Contribution of Atmospheric Circulation to Remarkable European Temperatures of 2011

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Western Europe witnessed remarkable temperature events during the year 2011. Hot and dry spring and autumn (the warmest and second warmest in France, respectively) have contrasted with an uneven summer and a cold and snowy winter 2010/11 (including cold records over the United Kingdom in December 2010). Our scientific challenge consists in putting such regional events into the context of climate change, either by evaluating anthropogenic fingerprints on each event [e.g. with calculations of fractions of attributable risk (Stott et al. 2004)] and/or by understanding how climate change affects physical processes at regional scales. The second approach is taken in this paper. In Europe,

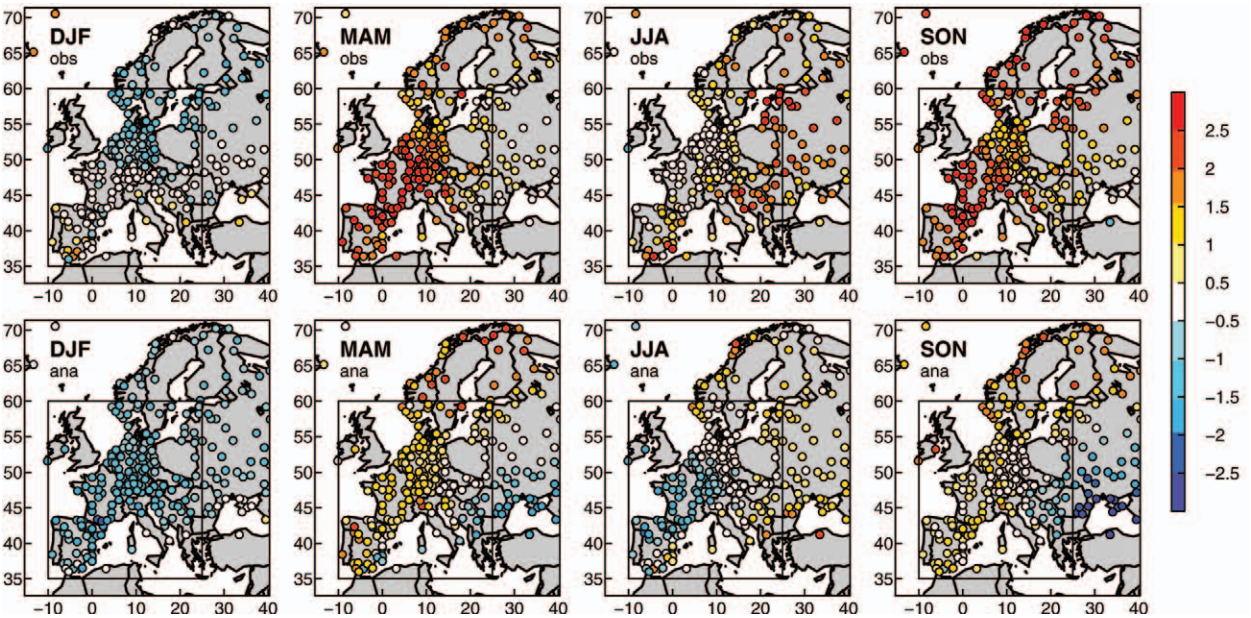

Fig. 10. (top) Observed temperatures of December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON) 2010/11, represented as normalized anomalies (σ levels) relative to 1971–2000 climatologies at each station. The box over western Europe encompasses the area retained for the regionally averaged statistics along the paper (171 stations over 306). (bottom) As at top, but for analog temperatures. Observed temperatures are quasi-systematically higher than analog ones, while spatial patterns are well correlated (Table 1).

studies have highlighted that recent temperatures have been systematically warmer than expected from the North Atlantic dynamics, which controls their intraseasonal to interannual variability (e.g., Cattiaux et al. 2010b; Vautard and Yiou 2009). Here we investigate the contribution of large-scale circulations to temperatures anomalies of 2011 using the same flow-analogue approach as in the analysis of winter 2009/10 by Cattiaux et al. (2010a, C10 hereafter).

Were 2011 temperatures anomalously warm compared to those expected from their flow analogues? We use in situ measurements provided by the European Climate Assessment dataset at more than 2500 stations over the period 1948–2011 (Klein-Tank et al. 2002). Similarly to C10, 306 stations are selected on the basis of (i) an altitude lower than 800 m, (ii) the availability of more than 90% of daily values between 1 January 1948 and 31 December 2011, and (iii) only one station per 0.5° × 0.5° latitude/longitude box for spatial homogeneity. We compute anomalies relative to 1971–2000 climatological standards [mean and standard deviation σ].

Winter 2010/11 was particularly cold in northern Europe, falling below −1σ at most of stations above 50°N (Fig. 10, top). Over western Europe (defined by the insert box in Fig. 10), it ranks as the nineteenth coldest winter of the whole period 1949–2011 (Table 1) and the fifth coldest of the last 25 years (after 1987, 1996, 2010, and 2006). It was followed by exceptionally warm anomalies from March to May 2011, especially over western Europe where seasonal temperatures locally exceeded 2.5σ, making 2011 the second hottest spring between 1948 and 2011 (after 2007). In this region, the temperature rise initiated in March climaxed during April, with respectively 25 of 30 and 14 of 30 days above 1 and 2σ (Fig. 11a). As shown in recent studies, dry soils in early summer are a necessary, but not sufficient, condition for the genesis of heat waves such as those experienced in 1976 and 2003 (e.g., Vautard et al. 2007).

In 2011, despite important deficits in soil moisture at the end of spring (comparable to those that preceded summer 2003 heat waves), summer temperatures turned out to be close to normal over most of western Europe. With a cool July and a warm spell at the end of August, it ranks as the fourteenth warmest summer of the period 1948–2011 but the third coolest since 2000 (after 2004 and 2005). The rest of the year was marked by anomalously mild temperatures over all of Europe, punctuated by a few moderate cold spells. Seasonal anomalies of autumn 2011 exceeded 2.5σ in most stations of western Europe, especially during September with respectively 17 of 30 and 9 of 30 days above 1 and 2σ, making 2011 the second warmest autumn of 1948–2011 (after 2006). Overall, the calendar year 2011 (January to December) is the

Table 1. Normalized anomalies of observed and analog temperatures averaged over western Europe (171 stations inside the box in Fig. 10), for DJF, MAM, JJA, and SON 2010/11 and the whole year 2011, with corresponding rankings in superscripts. Spatial (patterns in Fig. 10), intraseasonal (series in Fig. 11a), and interannual (series in Fig. 11b) correlations between observed and analog temperatures are all significant at 5%. Flow-analogues quality, as evaluated from mean correlations between observed and analog SLP.

	DJF	MAM	JJA	SON	Year (J–D)
Observed anomaly	-0.8^{45}	2.4^{2}	1.1^{14}	2.5^{2}	2.1^{1}
Analog anomaly	-1.3^{51}	0.9^{12}	-0.5^{36}	0.5^{15}	0.7^{10}
Spatial correlation	0.5	0.55	0.63	0.72	—
Intraseasonal correlation	0.59	0.57	0.44	0.24	0.55
Interannual correlation	0.85	0.70	0.60	0.58	0.75
Flow-analogues quality	0.72	0.68	0.63	0.67	0.68

warmest year over western Europe in our dataset (2.1σ, Fig. 11b). However, the hottest 12-month-long period remains July 2006–June 2007, which contains three seasonal warm records (autumn, winter, and spring) and an anomaly that reaches 3.8σ.

The contribution of the large-scale dynamics to temperature anomalies of 1948–2011 is estimated from the same flow-analogue approach as used in C10. For each day, we selected the 10 days with the most correlated atmospheric circulation among days of other years but within a moving window of 31 calendar days (for details, see Lorenz 1969; Yiou et al. 2007). The following results are insensitive to (i) the number of selected days (here 10) and (ii) the metrics used for assessing analogy (here Spearman's rank correlation). Further methodological details can be found in C10 and Vautard and Yiou (2009). Circulations are derived from sea level pressure (SLP) anomalies of National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalyzes (Kistler et al. 2001) and considered over the period 1948–2011 and the area (22.5°–70°N, 80°W–20°E). The quality of flow analogues for 2011 was checked by verifying that mean correlations between observed and analog SLP indicated in Table 1 were close to the 1948–2010 mean (not shown).

For all seasons of 2011, mean analog temperatures (i.e., averaged over the 10 analog days) were lower than observed ones at respectively 76%, 88%, 86%, and 89% of western Europe

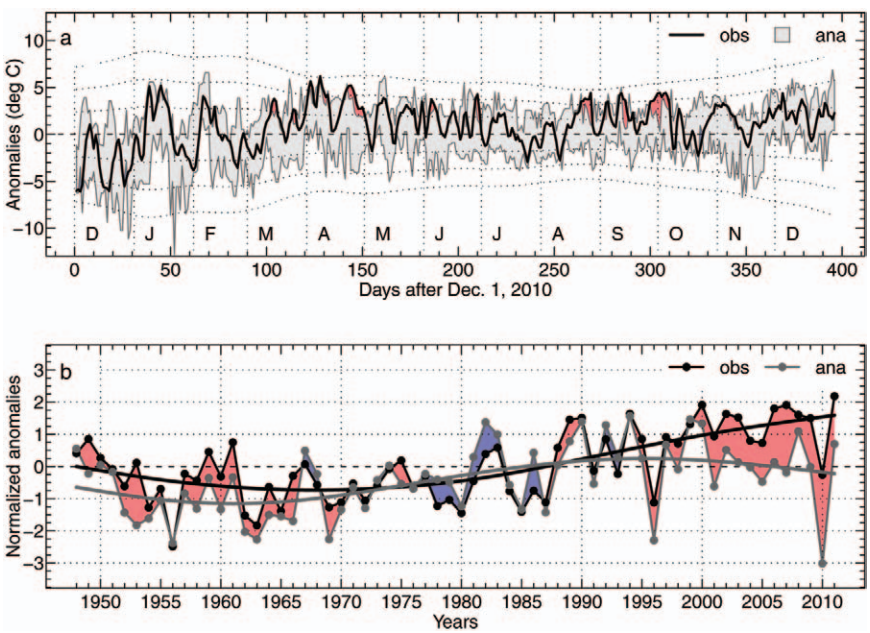

Fig. 11. (a) Daily anomalies (°C) of observed (black line) and analog (gray spread encompassing the 10 values) temperatures from December 2010 to December 2011. Dashed lines indicate climatological σ levels (higher variability in winter than in summer), and red (blue) indicates days with observed temperatures above (below) the 10 analog values. (b) Yearly observed (black) and analog (gray) temperatures averaged over western Europe, represented as normalized anomalies relative to the period 1971–2000. Smoothing by splines with 4 degrees of freedom is added, and red (blue) indicates years with observed temperatures above (below) analog ones. The recent tendency for observed temperatures to be warmer than analog temperatures is particularly prominent in both 2010 (cold record in analogues while close to normal in observations) and 2011 (warm record in observations while <1σ in analogues).

stations (Fig. 10, bottom, and Table 1). The persistence of a strong negative phase of the North Atlantic Oscillation in December 2010 could have made 2010/11 the thirteenth coldest winter since 1948 if large-scale dynamics was the sole driver of temperature variations. During this particular season the difference between observed and analog temperatures peaks over southwestern Europe, suggesting that local processes may have inhibited the maintenance of cold anomalies in this region. For all other seasons, spatial patterns of observed and analog anomalies are better correlated. In particular, large-scale circulations contributed to both exceptionally warm spring and autumn over western Europe, up to respectively ~40% and ~20% of observed anomalies. Summer dynamics were rather favorable to cold weather over France and Spain, thus preventing the development of a potential heat wave that dry conditions at the end of spring could have nurtured.

At the intraseasonal time scale, observed temperatures of 2011 were 29% of the time above the maximum of the 10 analog temperatures, and 77% above the median (Fig. 11a). This is significantly higher than the expected statistical values, respectively 1/11 = 9% (2.5–20%) and 1/2 = 50% (35%–65%) (brackets indicate 95% confidence intervals obtained from binomial quantiles assuming 40 independent days among the 396 of Fig. 11a). The heat waves of late April, late August, and late September were largely underestimated by the analogues, despite relatively high correlations between observed and analog SLP during these three periods (not shown). Overall, the analog temperature of year 2011 reaches 0.7σ, suggesting that large-scale circulations contributed to ~33% of the observed anomaly (Fig. 11b).

Conclusions. 2011 fits into the pattern of recent years where observed temperatures are distinctly warmer than analog temperatures. This is true for seasons with cold anomalies which are not as cold as expected from flow-analogues (e.g., winter 2009/10; see C10) and warm seasonal anomalies, that are hotter than the corresponding analog seasons (e.g., autumn–winter 2006/07; see Yiou et al. 2007). In addition, high interannual correlations between observed and analog temperatures confirm that the North Atlantic dynamics remains the main driver of European temperature variability, especially in wintertime.

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