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Comparing observed and hypothetical climates as a means of communicating to the public and policymakers: The case of European heatwaves

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ABSTRACT

The summer of 2015 in many parts of Europe was seen to break record hot temperatures, and was the second-hottest on record after the 2003 event. Here we use de-trended climate data since 1951 to assess the difference in peak temperatures and duration of hot summers had climate not warmed by over 1 °C at the scale of the Northern Hemisphere. The rise in mean European summer temperatures since the 1950s has certainly contributed to the intensity of European heatwaves (e.g., 2003, 2010, or 2015) compared to what they could have been in a more stationary climate. Here we show that the number of hot days in the de-trended record would have been reduced by 10–25% for the 30 °C threshold and by 25–50% for the 35 °C level. As a consequence, the severity of the impacts on natural and managed systems linked to extensive and prolonged heatwaves would have been far more limited. The simple statistical approaches presented in this study, that highlight the reduced intensity of heatwaves in a hypothetical "stationary climate", can serve to raise awareness as to the need to limit future warming and help guide policy, for example in the implementation of the "+1.5 °C policy" recently negotiated at the COP-21 climate conference in Paris.

1. Introduction

Europe has experienced a number of record-breaking, high-impact heatwaves (IPCC 2010; Stott et al., 2004) since the turn of the 21st century. In particular, the massive 2003 heatwave in Western and Central Europe has been the focus of much scientific attention (Beniston 2004; Schaer et al., 2004; Beniston and Diaz 2004), as was the Russian heatwave in 2010 (Grumm, 2011). Some studies have attempted to explore the physical mechanisms underlying these extreme events (Della-Marta et al., 2007; Easterling et al., 2000), and the negative impacts they generated on natural and socio-economic environments. The summer of 2015 broke many records, in particular in Spain, the UK, France, Switzerland, Germany, and Poland. A survey of the 2015 heatwave conducted by the Swiss weather service (Meteo Swiss, 2015) has shown that July 2015 has in many places been the hottest month since records began in the 19th century, and several all-time records of daily temperature maximum (T_{max}) have been broken. In the early days of July 2015, cities like Madrid, Spain (39.9 °C), London, UK (36.7 °C), Kitzingen near Würzburg, Germany (40.3 °C), Maastricht, Netherlands (38.7 °C) and Geneva, Switzerland (39.7 °C) broke their all-time record highs. However, the three summer months (June, July, and August, or JJA) of 2015 still lag 2003 as the hottest summer of the past 500 years (Luterbacher et al., 2004).

Studies pertaining to recent heatwaves have attempted to attribute the intensity and persistence of these events to climate change (Stott et al., 2004; Fischer and Schär, 2010; Fischer and Knutti, 2015; Rahmstorf and Coumou, 2011; Coumou and Rahmstorf, 2012). In this contribution, we show that the heatwaves experienced in Europe would not have been as remarkable had climate in the Northern Hemisphere not experienced a mean temperature increase of more than 1 °C since the 1950s, according to East Anglia's Climate Research Unit (CRU) temperature record (Brohan et al., 2006). However, we are not seeking here to undertake yet another attribution study which have been

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sufficiently convincing in recent papers. We are rather aiming, through some rather simple statistical approaches, at defining another way of communicating on extreme climate events to the general public and to decision makers. It is obvious that the heatwaves experienced in the last couple of decades have been damaging for many sectors, in particular health (e.g., Johnson et al., 2005; Kovats and Ebi, 2009); agriculture (e.g., van der Velde et al., 2010); water resources (e.g., Fink et al., 2004); energy resources (e.g., Koch and Vögele, 2009); or ecosystem functioning (e.g., Ciais et al., 2005; Teuling et al., 2010); to name but a few sectors. In terms of communication, however, it can be interesting to show how the world may have been had climate not experienced the rate of observed warming. In other words, if climate had remained as it was in the mid-20th century, then the duration and intensity of heatwaves would not been as severe as observed. The obvious sequel to this line of reasoning is that there is everything to be gained in acting rapidly in favor of limiting future warming, since this would help in averting even more severe heatwaves in coming decades.

The results of the investigations reported here can help in formulating novel communication approaches on issues of climatic change and climate extremes. Indeed, what is proposed here can be of interest not only for discourses pertaining to a very uncertain future (Meehl and Tebaldi, 2004), highly-dependent on the carbon emissions in the next decades, but also to highlight how heatwaves may have behaved in today's climate had temperatures not increased as observed. The "what if" approach outlined in this paper (i.e., what if climate had remained at its 1950s levels), helps to convey the notion that climate change is not simply a matter of shifts in mean values but also in their extremes. The approaches that will be outlined further in this text reinforce the notion of urgency to act in favor of limiting future warming as recognized *inter alia* through the signature of the COP-21 accord (21st meeting of the Conference of the Parties to the UN Framework Convention on Climate Change, December 2015; e.g., Hulme, 2016).

2. Methods and data

This study has used the climate records archived in the European Climate Assessment and Data (ECA&D) database (Klein Tank et al., 2002). ECA&D data is updated on a monthly basis and quality-checked for homogeneity, making it one of the more reliable European observation datasets for statistical studies as reported in this paper. Only homogenous data has been selected for this study, in order to ensure greater robustness in the upper tails (i.e., beyond the 90 or 95% quanties) of the probability density function (PDFs) of temperature, that can be sensitive to the quality of observational data. Unfortunately, very long data sets are available (i.e., dating back to at least the beginning of the 20th century) for only a few stations, so our focus is on the period 1951–2015, where substantially more stations are available. The primary data used in the present study is daily maximum temperature (T_{max}).

The locations selected for this study have a pan-European spread and are representative of its main climatic regimes (i.e., Mediterranean, maritime, continental). They are all representative of large centers of population or close to some of the leading cities of Europe, where a large proportion of its citizens live. They have been impacted significantly by recent heatwaves, and may well be increasingly affected in the future (Meehl and Tebaldi, 2004). Fig. 1

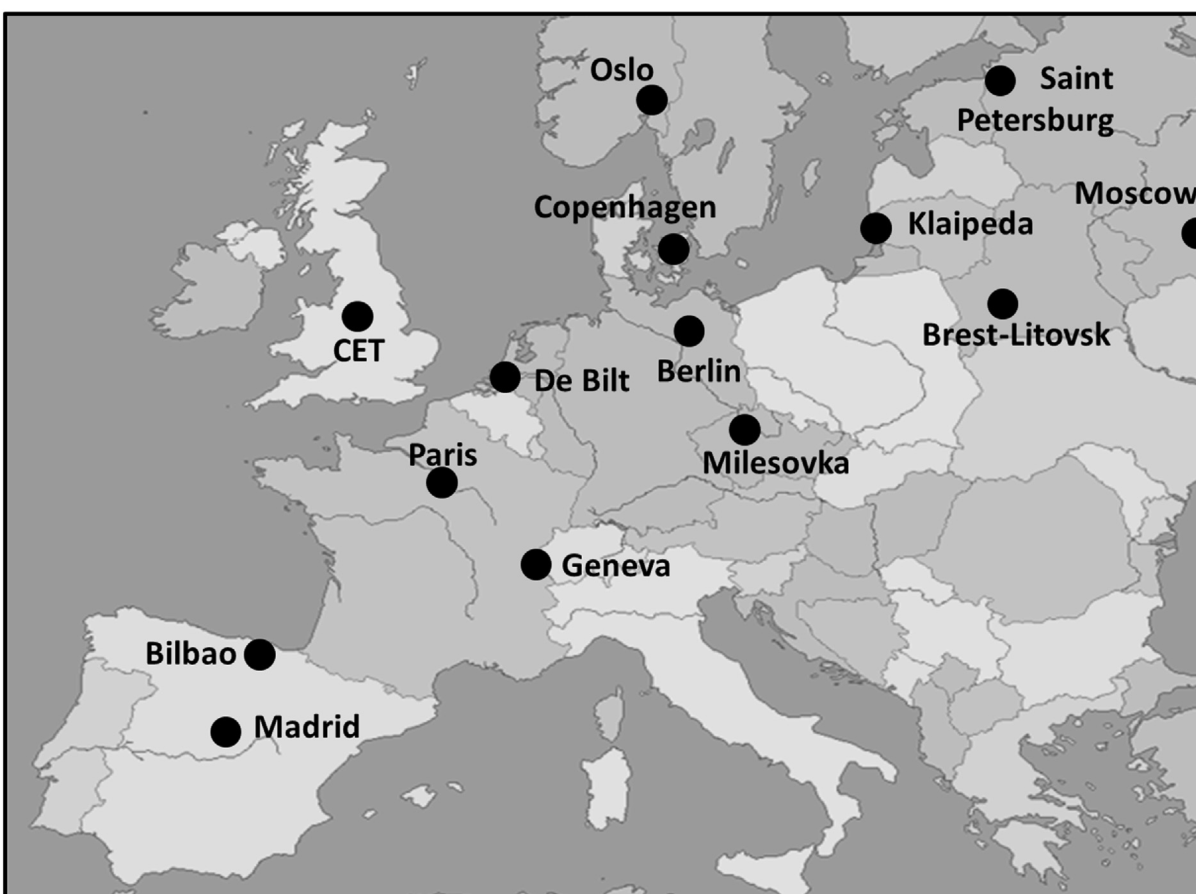

Fig. 1. Location of the 14 European climate stations used in this study.

shows the geographic location of the 14 stations that have been analyzed in this study and their geographical spread throughout the numerous climatic zones in Europe.

We have used the Northern Hemisphere (NH) dataset of the Climatic Research Unit (CRU) of the University of East Anglia, UK (www.cru.uea.ac.uk) in order to define the baseline that has been used to de-trend the observed data at each European location studied here. The CRU hemispheric data set is a recognized standard in the climate community, and using the NH data rather than the European Tmax trends implies that studies of this nature could be conducted elsewhere in the Northern Hemisphere with the same baseline data for comparison purposes. The linear temperature regression yields a trend of 0.21 °C per decade between 1951 and 2015 for the hemispheric data and 0.46 °C per decade for the European data. De-trending the observed temperature record enables a comparison of a range of statistics such as threshold exceedance between observed (real) climate over the past 65 years and a de-trended temperature record representative of a climate characteristic of the mid-20th century (the term '1950s-type climate' will hereafter refer to the climate record that has been de-trended using the Northern Hemispheric temperature trend as the baseline). The 1950s-type climate record itself exhibits a rising trend that is close to that of the NH record, suggesting a stronger-than-hemispheric warming in Europe as alluded to *inter alia* by Van Oldenborgh et al. (2009), Seneviratne et al. (2006) or Klein Tank et al. (2005). The 1950s climate is thus not stationary in the sense of data oscillating around a zero-trend line, but is representative of a climate much less strongly influenced by the forcing factors that have resulted in the current, observed, climate.

The statistics used to highlight the differences between the real and the stationary climates include exceedances beyond fixed temperature thresholds, and analyses of the upper tails of the T_{max} probability density functions (PDFs).

3. Results

Investigations reveal substantial differences between the real and hypothetical climates for all the 14 European locations considered in this study. Fig. 2 shows an example of the evolution of mean summer Tmax from 1951 to 2015 for Paris, for the observed record versus the hypothetical stationary (i.e., de-trended) climate. As for all the other European locations studied here, the Paris trends clearly highlight the fact that European summer temperatures have increased far more rapidly than the hemispheric trends since the early 1950s (Van Oldenborgh et al., 2009), with linear regression slopes of 0.46 °C per decade for the observed data and 0.21 °C per decade for the Northern Hemisphere data.

As an example of the differing duration and intensities of heatwaves in a de-trended (hypothetical) vs observed climate, Fig. 3 highlights the evolution over time of the difference in the number of events where observed temperatures exceed the 30 °C and 33 °C thresholds in Madrid, Paris and Moscow, and the de-trended data. These particular sites have been highlighted in view of the climatic zones that they represent, i.e., a transect from Mediterranean to Boreal regimes. The temperature thresholds, including the 36 °C threshold that will be referred to later, have been chosen arbitrarily, but do enable a comparison across the different European sites where almost all have exceeded one or more of these thresholds in the observed record since 1951. The days where the respective thresholds are exceeded in the observed record but not in the de-trended data only become apparent from the early 1980s onwards, which is when the observed and de-trended climate curves begin to diverge (as already seen between the red and blue curves in Fig. 2).

Table 1 summarizes for the three locations illustrated in Fig. 3 the cumulative exceedances of the 30, 33, and 36 °C thresholds between observed and de-trended data. The table thus shows how many additional days beyond this threshold have been recorded compared to the 1950s climate.

As time progresses, the de-trended record does not exhibit the large spread of days where the temperature thresholds are exceeded, even for the massive 2003 and 2015 events. In the observed climate, exceedances beyond 30 °C can be observed any time between the end of May and early September, whereas in the 1950s-type climate, it is mostly from mid-June to mid-August that such exceedances are encountered. This is illustrated in Fig. 4 using Geneva as an example representative of a central European location; the figure provides a Hovmoeller-type representation where we have plotted the dates of occurrence when the 30 °C, 33 °C, and 36 °C thresholds are exceeded in the observations but not in the 1950s-type climate. The first years of divergence between observed and de-trended hot-days appear in the early 1980s, and the data fans out over time into periods that can extend from late May into early September. Very similar conclusions can be reached for all the other locations studied, as provided in Table 2 below that summarizes the differences between the threshold exceedances of observed vs de-trended data for the entire period of record. Comparison between the two data sets in Geneva also reveals that the average observed JJA T_{max} was 31.5 °C for the 2015 heat wave, compared to 30.4 °C for the de-trended data, i.e., 1.1 °C cooler. The period with temperatures exceeding 30 °C during the 2015 heatwave was observed to begin on June 4 and end on August 31, whereas if climate had been of the 1950s-type, the respective dates would have been July 1 and August 31, i.e., a 27-day reduction in the number of days with temperatures exceeding 30 °C.

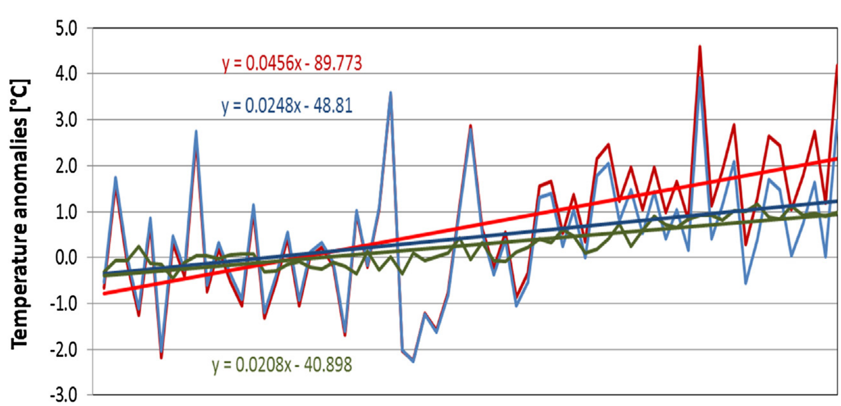

Fig. 2. T_{max} trends in Paris since 1951, for the observed record (Red), the Northern Hemisphere record (Green), and the de-trended data (Blue). The linear regression relationship is provided for all three curves.

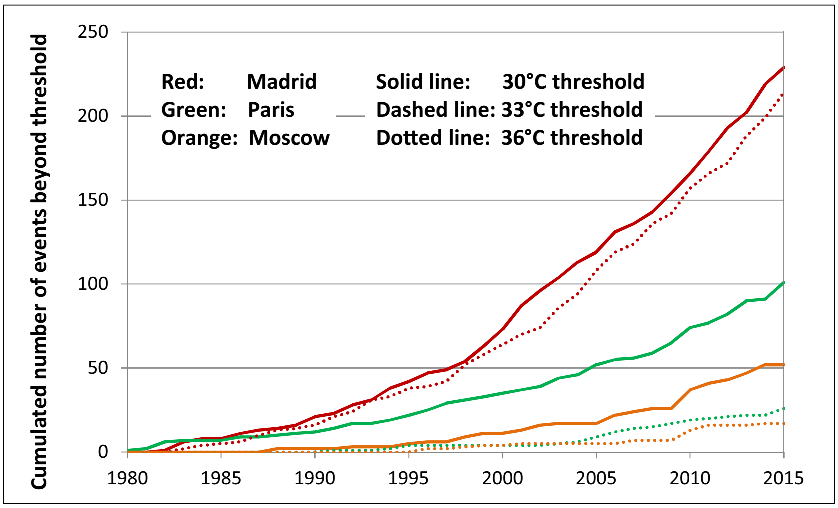

Fig. 3. Time evolution of the difference in the number of events between observed and de-trended climates where temperatures exceed the 30 °C and 33 °C thresholds in Madrid (Red), Paris (Green), and Moscow (Orange).

Table 1
Number of days during which particular temperature thresholds are exceeded in the observed climate by 2015 compared to the 1950s-type climate for four locations, three of which are illustrated in Fig. 3.

	30 °C	33 °C	36 °C
Madrid	229	214	104
Paris	104	26	8
Moscow	52	17	5

What Table 2 attempts to summarize is that if climate had not warmed at the observed Northern Hemisphere rate, then the duration and intensity of heatwaves in Geneva, and at the other studied European locations, would have been substantially lower than observed.

The behavior of the observed and de-trended data for the 14 European locations is provided in Fig. 5, with a focus on August that is generally one of the hottest months of the year. A clear shift toward higher temperatures is detected in the observed record over the period 1951–2015. Indeed the median (Q2), third quartile (Q3), and higher quantile temperature values all show pronounced upward trends. The same analyses were performed for the months of May, June, July, and September (not shown), and all months exhibit similar increasing trends. Looking at Fig. 5b for the de-trended data, we observe that increasing trends are much more modest for the higher quantile temperature values, as well as for the median (Q2) and third quartile (Q3). This conclusion also holds

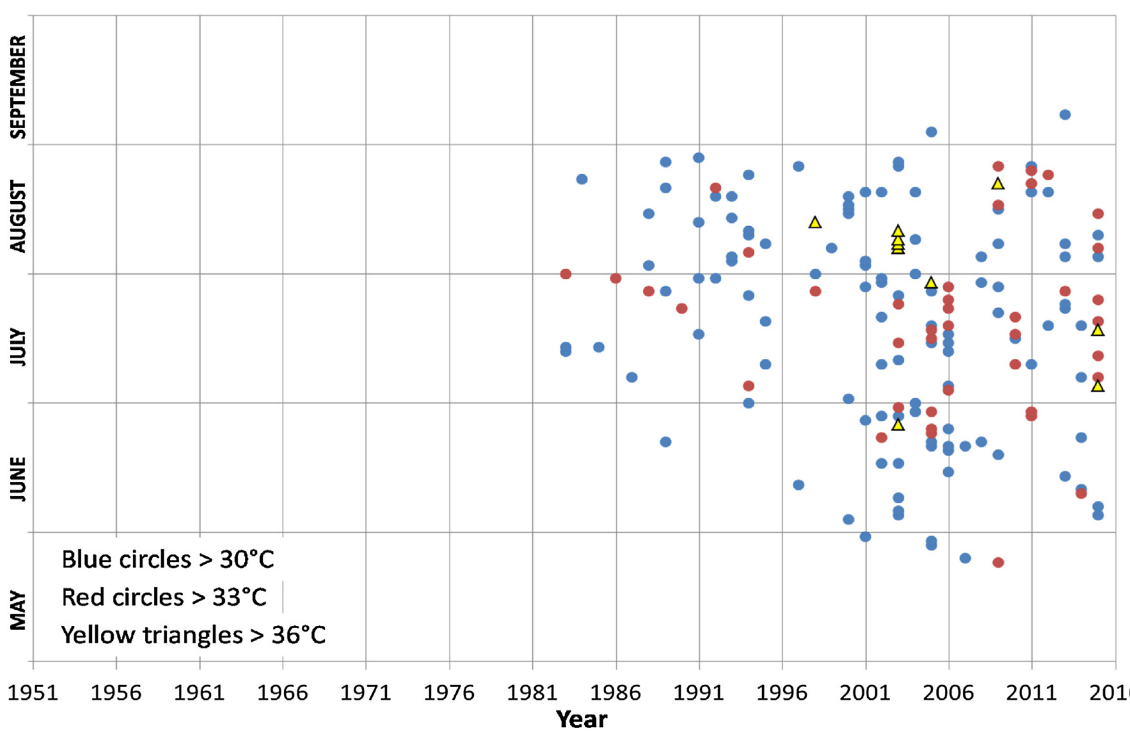

Fig. 4. Hovmoeller-type diagram showing the dates during which the 30 °C, 33 °C, and 36 °C thresholds are exceeded in the observed record in Geneva, Switzerland, but not in the de-trended record.

Table 2
Number of exceedances beyond the 30, 33, and 36 °C thresholds for the observed and 1950s-type climates, and the percent difference between the two climates, for all European locations considered.

Station	30 °C threshold			33 °C threshold			36 °C threshold		
	Obs	1950s	% diff	Obs	1950s	% diff	Obs	1950s	% diff
Berlin	471	405	14	90	66	26	13	8	38
Bilbao	864	787	8	331	298	9	94	81	13
Brest-Litovsk	440	367	16	76	48	36	3	1	66
CET	31	24	22	3	1	66	0	0	–
Copenhagen	32	21	34	3	1	66	0	0	–
De Bilt	188	164	12	25	14	44	0	0	–
Geneva	705	617	12	143	103	27	18	8	55
Klaipeda	92	63	31	13	3	76	2	0	–
Madrid	3517	3327	5	1395	1212	13	281	180	35
Milesovka	154	115	25	27	17	37	3	1	66
Moscow	312	266	14	53	37	30	10	5	50
Oslo	75	59	21	2	1	50	0	0	–
Paris	565	470	16	147	123	16	25	18	28
St Petersburg	135	107	20	17	11	35	3	2	33

Table 3
Years during which the record-breaking summers (June-July-August) have been observed for the selected study-sites.

	Berlin	Bilbao	Brest Litovsk	CET	Copenhagen	De Bilt	Geneva
Year	2003	2003	2015	1976	2006	2015	2003

	Klaipeda	Madrid	Milesovka	Moscow	Oslo	Paris	St Petersburg
Year	2002	2015	2003	2010	1955	2003	1972

for the months of May, June, and September (not shown), suggesting that if climate had not warmed at the hemispheric rate since 1950s, Europe would certainly not have experienced such an increase in the number, duration, and intensity of days beyond the 30 °C threshold over past decades.

These conclusions assume that the physical elements leading to the synoptic situations that have triggered the recent summer heatwaves would have been very similar in a cooler climate to those observed. A number of studies have shown that changing synoptic weather patterns may also play a role in the positioning, intensity and duration of heatwaves, and not simply extra heat in the system associated with the enhanced greenhouse effect (Trenberth et al., 2015). However, studies relating weather patterns to heatwave positioning (e.g., Fischer and Schär, 2010; Stefanon et al., 2012; Russo et al., 2015) suggest that there are three "privileged" zones for heatwave formation over Europe, namely Central-Western Europe (e.g., the 2003-type of event), Eastern Europe/Western Russia (the 2010 event), and Scandinavia (e.g., 1955, 1972). Our speculative assumption concerning a relative constancy in the physical mechanisms underlying heatwaves helps us establish a number of comparisons between a climate which would have been cooler in the absence of the large-scale Northern Hemisphere warming, and the true climate.

The years in which the hottest summer have been recorded vary between European locations. By way of example, from Paris through to Central Europe, the 2003 event is dominant; in Madrid and Bilbao, it is more the 2009 and 2012 events that are the highest on record; in Scandinavia, 1955, 1997 and 2006 were particularly warm summers for the region, while further east, in the Baltic States and Russia, the massive 2010 heatwave (Grumm, 2011) far outweighs all the others. Table 3 provides an overview of the hottest summers on record for the 14 selected sites.

To emphasize the large differences that can exist between the real and 1950s-type climates, it is of interest to compare T_{max} threshold exceedances as a measure of the lower intensity of hot summers in the de-trended climate. Fig. 6 provides an illustration for the 14 selected stations with a comparison between observed and de-trended statistics for 30 °C for the first and last 15 years of the record. This enables a visualization of the change in hot days that has taken place from the 1950s up to 2015 in the real climate, and the level of change that would have occurred had climate not warmed according to the NH temperature increase.

For example in Geneva, the exceedances beyond the 30 °C threshold increase almost three-fold in the observed climate, from 89 events in the mid-20th century to 261 events in the most recent 15 years, whereas they increase by less than a factor of 2 in the 1950s-type climate record, which represents only half the rate of increase compared to the observed climate. For the 33 °C threshold, the number of events in the observed climate undergo a 14-fold increase, whereas the de-trended data exhibits a 7-fold increase. Finally, for the 36 °C level, observed exceedances change from zero

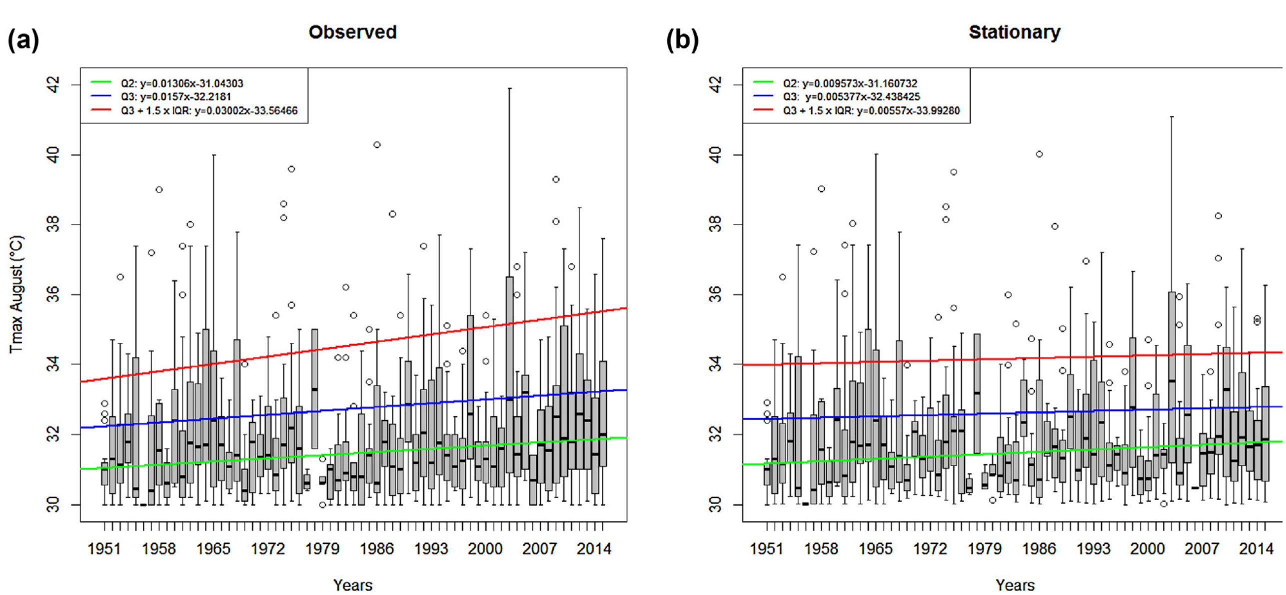

Fig. 5. a) Box plots by year representing the observed temperature recorded in August and exceeding 30 °C for the 14 European stations and for the period 1951–2015. Trend lines are shown for the median (Q2), the third (Q3) quartile, and 1.5 times the interquartile range (; b) as 5a) but for the de-trended climate.

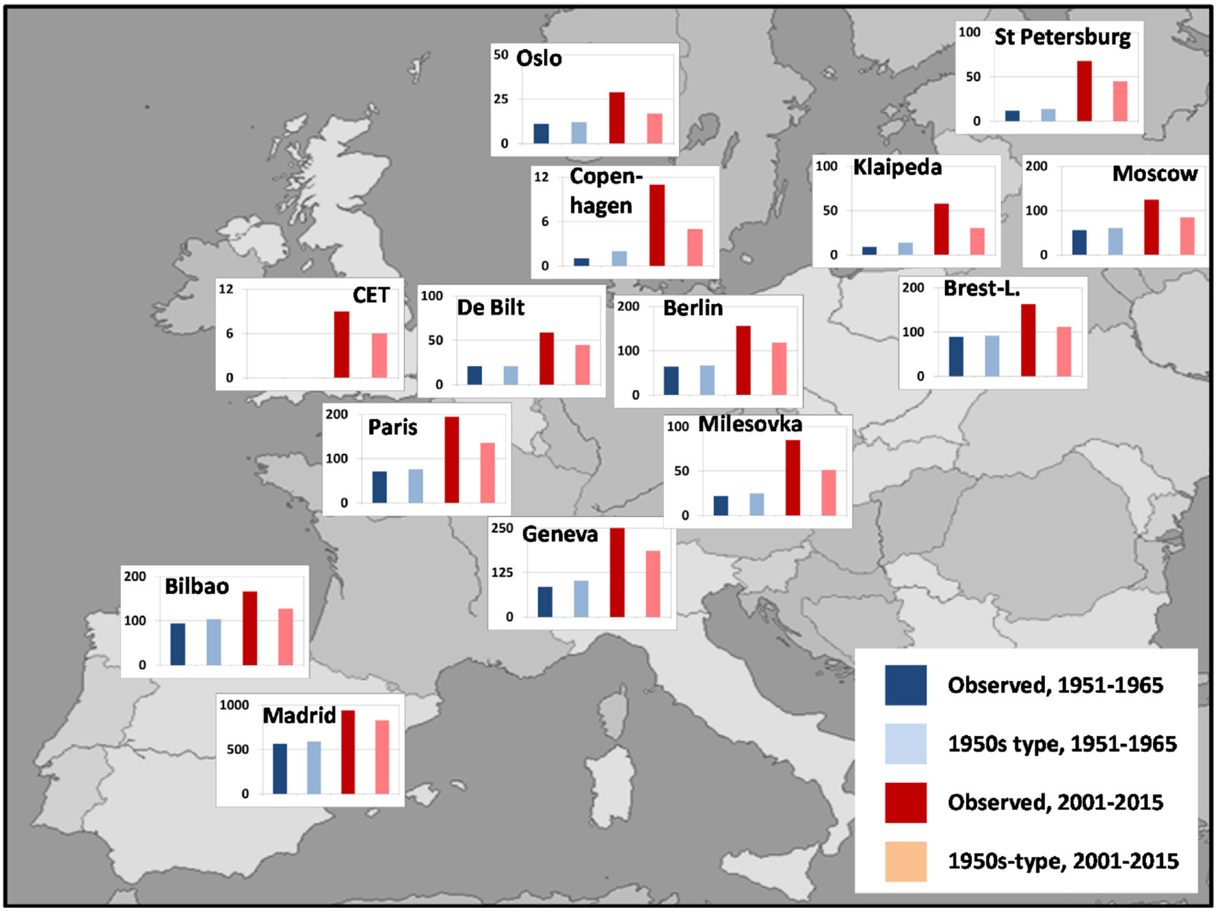

Fig. 6. Map representing the exceedances of the 30 °C threshold for the observed and de-trended climates for the periods 1951–1965 and 2001–2015, at the 14 European stations considered in this study. Please note the change in scale on the vertical axis for CET, Copenhagen, Oslo and Madrid with respect to all other locations.

events in the 1950s to 17 events today, compared to zero and 8 events, respectively, in the de-trended climate.

For other stations, it is seen for example in Berlin, the 30 °C threshold has experienced a 2.4-fold increase in just half a century, 1.8 times in Bilbao and 11 times in Copenhagen. For the de-trended climate, range from 1.2-fold increases to 3.2 for the 30 °C threshold exceedance. In almost every case, real climate exhibits threshold exceedances that are well above those of the de-trended climate, with ratios between 1950s-type and observed climates close to 1 for all locations in the first 15 years of record (i.e., the period when the two curves are almost identical), and from 0.9 (Madrid) to 0.5 (Copenhagen) for the period 2001–2015.

These simple analyses serve to demonstrate that not only the duration and intensity of hot summers would have been markedly lower had climate been similar to the de-trended data rather than actually observed, but also that the rate of change of hot summers in the observed climate has been more rapid than in the de-trended climate. According to location, the change is anywhere between 2 and 4 times greater in the observed climate.

An examination of the upper tails of the probability density functions (PDF) of T_{max} confirms the large ratios between observed and de-trended climates for different temperature classes. Fig. 7 illustrates the tails beyond the 32 °C threshold for four sites, namely Madrid (Mediterranean-continental climate), Moscow (continental), Paris (mid-latitude maritime), and Oslo (northern latitude maritime). Despite the markedly different climatic regimes, all sites exhibit overall lower frequencies in the de-trended climate for each T_{max} class beyond 32 °C. Differences between stations can be quantified by taking the ratio of frequencies of temperature classes between the real and hypothetical climates. For Madrid, this ratio is roughly 1:1 at 32 °C, but rises to 1.7:1 for the 37 °C class intervals and 5.5:1 for the 39 °C class. In Moscow, the ratios are 1.3:1 at 32 °C and 4:1 at 37 °C, while in Paris the respective ratios are 1.2:1 and 1.5:1. For Oslo, the ratio in the 32 °C class interval is 1.5:1, with one count at 34 °C in the observed climate but no counts in the de-trended data. There are no counts beyond 34 °C in Oslo in either data set.

4. Conclusions: implications for outreach and policy

This Europe-wide study has explored a number of temperature statistics for hot summers since 1951 at 14 sites, stretching from Madrid to Oslo, and from the UK to Western Russia, for both the observed and de-trended time series. The main objective was to show how a hypothetical climate that had not warmed according to the NH temperature trend would have exhibited significantly reduced durations and intensities of the many heatwaves observed during the past 65 years (Beniston 2004; Schaer et al., 2004; Beniston and Diaz 2004; Grumm 2011; IPCC 2010). The intensity of hot summers, identified by T_{max} exceedances beyond fixed thresholds, and the duration of an event, has been shown in the paper to be far greater in the observed temperature series than in the stationary data. Mean maximum temperatures for individual summer months or for the entire season can be anywhere between 1 and 2 °C cooler during the hot events detected in the de-trended record compared to those in the observed climate; overall persistence of hot summers is often less than half that of the real climate. A number of papers in the literature suggest that at

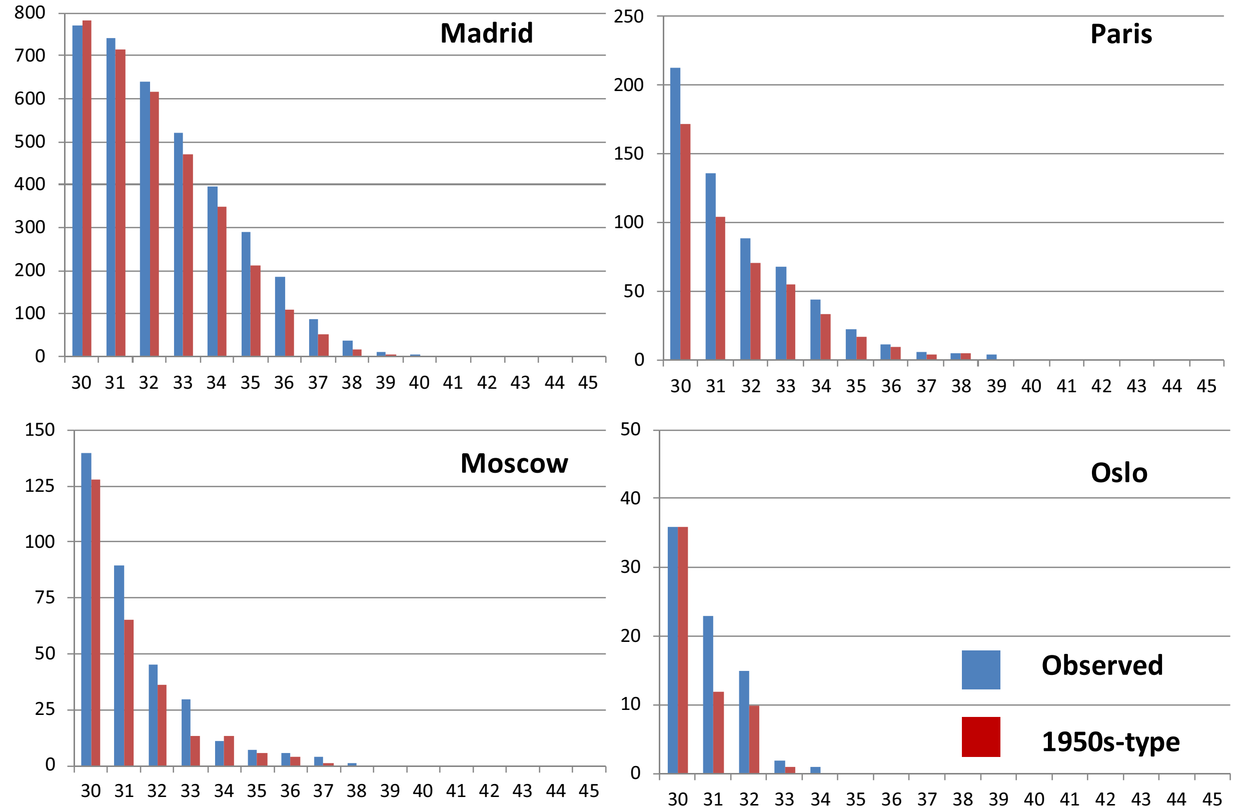

Fig. 7. Examples of frequencies of observed vs. stationary climates (blue and red histograms, respectively) of the upper tails of the probability density functions of maximum temperatures beyond the 32 °C threshold in Madrid (a), Paris (b), Moscow (c), and Oslo (d). Please note that for the sake of clarity the scale of the vertical axis changes from one location to the next.

least part of the observed decadal-scale European warming is attributable to human activities (i.e., the enhanced anthropogenic greenhouse-gas signal, e.g., Stott et al., 2004; Klein Tank et al., 2005; Christidis et al., 2012). As a consequence, this study is indeed comparing the behavior of heatwaves resulting from anthropogenic climate change to those in a more slowly-evolving climate characteristic of the 1950s, much less influenced by human activities.

Associated climate impacts in a stationary climate would likely have been far less severe than those observed in the 2003, 2010, and 2015 heatwaves, in terms of mortality and morbidity, water supply and use, energy supply and demand, food security, and ecosystem functioning. Indeed, because many of the European sites studied have already experienced a warming of 1 °C and more, the statistics shown here provide a measure of caution as to the fact that the *1.5 °C policy threshold* advocated by the recent COP-21 accord in December 2015 (Hulme, 2016), may still trigger many severe impacts (Hansen et al., 2015) through damaging heatwaves.

Using the simple illustrations presented in this paper of what climate could have been, had it not experienced the observed warming since the mid-20th century, we believe that convincing messages can be addressed to a wide range of audiences, from a more general public to the policy and decision-making spheres. The "what if" type of study reported here could provide an alternate set of arguments to help decision makers in communicating the urgency to keep climate within the bounds recommended by the COP-21 climate conference signed in Paris in December 2015. The comparison between the heatwaves experienced in the observed climate that has warmed by 0.5 °C per decade since the 1950s, and those that could have occurred in a climate with a lower rate of warming, serves to emphasize the advantages of a slowly-evolving climate that favors less frequent, damaging events. The illustrations of the differences in heatwave behavior reported here should thus provide incentives for decision makers to develop appropriate strategies in order to avert the more severe heatwave impacts on social, environmental and economic systems, and to formulate appropriate adaptation strategies whenever appropriate.

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