Uncertainties in the timing of unprecedented climates

Article

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Brief Communication Arising on "The projected timing of climate departure from recent variability" by Mora et al.

Ed Hawkins[1*], Bruce Anderson[2], Noah Diffenbaugh[3], Irina Mahlstein[4], Richard Betts[5,6], Gabi Hegerl[7], Manoj Joshi[8], Reto Knutti[9], Doug McNeall[5], Susan Solomon[10], Rowan Sutton[1], Jozef Syktus[11], Gabriel Vecchi[12]

1. National Centre for Atmospheric Science, Department of Meteorology, University of Reading, UK
2. Department of Earth & Environment, Boston University, USA
3. School of Earth Sciences and Woods Institute for the Environment, Stanford University, USA
4. Federal Office of Meteorology and Climatology, MeteoSwiss, Zurich, Switzerland
5. Met Office Hadley Centre, Exeter, UK
6. Department of Geography, Exeter University, UK
7. School of Geosciences, University of Edinburgh, UK
8. Centre for Ocean and Atmospheric Sciences, School of Environmental Sciences, University of East Anglia, UK
9. Institute for Atmospheric and Climate Science, ETH Zurich, Switzerland
10. Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, USA
11. Department of Science, Information Technology, Innovation and the Arts & University of Queensland, Australia
12. Geophysical Fluids Dynamics Laboratory, Princeton, USA

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] (M13) 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].

Any human-induced changes in climate will be modulated by natural fluctuations of the oceans and atmosphere (e.g. 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[3,4,5]. M13 discuss projections of when changes in climate emerge permanently above the levels of such fluctuations (a metric first considered by ref. 6). However, by ignoring the irreducible limits imposed by these same random fluctuations, M13 express their emergence dates with too much certainty.

Several methodological oversights contribute to the erroneous uncertainty quantification. Firstly, M13 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, M13 even artificially set the emergence date to equal 2100. This oversight produces several effects, including: (i) early and overconfident estimates of regional temperature emergence, and (ii) implausible emergence dates for precipitation of exactly 2100 with zero uncertainty almost everywhere.

Secondly, M13 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 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, as well as the climate-response uncertainty given by the inter-model spread, and is therefore inappropriate for use in

[*] Corresponding author. E-mail: e.hawkins@reading.ac.uk

emergence estimates. Given N=39 simulations, there is greater than 85% chance that the actual emergence time at any location will fall *outside* M13's quoted uncertainty values. Nor can the standard error simply be scaled to a more appropriate uncertainty range (e.g. a 16–84% range, equivalent to ±1σ for a Normal distribution), partly because M13's 'right-censored' emergence results have an explicit upper-bound of 2100, making their distribution highly non-Normal.

To demonstrate the impact of these methodological errors, we have replicated M13's analysis for surface air temperature using: (i) a multi-model ensemble of simulations that extends to the year 2300; and (ii) a large ensemble of simulations from a single-model that extends to 2115.

M13 report that their "*index has a global mean of 2069 (± 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 M13's grid-point means. However, the end-of-simulation effects fundamentally invalidate the concept of a global mean permanent emergence date. Even apparent emergence years as early as 2050 are not necessarily robust, and can actually emerge post-2100 in several models that extend to 2300 (compare 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 M13's dramatic underestimation of spatial emergence variability: whereas M13 report a spatial s.d. of ±18 years, the 16–84% grid-point range is >150 years for virtually all of the models (Fig. 1a). Finally, whilst some global-median emergence estimates utilizing post-2100 data are similar to the global-mean (and global-median) estimates utilizing 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 M13's multi-model mean values.

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 M13's biodiversity hotspots). In addition, the standard errors (as used by M13) 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 (M13's primary metric), it will be even more pronounced for other variables analysed by M13, such as monthly temperatures and precipitation, but less pronounced for annual temperatures in higher forcing pathways.

Finally, M13's main conclusion of early tropical emergence is so well established that it 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)*"[9]. The reason for 'high confidence' is that tropical temperature emergence has already been seen in observations[6,10,11] and in many previous studies examining climate simulations[3,4,6,11,12,13,14,15,16,17,18], none of which were cited by M13. 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 must be quantified within a framework that incorporates climate variability, as illustrated in the large body of literature that has already examined this issue.

METHODS SUMMARY

We use simulations of surface air temperature from 13 global climate models (GCMs) given historical radiative forcings from 1860–2005 and the RCP 4.5 scenario 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 whilst 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 (Fig. 1b).

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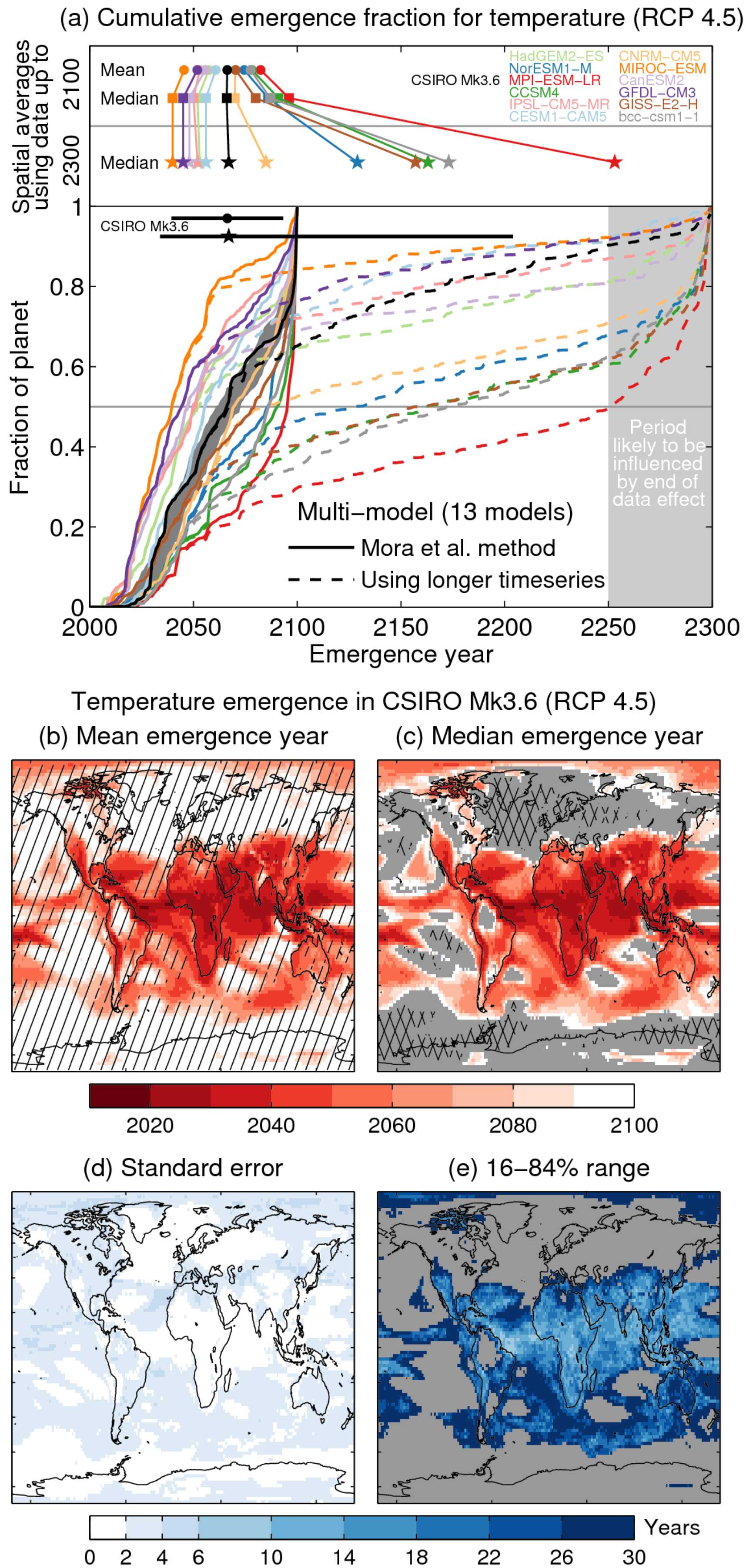
Figure 1: The year of unprecedented emergence for surface air temperature using RCP 4.5. (a) the cumulative fraction of the planet that has emerged by any particular year for 13 different GCMs when restricting the simulations to end in 2100 (solid lines, as in M13) and in 2300 (dashed lines). The emergence year for the globe as a whole was given by M13 using the mean and data up to 2100 (coloured circles). More appropriate medians based upon data up to 2100 (coloured squares) show a somewhat larger range, but remain constrained by 'right-censoring', as evidenced by the significant delay in the median based upon data up to 2300 (coloured stars) for several models which do not show median emergence until well after 2100. The grey shaded region highlights that the end-of-simulation pseudo-emergence effect likely affects the post-2100 data after about 2250. For CSIRO Mk3.6 (black curve), spatial variations in the grid-point emergence values are given by the global mean ± 1σ (black circle and bar, as in M13) and a more appropriate 16-84% range of emergence times in which 68% of the grid points lie (black bar and star). Although the mean/median value is the same using both methods in this particular GCM, the estimated window in which two-thirds of the planet experiences emergence is vastly underestimated using M13's approach. 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)**. **(b)** The mean (as in M13's approach) and **(c)** median (when considering data up to 2115) emergence year using 30 simulations of CSIRO Mk3.6 GCM. The diagonal hatching on the mean indicates regions where at least 1 simulation (of 30) has an emergence year beyond 2100 and as such the mean value cannot be estimated without resorting to arbitrarily setting post-2100 emergence dates to 2100 (61% by area). Grey regions on the median indicate where more than half the simulations have an emergence time after 2100 and hence no median emergence value can be determined (28% by area). The cross hatching on the median indicates where all members show emergence beyond 2100 (8% by area). **(d)** The standard error about the mean (as in M13's approach) and **(e)** 16-84% range about the median represent the temporal uncertainty in the estimated timing of emergence given the range of equally plausible outcomes found within 30 simulations (1860-2115) of a single GCM. Grey regions on the 16-84% range indicate where less than 84% of the simulations have emerged by 2100 and hence no 16-84% range can be estimated (44% by area).



(a) Cumulative emergence fraction for temperature (RCP 4.5)
Spatial averages using data up to
2100
2300
Mean
Median
Median
CSIRO Mk3.6
HadGEM2−ES
NorESM1−M
MPI−ESM−LR
CCSM4
IPSL−CM5−MR
CESM1−CAM5
CNRM−CM5
MIROC−ESM
CanESM2
GFDL−CM3
GISS−E2−H
bcc−csm1−1
Fraction of planet
0
0.2
0.4
0.6
0.8
1
Period likely to be influenced by end of data effect
Multi−model (13 models)
Mora et al. method
Using longer timeseries
2000
2050
2100
2150
2200
2250
2300
Emergence year
Temperature emergence in CSIRO Mk3.6 (RCP 4.5)
(b) Mean emergence year
(c) Median emergence year
2020
2040
2060
2080
2100
(d) Standard error
(e) 16−84% range
Years
0
2
4
6
10
14
18
22
26
30