Recent trends in monthly temperature and precipitation patterns in Europe

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Abstract During past decades climate change has been documented through an observed global temperature increase and changed precipitation regimes. This study aims at detecting the most recent trends in monthly temperature and precipitation in Europe, and if possible, attributing these trends to changes in the frequency of circulation types. Building on previous work that covered only parts of Europe, this study covers all of Europe, using the Watch Forcing Data Interim re-analysis data (1979–2009). The SynopVis Grosswetterlagen (SVG) is used to define circulation types. The study shows that temperature trends in February can be attributed to changes in circulation, but in all other months, circulation changes cannot explain the trends. For precipitation the picture is unclear.

Key words trend detection; attribution; circulation types; Europe; temperature; precipitation

INTRODUCTION

During the temperature increase of the last decades, precipitation and runoff regimes have been altered. Spatial patterns in runoff trends in Europe are documented by Stahl *et al.* (2010), Wilson *et al.* (2010) and Alderlieste & van Lanen (2013), among others. Because runoff is highly influenced by temperature and precipitation, identifying and understanding regional patterns of precipitation and temperature trends would help us better understand runoff trends. Stahl *et al.* (2010) pointed out that stratifying trends into seasons and months might reveal a more detailed spatial pattern, because the observed changes are not equally distributed across all seasons. For instance, according to Cahynová & Huth (2010), the temperature increase in central Europe is more pronounced during winter, when strengthened westerlies lead to higher temperatures. Bárdossy & Caspary (1990) found that fewer easterly circulation types (CTs) between 1980 and 1989 led to warm and humid winters in central Europe.

A great effort has been made to link local climate to atmospheric circulation, either by developing a CT classification (Buishand & Brandsma, 1997; Beck *et al*., 2007; James, 2007), or by using (an) existing CT classification(s) (e.g. Cahynová & Huth, 2010; Fleig *et al.,* 2011). Several of these studies investigated whether observed changes in climate variables can be attributed to changes in CT frequencies or whether the hydrothermal properties of CTs are changing. This can be achieved by calculating the hypothetical trends in temperature and precipitation which would result as a consequence of observed trends in CT frequencies only. Some of the trends that cannot be attributed to changing CT frequencies may be attributed to changing hydrothermal properties of the CTs, so-called within-type changes. Downscaling methods assume stationarity between circulation and climate, but Beck *et al*. (2007) showed that the ratio of circulation changes to within-type changes varies with time. Cahynová & Huth (2010) compared 26 CT classifications covering the Czech Republic and found that observed temperature and precipitation trends can only partly be explained by circulation changes. They found that temperature trends in spring, summer and autumn are caused by within-type trends, whereas trends in winter are caused by hypothetical trends. Further, precipitation trends in all seasons are dominated by within-type trends.

Most trend studies cover only a few stations, a country, or a selection of grid cells across Europe. This study aims at detecting potential regional patterns in observed temperature and precipitation trends covering all of Europe, using an up-to-date record of gridded climate variables.

A second objective is to investigate to what degree such trends can be attributed to changes in CT frequencies. It complements the work of Fleig *et al.* (2014) by extending the study to the whole of Europe and by using a more recent dataset.

DATA AND METHODS

Climate data

Precipitation and air temperature originates from the Watch Forcing Data Interim (WFDEI), a gridded historical climate dataset based on ERA-Interim reanalysis with 0.5° × 0.5° resolution (Weedon *et al.*, 2011). The WFDEI consists of daily data from 1 January 1979 to 31 December 2009 (31 years). Temperature is bias corrected based on CRU-TS2.1 and precipitation corrected based on both CRU-TS2.1 and GPCCv4 observations (Weedon *et al.*, 2011). The study area covers 34°–72°N and 13°W–32°E. This results in a total of 3950 land cells with a half degree resolution, each land cell having a daily time series. Trends are calculated for monthly, seasonal (three months) and annual (12 months) time steps. The SynopVis Grosswetterlagen (James, pers. comm.), a further improvement of the objective version of the Hess-Brezowsky Grosswetterlagen by James (2007), was used as the daily CT catalogue.

Trend analysis methods

Two types of temperature and precipitation trends are calculated, similar to Fleig *et al.* (2014): modelled observed annual, seasonal and monthly trends (t_{obs}) and hypothetical monthly trends (t_{circ}; following Huth, 2001). Further, the ratio of hypothetical to observed trends (r_{circ}) is derived. Hypothetical temperature (precipitation) trends are calculated by constructing a hypothetical time series. This is the trend that would result if circulation changes were the only reason for the trends. For each calendar month and grid cell, the mean temperature (precipitation) is derived for each CT (T_{CT} and P_{CT}). In the resulting hypothetical series the observed daily temperature (precipitation) are replaced by the mean temperature, T_{CT}, (precipitation, P_{CT}) for that calendar month and cell, according to the observed CT on that day. A monthly hypothetical temperature (precipitation) series is derived from the daily one, and finally, the trend is calculated from the monthly hypothetical series. Hence, the hydrothermal properties of the CTs are held stationary throughout the study period and monthly trends in the hypothetical temperature (precipitation) series can be attributed to changes in monthly CT frequencies. A positive hypothetical trend for temperature (precipitation) means more frequent warm (wet) weather types.

The role of circulation changes is calculated as trend ratios, i.e. hypothetical trends divided by observed trends. Ratios close to 1 indicate that the hypothetical trends are similar to the observed trends and that the observed trends mainly can be attributed to circulation frequency changes. Here, trend ratios above 1.5 are not considered as high trend ratios are mostly caused by very small observed trends close to zero. To avoid unrealistic trend ratios, values above 1.5 are truncated. Values less than 0.5 indicate that the trends can not be explained by CT frequency changes.

Trend magnitudes for each time step are quantified using the Theil-Sen slope (Theil, 1950; Déry *et al.* 2005). The Theil-Sen slope (m) is estimated as the median of the linear slopes between all pairs of observations in the time series:

$$m = median\ \left[(y_i - y_j)/(t_i - t_j) \right] \quad (1)$$

Because the median is used instead of the mean, the method is robust against outliers.

Absolute annual trends for the whole period, in °C, are calculated for temperature (the slope m times the number of time steps, n). For precipitation, however, relative trends for the whole period, in %, (S) are calculated following Stahl *et al.* (2012):

$$S = \left(\frac{m \cdot n}{\bar{x}} \right) \cdot 100\% \quad (2)$$

where n is the number of time steps in the time series and $\bar{x}$ is the average of the climate variable.

RESULTS

In the following, the estimated trends of all seasons and months are summarised. In addition to the annual plots, plots are shown for February, the only month dominated by circulation changes.

Observed trends – t_{obs}

An unambiguous signal appeared in the observed annual temperature trends: all parts of Europe experienced warming, some cells up to 2.5°C, or 0.8°C/decade (Fig. 1(a)). Seasonally, a consistent warming was found for spring and summer in most grid cells. The strongest warming was found in Scandinavia in winter, whereas the south experienced no warming. In autumn, warming trends were lower and the Mediterranean experienced cooling.

Annual trends in precipitation were patchier than the temperature trends. Mainly, increasing precipitation was found in Norway, northern Finland, central Europe east of the Elbe River, and in Spain (Fig. 1(b)). Drying trends were found in central and southwestern Europe, and eastern parts of Scandinavia.

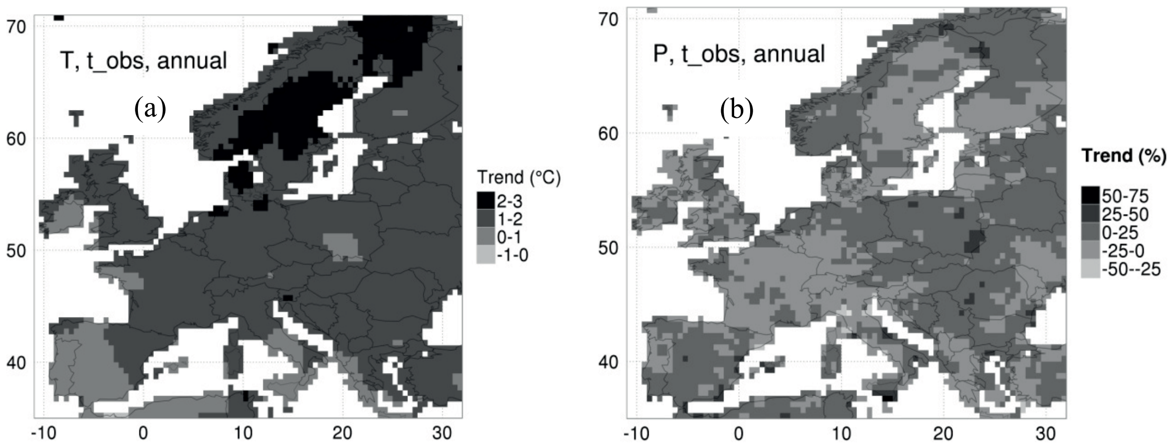

Fig. 1 Observed annual temperature (in °C) (a) and precipitation (%) (b) trends for the whole 31 year period. Note that the only negative annual temperatures are found in north Africa.

Seasonal trends for precipitation were also patchy (not shown). In winter, the strongest wetting trends were found in Scandinavia; in spring to the south and east of the Baltic Sea; and in summer, in Sicily and Denmark. In the Mediterranean area and regions east of Poland, drying trends were seen in summer. In autumn, strong wetting trends were found in the Mediterranean area and southeastern Europe, whereas marked drying was found in parts of northern Europe. The clearest regional pattern was seen in autumn, with marked wetting in southern Europe and drying in most of northern Europe.

Monthly temperature trends showed mostly warming across all months (Fig. 2(a) shows February, with the strongest trends of more than 4.5°C, or 1.5°C/decade, in Sweden). May showed cooling in the Baltic, September in southern Europe, and December revealed minor cooling in all areas except north and east of the Baltic Sea. The Scandinavian Peninsula was the only region not experiencing cooling in any month. A north–south pattern was seen in September and December, where Scandinavia and the Baltic warmed while the rest of Europe cooled or experienced no warming. The pattern was reversed in May, when cooling was found in the Baltic, Scandinavia experienced no trends, and southwestern Europe warmed.

The regional pattern in monthly precipitation trends varied from month to month. In general, all precipitation trends were patchy (Fig. 2(b)), but a regional signal could be seen in some months. In February, and to some extent in January and May, wetting trends were restricted to the area north of the Alps, and drying trends south of the Alps. In September and December the pattern was the opposite, with drying north of the Alps and wetting in the south.

Hypothetical trends – t_{circ}

Monthly hypothetical temperature trends based on circulation type frequency resembled the observed trends, but displayed more negative trends. Strong negative hypothetical trends were present in March, May, July, September, October and December. The strongest negative trends were found where the observed trend was close to zero. A clear north–south pattern was visible in some months, especially March, May, and October (negative trends in the north and positive in the south-west), and February (Fig. 2(c)), September and December (positive trends in the north and negative in the south).

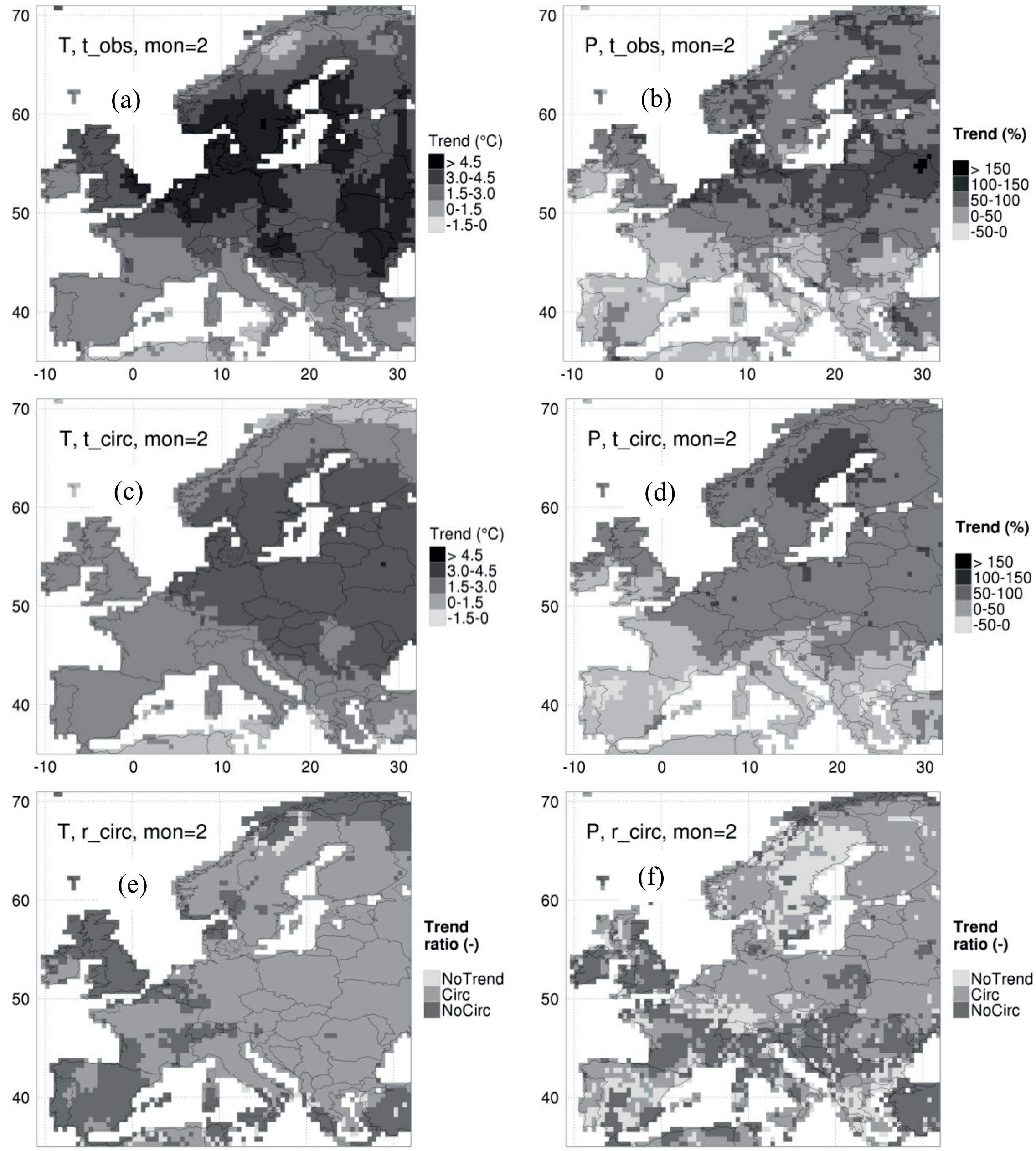

Fig. 2 Trends in February temperature (left column) and precipitation (right column). Observed absolute monthly temperature trends (in °C) are shown in (a), observed relative trend in precipitation in (b), hypothetical absolute temperature trends in (c), hypothetical relative precipitation trends in (d), trend ratios for temperature in (e) and trend ratios for precipitation in (f). Trend ratios of >1.5 (due to minor trends in observations) are shown in light grey and trend ratios < 0.5 are shown in dark grey.

The hypothetical precipitation trends resembled those of the observed precipitation trends, but displayed a clearer regional pattern and were weaker. In January and February, clear positive trends were found in the north and negative trends in the south (Fig. 2(d)). This pattern was reversed in September and December except the other northernmost parts of Scandinavia, which also showed a wetting trend.

Trend ratios – r_{circ}

For temperature, trend ratios between 0.5 and 1.5 were found in limited, but distinct, areas for each month. However, in most parts of Europe trend ratios were below 0.5, which means that the proportion of circulation-induced temperature trends was small compared to the observed temperature trends. The areas with a higher proportion of circulation induced temperature trends varied from month to month. February was the only month where more than half of Europe experienced trend ratios close to one (Fig. 2(e)). In all other months, circulation changes could not explain the observed trend.

Precipitation trend ratios between 0.5 and 1.5 were patchy in all months and did not clearly reveal distinct areas caused by circulation changes. Furthermore, many trend ratios exceeded 1.5, resulting from dividing by observed trends close to zero. Circulation-induced changes were most important in northern and eastern Europe in February. In other months, circulation-induced trends were not absent, but most observed trends could not be attributed to circulation changes. In February, all of northeastern Europe showed trend ratios near one (Fig. 2(f)), and also July in western and central Europe, in September in the Baltic region and in December in the Baltic region and most of central Europe (not shown).

DISCUSSION

This study revealed clear regional patterns in observed temperature and precipitation trends between 1979 and 2009. All of Europe experienced increasing temperatures, annually up to 0.8°C/decade (Fig. 1(a)) and for February, 1.5°C/decade. Klein Tank *et al.* (2002) report annual trends in Europe for the time period 1976–1999 of 0.1–0.3°C/decade and winter trends up to 3°C/decade (Klein Tank *et al.*, 2005). Our annual values are higher. Increasing annual precipitation was found in the northernmost countries and mountainous areas, except the Alps. Drying trends were found in central Europe and eastern Scandinavia. The precipitation trends do not resemble the results of Alderlieste & van Lanen (2013). They analysed a re-analysis data set ranging from 1963–2001 (WFD) and found annual wetting trends over Germany and strong drying trends in Portugal. The Portuguese drying trends in our study were not as strong as the trends they found. Also, trend directions over Germany deviated. Previous studies have shown high sensitivity to the time period (e.g. Hannaford *et al.*, 2013), which likely explain the differences found.

When separated into seasons or months, the trend patterns vary from month to month, revealing details that are not visible in the annual trend patterns, as suggested by Stahl *et al.* (2010). September and December stand out as months where observed trends differ from the rest of the year, i.e. with drying north of the Alps and wetting in the south; and cooling instead of warming in the south. Cahynová & Huth (2010) also found a cooling trend and increased cloudiness in the Czech Republic during autumn.

Positive hypothetical trends (t_{circ}) might represent either more frequent cold/dry CTs or less frequent warm/wet CTs. Trend ratios (r_{circ}) are used to determine if hypothetical trends are similar to observed trends. For temperature, circulation changes are only important in February in the northeastern parts of Europe. This is in agreement with Cahynová & Huth (2010) who found that in the Czech Republic hypothetical trends were only important for temperature in winter. Further, we found that circulation changes are also important for precipitation in northern Europe in February and December. In other months, circulation changes were less important. Overall, the ratio of hypothetical trends to observed trends showed a high spatial variability. Precipitation trends were especially patchy, which is likely caused by a combination of weak climate signals and uncertainties related to the data and methodology applied.

CONCLUSIONS

This study aimed at exploring regional patterns in temperature and precipitation trends in Europe and to attribute those changes to circulation changes wherever possible. The main findings include:

(a) The northern part of Europe experienced the strongest warming trends on the annual time scale, as well as in January and December. In May, the pattern was opposite, as southwestern Europe experienced stronger warming than the northeast.

(b) A regional signal in observed wetting trends was visible in February (drying around the Mediterranean, wetting in other regions), and September and December (wetting around the Mediterranean, drying in other regions).

(c) Hypothetical temperature trends were strongest in winter (eastern Europe in February). The north–south pattern was much clearer in the hypothetical trends than in the observed trends, and negative trends were present in more months than for the observed trends.

(d) Hypothetical precipitation trends were less patchy that observed trends, and a clearer regional pattern was present in all months. Hypothetical trends were weaker than observed trends.

(e) Temperature trends could only be attributed to circulation changes in February.

(f) For precipitation, circulation changes were important in northern Europe in February and December. They could also explain wetting trends in northwestern Europe in July and in the Baltic area in September. However, patchy trends made it hard to find clear regional patterns.

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