EXPLAINING EXTREME EVENTS OF 2018

From a Climate Perspective

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EXPLAINING EXTREME EVENTS OF 2018 FROM A CLIMATE PERSPECTIVE

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COVER CREDIT: iStock.com/Alena Kravchenko—River Thames receded during a heatwave in summer 2018 in London, United Kingdom.

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ANALYSES OF THE NORTHERN EUROPEAN
SUMMER HEATWAVE OF 2018P. YIOU, J. CATTIAUX, D. FARANDA, N. KADYGROV, A. JÉZÉQUEL, P. NAVEAU, A. RIBES,
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A heatwave struck Northern Europe in summer 2018. The probability of this event increased with human-induced climate change primarily due to thermodynamic changes.

A heatwave struck northern Europe in the summer of 2018. Daily temperature anomalies reached +14 K in Scandinavia, the Netherlands, and Belgium, which are record-breaking temperatures. This heatwave was exacerbated by a drought caused by a persisting circulation anomaly (Kornhuber et al. 2019; Toreti et al. 2019; World Weather Attribution 2018). The heatwave and drought favored unprecedented forest fires in Scandinavia (NASA Earth Observatory 2018).

This paper aims at characterizing this heatwave event and determining its probability in present and future climate conditions. This paper presents how the 2018 heatwave can be analyzed in terms of temperature

and atmospheric circulation patterns, and highlights the robustness of the signal to statistical hypotheses.

DEFINING THE EVENT. Defining the spatiotemporal scale of the event is inspired by the procedure of Cattiaux and Ribes (2018), which consists in selecting the space–time window for which the temperature has been the most extreme (i.e., its probability p is the smallest in present-day conditions). We use E-OBS (Haylock et al. 2008) daily mean temperatures over 1950–2018 and consider each N -day time window between 1 May and 31 October, and each n -country connected spatial domain. Overall, we find that the probability p is minimum for the 19-day window between 15 July and 2 August and the two-country domain covering Finland and Sweden. However, this minimum is not sharp and adding the Baltic countries, Denmark, and Norway to the spatial domain does not significantly change p . Since a larger domain is more robust for the latter analyses, we define the spatial scale as the 5°–30°E, 55°–70°N area (Fig. 1a). This corresponds to the “Scandinavian cluster” type of heatwave identified by Stefanon et al. (2012). Over this space–time window, the average temperature anomaly relative to the 1981–2010 climatology is +5.4 K (Fig. 1b), and each single day during this time period in 2018 is more than +3 K above the climatological mean seasonal cycle (see Fig. ES1a in the online supplemental material). The atmospheric circulation is characterized by prolonged high pressure conditions (Fig. 1c) over Scandinavia. This motivates the conditional attribution analysis with respect to the atmospheric circulation, because such circulation patterns generally enhance major heatwaves in the midlatitudes (Quesada et al. 2012; Mueller and Seneviratne 2012), as was observed in summers 2003 (Schär et al. 2004) or 2010 (Barriopedro et al. 2011).

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FIG. 1. Geographical and temporal features of the event from reanalyses and observations. (a) Map of temperature anomalies in E-OBS between 15 Jul 2018 and 2 Aug 2018, with respect to a 1981–2010 climatology. The rectangle indicates the zone to be analyzed (e.g., Scandinavia). (b) Time series of spatial [rectangle in (a)] and temporal (15 Jul to 2 Aug) average temperature (E-OBS) from 1950 to 2018, with reference 1981–2010 climatology. (c) Anomalies of Z500 in NCEP over the North Atlantic between 15 Jul 2018 and 2 Aug 2018, with respect to the 1981–2010 climatology. The rectangle indicates the zone for the computation of analogs.

UNCONDITIONAL ATTRIBUTION. The unconditional attribution compares the probability p_1 of observing the event (exceeding a temperature threshold) in the present day or in a climate influenced by human activities (a factual world), and the probability p_0 of the event in past conditions or in a climate without human influence (a counterfactual world). We focus on the probability ratio (PR) p_1/p_0 . The results from two different statistical approaches are presented here.

First, we determined p_1 and p_0 from annual maximum 19-day averaged temperature over the region in E-OBS data by fitting the period 1950–2017 to a generalized extreme value (GEV) distribution. The location parameter μ is a linear function of a proxy for global warming, for which we take the 4-yr smoothed global mean surface temperature [as in (Kew et al. 2019)]. This procedure excludes the observed extreme in 2018, as GEV parameter estimates are sensitive to the last value of a time series. The fit was extrapolated to the global temperature of 1900 as

a proxy of the preindustrial climate. The procedure was applied to a few ensembles of transient climate model experiments (EC-Earth2.3 T159 coupled 1860–2018; RACMO 2.2 11-km downscaling this EC-Earth ensemble 1950–2018; HadGEM3-A N219 prescribed SST 1960–2015; calibrated Euro-CORDEX ensemble 11-km 1971–2018; see Fig. 2a). These have realistic variability of 19-day heat extremes: the fitted scale and shape parameters are compatible with the fit to observations. Uncertainty ranges for each dataset were obtained from bootstrapping. Model spread was also added to the model estimates to obtain $\chi^2/\text{dof} = 1$. We plot the probability ratios and associated uncertainties in Fig. 2a. This diagnostic shows that PR values are significantly larger than 1, with a large range of variations (PR synthesis between models and observations between 5 and 2,000), indicating that such a heatwave is between 5 and 2,000 times more likely in the factual simulations.

A second unconditional attribution was performed on the E-OBS dataset and a CMIP5 (Taylor et al. 2012)

FIG. 2. (a) Probability ratios (PR) from observations (E-OBS) in blue, and climate model simulations (EC-EARTH, RACMO, HadGEM3, Euro-CORDEX ensemble) in pink, all models in red, and observation–model synthesis in purple. The black vertical lines indicate the value of the best fit. The white boxes represent the model spread that is added to the pink boxes, representing a conservative uncertainty due to natural variability to obtain $\chi^2/\text{dof} = 1$. **(b) Conditional temperature simulations in CMIP5 and in E-OBS for different periods.** The boxplots represent the temperature distributions, conditioned to the atmospheric circulation observed during event that are simulated through the analog procedure for different periods. For the CMIP5 models, the temperatures are simulated independently for each model and the boxplots represent the distribution of all the temperatures simulated for the CMIP5 models altogether. The circle points on the boxplots represent the simulated temperatures that are 1.5 times the interquartile range above the upper quartile and below the lower quartile. The red line denotes the value of the observed mean temperature between 15 Jul and 2 Aug 2018.

simulation ensemble using the method of (Ribes et al. 2019). The distribution of mean temperature over the considered space–time domain is assumed to follow a Gaussian distribution, and to covary with a variable representing climate change. This covariate is the summer mean continental temperature over the box -10° to 30°E , 35° to 70°N . The probability of the event can be estimated continuously in time. This calculation is made for each CMIP5 model and summarized into a multimodel synthesis. Then, changes in the covariate and the temperature distribution are constrained by E-OBS observations [see Ribes et al. (2019) for details]. Figure ES2a shows the probability ratio from 1850 to 2100, under the high-emission RCP8.5 scenario (van Vuuren et al. 2011),

according to the multimodel synthesis constrained by observations. The effect of human activities on the probability of such event cannot be detected before the end of twentieth century as the probability ratio is not significantly different from 1. After the year 2000, the probability ratio is significantly higher than 1 and suggests that human activities have increased the probability ratio of such events. In 2018, the probability of such events has increased by a factor of 39 (95% confidence interval: 3 to 3,400; see Fig. ES2a) due to human activities.

CONDITIONAL ATTRIBUTION. We determine the temperature distribution *conditional* to atmospheric patterns that are similar to 2018 changes

with time. Following the procedure of Jézéquel et al. (2018b), we computed analogs of geopotential height at 500 mb (Z500) over a zone covering Scandinavia (rectangle in Fig. 1c), which optimizes the temperature/circulation correspondence. The analogs are computed from Z500 in two subperiods (1950–84 and 1985–2018) of the NCEP reanalysis (Kistler et al. 2001). The Z500 data are detrended with a smoothing spline before computing analogs, in order to avoid a bias due to the temperature increase. Ten days (out of 19) yield good analogs (distance < 30th quantile and spatial correlation > 70th quantile). Mean analog temperatures are simulated by random selections of analog days from each subperiod, following the procedure of Jézéquel et al. (2018b). The change of temperature probability distributions describes the thermodynamic changes on a summer that is similar to 2018. A total of 10,000 stochastic samples are generated, with analogs selected in the two subperiods. The changes are significant according to a two-sided Kolmogorov–Smirnov test (p value < 10^{-15}).

Although the simulated values do not reach the 2018 record, we find a significant increase of the temperature distribution between the two subperiods (Fig. 2b). This ~1-K increase is comparable to the average increase of temperature between the two subperiods. When analogs are selected in RCP8.5 CMIP5 simulations, we find that similar atmospheric patterns lead to summer temperatures that are consistent with the 2018 record values. This means that temperature anomalies of a similar heatwave (same domain, duration, and atmospheric circulation) would reach or exceed 5 K by the end of the twenty-first century (Fig. 2b).

CHANGES IN ATMOSPHERIC CIRCULATION. We diagnosed atmospheric circulation trends by analyzing the distance values of the best analogs (Jézéquel et al. 2018a), the local dimension, and persistence (Faranda et al. 2017). This was done by comparing the observed Z500 anomaly sequence (in NCEP), and other observed sequences in NCEP or simulated in the RCP4.5 and RCP8.5 scenarios.

First, we computed the distribution of Z500 distances to the hottest day of the heatwave (17 July 2018) in NCEP and the RCP4.5 and RCP8.5 scenario simulations. We then counted the number of analogs whose distance is below the 5th quantile of all distances, for each summer. The distance distribution informs on the likelihood to have a similar atmospheric pattern as the observed one (Jézéquel et al. 2018a). We find no significant trend in the number of good analogs in NCEP reanalysis or scenario

simulations (Fig. ES2c); some CMIP5 simulations do identify marginally significant trends, but there is no consensus among models, as was found for the 2003 heatwave (Jézéquel et al. 2018a).

Second, we computed the *local dimension* of the observed Z500 sequence in CMIP5 RCP4.5 and RCP8.5 simulations. This assumes that the observed state belongs to the climate variability described by climate models, which is validated by the fact that the distribution of analog distances for each model is similar to the NCEP reanalysis distances (Rodrigues et al. 2018). The local dimension informs on the number of degrees of freedom of trajectories around a given state and hence on its predictability (Faranda et al. 2017). We find no significant trend in the local dimension of summer 2018 Z500 in CMIP5 RCP4.5 and RCP8.5 simulations.

Third, the *extremal index* informs on the persistence of a given state (i.e., the time it takes to leave its neighborhood in phase space) (Faranda et al. 2017). As for the local dimension, the local persistence of summer 2018 Z500 was evaluated on CMIP5 RCP simulations. We find a small but significant decrease of the persistence of these weather patterns (Fig. ES2d).

CONCLUSIONS. This paper refines the preliminary analyses of the World Weather Attribution for that event (World Weather Attribution 2018). Our analyses demonstrate the thermodynamic contribution of human-induced climate change to describe the probability and intensity of the summer 2018 event in Scandinavia. The bulk values and uncertainties of the probability ratios are significantly larger than 1 in two statistical approaches with different underlying technical assumptions. Hence we find a strong and robust contribution of human activities to 2018 heatwave in northern Europe from the unconditional attribution analysis. This is further supported by an analysis of record probabilities (see our online supplemental material S2b; Naveau et al. 2018). The wide range of probability ratios from the model ensemble calls for a calibration of the model outputs (Bellprat et al. 2019), which is outside the scope of this short paper. Therefore those probability ratios should be used in a qualitative manner, rather than quantitative.

The atmospheric conditions enhance the temperature signal (~+2 K; Fig. 2b), but the conditional attribution simulations cannot reach the observed record values, possibly because some physical processes are not taken into account (soil moisture feedbacks and ocean variability).

Those results emphasize the necessity of systematic analyses of European heatwaves (Stefanon et al. 2012), for which the properties of the atmospheric circulation do not change uniformly in scenario simulations (Jézéquel et al. 2018a). This also highlights uncertainties in the changes of atmospheric circulation.

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