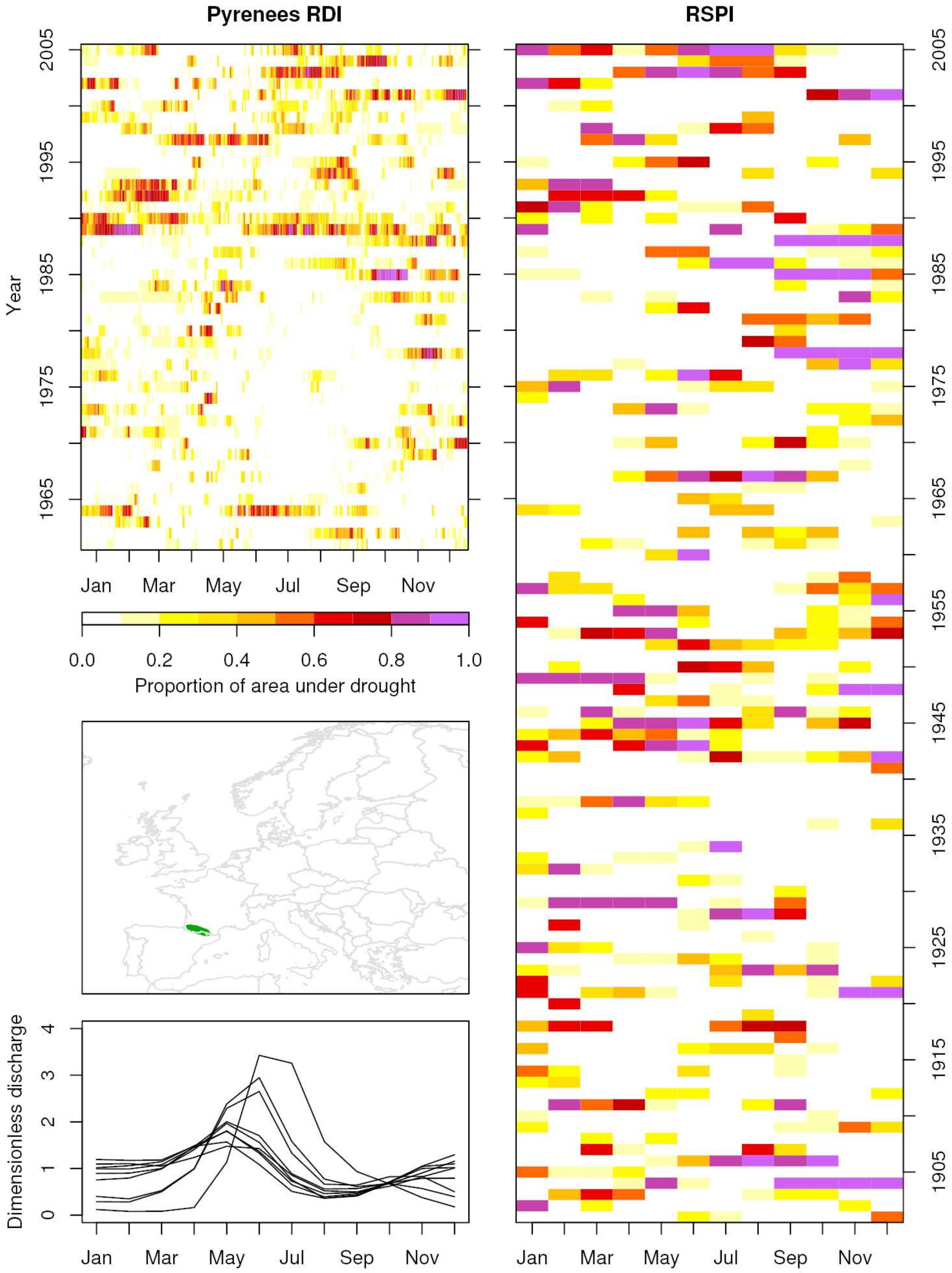
Notes

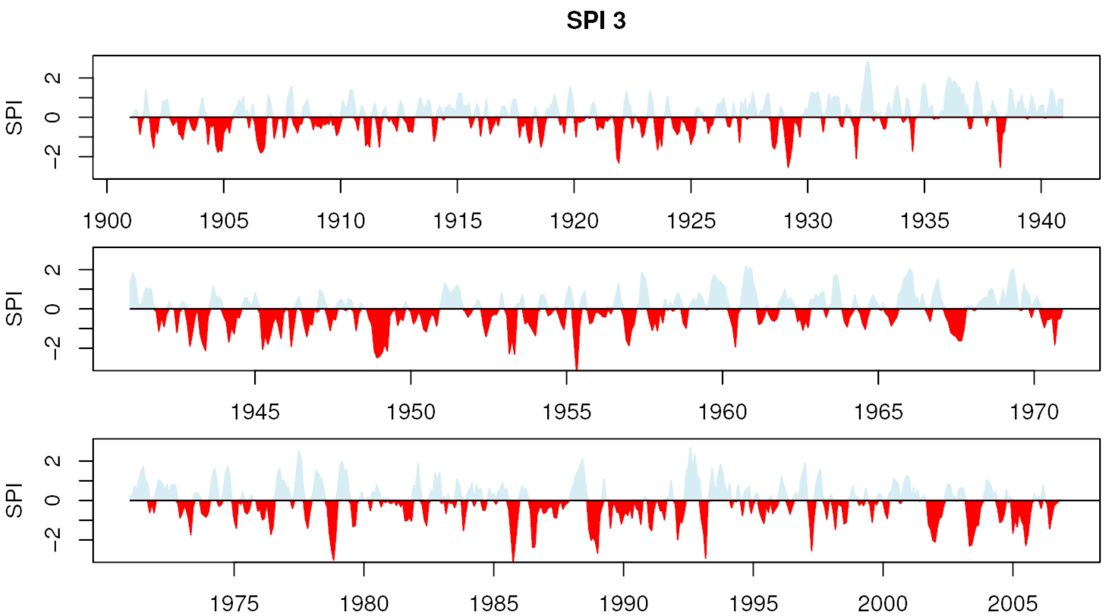
Regime: Precipitation–dominated, high flows in winter and spring, low flows in summer.
The optimal meteorological proxy for streamflow drought is SPI 3 at a lag of 0 months with a rank correlation of 0.58.
Low homogeneity.
Few spatial coherent hydrological droughts of short duration.
Many minor droughts affecting a small number of catchments.
Majority of the droughts start in winter.



Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

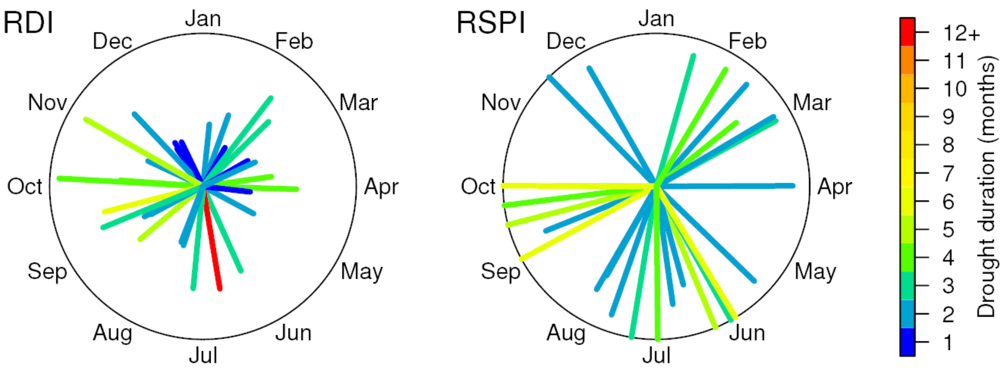
4.2.7 Pyrenees





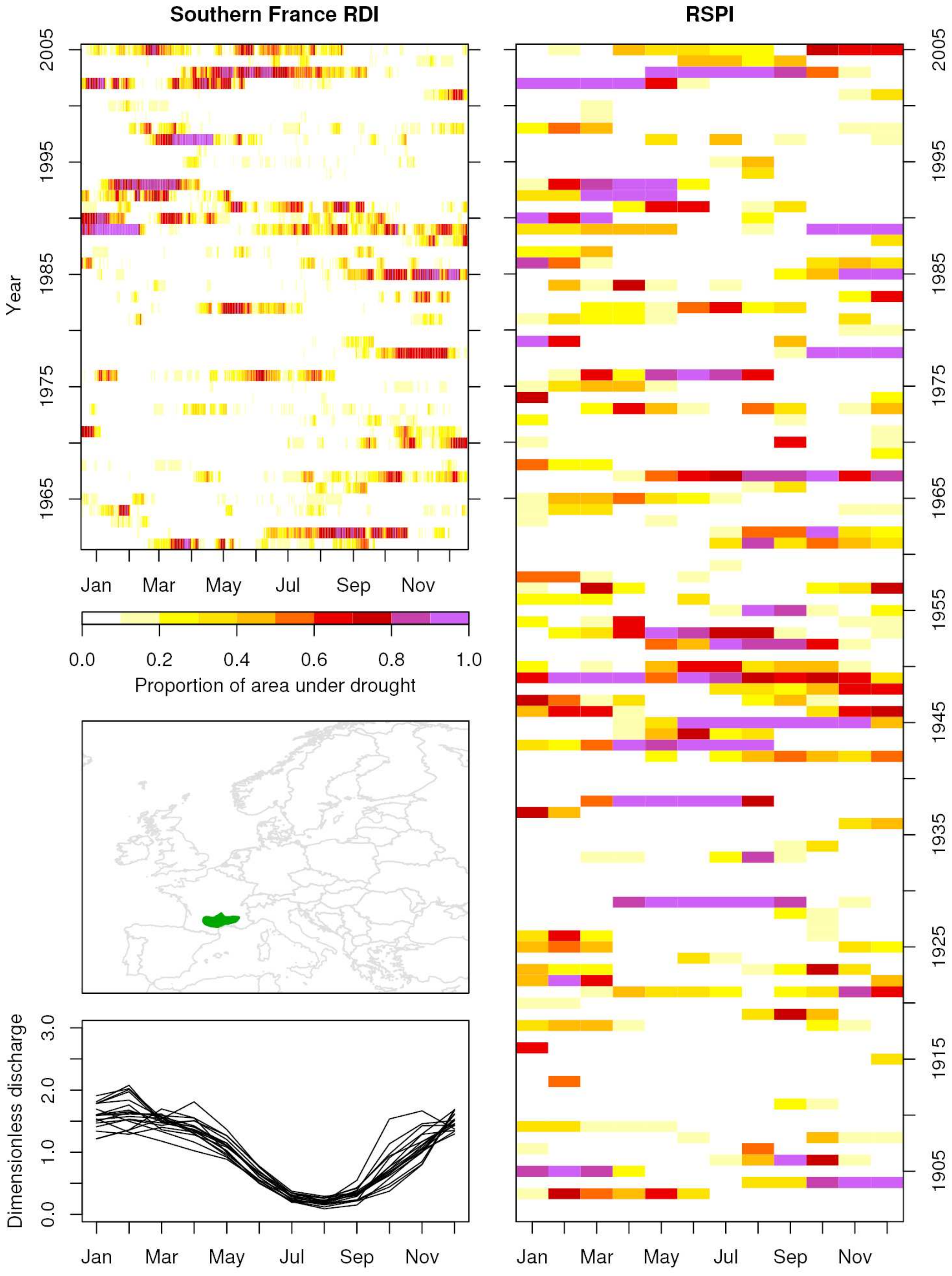
Notes

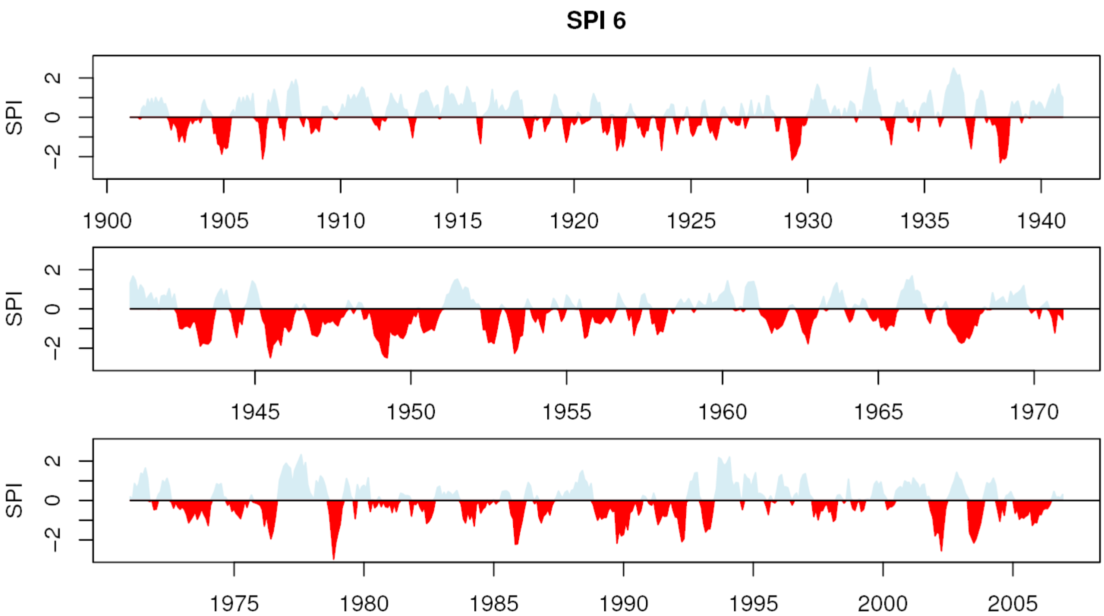
Regime: Snow–melt dominated regime, low flows in winter, high flows in spring/summer.
The optimal meteorological proxy for streamflow drought is SPI 3 at a lag of 0 months with a rank correlation of 0.33.
Some spatially coherent hydrological droughts of long duration, many minor droughts affecting a small number of catchments.
The longest, most coherent droughts start June to November.



Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

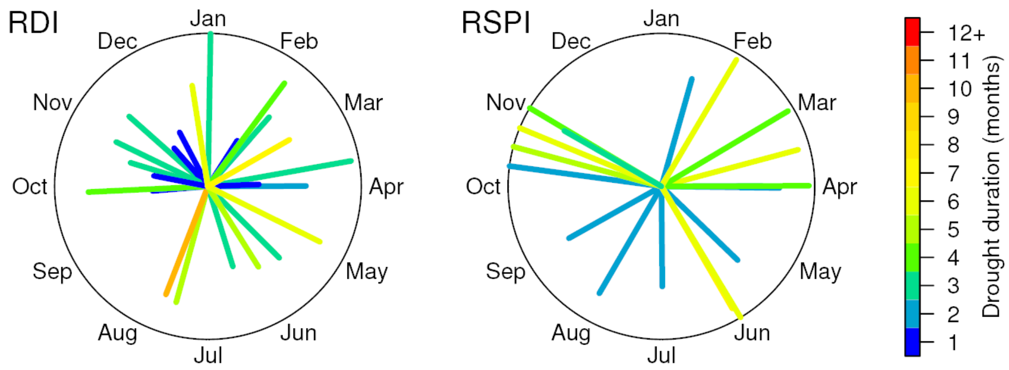
4.2.8 Southern France





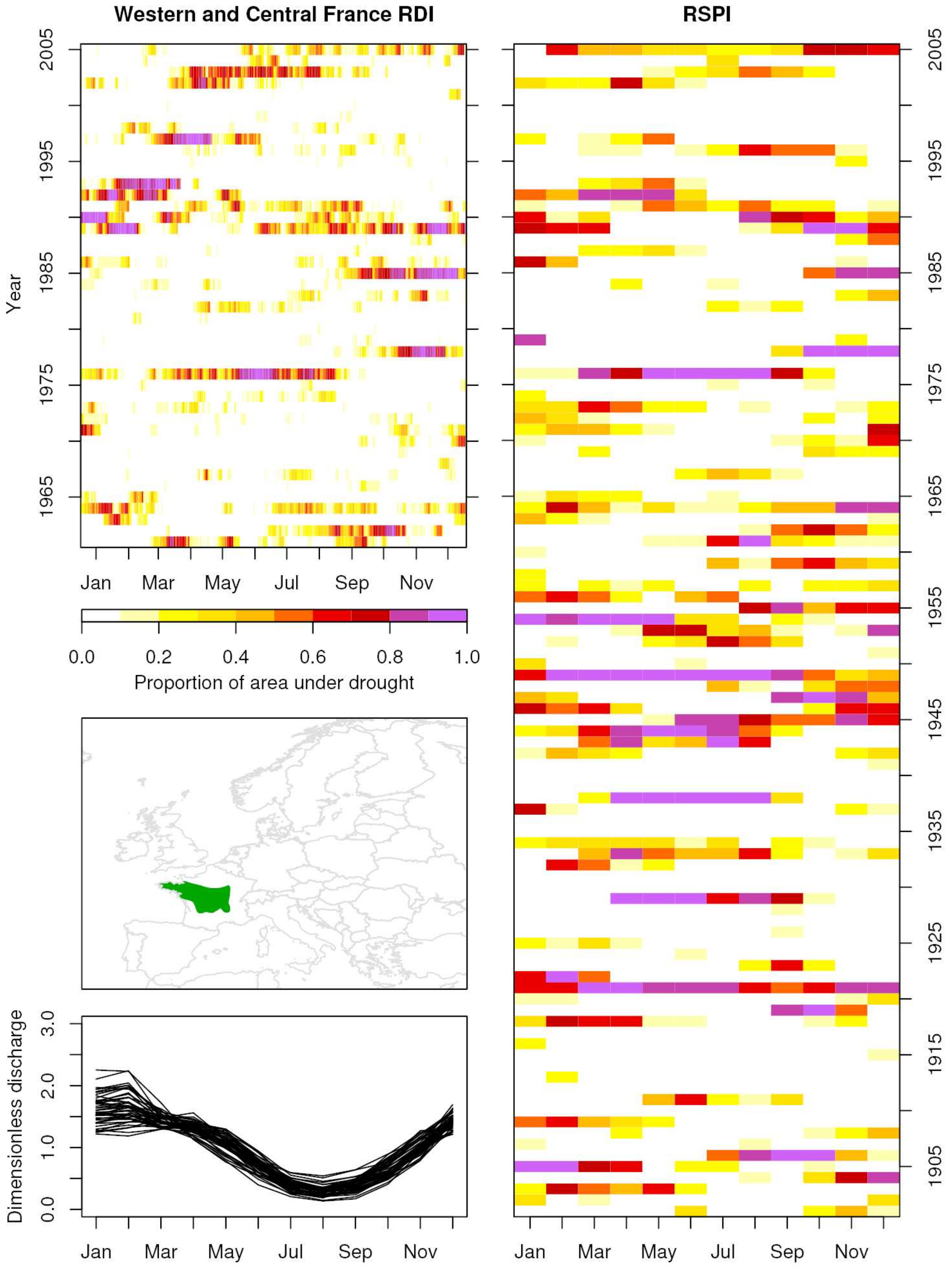
Notes

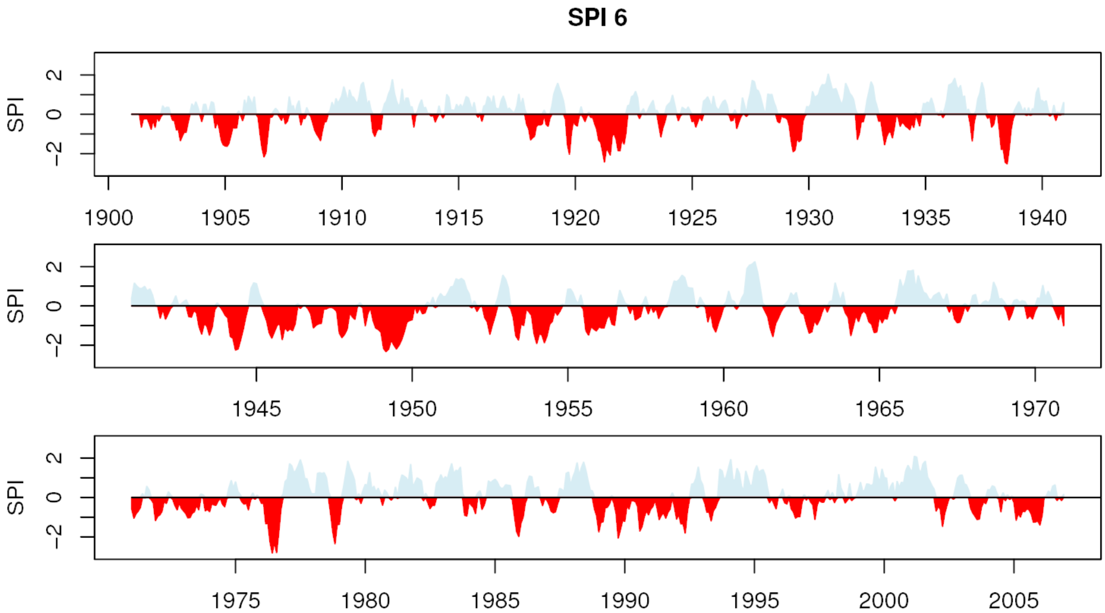
Regime: Precipitation−dominated, high flows in winter, low flows in summer.
The optimal meteorological proxy for streamflow drought is SPI 6 at a lag of 0 months with a rank correlation of 0.58.
Most droughts spatially coherent and shorter than 6 months, some up to 8 months.
Multi−year period of precipitation deficiency in the 1940s.
No clear seasonality in hydrological drought occurrence.



Circular plots of drought onset and duration 1961−2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

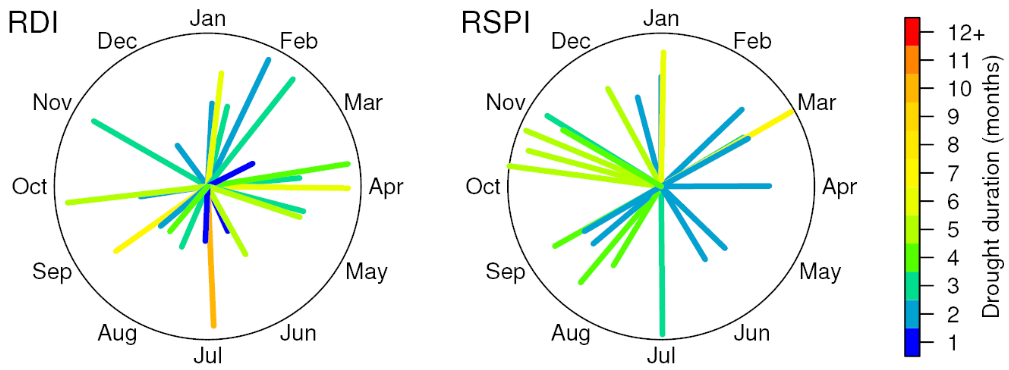
4.2.9 Western and Central France





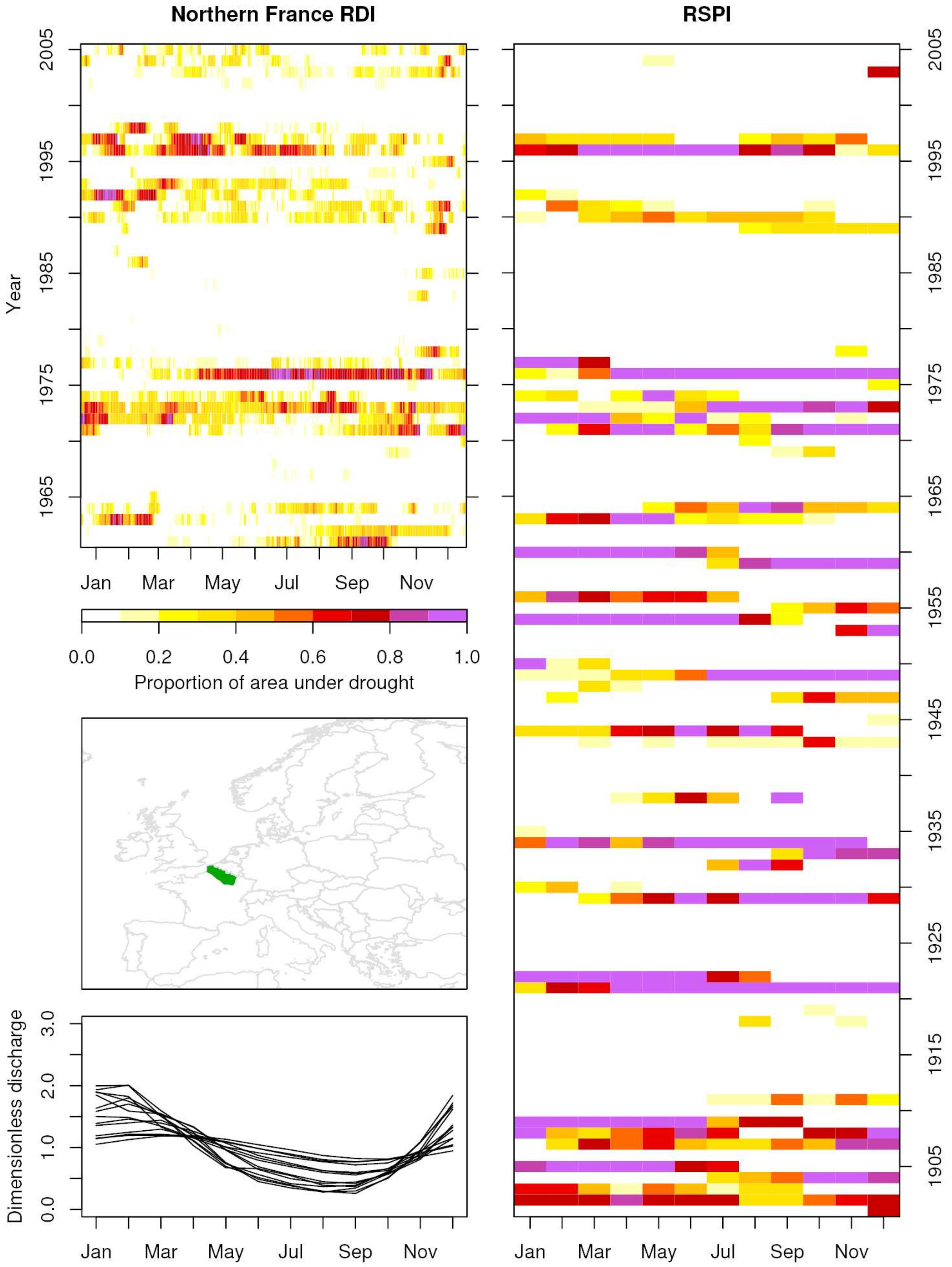
Notes

Regime: Precipitation−dominated, high flows in winter, low flows in summer.
The optimal meteorological proxy for streamflow drought is SPI 6 at a lag of 0 months with a rank correlation of 0.65.
Most droughts spatially coherent and lasting less than 9 months.
Multi−year period of precipitation deficiency in the 1940s.
No clear seasonality in hydrological drought occurrence.

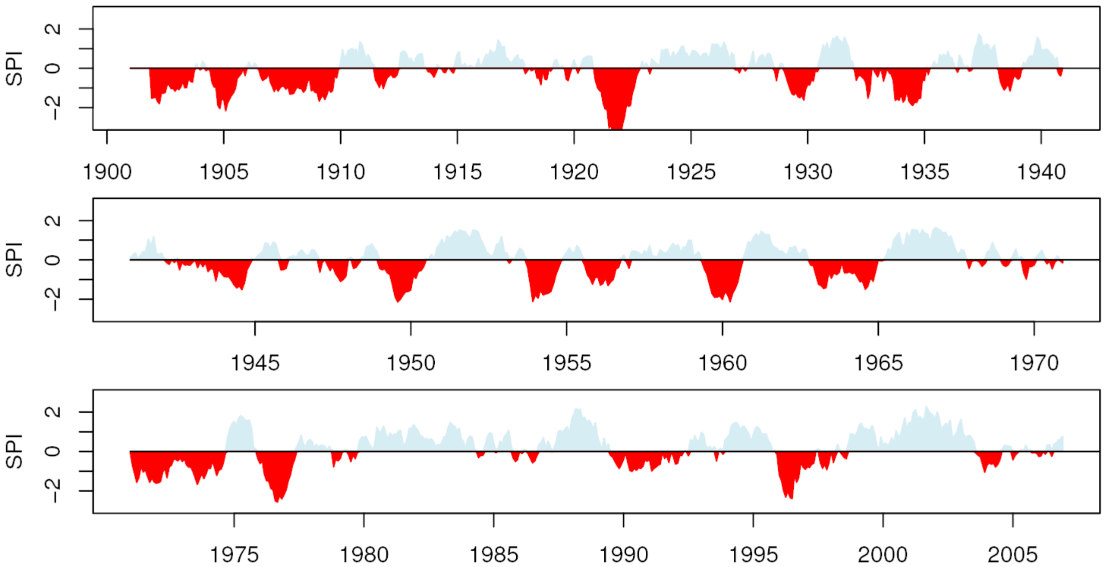


Circular plots of drought onset and duration 1961−2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

4.2.10 Northern France

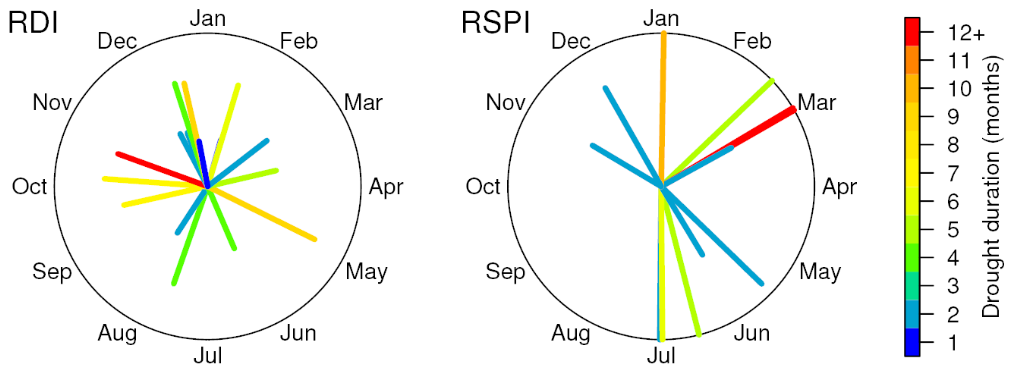


SPI 12



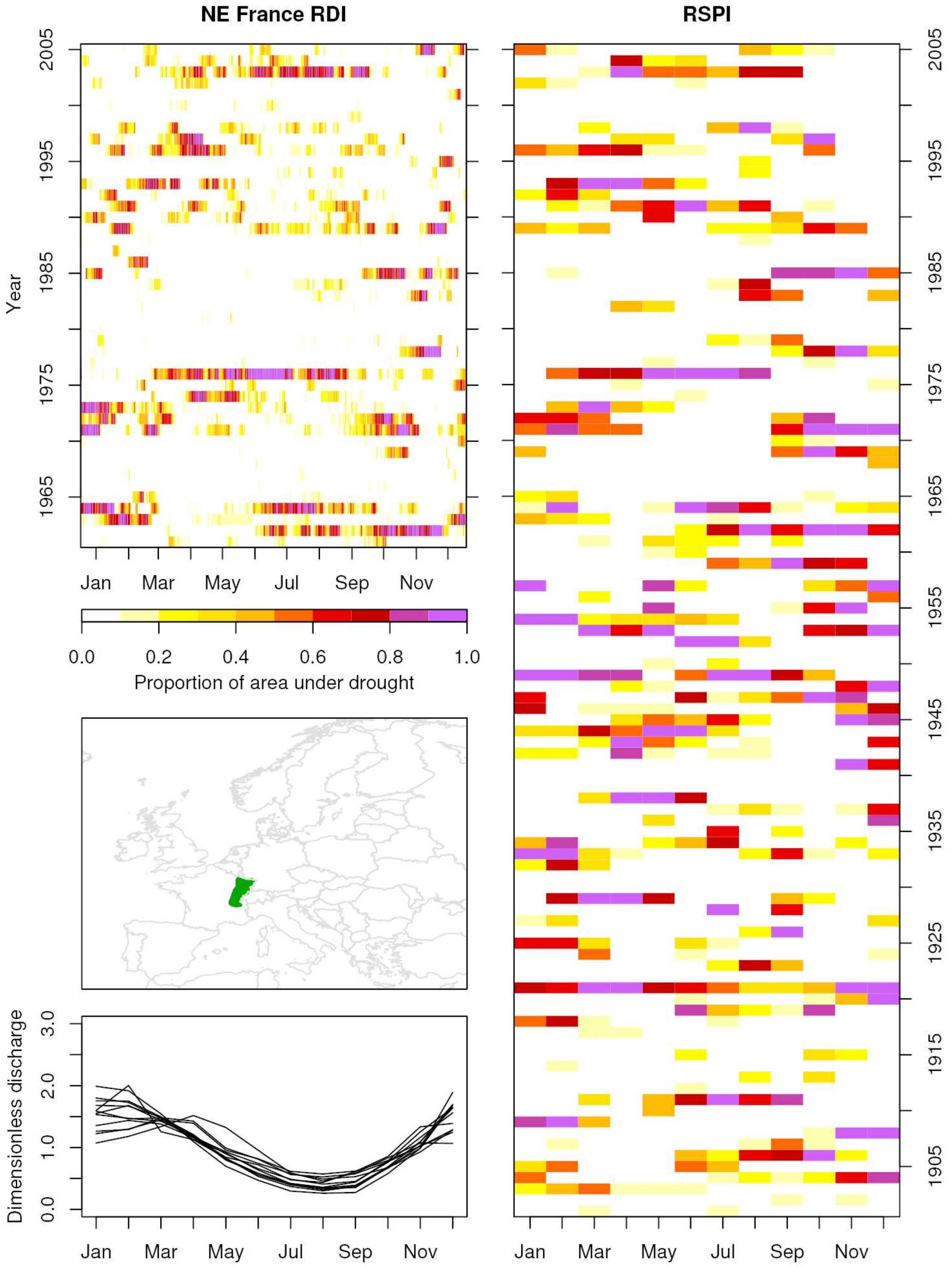
Notes

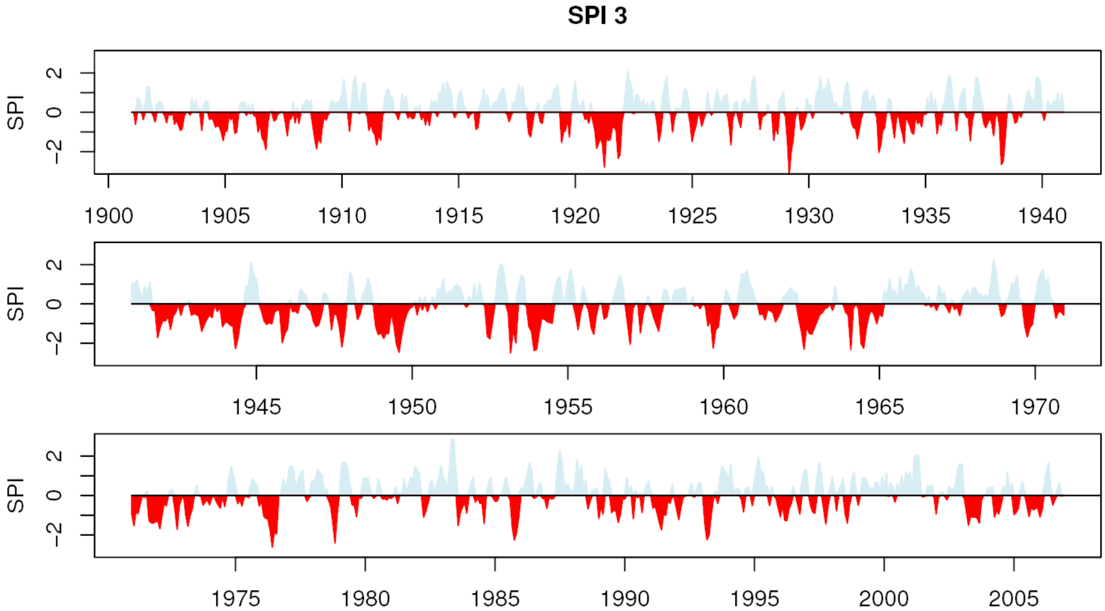
Regime: Precipitation–dominated, high flows in winter, low flows in summer.
The optimal meteorological proxy for streamflow drought is SPI 12 at a lag of 0 months with a rank correlation of 0.61.
Few short duration droughts, the majority lasting over 10 months.
No clear seasonality in hydrological drought occurrence.



Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

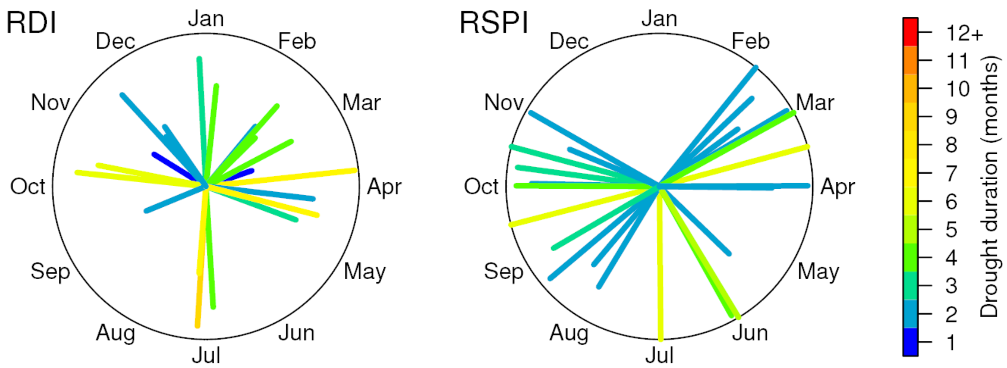
4.2.11 North East France





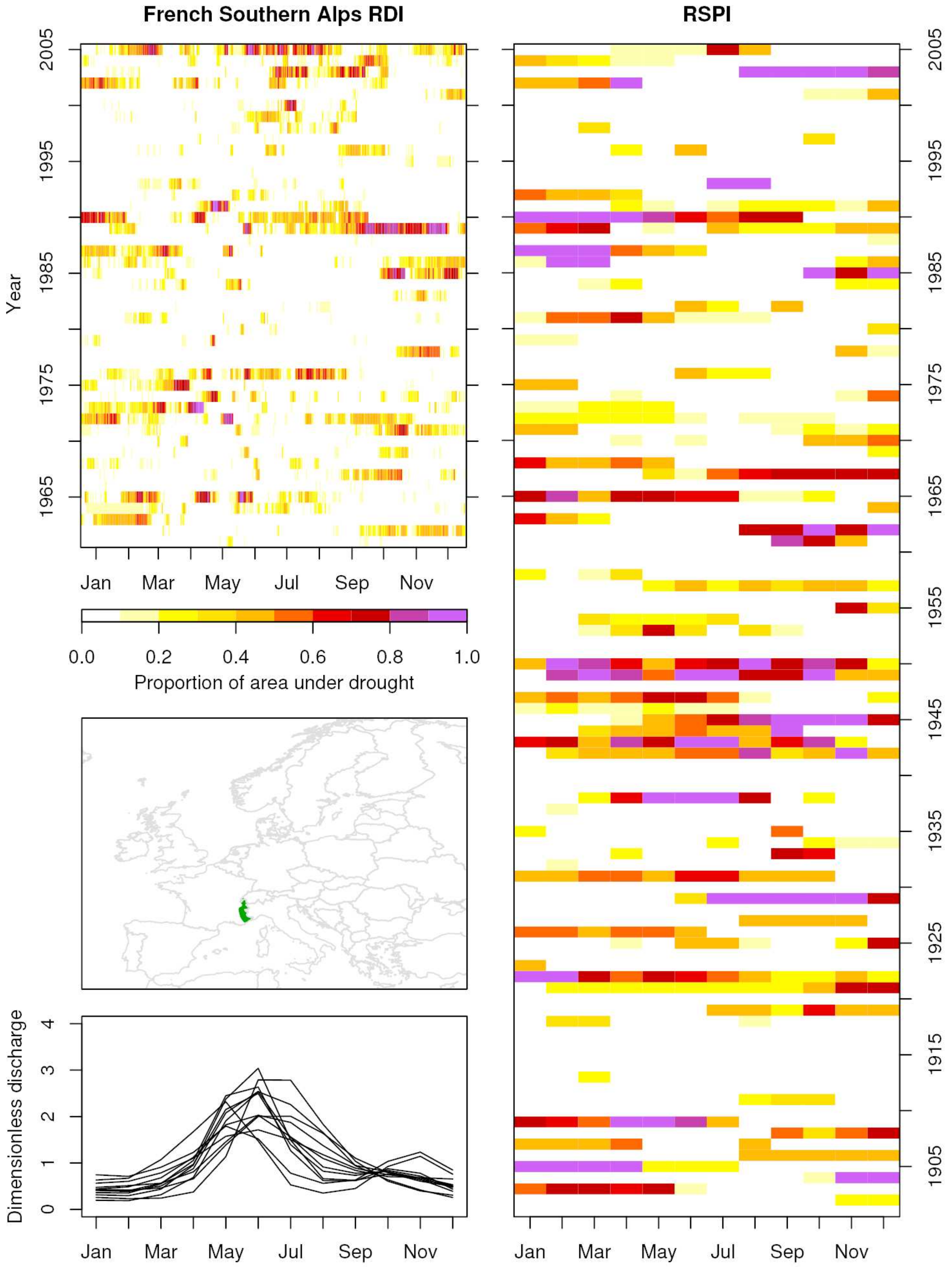
Notes

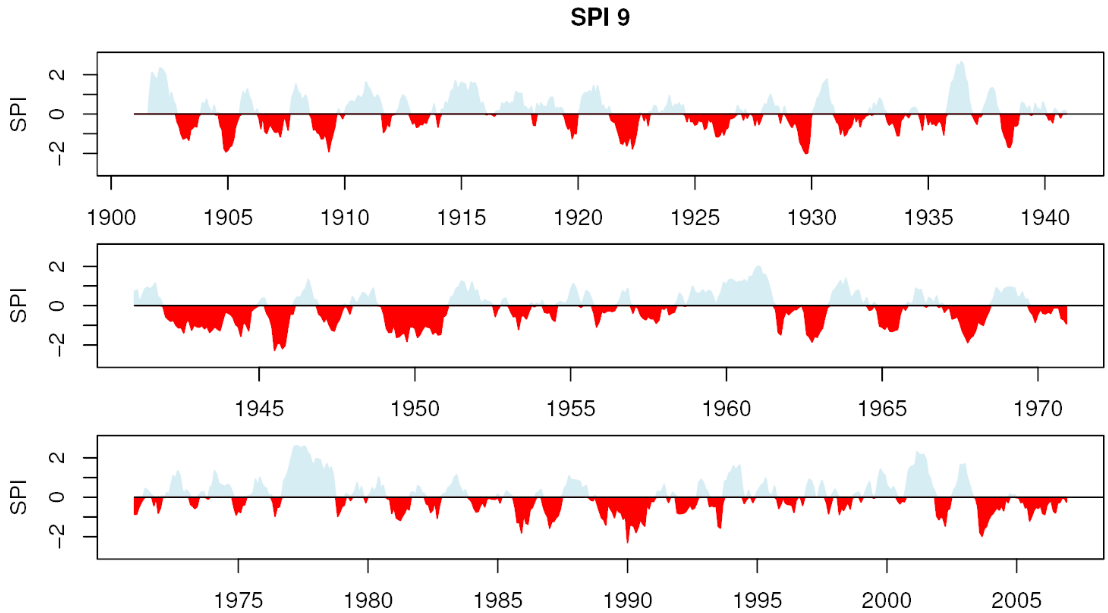
Regime: Precipitation−dominated, high flows in winter, low flows in summer.
The optimal meteorological proxy for streamflow drought is SPI 3 at a lag of 0 months with a rank correlation of 0.59.
Spatially coherent droughts mostly shorter than 6 months.
No clear seasonality in hydrological drought occurrence.



Circular plots of drought onset and duration 1961−2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

4.2.12 French Southern Alps





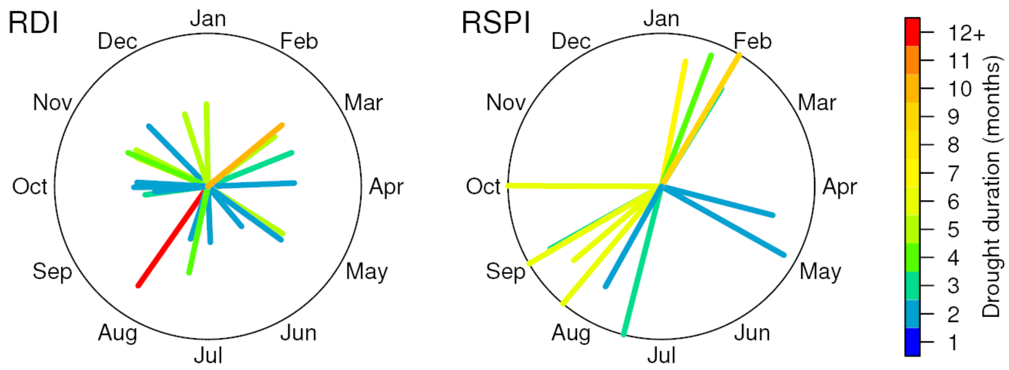
Notes

Regime: Mostly snow–melt dominated regime, low flows in winter, high flows in spring/summer.

The optimal meteorological proxy for streamflow drought is SPI 9 at a lag of 0 months with a rank correlation of 0.5.

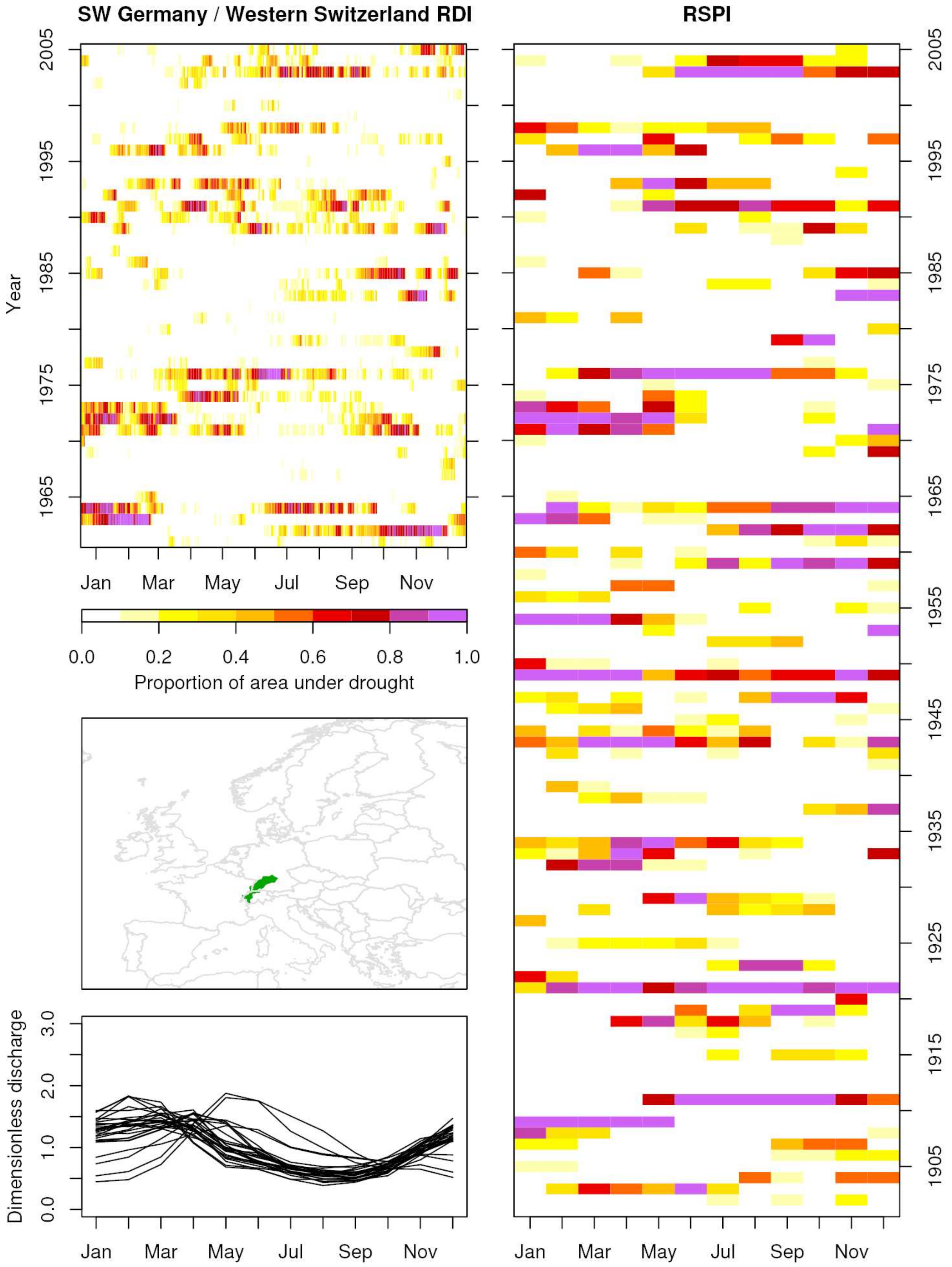
Generally hydrological droughts less than 6 months and not spatially coherent, but some droughts lasting up to 12 months.

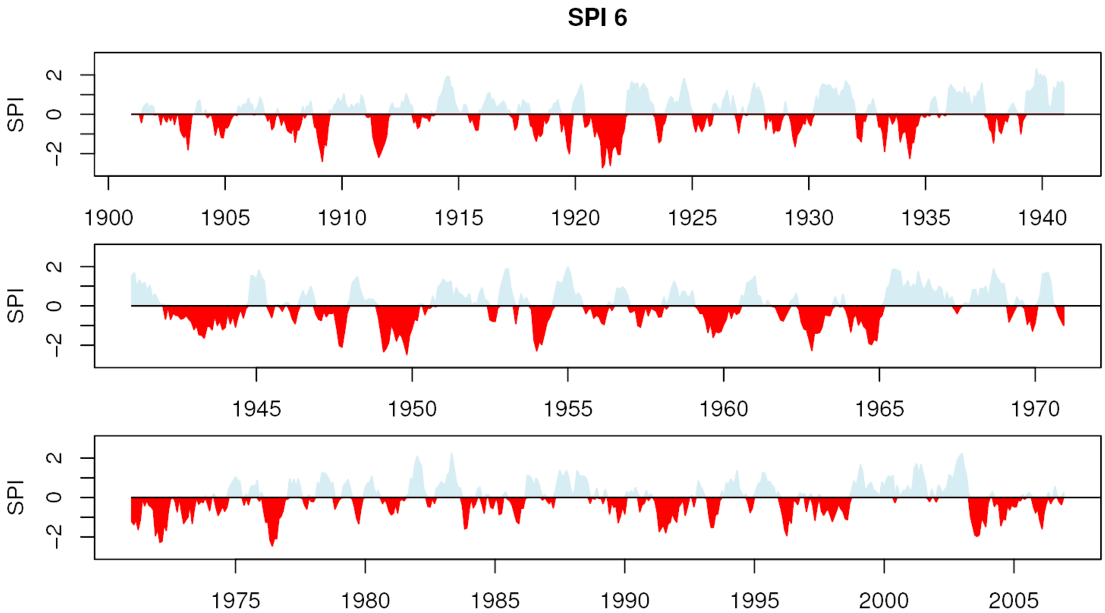
No clear seasonality in hydrological drought occurrence.



Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

4.2.13 South West Germany/ Western Switzerland





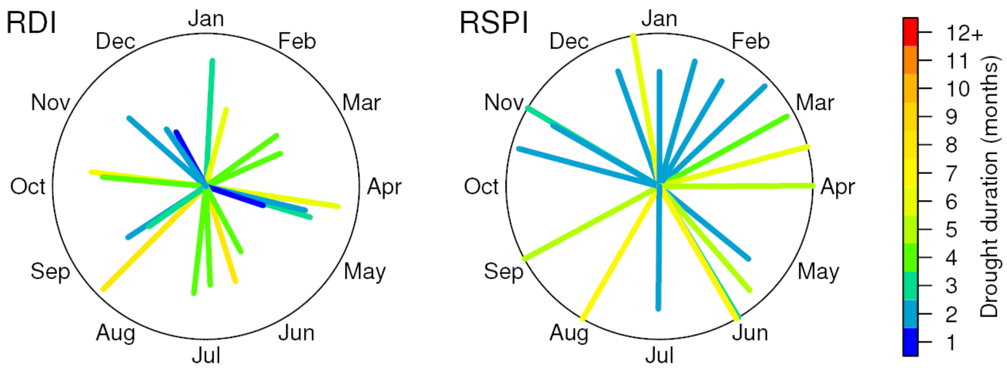
Notes

Regime: Mixed regime, predominantly rain–dominated but with snow–melt dominated. catchments in the Alps.

The optimal meteorological proxy for streamflow drought is SPI 6 at a lag of 0 months with a rank correlation of 0.62.

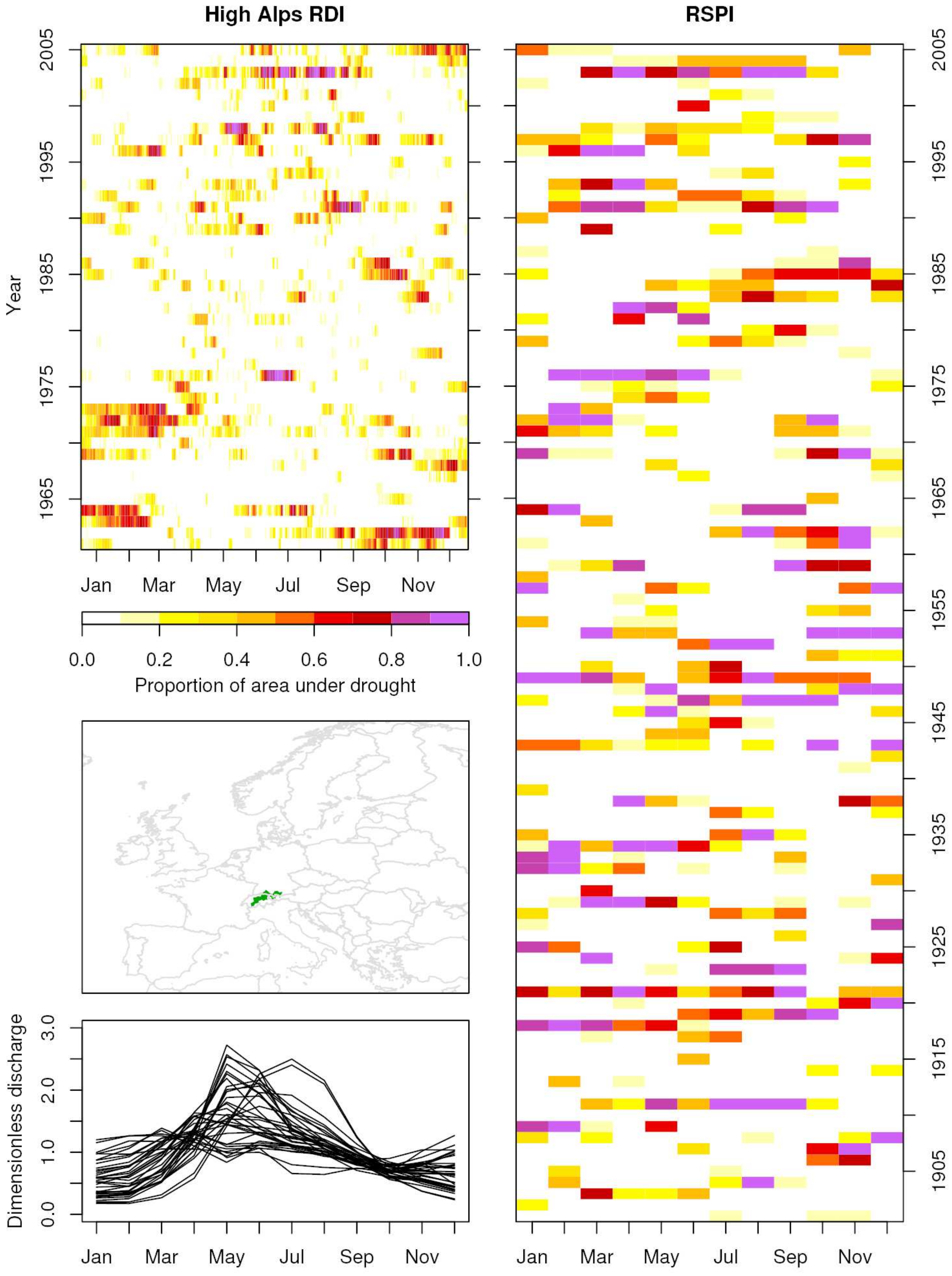
Most droughts spatially coherent lasting less than 6 months, some up to 9 months.

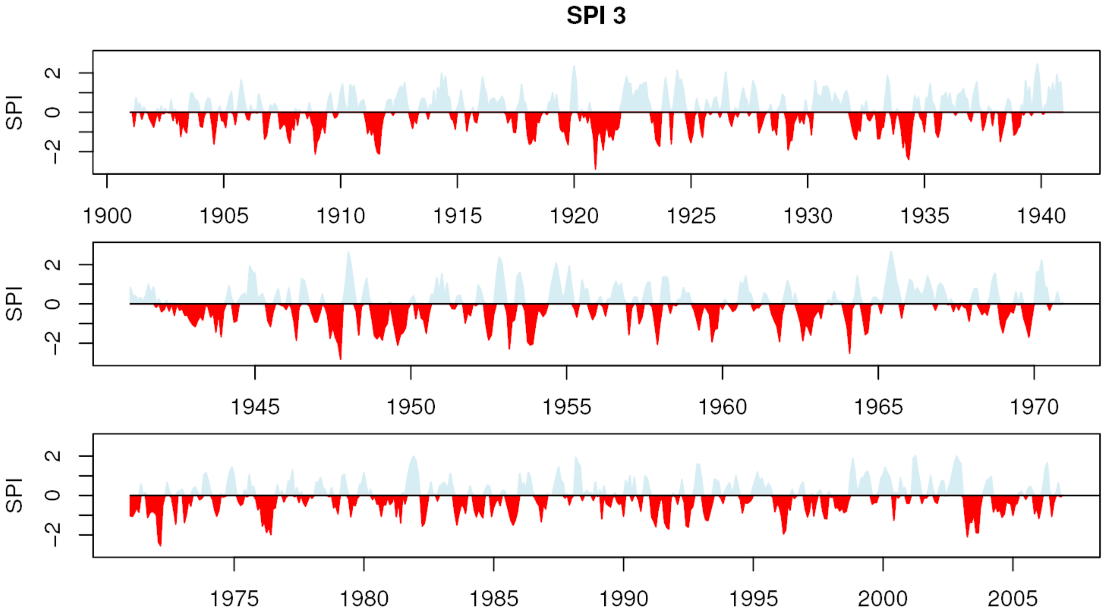
No clear seasonality in hydrological drought occurrence.



Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

4.2.14 High Alps





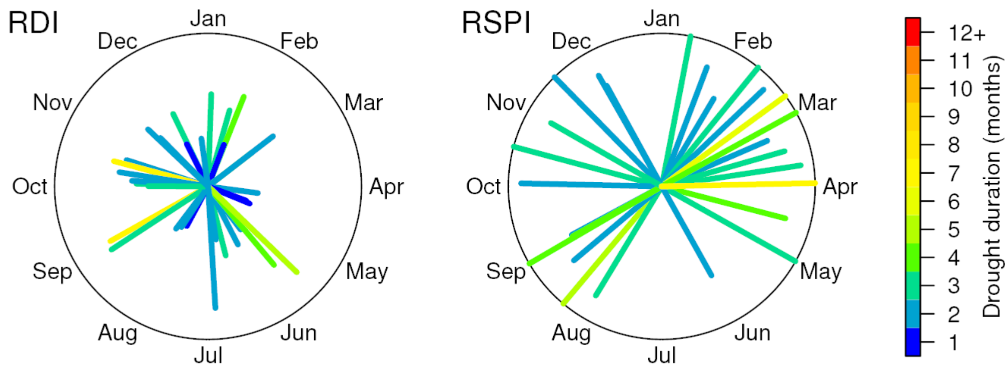
Notes

Regime: Mostly snow−melt dominated regime, low flows in winter, high flows in spring/summer.

The optimal meteorological proxy for streamflow drought is SPI 3 at a lag of 0 months with a rank correlation of 0.53.

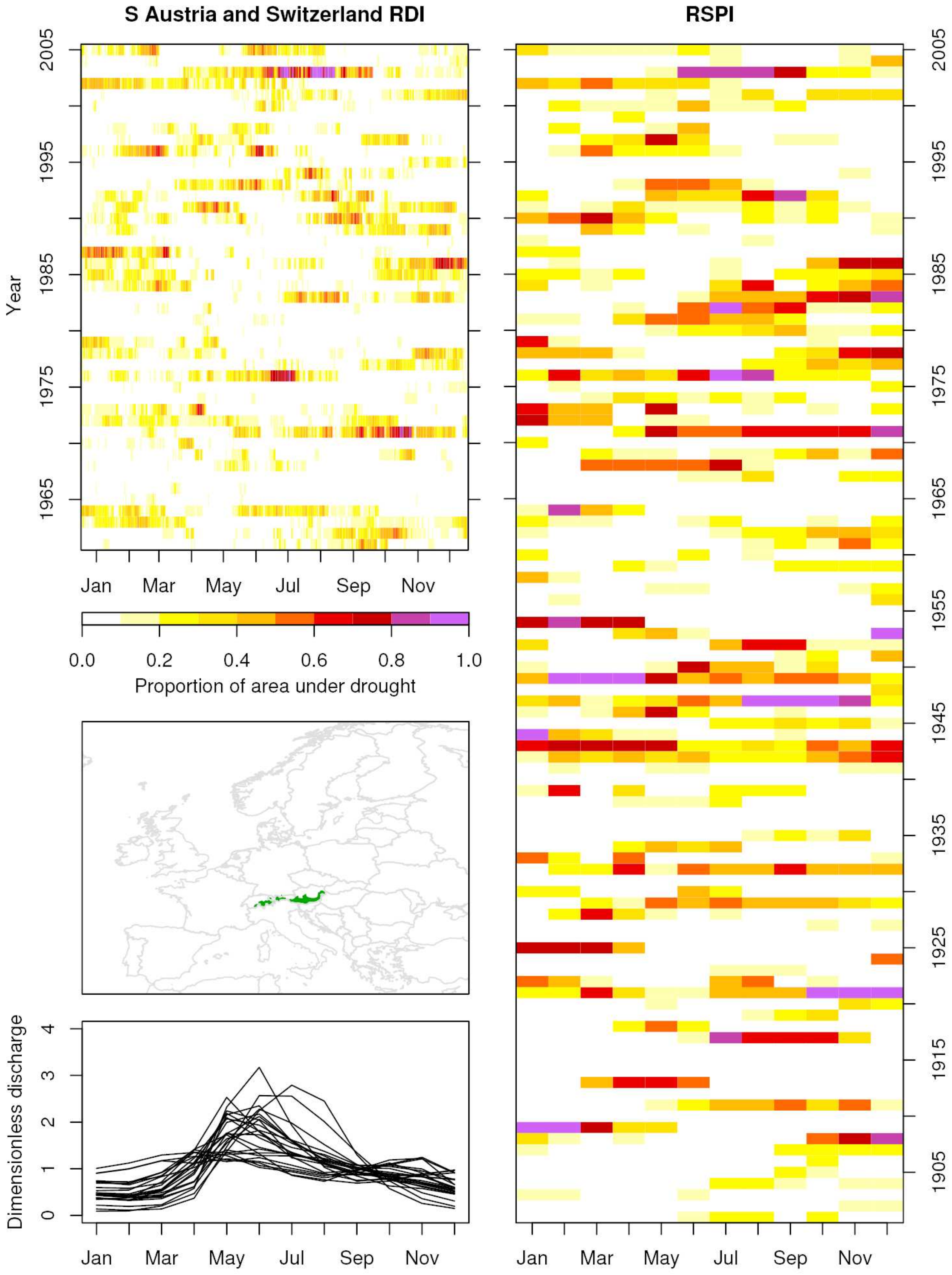
High number of short duration (less than 6 months) droughts not generally spatially coherent.

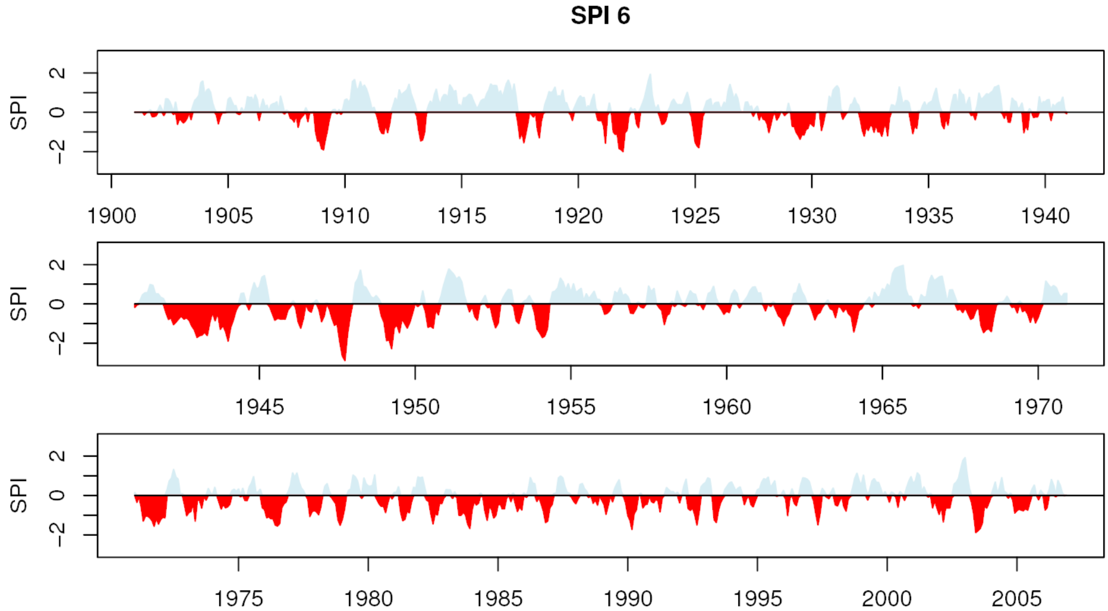
No clear seasonality in hydrological drought occurrence.



Circular plots of drought onset and duration 1961−2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

4.2.1 South Austria and Switzerland





Notes

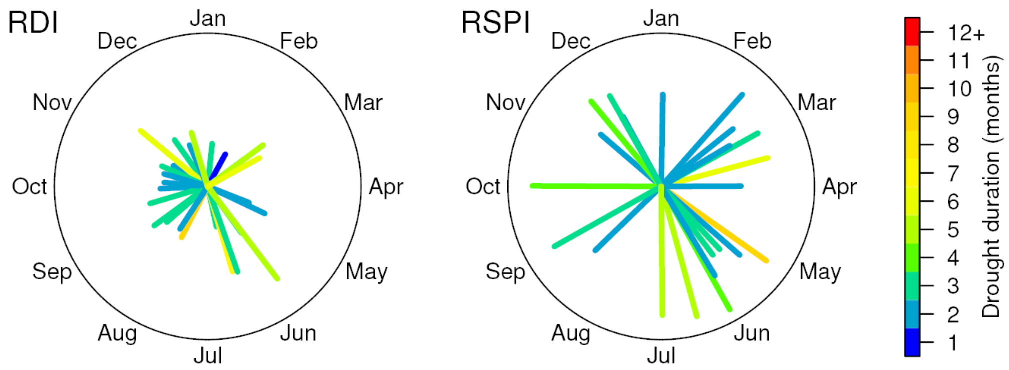
Regime: Mostly snow−melt dominated regime, low flows in winter, high flows in spring/summer.

The optimal meteorological proxy for streamflow drought is SPI 6 at a lag of 0 months with a rank correlation of 0.5.

Low homogeneity.

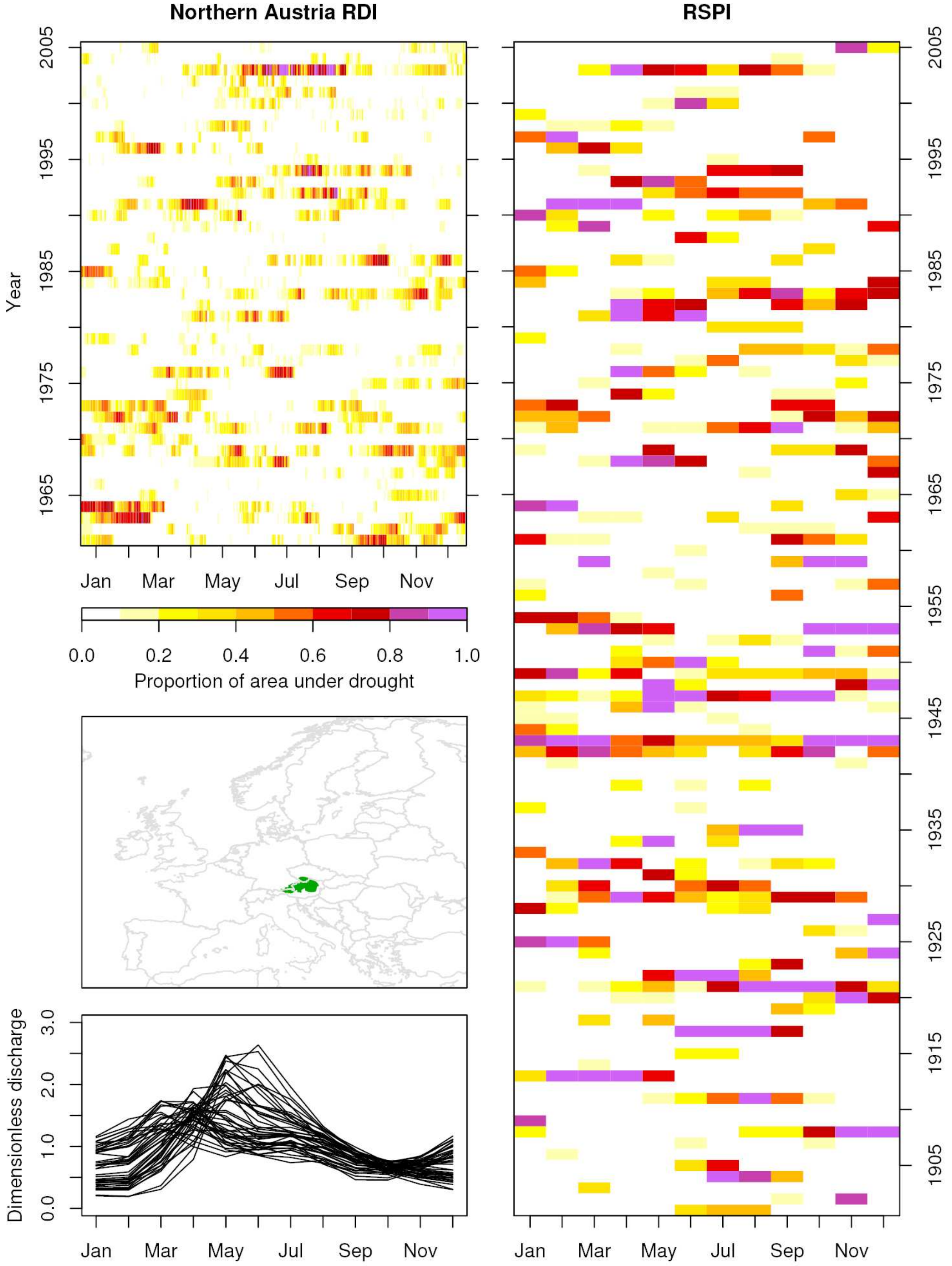
Very few spatially coherent droughts, many minor droughts affecting a small number of catchments.

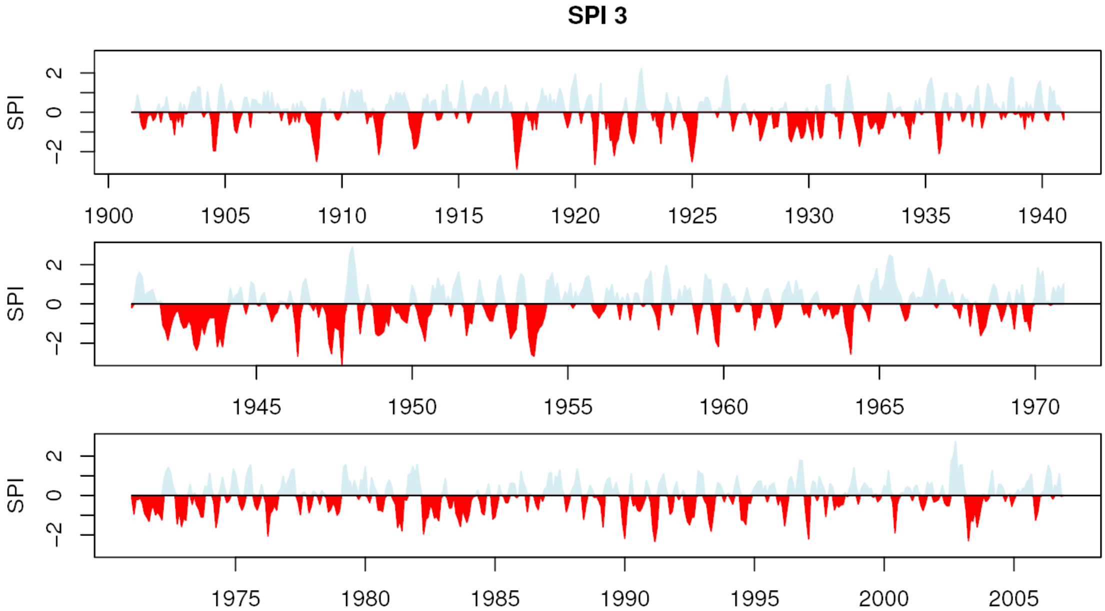
No clear seasonality in hydrological drought occurrence.



Circular plots of drought onset and duration 1961−2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

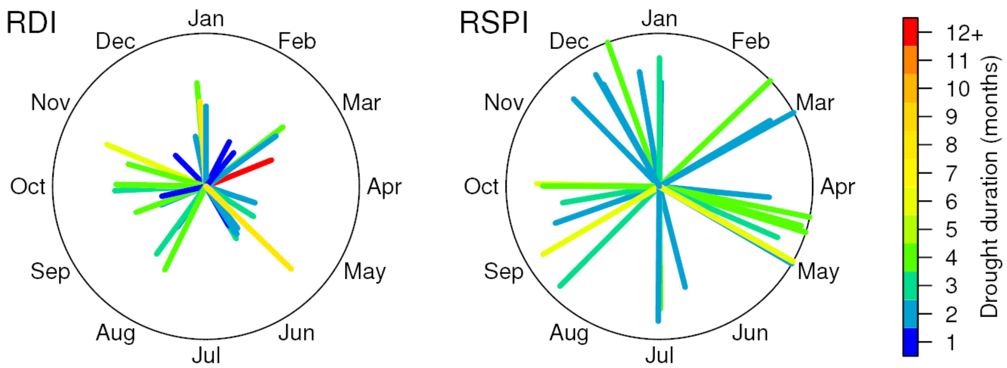
4.2.2 Northern Austria





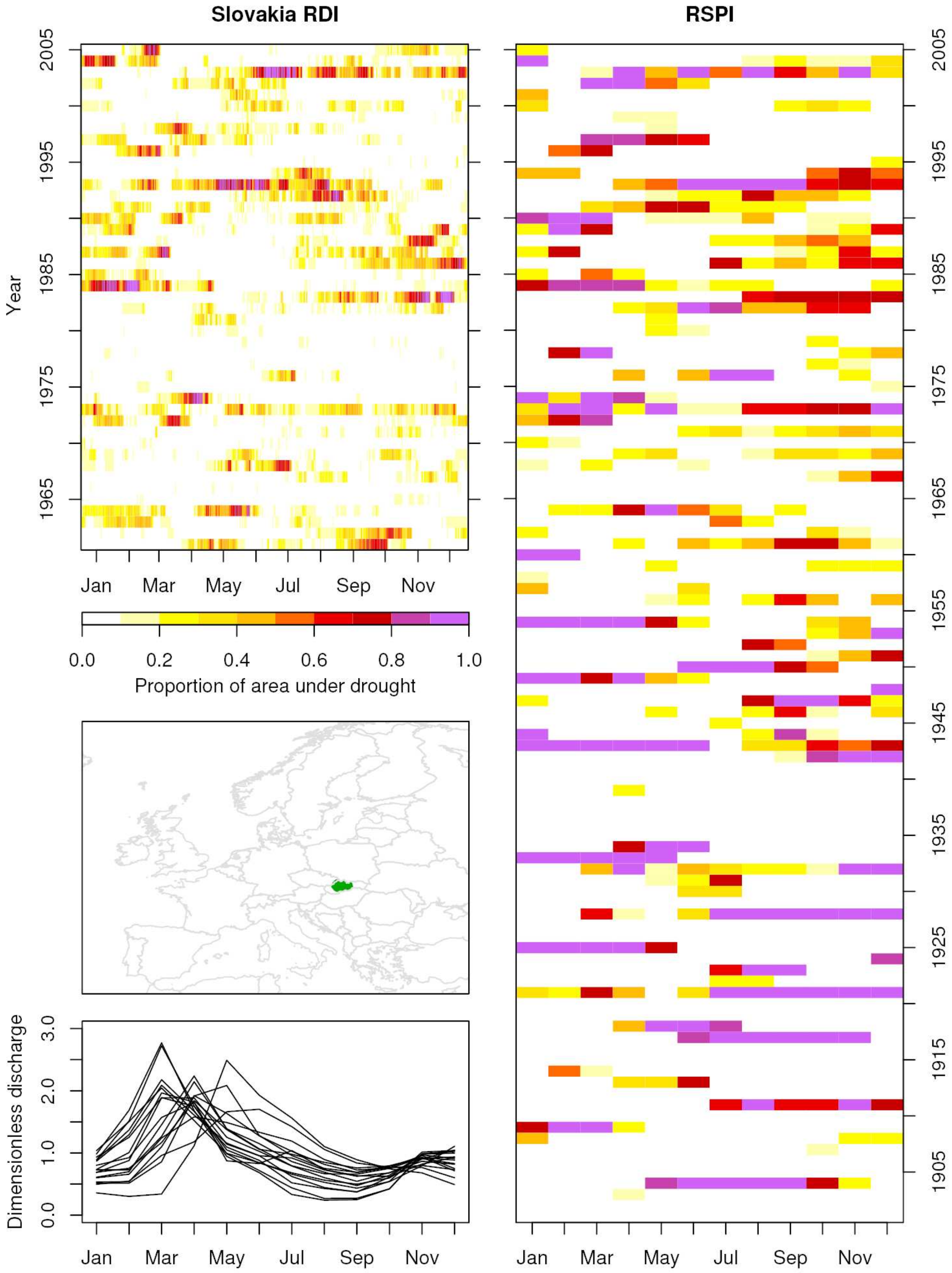
Notes

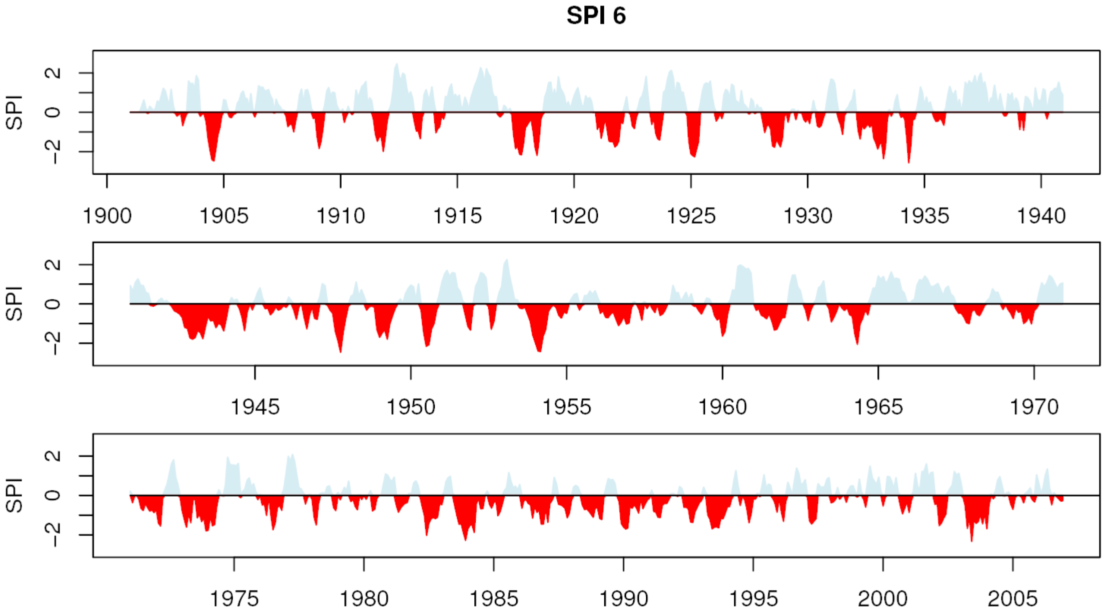
Regime: Mixed regime, predominantly snow−melt dominated.
The optimal meteorological proxy for streamflow drought is SPI 3 at a lag of 0 months with a rank correlation of 0.5.
High number of short duration hydrological droughts (less than 9 months) not generally spatially coherent.
No clear seasonality in hydrological drought occurrence.



Circular plots of drought onset and duration 1961−2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

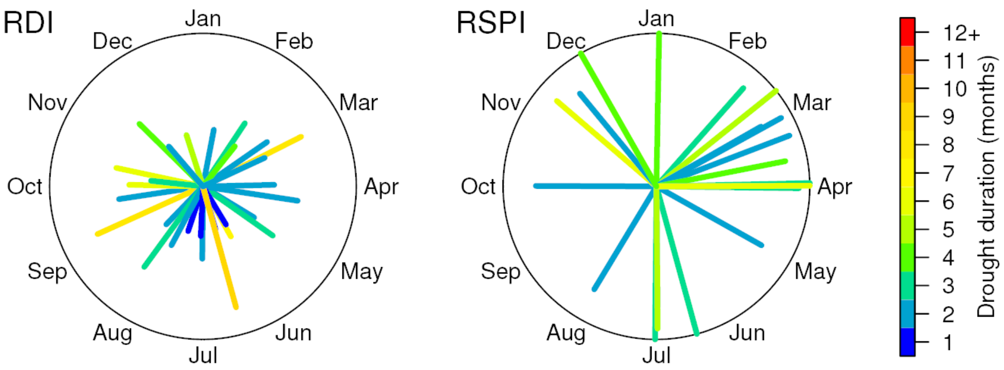
4.2.3 Slovakia





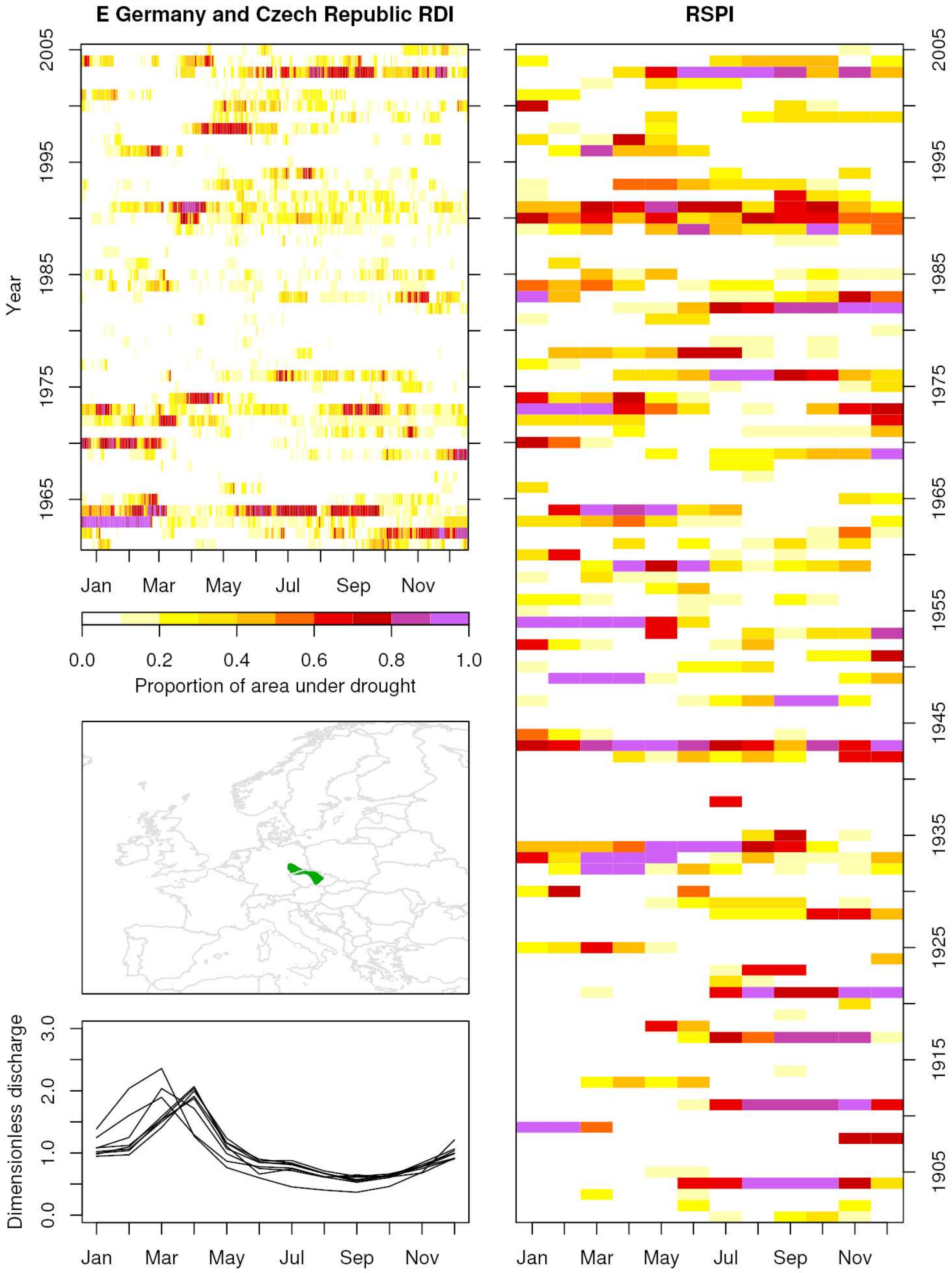
Notes

Regime: Precipitation–dominated, high flows in spring, low flows in summer.
The optimal meteorological proxy for streamflow drought is SPI 6 at a lag of 0 months with a rank correlation of 0.55.
Some spatially coherent droughts of up to 9 months, many minor droughts affecting a small number of catchments.
No clear seasonality in hydrological drought occurrence.

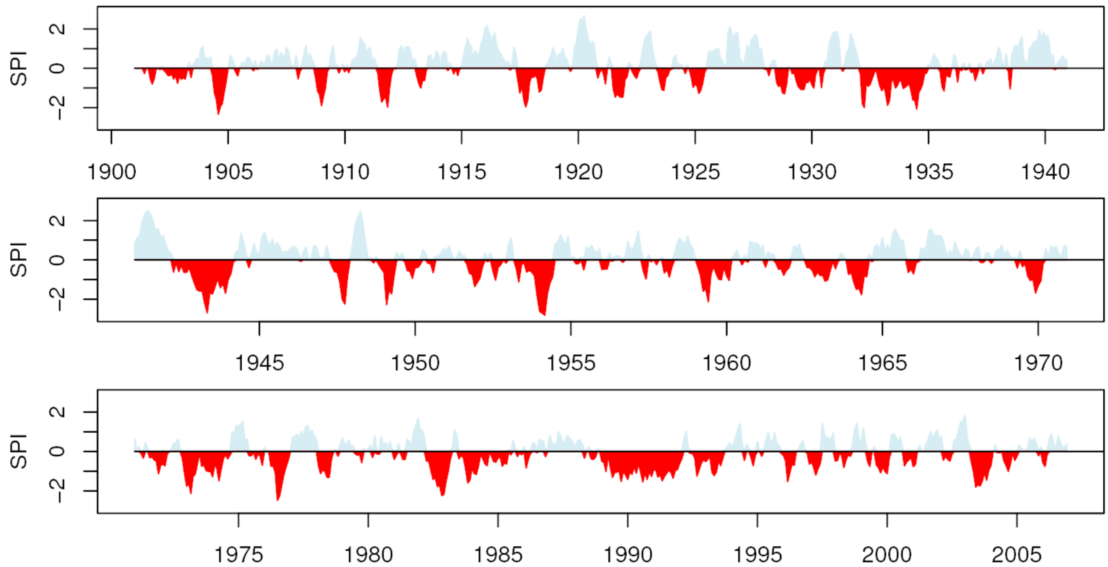


Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

4.2.4 East Germany and Czech Republic



SPI 6



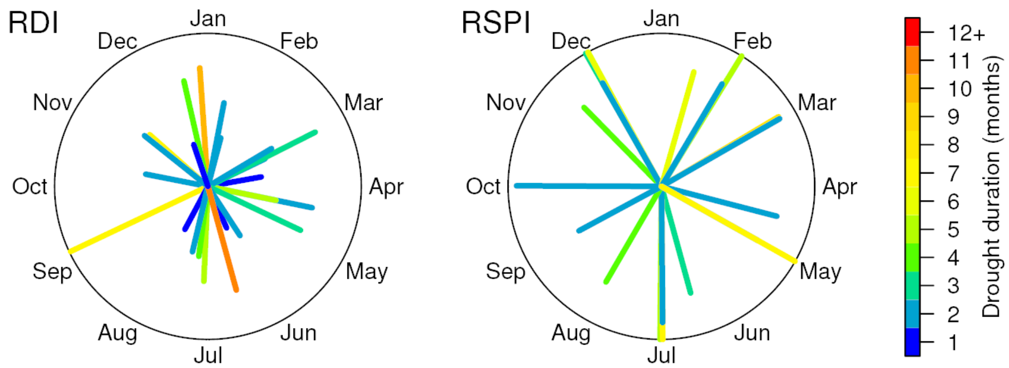
Notes

Regime: Precipitation–dominated, high flows in spring, low flows in summer.

The optimal meteorological proxy for streamflow drought is SPI 6 at a lag of 0 months with a rank correlation of 0.5.

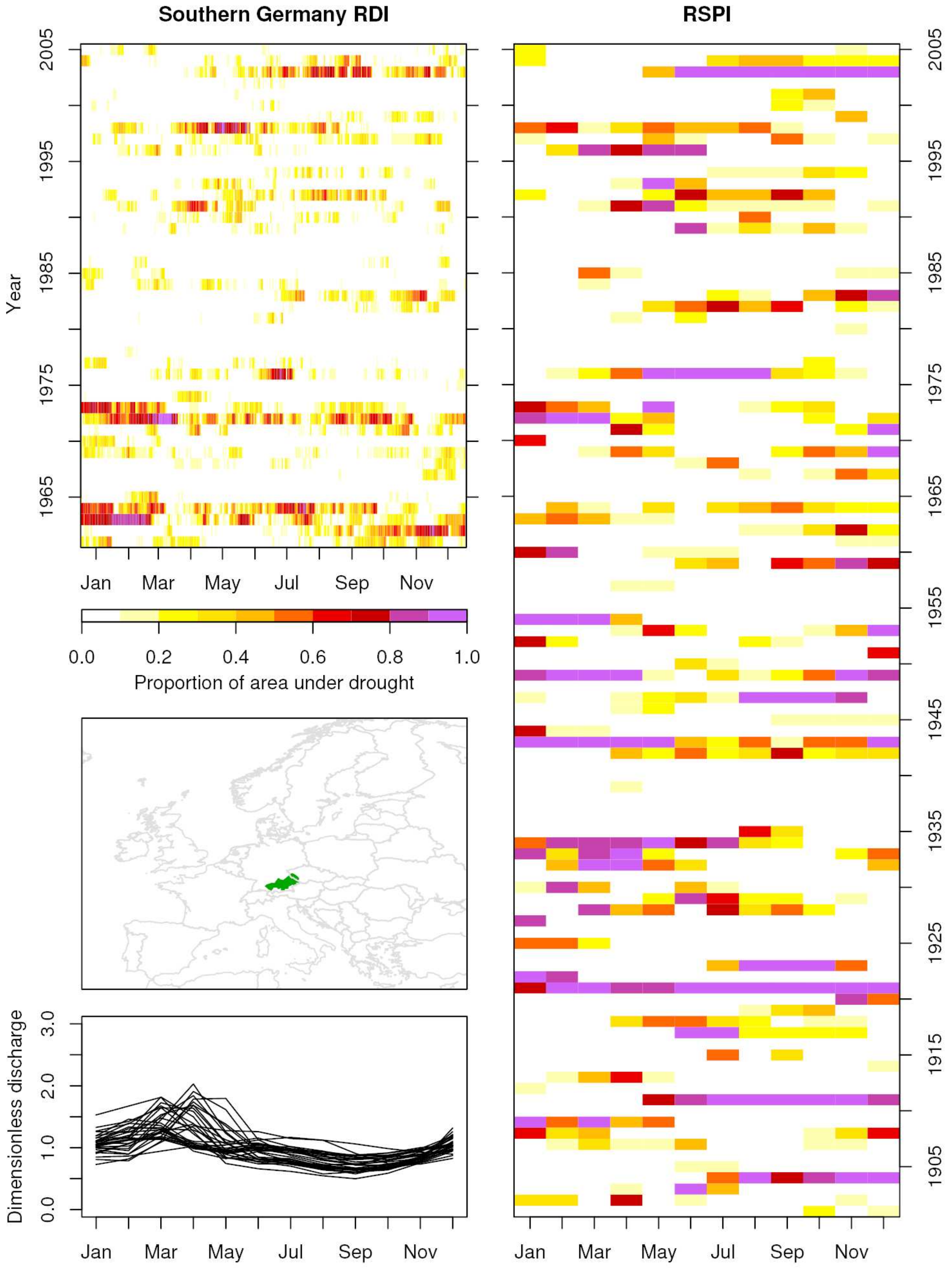
Some spatially coherent events of 4 to 12 months, many minor droughts affecting a small number of catchments.

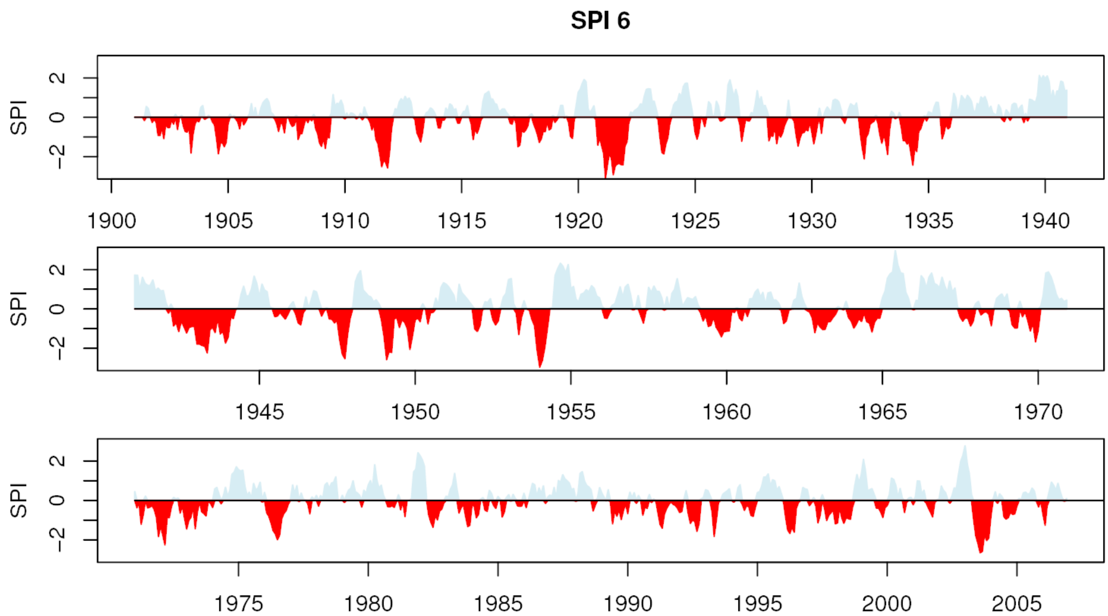
No clear seasonality in hydrological drought occurrence.



Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

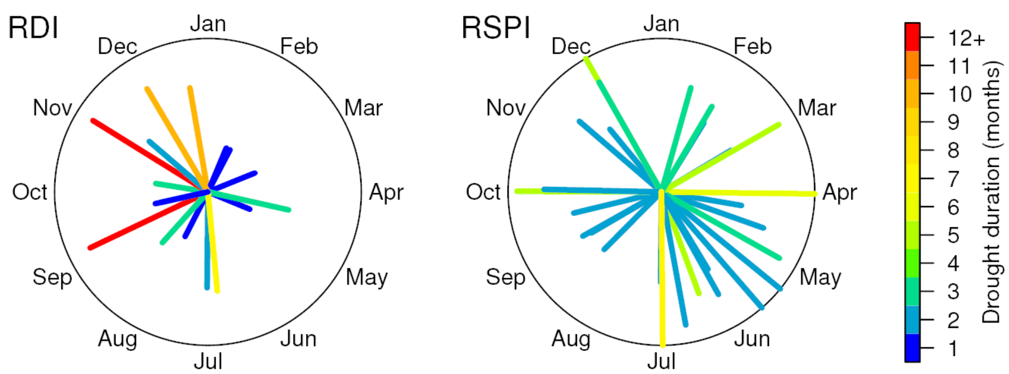
4.2.5 Southern Germany





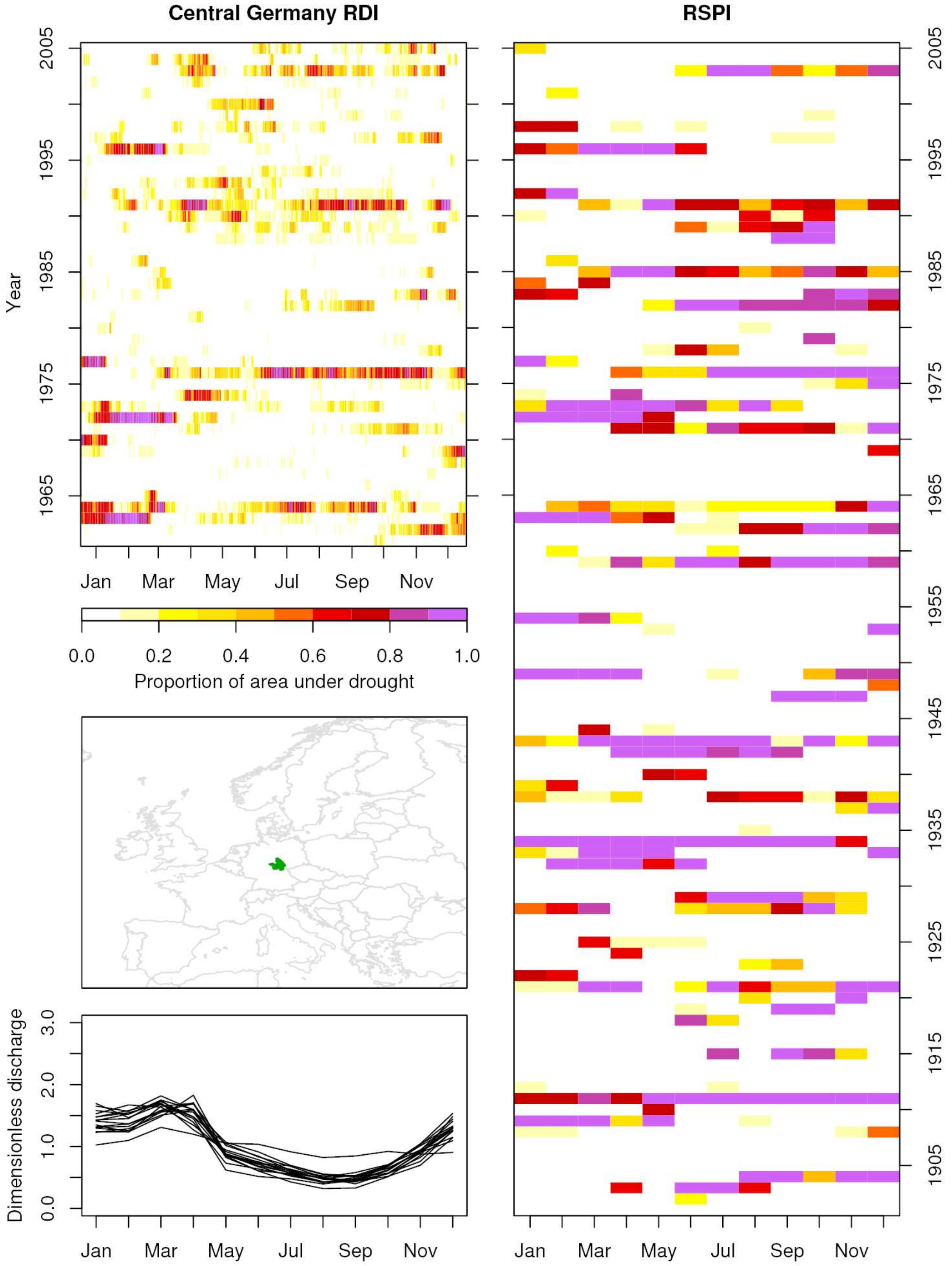
Notes

Regime: Mixed regime, predominantly rain–dominated with spring high flows.
The optimal meteorological proxy for streamflow drought is SPI 6 at a lag of 0 months with a rank correlation of 0.61.
Some spatially coherent hydrological droughts of more than 9 months, the longest being multi–annual.
Most droughts starting between September and January.

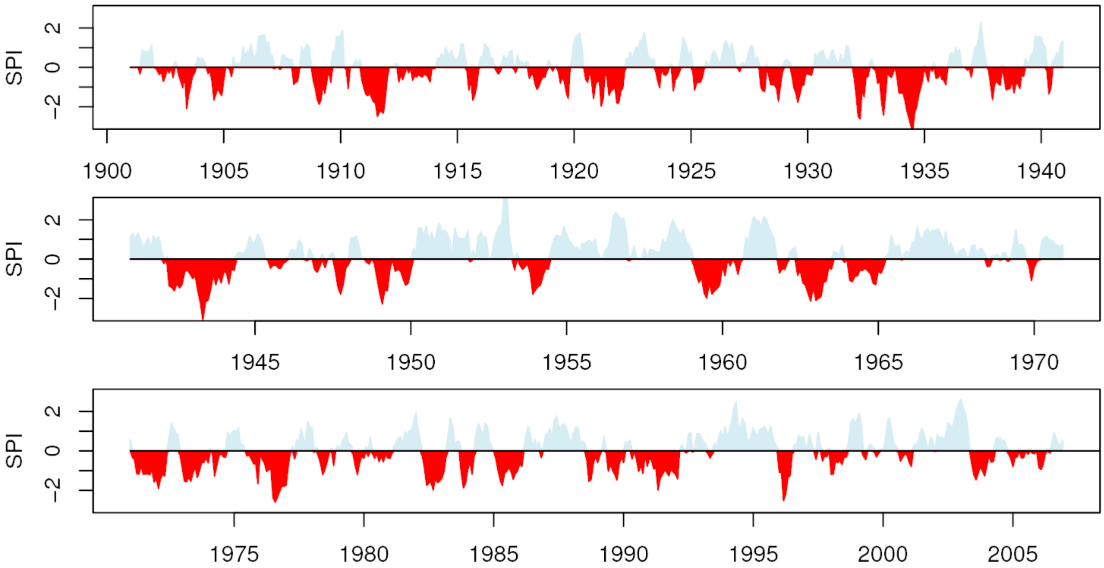


Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

4.2.6 Central Germany



SPI 6



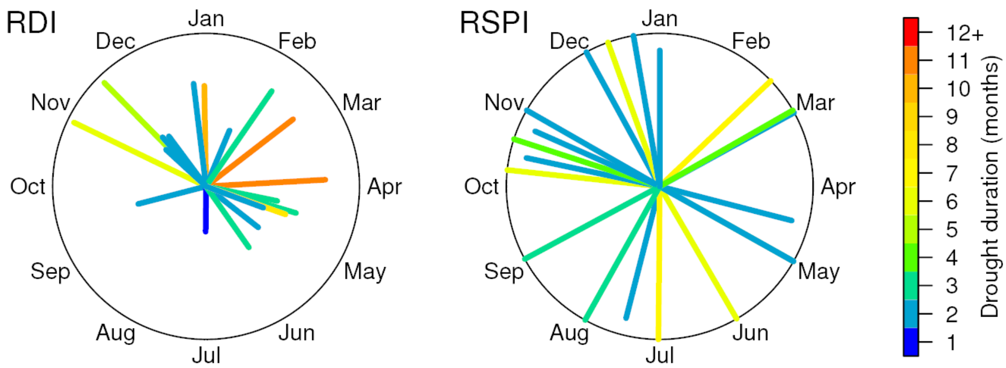
Notes

Regime: Precipitation–dominated, high flows in winter to spring, low flows in summer.

The optimal meteorological proxy for streamflow drought is SPI 6 at a lag of 0 months with a rank correlation of 0.5.

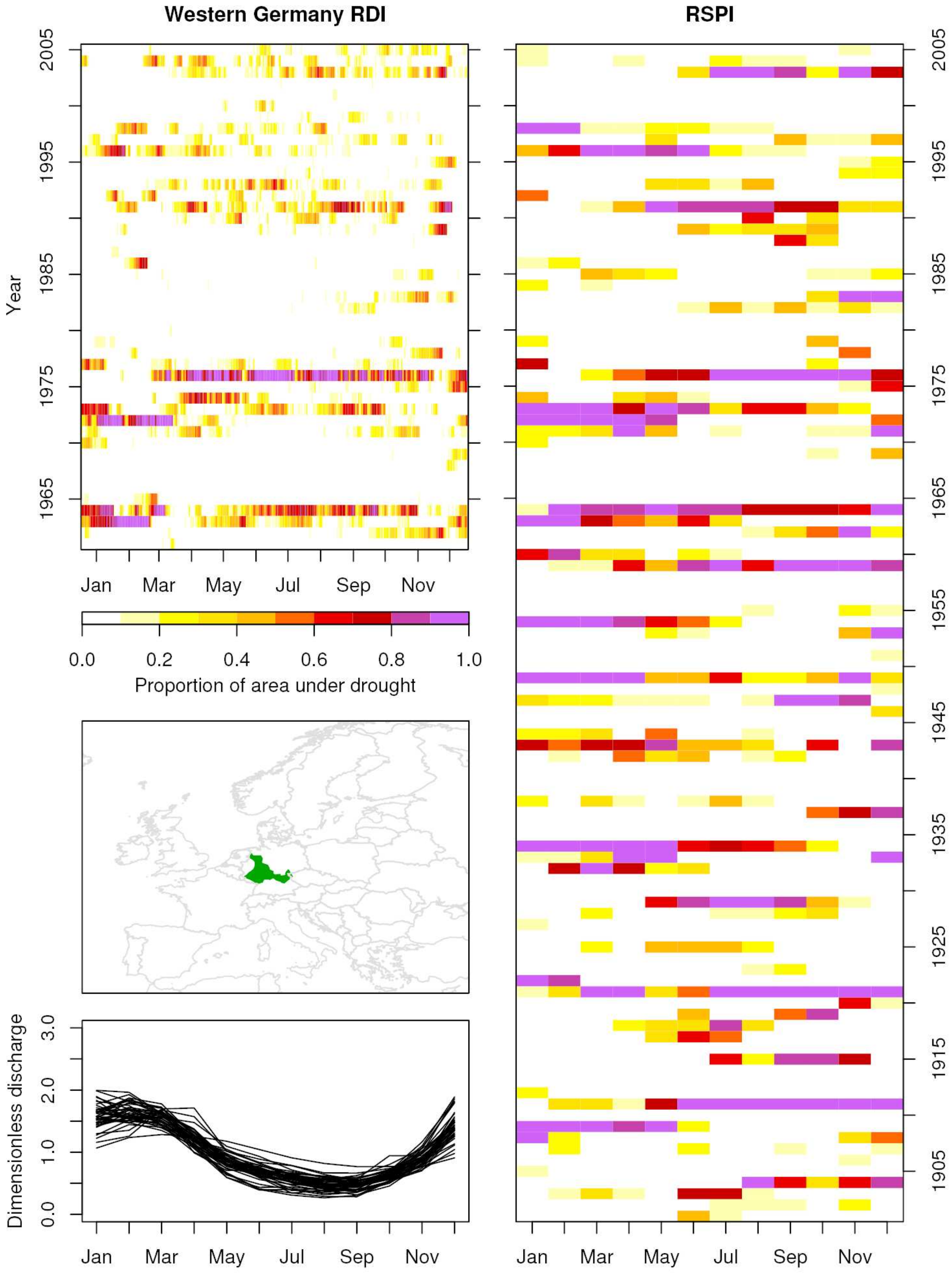
Some spatially coherent events of between 6 to 12 months.

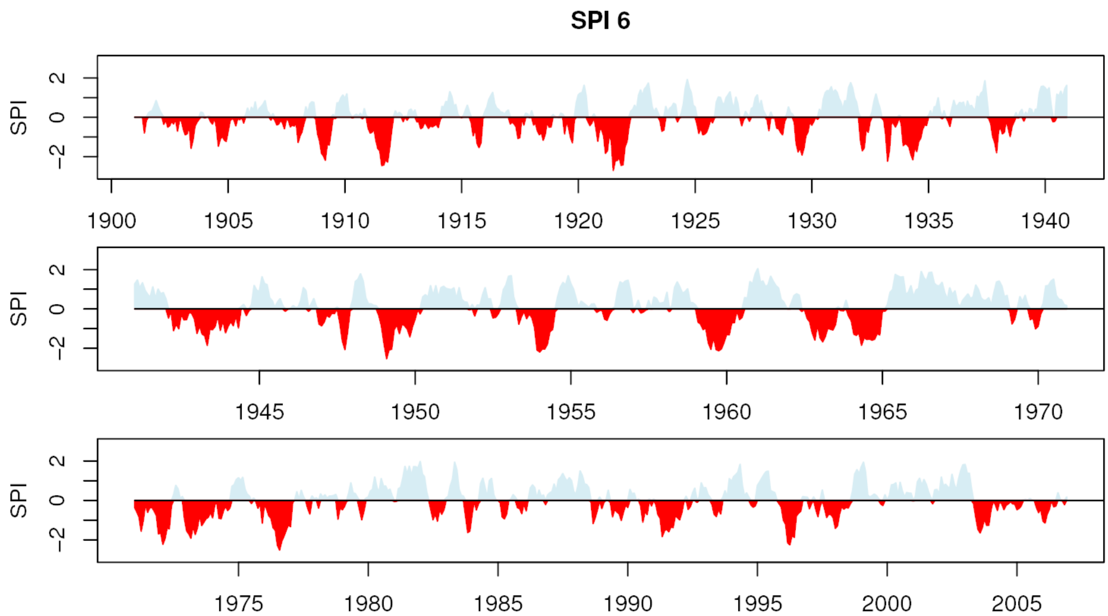
Droughts generally starting from November to May.



Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

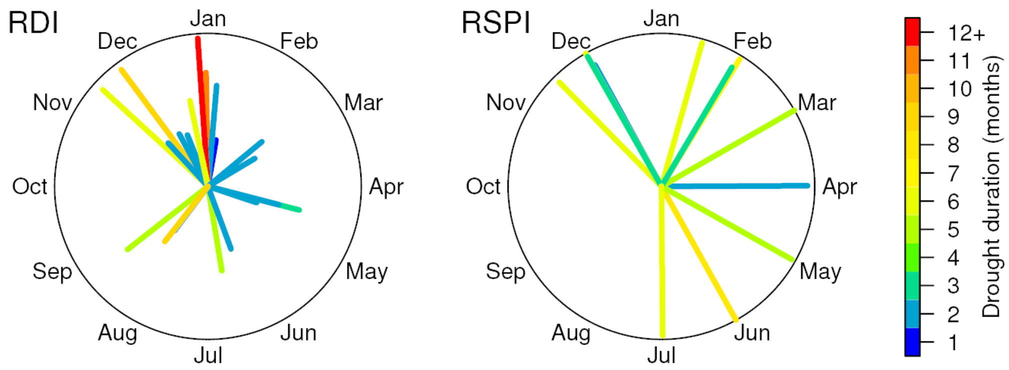
4.2.7 Western Germany





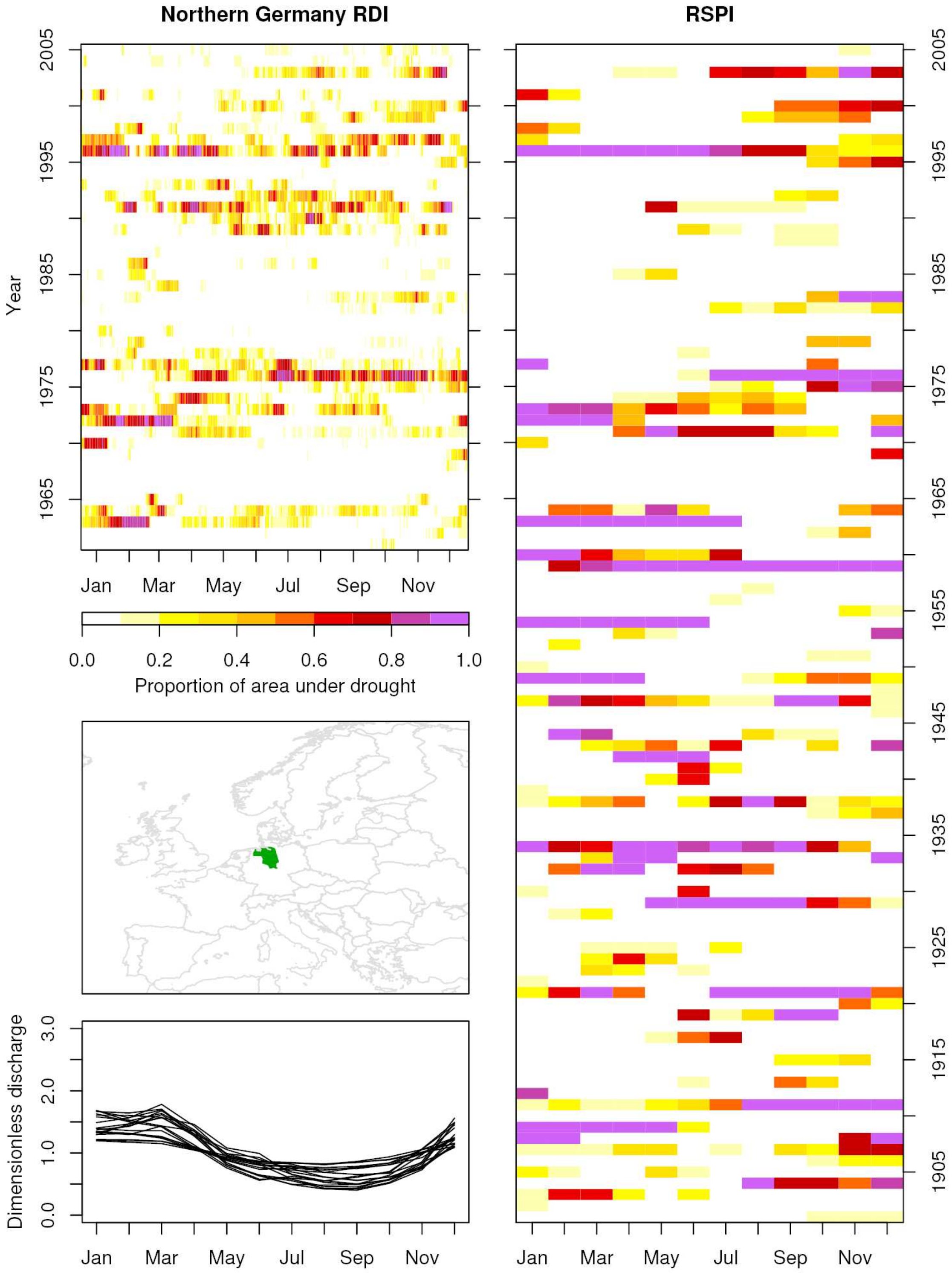
Notes

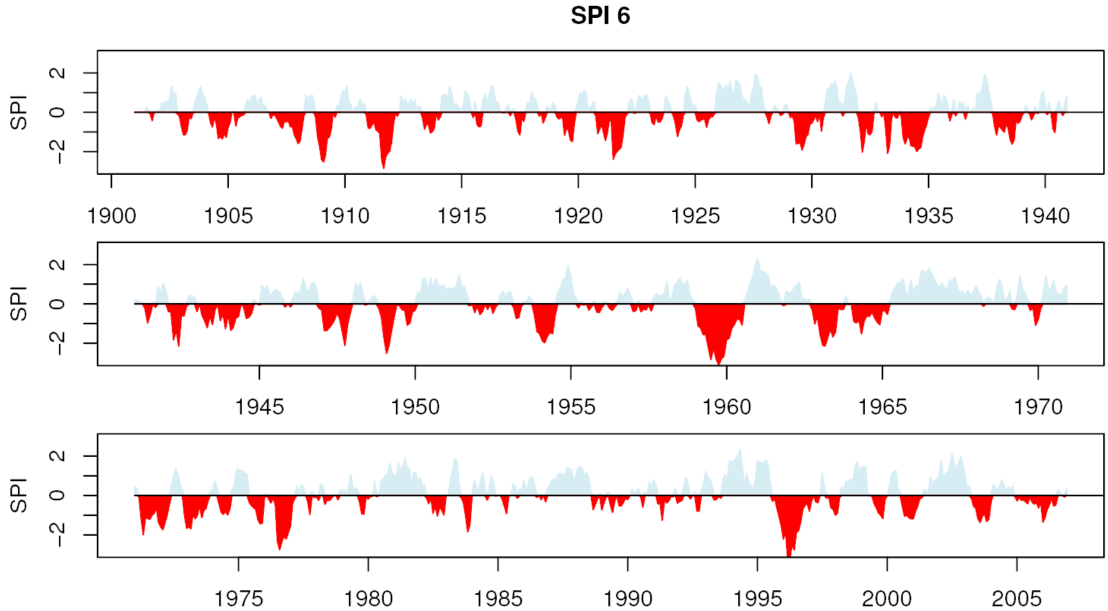
Regime: Precipitation–dominated, high flows in winter to spring, low flows in summer.
The optimal meteorological proxy for streamflow drought is SPI 6 at a lag of 0 months with a rank correlation of 0.68.
Few spatially coherent hydrological droughts of 6 to 12 months, most spatially coherent droughts from 9 months to multi–annual.
Longest and most coherent droughts starting in winter.



Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

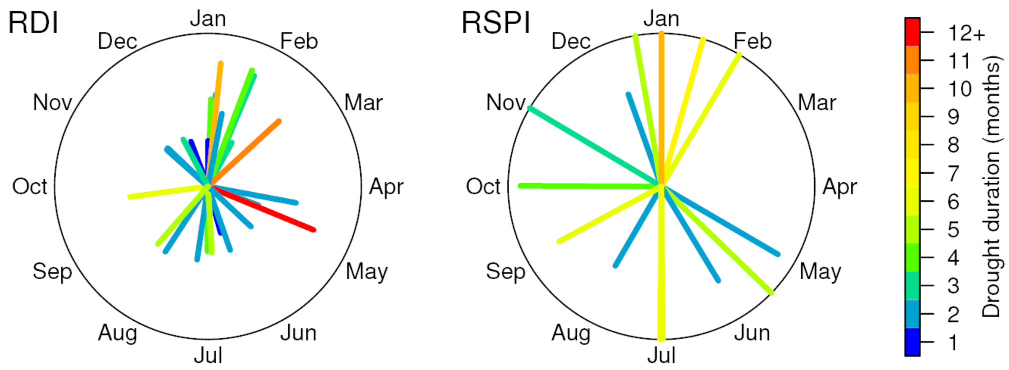
4.2.8 Northern Germany





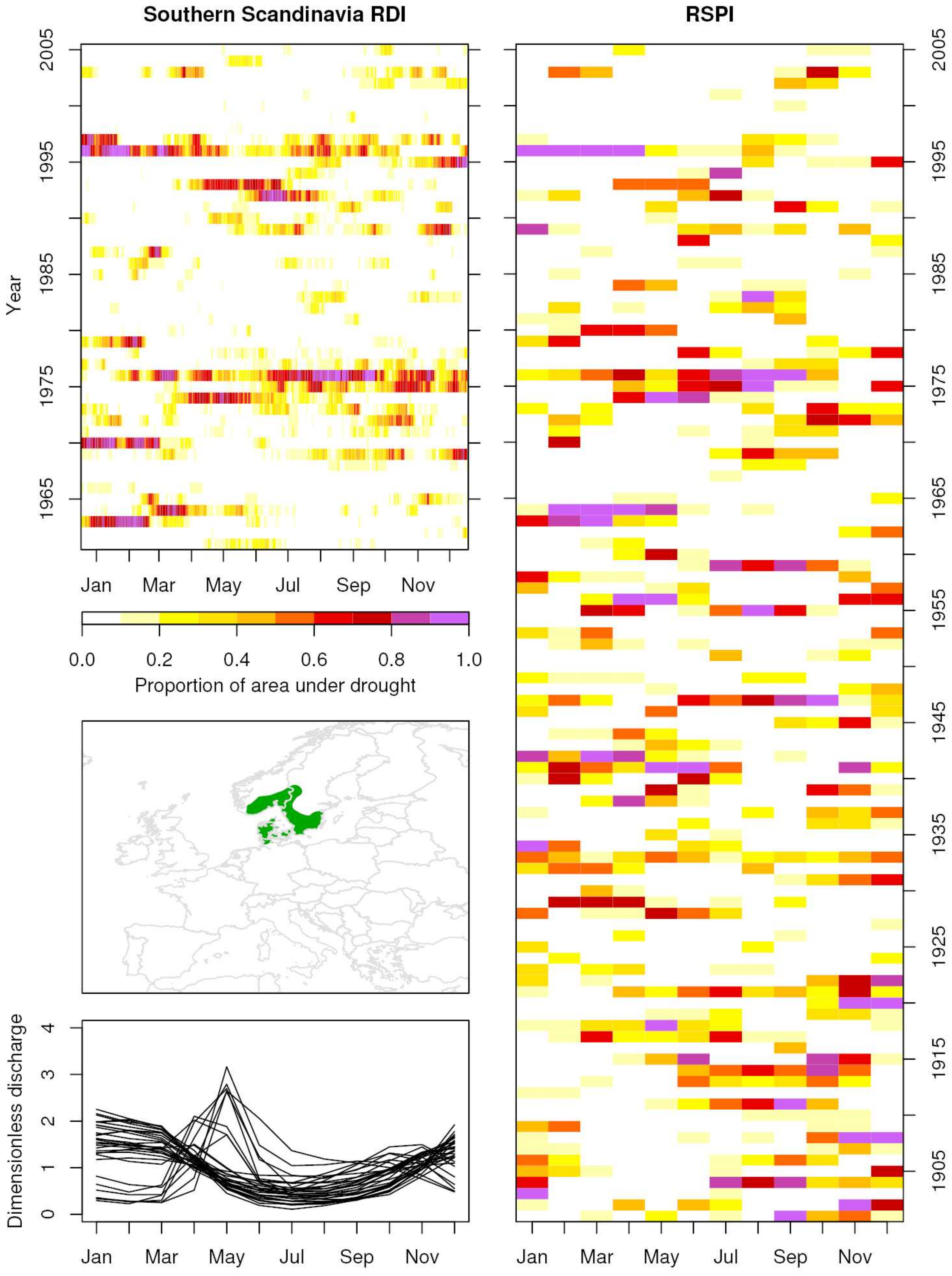
Notes

Regime: Precipitation–dominated, high flows in winter to spring, low flows in summer.
The optimal meteorological proxy for streamflow drought is SPI 6 at a lag of 0 months with a rank correlation of 0.58.
Some spatially coherent events of between 6 to 12 months.
No clear seasonality in hydrological drought occurrence.

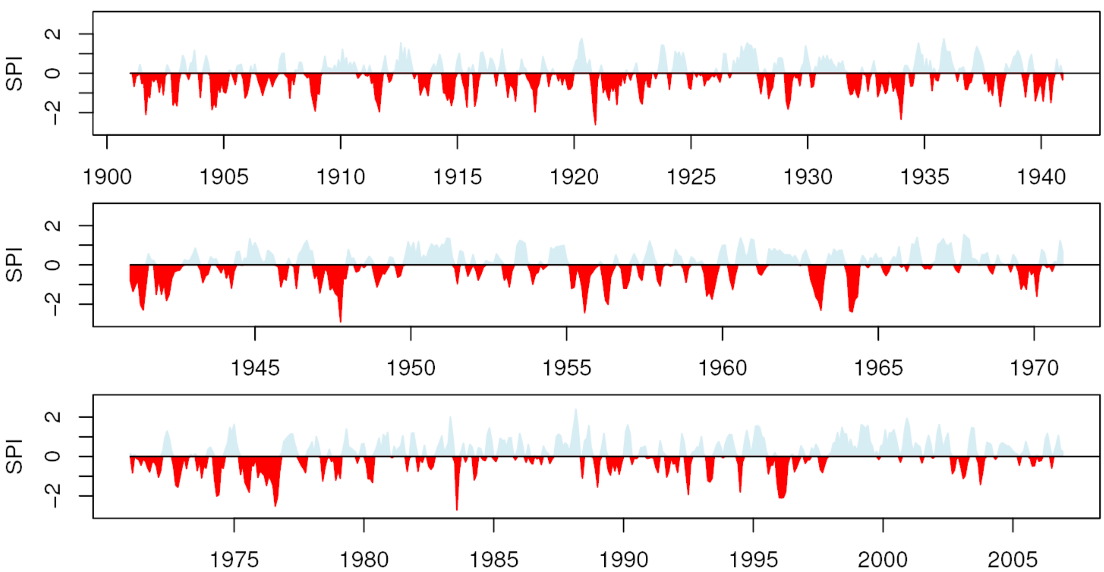


Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

4.2.9 Southern Scandinavia



SPI 3



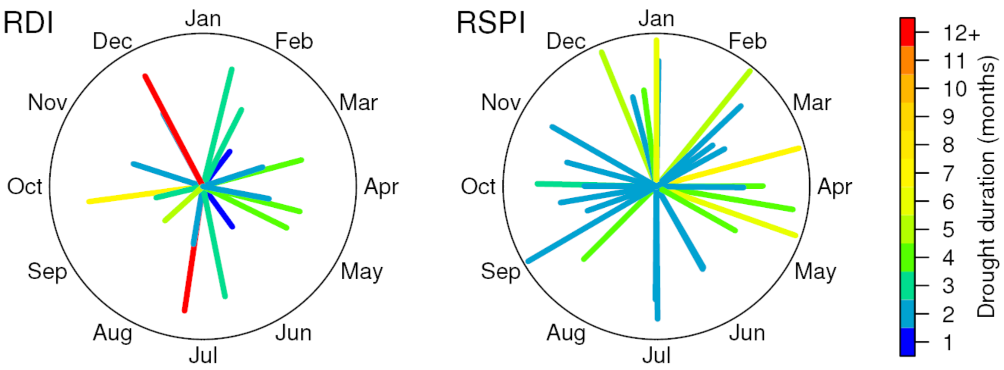
Notes

Regime: Mixed regime, a majority of rain–dominated with winter high flows with some snow–melt dominated catchments with high flows in spring.

The optimal meteorological proxy for streamflow drought is SPI 3 at a lag of 0 months with a rank correlation of 0.63.

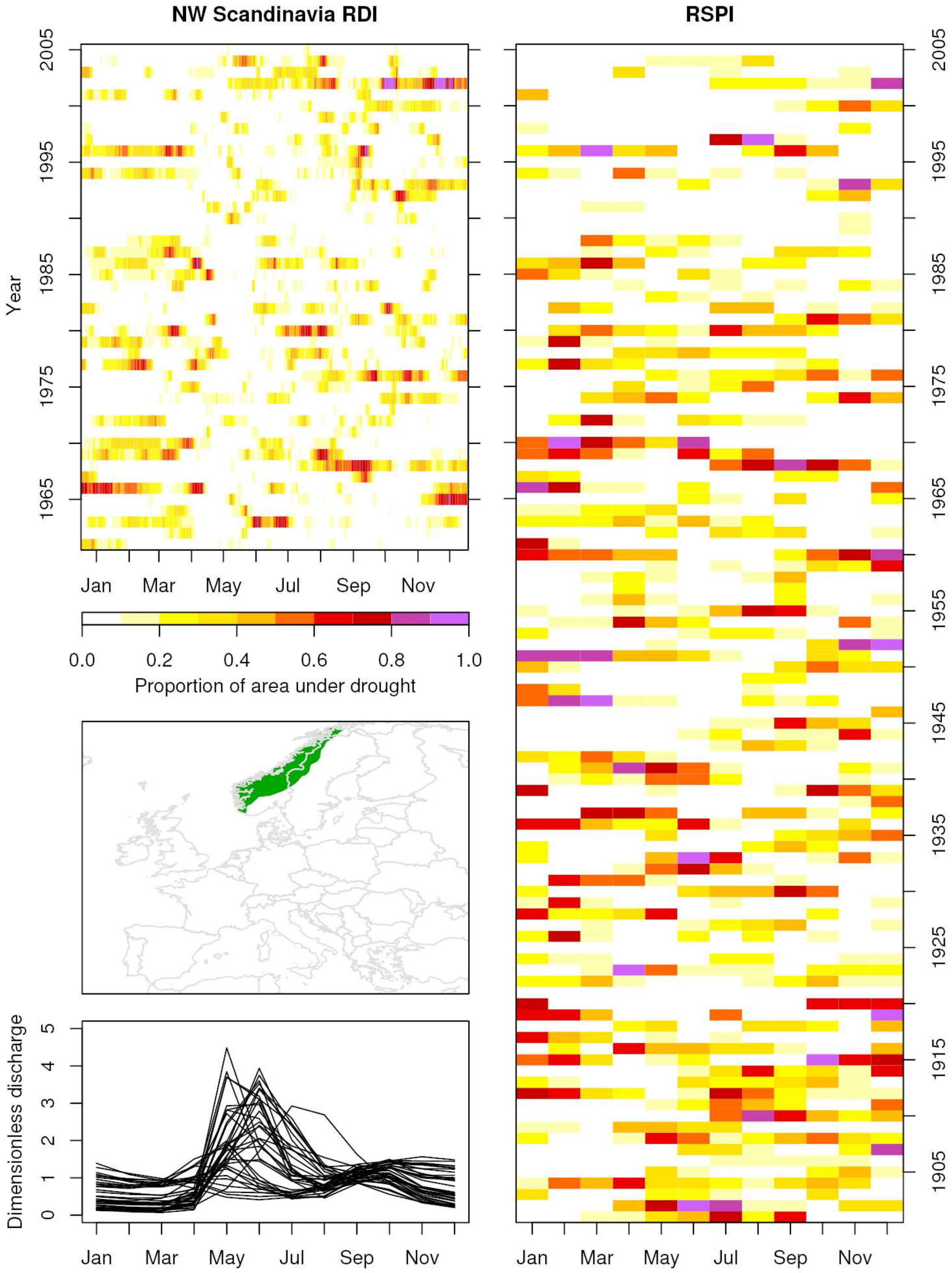
Generally spatially coherent events, often of short duration (less than 6 months). However, some longer droughts of more than 12 months.

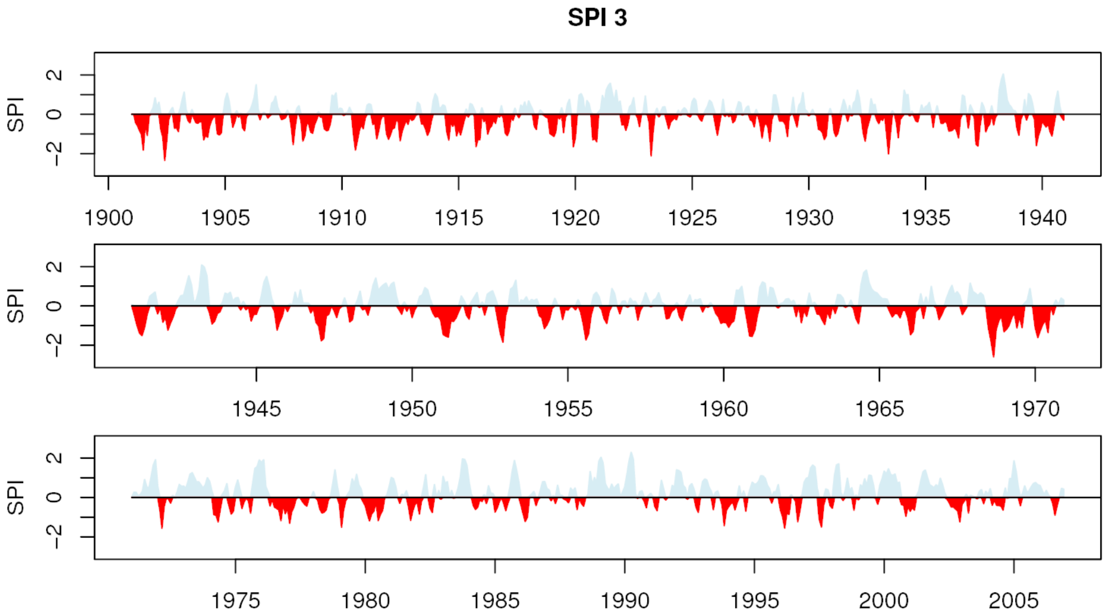
No clear seasonality in hydrological drought occurrence.



Circular plots of drought onset and duration 1961–2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

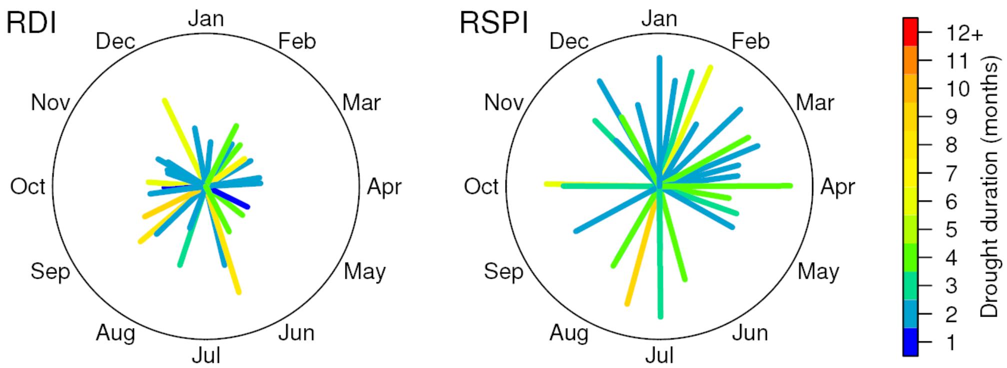
4.2.10 North West Scandinavia





Notes

Regime: Mostly snow−melt dominated regime, low flows in winter, high flows in spring/summer.
The optimal meteorological proxy for streamflow drought is SPI 3 at a lag of 0 months with a rank correlation of 0.65.
Low homogeneity.
Very few spatially coherent droughts.
Many minor droughts affecting a small number of catchments.
No clear seasonality in hydrological drought occurrence.



Circular plots of drought onset and duration 1961−2005. Radii are proportional to the cluster area under drought. The unit circle is 100%.

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