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Inconsistency between atmospheric dynamics and temperatures during the exceptional 2006/2007 fall/winter and recent warming in Europe

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[1] Europe witnessed unprecedented warmth persisting throughout fall and winter 2006–2007, with only a few cold breaks. Whether this anomaly and recent warming in Europe can be linked to changes in atmospheric dynamics is a key question in the climate change prospective. We show that despite the fall/winter atmospheric flow was favorable to warmth, it cannot explain alone such an exceptional anomaly. Observed temperatures remained well above those found for analogue atmospheric circulations in other fall and winter seasons. Such an offset is also found during the last decade and culminates in 2006/2007. These observational results suggest that the main drivers of recent European warming are not changes in regional atmospheric flow and weather regimes frequencies, contrasting with observed changes before 1994. **Citation:** Yiou, P., R. Vautard, P. Naveau, and C. Cassou (2007), Inconsistency between atmospheric dynamics and temperatures during the exceptional 2006/2007 fall/winter and recent warming in Europe, *Geophys. Res. Lett.*, *34*, L21808, doi:10.1029/2007GL031981.

1. Introduction

[2] The European winter climate is mostly driven by atmospheric quasi-geostrophic turbulence in mid latitudes, due to the unstable nature of the westerly jet stream that exits from the North-Eastern American continent [Blackmon *et al.*, 1977; Charney, 1947]. The flow instability generates waves travelling across the Northern Atlantic, feeding larger scale flow patterns over Europe, often called “weather regimes” [Legras and Ghil, 1985; Reinhold and Pierrehumbert, 1982; Vautard and Legras, 1988; Vautard, 1990]. Weather regimes persist from a few days to a few weeks. The variability of European winter climate has often been described as driven by the alternation among these weather regimes. For instance European blocking [Rex, 1950] is characterized by a persistent high pressure system over the British Isles or Northern Europe, and maintains cold weather over Western Europe in winter. Other regimes, associated with oceanic westerly winds induce mild temperatures. Weather regimes are mostly due to mid-latitude flow internal dynamics but their occurrence can be influenced by several external factors. For instance, weather regimes excitation can be favoured by tropical sea-surface temperature anomalies [Cassou *et al.*, 2005], dry soils [Fischer *et al.*, 2007] or Mediterranean sea-surface temperature anomalies [Feudale and Shukla, 2007]

in summer, which can play an important role in the development and maintenance of heat waves. Whatever the origin, the mean seasonal temperature over Europe largely depends on the frequency the weather regimes during the corresponding season [Palmer, 1999; Plaut and Simonnet, 2001]. Exceptionally high frequency of a mild regime may lead to exceptionally warm average temperature.

[3] The way weather regimes are modified by climate change and how they influence temperature changes is a key issue to understand European climate and predict its evolution. A possible answer has been proposed by Corti *et al.* [1999] among others [Coppola *et al.*, 2005; Philipp *et al.*, 2007; Terray and Cassou, 2002] who stated that surface temperature warming in Europe could be mostly explained by a reorganisation of atmospheric circulation patterns rather than directly through anthropogenic radiative forcing. Our paper revisits and tests this paradigm, in the perspective of observations during the last decade. The fall of 2006, which was by far the warmest recorded in Europe [Van Oldenborgh, 2007; Luterbacher *et al.*, 2007; Xoplaki *et al.*, 2005], provides a basis for such a discussion.

2. Fall/Winter 2006/2007 Temperature Anomaly

[4] Daily temperature minima averaged over 25 European stations (data from the European Climate Assessment project [Klein-Tank *et al.*, 2002]) and over the months of September to November (SON), underwent departures of +2.9°C from the 1900–2006 average (Figure 1a). Similar anomalies are found with maximal temperatures. These anomalies were calculated by selecting stations having spatial homogeneity and few missing observations [Vautard *et al.*, 2007]. We used only stations with an altitude lower than 1500 m and located within the (10W; 30E; 35N; 60N) region. For each day, the average of the minimal temperature over the available European stations was computed. A mean temperature seasonal cycle was subtracted to compute anomalies. The seasonal cycle was calculated as a running 10-day average centred about the calendar day. Only 25 stations were retained, which have less than 10% of missing data over the 1900–2006 period. When imposing homogeneity over the 1948–2006 period only, the number of stations reaches 95. The fluctuation amplitude remains unchanged when averaging over the larger set of 95 stations.

[5] From the latter data set the 2006 anomaly (2.5°C) is about twice as large as the previous warm anomaly (1.3°C in 2000). This corresponds to 3.5 standard deviations (σ) of fall seasonal anomalies from 1948 to 2006, and is comparable in amplitude to the summer 2003 seasonal mean daily

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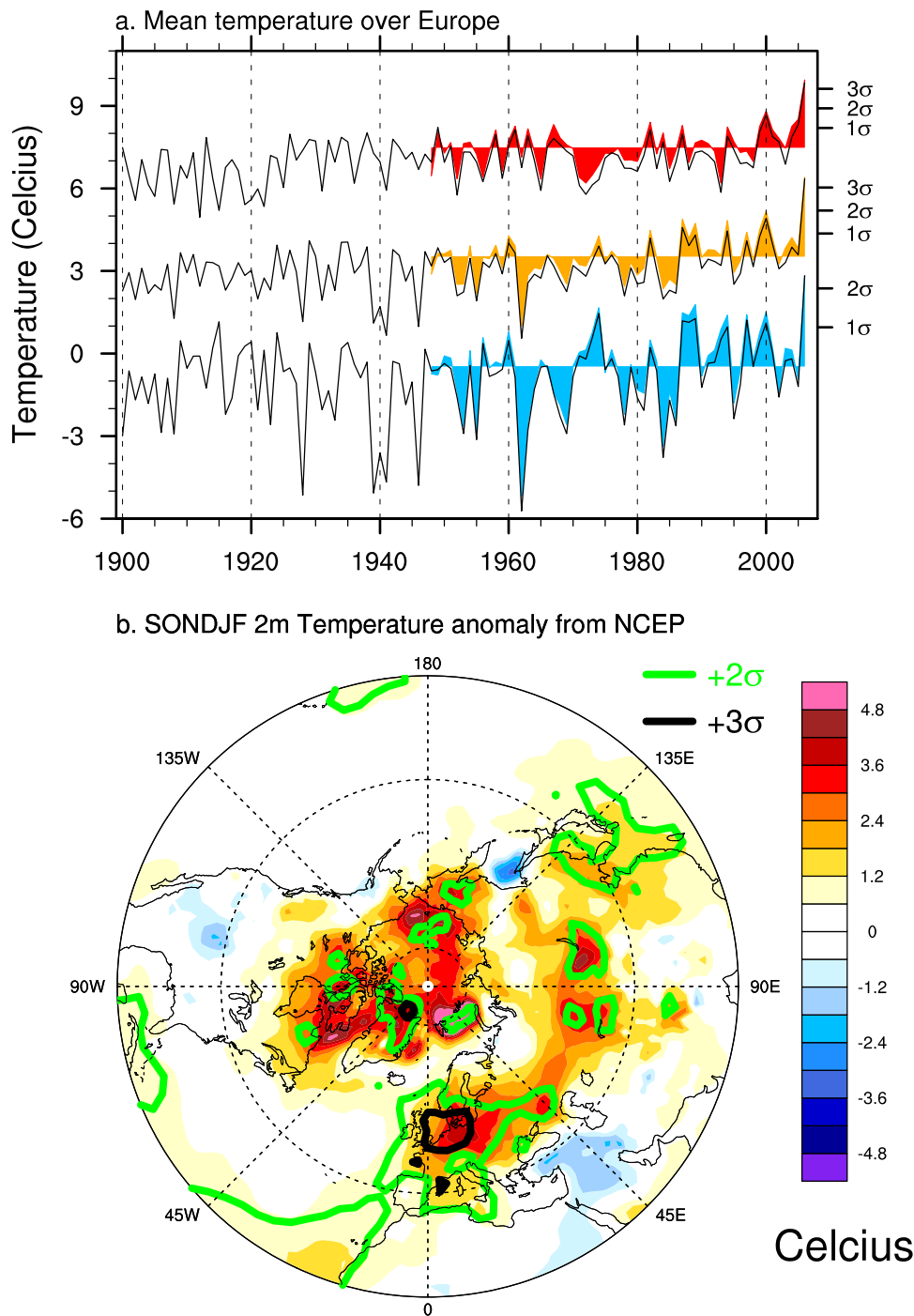


Figure 1. (a) Seasonal means of observed daily minimal temperatures averaged over Europe. Fall, upper curves; winter, lower curves; fall/winter, middle curves. Thin lines, averages over a homogeneous set of 25 stations since 1900; color lines, averages over a homogeneous set of 95 stations since 1948. Daily minimal temperatures are taken from the European Climate Assessment (ECA [Klein-Tank et al., 2002]) data base. (b) Mean September 2006 through February 2007 2-meter temperature anomalies from the National Centers for Environmental Prediction reanalyses. The green (resp. black) contour encompasses the areas where the anomalies are larger than twice (resp. three times) the standard deviation of the seasonal means (September through February).

maximal temperature anomaly over Europe [Chase et al., 2006; Schaer et al., 2004].

[6] Likewise, the following winter (December to February; DJF) had anomalously high temperatures [Hirshi, 2007; Luterbacher et al., 2007]. Again, the seasonal average of

daily minimal temperature (3.3°C) was the highest since the beginning of the century (Figure 1a). However, since variability is larger in winter than in fall, the relative anomaly (2.4 σ) was weaker. The resulting 6-month mean temperature anomaly (September through February) was

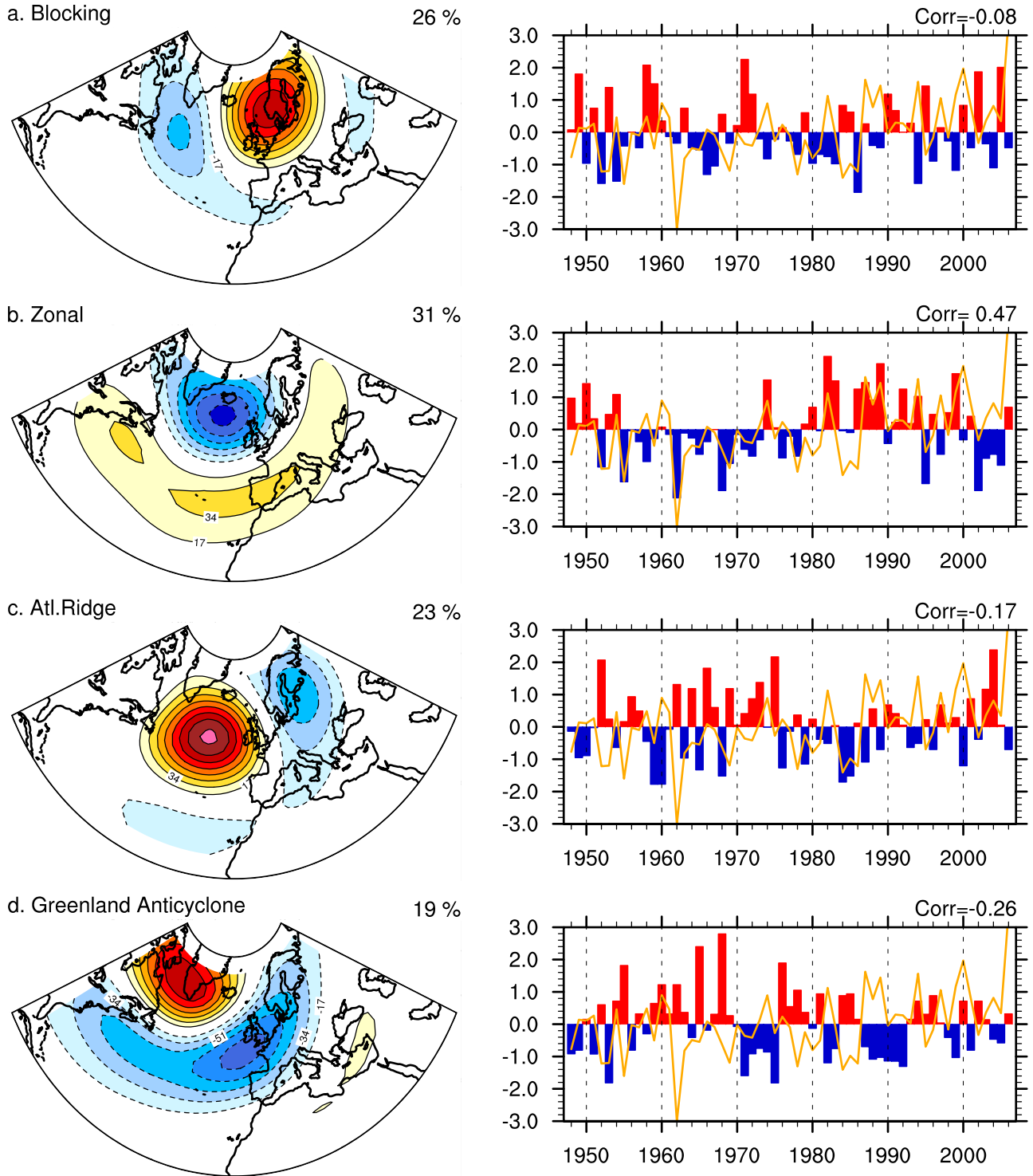


Figure 2. (a, b, c, d) Mean 500 hPa geopotential height anomalies for each of the four weather regimes obtained using the cluster analysis method. Regime #1 (blocking) is characterized by an anticyclonic anomaly over northern Europe, usually associated with North-Easterly winds over western Europe. Regime #2 (zonal) is characterized by a negative anomaly over the North-Eastern Atlantic, bringing mild oceanic south-westerly winds over Europe. Regime #3 (Atlantic Ridge), characterized by an Atlantic ridge brings colder air over Europe. Regime #4 (Greenland Anticyclone), with a blocking anticyclonic anomaly over Greenland, is associated with mild and wet conditions over western Europe. Their mean occurrence over 1948–2006 is given in the upper-right corner of the maps. (right) The seasonal (fall/winter) normalized frequency of each of the four weather regimes (blue and red bars) and the normalized seasonal temperature average (orange line). The correlation between the regime frequency and average temperature is indicated above each panel.

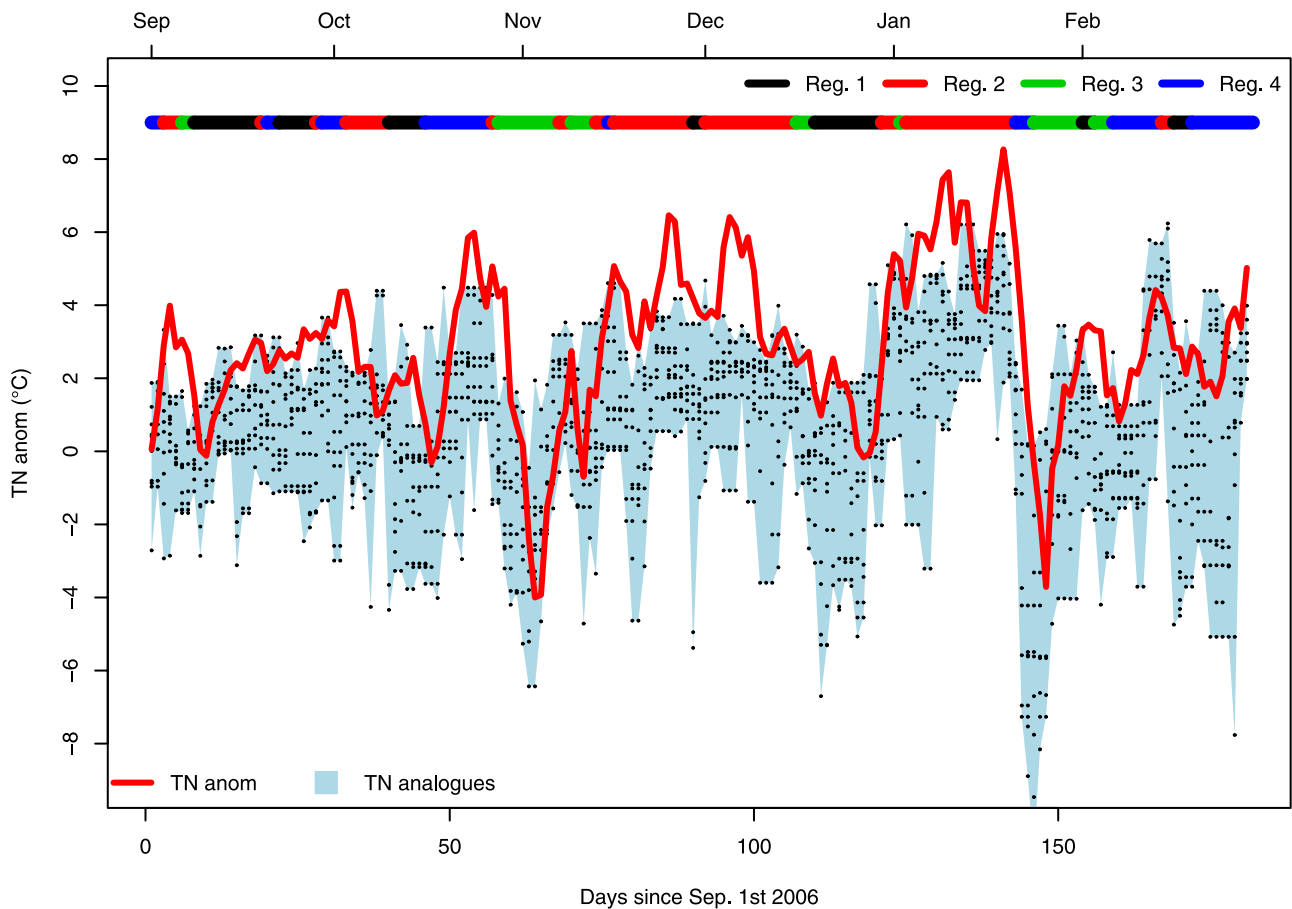


Figure 3. Time evolution, throughout the 2006/2007 fall/winter seasons, of the daily minimal temperature anomaly averaged over the 95 European stations, together with the temperature anomalies associated with the 10 best circulation analogues (dots), and their range (shaded cyan area). The weather regimes are also indicated with colour codes at the top.

2.9°C (3.5σ), i.e. about twice as large as the second positive anomaly (1.6°C in 2000).

[7] Placed in a more global context, the mean near-surface fall/winter temperature anomaly pattern (Figure 1b) is strongly positive over northern middle latitudes, with pronounced maxima over Northern Europe, Siberia, China and the Northernmost areas of Canada. As for the Summer 2003 heat wave case [Chase *et al.*, 2006], the 2006/2007 season (September to February) is the second having such a pronounced normalized anomaly after the 1998/1999 season over the northern hemisphere. Then, the — albeit weaker — anomaly located over the eastern Atlantic, was associated with a large sea-surface anomaly.

3. Fall/Winter 2006/2007 Weather Regimes

[8] In order to characterize the North-Atlantic atmospheric flow we used the geopotential height at 500 mb from the National Centers for Environmental Prediction (NCEP) reanalysis for the 1948–2007 period, over the (80W; 50E; 25N; 70N) area [Kalnay *et al.*, 1996]. The seasonal cycle of the geopotential height was also removed in the same manner as for temperature, in order to have atmospheric flow anomaly patterns. In order to retain only the large-scale features of the flow, we computed the first 14 Empirical

Orthogonal Functions (EOFs) and Principal Components [von Storch and Zwiers, 2001] (PCs) using weights on the cosine of latitude, retaining 90% of the total variance.

[9] Weather regimes were calculated using a “*k*-means” cluster analysis method [Cheng and Wallace, 1993; Michelangeli *et al.*, 1995] of the fall-winter 1948–2006 geopotential height anomalies. Four weather regimes are assumed, as is done in previous studies [Corti *et al.*, 1999; Michelangeli *et al.*, 1995]. The centroids of the weather regime clusters are displayed in Figure 2a. Each fall-winter day is then classified into one of the four regimes, based on its closest distance to the centroid. The frequency of weather regimes is the fraction of days spent in each regime during every “cold extended” season (September to February).

[10] Compared to other seasons, in 2006–2007 the frequency of the 500 mb geopotential height weather regimes does not exhibit an anomalous distribution (Figure 2b). One of four regimes (Regime #2, Figure 2b), associated with a mild south-westerly flow over Western Europe (the “zonal” regime [Michelangeli *et al.*, 1995]), is more frequent than any other regimes (68 out of 181 days) but this higher frequency is not unprecedented. For instance, fall/winters in the eighties or even in the early fifties were dominated by this regime as well, but the mean temperature, although high, was significantly lower than during fall-winter 2006–

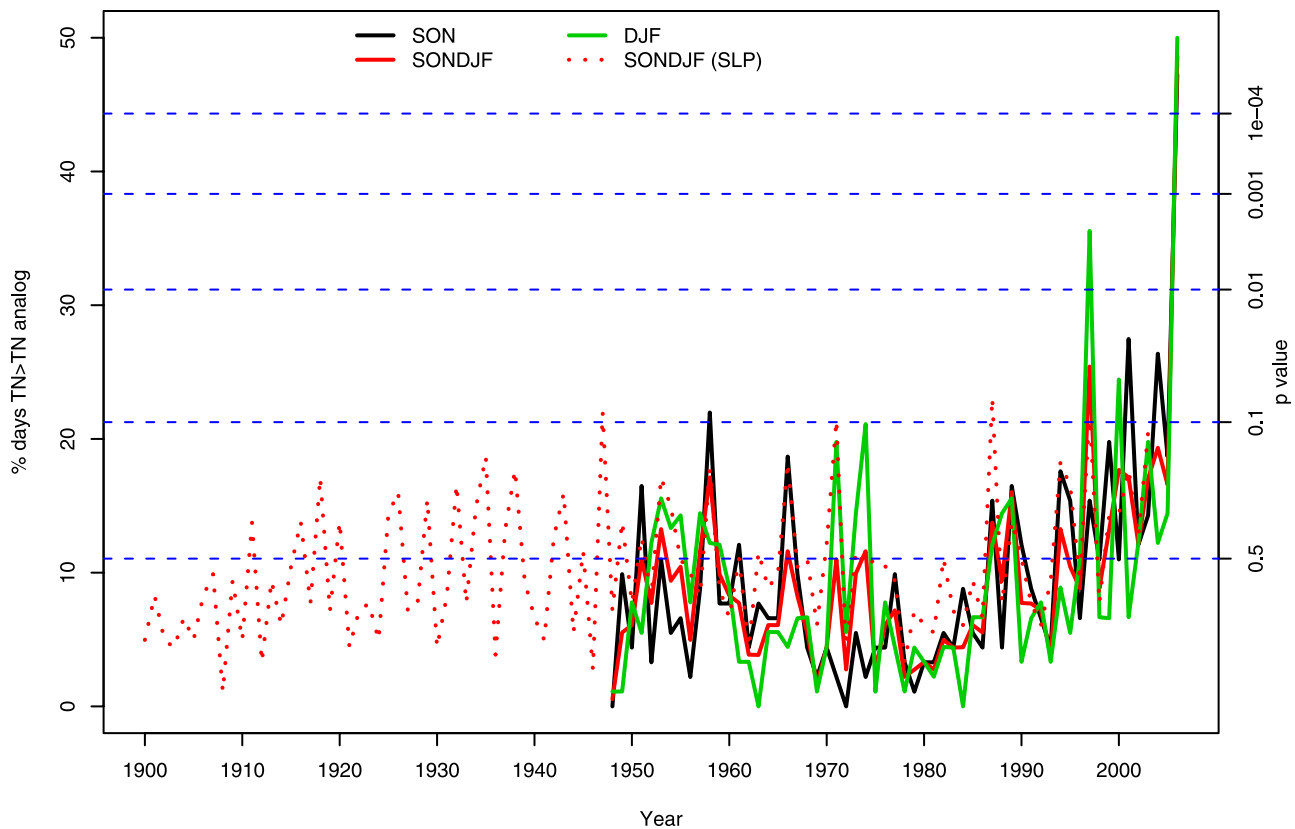


Figure 4. Frequency of fall (SON, black), winter (DJF, green), and fall + winter (SONDJF, red) days when actual average temperature exceeds that of all flow analogues, as a function of year. The fall + winter frequency for the EMULATE SLP dataset is indicated in red dotted lines. The horizontal dashed blue lines give the probability (p-value) that this frequency is reached or exceeded during fall/winter. This probability is computed from a binomial distribution by assuming a conservative decorrelation time of 10 days for temperature data, implying 18 degrees of freedom in a fall/winter season, and a probability of exceeding the highest of 10 analogues of $1/11$.

2007. A multiple linear regression of the mean European temperature over the regime frequencies explains $\sim 25\%$ of the variance of temperature, essentially because temperature yields a trend and regime frequencies do not. Thus the frequency of weather regimes alone cannot explain the exceptionally warm season.

4. Temperatures in Flow Analogues of 2006/2007

[11] In order to determine if the temperature anomaly was due to long-lasting mild flow only, we examine whether the same temperature anomaly could have been obtained during similar atmospheric flow situations in previous years. For each day of the fall-winter 2006/2007, we determined 10 circulation analogues that occurred between 1948 and 2005, chosen within the same calendar month, using the geopotential height anomalies at 500 hPa ($z500$). For a given daily $z500$ map the best analogues are the $z500$ maps which maximize the correlation during the same month of other years. Taking five analogues does not change the results in a significant way. Using the rank or linear correlation does not change the results.

[12] About 90% of the correlations between observed and analogue temperatures range in the 0.57–0.81 interval, with no specific trend over time. The fall and winter 2006–2007 seasons did not have poorer analogues than other years.

[13] Temperature anomalies encountered in 2006 are clearly higher than their flow-analogue values in previous years (Figure 3) with only a few cold sequences when the actual temperature anomaly lies in the middle or exceptionally in the lower part of the flow-analogue temperature range. The warmest temperature anomalies occurred during the first three weeks of January 2007, when they exceeded 8°C . During that period, the flow was clearly favourable to warmth (Regime #2), but flow-analogue temperature anomalies ranged only between 3 and 6°C . In the second half of February 2007, anomalies were 2 to 5°C above normal while flow-analogue temperature anomalies were mostly negative, down to -8°C .

[14] The average offset between actual and flow-analogue temperatures (2.2°C) depends weakly on the regime: it is respectively 2.0 (0.2), 2.4 (0.2), 1.7 (0.3) and 2.3°C (0.2) for Regimes #1 to #4 (numbers in parentheses indicate $1\text{-}\sigma$ confidence intervals with respect to regime frequencies). Over the two seasons, 49% (fall: 47%; winter: 50%) of the days had temperature anomalies above all of the 10 flow-analogue values (Figure 4). Assuming a conservative decorrelation time between atmospheric flows of 10 days, and therefore 18 degrees of freedom (independent days), the probability that the frequency reaches 49% or more is $p = 1.10^{-5}$. Therefore it is highly probable that the 2006–2007

temperature anomalies are driven by factors other than the direct atmospheric flow.

5. Temperature Anomaly of 2006/2007 and Recent Trends

[15] We now question how exceptional the previous results about temperature in analogue flows were. Repeating the flow analogue calculations for previous years (excluding the current year for analogue selection), the fraction of days with temperature anomaly above all flow-analogue ones does not exceed 20% in fall/winter seasons except in 1997, and often lies around 9% or below (Figure 4) as expected. Considering fall and winter seasons separately, this fraction exceeds 20% only in falls 1958, 2001 and 2004, and in winters 1974, 1997 and 2000.

[16] In order to put these results in a time longer perspective, we also calculated the analogues of sea-level pressure (SLP) since 1900 from the EMULATE gridded SLP dataset [Ansell *et al.*, 2006]. This SLP dataset covers the 1850–2003 period. Circulation analogues were determined in the same way as for z500, and the temperature analogues were computed from the reduced ECA set of stations, homogeneous since in 1900. The fraction of days when temperature exceeded that of the 10 analogues from September to February are also plotted in Figure 4. Although previous fluctuations of temperature seem to be controlled by those of the atmospheric circulation [Philipp *et al.*, 2007], the fall/winter 2006/2007 has an unprecedented anomaly of temperature departure from flow analogue.

[17] Interestingly, the excess temperature relative to that of flow analogues starts to appear during the last decade (1997–2006) (Figure 4) for fall/winter seasons. Over this period, a positive offset is also found for all regimes, as for the 2006–2007 case (Reg. #1: 0.67 (0.09)°C; #2: 0.60 (0.07)°C; #3: 0.67 (0.09)°C; #4: 1.07 (0.10)°C, with 1- σ confidence intervals in parentheses). Thus, like for the 2006–2007 period, the fall-winter European warming of the last decade is not driven by changes in North-Atlantic atmospheric circulations alone but by additional factors. In a previous study [Corti *et al.*, 1999], however, most of tropospheric climate changes were found to be attributable to changes in frequency of global atmospheric flow regimes. That study used atmospheric data until 1994 and changes that occurred in the preceding decades. Our analyses are consistent with this finding since we show that the offset between actual and flow-analogue European temperatures appears later than their period of study, and has steadily increased since 1995, especially in the fall (Figure 4). Therefore in recent and probably future European climate warming, our results suggest that the effects of circulation regimes frequency changes do not seem to be the dominant factors.

[18] However, the previous results do not help to determine the main drivers of the fall-winter 2006–2007 anomalies. Sea-surface temperatures (SSTs) were warm nearby Europe, and particularly warm in the North Sea, downwind of the mean flow (not shown), which is a consequence of the warm regional climate anomaly. By contrast Atlantic SSTs were not high, except in a band off the African coast during fall, which may have contributed to the fall European temperature anomaly through a more efficient heat transport

during Southwesterly wind episodes [Luterbacher *et al.*, 2007].

6. Conclusion

[19] Unparalleled since the beginning of the 20th century, persistent high daily minimal temperatures occurred during fall-winter 2006, making this period the warmest on record [Luterbacher *et al.*, 2007; Xoplaki *et al.*, 2005]. The fall temperature anomaly had amplitude comparable to that of summer 2003. Even though frequent south-westerlies brought mild air over Europe, the distribution of weather regimes was not unprecedented. Actual daily minimal temperatures were 1.9°C higher than those encountered in previous years under similar atmospheric flows. Thus persistent warmth in fall/winter 2006–2007 cannot be only due to favourable atmospheric circulations, and probably results from a more global phenomenon. The 2006–2007 fall/winter anomaly (even with respect to circulation-analogue temperatures) stands as an amplified version of a more general trend since 1997 (Figure 4). This is one reason to believe that it may prefigure the future regional European climate during these seasons.

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