Winter 2010 in Europe: a cold extreme in a warming climate

J. Cattiaux,[1] R. Vautard,[1] C. Cassou,[2] P. Yiou,[1] V. Masson-Delmotte,[1] and

F. Codron[3]

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[1]IPSL/LSCE, Unité mixte

CEA-CNRS-UVSQ (UMR8212),

Orme-des-Merisiers, 91191 Gif-sur-Yvette

Cedex, France

[2]CNRS/Cerfacs, 42 Avenue Gaspard

Coriolis, 31057 Toulouse, France

[3]IPSL/LMD, Unité mixte CNRS-Ecole

Polytechnique-ENS-UPMC, 4 Place Jussieu,

75252 Paris Cedex 05, France

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The winter of 2009/2010 was characterized by record persistence of the negative phase of the North-Atlantic Oscillation (NAO) which caused several severe cold spells over Northern and Western Europe. This somehow unusual winter with respect to the most recent ones arose concurrently with public debate on climate change, during and after the Copenhagen climate negotiations. We show however that the cold European temperature anomaly of winter 2010 was (i) not extreme relative to winters of the past six decades, and (ii) warmer than expected from its record-breaking seasonal circulation indices such as NAO or blocking frequency. Daily flow-analogues of winter 2010, taken in past winters, were associated with much colder temperatures. The winter 2010 thus provides a consistent picture of a regional cold event mitigated by long-term climate warming.

1. Introduction

The period December 2009 – January 2010 – February 2010 (hereafter winter 2010) was punctuated by series of cold weather events and unusual snow accumulation in several Northern Hemisphere countries (see http://www.ncdc.noaa.gov/sotc/). In Europe, three successive cold outbreaks and unusual persistence of snow cover were observed (see http://www.knmi.nl/cms/content/79165), which shaped the public perception of an exceptionally intense winter. Several states of Eastern United States also recorded their snowiest winter ever [*Seager et al.*, 2010] while a few cities witnessed record-breaking cold daily temperatures [*Wang et al.*, 2010]. These weather events occurred during and after intense media activity covering international climate negotiations in Copenhagen, and raised up questioning about global warming. A global perspective nevertheless highlights that winter 2010 was marked by a mean warm anomaly at global scale, especially over Greenland, Canada, North-Africa and Middle East (see http://data.giss.nasa.gov/gistemp/maps/). Understanding and improving the predictability of such mid-latitude cold spells is a key societal issue, since their fate in both frequency and intensity in a warming climate directly impacts sectors of energy demand, transport disruption and social emergency protection systems.

This paper focuses on European cold temperatures of winter 2010. The European wintertime climate is mostly driven by atmospheric dynamics over the North-Atlantic – European (NAE) area [*Walker*, 1924], characterized by a baroclinic instability of the westerly jet stream which generates planetary waves traveling from North-Eastern America to the European continent [e.g. *Charney*, 1947]. The unstable nature of the jet also triggers

quasi-stationary circulation patterns of larger scale, often referred to as "weather regimes", which can persist from a few days to a few weeks [*Legras and Ghil*, 1985; *Reinhold and Pierrehumbert*, 1982; *Vautard*, 1990]. The seasonal-to-decadal variability in European temperatures has often been considered as driven by the frequency of occurrence of each regime [*Vautard and Yiou*, 2009; *Philipp et al.*, 2007]. For instance the positive (negative) phase of the North Atlantic Oscillation (NAO) is generally associated with rather warm (cold) temperatures [e.g. *Hurrell*, 1995], while the persistence of a high-pressure system over Northern Europe or the British Isles, often referred to as "European blocking" conditions, leads to cold and dry weather over Western Europe [e.g. *Yiou and Nogaj*, 2004].

Our aim is to investigate which weather regimes were associated to the cold winter 2010, and their interplay with the temperature anomaly. In particular we use the "flow-analogues" approach developed in *Yiou et al.* [2007] to analyze this temperature anomaly based on past relationships between atmospheric circulation and temperatures.

2. Data and methods

The daily atmospheric dynamics is analyzed through re-analyses of geopotential height at 500hPa (Z500) provided by National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP-NCAR) [*Kistler et al.*, 2001] over the period 1948–2010 (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html). Anomalies are computed by removing at each grid point the 1961–1990 daily climatology.

Several indices are used for the statistical analysis of winter 2010 seasonal dynamics: (i) the seasonal NAO index (NAOi) defined as the difference between Azores and Iceland

normalized surface pressures [*Jones et al.*, 1998; *Osborn*, 2006] (computed from monthly values downloaded from http://www.cru.uea.ac.uk/~timo/datapages/naoi.htm), (ii) the frequency of blocking days throughout the winter season as defined by *Tibaldi and Molteni* [1990] (computed over $30°W$ ($\pm10°$)), (iii) the winter Seasonal Dynamics Index (SDI) defined in *Cattiaux et al.* [2010] and based on optimal correlation between European atmospheric circulation and temperatures, and (iv) the seasonal frequency of daily occurrences of North-Atlantic "weather regimes" obtained by *Cassou* [2008] from a "k-means" clustering method computed in the Empirical Orthogonal Functions phase space [*Michelangeli et al.*, 1995] over the NAE domain and the period 1974–2007.

Temperature data are from the European Climate Assessment and Dataset (ECA&D) project [*Klein-Tank et al.*, 2002], which provides daily minimum, maximum and mean temperatures (respectively Tmin, Tmax and Tavg) at European stations (http://eca.knmi.nl/dailydata/). The data set is geographically homogenized by selecting the stations on the basis of (i) the simultaneous availability of Tavg, Tmin and Tmax data, (ii) the availability of more than 80% of daily values between 1 January 1948 and 28 February 2010, (iii) a selection of only one station per grid cell of $0.75°\times0.5°$ size. This method is similar to that used in previous studies [*Vautard and Yiou*, 2009; *Yiou et al.*, 2007], and retains here 230 stations over Europe. Anomalies are computed by removing at each station the 1961–1990 daily climatology, and in order to better quantify their amplitude, normalized anomalies relative to the mean and the standard deviation (σ) of the 1949–2010 anomalies distribution are used.

The "flow-analogues" method, used in section 5 to estimate daily temperatures observed during similar flow conditions in past winters, was developed in *Yiou et al.* [2007] and consists as follows: for each day of winter 2010, ten flow-analogues are selected among winters 1949 to 2009 in a 30-day window centered on this given day. The selection is made on the basis of maximizing the Spearman's correlation of daily Z500 NAE maps. Then, for each station, the daily "analog" temperature anomaly is defined as the median of daily temperature anomalies of the ten flow-analogue days. Using rather Euclidean distance or linear correlation for Z500 ranking, five or twenty flow-analogues, and the mean in analog temperature computation does not change our results in a significant manner.

3. Extreme persistence of daily NAO− conditions during winter 2010

Winter 2010 is characterized by an exceptional Northern Hemisphere mean atmospheric circulation [*Wang et al.*, 2010]. The Z500 anomaly exhibits a strong zonal hemispheric pattern, with anomalously high (low) pressures over the pole (mid-latitudes) (Figure 1a). Such a structure corresponds to a negative phase of the Arctic Oscillation (AO) [*Thompson and Wallace*, 1998]. In particular *L'Heureux et al.* [2010] highlighted that the negative AO of December 2009 was a record.

Wintertime European temperatures are largely controlled by the NAO [*Hurrell*, 1995; *van Loon and Rogers*, 1978, among others], which can be interpreted, even if controversial, as the regional signature of the AO [e.g. *Ambaum et al.*, 2001]. Over the NAE domain, the winter 2010 hemispheric zonal structure is associated with an extremely negative phase of the NAO, even constituting a record of NAOi since winter 1824, almost 3σ below average (Figure 1b). Negative NAO events usually favor the development and persistence of

North-Atlantic atmospheric blockings [e.g. *Shabbar et al.*, 2001]. This is the case of winter 2010 which has the 2nd highest blocking frequency since 1949 (Figure 1c, $freq = 33\%$), close to the record of the winter 1963 ($freq = 34\%$). Moreover the winter 2010 SDI value is the 6th lowest recorded since 1949, which confirms the exceptional character of the winter 2010 dynamics at European scale (Figure 1c). Blocking frequency and SDI are significantly correlated with NAOi (respectively $r = -0.73$ and $r = 0.73$, $p - value < 1\%$).

Seasonal values of NAOi are closely linked to daily occurrences of NAE weather regimes presented in Figure 2. The first (third) regime is indeed generally connected to the positive (negative) phase of the NAO, the second one is referred to as Scandinavian Blocking and the fourth one as Atlantic Ridge [e.g. *Michelangeli et al.*, 1995]. Winter 2010 extreme NAO is thus caused by both a record frequency of NAO− occurrences over winters 1958–2010 (63/90 days, 8 more days than the previous record in winter 1966) and a very low frequency of NAO+ occurrences (5/90 days, the 3rd lowest after 1969, 3/90, and 1963, 4/90). Although referring to very different quantifications of the NAO, seasonal NAOi and frequencies of NAO+(NAO−) regimes are highly correlated ($r = 0.8$ (-0.75), $p - values < 1\%$). In addition, while positive (negative) phases of the NAO dominate winters 1980–1995 (1995–2010), we found no significative ($p - values < 5\%$) trends in any seasonal index or weather regime frequency over the last three decades.

4. How cold was winter 2010 in Europe?

Winter 2010 European temperatures were on average anomalously cold (Figure 3a), with largest negative anomalies (about -1.5σ) over North-Western Europe while milder conditions prevailed over Southern Europe. This seesaw latitudinal pattern is entirely

consistent with the canonical signature of the negative NAO [*Hurrell*, 1995]. More generally, *Wang et al.* [2010] showed that the winter 2010 negative NAO was responsible for the quadripole structure in NAE temperature anomalies (warm over Canada/Greenland and North Africa/Middle East, cold over United States and Eurasia).

Averaged over all European stations the winter 2010 anomaly of daily mean temperature is $-1.3°C$, corresponding to a departure of -0.9σ from the 1949–2010 distribution (Figure 3d). As in previous studies [e.g. *van Loon and Rogers*, 1978], we find high correlations between European temperatures and both the phase and amplitude of the NAO (e.g. $r = 0.70$ for Tavg–NAOi and $r = 0.75$ for Tavg–NAO+ regime frequency, both $p - values < 1\%$), and that most of cold peaks are associated with significantly low NAOi or NAO+ frequency (not shown). Note that the frequency of NAO− regime is less significantly anti-correlated with temperatures ($r = -0.56$, $p - value < 1\%$) since cold events can also be linked to Scandinavian blockings or Atlantic Ridge conditions (Figure 2).

Winter 2010 ranks as the 13th coldest winter since 1949 over Europe, far behind the cold record of 1963 ($-4.0°C$, -2.9σ) despite comparable atmospheric dynamics indices. Winter 1963 indeed experienced the 3rd lowest NAOi since 1824 (Figure 1b), and the 2nd lowest NAO+ regime frequency (Figure 2e). However cold temperatures of winter 1963 seem caused by both NAO− and strong Scandinavian blockings, while NAO− largely dominates in winter 2010 (Figure 2).

5. Temperatures in flow-analogues of winter 2010

For 84% of stations (193/230) flow-analogues sampled in past winters were associated with significantly colder daily mean temperature (Tavg) anomalies than observed in win-

ter 2010 (Figure 3b,c). Only a few stations in Southern Europe exhibit a higher analog temperature than observed. The maximal departure is found over the Alps region, where observed temperatures were close to average while analog anomalies reach -2σ. Averaged over all stations, past flow-analogues of winter 2010 were associated with a negative temperature normalized anomaly reaching -2.1σ, the 2nd coldest analog anomaly close behind winter 1963 (-2.3σ, see Figure 3d). In other words the daily atmospheric dynamics of the winter 2010 was favorable to a temperature anomaly comparable in amplitude to the cold record of winter 1963.

Analog temperatures of winters 1949 to 2010 are well correlated to observed ones ($r = 0.85$, $p - value < 1\%$) but miss the recent warming trend (linearly estimated to $0.44\sigma/decade$ over 1980–2009, $p - value = 3\%$), since no significant tendency is found in recent circulations (Figure 3d). Nine of the past ten winters exhibit positive differences between observed and analog temperatures, and winter 2010 departure is the 3rd highest of the whole period, behind 2008 and 2000. This inconsistency between recent European temperatures and changes in the North Atlantic atmospheric dynamics has been recently highlighted in other studies [*Cattiaux et al.*, 2010; *Yiou et al.*, 2007; *Vautard and Yiou*, 2009] and is also found in future climate projections [*Stephenson et al.*, 2006; *van Ulden et al.*, 2007]. Subtracting the 1980–2009 trend from observed Tavg time series ranks winter 2010 in 2nd position with -1.9σ, which is similar to the analog anomaly (Figure 3e), suggesting the long-term trend in European temperatures to cause the departure between temperatures and dynamics in winter 2010.

Winter 2010 cold anomaly is stronger for maximal (daytime, -1.2σ) than minimal (nighttime, -0.7σ) temperatures, which even constitutes a negative record in terms of diurnal range (-2.2σ of the Tmax$-$Tmin distribution) within a longer-term decreasing tendency ($-0.37\sigma/decade$ over 1980–2009, Figure 3f). This observed reduction of wintertime diurnal range is consistent with future climate projections that generally suggest a higher warming in minimal than maximal winter temperatures, due to the higher contribution of long-wave than short-wave net downward surface radiative flux for that season [*Vose et al.*, 2005]. Analog temperatures do not exhibit any significant tendency in recent diurnal ranges, and even exhibit a higher maximal than minimal temperature anomaly in winter 2010 (Figure 3f). The record dirunal range of winter 2010 may be linked to the unusual snow cover highlighted by *Seager et al.* [2010], modifying albedo and daytime surface energy budget (not shown).

6. Conclusions

Our findings indicate that the cold – albeit not exceptional – temperature anomaly of winter 2010 was mostly caused by an extreme persistence of the negative phase of the NAO. However similar dynamics were generally associated with even colder temperatures in past winters, so that the winter 2010 mean temperature expected from the sole atmospheric circulation is comparable to the cold record of winter 1963. Winter 2010 appears to be a remarkable event within a longer-term tendency: observed temperature anomalies have been quasi-systematically warmer than flow-analogues ones over the past two decades, which probably results from background climate warming [*Yiou et al.*, 2007; *Cattiaux et al.*, 2010]. The fact that the positive departure of observed temperatures from

flow-analogues is larger for minimal than for maximal temperatures is consistent with radiative consequences of increasing greenhouse gases concentrations.

Thus winter 2010 can thus be considered as an example of a cold extreme superimposed on a warming climate. Since (i) climate projections suggest the European warming will continue in future decades, and (ii) the extreme dynamics of winter 2010 was one of the most favorable to cold weather since the 1820s, this winter could be one of the coldest of the 21st century.

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Figure 1. **(a)** Geopotential height at 500mb (Z500) anomaly averaged over winter 2010 above $20°N$ (from NCEP). Units: m. Labeled gray contours indicate standard deviations levels. **(b)** Normalized 1824–2010 time series (bars) and spline-smoothing (line) of NAOi. Winter 2010 is indicated by the blue dashed line. **(c)** Normalized 1949–2010 time series of NAOi (bars), SDI (gray) and North-Atlantic blocking days frequency (black). Winter 2010 values are indicated by dashed lines. Levels are inversed for blockings, see right axis. NAOi differ from (b) to (c) since normalizing periods differ.

Figure 2. **(a–d)** Winter weather regimes as computed from Z500 by *Cassou* [2008]: NAO+, Scandinavian Blocking, NAO− and Atlantic Ridge. Units: m. Percentages represent each regime frequency over the computation period (1974–2007). **(e–h)** Frequencies of occurrence of each regime over 1958–2010. Units: days/90 (left axis) and σ (right). Winter 2010 values are highlighted in red and mean 1950–2010 frequencies are indicated.

Figure 3. **(a–b)** Winter 2010 normalized (a) observed and (b) analog Tavg anomaly (from ECA&D stations). **(c)** Difference between (a) and (b). **(d)** Normalized 1949–2010 time series of observed (analog) Tavg anomaly in black (gray) line. Red (blue) segments indicate positive (negative) observed–analog differences. Winter 2010 values are indicated by dashed lines. 1980–2009 linear trends are added. **(e)** Same as (d) with the 1980-2009 linear trend removed from observed Tavg time series. **(f)** Same as (d) for normalized Tmax–Tmin time series.

(a) NAO+ 30%

(b) Sc. Blocking 27%

(c) NAO− 20%

(d) Atl. Ridge 23%

(e) NAO+ — Mean = 26 days/90

(f) Scan. Blocking — Mean = 23 days/90

(g) NAO− — Mean = 20 days/90

(h) Atl. Ridge — Mean = 22 days/90