Attribution of European precipitation and temperature trends to changes in synoptic circulation

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Abstract

Surface climate in Europe is changing and patterns in trends have been found to vary at sub-seasonal scales. This study aims to contribute to a better understanding of these changes across space and time by analysing to what degree observed climatic trends can be attributed to changes in synoptic atmospheric circulation. The relative importance of synoptic circulation changes (i.e. trends in synoptic type frequencies) as opposed to trends in the hydrothermal properties of synoptic types (within-type trends) on precipitation and temperature trends in Europe is assessed on a monthly basis. The study is based on mapping spatial and temporal trend patterns and their variability at a relatively high resolution (0.5° x 0.5°; monthly) across Europe. Gridded precipitation and temperature data (1963-2001) originate from the Watch Forcing Dataset and synoptic types are defined by the objective SynopVis Grosswetterlagen. During the study period, relatively high influence of synoptic-circulation changes are found from January to March, contributing to wetting trends in northern Europe and drying in the South. Simultaneously, in particular dry synoptic types get warmer first in south-western Europe in November/December and affecting most of Europe in March/April. Strong influence of synoptic-circulation changes is again found in June and August. In general, changes in synoptic-circulation affect climate trends in north-western Europe stronger than the South-East. The exact locations of the strongest influence of synoptic-circulation changes vary with time of the year and to some degree between

precipitation and temperature. Throughout the year and across the whole of Europe, precipitation and temperature trends are caused by a combination of synoptic-circulation changes and within-type changes with their relative influence varying between regions, months and climate variables.

1 Introduction

The need to understand the influence of global change on the water cycle, has led to considerable scientific effort as seen by a number of studies of trends in hydrometeorological variables (IPCC, 2013). Large-scale studies covering all of Europe include for example Klein Tank et al. (2002), Klein Tank and Können (2003), Zolina et al. (2010), Teuling et al. (2011) and van den Besselaar et al. (2012) for precipitation and temperature. These studies cover both annual and seasonal averages as well as extremes and document changes in averages and the structure of European hydroclimatology, including more frequent precipitation extremes and longer wet-periods. Changes and trends in hydroclimatology are commonly analysed on an annual, seasonal or event basis. However, the transition from winter to summer conditions (and vice versa) in the atmospheric circulation over the North Atlantic and Europe, generally is a slow and gradual process (e.g. Vrac et al., 2014). Thus, higher temporal resolutions may be beneficial also when analysing changes in hydroclimatological variables. Up to now, less focus has been on the monthly scale. One example is the work by Serrano et al. (1999) who considered monthly precipitation trends on the Iberian Peninsula (1921-1995). They found a significant trend only in March. Paredes et al. (2006) similar found a decrease in March precipitation in the Mediterranean and southern France (1960-2000), and increasing precipitation in the north-western parts of the British Isles, large parts of Scandinavia and along the North-Sea coast of the Netherlands and Germany.

These climatic trends affect the continental hydrology. Stahl et al. (2010; 2012) systematically studied streamflow trends in Europe over the period 1962-2004 on annual, seasonal and monthly scales. Widespread increases in streamflow were found across most of Europe during December, with an exception around the Mediterranean and in the East. From January onwards, decreasing trends expand towards the West and North, covering large parts of Europe in June and, after a break in July, decreasing trends across Europe reach a maximum in August. Despite the differing temporal scales and study periods as well as the influence of locally varying hydrological characteristics, similarities can be seen in the most dominating large-scale patterns of monthly streamflow trends (Stahl et al., 2010; 2012) with seasonal trends in European precipitation and temperature as reported by Teuling et al. (2011) based on the E-OBS dataset (1979–2008). Both show a strong north-south gradient in trends across Europe during the winter season (DJF). These broad-scale patterns of change suggest considerable synoptic circulation forcing. However, the patterns in streamflow changes also suggest additional thermal forcing, for instance through changing proportions of rain versus snowfall. As such, Wilson et al. (2010) attributed earlier snowmelt floods to increased temperature and a tendency to longer summer droughts in rivers in south-eastern Norway, to an increase in temperature and higher evapotranspiration. A better understanding of the monthly varying large-scale patterns in European streamflow can be achieved by assessing monthly trends and causing processes in the two main drivers of streamflow: precipitation and temperature (through its influence on evapotranspiration and snow accumulation/melt).

Regional variability in hydroclimatology is part of larger-scale patterns and processes, and synoptic-scale meteorological data can provide complementary information on particular processes, as for example the contrasting precipitation anomalies between northern and southern Europe related to large-scale modes such as the North Atlantic Oscillation (NAO). Large-scale atmospheric modes and smaller scale synoptic types are frequently used for assessing local and regional climatic features (e.g. Huth et al., 2008) as well as climate-hydrology connections as recently reviewed by Hannah et al. (2014) for regional studies across Europe, including extremes, such as floods (e.g. Prudhomme and Genevier, 2011) and streamflow droughts (e.g. Fleig et al., 2010; 2011).

Synoptic types (STs) characterise the synoptic atmospheric situation of a large region as a single nominal variable and are usually strongly related to a number of local climatic variables including precipitation and temperature (e.g. James, 2007). They are most commonly characterised by their main large-scale features, cyclonicity and/or location of high- and low-pressure systems. However, their local climatological features may vary. For instance, precipitation has a relatively high spatial variability within the larger-scale atmospheric conditions. Temperature anomalies, on the other hand, are more coherent, but the relation to high- and low-pressure systems varies throughout the year and among regions according to absolute temperature values.

The hydrothermal properties of STs have also been found to be non-stationary, in particular during the summer season (e.g. Beck et al., 2007; Jacobeit et al., 2009; Cahynová and Huth, 2010; Küttel et al., 2011). Thus, changes in precipitation and temperature can be caused by changes in the occurrence frequencies of STs, which mainly corresponds to changes in the atmospheric circulation, as well as by changes in the local hydrothermal properties of a certain ST (so-called “within-type change”). This implies that the observed trend in precipitation (or temperature) is the sum of trends caused by circulation change and within-type change, respectively (e.g. Beck et al., 2007; Cahynová, 2010). Previous studies on non-stationarities in the hydrothermal properties of STs have focused on seasonal data or one season only (Küttel et al., 2011), on one region, and not on regional variability (Beck et al., 2007; Cahynová and Huth, 2010), or on specific processes such as the occurrence of extreme events (Jacobeit et al., 2009). However, changes in the occurrences of STs in Europe have been found to vary on a monthly time scale (Hoy et al., 2013a).

The question arises to which degree the regionally varying trend patterns in European hydroclimatology throughout the year are influenced by changes in the atmospheric circulation (referred to as “synoptic-circulation-induced trends”) as opposed to trends in the local hydrothermal properties of synoptic types (referred to as “within-type trends”). Here, we investigate their relative influence on trends in monthly precipitation and temperature. Special focus is given to trends in the frequencies of locally wet and dry STs, to improve our understanding of the physical causes controlling regional precipitation changes and the relations between precipitation and temperature trends within STs. As any trend analysis strongly depends on the study period and to some degree on the methodology (e.g. Hannaford et al., 2013), the focus in this study is not primarily on detecting trend magnitudes. Rather, we aim to provide a better understanding of key processes controlling observed trends in temperature and precipitation. The study period 1963–2001 was chosen due to the availability of a high quality gridded dataset for precipitation and temperature, the Watch Forcing Dataset (Weedon et al., 2011), and the comparability to previously observed monthly trend patterns in European streamflow (Stahl et al., 2010; 2012). The work adds to previous studies linking circulation and within-type changes to hydroclimatological variables by using a higher temporal (monthly) and spatial resolution (0.5° x 0.5°) as well as a larger study domain (Europe).

In the following, climate and synoptic type data are described (section 2), as well as the methods for analysing synoptic-circulation-induced trends in precipitation and temperature and trends within wet and dry STs (section 3). Following the results (section 4), the discussion in section 5 attributes monthly precipitation and temperature trends to changes in the atmospheric circulation or within-type changes. Finally, conclusions are drawn and the influence of changes in STs on monthly streamflow trends in Europe are summarized.

2 Data

2.1 Synoptic types

Daily synoptic types (STs) for the European domain are defined according to the classification procedure, SynopVis Grosswetterlagen (SVG). This is a new objective-automatic classification of the well-known 29-type Hess and Brezowsky Grosswetterlagen (GWL), which have been classified manually for many years at the German Weather Service, a series which extends back to 1881 (Werner and Gerstengabe, 2010). The SVG system is similar to the previously recommended (Fleig et al., 2010; 2011) Objective Grosswetterlagen (OGWL; James, 2007), but has several significant improvements that are summarised briefly below.

Whereas OGWL was based on only two variables, mean-sea-level pressure (MSLP) and the 500 hPa geopotential height (Z500), SVG also adds the relative thickness of the lower troposphere (Z500-Z1000) and total column precipitable water (PWAT) fields to improve the method’s ability to distinguish between relevant air mass types affecting the European region. This is especially important for hydroclimatological studies, since precipitation totals are clearly influenced by air mass in terms of moisture content and by the dynamics of frontal air mass boundaries. The data is derived from the 20th Century reanalysis (20CR) product (1871-2010; Compo et al., 2011) and the NCEP/NCAR reanalysis data for the most recent period (2011 onwards) in order to obtain a ST series as long and homogenous as possible. A spatial domain is used, which varies as a function of variable and season, covering the eastern North Atlantic and Europe. As in OGWL, the defining variables are correlated against a set of standard seasonally varying base patterns for each type in the original GWL. These base patterns have been significantly improved over James (2007) by optimising their distribution across the phase space of possible synoptic variability. For each synoptic situation, the highest correlating pattern is chosen as the classified GWL-type for that day. Finally, a temporal filter is employed to remove insignificant transient effects, resulting in a classification that has similar temporal characteristics to the manual Hess-Brezowsky GWL catalogue in which each ST must last at least three days by definition.

The 29 SVG-STs have a much flatter frequency distribution than the original manual GWL-types, since the most common type occurs on average no more than around four times as often as the least common type. This improves the usefulness of the SVG series, due to higher total information content. The SVG series has been used successfully, for example, to examine the large-scale variability of circulation patterns around Europe (Hoy et al., 2013a), to study the relationship between synoptic types and thunderstorm occurrence over Germany (Wapler and James, 2014) and in a local study on precipitation extremes in parts of Montenegro (Ducić et al., 2009). With the 29 STs grouped into four major types, mainly representing westerlies, northerlies, easterlies and southerlies, the SVG series has been found useful also in comparison with other classifications analysing the impact of large-scale atmospheric circulation on European temperature (Hoy et al., 2013b) and precipitation (Hoy et al., 2014).

2.2 Precipitation and temperature

Gridded (0.5° x 0.5°) time series of daily precipitation (P) and mean temperature (T) from the Watch Forcing Dataset (WFD) were used. The WFD is a historical climatic dataset (1958-2001) based on ERA-40 reanalysis with bias-corrected mean temperature and precipitation based on CRU-TS2.1 and GPCCv4 observations, respectively (Weedon et al., 2011). Precipitation is corrected for station undercatch, but not for elevation. The grid cells follow the CRU land surface mask. The higher spatial resolution as compared to ERA-40 and other climatological dataset makes the WFD particular useful for application in hydrological studies. The trends derived from the reanalysis and bias-corrected precipitation and temperature are hereafter referred to as trends in WFD-precipitation (WFD-P) and WFD-temperature (WFD-T).

3 Methods

3.1 Trends and trend ratios

The extent to which observed trends in temperature and precipitation can be explained by synoptic-circulation changes or changes in the hydrothermal properties of STs (within-type trends) is investigated following Cahynová and Huth (2010). This implies calculating a synoptic-circulation-induced trend and comparing it to the observed trend in P (or T; here WFD-P and WFD-T are used). The synoptic-circulation-induced trend calculation assumes that all changes in P (or T) come from synoptic changes only. The changes are quantified in terms of monthly ST-frequencies, and the calculation procedure is as follows:

1. For each ST, *s*, a long-term WFD-P (or WFD-T) mean value, $\overline{P}_{s,m,i}$ (or $\overline{T}_{s,m,i}$), is calculated for each calendar month, *m*, for each cell, *i*.

    Example: The long-term mean P in cell 1, for ST1 in January, $\overline{P}_{ST1,Jan,1}$, is derived as the mean of all P values in cell 1 occurring on days with ST1 in any January in the whole study period.

2. Daily hypothetical P (or T) time series are then constructed by replacing the daily WFD-P (or WFD-T) value with the long-term mean per calendar month according to the actual observed ST on that day. In this way, the hydrothermal properties of the STs are assumed stationary throughout the study period.

    Example: If the ST time series would start with the following STs on the first three days of January:
    ST5, ST9, ST9, ...
    the corresponding hypothetical P series for cell *i* would start with:
    $\overline{P}_{ST5,Jan,i}$, $\overline{P}_{ST9,Jan,i}$, $\overline{P}_{ST9,Jan,i}$, ...

3. From the hypothetical daily series, hypothetical monthly P (or T) series are derived.

4. Linear hypothetical, i.e. synoptic-circulation-induced, trends, $t_{\mathrm{circ}\,m,i}$, are then calculated for each calendar month, *m*, and cell, *i*.

5. Monthly ratios, $r_{\mathrm{circ}\,m,i}$, of the synoptic-circulation-induced trend divided by the WFD trend, $t_{\mathrm{WFD}\,m,i}$, finally indicate the proportion of the monthly WFD-P (or WFD-T) trends that can be related to synoptic-circulation changes:

$$r_{\mathrm{circ}\,m,i} = \frac{t_{\mathrm{circ}\,m,i}}{t_{\mathrm{WFD}\,m,i}} \tag{1}$$

Hence, whereas the synoptic-circulation-induced trends inform whether there is a trend or not due to synoptic-circulation changes, the trend ratio relates this trend to the total trend in

WFD-P (or WFD-T). In order to exclude irrelevant or unrealistic trend ratios due to very small trends in WFD, trend ratios are only calculated for grid cells and months where the WFD trend is significant at the 70% significance level. Linear trends are calculated using linear least-squares regression and the t-test is used to test the statistical significance. The rather low significance level is chosen as a compromise between excluding small trends and detecting large-scale regional trend patterns. Trend ratio values of 0 and 1 mean that no, respectively the whole WFD trend can be explained by the synoptic-circulation-induced trend. Values larger than 1 mean that the synoptic-circulation-induced trend is larger than the WFD trend, whereas values smaller than zero imply opposite signs of the trends. This can occur when circulation changes captured by the synoptic-circulation-induced trend and within-type changes have opposite directions.

3.2 Trends and trend ratios within wet and dry STs

To study the processes behind local precipitation and temperature trends further, the 29 STs were combined into groups of dry, wet and average-precipitation STs for each grid cell separately, and P and T trends explained by within-ST-group changes were derived. Local precipitation properties associated with a ST can vary somewhat throughout the year. Here, this seasonal variability is not accounted for, as a consistent grouping for all calendar months was preferred. Therefore, the grouping is based on the long-term mean precipitation per ST over the whole year in the considered grid cell. Hence, the sets of STs defined as wet, dry or average precipitation STs vary among grid cells. STs are defined as wet (dry), when they on average bring more (less) precipitation than the mean, μ, plus (minus) half a standard deviation, σ, (of all STs) to a grid cell (Eqs. 2 and 3). The remaining STs are considered as average-precipitation STs, hereafter referred to as “average STs” (Eq. 4).

Wet STs for cell i: $$\overline{P}_{s,i} \; > \; \mu\left(\overline{P}_{ST1,\ldots,29,i}\right) + 0.5\,\sigma\left(\overline{P}_{ST1,\ldots,29,i}\right) \qquad (2)$$

Dry STs for cell i: $$\overline{P}_{s,i} \; < \; \mu\left(\overline{P}_{ST1,\ldots,29,i}\right) - 0.5\,\sigma\left(\overline{P}_{ST1,\ldots,29,i}\right) \qquad (3)$$

Average STs for cell i:

$$\mu\left(\overline{P}_{ST1,\ldots,29,i}\right) - 0.5\,\sigma\left(\overline{P}_{ST1,\ldots,29,i}\right) \; \leq \; \overline{P}_{s,i} \; \leq \; \mu\left(\overline{P}_{ST1,\ldots,29,i}\right) + 0.5\,\sigma\left(\overline{P}_{ST1,\ldots,29,i}\right) \qquad (4)$$

where $\overline{P}_{s,i}$ is the mean precipitation of ST s in cell i over the whole year. For each ST-group, monthly frequency trends are derived.

Trends in P (or T) within the groups of wet, dry and average STs are calculated using only the days on which a ST of the respective ST-group occurred. For months when no ST of the considered ST-group occurred, the long-term monthly average WFD-P (or WFD-T) value for this ST-group is assigned, hence obtaining a complete monthly within-ST-group P (or T) time series. This constitutes along with the cell-wise grouping into wet, dry and average STs, a modification of the calculation suggested by Cahynová (2010). The calculation procedure consists of the following steps:

1. For each month, the days with a ST of the considered ST-group are selected and a monthly P (or T) value is calculated using the WFD-P (or WFD-T) data of these days only.
2. For the considered ST-group *g*, a long-term WFD-P (or WFD-T) mean value, $\overline{P}_{g,m,i}$ (or $\overline{T}_{g,m,i}$), is calculated for each calendar month, *m*, and each cell, *i*.

   Example: For cell *i*, the long-term mean P for wet STs in cell *i* in January, $\overline{P}_{wetSTs,Jan,i}$, would be calculated as the mean of all monthly January P values in cell *i* derived in step 1.
3. The monthly time series derived in step 1 might be incomplete as there might be months during which no ST of the considered ST-group occurred. For these months, the long-term WFD-P (or WFD-T) mean value of this calendar month is used.
4. Linear within-ST-group trends, $t_{\mathrm{wetSTs},\,m,i}$ (or $t_{\mathrm{drySTs},\,m,i}$, $t_{\mathrm{averageSTs},\,m,\,i}$), are then calculated for each ST-group and calendar month, *m*, and cell, *i*.
5. The finally derived monthly ratiosof the within-ST-group trends divided by the WFD trend, $t_{\mathrm{WFD},\,m,i}$, indicate the proportion of the monthly WFD-P (or WFD-T) trends that can be related to changes in wet, dry and average STs, respectively:

$$r_{\mathrm{wetSTs},\,m,i} = \frac{t_{\mathrm{wetSTs},\,m,i}}{t_{\mathrm{WFD},\,m,i}}, \qquad r_{\mathrm{drySTs},\,m,i} = \frac{t_{\mathrm{drySTs},\,m,i}}{t_{\mathrm{WFD},\,m,i}}, \qquad r_{\mathrm{averageST}s,\,m,i} = \frac{t_{\mathrm{averageSTs},\,m,i}}{t_{\mathrm{WFD},\,m,i}} \qquad (5)$$

Changes in the characteristics of wet, dry and average STs can either be changes of the hydrothermal properties within the single STs of a ST-group (e.g. all wet STs are getting wetter/drier and warmer/colder), or the frequencies of the single STs within a ST-group are changing (e.g. the wettest of the wet STs become more/less frequent and the driest of the wet STs become less/more frequent). Ratios of the within ST-group trends divided by the WFD trends are here analysed to identify possible differences between wet and dry STs and varying importance among regions and months. The overall proportion of WFD trends caused by changes in the hydrothermal properties summed over all STs is the difference between the total WFD trend and the synoptic-circulation-induced trend, i.e. 1 - $r_{circ, m,i}$.

4 Results

4.1 Precipitation: synoptic-circulation-induced trends and trend ratios

Monthly synoptic-circulation-induced precipitation trends during the study period (1963-2001) are presented in Fig. 1 (rows 1 and 3). In most months with strong trends, opposite synoptic-circulation-induced precipitation trends are found in northern and southern Europe. Synoptic-circulation-induced trends are strongest and most widespread in January, February and March with increasing precipitation across northern Europe and decreasing precipitation in the South. In April and May, there are only few synoptic-circulation-induced precipitation trends (not resembling the previous months). Clear regional trend patterns occur again in June with increasing precipitation across Scandinavia and decreasing trends mainly on the Iberian Peninsula. Strong synoptic-circulation-induced precipitation trends are found also in August, September and November, but the regional patterns differ considerably from the previous months with strong trends (i.e. January – March and June). In August, synoptic-circulation-induced precipitation increases are found in western Scandinavia together with strong decreases across all of Central Europe and parts of south-eastern Europe. The picture is notably different just one month later in September; now a strong precipitation decrease is seen in north-eastern Scandinavia and no significant trends elsewhere. In November, strongest decreasing synoptic-circulation-induced precipitation trends are seen around and particularly southeast of the Baltic Sea, and increasing trends in the very south of Europe from west to east. The latter are the only increasing synoptic-circulation-induced precipitation trends in southern Europe that are significant at the 95% level.

Trend ratios are presented in Fig. 2 (rows 1 and 3). They show that 50% or more of the precipitation trends in large parts of Europe can be attributed to synoptic-circulation change from January to March. Ratios as high as 0.8 – 1.0 are found, particular in January and February, in August in central Germany and in November in Central Europe. Whereas trend ratios less than 0.5 and often close to zero are found during late spring and early summer, regionally higher values are found in June in eastern Scandinavia and the south-western part of Iberia, locally in northern UK in March and in small regions of Central Europe in July. High trend ratios dominate again in August and September with a centre over Central Europe and north-eastern Europe, respectively. Trend ratios are also above 0.5 in western and parts of Central Europe in October and south of the Baltic region in November.

4.2 Temperature: synoptic-circulation-induced trends and trend ratios

Synoptic-circulation-induced temperature trends are presented in Fig. 1 (rows 2 and 4). Strong synoptic-circulation-induced temperature trends are found for the same months as synoptic-circulation-induced precipitation trends, i.e. the most widespread and strongest trends are in February and January, followed by March, June, August and November. Synoptic-circulation-induced temperature trends are mostly positive. However, weak decreasing trends are found around the North Sea and western parts of the Baltic Sea in June, in eastern Europe in September and south-eastern and Central Europe in November.

Trend ratios for temperature are shown in Fig. 2 (rows 2 and 4). As for precipitation, they are highest in January and February with values of 0.4 and above across all of Europe except for the South-East. Values up to 0.8 are found in large parts of north-western Europe. Ratios decrease during March and April. In May, they increase again on the British Isles and in western and Central Europe. In August, the highest ratios (around 0.5) are centred over Central Europe, but values of 0.3 and higher are seen in the surrounding regions, in particular to the South-West.

4.3 ST-frequencies trends

Trends in the frequency of wet STs are shown in Fig. 3 (similar results are obtained for dry and average STs, see supplementary material). The trends show a pronounced north-south pattern for months with widespread regional trends, including in January – March and August. There are increases (decreases) in wet (dry) STs in the North and decreases (increases) in wet (dry) STs in the South. Trends are strongest and most widespread in February. In December, there are relatively few significant trends and the trend pattern follows more a south-west to north-east divide (wetter in the West, drier in the East). In August, the decreasing trends in wet STs extend further north than during the winter months, whereas in March the increasing trends in wet STs extend east and southwards. In March, on the other hand, an increase in the frequency of dry STs is seen around the southern part of the

North Sea and further into Germany and northern France. In July, September and November the strong north-south pattern (from January to March and August) is completely reversed, but generally less strong, in particular in July. Strong synoptic-circulation changes are also found in June with increasing frequencies in wet STs in the North and East and decreases in the South-West. Frequency trends for all ST groups are fewest in April, July and October.

4.4 Precipitation: trends and trend ratios within ST-groups

Precipitation and temperature trends within-ST-groups (Fig. 4-5) and corresponding trend ratios (Fig. 6-7) show that changes within wet and dry STs have varying effects. Precipitation amounts associated with the groups of wet STs mainly increase or do not change throughout the year and across Europe (Fig. 4, rows 1 and 3). In particular, during winter until April and again in July, wetting trends are most widespread. Drying trends within wet STs are more local and most widespread in eastern Europe in October. Persisting drying trends are found in Iberia from January to March, spreading form western Iberia in January north-eastward to also include parts of France in March. Least wetting trends within wet STs are found in August, when also drying trends are only local.

The groups of dry STs show fewer wetting trends than the wet STs, with the exception of August, when the dry STs get wetter in southern Scandinavia (Fig. 5, rows 1 and 3). Throughout the year, there are large parts of Europe without significant precipitation trends within dry STs, and regions with drying trends dominate over those with wetting in December and January. Both regional wetting and drying trends occur during the remaining months. In February, the groups of dry STs get drier in eastern Europe and wetter in Central and north-western Europe. From April to August, drying within the dry STs is mostly seen in Central Europe.

The regional trend patterns in precipitation within the groups of average STs (see supplementary material) show similarities to the precipitation trend patterns within both the dry and wet ST-groups. During the summer months, trend patterns are weaker and regionally more variable than in the other ST-groups. Stronger precipitation trends are found in October in southern Europe with drying in the South-West. This is in contrast to a wetting trend within wet STs in the same region.

Precipitation trends within wet STs explain the largest part of the overall precipitation trends. High trend ratios are found regionally or locally across Europe in December, April, June and

July and in parts of Europe during the remaining months (Fig. 6, rows 1 and 3). The groups of dry STs (Fig. 7, rows 1 and 3) and, to some extent the groups of average STs (see supplementary material), show low or negative trend ratios. High negative trend ratios are in particular found from January to March in northern and north-eastern Europe. In particular, August shows positive and negative trend ratios varying on a small spatial scale for wet, dry and average ST groups.

4.5 Temperature: trends and trend ratios within ST-groups

Warming or no temperature trends dominates the regional monthly trend patterns within wet, dry and average ST-groups (Fig. 4-5, rows 2 and 4). Also the cooling trends in south-eastern Europe in February and March, northern and Central Europe in June and part of eastern Europe during the autumn months are at least partly found within the three kinds of groups. The wet STs show, however, a strong cooling trend in south-eastern Europe in January and south-western Europe in February, whereas the dry STs show warming trends in the same months and regions. Furthermore, dry STs show cooling trends in north-eastern Europe in May and July, where warming or no trends are found within wet and average STs.

Highest trend ratios for temperature are found within the groups of dry STs (Fig. 7, rows 2 and 4). Covering south-western Europe in December, a belt of high trend ratios extends to eastern Europe in February and then moves northward, covering western to north-eastern and eastern Europe in April. From July to November, higher ratios are again found in south-western Europe, extending also to Central and south-eastern Europe in August and covering the west and north coast of Scandinavia in September. Negative trend ratios are found within dry STs in Scandinavia in February, July and November and locally in May and August.

Within the groups of wet STs (Fig. 6, rows 2 and 4), negative trend ratios are found in south-western Europe in January, eastern Europe in April and August, south-eastern Europe in May and very locally otherwise. High positive values are mostly found around the Baltic in December, May and June, in south-eastern Europe in June and in northern and north-western Europe in July and November.

Within the groups of average STs, few negative temperature trend ratios are found (see supplementary material). The highest positive ratios occur in Central and parts of north-eastern Europe in January and April, south-eastern Europe in May and eastern Europe in August.

5 Discussion

5.1 Attribution of trends: Synoptic-circulation-induced versus within-ST-groups trends

Trends in ST frequencies show that the STs, which are moist in the North and dry in the South have become more frequent from January to March, whereas the STs, which are moist in the South and dry in the North have become less frequent. The studies of Paredes et al. (2006) and Hoy et al. (2014) support these results. Comparing the two periods 1951-1980 and 1981-2010, Hoy et al. (2014) found precipitation increases (decreases) during the winter half-year in northern (southern) Europe to be correlated to increasing frequencies of STs with westerly inflow over Central Europe and decreasing frequencies of easterly types. According to the authors, westerly (easterly) types are predominantly wetter (drier) than normal in northern Europe and drier (wetter) in the South. Similarly, Paredes et al. (2006), could explain monthly precipitation changes (1941-97) in Iberia specifically for the month of March by decreasing frequencies of wet cyclonic types with respect to Iberia and increasing frequencies of types which result in dry anticyclonic conditions there. For the UK, they found the opposite, i.e. a decrease in the frequency of dry anticyclonic types and an increase in the wet cyclonic types. However, since the mid-1990s the frequencies of westerly types during winter have slightly declined related to changes in the NAO (e.g. Hoy et al., 2013a).

As in our study, Hoy et al. (2013a) found generally less changes in ST-frequencies during the months of the summer half year as compared to winter for the period 1901-2010. They found, however, an increase of anticyclonic easterlies and decrease of westerlies during August. This is in agreement with our results for August, which show an increase (decrease) in wet (dry) STs in the North and a decrease (increase) in wet (dry) STs in the South.

In accordance with these changes in ST-frequencies, we find that during our study period a relatively high percentage of both precipitation and temperature trends can be attributed to changes in the atmospheric circulation (by the highest synoptic-circulation-induced trend ratios) during January to March, as well as during the remaining months with strong trends in the frequencies of wet and dry STs (i.e. in June, August, and regionally in September, November and December).

The trend patterns and trend ratio patterns often resemble the circular shape of high- or low-pressure systems (e.g. patterns in January, February and August). In particular, synoptic-circulation-induced temperature trends often extend over larger areas, whereas synoptic-circulation-induced precipitation trends and trend ratios are patchier. This is likely due to the higher sensitivity to regional and local topography and the higher spatial variability of precipitation compared to temperature. Furthermore, the regions where the synoptic-circulation-induced trends in precipitation and temperature are strongest do not necessarily coincide. On the contrary, the strongest synoptic-circulation-induced temperature trends within a month are often found in regions where synoptic-circulation-induced precipitation trends are weakest, if existing at all. This can be explained by the fact that high precipitation amounts are typically found in regions with low-pressure centres and their frontal systems and maritime air masses. The largest deviations from the mean monthly temperature, on the other hand, are more likely found in regions of high-pressure centres or high pressure-gradients, in particular when the air is coming from continental areas or transported over large zonal distances. Hence, with changes in circulation, i.e. in the location of high- and low-pressure systems and thus in the frequencies of STs, the regions where the effects on the local climate are strongest will also vary between precipitation and temperature.

The regional patterns in June, August, September and November, notable for precipitation, differ considerably from the previous months with strong trends (i.e. Jan – Mar). In the winter months, i.e. January and February, synoptic-circulation changes imply increasing precipitation trends in northern Europe associated with warming trends there. During the same months, the decreasing synoptic-circulation-induced precipitation trends in the South are mostly associated with no or decreasing temperature trends, with the exception of Iberia in February, where decreasing precipitation trends are accompanied by increasing temperature trends. During the summer months, on the other hand, synoptic-circulation-induced precipitation increases (decreases) are associated with cooling (warming) or no trends throughout Europe. Overall, the relative importance of synoptic-circulation changes appears to be slightly higher for precipitation than for temperature trends. Regionally low or negative synoptic-circulation-induced trend ratios similar show the importance of within-type changes in particular for temperature trends even during the months with strong synoptic-circulation changes. For instance, in south-eastern Europe in January, the influence of synoptic-circulation changes on temperature is low, whereas it is high in many other parts of Europe and for precipitation also in the South-East.

Within-ST-group trend ratios for precipitation are mostly lower for dry STs as compared to wet STs. Both dry STs as well as wet STs get wetter in some regions and drier in others. For instance in February, wet STs get wetter in Central Europe and drier in the South, whereas dry STs get drier in the East and wetter in the North-West. It has to be remembered that this applies to the sets of STs, which are locally defined as wet or dry.

Significant warming trends are found at least locally during all months within both dry as well as wet STs. Fewest warming trends within ST-groups are found in October. Trend ratios show that higher proportions of temperature trends can be attributed to warming within dry STs as opposed to wet STs. Most notable is the warming within dry STs in southern Europe. The fact that in particular dry STs get warmer in southern Europe may be related to land-surface feedbacks; more frequent dry STs in southern Europe (Jan – Mar) may lead to drier soils and the radiative energy, which cannot be used anymore to evaporate water from the land surface, causes increasing temperatures (Zampieri et al., 2009). Wet STs in northern Europe, on the other hand, might get wetter in response to increased evaporation with increasing temperature.

Overall, somewhat higher proportions of precipitation and temperature trends can be attributed to synoptic-circulation changes in northern Europe as compared to southern Europe. The only exception is the month of August, when synoptic-circulation changes have the strongest influence on temperature and precipitation trends in Central Europe. This north – south divide in the role of synoptic-circulation changes on local climate can be related to a dominance of frontal (compared to local convective) precipitation that is generally more frequent in northern and western Europe than in southern and eastern Europe (Trenberth et al., 2003). The high importance of synoptic-circulation changes for precipitation trends in Central Europe during August is in this respect interesting, as normally the proportion of convective precipitation compared to frontal precipitation would be higher during summer. Thus, one could expect precipitation to be less sensitive to circulation changes. The fact that these synoptic-circulation changes occur at the end of the summer season may suggest a memory effect in the system, such as low soil moisture content or high sea surface temperatures. By the end of the summer, these conditions may have become strong enough to force circulation changes. To test this hypothesis, a trend analysis on the monthly frequencies of anticyclonic and cyclonic STs was performed, and indeed, a strong increasing trend in anticyclonic circulation occurrence over Central Europe in August was found (not shown). This is in agreement with, for instance, the results of Hoy et al. (2013a), who also found increasing frequencies of anticyclonic circulation over Central Europe in summer (mid-July to mid-August) during the 20th century (1901-2010), when studying changes in ST frequencies using a 31-day moving window. Anticyclonic circulation may be caused by land surface feedbacks to the atmosphere during dry and warm summers (Zampieri et al., 2009).

Further work should investigate to which extent these circulation changes in August are indeed feedbacks related to the general warming in Europe in spring and summer and, in particular, to the drying within dry STs in southern Europe. In addition, the wetting and cooling trends in June, associated with both synoptic-circulation changes as well as within-type changes, could be related to local or more remote feedback processes, such as changes in snow-cover, sea surface temperatures or sea ice, and should be investigated further. Matsumura et al. (2010) and Matsumura and Yamazaki (2012), for instance, found that reduced springtime snow-cover in northern Eurasia affect atmospheric circulation in summer leading to precipitation anomalies over northern Eurasia. On longer time scales, also vegetation changes may play a role. According to Liess et al. (2012), a reduction in albedo due to expansion of the boreal forest may lead to a local increase in net radiation and a warming of the northern hemisphere during June. The associated changes in the meridional temperature gradient may enhance the Artic frontal zone, strengthen the summer jet and cause a shift in the position of the storm tracks, which might result in changes in temperature and precipitation regimes.

5.2 Uncertainty

Trend ratios as well as the comparison between dry/wet ST-frequencies and climate variables suggest that the relative importance of synoptic-circulation changes on precipitation and temperature trends varies among regions and months. However, some uncertainty issues should be discussed. The mean precipitation fields associated with one ST can differ in strength and exact location, so that the representativeness of the defined wet/dry STs may vary slightly among months. This could in particular affect transition months between winter and summer conditions in spring and autumn. Furthermore, simultaneous changes in ST-frequencies and within-type changes may have opposite effects on climate variables, which may disguise their real influence on precipitation (or temperature) in the trend ratios, in particular in regions where the resulting precipitation or temperature changes are non-significant. Still, it can be seen from the ST-frequency trends that synoptic-circulation changes are most important during late winter (Jan – Mar), June and August, whereas there are small changes in synoptic-circulation in late spring (Apr – May), July and autumn, particularly October. However, it is important to recall that the monthly synoptic-circulation-induced trends (used in the trend ratios) and the definition of wet/dry STs differ in their averaging period. Synoptic-circulation-induced trends consider the long-term mean precipitation values of a ST for each calendar month separately, whereas wet/dry STs are defined based on the annual mean precipitation of each ST.

The use of a monthly time resolution implies a higher risk of noise in the results compared to e.g. seasonal studies. On the other hand, the higher resolution shows, that the sub-seasonal variability is important to consider and that monthly differences do not necessarily follow the traditional division into four seasons. Both months and seasons are arbitrary fixed periods and do not necessarily capture the strongest signals occurring at the respective resolution. As such, also differences in trend patterns between consecutive months will be influenced by the temporal resolution and fixed periods chosen. Future studies could consider for instance a 3-month or 31-day moving average window as an alternative to fixed seasons or months to better account for the gradual transitions within the annual cycle.

Linear trends depend strongly on study period and method. This influences also the synoptic-circulation-induced and within ST-group trends. Therefore, the proportions of circulation versus within-type changes on precipitation and temperature trends cannot be seen as absolute and stationary magnitudes. Non-stationarities in the proportions of circulation versus within-type changes on European precipitation and temperature trends have previously been found by Küttel et al. (2011) using seasonal atmospheric data for the winter season. Strong regional patterns in trends and trend ratios, on the other hand, give trust in the overall results for the considered study period.

6 Conclusions

This studied aimed to attribute observed climatological trends in Europe to changes in the atmospheric circulation and in the hydrothermal properties of synoptic types, as a first step towards a better understanding of monthly varying patterns in streamflow trends in Europe. The relative importance of frequency changes in STs as opposed to within-type changes in the hydrothermal properties on precipitation and temperature trends was analysed, as well as the overall changes in the groups of STs, which are locally associated with wet and dry precipitation anomalies. Our results support previous studies in that both frequency changes in the occurrence of STs and within-type changes play an important role in controlling trends in precipitation and temperature, and that the relative proportions vary within the year and among regions. The importance of frequency changes is higher in winter, whereas within-type changes are dominating in the summer, except for August. The results further show the added value of studying trends over larger spatial areas to identify regional patterns and that the monthly time resolution reveals important within-year variability. Within the study period, the strongest influence of synoptic-circulation changes on both precipitation and temperature occur from January to March, in June and in August, and they are in general stronger in north-western Europe than in the South-East. The exact locations of the areas with highest influence of synoptic-circulation changes differ, however, between precipitation and temperature.

The study shows that changes in the hydroclimatological system show a clear seasonal pattern. The temporal variability in the large-scale patterns found in trends of STs and their hydrothermal properties can, through their combined effect on precipitation and temperature, explain monthly variations in streamflow trend patterns as reported in previous studies by Stahl et al. (2010; 2012). For instance, during late winter and early spring, synoptic-circulation changes dominate and STs, which are moist and warm in northern Europe and dry in southern Europe, have become more frequent during the study period (1963-2001). Stahl et al. (2010; 2012) accordingly found increasing streamflow trends in northern Europe and decreasing trends in the South. At the same time these STs, which are dry in the South, have become warmer there, which may possibly be related to drier soils and subsequent land-surface feedbacks. The warming within STs affects most of Europe during March/April. Together with rather small precipitation changes during April and May, this may account for decreasing streamflow trends first in southern and eastern Europe and then later in large parts of Europe in May. By the end of the summer, the drying and warming of the land surface maybe significant enough to cause the synoptic-circulation changes found in August with more frequent anticyclonic STs over Central Europe. This again favours drier and warmer conditions as reflected in widespread decreasing streamflow trends. Synoptic-circulation-induced precipitation increase in north-eastern Europe in June may explain increases streamflow trends there in June in July.

Considering the non-stationarities in the hydrothermal properties of STs as well as the varying importance of circulation change and within-type changes throughout the year and among regions, is a topic for further studies linking streamflow characteristics to STs. As the relative importance of within-type changes and circulation changes is not stationary, further investigation of the processes controlling the within-type changes in the hydrothermal properties of the synoptic types, is an important research task. In addition, possible local and remote feedback processes and the influence on the regional climate should be considered.

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References

Beck, Ch., Jacobeit, J. and Jones, P. D.: Frequency and within-type variations of large-scale circulation types and their effects on low-frequency climate variability in Central Europe since 1780. Int. J. Climatol. 27, 473–491, 2007.

Besselaar, van den E. J. M., Klein Tank, A. M. G. and Buishand, T. A.: Trends in European precipitation extremes over 1951–2010. Int. J. Climatol., doi:10.1002/joc.3619, 2012.

Cahynová, M.: The influence of long-term changes of atmospheric circulation on observed trends of surface climatic elements in the Czech Republic and Europe, Ph.D. thesis, Department of Physical Geography and Geoecology, Faculty of Science, Charles University in Prague, Czech Republic, 2010.

Cahynová, M. and Huth, R.: Circulation vs. climatic changes over the Czech Republic: A comprehensive study based on the COST733 database of atmospheric circulation classifications. Phys. Chem. Earth, 35, 422–428, doi:10.1016/j.pce.2009.11.002, 2010.

Compo, G. P., Whitaker, J.S., Sardeshmukh, P.D., Matsui, N., Allan, R. J., Yin, X., Gleason, B. E., Vose, R. S., Rutledge, G., Bessemoulin, P., Brönnimann, S., Brunet, M., Crouthamel, R. I., Grant, A. N., Groisman, P. Y., Jones, P. D., Kruk, M., Kruger, A. C., Marshall, G. J., Maugeri, M., Mok, H. Y., Nordli, Ø., Ross, T. F., Trigo, R. M., Wang, X. L., Woodruff S. D. and Worley, S. J.: The Twentieth Century Reanalysis Project. Quarterly J. Roy. Meteorol. Soc., 137, 1-28, doi: 10.1002/qj.776, 2011.

Ducić, V., Luković, J., Burić, D., Stanojević, G., and Mustafić, S.: Precipitation extremes in the wettest Mediterranean region (Krivošije) and associated atmospheric circulation types, Nat. Hazards Earth Syst. Sci., 12, 687-697, doi: 10.5194/nhess-12-687-2012, 2012.

Fleig, A. K., Tallaksen, L. M., Hisdal, H. and Hannah, D.M.: Regional hydrological droughts and associations with the objective Grosswetterlagen in north-western Europe. Hydrol. Process., 24, doi: 10.1002/hyp.7644, 2011.

Fleig, A. K., Tallaksen, L. M., Hisdal, H., Stahl, K. and Hannah, D.M.: Inter-comparison of weather and circulation type classifications for hydrological drought development. Phys. Chem. Earth, 35, 507–515, doi:10.1016/j.pce.2009.11.005, 2010.

Hannaford, J., Buys, G., Stahl, K., and Tallaksen, L. M.: The influence of decadal-scale variability on trends in long European streamflow records, Hydrol. Earth Syst. Sci., 17, 2717-2733, doi:10.5194/hess-17-2717-2013, 2013.

Hannah, D. M., Fleig, A. K., Kingston, D. G., Stagge, J. H. & Wilson, D.: Connecting streamflow and atmospheric conditions in Europe: state-of-the-art review and future directions, in: Hydrology in a Changing World: Environmental and Human Dimensions (Proceedings of the Sixth FRIEND-Water World Conference, Hanoi, Vietnam, February 2014), IAHS Publ. 363, 401-406, 2014.

Huth, R., Beck, C., Philipp, A., Demuzere, M., Ustrnul, Z., Cahynová, M., Kyselý, J. and Tveito, O.E.: Classification of atmospheric circulation patterns – recent advances and applications. Annals of the New York Academy of Sciences 1146, 105–152, 2008.

Hoy, A., Sepp, M. and Matschullat, J.: Atmospheric circulation variability in Europe and northern Asia (1901 to 2010). Theor. Appl. Climatol., 113(1-2), 105-126, doi: 10.1007/s00704-012-0770-3, 2013a.

Hoy, A., Sepp, M. and Matschullat, J.: Large-scale atmospheric circulation forms and their impact on air temperature in Europe and northern Asia. Theor. Appl. Climatol., 113(1-2), 643-658, doi: 10.1007/s00704-012-0813-9, 2013b.

Hoy, A., Schucknecht, A., Sepp, M. and Matschullat, J.: Large-scale synoptic types and their impact on European precipitation. Theor. Appl. Climatol., 116, 19-35, doi: 10.1007/s00704-013-0897-x, 2014.

IPCC: Observations: Atmosphere and Surface, in: Working group I contribution to the IPCC Fifth Assessment Report Climate Change 2013: The Physical Science Basis - Final Draft Underlying Scientific-Technical Assessment, A report accepted by Working Group I of the IPCC but not approved in detail, 2013, available from: http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_Chapter02.pdf

Jacobeit, J. Rathmann, J., Philipp, A. and Jones, P. D.: Central European precipitation and temperature extremes. Meteorol. Z., 18, 397-410, doi: 10.1127/0941-2948/2009/0390, 2009.

James, P. M.: An objective classification method for Hess and Brezowsky Grosswetterlagen over Europe. Theor. Appl. Climatol., 88, 17–42, 2007.

Klein Tank, A. M. G. and Können, G. P.: Trends in indices of daily temperature and precipitation extremes in Europe, 1946–99, J. Climate, 16, 3665–3680, 2003.

Klein Tank, A. M. G., Wijngaard, J. B., Können, G. P., Böhm, R., Demarée, G., Gocheva, A., Mileta, M., Pashiardis, S., Hejkrlik, L., Kern-Hansen, C., Heino, R., Bessemoulin, P., Müller-Westermeier, G., Tzanakou, M., Szalai, S., Pálsdóttir, T., Fitzgerald, D., Rubin, S., Capaldo, M., Maugeri, M., Leitass, A., Bukantis, A., Aberfeld, R., van Engelen, A. F. V., Forland, E., Mietus, M., Coelho, F., Mares, C., Razuvaev, V., Nieplova, E., Cegnar, T., Antonio López, J., Dahlström, B., Moberg, A., Kirchhofer, W., Ceylan, A., Pachaliuk, O., Alexander, L. V., and Petrovic, P.: Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment, Internat. J. Climatol., 22, 1441–1453, 2002.

Küttel, M., Luterbacher, J. and Wanner, H.: Multidecadal changes in winter circulation-climate relationship in Europe: frequency variations, within-type modifications, and long-term trends, Clim. Dyn., 36, 957–972, doi: 10.1007/s00382-009-0737-y, 2011.

Liess, S., Snyder, P. K. and Harding, K. J.: The effects of boreal forest expansion on the summer Arctic frontal zone, Clim. Dyn., 38(9-10), 1805–1827, doi: 10.1007/s00382-011-1064-7, 2012.

Matsumura, S. and Yamazaki, K.: Eurasian Subarctic Summer Climate in Response to Anomalous Snow Cover. J. Climate, 25, 1305–1317, doi: http://dx.doi.org/10.1175/2011JCLI4116.1, 2012.

Matsumura, S., Yamazaki, K. and Tokioka, T.: Summertime land-atmosphere interactions in response to anomalous springtime snow cover in northern Eurasia, J. Geophys. Res., 115, D20107, doi:10.1029/2009JD012342, 2010.

Paredes, D., Trigo, R. M, Garcia-Herrera, R. and Trigo, I. F.: Understanding Precipitation Changes in Iberia in Early Spring: Weather Typing and Storm-Tracking Approaches, J. Hydrometeor, 7, 101–113, doi: 10.1175/JHM472.1, 2006.

Prudhomme, C. and Genevier, M.: Can atmospheric circulation be linked to flooding in Europe? Hydrol. Process., 25(7), 1180-1190, doi: 10.1002/hyp.7879, 2011.

Serrano, A., Mateos, V. L. and García, J. A.: Trend analysis of monthly precipitation over the Iberian Peninsula for the period 1921–1995. Phys. Chem. Earth, 24, 85–90, 1999.

Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L. M., van Lanen, H. A. J., Sauquet, E., Demuth, S., Fendekova, M., and Jódar, J.: Streamflow trends in Europe: evidence from a dataset of nearnatural catchments, Hydrol. Earth Syst. Sci., 14, 2367–2382, doi:10.5194/hess-14-2367-2010, 2010.

Stahl, K., Tallaksen, L. M., Hannaford, J. and van Lanen, H. A. J.: Filling the white space on maps of European runoff trends: estimates from a multi-model ensemble. Hydrol. Earth Syst. Sci., 16, 2035-2047, doi:10.5194/hess-16-2035-2012, 2012.

Teuling, A. J., Stöckli, R. and Seneviratne, S. I.: Bivariate colour maps for visualizing climate data. Int. J. Climatol., 31, 1408–1412, doi: 10.1002/joc.2153, 2011.

Trenberth, K. E., Dai, A., Rasmussen, R. M. and Parsons, D. B.: The changing character of precipitation. B. Am. Meteorol. Soc., 84, 1205–1217, doi: 10.1175/BAMS-84-9-1205, 2003.

Vrac, M., Vaittinada Ayar, P. and Yiou, P.: Trends and variability of seasonal weather regimes. Int. J. Climatol., 34(2), 472–480, doi: 10.1002/joc.3700, 2014.

Wapler, K. and James, P.: Thunderstorm occurrence and characteristics in Central Europe under different synoptical conditions. Atmos. Res., 158-159, 231-244, doi: 10.1016/j.atmosres.2014.07.011, 2015.

Weedon, G. P., Gomes, S., Viterbo, P., Shuttleworth, W. J., Blyth, E., Österle, H., Adam, J. C., Bellouin, N, Boucher, O. and Best, M.: Creation of the WATCH Forcing data and its use to assess global and regional reference crop evaporation over land during the twentieth century. J. Hydrometerol. 12, 823-848, doi: 10.1175/2011JHM1369.1, 2011.

Werner, P.C. and Gerstengarbe, F.W.: Katalog der Growetterlagen Europas (1881-2009) nach Paul Hess und Helmut Brezowsky, 7., verbesserte und ergänzte Auflage. PIK-Report No. 119, Potsdam Institute for Climate Impact Research, 2010.

Wilson, D., Hisdal, H. and Lawrence, D.: Has streamflow changed in the Nordic countries? – Recent trends and comparisons to hydrological projections. J. Hydrol., 394, 334-346, doi:10.1016/j.jhydrol.2010.09.010, 2010.

Zampieri, M., D'Andrea, F., Vautard, R., Ciais, P., de Noblet-Ducoudré, N. and Yiou, P.: Hot European Summers and the role of soil moisture in the propagation of Mediterranean drought, J. Climate, 22, 4747–4758, doi: 10.1175/2009JCLI2568.1, 2009.

Zolina, O., Simmer, C., Gulev, S. G. and Kollet, S.: Changing structure of European precipitation: Longer wet periods leading to more abundant rainfalls. Geophys. Res. Lett., 37, L06704, doi:10.1029/2010GL042468, 2010.

Figure captions

Figure 1. Monthly circulation-induced trends for precipitation (rows 1 and 3) and temperature (rows 2 and 4) significant at the 70% (light colours) and 95% (dark colours). Precipitation: increasing trends in blue, decreasing trends in red. Temperature: increasing trends in red, decreasing trends in blue.

Figure 2. Monthly trend ratios for circulation-induced trends in precipitation (rows 1 and 3) and temperature (rows 2 and 4).

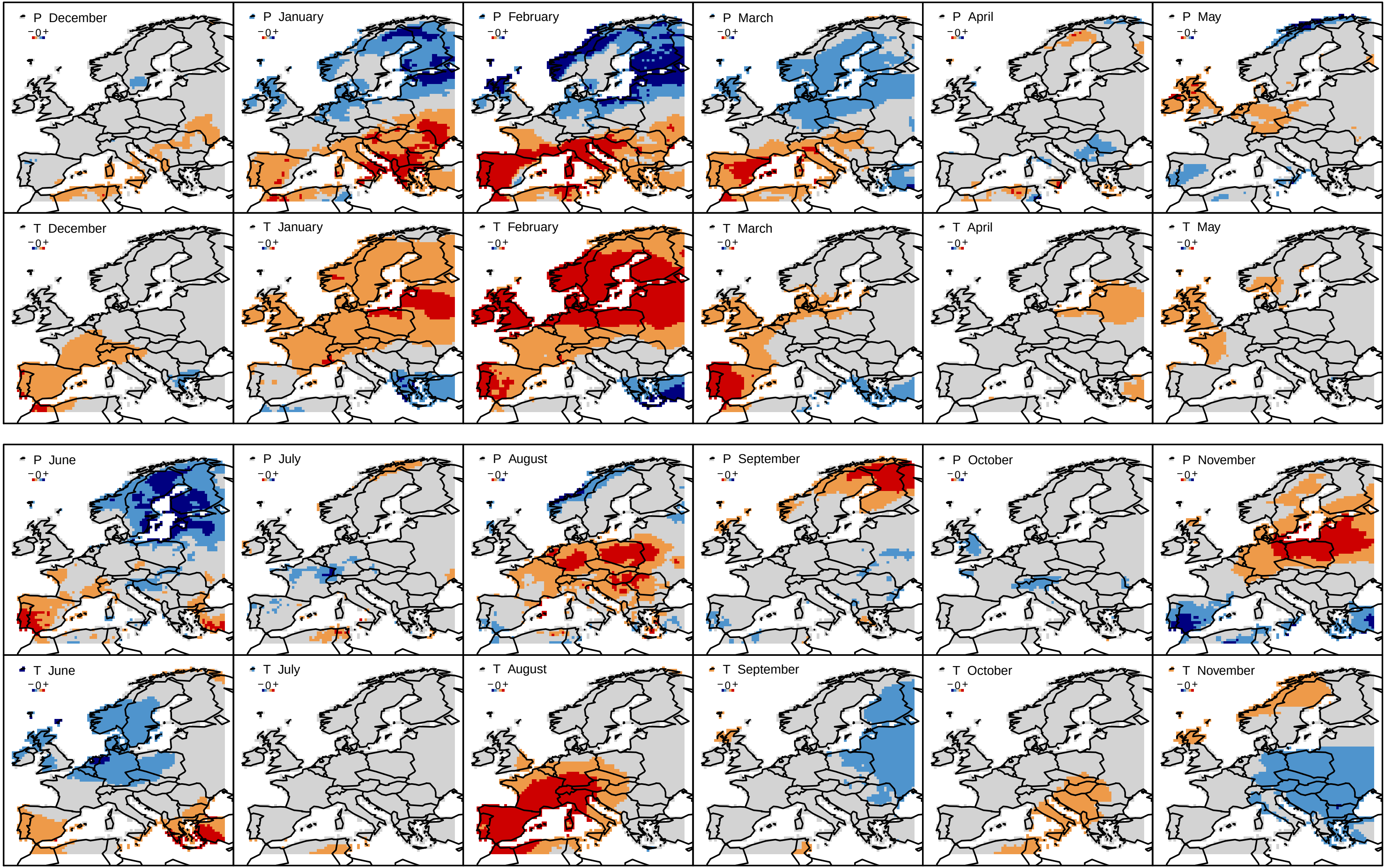
Figure 3. Monthly frequency trends in wet STs significant at the 70% (light colours) and 95% (dark colours); increasing trends in blue, decreasing trends in red.

Figure 4. Monthly trends within the groups of wet STs for precipitation (rows 1 and 3) and temperature (rows 2 and 4) significant at the 70% (light colours) and 95% (dark colours). Precipitation: increasing trends in blue, decreasing trends in red. Temperature: increasing trends in red, decreasing trends in blue.

Figure 5. Monthly trends within the groups of dry STs for precipitation (rows 1 and 3) and temperature (rows 2 and 4) significant at the 70% (light colours) and 95% (dark colours). Precipitation: increasing trends in blue, decreasing trends in red. Temperature: increasing trends in red, decreasing trends in blue.

Figure 6. Monthly trend ratios for trends within the groups of wet STs for precipitation (rows 1 and 3) and temperature (rows 2 and 4).

Figure 7. Monthly trend ratios for trends within the groups of dry STs for precipitation (rows 1 and 3) and temperature (rows 2 and 4).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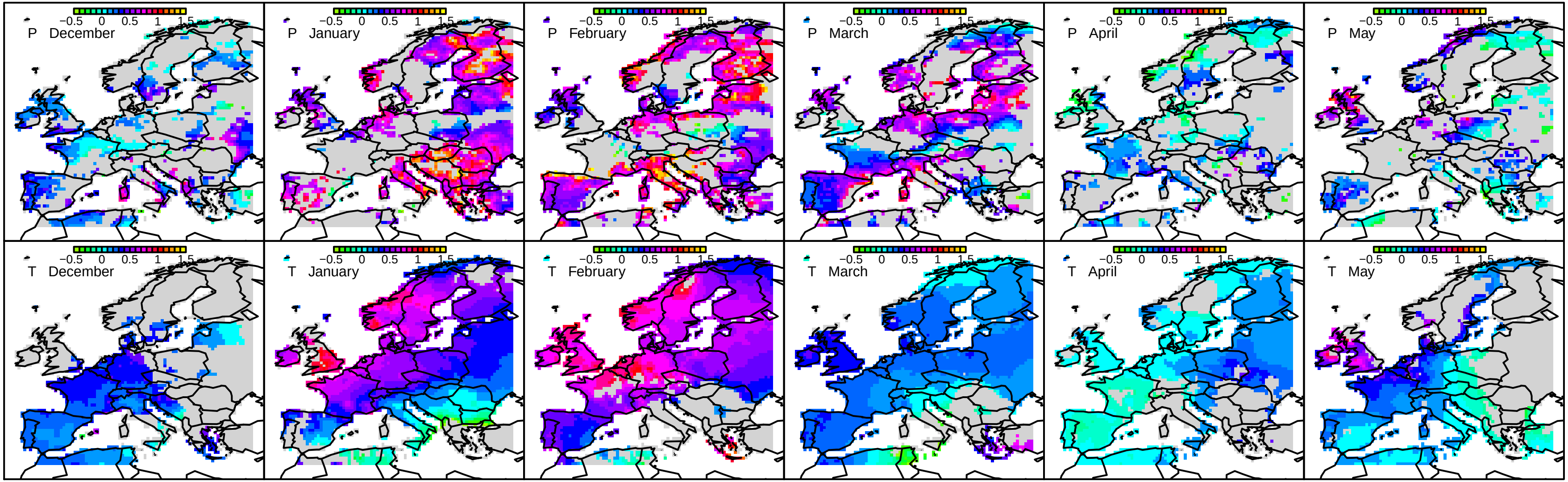

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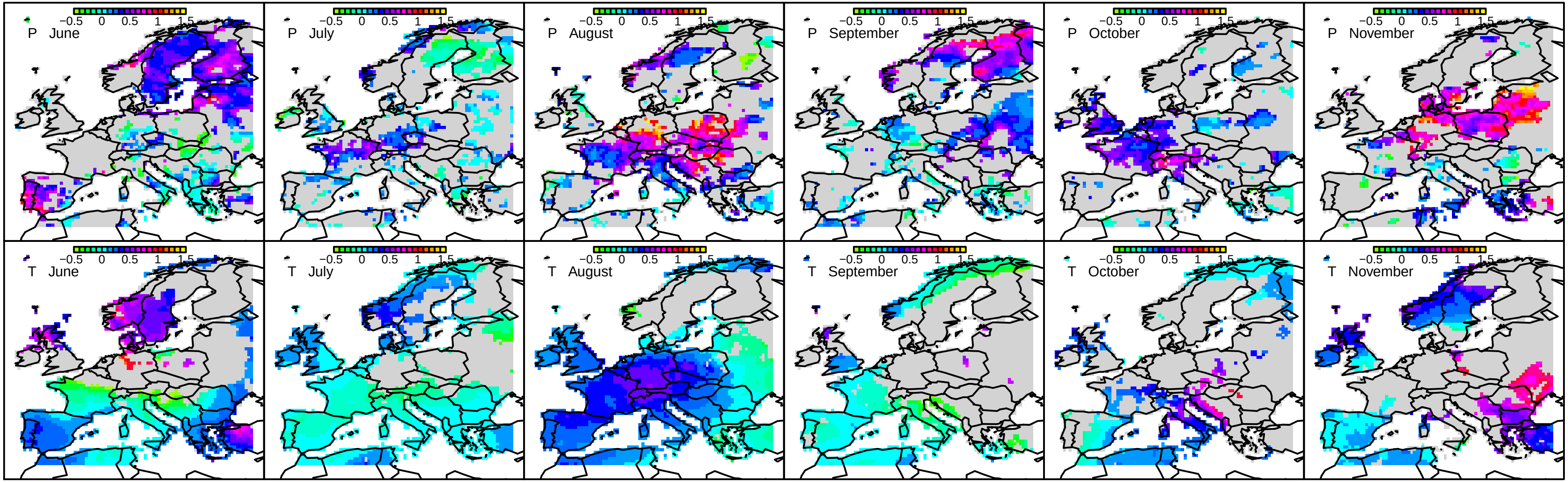

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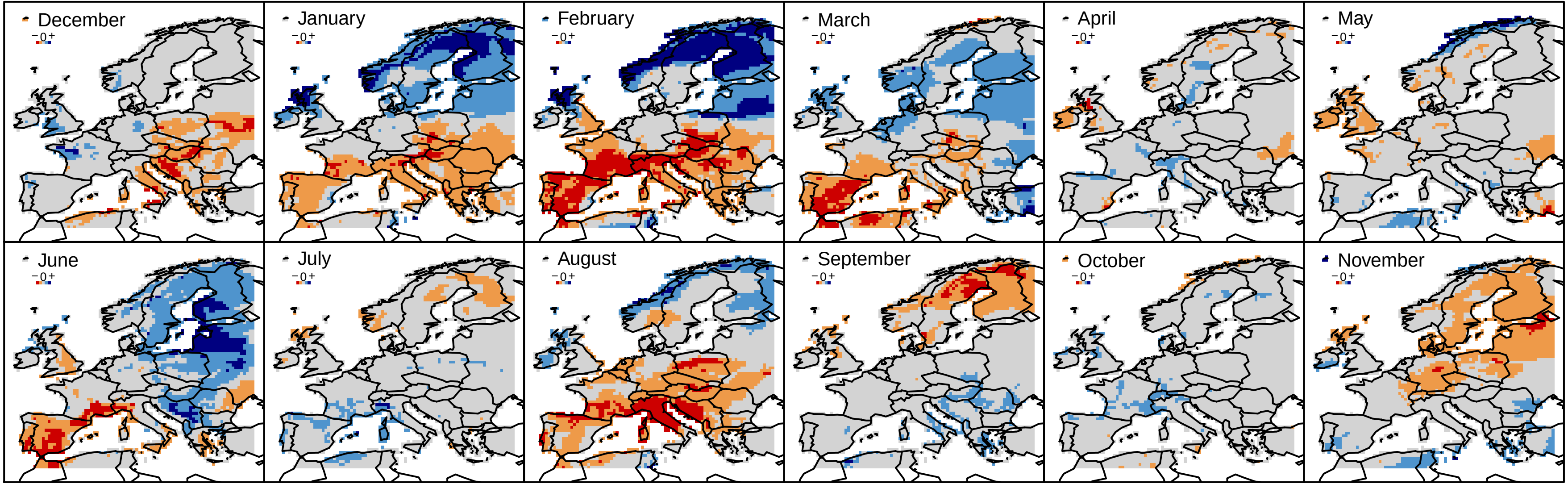
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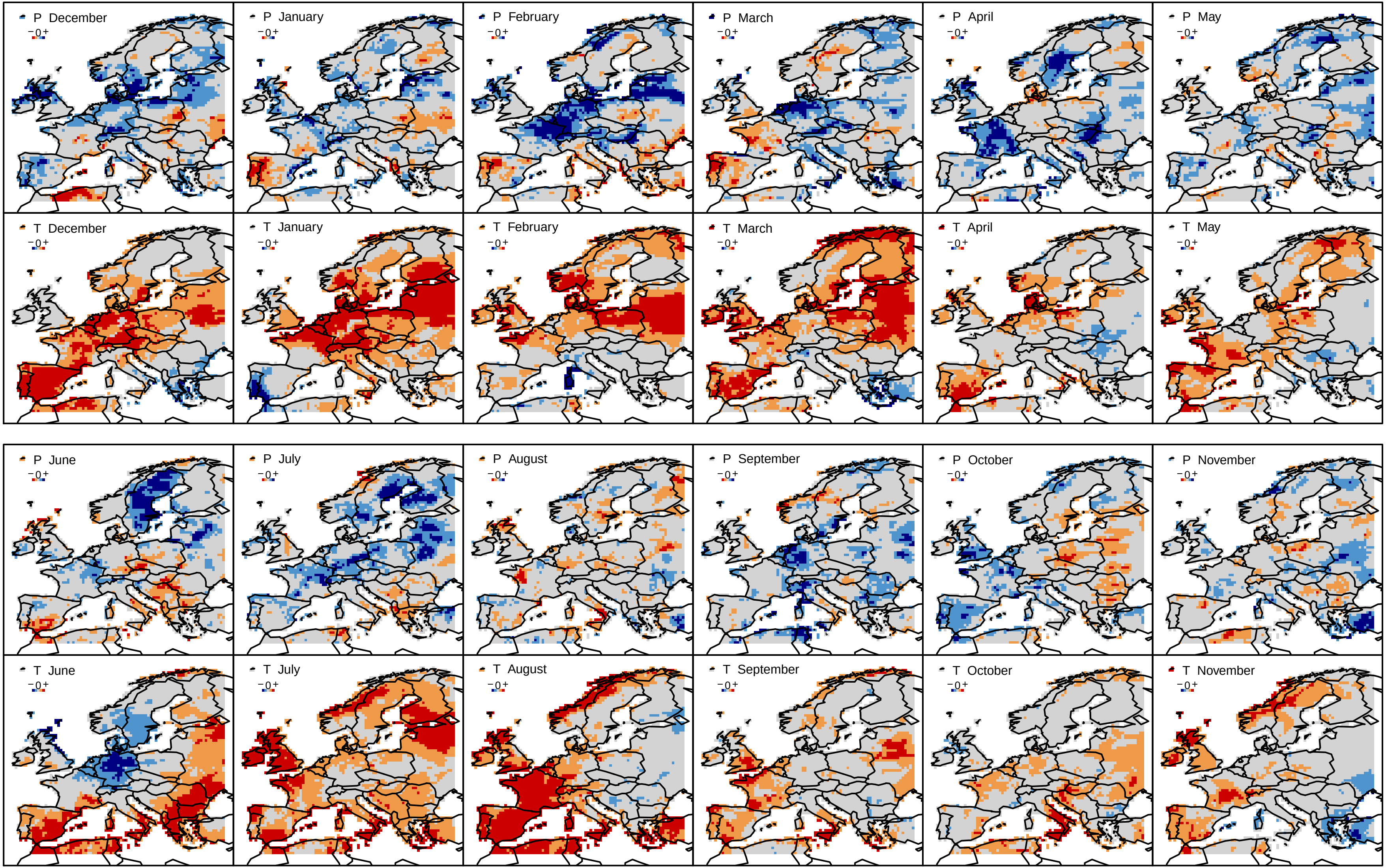
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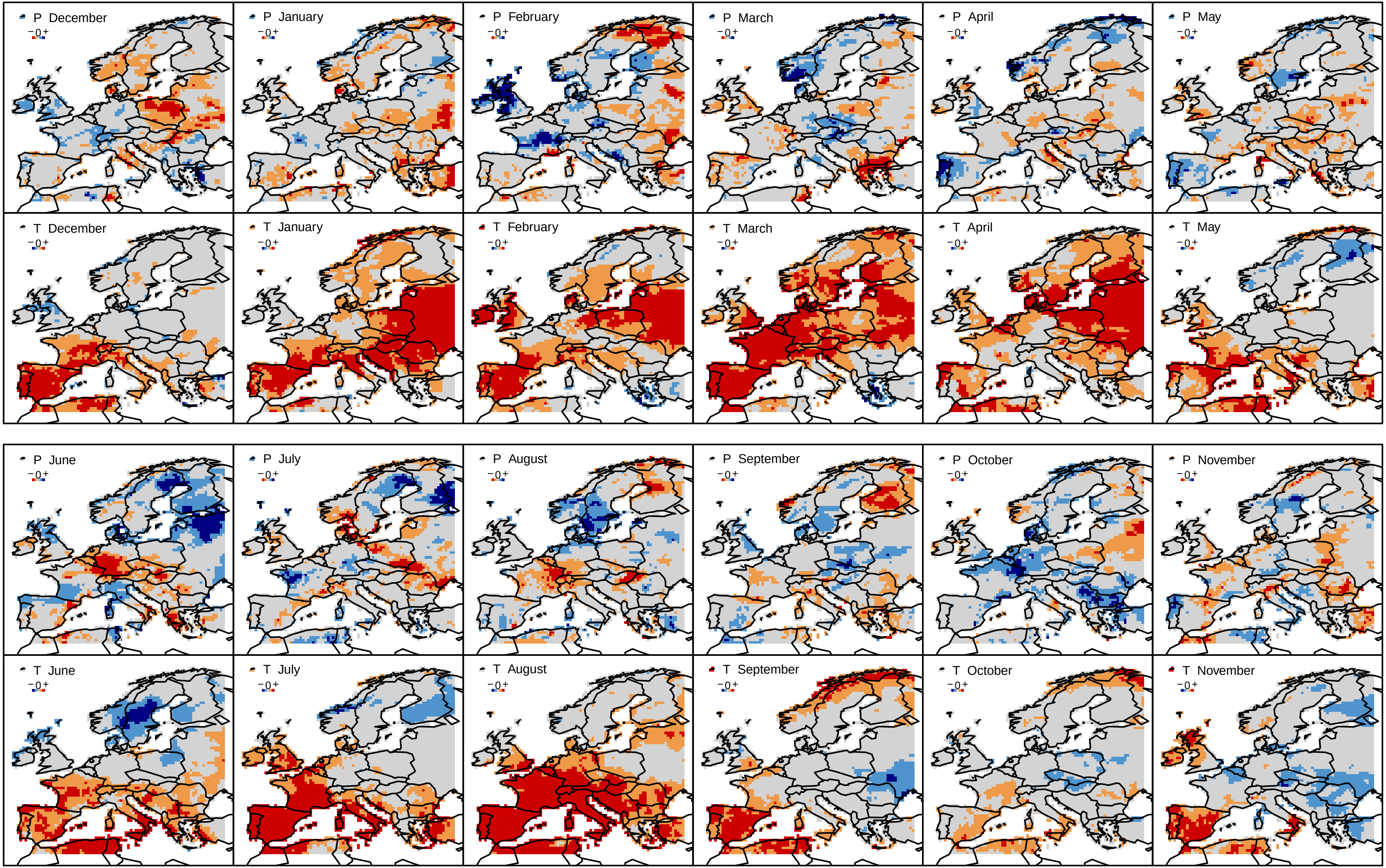
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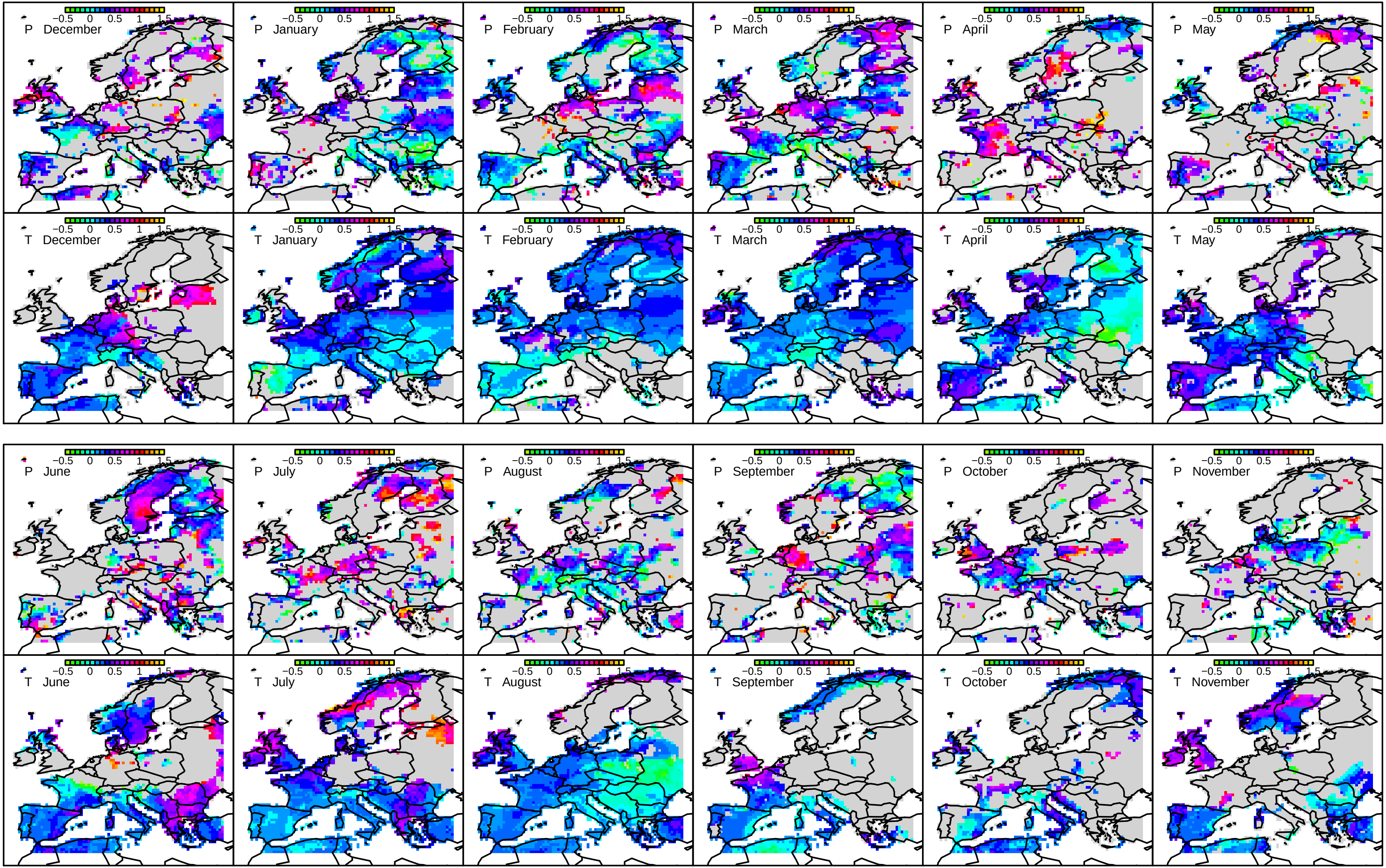
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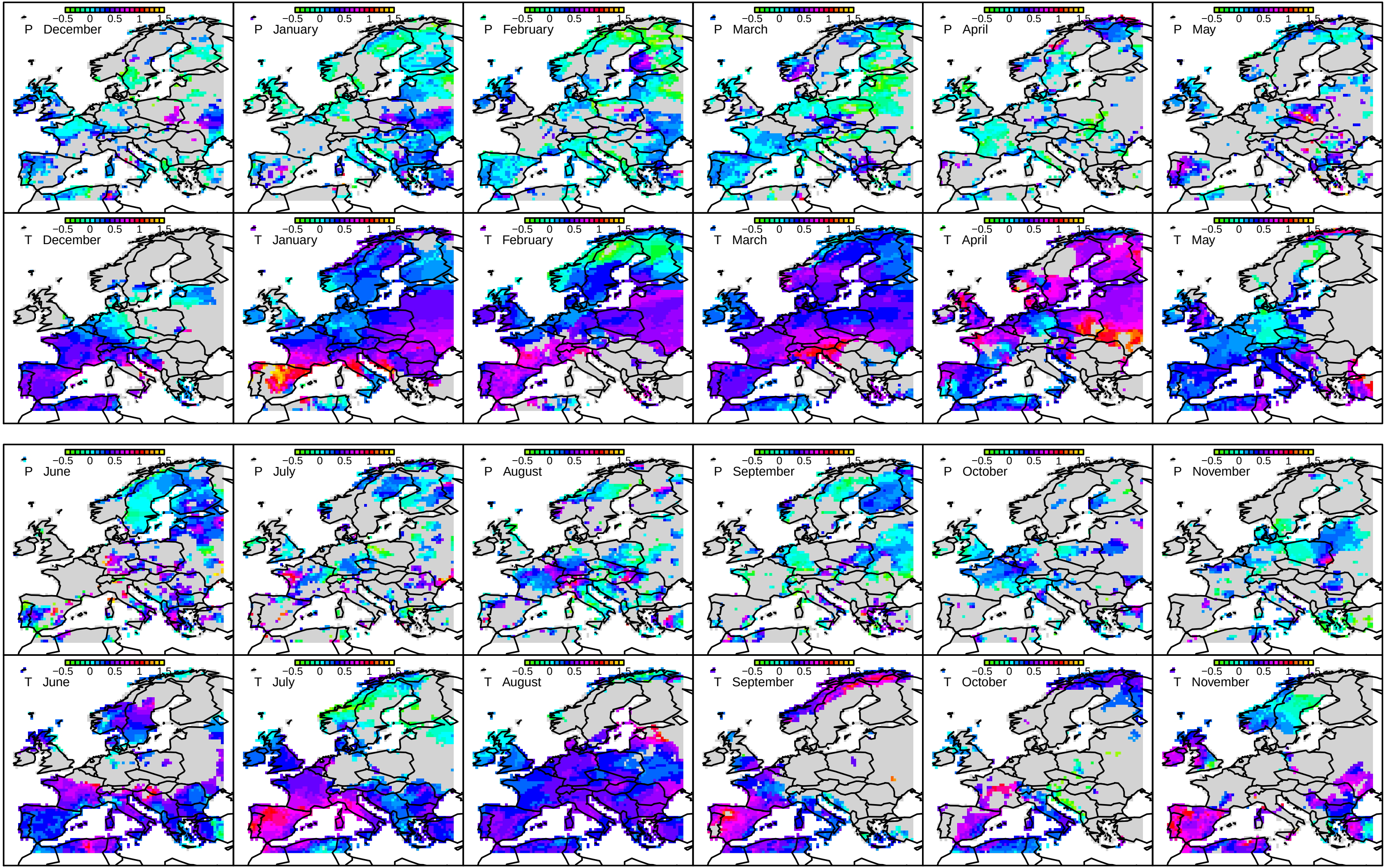
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