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Extreme heat waves under 1.5 °C and 2 °C global warming

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Abstract

Severe, extreme, and exceptional heat waves, such as those that occurred over the Balkans (2007), France (2003), or Russia (2010), are associated with increased mortality, human discomfort and reduced labour productivity. Based on the results of a very high-resolution global model, we show that, even at 1.5 °C warming, a significant increase in heat wave magnitude is expected over Africa, South America, and Southeast Asia. Compared to a 1.5 °C world, under 2 °C warming the frequency of extreme heat waves would double over most of the globe.

In a 1.5 °C world, 13.8% of the world population will be exposed to severe heat waves at least once every 5 years. This fraction becomes nearly three times larger (36.9%) under 2 °C warming, i.e. a difference of around 1.7 billion people. Limiting global warming to 1.5 °C will also result in around 420 million fewer people being frequently exposed to extreme heat waves, and ∼65 million to exceptional heat waves.

Nearly 700 million people (9.0% of world population) will be exposed to extreme heat waves at least once every 20 years in a 1.5 °C world, but more than 2 billion people (28.2%) in a 2 °C world. With current emission trends threatening even the 2 °C target, our study is helpful to identify regions where limiting the warming to 1.5 °C would have the strongest benefits in reducing population exposure to extreme heat.

1. Introduction

At the 21st Conference of the Parties in Paris (2015) governments committed themselves to keep global warming to below 2 °C above pre-industrial levels, with the aim of limiting it to 1.5 °C. The United Nations Framework Convention on Climate Change (UNFCCC) asked the Intergovernmental Panel on Climate Change (IPCC) to provide in 2018 a special report on the impacts of global warming of 1.5 °C. Studies specifically aimed at quantifying the benefit of limiting warming to 1.5 °C compared to 2 °C are therefore needed, but they are still limited (Schleussner *et al* 2016, King *et al* 2017, Russo *et al* 2017, King and Karoly 2017, Dosio and Fischer 2018, and references within Aalto *et al* 2017 and Lennard *et al* 2018).

Some of the most severe effects of global warming will be related to an increase in the frequency and intensity of extreme events (Seneviratne *et al* 2012). Regional maximum temperature on land is expected to increase more than mean global temperature (supporting information figure S1, Seneviratne *et al* 2016); together with greater temperature variability, this will result in more intense and longer heat waves (e.g. Fischer and Schär 2008). Heat waves can greatly reduce labour productivity (e.g. Dunne *et al* 2013) and affect human health, with a documented relationship existing between extreme heat events and increased mortality (García-Herrera *et al* 2010, Robine *et al* 2008, Barriopedro *et al* 2011, Mitchell *et al* 2016, Mora *et al* 2017, Gasparrini *et al* 2017).

Many studies investigated future projections of extreme temperatures and heat waves at both global and regional scale (e.g. Meehl and Tebaldi 2004, Cowan *et al* 2014, Russo *et al* 2014, Pal and Eltahir 2016, Russo *et al* 2015, Lehner *et al* 2016, Dosio 2017, Mora *et al* 2017, Im *et al* 2017, King *et al* 2017, Perkins-Kirkpatrick *et al* 2017) and some assessed the population exposed, at the end of the century, to the risk of extreme heat (Huang *et al* 2011, Dong *et al* 2015, Lee and Kim, 2016, Liu *et al* 2017, Mora *et al* 2017, Gasparrini *et al* 2017); however, direct and thorough comparisons of the characteristics of extreme heat waves and the population exposed to them under 1.5 °C and 2 °C warming are still rare. Furthermore, previous global assessments are mostly based on relatively coarse resolution Global Climate Models (GCMs), which cannot resolve local details and small scale processes.

In this study, we use the results of a high-resolution global atmosphere model to investigate the change in magnitude, frequency, and extension of heat waves at 1.5 °C and 2 °C warming levels. Future heat waves are not only analyzed in terms of geographical extension, intensity, and frequency (return period), but we also estimate the number of people that will be exposed to them, in order to explicitly quantify the benefit of limiting warming to 1.5 °C compared to 2 °C, and to identify regions where adaptation options may be needed.

2. Data and methods

2.1. Climate data

Daily maximum temperature data for the period 1971–2100 were produced by the Swedish Meteorological and Hydrological Institute by means of the high resolution earth system model EC-EARTH3-HR v3.1 (Alfieri *et al* 2017), with spectral horizontal grid T511 (approximately 40 km at the equator) and 91 vertical levels. The model was used to downscale the results of seven GCMs from the Coupled Model Intercomparison Project Phase 5 (CMIP5; supplementary information table S1 available at stacks.iop.org/ERL/13/054006/mmedia) by using the GCMs' sea surface temperature and sea-ice content as lower boundary conditions. The high-resolution atmospheric model is able to resolve more of the atmospheric key drivers and to simulate fine-scale climate variations (especially in regions of complex topography or coastlines, or with highly heterogeneous land cover) that cannot be resolved by coarse resolution GCMs.

Historical runs, forced by observed natural and anthropogenic atmospheric composition, cover the period from 1971 until 2005, whereas the projections (2006–2100) are forced by the Representative Concentration Pathways RCP8.5 (Moss *et al* 2010, Van Vuuren *et al* 2011, Riahi *et al* 2011). The model's original outputs were bilinearly interpolated on a regular 0.5° latitude-longitude grid.

We define the 30 year period from 1976–2005 as reference, as it corresponds to the historical period of the CMIP5 GCMs runs. After applying a 20 year running mean to the observed annual mean global temperature (NASA GISTEMP, Hansen *et al* 2010), we estimate in 0.81 °C the warming, compared to preindustrial period 1880–1900, for the 20 year period centered around 2005 (least year of the historical runs, supplementary information figure S1). For each of the model runs, we then estimate, from the 20 year running average of annual mean global temperature, the year when a further 0.7 °C (1.2 °C) is reached. The 30 year period centered on this year is then used to define the 1.5 °C (2 °C) world and compared to the reference. The resulting mean global warming, compared to the reference period 1976–2005 corresponds to 0.93 °C in a 1.5 °C world, and 1.43 °C in a 2 °C world, respectively.
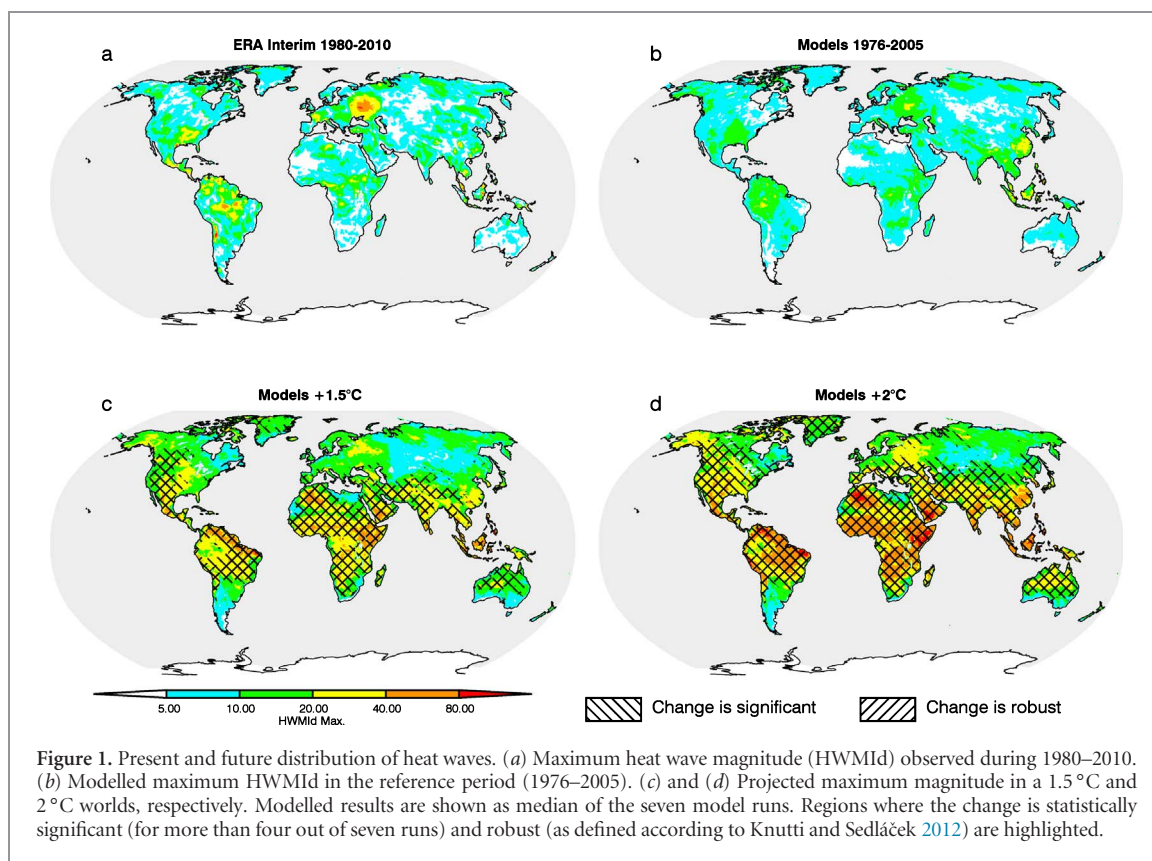
2.2. Population data

Population data, developed by the International Institute for Applied Systems Analysis (IIASA) and the National Center for Atmospheric Research (NCAR), provides a projection of global population under shared socioeconomic pathways (SSP): the dataset, which includes actual population for the period 1980–2010 and estimated projection for the period 2020–2100, has been regridded on a 0.5 × 0.5 degree grid (Murakami and Yamagata 2016). The SSP3, used in this work, assumes a high population growth compatible with the RCP8.5 used for the climate simulations (van Vuuren and Carter 2014).

We use the same projected population for both warming levels, in order to make the results independent of the different years of reaching 1.5 °C and 2 °C. We calculate the fraction of future world population exposed to heat waves for different return periods (5, 20 and 50 years, respectively); only land points where the change between different warming levels is significant are used (as described in section 2.5).

2.3. Heat wave magnitude index

An univocal and optimal definition of heat wave is still under debate (Perkins and Alexander 2013). Perkins (2015) reviews the methodologies to define and characterize heat waves used in the climate and impact communities. These include commonly used indices, such as the warm spell duration index (WSDI), but also more complex ones based on a combination of e.g. maximum and minimum temperature (Meehl and Tebaldi 2004, Nairn and Fawcett 2014) or temperature and humidity (Steadman 1979, Robinson 2001, Fischer and Schär 2010, Russo *et al* 2017, Im *et al* 2017, Mora *et al* 2017)

Here we use the Heat Wave Magnitude Index daily (HWMId, Russo *et al* 2015), designed to take into account both heat wave duration and intensity. The HWMId is defined as the maximum magnitude of the heatwaves occurring in a year, where a heatwave is defined as the period of at least three consecutive

Figure 1. Present and future distribution of heat waves. (*a*) Maximum heat wave magnitude (HWMId) observed during 1980–2010. (*b*) Modelled maximum HWMId in the reference period (1976–2005). (*c*) and (*d*) Projected maximum magnitude in a 1.5 °C and 2 °C worlds, respectively. Modelled results are shown as median of the seven model runs. Regions where the change is statistically significant (for more than four out of seven runs) and robust (as defined according to Knutti and Sedláček 2012) are highlighted.

days with maximum temperature Td above the calendar 90th percentile centered on a 31 day window for the reference period. The magnitude of a heatwave is defined as the sum of the daily magnitude Md(Td) of all the consecutive days composing a heatwave, and it is calculated as follows:

$$
Md(Td) = \begin{cases} \frac{Td - T30y25p}{T30y75p - T30y25p}; & Td > T30y25p \\ 0; & Td \leqslant T30y25p \end{cases}.
$$

Here, T30y25p and T30y75p are the 25th and 75th percentiles of the yearly maximum temperatures (TXx) over the reference period (1976–2005). The interquantile range T30y75p−T30y25p defines the heatwave daily magnitude unit: as a consequence, a daily magnitude Md(Td) equal to *n* indicates that the temperature anomaly on the day *d* with respect to T30yp25 is *n* times the climatological interquantile range.

HWMId was successfully used to classify observed heat waves occurred globally (Zampieri *et al* 2016), and regionally, over Europe (Russo *et al* 2015) and Africa (Ceccherini *et al* 2017). It was also applied to assess heat waves future projections over Africa by Russo *et al* (2016).

A detailed analysis of the difference between HWMId and other commonly used heat waves indices has been performed by Dosio (2017): contrary to e.g. WSDI, which is a measure of the length of the warm spell, but it does not take into account its intensity, HWMId is not only proportional to the heat wave length, but it also depends, crucially, on the temperature anomaly with respect the climatological 25th
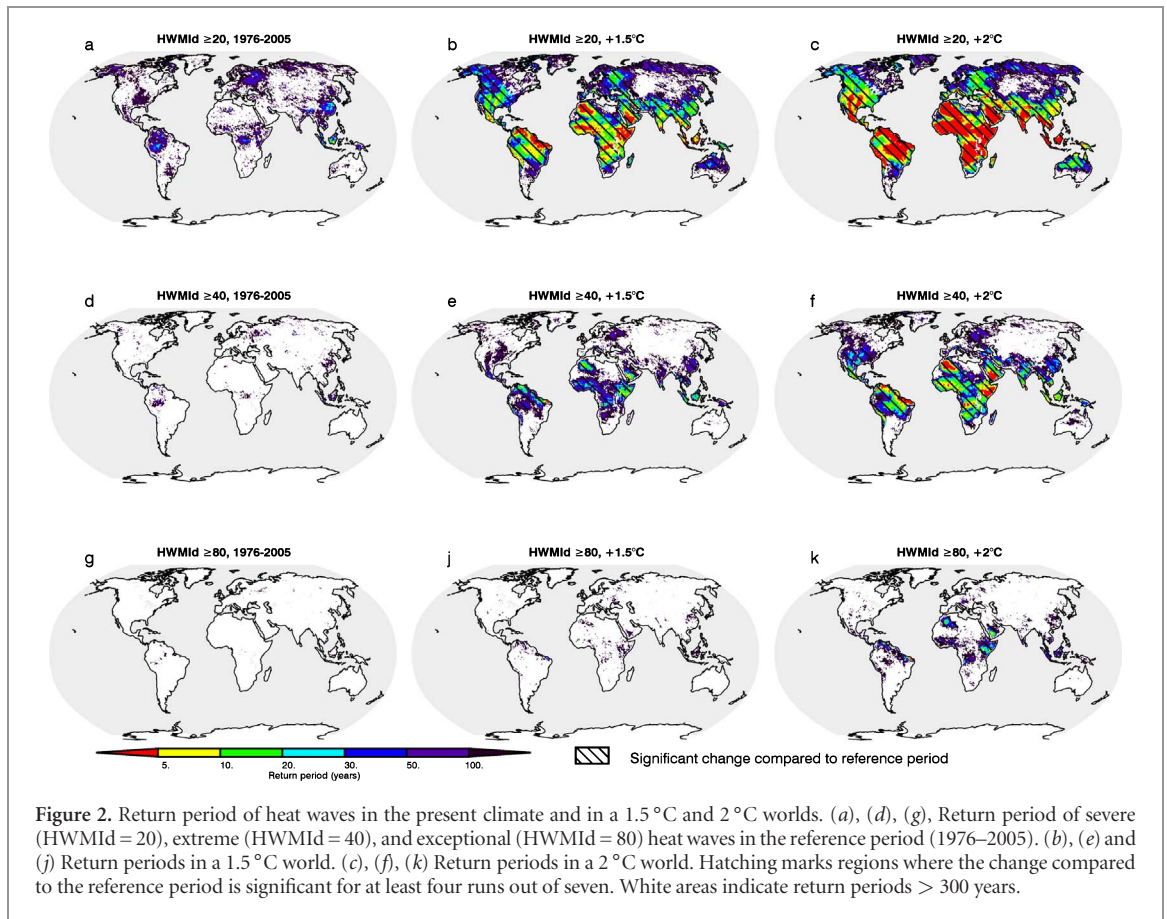
percentile: as a result, it is possible that relatively short but intense heat waves (i.e. with very high values of Tx) may have values of HWMId larger than long but 'weak' warm spells (Dosio 2017).

The magnitude of the most severe heat waves occurred during 1980–2010 are shown in figure 1(*a*). As an example, the heat waves that hit the Balkans (2007), the Midwestern United States (1980), France (2003) and Russia (2010), which were all associated to increased mortality (Mora *et al* 2017), have peak magnitudes of 23.6, 43.6, 39.8 and 81.9, respectively (i.e. the local maximum HWMId value in the region affected by the heat wave, see supporting information table S2): HWMId levels of 20, 40 and 80 are hereafter considered as reference levels for severe, extreme and exceptional heat waves, respectively.

2.4. Return levels

Return levels and return periods are calculated for every model run with a transformed-stationary methodology developed by Mentaschi *et al* (2016) and successfully applied to the projection of extreme coastal waves by Mentaschi *et al* (2017).

This technique consists in (i) transforming a non-stationary time series into a stationary one to which the stationary extreme value theory can be applied; and (ii) reverse-transforming the result into a non-stationary extreme value distribution, for instance a generalized extreme value (GEV) distribution. This technique returns estimations of the extremes comparable with those based on non-stationary

Figure 2. Return period of heat waves in the present climate and in a 1.5 °C and 2 °C worlds. (*a*), (*d*), (*g*), Return period of severe (HWMId = 20), extreme (HWMId = 40), and exceptional (HWMId = 80) heat waves in the reference period (1976–2005). (*b*), (*e*) and (*j*) Return periods in a 1.5 °C world. (*c*), (*f*), (*k*) Return periods in a 2 °C world. Hatching marks regions where the change compared to the reference period is significant for at least four runs out of seven. White areas indicate return periods > 300 years.

Maximum Likelihood Estimators, but is generally more stable (Mentaschi *et al* 2016).

Here, from the long term (1979–2100) time series of heat wave magnitudes, a non-stationary GEV is calculated for each warming level, together with the standard error associated with it. For each return period, (e.g. 10 years), the change in HWMId return level between different warming levels (e.g. 2 °C vs. 1.5 °C) is considered significant if it is larger than two standard errors.

2.5. Statistical analysis

Statistical significance is calculated for each grid point and individual model run with a two-sample Kolmogorov-Smirnov test with the null hypothesis that the discrepancies between HWMId distributions for e.g. the reference and the 1.5 °C periods are only due to sampling error. A significance level of 5% indicates that the null hypothesis can be rejected statistically. When results are presented as median of the model runs, the change is considered statistically significant if it is so for more than four runs out of seven.

Statistical robustness (R) is calculated according to Knutti and Sedláček (2012), R is a measure of the agreement of the model runs, and it depends on the ratio between the uncertainty in the model's projections (spread of the future value) and the mean change (i.e. the difference between future projection and present climate). A value of R equal to 1 means that all model

runs project the same value of heat wave magnitude. $R = 0$ means that the uncertainty in the future HWMId is as large as the mean change between the future and the present. A value of $R = 0.8$ is used as threshold to determine robust model agreement.

Empirical cumulative distribution functions (CDF) in supplementary figures S3, S5, S6 and S7 are calculated, for each sub-region (show in Supplementary figure 2(*b*)), by counting the number of land points (weighted according to their latitude) falling in each bin. The CDF at each HWMId value *x* represents, therefore, the land area fraction that is affected by a heat wave with HWMId equal or greater than *x*.
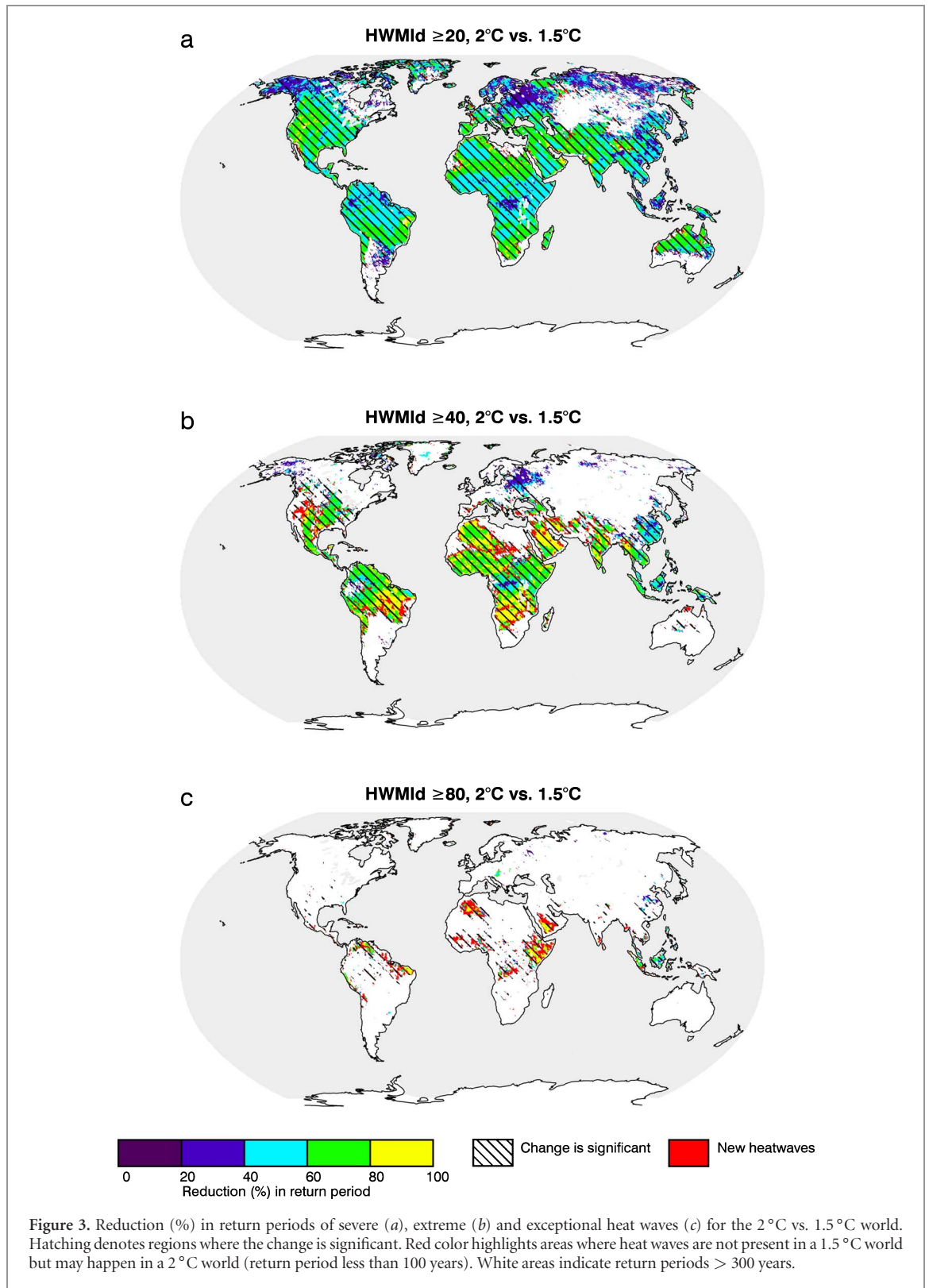
Similarly, empirical CDFs in figure 3 represent, for fixed return levels, the population exposed to a heat wave of magnitude equal or greater than a given HWMId value *x*. Here, only land points where the change in HWMId between different warming levels is significant are used.

3. Results

3.1. Model evaluation

We first evaluate the ability of the model to reproduce present climate observed temperature extremes. Annual maximum temperature (TXx) for the years 1979–2005 are compared to those of two widely used global reanalysis datasets, namely the European Centre for Medium-range Weather Forecast Interim

Figure 3. Reduction (%) in return periods of severe (*a*), extreme (*b*) and exceptional heat waves (*c*) for the 2 °C vs. 1.5 °C world. Hatching denotes regions where the change is significant. Red color highlights areas where heat waves are not present in a 1.5 °C world but may happen in a 2 °C world (return period less than 100 years). White areas indicate return periods > 300 years.

Reanalysis (Dee *et al* 2011) and the National Centers For Environmental Prediction (NCEP) Department of Energy Atmospheric Model Intercomparison Project 2 reanalysis (NCEP-2, Kanamitsu *et al* 2002). Model simulations satisfactorily capture the temporal and geographical variability of observed extreme temperature (supporting information figure S2), with biases usually smaller than those shown by

e.g. Sillmann *et al* (2013a) for the full CMIP5 ensemble.

The spatial extent and magnitude of the most severe heat waves (maximum HWMId) in the present climate is generally captured by the model (figure 1(*b*)); although a direct year to year comparison with the reanalysis is not possible when analyzing fully-coupled climate models' results, it is remarkable that

the model is able to locate correctly most of the hot spots of extreme temperature events, such as continental U.S.A., Russia, the Amazon region, central Africa, and south East Asia (although the HWMId maximum intensity is sometimes underestimated, in line with e.g. Russo *et al* 2015).

Over most regions of the world, the model results lie within the range of the two reanalysis datasets (supporting information figure S3), which show discrepancies in the values of indices of extreme climate over some regions (Sillmann *et al* 2013a). However, over some regions (e.g. northern Europe) the model tends to overestimate the geographical extent of low magnitude heat waves (figure S3). The tendency of climate models to overestimate the intensity and duration of heat waves over Europe was found also by Vautard *et al* (2013).

3.3. Heatwaves in 1.5 °C and 2 °C worlds

Future projections under 1.5 °C and 2 °C warmings show a significant and robust increase in annual maximum temperatures (TXx) over most of the globe (supporting information figure S4), consistent with the results of Schleussner *et al* (2016) based on an ensemble of GCMs. However, very large regional variations exist; for instance, in a 1.5 °C world (i.e. in a world 0.93 °C warmer than the reference climate 1976–2005), the increase in TXx over Northern Asia corresponds to 1.0 °C, whereas in a 2 °C world (a world 1.43 °C warmer than the reference climate) the increase is 1.5 °C. In Western North America the increase ranges between 1.7 °C and 2.4 °C, respectively (supporting information figure S5). Interannual variability is also very different, regionally, with the tropics (e.g. East Africa) showing a markedly smaller variability, in both the present and future climate, compared to higher latitudes (e.g. Northern Europe, supporting information figure S5, Fischer *et al* 2012a, King *et al* 2015, Harrington *et al* 2016).

Under moderate warming (1.5 °C), a significant and robust increase in the heat waves maximum magnitude is projected over most of the globe, especially over Africa, central and south America, and Southeast Asia (figure 1(*c*)). This geographical distribution is consistent to other studies (Russo *et al* 2017, Mora *et al* 2017 although the latter study focuses on projections at the end of the century under different RCPs rather than at specific warming levels) reporting an expected increase of deadly heat-related climatic conditions over most of the tropical developing countries.

In a 2 °C world (figure 1(*d*)), exceptional heat waves, with magnitude similar or higher than that of Russia 2010, are expected to occur especially over regions particularly vulnerable to climate change (Algeria, the Horn of Africa) and the Arabian Gulf, which has been identified as hotspot for critical future human habitability because of extreme temperatures (Pal and Eltahir 2016).

The different geographical rate of increase in heat wave magnitude is due to the combination of the increase in both mean temperature and its variability. In tropical regions, where the present-day variability and the seasonal cycle is small, even a moderate temperature increase will result in longer heat waves (e.g. West Africa, supporting information figure S5, Fischer *et al* 2012a, King *et al* 2015, Harrington *et al* 2016, Dosio 2017). On the other hand, where present temperature variability is large (e.g. Northern Europe), future temperature may still fall within the range of present-day conditions, even under a marked temperature increase (2 °C).

Heat waves will become not only more intense, but also more frequent. In a 1.5 °C world, the return period of severe heat waves is significantly reduced, compared to that of the present-day climate, over most of the world (figure 2); under 2 °C warming, most of the tropical countries will face severe heat waves at least once every five years (in particular 72.9% and 73.2% of land in West and East Africa, supporting information figure S6), and extreme heat waves at least once every 20 years (55.2% of land in West Africa, 58.5% of land In East Africa and 57.6% of land in Southeast Asia, supporting information figure S7).

Compared to the 1.5 °C world, a 2 °C warming will result in a reduction of more than 60% in the return period of extreme heat waves over most of the tropical countries, continental United States and the Mediterranean countries (figure 3(*b*)), with an increase of more than 30% in the fraction of land hit by extreme heat waves every 20 years or less over the Amazon region, West and East Africa and Southeast Asia (supporting information figure S7).

Note, in a 2 °C world, the appearance, in some areas, of exceptional heat waves that are not present in a 1.5 °C world (figure 3(*c*)): in particular, 10% of the land over East Africa and Southeast Asia will be affected by exceptional heat waves at least once every 20 years (supporting information figure S7).

3.4. Impact on population

Even at 1.5 °C warming, 13.8% (model range 9.4%–18.2%) of the global population will be regularly exposed to severe heat waves (on average at least once in 5 years). This fraction becomes nearly three times larger (36.9%, range 32.1%–45.0%) in a 2 °C world (figure 4(*a*)). Limiting global warming to 1.5 °C will therefore reduce the population exposed to severe heat waves by 1.7 billion, by around 420 million for extreme heat waves, and by ∼65 million for exceptional heat waves (figure 4(*b*)). The sudden decline of the curve for HWMId higher than ∼25 is due to the fact that, in a 1.5 °C world, extreme and exceptional heat waves are particularly rare.

Around half (best estimate 49.9%, range 43.2%–56.1%) of the world population will be exposed to severe heat waves and 9.0% (6.1%–14.4%) to extreme
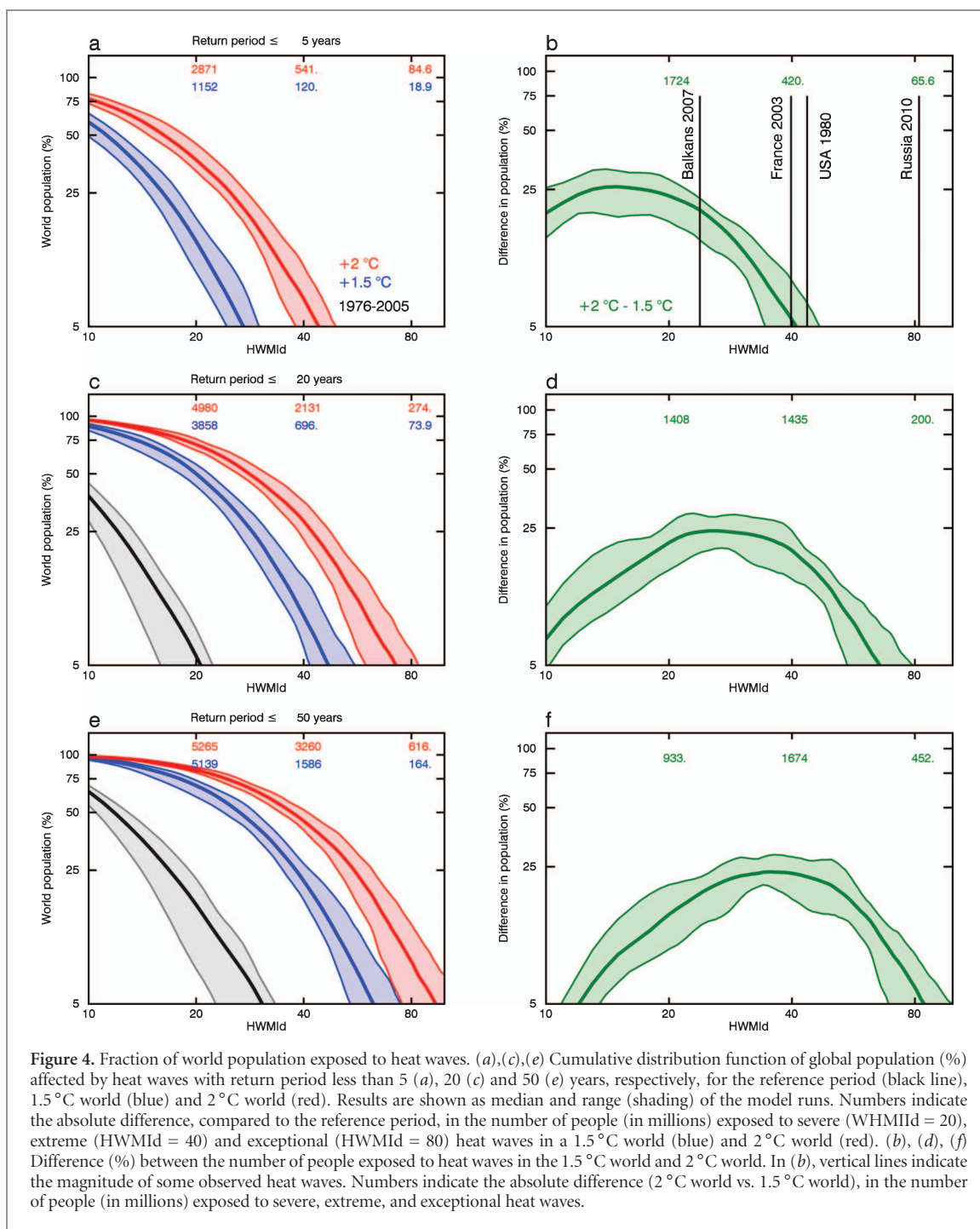
Figure 4. Fraction of world population exposed to heat waves. (*a*),(*c*),(*e*) Cumulative distribution function of global population (%) affected by heat waves with return period less than 5 (*a*), 20 (*c*) and 50 (*e*) years, respectively, for the reference period (black line), 1.5 °C world (blue) and 2 °C world (red). Results are shown as median and range (shading) of the model runs. Numbers indicate the absolute difference, compared to the reference period, in the number of people (in millions) exposed to severe (WHMIId = 20), extreme (HWMIId = 40) and exceptional (HWMIId = 80) heat waves in a 1.5 °C world (blue) and 2 °C world (red). (*b*), (*d*), (*f*) Difference (%) between the number of people exposed to heat waves in the 1.5 °C world and 2 °C world. In (*b*), vertical lines indicate the magnitude of some observed heat waves. Numbers indicate the absolute difference (2 °C world vs. 1.5 °C world), in the number of people (in millions) exposed to severe, extreme, and exceptional heat waves.

heat waves at least once every 20 years in a 1.5 °C world, but 70.9% (66.3%–75.9%) and 28.2% (22.4%–36.0%) in a 2 °C world, which corresponds to a difference of around 1.4 billion people (figure 4(*d*)). Note that in a 2 °C world exceptional heat waves may hit, at least once every 50 years, 8.3% (3.9%–13.1%) of the world population, which corresponds to around 452 million more people than in a 1.5 °C world (figure 4(*f*)). These persons are mainly located in developing countries such as the Horn of Africa, the area of the gulf of Guinea, Indonesia and the coastal regions of South-America from Venezuela to Brazil (figure 2(*k*)).

5. Discussion and conclusions

In this study, we showed that even at 1.5 °C global warming a significant increase in heat waves magnitude and frequency is expected over large areas of the world, especially over Africa, South America, and Southeast Asia. Compared to a 1.5 °C world, under 2 °C warming the frequency of extreme heat waves would double over most of the globe. Exceptional heat waves will occur over large regions of Africa.

This will result in more than 500 million people being exposed to extreme heat waves on average at least once every 5 years, and more than 2 billion people (28%

of projected population) at least once every 20 years; this corresponds to around 420 million and 1.4 billion more people than in a 1.5 °C world, respectively.

However, there are some caveats to our study that need to be mentioned, in particular:

– Heat waves can be described and categorized by several definitions and indexes (based on mean, maximum, minimum temperature, humidity, and a combination of those) which can lead to different quantitative results. Our results are based on the anomaly of maximum temperature, which is often used to assess the risk of extreme heat to human health (e.g. Dong *et al* 2015, Liu *et al* 2017). In addition, the HWMId index has proven to be very successful for the identification and characterization of past heatwaves both globally (Zampieri *et al* 2016) and regionally (Russo *et al* 2015, Russo *et al* 2016, Dosio 2017). Finally, although not directly comparable, our findings agree with others (e.g. Russo *et al* 2017; Mora *et al* 2017) that project increased risk of temperature extremes especially over tropical areas. Also Gasparrini *et al* (2017) project an increase in heat-related mortality, at the end of the century, over central America, southern Europe and South East Asia (although Africa is not included in their work), which is consistent with our findings.

– Being based on the results of 7 GCMs, our study may underestimate the inter-model spread of the full CMIP5 ensemble. However, Sillmann *et al* (2013b) showed that the CMIP5 spread in simulating global mean change in TXx at the end of the century, is usually less than 1 °C (although regional variations are larger), and even less around the middle of the century (i.e. at times compatible with 1.5 °C and 2 °C warmings).

– The impact and related damage of heatwaves having the same HWMId can be different depending on where they occur, since vulnerability can be largely different; for instance, an extreme heat wave in Siberia may have strong ecological impacts, whereas one in the Ganges Delta would be devastating in terms of risk for human health and, eventually, increased mortality.

– When analyzing the effect of climate change under a moderate warming (1.5 °C) it must be remembered that internal (natural) variability can be comparable (if not larger) than the signal. Here, however, we show that there are regions of the world where even a small increase (0.5 °C) in global warming will result in a statistically significant difference, both in intensity (HWMId) and in frequency (return period) of extreme and exceptional heat waves.

– As pointed out by e.g. Fischer *et al* (2012b) the heat stress may be different between urban and rural areas. Heat stress in urban areas is particularly amplified for nighttime minimum temperatures whereas our studies focuses on daytime temperature maxima.

Taking into account this distinction would require the quantification of both urbanization in SSP3 and the urban heat island effect, which are not considered in this study.

– In our assessment of the future risk of heat waves, we only considered the hazard (i.e. heat waves intensity and frequency) and the exposure (i.e. the fraction of population located in areas were heat waves are projected to occur). As in e.g. Gasparrini *et al* (2017) we do not account for vulnerability, adaptation options, and acclimatization of the population (that would reduce the impact of heat waves, e.g. Wu *et al* 2014), or the shifts in the relationship between temperature and mortality (Linares *et al* 2014), which would need thorough and dedicated research (Anderson *et al* 2018, Lee and Kim 2016, Chen *et al* 2017) and would be beyond the scope of this work. As a consequence, our analysis can be considered as an estimate of the number of people exposed to severe heat waves, but the number of people whose health will be affected by them may be significantly lower. Population exposure to extreme heat is further relevant for a potential reduction of labour productivity (e.g. Dunne *et al* 2013), an aspect that is also not addressed in this study.

The findings of our study are particularly relevant because although many previous studies investigated the impact of severe heat events over e.g. Europe or Australia (e.g. Russo *et al* 2015, Cowan *et al* 2014), only few focused specifically on tropical regions where most of the developing countries are located (Harrington *et al* 2016, Pal and Eltahir 2016, Dosio 2017, Im *et al* 2017). The fast population growth and low adaptive capacity makes these regions particularly vulnerable to the impacts of climate change.

Our study shows that implementing ambitious mitigation strategies to limit warming below 2 °C or even to 1.5 °C will drastically reduce exposure to the most severe impact of temperature related extreme events in terms of intensity and frequency of extreme heat waves; moreover, it will drastically reduce the probability of occurrence of exceptional heat waves, with magnitude similar of higher than that occurred in Russia 2010. With the current trend in greenhouse gases emissions, however, even the 2 °C target is considered too optimistic, even with substantial mitigation policies (Raftery *et al* 2017); in this case, our study is useful to identify regions where adaptation options are most strongly and urgently needed.

The EC-EARTH3-HR simulations were performed on resources provided by the Swedish National Infrastructure for Computing (SNIC) at PDC.

The GISS Surface Temperature Analysis (GISTEMP), developed by the NASA Goddard Institute for Space Studies is available at https://data.giss.nasa.gov/gistemp/.

NCEP_Reanalysis 2 data is provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at www.esrl.noaa.gov/psd/.

ERA-Interim data can be downloaded from the ECMWF Public Datasets http://apps.ecmwf.int/datasets/.

SSP database is available from the *Institute for Applied Systems Analysis (IIASA)* https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about.

The HWMId can be calculated via an R package called 'extRemes'.

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