Uncertainties in the timing of unprecedented climates

ARISING FROM C. Mora *et al. Nature* **502,** 183–187 (2013)

The question of when the signal of climate change will emerge from the background noise of climate variability—the 'time of emergence'—is potentially important for adaptation planning. Mora *et al.*[1] presented precise projections of the time of emergence of unprecedented regional climates. However, their methodology produces artificially early dates at which specific regions will permanently experience unprecedented climates and artificially low uncertainty in those dates everywhere. This overconfidence could impair the effectiveness of climate risk management decisions[2]. There is a Reply to this Brief Communication Arising by Mora, C. *et al. Nature* **511,** http://dx.doi.org/10.1038/nature13524 (2014).

Any human-induced changes in climate will be modulated by natural fluctuations of the oceans and atmosphere (for example, El Niño events). These fluctuations occur randomly and independently, in both reality and individual model-based projections, and act to obscure the climate change signal[3–5]. Mora *et al.*[1] discuss projections of when changes in climate emerge permanently above the levels of such fluctuations (a metric first considered in ref. 6). However, by ignoring the irreducible limits imposed by these same random fluctuations, Mora *et al.*[1] express their emergence dates with too much certainty.

Several methodological oversights contribute to the erroneous uncertainty quantification. First, Mora *et al.*[1] ignore the possibility that emergence dates before the end of the simulations are not permanent deviations from the historical range[6] (termed 'pseudo-emergence'). In many regions where emergence has not occurred by the year 2100, Mora *et al.*[1] artificially set the emergence date to equal 2100. This oversight produces several effects, including: (1) early and overconfident estimates of regional temperature emergence; and (2) implausible emergence dates for precipitation of exactly 2100 with zero uncertainty almost everywhere.

Second, Mora *et al.*[1] estimate precision of regional emergence timing using the standard error of the ensemble mean ($\sigma/\sqrt{N}$), where N ($=39$) is the number of simulations and σ is their standard deviation. While the estimate of the ensemble-mean becomes more precise with larger ensemble size, natural fluctuations of the climate (such as El Niño) dictate that the future evolution of climate will not behave like the ensemble mean, but as a single realization from a range of outcomes[5,7]. The use of $\sigma/\sqrt{N}$ greatly underestimates[8] this irreducible uncertainty,

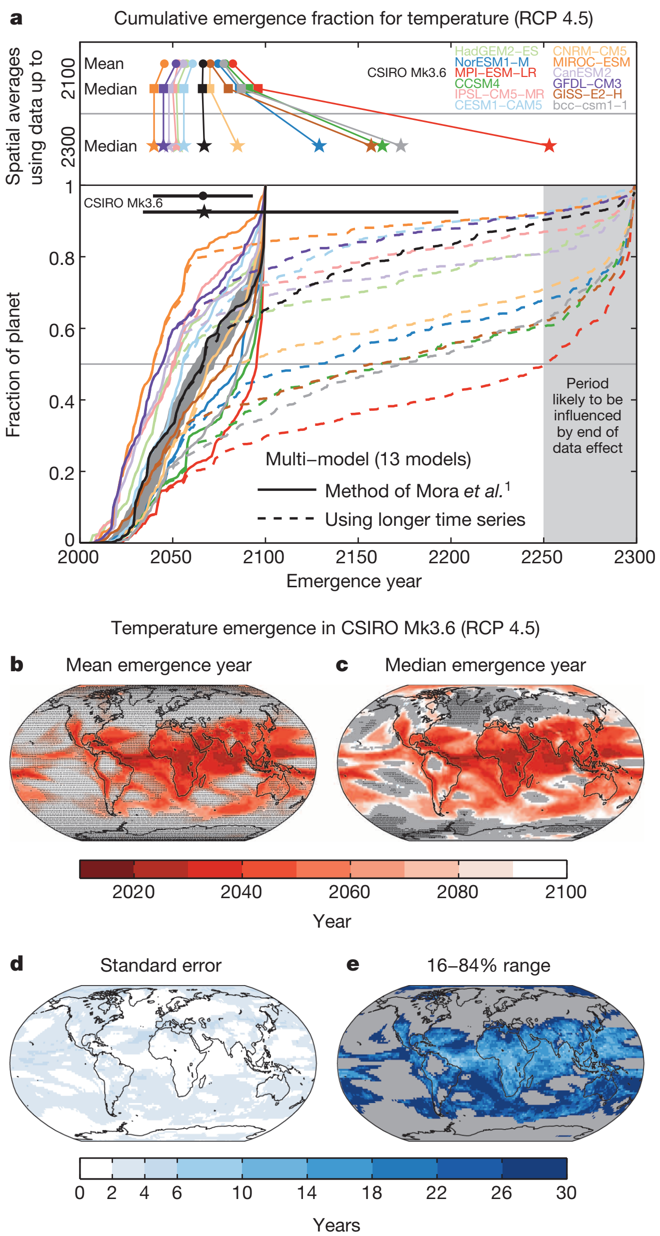

Figure 1 | The year of unprecedented emergence for surface air temperature using RCP4.5. a, Lower panel: the cumulative fraction of the planet that has emerged by any particular year for 13 different GCMs when restricting the simulations to end in 2100 (solid lines, as in ref. 1) and in 2300 (dashed lines). The grey shaded region highlights that the end-of-simulation pseudo-emergence effect probably also affects the post-2100 emergence dates after about 2250. For CSIRO Mk3.6 (black curve), spatial variations in the grid-point emergence values are given by the global mean $\pm$ 1σ (black circle and bar, as in ref. 1) and a more appropriate 16–84% range of emergence times in which 68% of the grid points lie (black bar and star). The grey shading around the black curve represents the range in coverage for the period 2000–2100 amongst the 30 CSIRO Mk3.6 simulations analysed in **b–e**. **a**, Upper panel: the year of global emergence using means and data up to 2100 (as in ref. 1, coloured circles), medians and data up to 2100 (coloured squares), and medians and data up to 2300 (coloured stars), showing a substantial delay for several models which do not show median emergence until well after 2100. **b**, The mean (as in the approach of ref. 1) and **c**, median (when considering data up to 2115) emergence year using 30 simulations of CSIRO Mk3.6 GCM. Stippling in **b** shows where at least 1 simulation (of 30) emerges beyond 2100; as such the mean must be estimated by arbitrarily setting post-2100 emergence dates to 2100 (61% by area). Grey regions in **c** show where more than half the simulations emerge after 2100 and hence no median emergence value can be determined (28% by area). Stippling in **c** indicates where all members show emergence beyond 2100 (8% by area). **d**, The standard error about the mean (as in the approach of ref. 1) and **e**, the more appropriate and much larger 16–84% range about the median, with grey regions showing where less than 84% of the simulations have emerged by 2100 and hence no 16–84% range can be estimated (44% by area).

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as well as the climate-response uncertainty given by the inter-model spread, and is therefore inappropriate for use in emergence estimates. Given $N = 39$ simulations, there is greater than 85% chance that the actual emergence time at any location will fall outside the uncertainty values of ref. 1, and an infinite number of simulations would implausibly suggest zero uncertainty in the projected emergence time. Nor can the standard error simply be scaled to a more appropriate uncertainty range (for example, a 16%–84% range, equivalent to $\pm1\sigma$ for a normal distribution), partly because the 'right-censored' emergence results of ref. 1 have an explicit upper-bound of 2100, making their distribution highly non-normal.

To demonstrate the impact of these oversights, we have replicated the analysis of ref. 1 for surface air temperature using: (1) a multi-model ensemble of simulations that extends to the year 2300; and (2) a large ensemble of simulations from a single model that extends to 2115.

Mora *et al.*[1] report that their "index has a global mean of 2069 ($\pm$18 years s.d.) for near-surface air temperature" in the RCP4.5 forcing pathway, where "s.d." refers to the spatial standard deviation of their grid-point means. However, the end-of-simulation effects invalidate the concept of a global mean permanent emergence date. Even apparent emergence years as early as 2050 may not actually permanently emerge until post-2100, as evidenced by the time of divergence between dashed and solid lines in Fig. 1a. Further, 41% (multi-model median) of the pre-2100 emergence values (by area) are either pseudo-emergent (31%) or artificially set to 2100 (10%). We also find that no model shows permanent emergence everywhere by 2100, or even by 2250. The large fraction of grid points exhibiting post-2100 emergence also highlights the underestimation of spatial emergence variability: whereas Mora *et al.*[1] report a spatial s.d. of $\pm$18 years, the 16–84% grid-point range is >150 years for virtually all of the models (see specific example for CSIRO Mk3.6 model in Fig. 1a). Finally, while some global-median emergence estimates using post-2100 data are similar to the global-mean (and global-median) estimates using only pre-2100 data, such agreement is fortuitous—as evidenced by the substantial delay in several models (compare coloured circles and stars in Fig. 1a)—and should not be expected a priori for the multi-model mean values from ref. 1.

The large single-model ensemble helps clarify the spatial pattern of irreducible uncertainty (Fig. 1b). In this ensemble, 61% of the planet exhibits the possibility of post-2100 emergence, thwarting the calculation of mean emergence and biological impacts in these regions (including Amazonia and the Southern Ocean which are in the biodiversity hotspots of ref. 1). In addition, the standard errors (as used by Mora *et al.*[1]) are less than 6 years everywhere, whereas the irreducible 16–84% uncertainty range is more than 6 years everywhere, and 75% of the planet has a 16–84% range of more than 20 years. Note that inter-model uncertainty will further increase the spread in grid-point emergence times (compare the multi-model spread with the shaded intra-model spread in Fig. 1a), and decrease the coverage of well-defined grid-point averages. Finally, while the delay in emergence and increase in uncertainty is evident for annual temperatures (the primary metric of ref. 1), it will be more pronounced for other variables analysed[1], such as monthly temperatures and precipitation, but less pronounced for annual temperatures in higher forcing pathways.

Last, the main conclusion of ref. 1—of early tropical emergence—is already a key summary statement in the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5): "Relative to natural internal variability, near-term increases in seasonal mean and annual mean temperatures are expected to be larger in the tropics and subtropics than in mid-latitudes (high confidence)" (ref. 9). The reason for 'high confidence' is that tropical temperature emergence has already been seen in observations[6,10–12] and in many previous studies examining climate simulations[3,4,6,11,13–18], none of which were cited by ref. 1. While projections of emergence times are clearly important for estimating a wide range of impacts (as demonstrated for food security[17], biodiversity hotspots[18] and ocean biogeochemistry[19]), they need to be quantified within a framework that incorporates climate variability, as illustrated in the large body of literature that has already examined this issue.

METHODS

We use simulations of surface air temperature from 13 global climate models (GCMs) given historical radiative forcings from 1860–2005 and the RCP4.5 forcing pathway from 2006–2300. We estimate the unprecedented emergence time for every grid point in each simulation independently. The cumulative fraction of emergence (Fig. 1a) shows the proportion of the surface area of the planet that has emerged by each year. The emergence calculations are repeated while restricting the data to end in either 2100 or 2300. We also use an ensemble of 30 simulations of the CSIRO Mk3.6 GCM[20] which were given the same radiative forcings for the period 1860–2115. The CSIRO GCM is chosen because of the availability of the large ensemble of simulations and its similarity to the multi-model mean/median behaviour. This ensemble of emergence years is used to estimate the grid-point averages and uncertainty ranges (Figs 1b–e).

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Mora *et al.* reply

REPLYING TO E. Hawkins *et al. Nature* **511,** http://dx.doi.org/10.1038/nature13523 (2014)

In the accompanying Comment, Hawkins *et al.*[1] suggest that our index[2] of the projected timing of climate departure from recent variability is biased to occur too early and is given with overestimated confidence. We contest their assertions and maintain that our findings are conservative and remain unaltered in light of their analysis.

We presented an index[2] that quantifies the year after which the climate continuously exceeds the bounds of historical variability, using 39 CMIP5 Earth System Models. Uncertainty in climate projections from these models arises chiefly from natural ('internal') climate variability, model error and uncertainty in the future evolution of greenhouse gas concentrations[3]. Hawkins *et al.*[1] suggest that by "ignoring the irreducible limits imposed by… random fluctuations, Mora *et al.*[2] express their emergence dates with too much certainty". However, our index was calculated independently for individual model simulations, which include internal variability. By considering individual simulations (internal variability) from each of 39 models (model-to-model error), under two emission pathways (scenario uncertainty), our results account for the three major sources of uncertainty in climate projections.

Our analysis of climate departure included only projections to the year 2100 due to their greater availability (only a third of the CMIP5 models have projections beyond 2100). Hawkins *et al.*[1] assert that the use of model projections to the year 2100 reduces the global mean timing of climate departure because we assigned the year 2100 to cells where unprecedented climates might occur after 2100. This is a valid constraint, and thus, climate departure at 2100 in our results should be interpreted as emergence that will occur in 2100 or later, or not at all.

The implications of using projections to 2100 are, however, exaggerated by Hawkins *et al.*[1]. First, we recalculated our index using the multi-model median, which is less affected than the mean by outlier projections of climate departure after 2100, and found only small differences. The global median temperature departure was 2076 under RCP4.5 (the reported global mean was 2069) and 2045 under RCP8.5 (the reported global mean was 2047). The multi-model median delivers similar results to the mean, even if projections to 2300 are used. For instance, the analysis in ref. 1 shows that 7 out of 13 models exhibit similar or even earlier global median temperature departures using projections to 2300 compared to global mean based on projections to 2100 (upper plot in figure 1a in ref. 1). Second, Hawkins *et al.*[1] chose RCP4.5, stating that the limitation is "less pronounced for annual temperatures in higher forcing pathways". Indeed, by 2080, 97% of the planet will face temperature departure for the remainder of the twenty-first century under RCP8.5. Under the RCP4.5 pathway, 67% of the planet will face temperature departure by 2080, highlighting the imminent departure of Earth's climate even under an optimistic mitigation scenario. Finally, from a global biological and social perspective, the potential limitation associated with climate departures beyond 2100 is small, as it is relevant only to high latitudes and not for areas where the majority of people and species on the planet live.

Any statistical value should be interpreted based on the metric it represents. Hawkins *et al.*[1] claim that by reporting the standard error of the mean our results are given with too much confidence. Our paper is transparent and clearly states that the standard error of the mean was our metric of uncertainty among models, and although the values provided should be interpreted in the context of that metric, they can easily be converted to another choice of statistic if so desired (for example, our standard error can be multiplied by $\sqrt{N}$ to obtain the standard deviation). Hawkins *et al.*[1] further suggest that the standard error is the wrong choice as "the future evolution of climate will not behave like the mean, but as a single realization from a range of outcomes". In other words, all models' simulations are equally likely, and thus, statistics that describe the broad range of projections are more suitable. This premise, however, conflicts with findings that it is the multi-model average that best approximates mean observed conditions, often better than any individual model, as demonstrated by prior studies[4] and confirmed in our paper[2]. Although there is no established "correct" way to express uncertainty, at least for the results from Earth System Models that can be verified, metrics of variability around the consensus mean are more appropriate.

Hawkins *et al.*[1] also suggested that the standard deviation cannot be scaled to their suggested 16–84% range multi-model dispersion as the climate departures are not normally distributed. However, "contrary to popular misconception, the standard deviation is a valid measure of variability regardless of the distribution. About 95% of observations on any distribution usually fall within 2 standard deviation limits…"[5]. We recalculated multi-model uncertainty as the standard deviation and as the 16–84% range among model projections for temperature and found small differences. The global median multi-model uncertainty estimates by these two metrics differ by 2.5 years under RCP4.5 and 1.6 years under RCP8.5.

Our paper[2] used all (not a subset) of the latest generation of Earth System Models that have complete projections for RCP4.5, RCP8.5 and historical experiments, under very conservative criteria for estimating climate departure (for example, using the minimum and maximum

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historical values to set bounds, defining climate departure as the year after which all subsequent years are out of historical bounds, and using a historical period already affected by human greenhouse gas emissions; we demonstrated that all these criteria delay the estimated year of climate departure). We also used data on species distributions, protected areas and socio-economic conditions to show that the earliest emergence of unprecedented climates will occur in areas with the greatest number of species on Earth, where a large proportion of the world's human population lives and where conservation and economic capacity to adapt are limited. These conclusions remain unaltered.

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