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LETTER

Tropical Atlantic Influence on European Heat Waves

CHRISTOPHE CASSOU AND LAURENT TERRAY

Climate Modelling and Global Change Project, CERFACS/CNRS, Toulouse, France

ADAM S. PHILLIPS

Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, Colorado

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ABSTRACT

Diagnostics combining atmospheric reanalysis and station-based temperature data for 1950–2003 indicate that European heat waves can be associated with the occurrence of two specific summertime atmospheric circulation regimes. Evidence is presented that during the record warm summer of 2003, the excitation of these two regimes was significantly favored by the anomalous tropical Atlantic heating related to wetter-than-average conditions in both the Caribbean basin and the Sahel. Given the persistence of tropical Atlantic climate anomalies, their seasonality, and their associated predictability, the suggested tropical–extratropical Atlantic connection is encouraging for the prospects of long-range forecasting of extreme weather in Europe.

1. Link between summer North Atlantic weather regimes and extreme warm days

Europe has been rapidly warming up since the late 1970s (Jones and Moberg 2003). Concurrently, extreme weather events have become more frequent over most of the continent (Klein Tank and Können 2003). The last in date is the summer 2003 heat wave (e.g., Schär et al. 2004) responsible for massive overmortality and tremendous socioeconomic impacts in many European countries. Large-scale synoptic pressure systems over a broad North Atlantic domain directly contribute to a significant fraction of the daily to seasonal variability of the European weather. The North Atlantic–European dynamical signature of the summertime atmospheric variability is examined here through a nonlinear approach known as cluster analysis (e.g., Cheng and Wallace 1993). This method based on classification techniques seeks preferred and/or recurrent quasi-stationary atmospheric patterns or weather regimes (Reinhold and Pierrehumbert 1982) that are spatially well defined and limited in number. The day-to-day weather fluctuations can thus be interpreted as the temporal transition between them (Vautard 1990). Here, we applied the so-called k-means partition algorithm (Michelangeli et al. 1995) to 500-hPa geopotential height (Z500) anomalies estimated from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis product over the 1950–2003 period. Daily summer maps (from 1 June to 31 August; i.e., 92 days per year) are used for the analysis, and the geographical domain is limited to the North Atlantic–European region (20°–80°N, 90°W–30°E). The optimal partition is obtained for $k = 4$ summertime regimes that are about equally excited (Figs. 1a–d). The first and third can be viewed as the positive and negative phases of the "summer North Atlantic Oscillation (NAO)" (NAO+ and NAO−, respectively) (Hurrell et al. 2003). Interesting spatial asymmetries revealed by the nonlinear approach are evident between the two phases. Maximum loading is found over Scandinavia and the North Sea for NAO+ (Fig. 1a), while a clear dipole between Greenland and northern Europe dominates the NAO– pattern (Fig. 1c). The NAO+ regime can be viewed as a

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Corresponding author address: Christophe Cassou, CERFACS/CNRS, 42, Avenue Gustave Coriolis, 31057 Toulouse Cedex, France.
E-mail: cassou@cerfacs.fr

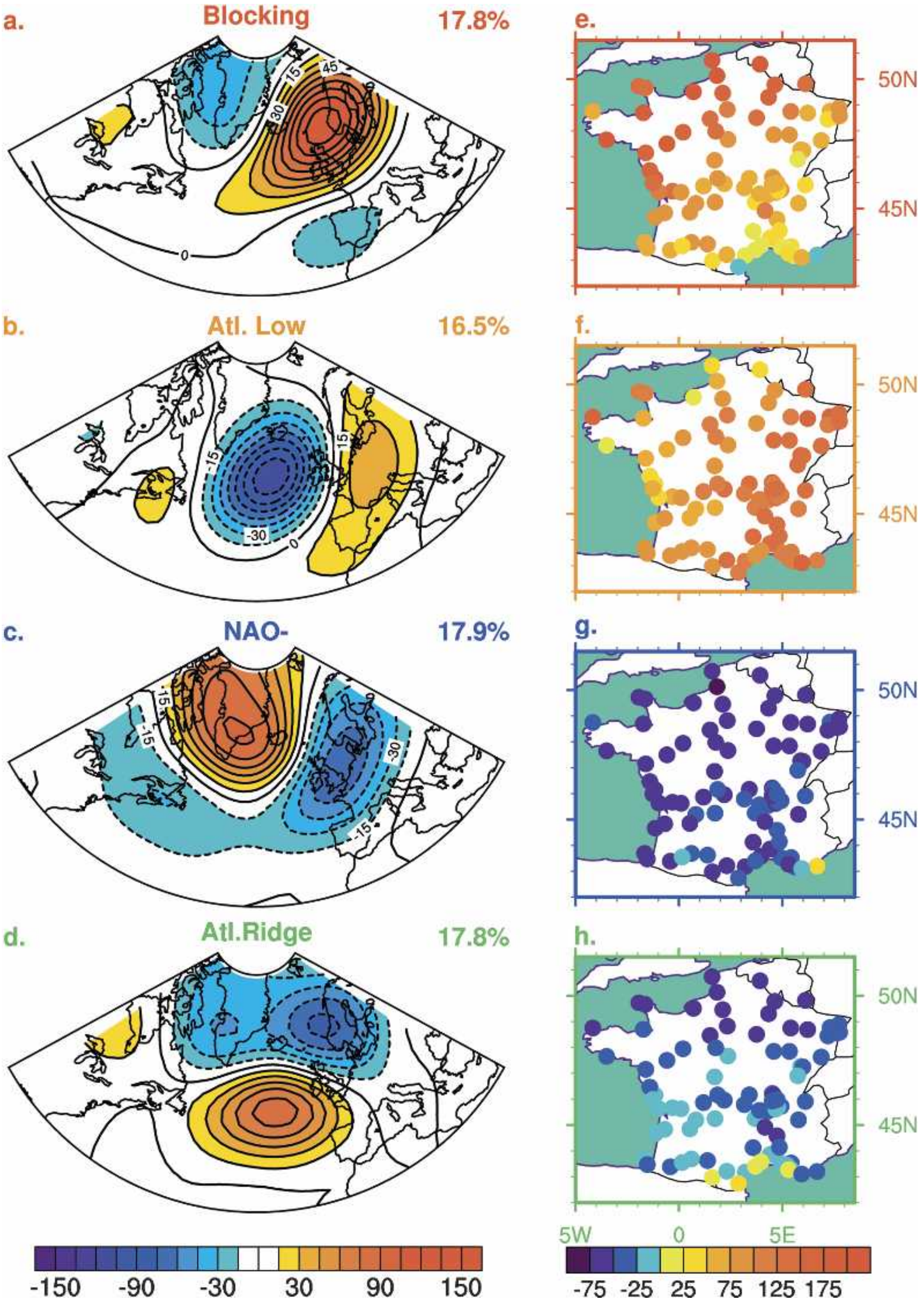

FIG. 1. (a)–(d) Summer Z500 weather regimes computed over the North Atlantic–European sector from 1950 to 2003. Contour interval is 15 m. To eliminate transient and ambiguous episodes, only sequences of 5 days or more occupied by the same cluster are retained following the regime paradigm. As a result of such a 5-day cutoff, the sum of the four regimes' 54-yr-averaged occurrence, given on the right side of the map, is not equal to 100% but is close to 70%. For simplicity, a color code is associated with each individual regime and will be kept in the following: red for Blocking, orange for Atl.Low, blue for NAO–, and green for Atl.Ridge. (e)–(h) Relative changes (%) in the frequency of extreme warm days for each individual regime as computed in Plaut and Simonnet (2001). Color interval is 25% from −100% to 200%, and red above that (max equal to 233%). As an example, 100% corresponds here to the multiplication by 2 of the likelihood for extreme warm days to occur.

TABLE 1. Percentage of occurrence for each regime for the five warmest summers in France since 1950. The selection of the year is simply based on the five highest anomalous temperatures averaged over the 91 weather stations for JJA (anomalous values given in parentheses with the year). Sums for warm regimes (Blocking + Atl.Low) and cold regimes (NAO– + Atl.Ridge) are provided in the fourth and last columns, respectively.

	Warm regimes			Cold regimes		
Year (temperature)	Blocking	Atl.Low	Sum	NAO−	Atl.Ridge	Sum
Mean occurrence	18	17	35	18	18	36
2003 (+3.21°C)	20	40	60	15	0	15
1976 (+2.18°C)	37	25	62	0	7	7
1950 (+1.99°C)	0	45	45	18	10	28
1983 (+1.39°C)	43	0	43	0	32	32
1994 (+1.02°C)	24	32	56	0	14	14

blocking-like feature (Liu 1994) and will be henceforth referred to "Blocking." The second regime (Fig. 1b), named Atl.Low, is dominated by a deep anomalous trough covering the North Atlantic Ocean, while weaker positive anomalies extend northeastward over the European continent from the Iberian Peninsula to the Baltic Sea. The fourth regime (Fig. 1d), or Atl. Ridge, displays a strong anticyclonic anomalous core off western Europe flanked to the northeast by a low pressure center. Atl.Low and Atl.Ridge bear some resemblance to the east Atlantic teleconnection pattern (Barnston and Livezey 1987).

Relationships between weather regimes and extreme warm temperatures are examined using daily maximum temperature records for 91 Météo-France meteorological stations (Moisselin et al. 2002) from 1950 to 2003. In the following, extreme warm days (or hot days) simply refer to those exceeding the 95th percentile of the temperature standard-normal climatological distribution. Our goal is to determine if the excitation of a given regime modifies the corresponding 5% probability to get a hot day. Two regimes, namely Blocking and Atl. Low, significantly favor extreme warm days, whereas NAO– and Atl.Ridge clearly inhibit their occurrence (Figs. 1e–h). Impacts from Blocking episodes are stronger in the northwestern part of France where chances for hot days to happen are locally increased by more than 3. The Blocking influence progressively diminishes, heading southeast to the Mediterranean Sea where the Atl.Low signature is more pronounced. NAO– regimes clearly preclude soaring temperatures. A latitudinal gradation is associated with Atl.Ridge, showing a quasi absence of hot days in the north of France but a slight increase of their occurrence along the Mediterranean shore and the Pyrenees foothills. For Blocking, the massive high covering the northeastern Atlantic–European domain deflects the extratropical frontal systems northward and suppresses the local convective instabilities, leading to light winds, dryness, clear skies, and warming. For Atl.Low, the advection of warm air masses from northern Africa and the Mediterranean basin dominates. Interestingly, the decomposition in regimes and their associated changes in the occurrence of extremes is able to reveal regional patterns potentially very important in terms of local impacts.

An increase (decrease) in the number of extreme warm days associated with Blocking and Atl.Low (NAO– and Atl.Ridge) is associated with a global shift in the temperature distribution. Consistently, we show that the five warmest summers in France estimated from the June–August (JJA) average for 1950–2003 are dominated by the occurrence of the Blocking and/or Atl.Low regimes, while the other two are in the minority (Table 1). The imbalance between "warm and cold regimes" is particularly clear but for summer 1983. The latter corresponds to a post–strong El Niño year where the persistent accompanying modifications in the western part of the tropical Atlantic and over Africa (basinwide suppressed convection) are expected to have played a great role following the tropical–extratropical connection detailed subsequently. In addition to the regime/extreme links, we confirm here that mean seasonal anomalies over Europe can be interpreted as the temporal integration of changes in the occurrence of shorter synoptic entities represented here by regimes. The latter are considered as the physico-dynamical attractors of the extratropical circulation, and the study of their day-to-day excitation give an alternative and powerful description for understanding midlatitude low-frequency signals (Cassou et al. 2004b).

2. Tropical Atlantic forcing for 2003

If low-frequency fluctuations in weather regime occurrence could be predicted, it might then be possible to exploit their relationship with extremes to forecast the likelihood for heat waves to arise. Midlatitude predictability is most often associated with predictable tropical forcings that induce changes of the extratropical variability across the synoptic to seasonal time scales. Previous studies have suggested a connection between tropical Atlantic diabatic heating anomalies and North Atlantic conditions mostly in winter (e.g., Hoskins and Sadershmukh 1987). Here we investigate the possible role of the tropical Atlantic in contributing to the European heat wave during summer 2003.

JJA 2003 in central and western Europe could be considered an unprecedented warm summer in the historical record (Table 1). Exceptional heat occurred during two distinctive periods: the first one in June with recorded anomalous temperature over southern France as high as +10°C, and the second one in early August coinciding with the climatological peak of summer temperature. In terms of regime, June 2003 is overly dominated by Atl.Low with 24 days out of 25 classified for this month, while the first half of August is affected by persistent Blocking conditions (not shown). We confirm here that the 2003 heat waves' timing is consistent with the regime/extreme mean relationship illustrated earlier. At the same time, the 2003 rainy season in the Sahel is the third wettest since the mid-1960s (Levinson and Waple 2004). The regional precipitation pattern reflects the intensification of the monsoon circulation associated with the anomalous persistent northward position of the entire Atlantic intertropical convergence zone (ITCZ), from the Caribbean to Africa, as estimated from outgoing longwave radiation (OLR) satellite data (Liebmann and Smith 1996). Anomalies are particularly pronounced in June in the Caribbean basin and western Africa (Fig. 2a). The contrast between prevailing wet conditions between 10° and 20°N and dry conditions along the equator clearly reflects the northward shift and/or reinforcement of the ITCZ both in July and August, especially over Africa for the latter month (Figs. 2b,c).

We analyze the possible driving impact of the alteration of the 2003 Atlantic ITCZ upon the frequency of the North Atlantic regimes using the NCAR Community Atmosphere Model (CAM)2/Community Land Model (CLM)2, coupled to a simple mixed layer oceanic component. A control coupled simulation has been first carried out for 120 yr and is used as reference. An ensemble of 40 members is then performed. Each member is integrated over 6 months, starting 1 April with the same initial oceanic conditions corresponding to the 120-yr average of 1 April ocean states in the control simulation, but differing by their initial atmospheric conditions. Spatial convective heating anomalies derived from the observed 2003 OLR monthly maps are imposed in the atmospheric model on a daily basis (Branstator and Haupt 1998) from 15 May onward. The heating perturbations are limited to the sole tropical Atlantic band (blue box in Fig. 2) and account for their intraseasonal evolution following the observations (Figs. 2a–c). Strictly speaking, the anomalous diabatic heating is treated in the model as a three-dimensional (longitude–latitude–level) additional temperature term in the temperature equation. Maximum value is reached around 500 hPa and is locally equal to ±1.2°C day^{-1} at most.

Using the exact same techniques we applied previously to reanalysis data, we verified that the model is able to correctly simulate the spatial shape of the summer Atlantic Z500 regimes as well as their residence frequency (not shown). All 92 summer days from the 40 perturbed members have been concatenated together with a 40-yr dataset (for consistency with the duration of the sensitivity experiments) taken randomly from the 120-yr-long-run control experiment. A total of 7360 maps have thus been classified and the influence of the 2003 anomalous tropical Atlantic conditions on the extratropical variability is estimated through the relative changes of the regime residence frequency (e.g., Farrara et al. 2000) in the perturbed versus control ensemble (Fig. 2d). When the 2003 tropical Atlantic conditions are introduced in the model, Atl.Ridge is clearly less excited during the three summer months. Maximum decrease occurs in August with a significant drop (−54%) of its mean occurrence. Note that the Atl.Ridge regime is totally absent during the observed summer of 2003 (Table 1). By contrast, the tropical forcing acts to amplify the residence frequency of the Atl.Low and Blocking regimes. Atl.low is significantly favored in June (+50%), while changes for Blocking are striking in August with enhanced occurrence by +69%. NAO– regimes are not significantly affected. In the present paper, we do not pretend to explain the intensity of the exceptional 2003 European heat waves. We simply suggest that, based on model results and observed regime/extreme relationships, the probability for hot days to occur was higher for this specific year because or favorable tropical Atlantic conditions acting as a forcing. In addition to synoptic features, a combination of factors, such as soil moisture, persistent drought spells, sea surface temperature anomalies along the European coasts, etc., may have significantly contributed to the intensification of the heat, as they could certainly act in combination with the perturbation of the large-scale atmospheric circulation.

3. Discussion and perspectives

Considering individual months, it is worth noting that the residence frequency changes in the perturbed en-

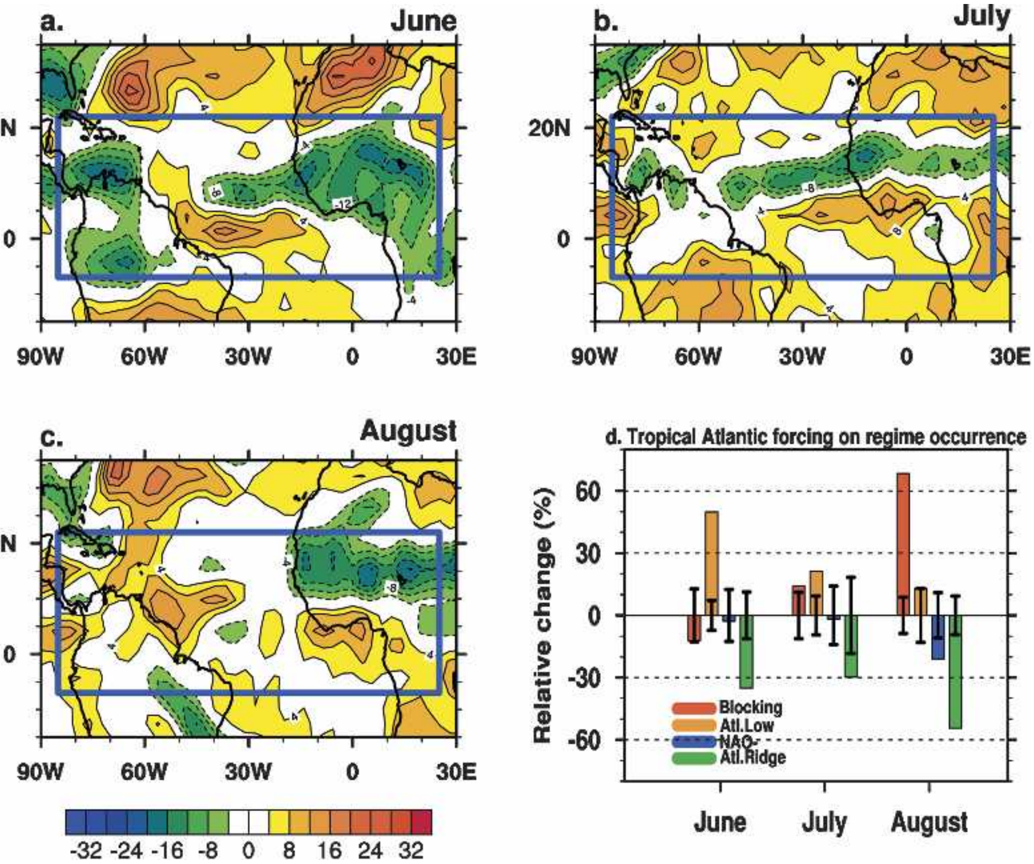

FIG. 2. (a)–(c) Observed OLR anomalies obtained from satellite product (available online at http://nomad2.ncep.noaa.gov/ncep_data/index.html). Anomalies (the base period for climatology is 1979–95) are computed for the three summer months taken individually. Greenish (orange) colors correspond to enhanced convective activity or wetter (drier) conditions. The blue box shows the tropical domain where the diabatic heating perturbations are estimated from OLR anomalies and further imposed in model experiments as detailed subsequently. Contour interval is 4 W m^{-2}. (d) Relative change (%) of occurrence of the four regimes due to the prescribed tropical forcing in the atmospheric model. We tested that the relative changes are not dependent on the choice of the 40-yr period for the control simulation. As a final estimate of the significance, the error bars indicate the range of uncertainty due to internal atmospheric variability as given by one standard deviation of the within-ensemble variability (Farrara et al. 2000).

semble are consistent with the observed timing of the 2003 regime occurrence and associated heat waves (June: Atl.Low; August: Blocking). To further illustrate this subseasonal characteristic and to go beyond the 2003 case study, we used observed monthly temperature and precipitation station data and NCEP–NCAR Z500 over 1950–2002. It is found (not shown) from correlation analyses that warm Junes in western Europe could be associated with a Rossby wave train pattern, upon which the Atl.Low regime projects very well and that originates from the Caribbean in agreement with previous studies (e.g., Ambrizzi et al. 1995; Cassou et al. 2004a). Conditions are then wetter in the northernmost part (north of the equator) of the South American continent but drier over the Amazonian basin, indicative of changes of the local meridional atmospheric circulation. By contrast, we suggest that warm Augusts are associated with a summer NAO-like pattern and enhanced monsoon across the northern and central Sahel. The model results for August 2003 reveal the existence of a direct atmospheric cell triggered by enhanced African monsoonal flow that is compensated for by reinforced sinking motion over southern Europe. But signals appear less striking from reanalysis data, and the physical mechanism responsible for the August tropical–extratropical connection is yet to be clearly determined. Our combined model and observational analyses suggest the existence of several physical mechanisms leading to warmer conditions over Europe. They seem to be associated here with the intraseasonal variability of the forcing (latitudinal migration of the ITCZ, western versus eastern tropical Atlantic heating sources, etc.) and the related intraseasonality of the tropical–extratropical teleconnection.

From a seasonal forecast perspective, we emphasize the need for time-scale interactions to be well represented in models, from climatological features within the tropical Atlantic band to the spatiotemporal properties of the regimes, especially in coupled mode. European long-range forecasts could improve with the knowledge that the summer midlatitude atmospheric circulation might be influenced by tropical Atlantic anomalous rainfall patterns that are persistent over several months, and which in turn are linked in part to oceanic surface conditions from interannual to decadal time scales (Giannini et al. 2003). It is beyond the scope of the paper to quantify the relative importance between predictable signals (SST forcings) and internal dynamics. We just detailed one "vector" of the tropical–extratropical connections, which can be potentially excited by both forced and internal variability. Despite the fact that extratropical persistent events are traditionally linked to anomalous tropical conditions leading to quasi-stationary atmospheric anomalies in higher latitudes, the role of the planetary wave anomalies propagating from the extratropics to the tropical Atlantic band should also be investigated to get a more complete view of the summer 2003 dynamics.

Finally, our results provide a dynamical basis to describe both the observed upward trend of European mean temperature and the persistent positive phase of the summer NAO (Hurrell and Folland 2002) over the last three decades. Contrasting two decadal periods (1950–70 and 1980–2003), we found that the Blocking and Atl.Low regimes are +36% and +14% more excited, respectively, at the end of the century as opposed to the occurrence of the NAO– and Atl.Ridge regimes correspondingly reduced. Our results also offer a new dynamical perspective on the projected increasing frequency of European heat waves suggested in many climate change scenarios (Meehl and Tebaldi 2004). Indeed, the northward migration/intensification of the Atlantic ITCZ is also found in paleoclimate proxy records (Poore et al. 2004) when the Northern Hemisphere continents are warmer.

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