with mounting domestic concern over the state of global action could motivate the EU and China to ruthlessly pursue an unassailable comparative economic advantage. A withdrawal could also make the US into a climate pariah and provide a unique opportunity for China and the EU to take control of the climate regime and significantly boost their international reputations and soft power.

A new coalition between the EU and China could take numerous forms. One approach is the linkage of their emissions trading systems[19], although this would be subject to technical challenges. Other options include the creation of a more ambitious jointly determined contribution between the two countries[20]. Either of these options could be combined with a common border carbon adjustment. Trade pressure and a loss of both competitiveness and political influence could drive US climate action in the longer-term[19].

Forceful leadership by the EU and China is doubtful if the US does not make the drastic move of withdrawal.

Looking to the future

It appears that the Paris Agreement will not be 'Trump-proofed'. Indeed, US-proofing the agreement would require wide-reaching amendments to the agreement[19]. The Paris Agreement was blind to the threat of US recalcitrance, and instead was weakened to allow for US legal participation[21]. It was a short-sighted mistake that future international agreements can learn from. While Paris is fragile, international climate action can be antifragile[22]: the shock of Trump could make action stronger by allowing trade measures and new, emboldened leadership to blossom. ❐

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COMMENTARY:

In the observational record half a degree matters

Carl-Friedrich Schleussner, Peter Pfleiderer and Erich M. Fischer

Discriminating the climate impacts of half-degree warming increments is high on the post-Paris science agenda. Here we argue that evidence from the observational record provides useful guidance for such assessments.

A key challenge for the upcoming IPCC special report on 1.5 °C is to discriminate between climate impacts at half-degree warming increments. The differences between present-day warming of about 1 °C, and warming levels of 1.5 °C and 2 °C global mean temperature (GMT) increase above pre-industrial levels are of special interest.

Preliminary research has found discernible differences between model-projected regionally aggregated impacts at 1.5 °C and 2 °C for extreme weather indices and vulnerable systems and regions[1]. The differences between 1.5 °C and 2 °C warming are further addressed with targeted climate model experiments[2]. However, such model-based efforts include substantial uncertainties, for example those introduced by different model parameterizations or representations of ocean variability. As a complementary line of evidence for the consequences of half a degree of warming we here revisit the observational record. In the following, we illustrate the implications of 0.5 °C observed warming on the occurrence of temperature and precipitation extremes.

Due to limitations in length and spatial coverage of the observational record, attribution studies typically refer to climate change since the 1950s or later, which corresponds to only slightly more than 0.5 °C of observed warming at most[3]. We here assess extreme weather indices for the 1991–2010 versus the 1960–1979 period, which corresponds to just about 0.5 °C GMT difference in the GISTEMP temperature record[4]. The warming between the two periods in alternative GMT records is somewhat smaller, rendering the estimates presented rather conservative. We quantify probability density functions for the globally aggregated differences between grid-cell-averaged extreme event indices (see Supplementary Methodology). In Fig. 1 we show results for two observational datasets, HadEX2 and GHCNDEX, as well as for reanalysis datasets for hot temperature extremes.

Substantial changes due to 0.5 °C warming are apparent for indices related to hot and cold extremes (annual maximum value of daily maximum temperature TXx, annual minimum value of daily minimum temperature TNn) as well as the Warm Spell Duration Indicator (WSDI, see supplementary material for further information on the indices used). Even though for all indices some individual grid cells experience a decline, the changes aggregated over the observational network exhibit an increase that is substantially larger than what would be expected by chance (Fig. 1, shaded regions). One quarter of the land mass has experienced an intensification of hot extremes (TXx) by more than 1 °C and a reduction of the intensity of cold extremes by at least 2.5 °C (TNn). Half of the global land mass has experienced changes in WSDI of more than 6 days and the emergence of extremes outside the range of natural variability is particularly pronounced for this duration-based indicator.

The use of reanalysis data allows us to expand the analysis of temperature-related extremes to the global landmass including low latitudes[5], where the observational network is sparse. As depicted in Fig. 1, the mean change over the global landmass (excluding Antarctica and Greenland) in 20CR is similar to those in the observational datasets. The mean increase in the ERA reanalyses, however, is considerably more pronounced as a result of strong regional increases in extreme temperature in tropical Africa and South Asia (Supplementary Fig. 4). Given their limitations, reanalyses products need to be interpreted with care. However, the aggregated change for extreme temperatures are similar between all datasets when compared over the same regional mask (Supplementary Fig. 3). For extreme precipitation, a robust increase is observed for both indices investigated here (annual maximum 1-day precipitation, RX1day, and consecutive 5-day precipitation, RX5day). A quarter of the land mass has experienced an increase of at least 9% for extreme precipitation (RX5day).

Influenced by natural variability and anthropogenic changes in aerosol forcing[6] and land use, the change in extreme event indices exhibits distinct regional patterns (Supplementary Figs 4–8). Changes in hot extremes (TXx) can clearly be identified and exceed the changes expected due to internal variability (light-coloured envelopes) — also at the scale of world regions including Europe, North America, Russia and Asia (Supplementary Fig. 9). It is important to note that some of the regional effects of half a degree warming over the historical period, during which the aerosol forcing has substantially changed[6], may be different to those in the future.

We test this within an ensemble of models from the Coupled Model Intercomparison Project (CMIP5) and demonstrate that the changes in hot extremes and heavy rainfall induced by 0.5 °C GMT warming in the historical simulations are good analogues for

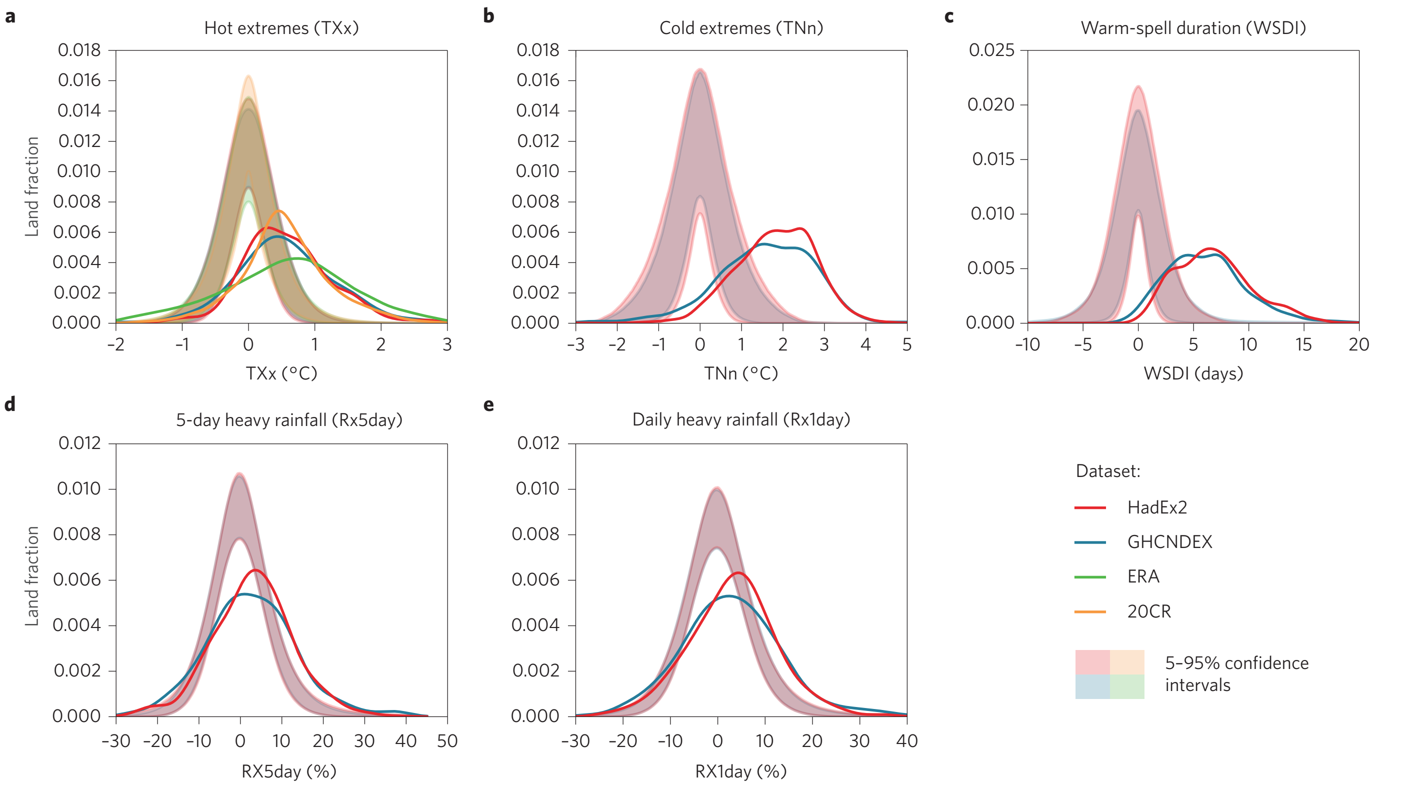

Figure 1 | Differences in extreme weather event indices for 0.5 °C warming over the observational record. Probability density functions show the globally aggregated land fraction that experienced a certain change between the 1991–2010 and 1960–1979 periods for the HadEX2 and GHCNDEX datasets. For TXx, we also included reanalysis data from ERA and 20CR over the global land area. Light-coloured envelopes illustrate the changes expected by internal variability alone, estimated by statistically resampling individual years (see Supplementary Information).

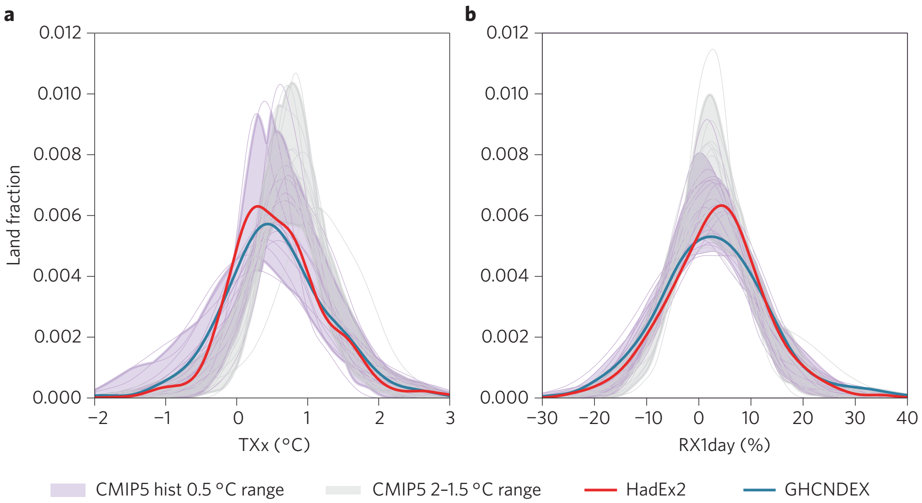

Figure 2 | Historical 0.5 °C warming is representative for 1.5 °C versus 2 °C differences. Changes in hot extremes (**a**) and extreme precipitation (**b**) due to 0.5 °C warming over the historical period (purple) and between 1.5 °C and 2 °C (grey) as simulated in an ensemble of CMIP5 models. Model-specific time slices are derived to match historical 0.5 °C warming up to the 1991–2010 reference period and future warming levels of 1.5 °C and 2 °C above pre-industrial conditions (see Supplementary Information). The filled envelope depicts the 5–95% ensemble range and thin lines represent individual models. The observed differences are given for comparison in blue and red as in Fig. 1.

the changes between a 1.5 °C and 2 °C warming (Fig. 2). Our findings indicate that despite different forcings and potential non-linearities, half a degree of warming in the observational record provides valuable insights into the differences between the 1.5 °C and 2 °C warming levels. This is consistent with evidence in the scientific literature that in contrast to mean precipitation, heavy precipitation is less forcing dependent[7] and that indices such as TNn, TXx and Rx1day scale remarkably linearly with GMT[8]. For hot temperatures (TXx), however, there appears to be a more pronounced lower tail of the distribution for the historical 0.5 °C warming that might be linked to the substantial changes in aerosol forcing over Asia[9]. Our results indicate that observation-based findings for changes in hot temperatures are conservative estimates for the differences between 1.5 °C and 2 °C. For cold extremes (TNn), we find that the models systematically underestimate the changes in the observational record (compare Supplementary Fig. 11)[10]. The linear scaling is furthermore limited to magnitude-based indices, whereas threshold indices such as the duration of warm spells (WSDI) will increase non-linearly, so that any additional warming such as between 1.5 °C and 2 °C warming will have substantially larger effects than the one observed.

Taken together, the observed changes in extreme weather event indices are consistent with the established understanding of changes in the climate system attributable to anthropogenic influence[3]. A range of detrimental effects of climate change on natural and human systems is evident from the observational record[11]. Among many other examples, Arctic sea-ice cover and mountain glacier volume have dramatically decreased[12], and tropical coral reefs have experienced drastic losses in coral abundance[13]. Due to time-lagged effects in many systems, we have not experienced the full impact of present-day warming yet.

Observed impacts may in many cases present a lower bound for the impacts of future 0.5 °C warming increments on human and natural systems. These are likely to be more pronounced for additional warming differences as these systems are expected to be increasingly susceptible to change outside the range of pre-industrial natural variability[11]. Crossing tipping points[1] and systemic limits like heat stress in agricultural production[14] or human health[15] will further add to non-linearly increasing risks with higher levels of warming.

Revisiting the observational evidence for changes in response to 0.5 °C warming is beneficial in several ways. As demonstrated here for a selection of extreme weather indices, it can inform assessments of future model projections and the ability to discriminate potential differences in projections in the light of uncertainty. Secondly, it allows researchers to assess scientific evidence on the impacts of 0.5 °C warming for systems and sectors for which quantitative modelling approaches are lacking. Making use of half-degree warming analogues over the observational record can greatly increase the evidence base for the forthcoming IPCC special report on 1.5 °C. Finally, relating differences in an abstract quantity like GMT to documented and personal experiences of change over the last decades can illustrate what a difference in 0.5 °C 'means'. This could prove highly useful for the communication of scientific findings on 1.5 °C in light of the generally high confidence of decision-makers and the public in observations. ❐

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Additional information

Supplementary Information is available in the online version of this paper.