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Historic and future increase in the global land area affected by monthly heat extremes

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Abstract
Climatic warming of about 0.5 °C in the global mean since the 1970s has strongly increased the occurrence-probability of heat extremes on monthly to seasonal time scales. For the 21st century, climate models predict more substantial warming. Here we show that the multi-model mean of the CMIP5 (Coupled Model Intercomparison Project) climate models accurately reproduces the evolution over time and spatial patterns of the historically observed increase in monthly heat extremes. For the near-term (i.e., by 2040), the models predict a robust, several-fold increase in the frequency of such heat extremes, irrespective of the emission scenario. However, mitigation can strongly reduce the number of heat extremes by the second half of the 21st century. Unmitigated climate change causes most (>50%) continental regions to move to a new climatic regime with the coldest summer months by the end of the century substantially hotter than the hottest experienced today. We show that the land fraction experiencing extreme heat as a function of global mean temperature follows a simple cumulative distribution function, which depends only on natural variability and the level of spatial heterogeneity in the warming.

Keywords: climate change, extremes, heat waves, climate impacts

S Online supplementary data available from stacks.iop.org/ERL/8/034018/mmedia

1. Introduction

The recent decade has seen an exceptional number of extreme heat waves around the world that caused severe damage to society and ecosystems (WMO 2011, Coumou and Rahmstorf 2012). Examples of such events include the European heat wave of 2003 (Schär *et al* 2004), the Greek heat wave of 2007 (Founda and Giannakopoulos 2009), the Australian heat wave of 2009 (Karoly 2009), the Russian heat wave of 2010 (Barriopedro *et al* 2011), the Texan heat wave of 2011 (Rupp *et al* 2012) and the US heat wave of 2012 (NOAA 2012). These events were highly unusual with temperatures typically three standard deviations warmer than the local climatology lasting for several weeks (see SOM figure 1 available at stacks.iop.org/ERL/8/034018/mmedia).

Statistical studies have shown that extremely warm monthly and seasonal temperatures associated with persistent heat waves can now largely be attributed to the observed climatic warming over the last 50 years (Hansen *et al* 2012, Coumou *et al* 2013), which has been about 0.5 °C

(Betts *et al* 2011). In the 1960s summertime extremes of more than three standard deviations warmer than climatology were practically absent, covering less than 1% of the Earth's land surface. Now such extremely hot seasonal temperatures typically cover about 10% of the land area (Hansen *et al* 2012). At the same time, the number of record-breaking monthly temperatures increased strongly, in agreement with the increase expected by a shift in the mean towards warmer values (Coumou *et al* 2013). The rapid increase in frequencies of very warm seasonal temperatures have directly been attributed to the human influence on climate using advanced climate models (Jones *et al* 2008, Stott *et al* 2011). In addition, attribution studies of individual heat waves, like the one in Europe in 2003 (Schär *et al* 2004, Stott *et al* 2004), in Russia in 2010 (Rahmstorf and Coumou 2011, Otto *et al* 2012) and in Texas in 2011 (Rupp *et al* 2012) have shown that their occurrence-probability had increased several fold due to greenhouse gas forcing.

The limited global warming to date thus already strongly increased the frequency of heat extremes on monthly to seasonal time scales, exacerbating societal impacts. This raises the question how and how rapidly this trend is likely to continue under future warming, which is expected to be substantially larger than the 0.5 °C observed so far. To address this question, we analyze extremes in the state-of-the-art CMIP5 (Coupled Model Intercomparison Project) climate projections for the 21st century (Taylor *et al* 2011). Recent extreme heat waves in different parts of the world have caused monthly temperatures to exceed the local mean by three standard deviations over extended regions (SOM figure 1). Monthly mean temperatures beyond the three standard deviation threshold (i.e. 3-sigma events) during summertime can therefore be considered as proxies for such severe heat waves. Here we analyze extremes exceeding thresholds at different levels defined by the local historically observed natural variability (sigma). Because summertime heat extremes will have the biggest impact on humanity and since the bulk of the global land mass is located in the northern hemisphere, we focus on extremes in boreal summer in this letter. Results for austral summer (DJF) are given in the supplementary material (available at stacks.iop.org/ERL/8/034018/mmedia), where we note that over the southern hemisphere land mass the changes in extremes for DJF are very similar to those for JJA.

2. Methods

For each of the 29 CMIP5 simulation runs (Taylor *et al* 2011) available for both the RCP2.6 and RCP8.5 scenarios, we determine for each calendar month the local standard deviation due to natural variability of the monthly mean surface temperature. To do so, we first use a singular spectrum analysis to extract the long-term (periods of 30 years or greater) non-linear trend over the 20th century. Next we detrend the 20th century monthly time series by subtracting the long-term trend, which gives the year-to-year variability. From this detrended signal, monthly standard deviations are calculated, which are then averaged seasonally (i.e., seasonally averaged monthly standard deviations) (World Bank 2012). In the present analysis, we calculated the standard deviation using the last 60 years (1951–2010), however, we found that this estimate was robust with respect to different time periods. Following Hansen *et al* (2012), we use 1951–1980 as the reference time period, which has the advantage that it was a period of relatively stable global mean temperature prior to rapid global warming.

3. Results

During the 2000–2012 period, a sizable percentage of summer months exceeded 3-sigma, mainly in tropical regions but also over western Europe, the Mediterranean and the Middle East (figure 1). Such heat extremes have only recently emerged, but now cover about 5% of the global land surface (figure 2). Upward trends in more moderate extremes (i.e. 1- and 2-sigma events) can be detected further back in time, starting around 1980. Such extremes now cover about 40% and 15% of the global land surface, respectively, mainly concentrated in the tropics, Mediterranean and Middle East. The CMIP5 multi-model mean accurately captures the timing of the observed increase in the land fraction experiencing extremes since the 1970s for all three threshold levels (figure 2). Also the modeled spatial patterns are similar to those observed, though smoother because an average of 29 models is taken.

The favorable agreement between observations and models suggests that the multi-model mean can provide reasonable estimates of future changes in heat extremes on monthly time scales. The projections show that in the near-term such heat extremes become much more common, irrespective of the emission scenario. By 2020, the global land area experiencing temperatures of 3-sigma or more will have doubled (covering ∼10%) and by 2040 quadrupled (covering ∼20%). Over the same period, more-extreme events will emerge: 5-sigma events, which are now essentially absent, will cover a small but significant fraction (∼3%) of the global land surface by 2040. These near-term projections are practically independent of emission scenario.

The rise in the frequency of extremes becomes strongly dependent on the emission scenario only by mid-century. Under the low emission scenario (RCP2.6), the number of extremes stabilizes at 2040-levels. This implies that in the tropics, including South America, western Africa and the Maritime continent, 3-sigma heat effectively becomes the new norm (about 50% of summer months, see figure 3) and 5-sigma heat will be common (about 20% of summer months). In the extra-tropics, 3-sigma extremes will also increase, occurring for example in western Europe in roughly 20% of summer months, but 5-sigma events will still be essentially absent. In the southern hemisphere, the increase in monthly heat extremes is essentially independent on the season. Here, the spatial patterns and magnitudes of the increase in frequency for austral summer extremes (DJF) are very similar to those for JJA (compare SOM figure 4, available at stacks.iop.org/ERL/8/034018/mmedia, with figure 3).

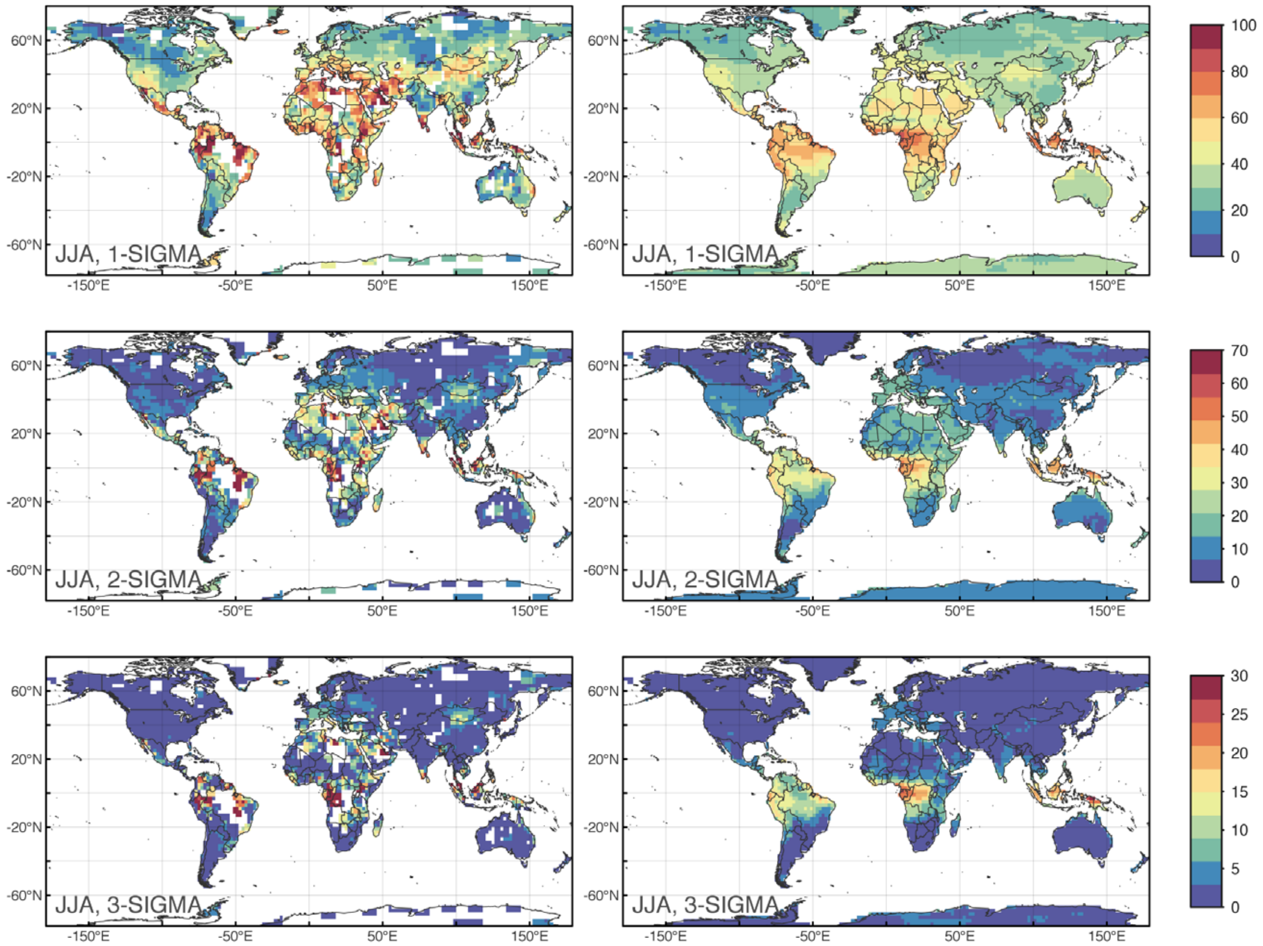

Figure 1. Percentage of boreal summer months in the time period 2000–2012 with temperatures beyond 1-, 2- and 3-sigma (top, middle and bottom, respectively) for observations (left) and the CMIP5 multi-model mean (right). Please note the different color bar ranges for the different threshold levels. Figures showing results for boreal winter months (DJF) can be found in the supplementary material (available at stacks.iop.org/ERL/8/034018/mmedia).

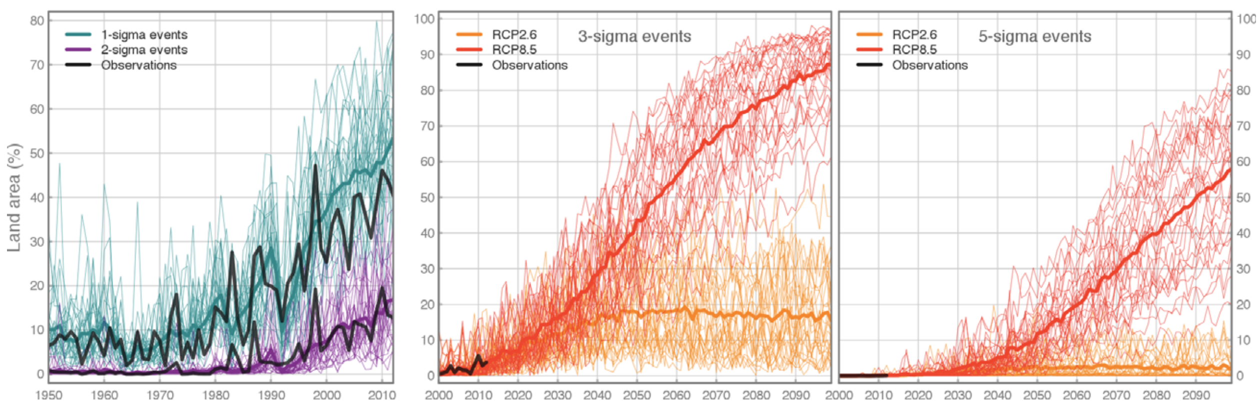

Figure 2. Percentage of global land area during boreal summers with monthly temperatures beyond different sigma-thresholds for historic (left) and 21st century (middle and right). The CMIP5 multi-model mean (thick colored lines) accurately reproduces the observed increase in 1-, 2- and 3-sigma extremes in the GISS surface temperature data (solid black lines). Future projections are given for 3-sigma (middle) and 5-sigma (right) for scenarios RCP2.6 and RCP8.5.

Under the high-emission scenario (RCP8.5), the area of land experiencing 3- or 5-sigma events grows by roughly 1% yr^{-1} after 2040. By 2100, 3-sigma heat covers about 85% and 5-sigma heat about 60% of the global land area. The occurrence-probability of months warmer than 5-sigma reaches up to 100% in some tropical regions. Over extended areas in the extra-tropics (Mediterranean, Middle East, parts of western Europe, central Asia and the US) most (>70%)

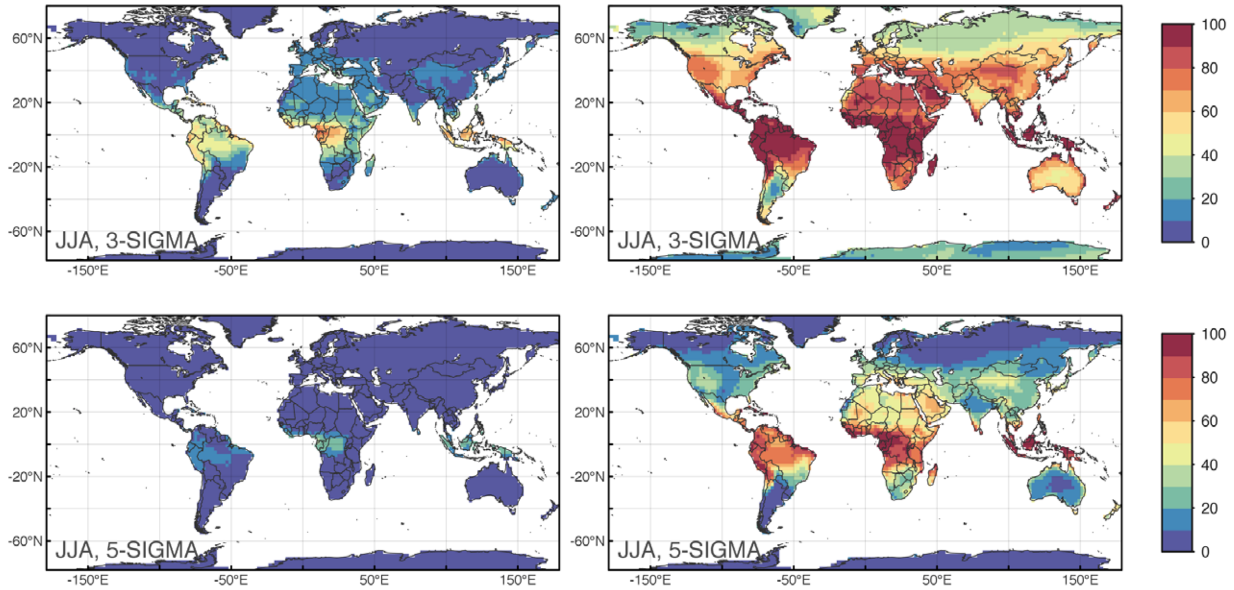

Figure 3. Multi-model mean of the percentage of boreal summer months in the time period 2071–2099 with temperatures beyond 3-sigma (top) and 5-sigma (bottom) under RCP2.6 (left) and RCP8.5 (right).

summer months will be beyond 3-sigma, and 5-sigma events will be common.

To understand how threshold-exceeding extremes increase in a warming world, we compare the percentage of land covered by temperatures greater than a given sigma level with global mean temperature (figure 4). The CMIP5 data broadly follows a cumulative density function with a rapid onset of extremes at low temperatures (also seen in observations) followed by a more gradual asymptotic behavior towards maximum land fractions at high temperatures. This behavior can be understood with a first-order equation for the percentage of land area (A) covered by heat beyond a certain threshold (x):

$$A(x) = \left[\frac{1}{2} - \frac{1}{2}\mathrm{erf}\left(\frac{1}{\sigma_w(\Delta T)\sqrt{2}}\left(x - \frac{\Delta T}{\sigma_n}\right)\right)\right] \times 100\%. \quad (1)$$

In this equation, which assumes Gaussianity of the underlying probability density functions, ΔT is the land-mean surface warming, σ_n is the mean monthly standard deviation over land due to natural variability (which is about 1 °C for JJA), and x is the threshold level in units of sigma. σ_w captures the increasing variability, i.e. broadening, of the land temperature anomaly distribution curve due to spatially heterogeneous warming. Its value is estimated from the model output assuming that warming at any location scales linearly with ΔT (see supplementary material available at stacks.iop.org/ERL/8/034018/mmedia). Equation (1) shows that 50% of the land area will experience threshold-exceeding extremes beyond level x when $\Delta T = x\sigma_n$. Thus, for 3-sigma events this happens at 3 °C of land surface warming (2.2 °C of global warming) and for 5-sigma events at 5 °C of land surface warming (3.7 °C of global warming). The rate of increase of the cumulative density curves depends both on σ_n,

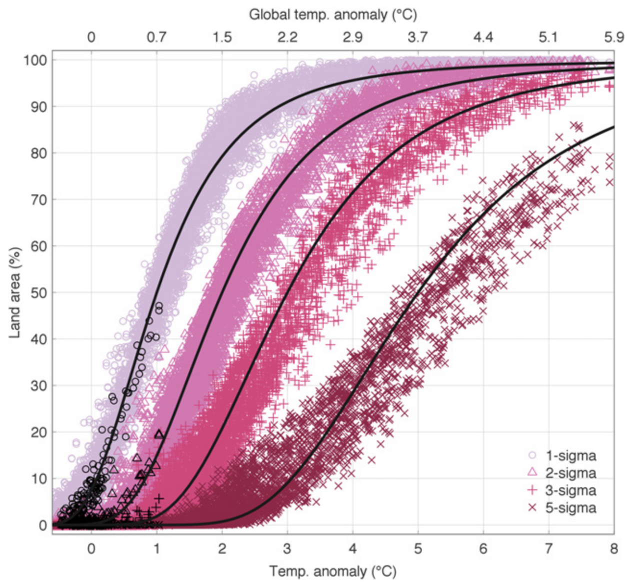

Figure 4. Percentage of global land area during boreal summers with monthly temperatures beyond a specified threshold level in terms of standard deviation (sigma) versus the mean summer land surface temperature (primary horizontal axis) and the global annual mean temperature (upper horizontal axis) for GISS surface temperature data (black symbols), CMIP5 data (colored symbols) and equation (1) (solid lines).

assumed to be constant, and σ_w, which increases for higher levels of warming. Since 5-sigma events appear at higher levels of warming, their rate of increase is smaller than more moderate extremes. This also affects the onset of extremes, i.e., the temperature anomaly at which a particular extreme first becomes detectable: the onset of the 5-sigma curve occurs at 1.5 °C land surface warming, only 1.0 °C warmer than the onset of the 3-sigma curve.

Equation (1) closely follows the center of the model spread over most land fractions for the lower threshold levels, with an overall RMSE of 3.7 percentage points. This implies that, on a global scale, the increase in extremes can largely be explained by equation (1), and thus by a shift in the mean of the local temperature distributions to warmer values, with spatially heterogeneous warming but essentially no change in the local variability. Land fractions of the 5-sigma threshold as predicted by the simple analytical equation begin to deviate from the mean model predictions above 20–30% land fraction slightly overestimating the land area compared to the mean model predictions (though the curve is still within the model uncertainty range). At such high levels of warming the basic underlying assumptions of equation (1) fail and non-linearities are likely to become dominant.

4. Discussion

Though recent heat waves in the northern hemisphere extra-tropics have received much scientific and media attention (Jones *et al* 2008, Rahmstorf and Coumou 2011, WMO 2011, Duffy and Tebaldi 2012, Otto *et al* 2012, Petoukhov *et al* 2013), it is the tropics that have actually seen the strongest increase in threshold-exceeding heat extremes, with the threshold defined by the historic variability. This can be explained by the relatively small year-to-year natural variability in the tropics. This is consistent with numerical studies that have highlighted the vulnerability of the tropics to such extremes (Diffenbaugh and Scherer 2011, Sillmann *et al* 2013). Here we report that this 'tropical fingerprint' can already be detected in surface temperature observations of the 2000–2012 period.

Apart from the tropics, the Mediterranean has also seen a strong increase in extremes in recent years (figure 1). Models project strong increases in heat extremes for this region by the end of the century (Sillmann *et al* 2013) (figure 3), but simulations of the historic period underestimate the number of heat extremes seen in observations (figure 1). The historic rise in heat extremes in the Mediterranean is accompanied by a long-term drying trend (Hoerling *et al* 2012). Possibly, the models either fail to reproduce this drying trend or underestimate the non-linear feedbacks between precipitation and temperature (Schär *et al* 2004, Coumou and Rahmstorf 2012).

We show that the frequency of summer months with extreme heat (3-sigma) and unprecedented heat (5-sigma) will strongly increase under expected future global warming. Even strong mitigation (RCP2.6) cannot stop the increase in occurrence-frequency of 3-sigma heat by a factor four in the near-term. Also, 5-sigma events will emerge and become common in some tropical regions. Mitigation however can strongly reduce the expected number of heat extremes in the second half of the 21st century. The impacts to societies and ecosystems of the projected increase in extremes beyond thresholds defined by the historic variability will be different depending on the region. In the tropics, natural variability is generally small and hence a 3-sigma event might not be a large anomaly in absolute temperatures. Also the vulnerability to extreme heat can differ strongly between regions (Bouwer *et al* 2007, Kershaw and Millward 2012, Bouwer 2013). Nonetheless, in general, society and ecosystems are adapted to extremes experienced in the past and much less so to extremes outside the historic range. For example, most of the 3-sigma extremes that have occurred in recent years resulted in serious impacts to society, causing many heat-related deaths, massive forest fires or harvest losses (Robine 2008, Karoly 2009, WMO 2011, Coumou and Rahmstorf 2012). Thus, the expected future increase in extremes beyond thresholds defined by the historic variability, as reported here, is likely to pose serious adaptation challenges. The metric used here can be useful to identify regions for which adaptation strategies are needed.

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References

Barriopedro D, Fischer E M, Luterbacher J, Trigo R M and García-Herrera R 2011 The hot summer of 2010: redrawing the temperature record map of Europe *Science* **332** 220–4

Betts R A, Collins M, Hemming D L, Jones C D, Lowe J A and Sanderson M G 2011 When could global warming reach 4 °C? *Phil. Trans. R. Soc.* A **369** 67–84

Bouwer L M 2013 Projections of future extreme weather losses under changes in climate and exposure *Risk Anal.* **33** 915–30

Bouwer L M, Crompton R P, Faust E, Höppe P and Pielke R A Jr 2007 Confronting disaster losses *Science* **318** 753

Coumou D and Rahmstorf S 2012 A decade of weather extremes *Nature Clim. Change* **2** 491–6

Coumou D, Robinson A and Rahmstorf S 2013 Global increase in record-breaking monthly-mean temperatures *Clim. Change* **118** 771–82

Diffenbaugh N S and Scherer M 2011 Observational and model evidence of global emergence of permanent, unprecedented heat in the 20th and 21st centuries *Clim. Change* **107** 615–24

Duffy P B and Tebaldi C 2012 Increasing prevalence of extreme summer temperatures in the US *Clim. Change* **111** 487–95

Founda D and Giannakopoulos C 2009 The exceptionally hot summer of 2007 in Athens, Greece—a typical summer in the future climate? *Glob. Planet. Change* **67** 227–36

Hansen J, Sato M and Ruedy R 2012 Perception of climate change *Proc. Natl Acad. Sci.* **109** E2415–23

Hoerling M, Eischeid J, Perlwitz J, Quan X, Zhang T and Pegion P 2012 On the increased frequency of Mediterranean drought *J. Clim.* **25** 2146–62

Jones G S, Stott P A and Christidis N 2008 Human contribution to rapidly increasing frequency of very warm northern hemisphere summers *J. Geophys. Res.* **113** B08S05

Karoly D J 2009 The recent bushfires and extreme heat wave in southeast Australia *Bull. Aust. Meteorol. Oceanogr. Soc.* **22** 10–3

Kershaw S E and Millward A A 2012 A spatio-temporal index for heat vulnerability assessment *Environ. Monit. Assess.* **184** 7329–42

NOAA 2012 *State of the Climate: Wildfires for August 2012* (Asheville, NC: National Climatic Data Center (NCDC)) (www.ncdc.noaa.gov/sotc/fire/2012/8)

Otto F E L, Massey N, van Oldenborgh G J, Jones R and Allen M R 2012 Reconciling two approaches to attribution of the 2010 Russian heatwave *Geophys. Res. Lett.* **39** L04702

Petoukhov V, Rahmstorf S, Petri S and Schelnhuber H J 2013 Quasiresonant amplification of planetary waves and recent Northern Hemisphere weather extremes *Proc. Natl Acad. Sci. USA* **110** 5336–41

Rahmstorf S and Coumou D 2011 Increase of extreme events in a warming world *Proc. Natl Acad. Sci. USA* **108** 17905–9

Robine J M 2008 Death toll exceeded 70,000 in Europe during the summer of 2003 *C. R. Biol.* **331** 171–8

Rupp D E, Mote P W, Massey N, Rye C J and Allen M 2012 Did human influence on climate make the 2011 Texas drought more probable? *Bull. Am. Meteorol. Soc.* **93** 1053–7

Schär C, Vidale P L, Lüthi D, Frei C, Häberli C, Liniger M A and Appenzeller C 2004 The role of increasing temperature variability in European summer heatwaves *Nature* **427** 3926–8

Sillmann J, Kharin V V, Zwiers F W, Zhang X and Bronaugh D 2013 Climate extreme indices in the CMIP5 multi-model ensemble. Part 2: future climate projections *J. Clim.* **118** 2473–93

Stott P A, Jones G S, Christidis N, Zwiers F, Hegerl G and Shiogama H 2011 Single-step attribution of increasing frequencies of very warm regional temperatures to human influence *Atmos. Sci. Lett.* **12** 220–7

Stott P A, Stone D A and Allen M R 2004 Human contribution to the European heatwave of 2003 *Nature* **432** 610–4

Taylor K E, Stouffer R J and Meehl G A 2011 An overview of CMIP5 and the experiment design *Bull. Am. Meteorol. Soc.* **93** 485–98

WMO 2011 *Weather Extremes in a Changing Climate: Hindsight on Foresight* (Geneva: World Meteorological Organization)

World Bank 2012 *Turn Down the Heat: Why a 4 °C Warmer World Must be Avoided. A Report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics* (Washington, DC: World Bank)