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Reconciling two approaches to attribution of the 2010 Russian heat wave

F. E. L. Otto,[1] N. Massey,[2] G. J. van Oldenborgh,[3] R. G. Jones,[4] and M. R. Allen[1]

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[1] In the summer 2010 Western Russia was hit by an extraordinary heat wave, with the region experiencing by far the warmest July since records began. Whether and to what extent this event is attributable to anthropogenic climate change is controversial. Dole et al. (2011) report the 2010 Russian heat wave was "mainly natural in origin" whereas Rahmstorf and Coumou (2011) write that with a probability of 80% "the 2010 July heat record would not have occurred" without the large-scale climate warming since 1980, most of which has been attributed to the anthropogenic increase in greenhouse gas concentrations. The latter explicitly state that their results "contradict those of Dole et al. (2011)." Here we use the results from a large ensemble simulation experiment with an atmospheric general circulation model to show that there is no substantive contradiction between these two papers, in that the same event can be both mostly internally-generated in terms of magnitude and mostly externally-driven in terms of occurrence-probability. The difference in conclusion between these two papers illustrates the importance of specifying precisely what question is being asked in addressing the issue of attribution of individual weather events to external drivers of climate. **Citation:** Otto, F. E. L., N. Massey, G. J. van Oldenborgh, R. G. Jones, and M. R. Allen (2012), Reconciling two approaches to attribution of the 2010 Russian heat wave, *Geophys. Res. Lett.*, *39*, L04702, doi:10.1029/2011GL050422.

1. Introduction

[2] Apparently contradictory answers have been given to the question of whether the Russian heat wave might have been anticipated, and to what extent anthropogenic greenhouse gas emissions were a cause [*Dole et al.*, 2011, hereinafter D11; *Rahmstorf and Coumou*, 2011, hereinafter RC11]. However, given the fact the 55,000 people died, the annual crop production dropped by 25%, and the total loss to the economy of more than 15 billion US dollar [*Barriopedro et al.*, 2011] this answer is of vital interest to wider society.

[3] The Russian heat wave in 2010 started at the beginning of July, reaching its record temperatures in late July with temperatures slowly decreasing at the beginning of August with the heat wave finally breaking by the 19th of August. The persistence of such anomalously high temperatures for over a month was possible due to a blocking situation not uncommon for this region. In 2010 the blocking high was extremely intense and persistent, accompanied by temperatures more than 5°C above the long term mean. Given the ecological and socioeconomic impacts of such an event it is of interest whether, or to what extent, anthropogenic greenhouse gas emissions have contributed to the likelihood or magnitude of this event and if it could have been anticipated. D11 conclude that natural variability primarily caused this event while RC11 report that there is a "80% probability that the 2010 July heat record would not have occurred without climate warming", although we suggest a clearer formulation of this conclusion is the probability increased by a factor of five, or 80% of current risk is attributable to the external trend [*Allen*, 2003].

[4] D11 concentrate their analyses on the magnitude of the event in observed data for the whole year and two 50 member atmospheric general circulation ensembles for July 2010, while RC11 analyze the frequency of occurrence of heat waves by comparing Monte Carlo simulations of stable climates against those showing a trend, by using the Russian heat wave of 2010 as one example. It is important to highlight here that RC11 inquire the frequency of occurrence of a record breaking heat wave, thus the magnitude of the heat wave is irrelevant for their analysis while it is central to D11.

[5] In this study we argue that both results need not be contradictory, as the natural climate variability can account for an event of this magnitude. However, the frequency of occurrence of such an event is likely to have increased due to a global warming trend which is attributed to anthropogenic increase of greenhouse gas forcing, as shown for the European summer heat wave of 2003 by, e.g., *Stott et al.* [2004] and for the autumn of 2006 by *van Oldenborgh* [2007]. Furthermore, the question that D11 also address is whether the event was predictable on the seasonal time scale. The conclusion is that there are no predictors beyond the global warming trend. However, for intrinsically low-probability events the question of whether the event was predictable is separate from the question what fraction of risk is attributable to external forcing. It is important to highlight that we do not assess the actual fraction of risk attributable to anthropogenic climate change, which would require a thorough assessment of errors and uncertainties, but show how an experiment could be designed to answer that question, and give illustrative results.

[6] The method requires access to a sufficiently large number of simulations so that statistics of the occurrence of a rare event can be estimated with confidence. The weather*at*home project provides such a large ensemble using

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[1] Environmental Change Institute, School of Geography and the Environment, University of Oxford, Oxford, UK.

[2] Smith School of Enterprise and the Environment and Department of Atmospheric Oceanic and Planetary Physics, University of Oxford, Oxford, UK.

[3] Department of Climate Research and Seismology, Koninklijk Nederlands Meteorologisch Instituut, De Bilt, Netherlands.

[4] Met Office Hadley Centre, Exeter, UK.

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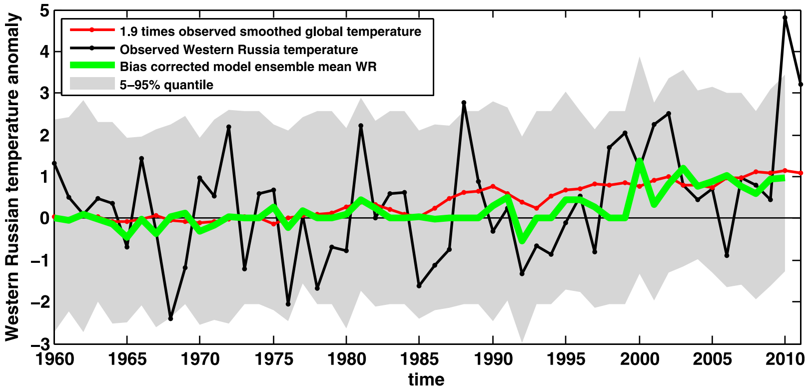

Figure 1. Modeled and observed temperature anomalies averaged over 50°–60°N, 35°–55°E. Also shown is the smoothed global mean temperature multiplied by the regression coefficient of Western Russian temperatures. The reference period is 1950–2009 for observed data and 1960–2009 for the model.

publicly volunteered distributed computing [*Allen*, 1999; *Massey et al.*, 2006].

2. Methodology and Results

[7] The area of the Russian heat wave is roughly encompassed by the region 50°–60°N, 35°–55° E, as D11 used. The daily mean temperature anomaly over this region in the GISTEMP 1200 dataset [*Hansen et al.*, 2010] is shown in Figure 1. To analyze the possibility of attributing the heat wave of 2010 in that region, the frequency of occurrence of an event of this magnitude is of central interest. We first analyze observed data to assess if the distribution shifts due to the existence of a trend. However, to account for a change in the return time of rare events large ensembles are required, so our main analysis is based on a large GCM ensemble.

2.1. Empirical Analysis

[8] Assuming a stationary climate with no rise in yearly mean temperature, the observed monthly mean temperatures for July 2010 would be very improbable in relation to the distribution defined over 1950–2009. A Generalized Pareto Distribution (GPD) fit over the 20% highest values defines a distribution in which the return time of the value observed in July 2010 is about 1000 years, with a lower bound of the 95% confidence interval of about 250 years (estimated with a non-parametric bootstrap method). Without a warming trend the 2010 heat wave would have been a very unusual event.

[9] D11 show that there is no significant long-term regional temperature trend in July mean temperatures over the 130-year period 1880–2009 using long-term linear trend analysis, or significant difference in mean temperatures between the first and second 65-year periods of this record. We employ a non-linear trend and use a more sensitive measure, the regression on the global mean temperature, smoothed with a 3-year running mean to decrease the effects of ENSO as by *van Oldenborgh* [2007] and *van Oldenborgh et al.* [2009]. We also restrict ourselves to observations after 1950, which are deemed more reliable with the spatial homogeneity of station data trends much improved since 1950 and possible discontinuities in data prior to 1950 due to relocation of stations from city centres to airports. RC11 showed furthermore that the recent decades are the relevant years with respect to a regional trend. This gives a rise in temperature from 1950 to 2009 of 1.9 ± 0.8 times the global mean rise in the GISTEMP-1200 dataset [*Hansen et al.*, 2010]. The trend is significant at $p < 0.02$. Figure 1 shows the result of this analysis in the observed temperatures over Western Russia and the global temperatures multiplied by the best-fit regression coefficient. The trend is also comparable with the warming rate in surrounding areas to the West and South and in the months of June and August. Single-month trends are by definition very noisy, but given the global warming trend and modeling results the values of 2010 and 2011 confirm the interpretation of a background trend obscured by natural variability rather than evidence for no trend.

[10] The increase in temperature is much smaller than the anomalies observed during the heat wave, yet the trend has increased the probability of a heat wave as large as observed in 2010 considerably. Under the assumption that the probability density function (PDF) has not changed in shape but just shifted to higher values, the return time for the 2010 July temperature is estimated to be 250 years, with a lower boundary of the 95% confidence interval of about 90 years when taking the trend estimated over 1950–2009 into account. The probability of a heat wave of this magnitude is thus increased by a factor of three to four compared to a stationary climate by taking the trend prior to the event into account. Considering that the area covers less than 1% of the land area of the world and was chosen *a posteriori*, a 1/250-year event could occur every few years somewhere on the globe. Hence modeling is needed to confirm the result.

2.2. Modelling Analysis

[11] To create an ensemble large enough to be able to assess the fraction of risk of the heat wave which is attributable to external forcing, we use the global circulation model HadAM3P. This is an atmosphere only general circulation model with N96 resolution, (1.25 × 1.875 degrees resolution, 19 levels), with 15 minute time steps for dynamics. HadAM3P is based on the atmospheric component of the Hadley Centre GCM HadCM3 [*Pope et al.*, 2000; *Gordon et al.*, 2000], but with some major differences in the parameterizations [*Jones et al.*, 2004]. Weather*at*home uses the sea surface temperatures and sea ice extent compiled in the HadISST data set described by

z500(x,y,t)=alpha(x,y)*T(Moscow,July)+beta(x,y); plotted: alpha(x,y)

alpha units: [z500]/[T]

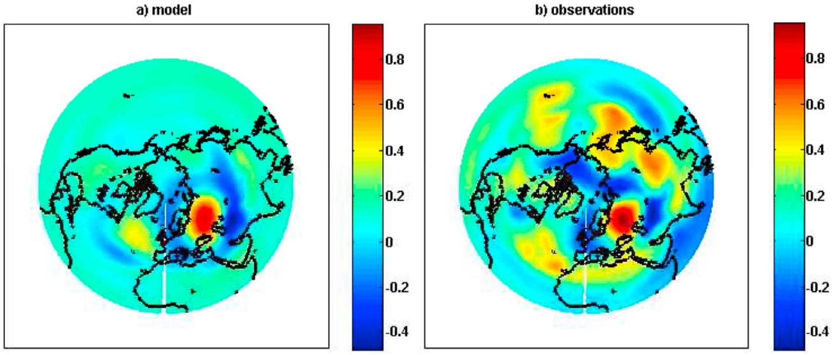

Figure 2. Regression maps on synoptic structure of northern hemisphere 500 hPa geopotential height patterns associated with July mean temperatures in (a) the model and (b) observations.

Rayner et al. [2003] and the MOSES land-surface exchange scheme from the UK Met Office [*Cox et al.*, 1999]. A large ensemble size is needed to provide results from which statistical significance and the shape of the distribution of key variables, which is mainly temperature in the case of a heat wave, can be assessed. Also, a sufficiently long period of time must be simulated to evaluate model bias and whether the model captures the observed distribution of the relevant variables. To generate a sufficiently large ensemble the model was run for several years many hundreds of times with different initial conditions. Output of the global model for the region of interest provides only monthly diagnostics, whereas blocking is normally defined using a daily blocking index. However, the Russian heat wave persisted for much more than a month, with exceptionally high positive anomalies in the July mean temperature and geopotential height clearly visible in the ERA-Interim reanalysis data over a region centered on Moscow identified by D11. In this region the extreme temperature anomalies in July 2010 occurred with anomalies more than 5°C above the average from 1948–2009 that D11 use and also more than 5°C above the average from 1979–2009 in ERA-Interim data which we use as observational data. Additionally the 500 hPa geopotential height was exceptionally high in that region. Since it is also common to define blocking indices on basis of the geopotential height at 500 hPa [*Tibaldi and Moltini*, 1990], we base our analysis throughout this study on monthly 1.5 meters temperatures and 500 hPa geopotential height in western Russia (50°–60°N, 35°–55°E) to identify heat wave conditions comparable to 2010.

[12] The crucial analysis of our study is the comparison of the return time of a 2010-like heat wave in a 1200 member ensemble of model runs for the 2000s with the return period of such an event in an 1600 member ensemble representing the 1960s.

[13] To check whether the model is capable of representing the conditions defining the heat wave we calculate the geopotential height anomalies and produce a map regressing these anomalies against the ensemble Russian mean temperature averaged over the time period 1979–2009, with the temperatures being the independent variable. These regression maps (Figure 2) show the synoptic pattern in July over

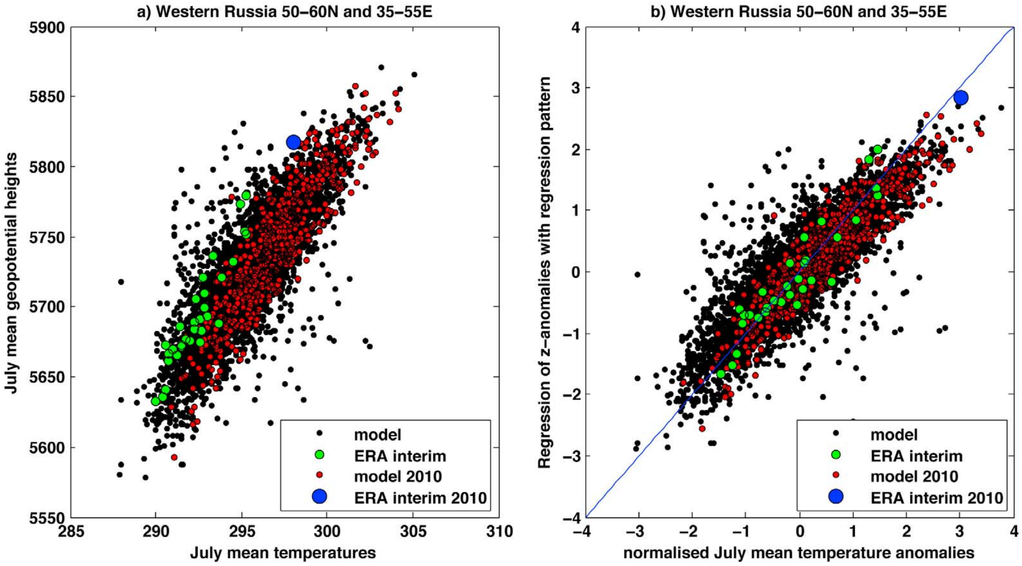

Figure 3. Scatter plot of (a) Russian mean temperature and mean geopotential heights and (b) bias corrected Russian mean temperature anomalies and the regression of normalized geopotential height anomalies against the synoptic structure regression pattern. The blue line in Figure 3b represents the one-to-one line of perfect correlation.

for y axis of Fig 3: z500(x,y)=gamma*alpha [gamma]=[z500]/[alpha]=[T]

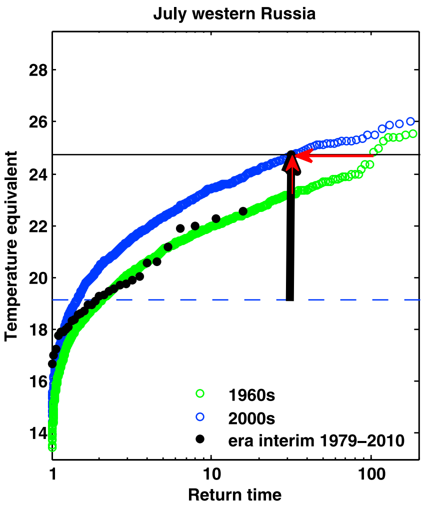

Figure 4. Return periods of temperature-geopotential height conditions in the model for the 1960s (green) and the 2000s (blue) and in ERA-Interim for 1979–2010 (black). The vertical black arrow shows the anomaly of the Russian heat wave 2010 (black horizontal line) compared to the July mean temperatures of the 1960s (dashed line). The vertical red arrow gives the increase in the magnitude of the heat wave due to the shift of the distribution whereas the horizontal red arrow shows the change in the return period.

the northern hemisphere and compare well with reanalysis data. However, there is more variability in the observations which is to be expected as the regression is made with much less data. This comparison, as also used, for example, in an attribution study by *Pall et al.* [2011], provides confidence in the model's ability to represent the relevant pattern of atmospheric circulation.

[14] To identify conditions comparable to the heat wave in 2010 we regress the pattern resulting from the linear regression above with the geopotential height anomalies over western Russia. If the temperature and geopotential height anomaly were perfectly correlated over western Russia, this new regression coefficient plotted against the mean temperature over that region would lie perfectly on the one-to-one line. Figure 3b shows that the geopotential height anomalies are scattered along that line, indicating that the regression pattern is an effective, but far from perfect, predictor for Russian temperatures.

[15] The dot representing the observed conditions in 2010 is located close to the one-to-one line and much more towards the right upper corner accounting for the exceptional heat wave. Hence, conditions in 2010 represent an amplification of this temperature-geopotential height condition, not fundamentally differing conditions. Figure 3a shows the mean temperatures over the region of interest plotted against the mean geopotential height. In this figure the model data is shifted towards higher temperatures, indicating a model bias towards too hot conditions. Furthermore the spread of the geopotential heights in the model data is much larger than in the observations. For the one-to-one line being the line of perfect correlation, and thus serving as an index for heat waves, these two biases need to be addressed. We have done this by subtracting the difference of 3°C between model and observed mean temperatures and corrected temperature and geopotential height anomalies by scaling to give the same standard deviation as the observations. After removing the bias the model data lies along the one-to-one line with the ERA data, so we use this position on the line as an index to studying the magnitude and return period of heat waves in western Russia. However, further studies with larger ensembles and inducing perturbed physics parameters might address the bias more satisfactorily.

[16] Taking the heat wave index defined in this way, the projection of the dots in Figure 3b onto the one-to-one line, we can assess the return period of a July 2010 event, by plotting this index against the size of the sample divided by the rank of the index within the sample. Figure 4 displays the results of this analysis of the Russian heat wave area temperature equivalents given by the heat wave index in the simulations of the 1960s and the 2000s. It shows a marked change in the distribution between the two decades and that in the 1960s a 2010-magnitude heat wave was to be expected every 99 years whereas in the 2000s this has changed to every 33 years. Due to the use of distributed computing the number of ensemble members per years is not constant. In the sixties we have an average of 215 ensemble members per year with a standard deviation of 120 and in 2000–2009 an average of 67 ensemble members per year with a standard deviation of 27. For 2010 we use an ensemble of 564 members per year. We show aggregated results here, emphasizing 2010 in the return times. However, excluding the year 2010 from calculating return times for Figure 4 is visually the same. Thus the simulated expected frequency of occurrence of an extreme Russian heat wave has tripled due to the large-scale warming within the last four decades. Note that this assessment is based on the observed magnitude of the event which is useful within these illustrative results and especially when interested in this magnitude.

[17] In contrast to return times of precipitation events like river runoff [*Pall et al.*, 2011] the lines in Figure 4 are not straight as would be expected for Pareto distributed variables. Note that, contrary to the assumption of, e.g., *Stott et al.* [2004] and *Allen et al.* [2007], the actual value of the threshold matters for the fraction of attributable risk (FAR) analysis of heat waves, so the issue of model bias is important. We have attempted to correct the bias in a sensible and effective way but this result depends on that correction and should thus be considered as illustrative only. However it corroborates the assumption of the empirical analysis above that the distribution shifts but does not seem to change, since both lines are parallel. It serves, furthermore, to demonstrate the methodological point in relating the studies by D11 and RC11. It also underlines the importance, when assessing the FAR, of both the magnitude of an event and the return period [*Allen*, 2003; *Stone and Allen*, 2005].

3. Conclusion

[18] D11 approach the question of whether or not the Russian heat wave of 2010 might have been anticipated from a seasonal forecasting perspective, thoroughly analyzing the regional data and atmospheric conditions leading to the heat wave.

[19] RC11 take a different approach by fitting a non-linear trend to central Russian temperatures and showing that the warming which has occurred in this region since the 1960s has increased the risk of a heat wave that set a new

temperature record for the region by around a factor of 5, corresponding to a FAR of 0.8. This is only a partial attribution study, since they do not address the question of what has caused the trend since 1960, although they note that other studies have attributed most of the warming that has occurred over this period to the anthropogenic increase in greenhouse gas concentrations. These two approaches are different but complementary in quantifying the role of human influence on a 2010-like Russian heat wave. This is illustrated by Figure 4, which shows return times of the heat wave conditions for the 1960s (green) and 2000s (blue). The threshold exceeded in 2010 is shown by the solid horizontal line, which is more than 5°C above 1960s mean July temperatures, shown by the dashed line. The difference between the green and the blue lines could be characterized as a 1°C increase in the magnitude of a 33-year event as shown by the vertical red arrow. This arrow is substantially smaller than the size of the anomaly itself, supporting the assertion that the event was "mainly natural" in terms of magnitude which is consistent with D11. Alternatively it could be characterized as a three-fold increase in the risk of the 2010 threshold being exceeded, supporting the assertion that the risk of the event occurring was mainly attributable to the external trend as also stated by RC11.

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M. R. Allen and F. E. L. Otto, Environmental Change Institute, School of Geography and the Environment, University of Oxford, South Parks Road, Oxford OX1 3QY, UK. (friederike.otto@ouce.ox.ac.uk)

R. G. Jones, Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK.

N. Massey, Smith School of Enterprise and the Environment, University of Oxford, 75 George St., Oxford OX1 2BQ, UK.

G. J. van Oldenborgh, Department of Climate Research and Seismology, Koninklijk Nederlands Meteorologisch Instituut, NL-3730 AE De Bilt, Netherlands.