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Poorest countries experience earlier anthropogenic emergence of daily temperature extremes

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Abstract

Understanding how the emergence of the anthropogenic warming signal from the noise of internal variability translates to changes in extreme event occurrence is of crucial societal importance. By utilising simulations of cumulative carbon dioxide (CO_2) emissions and temperature changes from eleven earth system models, we demonstrate that the inherently lower internal variability found at tropical latitudes results in large increases in the frequency of extreme daily temperatures (exceedances of the 99.9th percentile derived from pre-industrial climate simulations) occurring much earlier than for mid-to-high latitude regions. Most of the world's poorest people live at low latitudes, when considering 2010 GDP-PPP per capita; conversely the wealthiest population quintile disproportionately inhabit more variable mid-latitude climates. Consequently, the fraction of the global population in the lowest socio-economic quintile is exposed to substantially more frequent daily temperature extremes after much lower increases in both mean global warming and cumulative CO_2 emissions.

1. Introduction

To understand how detectable anthropogenic influences on the climate system will proliferate with time, a large body of literature has considered the question of when the signal of climate change emerges from the background noise of internal variability. This 'time of emergence' concept has been considered in both observational records and climate model simulations, for a range of climate indices such as temperature (Hawkins and Sutton 2009, Diffenbaugh and Scherer 2011, Joshi *et al* 2011, Mahlstein *et al* 2011, Hawkins and Sutton 2012, Hawkins *et al* 2014), precipitation (Giorgi and Bi 2009, Maraun 2013), the hydrological cycle (Sedláček and Knutti 2014), sea level rise (Lyu *et al* 2014) and even transitions between different ecosystem regimes (Mahlstein *et al* 2013).

There has also been intense public and scientific interest in recent years as whether and to what extent the severity and frequency of extreme weather events have increased in response to anthropogenic climate warming (Peterson *et al* 2012, 2013, Herring *et al* 2014). However, determining how the 'time of emergence' concept can be applied in the context of extreme events continues to be a developing area of research. Recent work (Fischer and Knutti 2015) has quantified the fraction of all moderate heat extremes and precipitation extremes globally which could be attributed to anthropogenic climate change in the present-day as well as for future climate change scenarios, while the emergence of statistically significant changes to specific climate extreme indices have also been demonstrated (King *et al* 2015).

A key interpretation of studies on the time of emergence of climate change indicators suggests that, on seasonal timescales (Diffenbaugh and Scherer 2011, Mahlstein *et al* 2011, Kirtman *et al* 2013, Mora *et al* 2013), climate signals may emerge from the 'noise' of internal climate variability more quickly for low latitude regions than elsewhere around the world. This has been convincingly demonstrated for mean climate indicators (Diffenbaugh and Scherer 2011, Mahlstein *et al* 2011), but these implications have not been explored when considering the exposure of different parts of the global population to the emergence of extremes, particularly temperature extremes which have been found to occur much earlier than precipitation-related extremes (Fischer *et al* 2014, King *et al* 2015).

When considering the regional-scale impacts which may occur in response to a changing climate, the majority of results are communicated with respect to corresponding changes in global mean temperature—this comparison is useful in the context of international climate targets, which are also framed in relation to global mean temperature anomalies (Knutti *et al* 2016). However, progress in recent years quantifying the near-linear correlation between cumulative carbon dioxide (CO_2) emissions with corresponding global temperature anomalies (Allen *et al* 2009, Matthews *et al* 2009, Meinshausen *et al* 2009) have permitted a more in-depth consideration of how the regional impacts of climate change may respond directly to the emission of long-lived greenhouse gases, with potentially important policy implications (Frame *et al* 2014).

In this study, we examine evidence for spatial heterogeneity in the time-evolution of extreme temperature exceedances between different regions of the world aggregated according to local population and income characteristics, using for the first time, a direct comparison with the accumulation of simulated CO_2 emissions.

2. Data and methods

Following the methodology of previous work by Fischer and Knutti (2015), we employ the use of the 'probability ratio' (PR) metric, defined as PR $= P_1/P_0$ where P_0 is the probability of exceeding a certain quantile during the pre-industrial control period and P_1 is the likelihood of exceedance in a more recent period, for example the last 30 years. PR can be interpreted in a climate modelling framework as the increased likelihood of an extreme temperature threshold being exceeded, when comparing a more recent time period with a representation of a climate in the absence of human interference (Allen 2003, Stott *et al* 2004).

Using models from the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor *et al* 2012), we concatenate 'Historical' simulations for the period 1901–2005 with corresponding representative concentration pathways (RCPs) for the period 2006–2100, and then consider time-varying PR values using moving 30-year windows. In this analysis, we choose to define P_0 as the 99.9th percentile of daily temperatures (corresponding to a 1-in-1000 day temperature extreme) based on 200 years of pre-industrial simulations. By focussing on changes to the number of exceedances above a fixed, well-defined percentile threshold over running 30-year intervals, our analysis does not require any assumptions about the shape and type of the underlying statistical distribution, and thus avoids recent concerns relating to the use of parametric analysis when considering a non-stationary time-series for the analysis of climate extremes (Sardeshmukh *et al* 2015, Sippel *et al* 2015).

In order to improve confidence in temperature projections by reducing model uncertainty associated with carbon cycle feedbacks, the RCP scenarios have been created with prescribed concentrations rather than emissions (Moss *et al* 2010). Consequently, the only previous studies considering the physical climate impacts of cumulative emissions from RCP scenarios have inferred cumulative CO_2 based on a best-guess linear scaling of global mean temperature anomalies (Seneviratne *et al* 2016). Here, we instead utilise estimated RCP emissions calculated by Jones and colleagues (2013), whereby the time-evolution of atmospheric carbon and corresponding simulated exchange of carbon with land and ocean sinks for a smaller subset of earth system models (table S1) have been used to infer anthropogenic emissions that are compatible with each prescribed concentration pathway. Thus, all subsequent calculations of cumulative emissions corresponding to extreme climate impacts include the uncertainty in translating global warming anomalies to cumulative emissions as well as the uncertainty in linking global temperatures to PRs (figure S1).

Previous work has considered the temporal evolution of PR (or similarly, risk ratios) averaged either globally or over large regions (figure 1(a)). Here, we choose to focus instead on when specific PR thresholds are exceeded at a single grid scale. Framing the emergence of temperature extremes in this manner also enables a consistent method of comparison between individual locations, as well as between different RCP scenarios. We define the cumulative emissions of probability ratio emergence ($CEPRE_X$) as the simulated accumulation of CO_2 emissions (since 1870) corresponding to the central year of the 30-year period over which a specific PR threshold (X) is exceeded at a specific grid cell—we note that a PR threshold is only considered to be exceeded when all subsequent values remain above the same threshold for the remainder of the time series available (2100). For example, figures 2(a), (c) and (e) show, respectively, the CEPRE corresponding to when the PR exceeds 2,

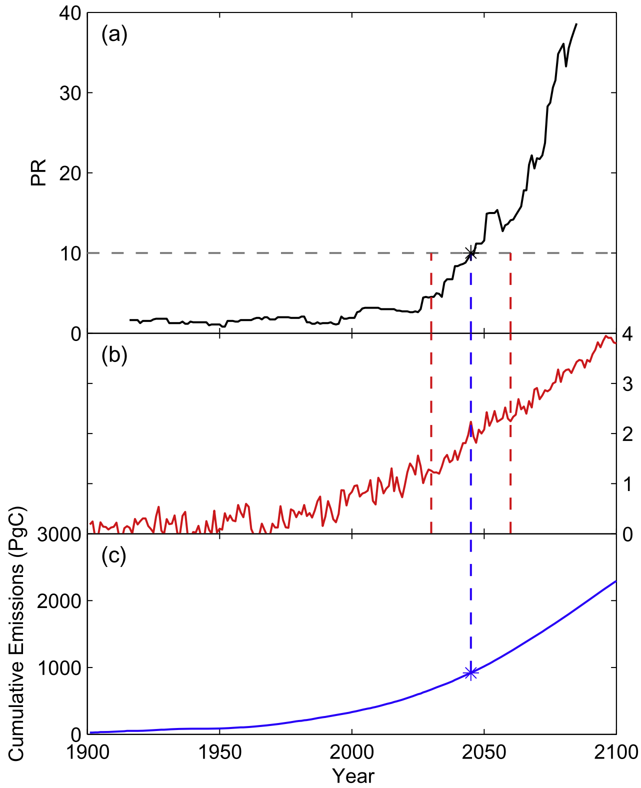

Figure 1. Schematic illustrating how the time-evolution of high-temperature probability ratios are converted to the CEPRE metric. (a) Time-evolution of PR for an individual grid point, presented at the central year of the 30-year period (dashed red line given as example) over which each PR value was calculated. (b) Corresponding global mean temperature anomalies (relative to 1861–1880) over the period 1901–2100. (c) Compatible cumulative CO_2 emissions over the same period, measured as a total since 1870. The black asterisk corresponds to the year when a PR threshold of 10 (grey dashed line) is first exceeded, and continues to remain so, with the corresponding blue asterisk indicating the $CEPRE_{10}$ value for that particular grid box.

10 and 50 for each grid point globally. Hawkins *et al* (2014) highlighted possible endpoint effects with this type of analysis, but sensitivity tests (figure S8) have shown this is negligible in this study, due to the low variability in PR.

To consider how these emergent changes in PR are experienced by the populated regions of the world, we overlay global population and gross domestic product data, accounting for purchasing power parity (GDP-PPP), prepared for the year 2010 by the Global Carbon Project (http://www.cger.nies.go.jp/gcp/population-and-gdp.html) at a spatial resolution of 0.5° × 0.5° (figure S5). Future changes to population and economic growth will have clear influences on these results—we have chosen to focus on fixed data of the present-day to ascertain emergent risks for present populations, and consider future projections of population and economic data in the supplementary material. While internal variability in temperature is greater over smaller spatial scales, the aggregation of grid cells over areas comparable in size to populated regions of the world have previously demonstrated discernible shifts in the probability distributions of temperature and precipitation extremes (Fischer *et al* 2013, 2014), and thus will be suitable for analysing the emergence of high-temperature PRs.

3. Results

Figure 2 illustrates the cumulative emissions required for PR thresholds of 2, 10 and 50 to be exceeded in different regions of the world. The maps show the median model CEPRE for each PR threshold using RCP8.5 simulations, while the corresponding timing of exposure of the poorest and wealthiest quantiles of the global population are also presented. Considering the spatial distribution of CEPRE for each PR threshold, it is clear that fewer cumulative emissions are required for the continual exceedance of these PR thresholds to occur for lower latitudes, compared with higher latitudes, while oceanic regions also generally appear to experience a more rapid time of emergence than corresponding land surfaces nearby. These results are consistent with previous research (Diffenbaugh and Scherer 2011, Fischer and Knutti 2015) and suggests that although land and high latitude regions experience larger warming signals than the global mean, the variability in daily temperatures over ocean and low latitude regions are significantly lower, thereby resulting in the earlier emergence of more frequent high-temperature extremes.

Considering the differences over quintiles in GDP-PPP per capita, we find increasingly large differences in CEPRE between the wealthiest and poorest

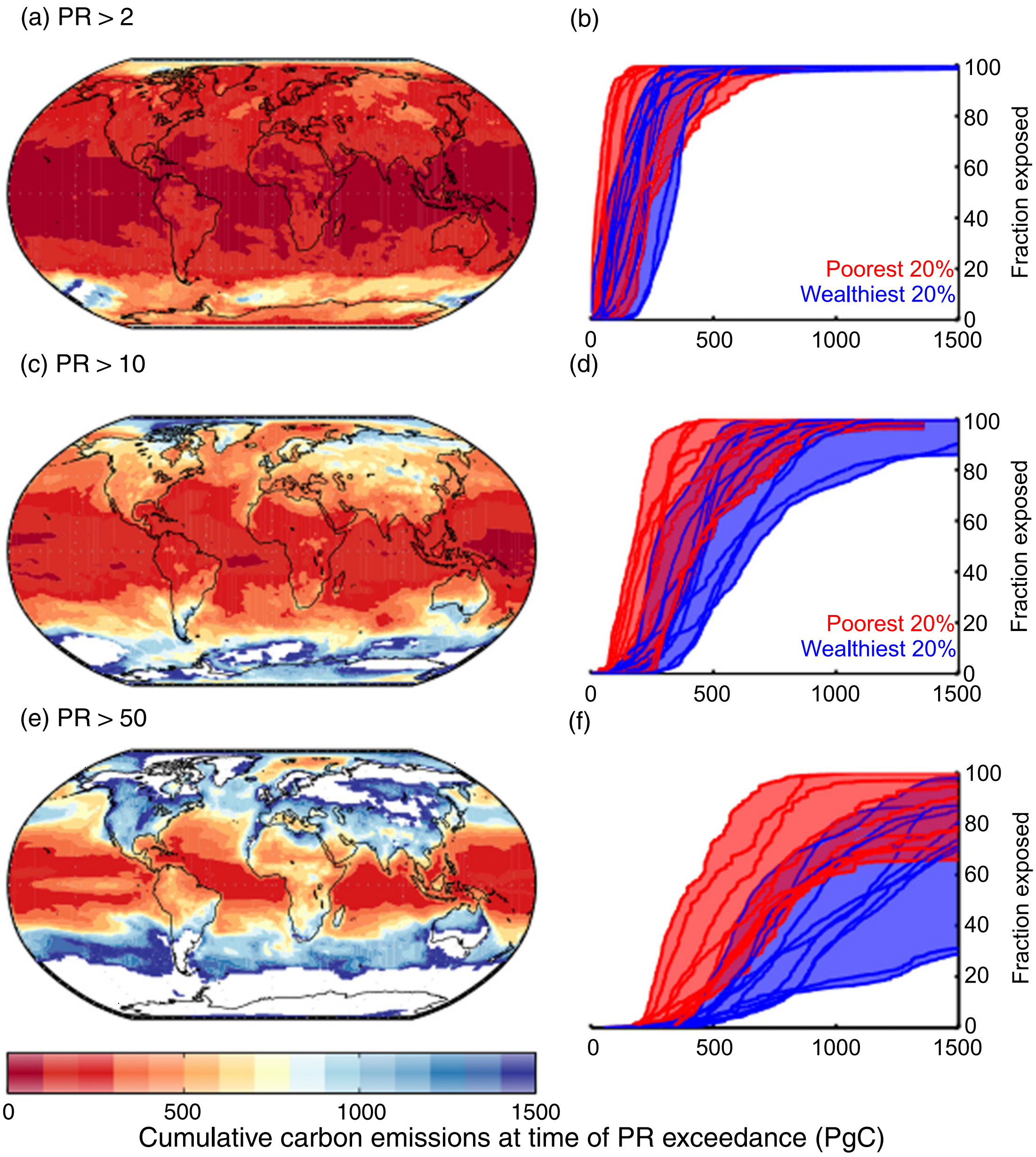

Figure 2. Left-hand panels show the global distribution of the median model estimate of the cumulative emissions of probability ratio emergence (CEPRE). This is defined at the simulated cumulative emissions of carbon dioxide (in Petagrams of carbon, with respect to 1870) at the central year of the 30-year period when the probability ratio for one-day temperature extremes permanently exceeds a threshold of (a) 2; (c) 10 and (e) 50 at each individual grid point. White regions indicate where the median model response shows no exceedance of the respective PR threshold by the end of 2100. Corresponding right-hand panels show the cumulative fraction of the poorest (red) and wealthiest (blue) quintiles of the global population (based on 2010 GDP-PPP per capita) which are exposed to the specified PR threshold exceedances, also as a function of cumulative carbon emissions, for eleven CMIP5 models over the period 1901–2100, using 'Historical' and 'RCP8.5' simulations.

populations, as the PR threshold increases. For example, comparing the panels in figure 2 for a PR of 2 (figure 2(b)) shows minor differences in the evolution of population exposure with warming between the two economic groupings, but considering the cumulative emissions required for population exposure to a much higher PR threshold of 50 reveals a much wider gap in the time of emergence between the two sub-populations, albeit with large variability between models. It is also noted that $CEPRE_2$ is less than 400 PgC for nearly 100% of both sub-populations, which corresponds to present-day estimates of global cumulative emissions (Peters *et al* 2015). Interestingly, when considering the CEPRE for RCP4.5 and RCP2.6 simulations instead (figures S10 and S11), the differences in the timing of PR exposure for the lower latitude locations are negligible. Instead, it is exceedances of the higher PR thresholds which are not reached for mid-to-high latitudes by the end of the century.

It is important to note that the wealthiest quintile of the global population is dispersed over a land area seven times greater than that of the poorest quintile—however, even considering regions of equal land area, an equivalent fraction of the poorest populations

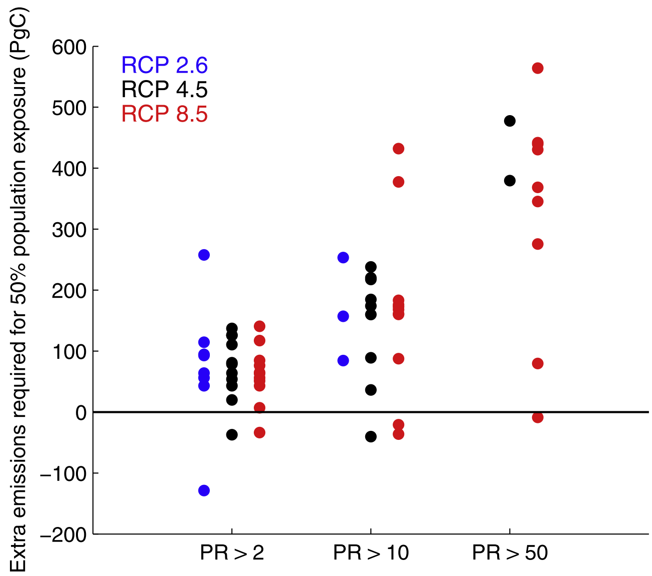

Figure 3. The difference in cumulative emissions between the central year (of the 30-year period) when 50% of the poorest population quintile experiences the continuous exceedance of a given PR threshold, and the corresponding central year when 50% of the wealthiest population quintile exceeds that same threshold. Only model values are shown where greater than 50% cumulative exposure occurs for both sub-populations by 2100. Blue, black and red circles correspond to each model using RCP2.6, RCP4.5 and RCP8.5 simulations, respectively.

continues to experience earlier emergence of all three PR thresholds than their wealthier counterparts (figure S6).

Comparing, for each individual model, the difference in cumulative emissions required for 50% of the poorest population quintile to exceed each PR threshold versus the equivalent to occur for 50% of the wealthiest quintile, figure 3 reveals that nearly all models across all RCP scenarios show high-temperature PRs occurring earlier for the poorest populations than for their wealthier socio-economic counterparts. Under an RCP8.5 scenario for example, models suggest that between −10 and 560 PgC of additional carbon would be emitted between the time when 50% of the poorest members of society continually experience a 50-fold increase in 1-in-1000 day hot extremes and the time when exposure occurs for an equal number of citizens within the wealthiest population quintile, thereby emphasising the contrasting time horizons available for adaptation measures. Supplementary analysis reveals that models which exhibit the largest differences in the timing of exposure between the two sub-populations are actually those with a relatively modest transient climate response to cumulative carbon emissions (TCRE, Gillett *et al* 2013), and vice versa (figure S2). Rapid increases in PRs occur in tropical latitudes for all models, while corresponding PR increases in higher latitudes only occur quickly for the high-TCRE models (figure S4), subsequently resulting in smaller differences in CEPRE between the two sub-populations.

Further interrogating the differences in the cumulative distribution of CEPRE between the wealthiest and poorest socio-economic quintiles, figure 4 shows the differences in the fractions of each population quintile which have experienced emergence of each PR threshold, as a function of global cumulative CO_2 emissions. This figure demonstrates that (1) after a given level of cumulative emissions, up to an additional 60% of the poorest members of society cross each of these PR thresholds than corresponding wealthy populations; and (2) these patterns of unequal population exposure in response to accumulating CO_2 emissions occur consistently across all three RCP scenarios. This shows that the differences in the timing of emergence of temperature extremes between low latitude and high latitude regions are insensitive to the rate of temperature change over the twenty-first century.

In 2013, the United Nations Framework Convention on Climate Change established the Warsaw International Mechanism to address the potential loss and damage from climate change impacts for developing countries (James *et al* 2014). The policy-relevance of our result lies in the disparity between richer and poorer people in terms of their exposure to the timing of emergence of temperature extremes. Whilst exposure to higher PRs does not result in higher vulnerability, the adaptive capacity of a region can generally be considered to scale with (1) climate variability and (2) income—certainly across the range implied by considering the richest and poorest quintiles (Grambsch and Menne 2003, Hayden *et al* 2011). These results do therefore suggest, *ceteris paribus*, earlier and more significant relative vulnerability to temperature extremes among the world's poor and are thus of potential importance to policymakers.

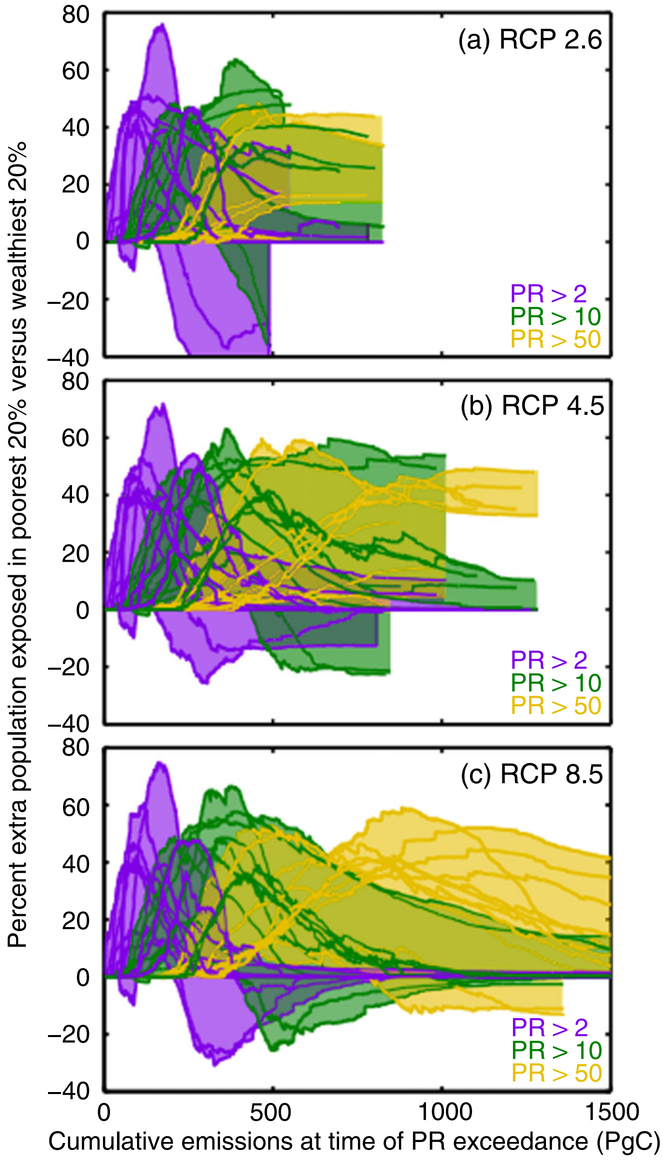

Figure 4. Difference in the fraction of population exposure to specified PR thresholds (colours) between the poorest 20% and the wealthiest 20% of the global population, as a function of CEPRE. Positive values indicate that a greater fraction of the poorest population quintile is experiencing permanent exceedances of each specified PR threshold, compared with the wealthiest quintile, after a given quantity of cumulative carbon emissions.

4. Discussion

In this study, we have for the first time simulated the direct influence of cumulative carbon emissions on the time of emergence of daily extreme temperatures, by considering the CEPRE metric at specific PR thresholds. In considering only the persistent emergence of given PR thresholds in the context of fractional population exposure, our results are less sensitive to internal variability, despite the smaller spatial scales considered. Moreover, previous research has found the emergence of more frequent heat extremes averaged over a longer time period (such as 5-day or 30-day anomalies) occurs even earlier when compared with 1-day extremes (Fischer and Knutti 2015).

By assessing emergent PR increases as a function of cumulative CO_2 emissions, this approach serves well to evaluate the relative changes in heat extremes between different regions in the world, as well as across scenarios, and could therefore be of use to those working in vulnerability, impacts and adaptation, and to integrated assessment modellers, with the caveat that the continuing exceedance of specific PR thresholds could be interpreted as a proxy for heat-related damages (Dunne *et al* 2013, Burke *et al* 2015, Hansen and Sato 2016).

While the compatible emissions profiles used in this study have shown to accurately replicate the original Integrated Assessment Models used in developing the RCPs (Jones *et al* 2013), it has been demonstrated that emission-driven simulations overestimate warming projections when compared with concentration-driven simulations (Friedlingstein *et al* 2014). We therefore choose to avoid specifying absolute cumulative emission targets for preventing the emergence of specific PR thresholds. However, even with the added uncertainty of considering the end-to-end link between cumulative emissions and extreme temperatures, the key differences in fractional exposure of emergent high-temperature PRs between the wealthiest and poorest global population quintiles remain clear, as evidenced by the equivalent results found when considering the link with rises in global mean temperatures directly (figures S12–S14).

Even if emissions are towards the low end of the range considered by the RCP scenarios, this analysis shows that the pattern of changes in frequency of daily temperature extremes remains robust: daily temperature extremes emerge to more frequently affect the poorest 20% of the global population, when compared with the wealthiest 20% of the global population for all RCP scenarios, for a range of PRs. This result can be explained primarily due to the fact that the poorest people in the world densely populate lower latitude regions, where the low variability in temperature enhances the pace of emergence of a given signal-to-noise ratio when compared with higher latitude regions (Hawkins and Sutton 2009, Diffenbaugh and Scherer 2011, Mahlstein *et al* 2011, Hawkins *et al* 2014, Hansen and Sato 2016).

As global cumulative carbon dioxide emissions continue to increase, the fractional gap in population exposure between the poorer and wealthier members of society will only widen for exponentially higher PR thresholds (figure 4). While all populated regions around the globe will enter a new regime of temperature extremes with no observed historical precedence if cumulative emissions continue to increase at current rates, the impacts, in terms of frequency of heat extremes, will become significantly worse for poorer nations when compared with their wealthier counterparts. We therefore argue that, even though our results show the emergence of more severe temperature extremes will always occur for poorer populations first, the potential prevention of crossing extreme PR thresholds means that the poorest members of the global community will always be the greatest beneficiaries of action towards a low-carbon pathway.

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References

Allen M 2003 Liability for climate change *Nature* **421** 891–2

Allen M R, Frame D J, Huntingford C, Jones C D, Lowe J A, Meinshausen M and Meinshausen N 2009 Warming caused by cumulative carbon emissions towards the trillionth tonne *Nature* **458** 1163–6

Burke M, Hsiang S M and Miguel E 2015 Global non-linear effect of temperature on economic production *Nature* **527** 235–9

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

Dunne J P, Stouffer R J and John J G 2013 Reductions in labour capacity from heat stress under climate warming *Nat. Clim. Change* **3** 563–6

Fischer E M, Beyerle U and Knutti R 2013 Robust spatially aggregated projections of climate extremes *Nat. Clim. Change* **3** 1033–8

Fischer E M and Knutti R 2015 Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes *Nat. Clim. Change* **5** 560–4

Fischer E M, Sedláček J, Hawkins E and Knutti R 2014 Models agree on forced response pattern of precipitation and temperature extremes *Geophys. Res. Lett.* **41** 2014GL062018

Frame D J, Macey A H and Allen M R 2014 Cumulative emissions and climate policy *Nat. Geosci.* **7** 692–3

Friedlingstein P, Meinshausen M, Arora V K, Jones C D, Anav A, Liddicoat S K and Knutti R 2014 Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks *J. Clim.* **27** 511–26

Gillett N P, Arora V K, Matthews D and Allen M R 2013 Constraining the ratio of global warming to cumulative CO_2 emissions using CMIP5 simulations *J. Clim.* **26** 6844–58

Giorgi F and Bi X 2009 Time of emergence (TOE) of GHG-forced precipitation change hot-spots *Geophys. Res. Lett.* **36** L06709

Grambsch A and Menne B 2003 Adaptation and adaptive capacity in the public health context *Clim. Change Health Risks Responses* ed A J McMichael (Geneva: World Health Organization) pp 220–36

Hansen J and Sato M 2016 Regional climate change and national responsibilities *Environ. Res. Lett.* **11** 034009

Hawkins E *et al* 2014 Uncertainties in the timing of unprecedented climates *Nature* **511** E3–5

Hawkins E and Sutton R 2009 The potential to narrow uncertainty in regional climate predictions *Bull. Am. Meteorol. Soc.* **90** 1095–107

Hawkins E and Sutton R 2012 Time of emergence of climate signals *Geophys. Res. Lett.* **39** L01702

Hayden M H, Brenkert-Smith H and Wilhelmi O V 2011 Differential adaptive capacity to extreme heat: a phoenix, arizona, case study *Weather Clim. Soc.* **3** 269–80

Herring S C, Hoerling M P, Peterson T C and Stott P A 2014 Explaining extreme events of 2013 from a climate perspective *Bull. Am. Meteorol. Soc.* **95** S1–104

James R, Otto F, Parker H, Boyd E, Cornforth R, Mitchell D and Allen M 2014 Characterizing loss and damage from climate change *Nat. Clim. Change* **4** 938–9

Jones C *et al* 2013 Twenty-first-century compatible CO_2 emissions and airborne fraction simulated by CMIP5 earth system models under four representative concentration pathways *J. Clim.* **26** 4398–413

Joshi M, Hawkins E, Sutton R, Lowe J and Frame D 2011 Projections of when temperature change will exceed 2 °C above pre-industrial levels *Nat. Clim. Change* **1** 407–12

King A D, Donat M G, Fischer E M, Hawkins E, Alexander L V, Karoly D J, Dittus A J, Lewis S C and Perkins S E 2015 The timing of anthropogenic emergence in simulated climate extremes *Environ. Res. Lett.* **10** 094015

Kirtman B *et al* 2013 Near-term climate change: projections and predictability *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T F Stocker *et al* (Cambridge: Cambridge University Press) pp 953–1028 (http://ebooks.cambridge.org/ref/id/CBO9781107415324A031)

Knutti R, Rogelj J, Sedláček J and Fischer E M 2016 A scientific critique of the two-degree climate change target *Nat. Geosci.* **9** 13–8

Lyu K, Zhang X, Church J A, Slangen A B A and Hu J 2014 Time of emergence for regional sea-level change *Nat. Clim. Change* **4** 1006–10

Mahlstein I, Daniel J S and Solomon S 2013 Pace of shifts in climate regions increases with global temperature *Nat. Clim. Change* **3** 739–43

Mahlstein I, Knutti R, Solomon S and Portmann R W 2011 Early onset of significant local warming in low latitude countries *Environ. Res. Lett.* **6** 034009

Maraun D 2013 When will trends in European mean and heavy daily precipitation emerge? *Environ. Res. Lett.* **8** 014004

Matthews H D, Gillett N P, Stott P A and Zickfeld K 2009 The proportionality of global warming to cumulative carbon emissions *Nature* **459** 829–32

Meinshausen M, Meinshausen N, Hare W, Raper S C B, Frieler K, Knutti R, Frame D J and Allen M R 2009 Greenhouse-gas emission targets for limiting global warming to 2 °C *Nature* **458** 1158–62

Mora C *et al* 2013 The projected timing of climate departure from recent variability *Nature* **502** 183–7

Moss R H *et al* 2010 The next generation of scenarios for climate change research and assessment *Nature* **463** 747–56

Peters G P, Andrew R M, Solomon S and Friedlingstein P 2015 Measuring a fair and ambitious climate agreement using cumulative emissions *Environ. Res. Lett.* **10** 105004

Peterson T C, Stott P A and Herring S 2012 Explaining extreme events of 2011 from a climate perspective *Bull. Am. Meteorol. Soc.* **93** 1041–67

Peterson T C, Stott P A and Herring S 2013 Explaining extreme events of 2012 from a climate perspective *Bull. Am. Meteorol. Soc.* **94** S1–74

Sardeshmukh P D, Compo G P and Penland C 2015 Need for caution in interpreting extreme weather statistics *J. Clim.* **28** 9166–87

Sedláček J and Knutti R 2014 Half of the world's population experience robust changes in the water cycle for a 2 °C warmer world *Environ. Res. Lett.* **9** 044008

Seneviratne S I, Donat M G, Pitman A J, Knutti R and Wilby R L 2016 Allowable CO_2 emissions based on regional and impact-related climate targets *Nature* **529** 477–83

Sippel S, Zscheischler J, Heimann M, Otto F E L, Peters J and Mahecha M D 2015 Quantifying changes in climate variability and extremes: pitfalls and their overcoming *Geophys. Res. Lett.* **42** 2015GL066307

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 2012 An overview of CMIP5 and the experiment design *Bull. Am. Meteorol. Soc.* **93** 485–98