## 15. ANALYSIS OF THE EXCEPTIONALLY WARM DECEMBER 2015 IN FRANCE USING FLOW ANALOGUES

Aglaé Jézéquel, Pascal Yiou, Sabine Radanovics, and Robert Vautard

## December 2015 in France was an extreme of circulation and temperature. Both circulation and climate change partly explain the 4°C anomaly. We found no link between climate change and circulation.

The event. The December 2015 average temperature broke a record in France, with an anomaly of +4.1°C (Fig. 15.1a) with respect to the 1949–2015 climatology. The linear trend of average December temperature (red in Fig. 15.1a) is not significant (p-value > 0.05), as regional temperature variability is high in winter. Such a positive temperature anomaly has impacts on the vegetation cycle (the French press covered this topic in the daily newspaper Le Mondel). It also affects local economies (e.g., tourism in ski resorts). The temperature anomaly was concomitant with a zonal atmospheric circulation over western Europe (Fig. 15.1b), directing mild subtropical air masses toward France. We found that the mean monthly SLP (sea level pressure) anomaly over the black box of Fig. 15.1b is also a record high for the NCEP reanalysis. Such a circulation type generally leads to warm temperatures over France (Yiou and Nogaj 2004).

In this paper, we seek to address three questions: How much does the circulation anomaly explain the temperature anomaly during December 2015 in France? What is the influence of climate change on the occurrence of the circulation anomaly? How does the distribution of temperature conditional to the atmospheric circulation evolve with climate change? We hence perform a *conditional attribution* exercise (NASEM 2016, p. 30), with a circulation that is fixed to the observation of December 2015. This estimates the thermodynamic contribution of climate change on the increase of temperature (Vautard et al. 2016; Yiou et al. 2017).

**AFFILIATIONS:** JÉZÉQUEL, YIOU, RADANOVICS, AND VAUTARD— Laboratoire des Sciences du Climat et de l'Environnement, UMR8212 CEA/CNRS/UVSQ, Institut Pierre Simon Laplace Climate Modelling Centre, and Université Paris, Saclay, Gif-sur-Yvette, France

DOI:10.1175/BAMS-D-17-0103.1

A supplement to this article is available online (10.1175 /BAMS-D-17-0103.2)

Flow analogues and the role of circulation. We evaluated the link between the SLP anomalies over the black box in Fig. 15.1b and temperature in France using the method of flow analogues (e.g., Yiou et al. 2017). We considered the French national temperature index supplied by Météo France (Soubeyroux et al. 2016). This daily index is computed as the average of 30 stations distributed over France and starts in 1949. We use temperature anomalies with respect to a daily seasonal cycle obtained by spline smoothing (cf. Yiou et al. 2008). The circulation proxy is the SLP from the National Centers for Environmental Predictions (NCEP) reanalysis, between 1949 and 2015. For each day of December 2015, we identified the 30 best analogues of SLP (with a Euclidean distance) from 1949 to 2015 on the domain delimited by the black rectangle in Fig. 15.1b. Jézéquel et al. (2017) showed that the results on analogues are qualitatively insensitive to the number of analogues (between 5 and 30 analogues). We simulate daily sequences of SLP by randomly picking one of the 30 best analogues within the NCEP dataset for each day. The repetition of this random selection (with replacements) builds an ensemble of uchronic months. Those uchronic months reproduce the SLP anomaly of December 2015 (see Figs. ES15.1a-d). We then compute monthly averages for December of the national temperature index. We hence obtain uchronic French seasonal anomalies of temperature for December. We iterated this process 104 times in order to produce *uchronic* probability distributions of monthly mean temperatures (see Jézéquel et al. 2017 for more details). This uchronic distribution of temperatures represents the ensemble of temperatures that could have been expected for the circulation observed in December 2015. We compared the uchronic distribution of temperature anomalies to a distribution built from randomly picked December days. In Fig. 15.1c, the control experiment corresponds to a monthly average of the daily temperature anomalies from the 10<sup>4</sup> random samples without conditioning on the atmospheric circulation. In order to take

<sup>&</sup>lt;sup>1</sup>http://abonnes.lemonde.fr/biodiversite/article/2015/12/30/la -nature-deboussolee-par-un-hiver-tres-doux\_4839801 \_1652692.html?xtmc=temperature&xtcr=1



Fig. 15.1. (a) Evolution of French national temperature index (°C) for Dec between 1949 and 2015. Red line is (nonsignificant) linear trend. (b) SLP anomalies for Dec 2015 relative to 1949-2015 average of NCEP Reanalysis I dataset (Kalnay et al. 1996). (c) Comparison of uchronic monthly seasonal anomalies of national index distribution for randomly picked days (control) and randomly picked analogues. Red line is observed temperature anomaly (+4°C). Three lines composing box plots are, respectively, from bottom to top, 25th (p25), median (p50), and 75th percentile (p75) of uchronic temperature anomaly distribution. Value of upper whiskers is min [1.5 × (p75 - p25) + p50, max (temperature anomaly)]. Value of lower whiskers is its conjugate. Circles represent values that are outside of whiskers.

into account the dependence between consecutive days in the *Control* distribution, we calculated the monthly means using only every third day (Jézéquel et al. 2017).

We find that the SLP partly explains the monthly temperature anomaly in France during December 2015 (Fig. 15.1c). The median of the *uchronic* temperature anomaly distribution is 1.3°C (i.e., ~30% of the anomaly). The other ~70% of the anomaly could be explained by other factors (e.g., snow cover feedback). This positive anomaly demonstrates the link between the synoptic situation and the anomaly of temperature in France and justifies the choice of a conditional attribution approach.

Role of climate change. In order to estimate the role of climate change, we rely on the CESM1 model large ensemble, CESM-LENS (Kay et al. 2015). We use 30 members for both surface temperature and SLP using historical runs between 1951 and 2005 and RCP8.5 between 2006 and 2100. We reconstitute the French national temperature index from the surface temperature using the coordinates of the 30 stations used to calculate the index. Kay et al. (2015) showed that CESM-LENS reproduces reasonably well features of the Northern Hemisphere atmospheric circulation. An analysis of the SLP distances between those observed during December 2015 and CESM simulations indicates that they are not statistically different from the NCEP reanalysis (Fig. ES15.1e). We hence consider that this model does not yield biases that prevent its use for the purpose of this study.

We estimate the influence of climate change on the circulation pattern leading to December 2015 by computing the probability distributions of distances between SLP anomalies among all the December days in both NCEP and CESM and the closest day of December 2015 (Fig. 15.2a). We keep only the distances below the 5th percentile of the distribution, in order to focus on the days with SLP anomalies closest to those observed in December 2015. For each December, we count the number of days below this threshold for each ensemble member (NCEP and CESM). If the circulation that prevailed in December 2015 became more frequent with time, then a trend should be detected in this number of days. We detect no such trend. Therefore it is not possible to conclude there is an impact of climate change on the atmospheric circulation itself.

We then estimate the temperature anomaly for a similar event in terms of synoptic circulation without climate change, and in future climate change sce-



Fig. 15.2. (a) Number of days per year with SLP distances below 5th percentile of distribution of daily distances to closest December 2015 day. Box plots show dispersion of CESM ensemble members. Blue lines-dots are values for NCEP reanalysis. Red line is (nonsignificant) linear trend of median of CESM ensemble members. (b) Box plots of control distributions (respectively *uchronic* distributions) of anomalies of national temperature index relative to observed climatology of this index between 1948 and 2015, in yellow (orange) using NCEP and in red (pink) using CESM-LENS subsets.

narios by computing analogues of circulation from different periods of observations and CESM simulations. We analyzed the uchronic temperature anomalies constructed with analogues of the December 2015 flows from two time periods of the NCEP dataset. We compared an early subset of 33 years (1949-1981) to a more recent one (1982-2014). The two gold box plots in Fig. 15.2b represent those two experiments. We detected a difference of 0.4°C between the two distributions, in contrast with the monthly temperature trend for 1949-2015 displayed in Fig. 15.1c, which is not significant. However, it is not possible to attribute this difference of temperature to climate change, as it could also relate to interdecadal variability, especially for very small subsets of 33 years, whose length was imposed by the NCEP reanalysis length.

In order to study the relative influences of climate change and variability, we rely on CESM-LENS. We study three periods of 50 years: 1951-2000, 2001-50, and 2051-2100. Using 30 members, we have 1500 years of data for each subperiod from which we can calculate the analogues (which correctly represent the observed SLP anomaly as displayed in Figs. ES15.1ad). This reduces the uncertainty related to the quality of the analogues we picked. The three pink box plots in Fig. 15.2b represent the uchronic distributions for SLP analogues picked from CESM-LENS. The three red box plots represent the *control* distributions for the same subperiods. We observe that the December 2015 anomaly of temperature was never reached before 2000. It is still not reached for 2001-50 under the RCP8.5 scenario. For the second half of the twentyfirst century, the temperature anomaly is expected to exceed 4°C for the same synoptic situation. The observed anomaly is still warmer than the median of the *control* distribution. A caveat of this study is that we only used one model, which could have biases especially in the future.

Conclusion. The month of December 2015 set a record temperature in France. The zonal circulation that prevailed over western Europe during the whole month accounts for ~30% or 1.3°C of the temperature anomaly. No trend was found in the atmospheric circulation patterns themselves (Fig. 15.2a). For this given circulation, our analysis shows that the observed temperature is never reached in the second half of the twentieth century (Fig. 15.2b), and the model is unable to reach it even during the first half of the twenty-first century. However, the December temperature observed in 2015 is projected to be exceeded in the second half of the twenty-first century under the same synoptic situation. Cattiaux et al. (2010) found with a similar analysis that the cold winter of 2009/10 would have been colder if not for climate change. Our analysis of December 2015 is a warm counterpart to that study. We find a 1.4°C difference between the median of the uchronic temperatures of the second half of the twentieth century and the first half of the twenty-first century and an additional 1.9°C for the second half of the twenty-first century. We find approximately the same differences between control distribution medians, which means that the trend conditional to the circulation equals the unconditional trend.

**ACKNOWLEDGMENTS**. PY, AJ, and SR are supported by the ERC grant No. 338965-A2C2. This work is also supported by the Copernicus EUCLEIA project No. 607085. We thank two anonymous reviewers, Marty Hoerling and Stephanie Herring for their constructive comments.

## REFERENCES

- Cattiaux, J., R. Vautard, C. Cassou, P Yiou, V. Masson-Delmotte, and F. Codron, 2010: Winter 2010 in Europe: A cold extreme in a warming climate. *Geophys. Res. Lett.*, **37**, L20704, doi:10.1029/2010GL044613.
- Jézéquel, A., P. Yiou, and S. Radanovics, 2017: Role of circulation in European heatwaves using flow analogues. *Climate Dyn.*, First Online, doi:10.1007 /s00382-017-3667-0.
- Kay, J. E., and Coauthors, 2015: The Community Earth System Model (CESM) large ensemble project: A community resource for studying climate change in the presence of internal climate variability. *Bull. Amer. Meteor. Soc.*, **96**, 1333–1349, doi:10.1175 /BAMS-D-13-00255.1.
- Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, 77, 437–471, doi:10.1175/1520-0477(1996)077<0437 :TNYRP>2.0.CO;2
- NASEM, 2016: Attribution of Extreme Weather Events in the Context of Climate Change. National Academies Press, 165 pp., doi:10.17226/21852.
- Soubeyroux, J.-M., G. Ouzeau, M. Schneider, O. Cabanes, and R. Kounkou, 2016 : Les vagues de chaleur en France: Analyse de l'été 2015 et évolutions attendues en climat futur (in French). *La Météorologie*, 94, 45–51, doi:10.4267/2042/60704.
- Vautard R., P. Yiou, F. Otto, P. Stott, N. Christidis, G. J. van Oldenborgh and N. Schaller, 2016: Attribution of human-induced dynamical and thermodynamical contributions in extreme weather events. *Environ. Res. Lett.*, **11**, 114009, doi:10.1088/1748 -9326/11/11/114009.
- Yiou, P., and M. Nogaj, 2004: Extreme climatic events and weather regimes over the North Atlantic: When and where? Geophys. Res. Lett., 31, L07202, doi:10.1029/2003GL019119.
- —, K. Goubanova, Z. X. Li, and M. Nogaj, 2008: Weather regime dependence of extreme value statistics for summer temperature and precipitation. *Nonlin. Processes Geophys.*, **15**, 365–378, doi:10.5194 /npg-15-365-2008.
- —, A. Jézéquel, P. Naveau, F. E. L. Otto, R. Vautard, and M. Vrac, 2017: A statistical framework for conditional extreme event attribution. *Adv. Stat. Climatol. Meteor. Oceanogr.*, **3**, 17–31, doi:10.5194 /ascmo-3-17-2017.