What is needed

Unfortunately, this is not a game. How our climate system responds to human activities has serious implications for society, as does the role of natural variability in our realization of climate change. Although the international community has invested in numerous observational systems — in the oceans, on land and in space — we still lack the long-term and continuous observations, and their synthesis, that are critical to understanding the climate system as a whole. Observing systems must be sustained, and where critical gaps are identified — such as the deep oceans — they should be enhanced. For example, the TOGA/TAO array of buoys in the tropical Pacific, which has been critical to our understanding, monitoring and prediction of ENSO, has fallen into decay and is threatened with extinction. Those buoys have done more than any other single project to mitigate the impacts of climate on society worldwide. Not only should that array be refreshed, it should be expanded into the mid-latitudes of the Pacific Ocean. That could provide an unprecedented view of the processes behind things like the PDO, and perhaps lead to predictions of the next hiatus or acceleration.

The information needed to help manage the risks and opportunities of future climate changes, whether natural or man-made, must be based on solid science. Science starts with good observations and their synthesis, but it cannot stop there. It must serve improved understanding, monitoring, and prediction of interannual to decadal variability and its manifestation against a changing mean climate. ❐

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COMMENTARY:

No pause in the increase of hot temperature extremes

Sonia I. Seneviratne, Markus G. Donat, Brigitte Mueller and Lisa V. Alexander

Observational data show a continued increase of hot extremes over land during the so-called global warming hiatus. This tendency is greater for the most extreme events and thus more relevant for impacts than changes in global mean temperature.

In the wake of the release of the Working Group I contribution to the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5)[1], much attention in the media and scientific community has been devoted to the so-called hiatus[2–4]. This identified 'pause' in the increase of global mean temperature has been ascribed to various possible causes: for example, internal climate variability, a minimum in solar energy output, heat uptake in lower ocean layers, increased stratospheric water vapour, emission reductions of ozone-depleting substances and methane, data sampling and/or stronger shifts to La Niña states[4–10].

Based on existing observational evidence, we highlight that the term pause, as applied to the recent evolution of global annual mean temperatures, is ill-chosen and even misleading in the context of climate change. Indeed, an apparently static global mean temperature can mask large trends in temperatures at both regional[4] and seasonal[11] scales. More importantly, it is land-based changes in extreme temperatures, particularly those in hot extremes in inhabited areas, that have the most relevance for impacts[12]. It seems only justifiable to discuss a possible pause in the Earth's temperature increase if this term applies to a general behaviour of the climate system, and thus also to temperature extremes.

However, we show that analyses based on observational data[13,14] reveal no pause in the evolution of hot extremes over land since 1997. We focus on 'extreme extremes', whereby we first investigate the total land area affected by various exceedances of the number of warm days over the local 90th percentile respective to a given base period (see Supplementary Information for more details). Figure 1a shows the time series of the ratio of land area affected by an exceedance of 30 extreme warm days (ExD30) per year relative to the 1979–2010 average for the ERA-Interim[13] and HadEX2 datasets[14]. The datasets agree well despite differences in spatial coverage and base periods (Supplementary Information). More importantly, they reveal a positive trend in ExD30 during the hiatus period. These results are further confirmed for other exceedance frequencies (for example, 50

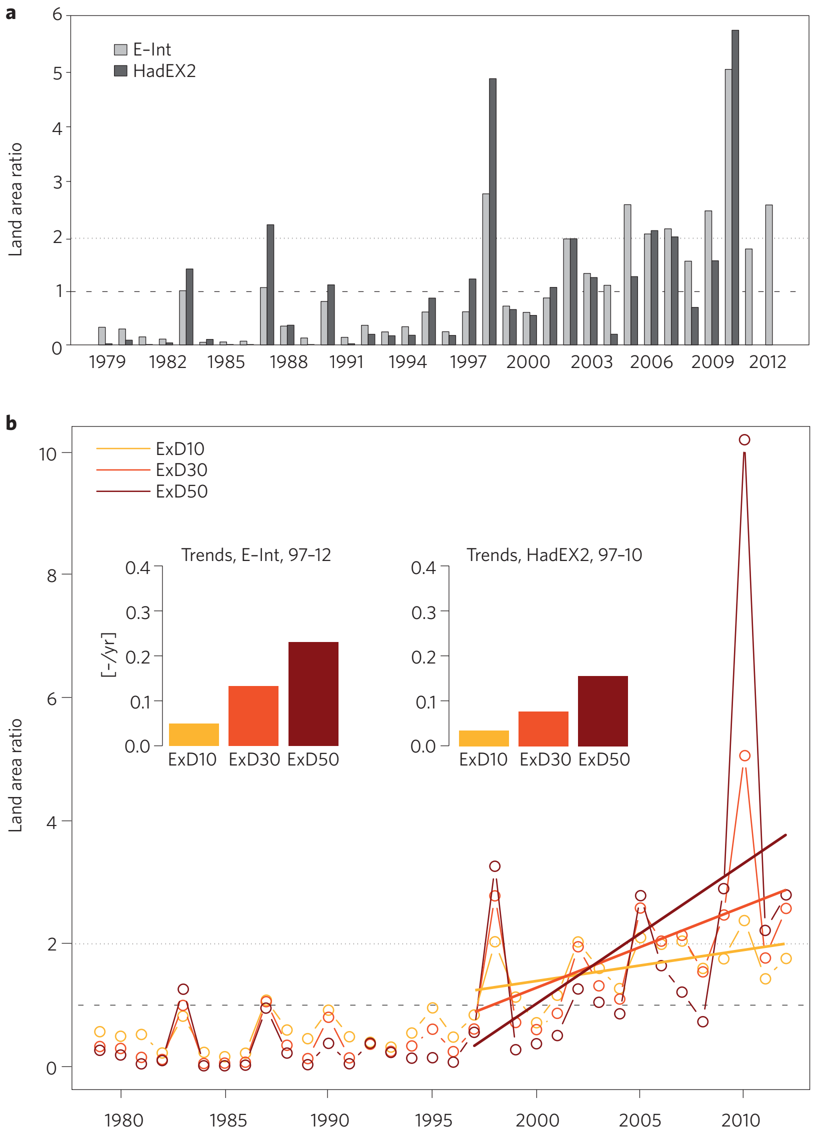

Figure 1 | Time series of land area affected by exceedance of hot temperature extremes. **a**, Ratio of land area affected by exceedances of 30 extreme warm days per year relative to the 1979–2010 average in ERA-Interim (E-Int, light grey) and HadEX2 (dark grey) datasets. The grey dashed line indicates a ratio of 1. The grey dotted line indicates a ratio of 2 (that is, a doubling of the affected area compared with the reference period). The Spearman correlation between the two time series over the time period 1979–2010 is 0.92. **b**, Time series of the ratio of land area affected by exceedances of 10, 30 and 50 extreme warm days per year relative to 1979–2010 average (ExD10, ExD30 and ExD50) in ERA-Interim (E-Int). The respective tendencies over the time period 1997–2012 are overlaid on the time series (trend lines) and displayed in the left panel of the inset plot. The corresponding values over 1997–2010 for HadEX2 are provided in the right panel of the inset plot. (See Supplementary Information for details.)

or 10 excess extreme warm days per year, ExD50 and ExD10, respectively), and the largest trends are found for the highest — that is, the most extreme — exceedance frequencies (ExD50, Fig. 1b). Because of the shortness of the hiatus period, significance testing of the trends has limited relevance[15]. Still, over the 15-year period from 1997 to 2012, increases in ERA-Interim are significant at the 5% level (Mann-Kendall test). Furthermore, the two, mostly independent, observational datasets agree well regarding the overall tendencies in trends of temperature extremes (Fig. 1b).

It is interesting to note that the effects of the strong El Niños that occurred in 1982/83 and 1997/98 on extreme temperatures are apparent, as are the weaker El Niño seasons of 1986/87 and 2009/10 (Fig. 1a,b), in particular in years displaying the largest geographical extent of extreme warm day exceedances. However, despite this feature, since 1998, and in the absence of a strong El Niño, the frequency of extreme exceedance ratios has continued to increase. These various results demonstrate that despite the slowed rate of increase in annual global mean temperature during the so-called hiatus period, the frequency of the most extreme warm days has continued to increase across the globe.

To further identify possible underlying causes for this dichotomy between recent trends in warm extremes over land and those in global mean temperature, we display in Fig. 2 the trends in the 95th percentile of maximum temperature over land, based on ERA-Interim, against respective trends in global (land and ocean) mean temperature in both ERA-Interim and HadCRUT4[16]. This analysis reveals a distinct warming of extreme hot daily temperatures over land over the past decade, unlike the behaviour of the mean global temperature. Further analyses show that the identified preferential warming of hot extremes over land compared with the trends in global mean temperature is partly related to a larger increase in mean temperatures over land relative to the global mean (Supplementary Information S4). However, the ERA-Interim dataset suggests that there is also an additional warming of hot extremes compared with the mean land-temperature tendencies, as well as a specific heating of hot daily extremes compared with cold daily extremes over land, the latter displaying no trend or a slight cooling (Supplementary Information S6).

There are many possible explanations for this behaviour. First, several lines of evidence suggest that the slowing down of the global mean temperature increase since 1997 is mostly related to a cooling of ocean surface temperatures[1], as well as to a cooling of boreal winter temperatures[4,11,17]. Thus, this would be consistent with a further increase in warm-season temperatures (including hot extremes) over most land areas over the same time period, given a constant (or slightly warming[10]) global mean temperature. Indeed, analyses of trends in seasonal warm extremes suggest that the identified signal is mostly found in the warm season, whereas there is a cooling of warm extremes in boreal winter in a large fraction of the northern hemisphere mid- and high latitudes (Supplementary Fig. 6). Furthermore, there is substantial evidence that processes controlling temperature extremes are partly independent of those affecting mean temperatures, for instance due to the role of amplifying feedback mechanisms directly affecting heat extremes over land[18,19]. This effect seems relevant for the identified warming trends in hot extremes, because these are particularly strong in mid-latitude regions where the drying of soil moisture can induce such feedbacks[19] (Supplementary Fig. 5). In addition, there is also evidence of a stronger warming of hot extremes over Greenland, possibly related to the Arctic ice and snow melt (Supplementary Fig. 5). Hence, trends in warm temperature extremes need not necessarily parallel those in global mean temperatures, as identified here from the available observational data.

These results have several important implications. First, they show that it would be erroneous to interpret the recent slowdown of the global annual mean temperature increase as a general slowdown of climate change. Indeed, similar to what is observed for other elements of the climate system (for example, the melting of Arctic sea ice, increases in sea-level rise and ocean heat content[1,17]), increases in the occurrence of the warmest daytime (and night-time, Supplementary Information S7) temperature extremes are found to display a continued amplification over the recent decade. In addition, these results also emphasize that care is needed to avoid over-interpreting changes in global mean temperatures and their possible links to impacts. This conclusion also applies to climate change projections, which are often expressed as changes in the global mean surface temperature[1], although some of the most relevant impacts are related to temperature extremes over land rather than changes in mean temperature *per se*. In this context, a better understanding of the full complexity of changes resulting from greenhouse gas emissions, focusing on the identification of individual processes contributing to the global-scale response, is necessary.

In summary, this analysis shows that not only is there no pause in the evolution of the warmest daily extremes over land but that they have continued unabated over the observational record. Furthermore, the available evidence suggests that the most 'extreme' extremes show the greatest change. This is particularly relevant for climate change impacts, as changes in the warmest temperature extremes over land are of the most relevance to human health, agriculture, ecosystems and infrastructure[12].

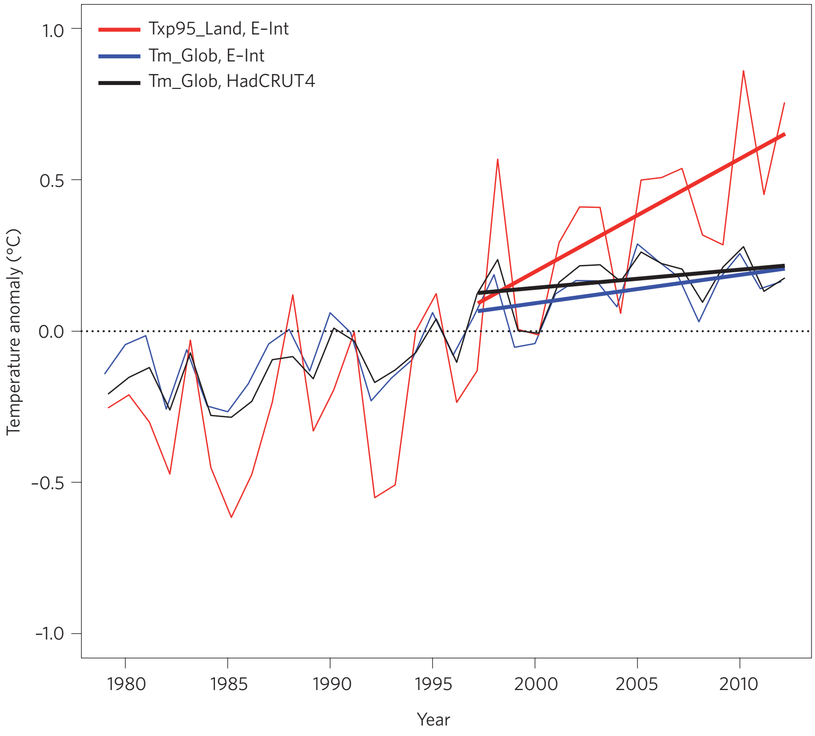

Figure 2 | Time series of temperature anomalies for hot extremes over land (red) and global mean temperature (black, blue). The anomalies are computed with respect to the 1979–2010 time period. The time series are based on the ERA-Interim 95th percentile of the maximum temperature over land (Txp95_Land, red) and the global (ocean + land) mean temperature (Tm_Glob) in ERA-Interim (blue) and HadCRUT4 (black). (See Supplementary Information for details.)

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Author contributions

S.I.S. designed the study with substantial inputs from all authors. M.G.D., B.M. and S.I.S. analysed the data. S.I.S. and L.V.A. wrote the article, with inputs from M.G.D. and B.M.

Additional information

Supplementary information is available in the online version of the paper.

Correction

In the Commentary 'No pause in the increase of hot temperature extremes' (*Nature Climate Change* **4,** 161–163; 2014) references 12 and 18 were incorrect, and should have appeared as:

12. IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (eds Field, C. B. *et al.*) (Cambridge Univ. Press, 2012).

18. Seneviratne, S. I. *et al.* in IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (eds Field C. B. *et al.*) 109–230 (IPCC, Cambridge Univ. Press, 2012).

These have now been corrected in the HTML and PDF versions after print 25 March 2014.