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Control of recent European surface climate change by atmospheric flow

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[1] Many changes in European surface climate have occurred over the past decades, but most of the processes driving them are not identified. In particular, the role of atmospheric flow in driving surface trends needs to be evaluated to better predict future regional climate. We compare observed surface climate trends with those constructed from daily flow analogues. We find that during the last 60 years atmospheric circulation changes are the main drivers of surface weather trends in winter, but not in summer where temperature strongly interacts with the water cycle. For instance, increasing anticyclonic conditions control the decreasing summer rainfall frequency, but rainfall amount and cloud cover have not decreased accordingly, because individual rainfall events bring more rain now than decades ago. Over the past three decades the control by atmospheric flow changes has weakened, indicating evolutions in the processes steering European surface climate change. **Citation:** Vautard, R., and P. Yiou (2009), Control of recent European surface climate change by atmospheric flow, *Geophys. Res. Lett.*, 36, L22702, doi:10.1029/2009GL040480.

1. Introduction

[2] The detection of regional climate trends has received a growing interest in recent years. Over the North Atlantic region, the increase in the positive phase of the North Atlantic Oscillation (NAO) during the 1990s [Hurrell *et al.*, 2004] induced more anticyclonic weather over Southern and Central Europe and increased south-westerlies associated with mild weather in Northern Europe. Over European land areas, trends in the statistics of surface temperatures and their extremes have been detected [Klein-Tank and Können, 2003; Moberg and Jones, 2005], with a high warming rate of 0.5°C/decade over the past 30 years [van Oldenborgh *et al.*, 2009; Xoplaki *et al.*, 2005]. Precipitation generally increased in Northern Europe and decreased in Mediterranean regions [Solomon *et al.*, 2007]. Surface solar radiation [Norris and Wild, 2007], sunshine duration [Sanchez-Lorenzo *et al.*, 2008], aerosol optical depth, cloud cover [Ruckstuhl *et al.*, 2008] horizontal visibility [Vautard *et al.*, 2009] all indicate increasing incoming energy during the past three decades.

[3] However physical and functional links between these trends in European recent climate still need to be identified and understood, which is made difficult because climate models often fail to quantify important factors of regional forcing especially for extremes [van Oldenborgh *et al.*,

2009]. As several recent studies focused on regional radiative forcing, this study addresses the extent of the control of regional European surface weather trends by solely upper-air dynamical flow changes. In a pioneering observational study it was suggested that observed surface changes could result from a progressively changing balance between the frequencies of occurrence of different flow patterns or “weather regimes” [Reinhold and Pierrehumbert, 1982]. Such a theoretical scenario for climate change is compatible with changes in temperature extremes frequency [Nogaj *et al.*, 2006] and duration [Della-Marta *et al.*, 2007], which are more robust than changes in their amplitude. However recent extreme events, such as the 2003 summer heat wave [Beniston, 2004; Schär *et al.*, 2004] had no temperature analogues. The long-lasting temperature anomaly of fall-winter 2006–2007 in Europe was also unprecedented [Luterbacher *et al.*, 2007; van Oldenborgh, 2007; Yiou *et al.*, 2007], and the atmospheric flow explains only about half of the temperature anomaly [Cattiaux *et al.*, 2009].

[4] The control of surface climate change by atmospheric flow is also a relevant issue for future local climate projections and impacts, because small-scale climate projections are often based on statistical downscaling approaches [Zorita *et al.*, 1995] based on large-scale predictors such as atmospheric flow, even though more predictors than flow alone generally provide better downscaling estimations [Charles *et al.*, 1999; Xoplaki *et al.*, 2004].

2. Data and Methods

[5] Surface weather observations are taken from the European Climate Assessment and Dataset (ECA&D [Klein-Tank *et al.*, 2002]). We study daily maximal temperatures (T_{\max}), daily precipitation amounts, cloud cover and sunshine duration coming from blended data sets. We used the data quality index provided with the data and removed data flagged as suspicious. The 60-year period 1948–2007 is considered in this article. Stations where more than 10% of the data were missing are removed. In order to have a spatially homogeneous coverage of the domain, we retained only one station, if any, per grid-cell of $0.75^\circ \times 0.5^\circ$. For temperature and precipitation, the retained data have a large spatial coverage over Europe, with 152 stations for T_{\max} , and 155 for precipitation. Only 40 stations were retained for cloud cover and 39 for sunshine duration, and spatial coverage is limited. The seasonal cycle is calculated as a running 10-day average centred about the calendar day and removed, so that only anomalies relative to the 60-year mean seasonal cycle are considered. In addition to daily precipitation amount, we also considered *rainfall frequency*, i.e., the number of rainfall events (daily precipitation

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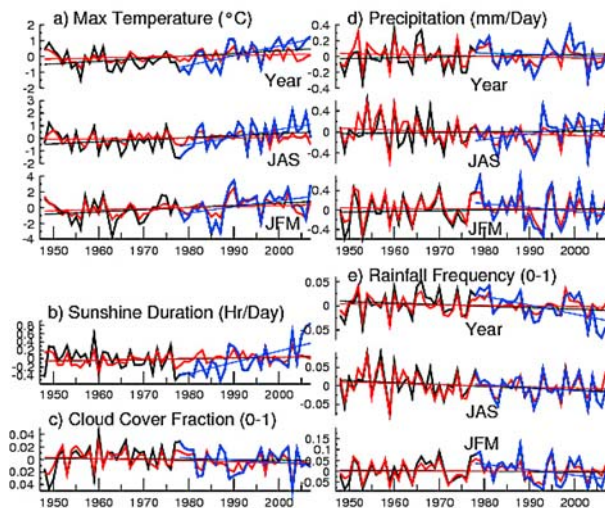


Figure 1. Time evolution of the annual or seasonal average, over all available European stations, of observed (black curves for the earliest 30 years and blue curves for the latest 30 years) or constructed (red curve) anomalies, together with linear regression lines; (a) maximal temperature ($^{\circ}\text{C}$) for (top) annual average, (middle) summer (JAS) average, and (bottom) winter average; (b) sunshine duration (h/day); (c) cloud cover (0–1 fraction); (d) as in Figure 1a for precipitation amounts (mm/day); (e) as in Figure 1a for rainfall frequency (0–1 fraction).

amount above 0.5 mm) divided by the number of days considered.

[6] We use a statistical methodology based on circulation analogues [Lorenz, 1969] to link instantaneous tropospheric flow, given by the 500 hPa geopotential heights over a North-Atlantic domain with surface weather [Martin *et al.*, 1996; You *et al.*, 2008; Zorita and von Storch, 1999], described by surface observations over the past 60 years as given by the ECA&D set [Klein-Tank *et al.*, 2002]. In theory, if we assume that surface weather trends were only driven by changes in atmospheric circulation, equivalent trends should be found by replacing observed daily surface parameters by those taken at the date of analogue flows in other years. The use of the comparison of surface observations with data obtained from a modelling approach (here statistical modelling) in order to explain trends is standard in climate science, although with various degrees of sophistication [Solomon *et al.*, 2007].

[7] In order to characterize Euro-Atlantic atmospheric circulations, 500 hPa geopotential heights (Z_{500}) from the National Centers for Environmental Prediction (NCEP) reanalysis [Kalnay *et al.*, 1996] for the 1948–2007 period and over the (80W–50E; 25N–70N) domain are considered. For each grid point of the reanalysis dataset, the daily seasonal cycle is computed by averaging over calendar days, and smoothing with a spline function. This average seasonal cycle is removed from the Z_{500} data to obtain the geopotential height anomalies.

[8] For each day d of the 60-year period, we determine the best 10 anomaly circulation analogues $Z_{d1}, Z_{d2}, \dots, Z_{d10}$ that occur within 15 days (before or after) of the same calendar day, but not in the same year. We verified, by

extending this period to 30 days or taking 20 analogues, that our results are insensitive to the period length and number of analogues. The metric used to quantify analogy is the Pearson rank correlation (rather than linear correlation). This choice is motivated by the fact that rank correlation is more robust to local outliers that can deteriorate linear correlation; hence we expect analogues to better capture the large-scale structures.

[9] The time-averaged correlation ranges from 0.74 for the best analogue to 0.64 for the 10th best one. We verified that the analogue dates are distributed uniformly along the whole historical archive, so that possible trends in reconstructed surface variables are not due to trends in the atmospheric circulation (not shown).

[10] We compare time series of seasonal or annual means of several surface weather parameter p , at individual sites or on average over all selected sites, with equivalent constructed analogue seasonal or annual temperature time series, obtained by averaging the 10 best “flow-analogue” parameter values $p_{d1}, p_{d2}, \dots, p_{d10}$, or by simply taking the best analogue case p_{d1} .

3. Results

[11] Flow analogues provide a relatively skillful prediction of European surface temperature interannual variability (Figure 1), with linear correlation coefficients for maximal temperature (T_{\max}) $r \geq 0.55$, with a maximum of 0.85 in winter, as found in previous studies [Osborn *et al.*, 1999]. The skill is poorer in summer, presumably because other processes than circulation, such as soil moisture [Fischer *et al.*, 2007] are alternative key drivers or amplifiers. In winter, the long-term (1948–2007) observed trend of T_{\max} is twice the flow-analogue constructed trend, consistent with previous results [van Oldenborgh *et al.*, 2009]. However the large increase of the T_{\max} trend in the last half of the period (1978–2007: 0.6–0.8 $^{\circ}\text{C}/\text{decade}$) is not captured by analogues (Table 1 and Figure 1). This increasing warming rate could partly come from the increase in solar radiation, the so-called “brightening” effect due to decreasing aerosol load, hazy and foggy weather [Philipona *et al.*, 2009]. In summer the flow control of temperatures is weaker as the constructed trend is four times smaller than the observed one.

[12] In summer, observed T_{\max} trends are maximal over North-Western Europe (Figure 2). This pattern is also found in constructed trends, with smaller amplitude. The similarity is less marked in winter, since observed trends are largest from Germany to Eastern Europe, Balkans and Ukraine, while constructed trends are largest in Germany and further North around the Baltic Sea. The clue to the inconsistency between the large observed wintertime trend and the weak flow influence in Eastern Europe may be the decline of haze, because it is the European area where its effect on temperature was shown to be maximal [Vautard *et al.*, 2009], as a probable result of sulphur dioxide emission control since the eighties, together with the decline of economy in eastern countries. But continental areas also undergo several surface-atmosphere processes and feedbacks that could additionally contribute and hinder the direct flow change responses, such as those associated with snow-cover changes [Bednorz and Kossowski, 2004].

Table 1. Correlations Between Observed and Constructed Annual or Seasonal Average Over European Stations and Trends Calculated Over 60 Years for Observed Series or Constructed Series or Calculated Over the Latest 30 Years^a

Variable	r 1948–2007	Observed Trend 1948–2007	Constructed Trend 1948–2007	Constructed Trend 1948–2007 a/b/c/d	Observed Trend 1978–2007	Constructed Trend 1978–2007
Tmin °C/decade						
Year	0.65	0.22	0.04	0.04/0.03/0.03/0.04	0.57	0.01
JAS	0.55	0.20	0.00	0.01/0.00/0.02/0.01	0.54	0.00
JFM	0.85	0.34	0.13	0.13/0.13/0.13/0.13	0.69	0.09
Tmax °C/decade						
Year	0.74	0.17	0.05	0.06/0.06/0.04/0.06	0.62	0.02
JAS	0.76	0.16	0.03	0.04/0.03/0.01/0.04	0.60	0.01
JFM	0.90	0.27	0.13	0.12/0.13/0.13/0.13	0.77	0.15
Rainfall Amount						
Year	0.78	0.010	−0.011	−0.014/−0.013/−0.009/−0.012	−0.018	−0.020
JAS	0.78	0.009	−0.025	−0.029/− 0.028 /− 0.025 /− 0.023	0.111	0.037
JFM	0.92	0.012	−0.006	−0.003/−0.002/0.000/−0.001	−0.081	−0.065
Rainfall frequency						
Year	0.79	−0.32	−0.11	−0.16/−0.14/−0.08/−0.15	− 1.84	−0.34
JAS	0.86	− 0.50	−0.33	− 0.44 /−0.36/− 0.38 /− 0.50	−0.82	−0.10
JFM	0.90	−0.17	0.02	0.04/0.06/0.15/−0.03	− 2.50	−0.85
Sunshine duration						
Year	0.45	0.018	0.019	0.020/0.022 0.013/ 0.019	0.267	0.026
JAS	0.59	0.015	0.037	0.046/0.034/0.029/0.034	0.201	−0.018
JFM	0.74	0.027	0.010	0.005/0.010/0.006/0.012	0.320	0.084
Cloud cover %/decade						
Year	0.84	−0.07	− 0.14	− 0.18 /− 0.17 /− 0.09/− 0.15	−0.36	−0.24
JAS	0.79	0.17	−0.20	−0.30/−0.20/−0.18/0.20	0.29	−0.01
JFM	0.83	−0.18	−0.17	−0.16/−0.18/−0.07/−0.16	−0.84	−0.72

^aCorrelations (3rd column) between observed and constructed annual or seasonal average over European stations, and trends calculated over 60 years for observed series (4th column) or constructed series (5th column), or calculated over the latest 30 years (7th and 8th columns). The 6th column contains trends obtained using the best analogue in the construction process instead of the best 10 analogues (a), a smaller and eastward shifted domain for the characterization of atmospheric flows (b), the 700 hPa wind for calculating flow analogues (c), and the Euclidian distance of 500 hPa height maps for analogues calculations (d). Variables and units are given in the first column. Correlations larger than 0.8 and trend values significant to the 95% level ($p < 0.05$) stand in boldface characters.

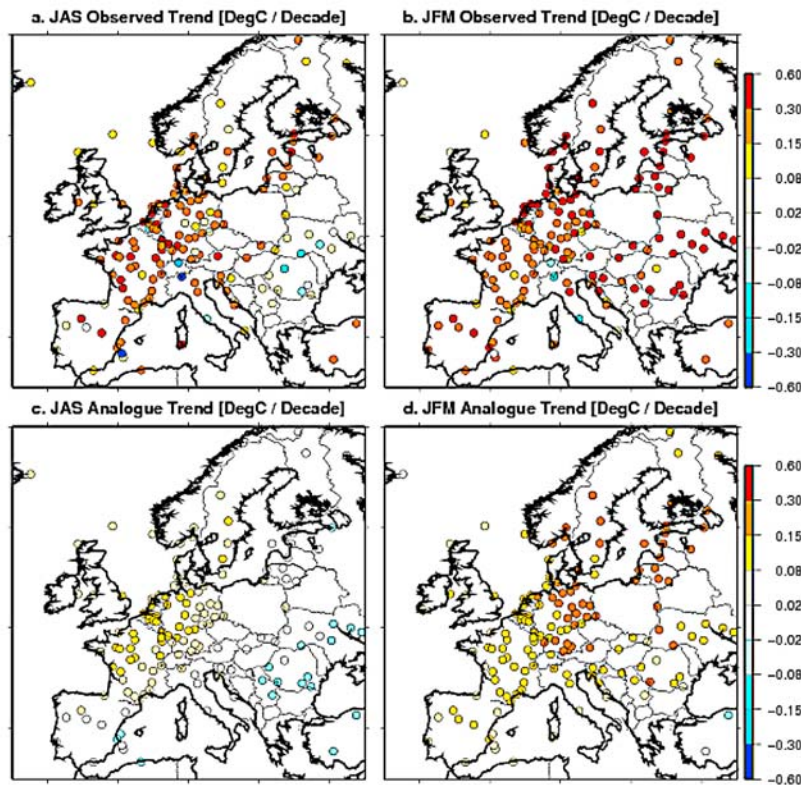


Figure 2. Spatial distribution of 60-year daily maximal temperature trends throughout the European domain used, for (left) summer means and (right) winter means, and (top) for observed series and (bottom) for constructed series. Trends are in °C/decade.

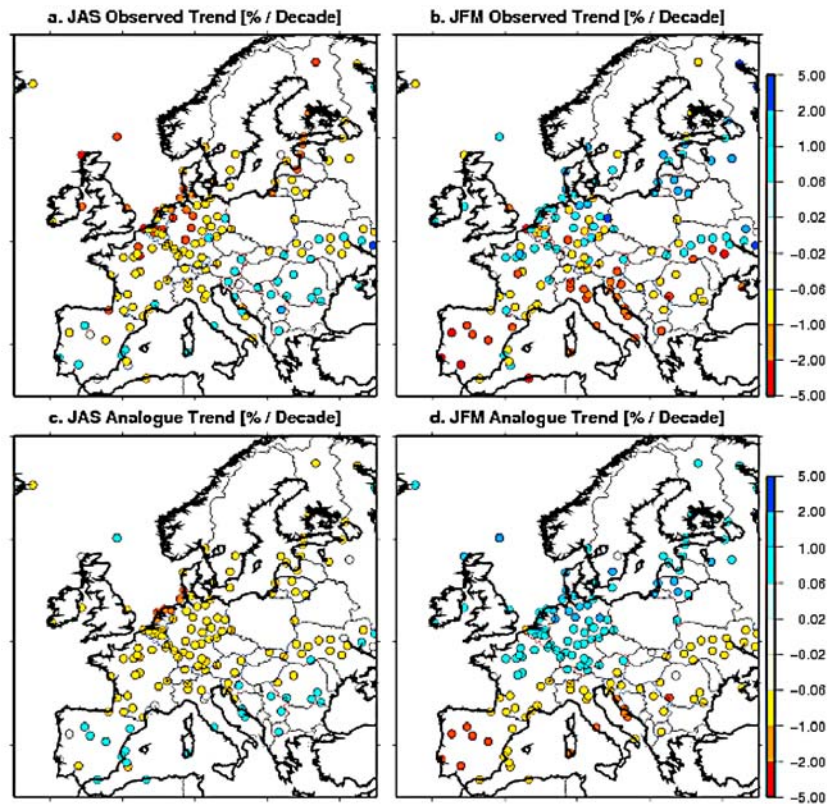


Figure 3. Spatial distribution of 60-year rainfall frequency trends throughout the European domain used, for (left) summer means and (right) winter means, and (top) for observed series and (bottom) for constructed series. Trends are in %/decade. Positive values are in blue and negative values are in red.

[13] Minimal temperatures have similar trends as maximal temperatures in amplitude and space, winter and annual averages only having significant constructed trends of the same amplitude as for maximal temperatures.

[14] The variability of rainfall variables is well predicted by Euro-Atlantic flow on interannual scale (Figures 1d and 1e) since the mean correlation r between observed and constructed trends exceeds 0.78 for amounts, and 0.8 for frequency (Table 1). The highest correlations are obtained in winter ($r \geq 0.9$). This was already noticed for a smaller domain using several statistical downscaling approaches [Boé and Terray, 2008; Zorita and von Storch, 1999].

[15] Observed rainfall amounts show no significant trends over the last 60-year period, but during the last 30 years they significantly increased in summer (Table 1), at odds with the absence of significant positive trend in flow-analogue reconstructions, due to increasing European anticyclonic weather. Observed and constructed trends in rainfall frequency are more coherent. This shows that the amount of rain per precipitation event is increasing in summer, compensating the atmospheric flow changes influence inducing less rainfall events.

[16] The similarity, both in amplitude and in spatial distributions (Figure 3) of observed and constructed rainfall frequency trends further confirms the control by the atmospheric flow in all seasons. In summer the reduction in precipitation frequency is general in Europe except in Mediterranean areas where the tendency is slightly reversed.

In winter, the marked sea-saw between more frequent rainfall in Northern Europe and less frequent rainfall in Southern areas is found both in observed and constructed trends. For rainfall amounts (not shown), the trend distribution similarity only holds for winter. In summer flow changes induce less rain everywhere but in Mediterranean areas while observed trends are only clearly negative around the North Sea. Precipitation amounts appear therefore driven both by changes in atmospheric flow and by an increase of rain yield per event, which is most probably characteristic of changes in convective rainfall.

[17] The driving nature of atmospheric flow for sunshine duration is more difficult to depict. Increasing anticyclonic weather over Europe induces significantly positive constructed trends in sunshine duration, which are larger in summer and smaller in winter than observed ones. This behaviour presumably results from the combined action of several drivers: flow changes, cloud changes and aerosol dimming and brightening effects.

[18] The control of interannual variability of cloud cover by large-scale flow is also dominant since constructed cloud cover annual or seasonal means correlate well with their observed counterparts ($r = 0.79$ in summer and $r = 0.83$ in winter). Observed trends are slightly positive in summer and slightly negative in winter, albeit small, while constructed trends are negative in both seasons due to anticyclonic tendency (Table 1). The similarity of trends in winter, both along the 60-year period and the latest 30-year period

indicate a control by atmospheric flow only. The summertime dissimilarity, like for rainfall amount, indicates superimposition of changes due to flow and other changes in cloudiness.

4. Conclusion and Discussion

[19] From our analysis, we conclude that the control of surface weather changes by Euro-Atlantic large-scale circulation changes is large in the winter season, but not in summer. Wintertime rainfall and cloud cover interannual variability and trends (amount and frequency) are well reproduced by flow-analogue time series while the control is only partial for temperature, for which eastern Atlantic sea-surface temperature trend also has a significant contribution [Cattiaux *et al.*, 2009], as well as other processes like aerosols and snow cover. In summer, atmospheric flow changes are not the leading drivers of surface weather trends, except for rainfall frequency. Rainfall amount and cloud cover undergo other driving processes in the rainfall and cloudiness nature. The fact that rainfall amount is not declining as predicted by more anticyclonic weather indicates increasing amounts of rain per rainfall event, a possible consequence of warming.

[20] The caveat of our approach is that finding quasi-identical flow configurations in meteorological archives over a region like the Euro-Atlantic domain depends on subjective factors [Lorenz, 1969; Zorita *et al.*, 1995]. We verified that our results are insensitive to the number of analogues (10 or 20) and the type of correlation (Pearson vs. Spearman). Table 1 also contains similar results obtained using the more classical Euclidean distance. We then tested the method on a smaller domain, shifted eastward, and found similar results (Table 1). Finally we also tested the use of a different predictor to characterize flow: winds (zonal and meridian) at 700 hPa. From Table 1 it is clear that the change of predictor does not qualitatively alter the trends found using altitude of the 500 hPa surface. Those sensitivity experiments suggest that the results are quite robust and consistent with respect to subjective choices of analysis parameters.

[21] Another conclusion is that an acceleration of the trends discussed here has taken place in the latest half of the record, i.e., during the past three decades (see Table 1 and Figure 1). For most variables observed and constructed trends have a larger difference than when considered over the whole record, indicating an evolution to less atmospheric flow control. Extrapolating this late behaviour, it is not clear whether the atmospheric flow control discussed here will still apply in the next decades, and it is expected that its influence will weaken.

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