Importance of the pre-industrial baseline for likelihood of exceeding Paris goals

Andrew P. Schurer[1]*, Michael E. Mann[2], Ed Hawkins[3], Simon F. B. Tett[1] and Gabriele C. Hegerl[1]

During the Paris conference in 2015, nations of the world strengthened the United Nations Framework Convention on Climate Change by agreeing to holding 'the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C' (ref. 1). However, 'pre-industrial' was not defined. Here we investigate the implications of different choices of the pre-industrial baseline on the likelihood of exceeding these two temperature thresholds. We find that for the strongest mitigation scenario RCP2.6 and a medium scenario RCP4.5, the probability of exceeding the thresholds and timing of exceedance is highly dependent on the pre-industrial baseline; for example, the probability of crossing 1.5 °C by the end of the century under RCP2.6 varies from 61% to 88% depending on how the baseline is defined. In contrast, in the scenario with no mitigation, RCP8.5, both thresholds will almost certainly be exceeded by the middle of the century with the definition of the pre-industrial baseline of less importance. Allowable carbon emissions for threshold stabilization are similarly highly dependent on the pre-industrial baseline. For stabilization at 2 °C, allowable emissions decrease by as much as 40% when earlier than nineteenth-century climates are considered as a baseline.

In the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the likelihood of global mean temperatures exceeding 1.5 °C and 2 °C above 1850–1900 levels was estimated[2,3]. No estimates were provided, however, for a true 'pre-industrial' baseline in this context. Given that the industrial revolution and concomitant increase in greenhouse gases (GHG) was well underway by the late-eighteenth century[4,5], the late-nineteenth-century temperatures do not provide an accurate 'pre-industrial' baseline as specified by the Paris Agreement[1]. Unfortunately, the estimation of pre-industrial temperature is far from straightforward[6]. GHG concentrations have been increasing since industrialization began around 1750, and are likely to have impacted global temperatures[7,8]. Consequently, estimates of a temperature baseline prior to the industrial revolution would be desirable[6,9]. However, very few instrumental measurements of temperature exist prior to the nineteenth century, and these are concentrated in the Northern Hemisphere[10]. To further complicate matters, natural fluctuations in global temperature are ever-present, leading to multi-decadal and longer-term changes throughout the last millennium[11–14], implying that there is no single value for pre-industrial global mean temperature. Some of this variability is linked to natural forcings, particularly volcanic eruptions, and variations in GHG concentration, such as the small drop in 1600[5,15]. Here, we estimate probabilities

for exceeding key temperature thresholds, under different emission scenarios, including the impact of differing assumptions regarding the pre-industrial temperature baseline.

To determine the effect of the pre-industrial baseline on the probability of exceeding projected temperature thresholds, we use model simulations performed as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5)[16]. We use historical simulations and projections from three different future representative concentration pathways (RCPs), namely RCP2.6, RCP4.5 and RCP8.5, to calculate continuous global temperature time series from 1861 to 2100. We employ a global blend of simulated sea surface temperatures and surface air temperatures (SATs)[17] (Fig. 1). In contrast to other studies that just use SATs[2,18], this allows the most rigorous and unbiased comparison with current blended observational data sets[19–21], which we have assumed will be those used to determine whether a temperature threshold has been reached in the future. Following the approach of refs 2,3,18, we first calculate anomalies relative to the period 1986 to 2005, and add an estimate of the difference between this period and pre-industrial. To estimate the latter, we combine warming over the 1850–2005 period, calculated from observations, with an estimate of warming prior to 1850. Similar analyses have been found to be particularly sensitive to the choice of anomaly period[22], and we choose this method because tying projections to more recent observations will reduce the impact of the uncertainty in past radiative forcing, since we do not rely on modelled warming prior to 1986. We define threshold exceedance on the basis of 5-year annual mean temperatures (see Methods), to avoid temporary early threshold exceedances due to internal variability, such as that linked to large El-Niño events.

If we assume that 1850–1900 can be used as a pre-industrial baseline (that is, warming before 1850–1900 has been negligible), it is almost certain that 2 °C will be exceeded in the high future emissions scenario (RCP8.5), very likely by the middle of the century ($p = 0.85$), with a median estimate of a 3.9 °C increase by the end of the century (Fig. 1). In the scenario with moderate mitigation (RCP4.5), it is still unlikely that the temperature increase can be limited to below 2 °C ($p < 0.2$), with a median estimate warming of 2.3 °C by the end of the century. It is only in the pathway with strong mitigation (RCP2.6) where preventing a temperature rise above 2 °C becomes probable ($p = 0.75$) and holding temperatures below 1.5 °C possible ($p = 0.40$). These projected temperatures are slightly lower than those presented in IPCC AR5 (ref. 2). This is because the use of blended temperatures instead of global mean SATs results in about 4–10% less warming[17] (see Supplementary Information). Note that these estimates rely on the model spread encapsulating the true response, and uncertainties would be larger if the

[1]School of GeoSciences, University of Edinburgh, Crew Building, Alexander Crum Brown Road, Edinburgh EH9 3FF, UK. [2]Department of Meteorology and Atmospheric Science & Earth and Environmental Systems Institute, Pennsylvania State University, State College, Pennsylvania 16802, USA. [3]NCAS-Climate, Department of Meteorology, University of Reading, Reading RG6 6BB, UK. *e-mail: a.schurer@ed.ac.uk
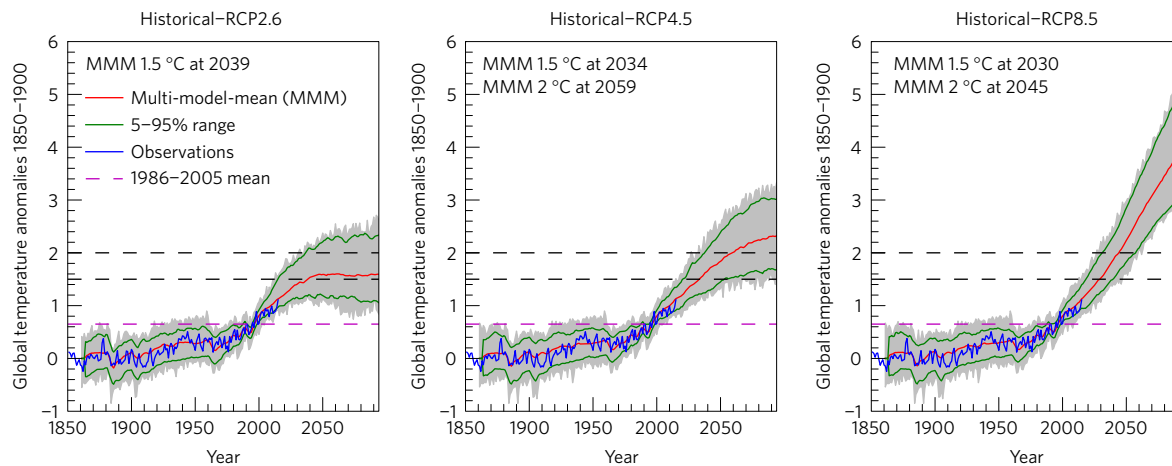
Figure 1 | Historical data and future projections for global mean temperature. Annual global mean temperature for observations[17] (blue) and model simulation range (grey) is shown for three different future scenarios. The probability distribution for the model simulations is represented by the model mean (red) and 5–95% range (green) smoothed by a 5-year running mean. All anomalies are first calculated for 1986–2005 and then observed warming since 1850–1900 (0.65 °C (ref. 17)—purple dashed line) has been added. Years when the median of the model distribution relative to 1850-1900 crosses the 1.5 °C and 2 °C thresholds are given in the text.

uncertainty in transient climate response beyond the model range was included[2].

How large an impact could choosing a pre-industrial period before 1850–1900 have on these probabilities, given the observed fluctuations in temperature throughout the last millennium and beyond? A number of model simulations now exist covering the last millennium and these can be used to calculate global temperatures over different periods between 1401 and 1850, to determine how much warmer (or colder) the late-nineteenth century is compared with a 'true' pre-industrial baseline. We concentrate on the period 1401–1800, as it predates the major anthropogenic increase in GHGs and coincides with a diverse range of natural (volcanic and solar) forcing[5]. It is a period where models agree well with reconstructions[13,23] and given that this is when reconstructions are in good agreement with each other and are based on the most data[11,13] this leads to greater confidence in the model simulations. In addition, it is also the period where we have most model data and further back in time orbital forcing begins to diverge from that of present day, making earlier periods less suitable.

In total, spatially complete blended global temperatures from 23 simulations, from 7 different models, were analysed with the means of each model for the period 1401–1800 found to be cooler than the late-nineteenth-century baseline (1850–1900) by 0.03 °C to 0.19 °C (multi-model mean of 0.09 °C, Fig. 2b). In these simulations, and in temperature reconstructions of the past millennium[11,12], there is considerable centennial variability. Some periods, such as the sixteenth century, are of comparable warmth to the late-nineteenth century, while other periods have a multi-model mean nearly 0.2 °C cooler.

Simulations from three models run with single forcings (Fig. 2c–e) show that the major cause of variations in pre-industrial temperature between centuries is a varying frequency of volcanic eruptions; with a consistent cooling due to lower CO_2 levels and a smaller solar influence consistent with a small attributed response to solar forcing over the Northern Hemisphere[15]. Choosing any particular sub-interval over the past millennium to define pre-industrial temperatures thus involves a certain level of subjectivity. To quantify this, we calculate a combined distribution of 100-year periods from 1401 to 1800 from each of the 7 models (see Methods; Supplementary Fig. 7 and Fig. 3), resulting in a 5–95% range of −0.02 to 0.21 °C. Several studies have identified that the cooling response to very large volcanic eruptions in model simulations exceeds the response estimated in many proxy

temperature reconstructions[7,13]. While there is ongoing debate in the literature over the cause[24,25], this remains a source of uncertainty when analysing model simulations during the volcanically active seventeenth–nineteenth centuries. Also, the magnitude of past solar forcing is uncertain, although most likely small[5,15], as are estimates of early industrial aerosols and land use. Hence, the true uncertainties are almost certainly larger than shown in Fig. 2.

Another way to approach the question of an appropriate pre-industrial baseline is to ignore natural forced variability and consider how much warmer 1850–1900 is due to just anthropogenic forcing. To estimate this, we use climate models driven only with changes in GHG concentrations (Fig. 2c). The calculated mean difference between 1850–1900 and the period 1401–1800 in different models ranges from 0.10 to 0.18 °C (multi-model mean 0.13 °C, see Supplementary Information for more details), with some dependence on the period analysed due to the dip in GHGs in 1600. This yields an estimate of warming to 1850–1900 with a 5–95% range of 0.02 to 0.20 °C. This approach, however, assumes that the increase in CO_2 since the Little Ice Age is largely anthropogenic in origin. As the cause of the Little Ice Age CO_2 drop is unknown, this is far from clear, although supported by a previous modelling study that found only a small contribution from natural forcings to the eighteenth- and nineteenth-century GHG concentration increase[4]. Implicit in estimating pre-industrial temperatures on the basis of the climate's response to changes in GHGs alone, is also the assumption that the late-nineteenth century experienced 'typical' natural forcings, since we are not accounting for differences in natural forcing. It also does not account for changes in other potential anthropogenic forcings, particularly a cooling from early anthropogenic aerosols, which could have been substantial[26] but is highly uncertain[27,28], as is a potential radiative effect of early land-use change[29,30].

The estimates obtained above, suggest that depending on the definition of pre-industrial and the model used, the late-nineteenth century could provide a reasonable estimate of the pre-industrial temperature baseline or alternatively this choice could underestimate the true warming since pre-industrial by as much as 0.2 °C. This is a slightly higher range than that calculated by Hawkins et al. (H17) (ref. 6) (see Fig. 3), which was based on choosing 1720–1800 as a pre-industrial period, but H17 also acknowledged that this chosen period has relatively low levels of volcanism. It should be noted that these values are specific to the period 1401–1800 and the range of possible pre-industrial temperatures is likely to increase if periods further back in time are analysed.
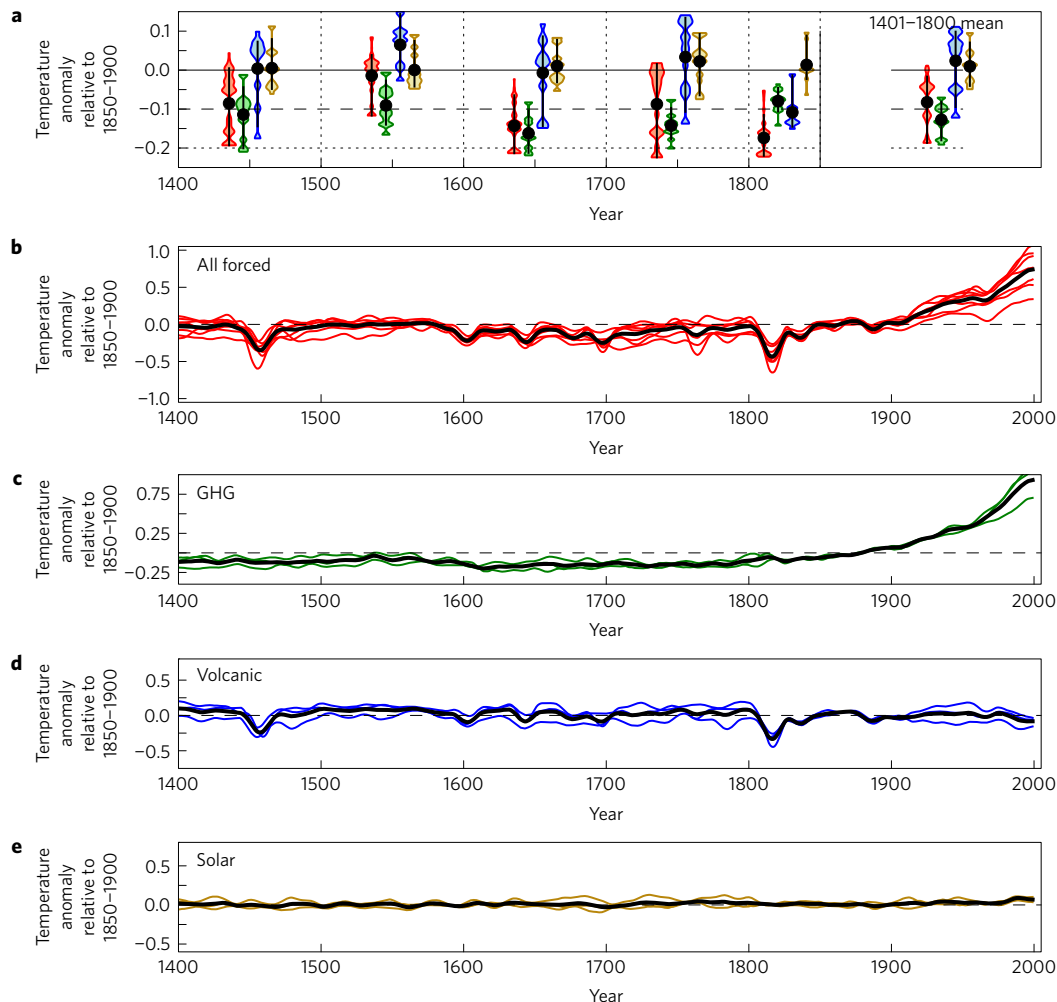
Figure 2 | Model-simulated difference in global mean temperature between different pre-industrial periods and 1850–1900. a, Range of ensemble means for different models, and for different forcing combinations. Model distribution fitted with a kernel density estimate (violin plot)—red, all forcings combined; green, greenhouse gas forcing alone; blue, volcanic forcing alone; yellow, solar forcing alone. Model mean: circle; 10–90% model range: bar. Differences refer to the mean of the period enclosed by the dashed lines; except on the far right, where they are means for the full period 1401–1800 (relative to 1850–1900). **b–e**, Model means for different forcing combinations—colours, ensemble means for individual models; black line, mean over all models.

In particular, periods during the medieval climate anomaly at the start of the last millennium may have warmer temperatures than the late-nineteenth century, particularly in the eleventh and twelfth century. In models, this is due to a combination of orbital forcing and solar forcing with reduced volcanic forcing (Supplementary Fig. 6) and this range should increase even more further back in time[11].

To calculate the effect that our new estimated range of additional warming since pre-industrial could have on the likelihood of crossing key (that is, 1.5 °C and 2 °C) thresholds under different scenarios, we re-calculate the probabilities with a wide, but plausible range of additional pre-industrial warming, covered by our 5–95% distributions (approximately 0 to 0.2 °C), with results shown in Figs 3 and 4. The results highlight the particular importance of the definition of pre-industrial temperature to the exceedance likelihoods for the strong mitigation scenario RCP2.6. For this scenario, the probability of exceeding the 1.5 °C threshold increases from 61% to 88% if the late-nineteenth century is assumed to be 0.2 °C warmer than the true pre-industrial. The probability of exceeding 2 °C increases from 25% to 30% under RCP2.6 and from 80% to 88% under RCP4.5. The choice of pre-industrial period also effects the time of threshold crossing with the greater assumed pre-late-nineteenth-century warming leading to earlier reaching of

thresholds (Fig. 4). This effect is larger under scenarios with more mitigation because the associated rate of temperature change is smaller (Fig. 3). For RCP4.5, for example, the year in which the 50% probability for 2 °C warming is crossed is reduced from 2059 to 2048 if 0.2 °C of pre-late-nineteenth-century warming is assumed.

It is possible to weight model projections on the basis of the agreement between the models simulated past temperatures and observed temperature. Results where each model is weighted by its agreement with observations from 1865 to 2005 are shown in the Supplementary Information (Supplementary Figs 11–13). The probability of avoiding 1.5 °C and the importance of the pre-industrial baseline is unaffected by the weighting. Weighting does however reduce the uncertainty of the projections, and thus the probability of avoiding 2 °C in both the RCP2.6 and RCP4.5 scenarios is reduced.

The relatively small early warming can also have dramatic impacts on cumulative carbon budgets. In the most recent IPCC report[2], the total carbon budget allowed to avoid exceeding 1.5 °C and 2 °C was given as the amount of carbon emissions since 1870 that would lead to a warming relative to an 1861–1880 baseline. If we assume linearity, these values will still hold for temperature increases relative to a true pre-industrial baseline provided that the carbon emissions are also re-calculated from a true pre-industrial period. If
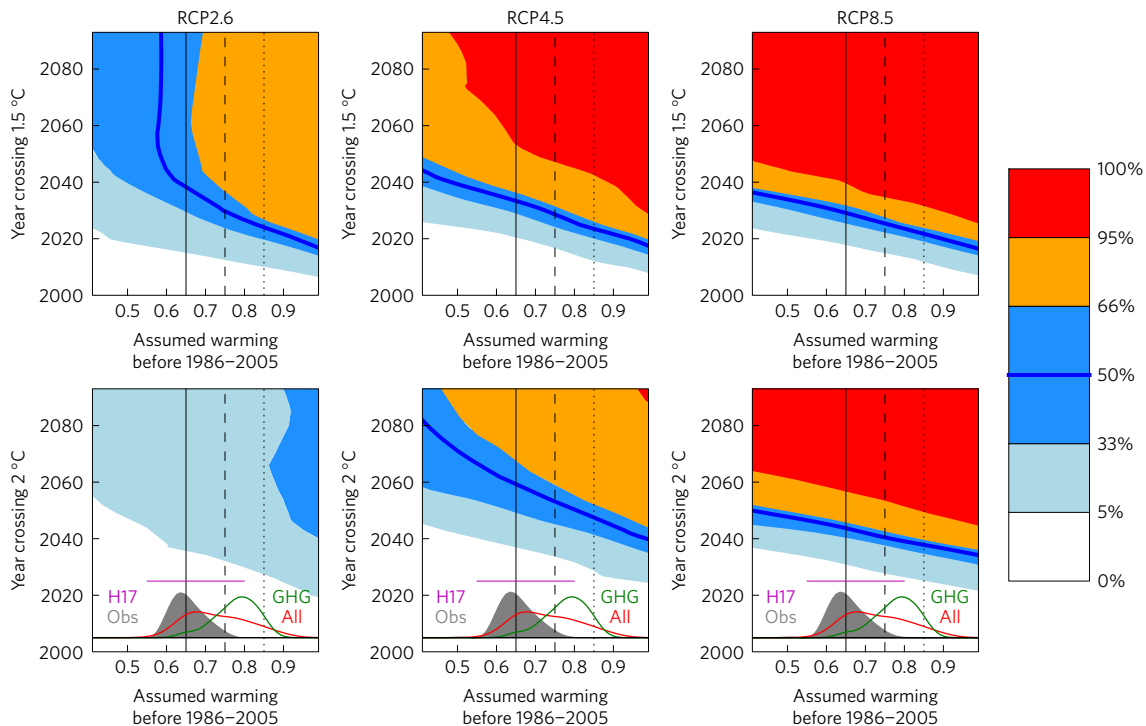
Figure 3 | Probability of exceeding temperature threshold for different assumed pre-industrial baselines. Probabilities for exceeding a particular global mean temperature threshold in any given year are given (%), smoothed by a 30-year Lowess filter for clarity (un-filtered version in Supplementary Information). The vertical lines indicate assumed pre-instrumental warming of 0 °C relative to 1850–1900 (solid), 0.1 °C (dashed) and 0.2 °C (dotted). Distributions in bottom panels show uncertainty in the observational estimate of warming from 1850–1900 to 1986–2005 (grey) and model distributions of 100-year mean temperatures in periods prior to 1800 relative to the 1850–1900 mean added to the mean warming from 1850–1900 to 1986–2005, using all forcings (red) and GHG forcings alone (green); the purple line shows the equivalent 1720–1800 temperature range estimated by Hawkins and colleagues[6].
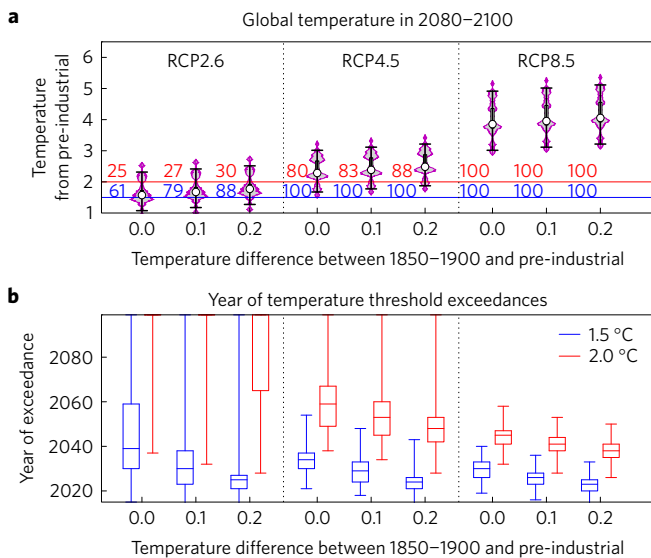

Figure 4 | Probability distributions for mean temperatures and time of threshold exceedance. a, Model temperature projections. Model distribution (violin plot, purple line), 33–66% range (thick black line), 5–95% range (whiskers) and median value (white circle). The text gives the probability of exceeding 1.5 °C (blue) and 2 °C (red). **b**, Probability of threshold crossing year for 1.5 °C (blue) and 2 °C (red). 5–95% range (whiskers), 33–66% range (box) and median value (horizontal line).

accordingly. The IPCC estimated that there is a 50% likelihood of keeping temperature to a 2 °C threshold (relative to 1861–1880) if 1210 GTC is emitted since 1870[2] (which equates to 605 GTC per degree warming). If non-CO$_2$ forcings are also taken into account, under the RCP2.6 scenario, the allowed emissions of carbon reduce further to 820 GTC. Given that the IPCC estimates that 515 GTC had been emitted up until 2011 (since 1870) this leaves 305 GTC still to be emitted. But, assuming linearity, if a warming of 0.1 °C had already occurred due to CO$_2$ increases by 1861–1880, then around 60 GTC of the budget would have already been used. This corresponds to roughly 20% of the budget still remaining (in 2011), and approximately 40% if the early warming was as much as 0.2 °C. The corresponding fractions of the remaining budget are likely to be even larger for a 1.5 °C target.

Despite remaining uncertainties there are at least two robust implications of our findings. Firstly, mitigation targets based on the use of a late-nineteenth-century baseline are probably overly optimistic and potentially substantially underestimate the reductions in carbon emissions necessary to avoid 1.5 °C or 2 °C warming of the planet relative to pre-industrial. Secondly, while pre-industrial temperature remains poorly defined, a range of different answers can be calculated for the estimated likelihood of global temperatures reaching certain temperature values. We would therefore recommend that a consensus be reached as to what is meant by pre-industrial temperatures to reduce the chance of conclusions that appear contradictory being reached by different studies and to allow for a more clearly defined framework for policymakers and stakeholders[6].

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

instead we wish to keep temperature beneath a threshold relative to a pre-industrial baseline but use the existing estimates for carbon emissions since 1870, then the carbon budget must be lowered

References

1. *Adoption of the Paris Agreement* FCCC/CP/2015/10/Add.1 (UNFCCC, 2015).
2. Collins, M. *et al*. in *Climate Change 2013: The Physical Science Basis* 1029–1136 (IPCC, Cambridge Univ. Press, 2013).
3. Kirtman, B. *et al*. in *Climate Change 2013: The Physical Science Basis* 953–1028 (IPCC, Cambridge Univ. Press, 2013).
4. Gerber, S. *et al*. Constraining temperature variations over the last millennium by comparing simulated and observed atmospheric CO_2. *Clim. Dynam.* **20**, 281–299 (2003).
5. Schmidt, G. a. *et al*. Climate forcing reconstructions for use in PMIP simulations of the Last Millennium (v1.1). *Geosci. Model Dev.* **5**, 185–191 (2012).
6. Hawkins, E. *et al*. Estimating changes in global temperature since the pre-industrial period. *Bull. Am. Meteorol. Soc.* https://dx.doi.org/10.1175/BAMS-D-16-0007.1 (in the press).
7. Schurer, A. P., Hegerl, G. C., Mann, M. E., Tett, S. F. B. & Phipps, S. J. Separating forced from chaotic climate variability over the past millennium. *J. Clim.* **26**, 6954–6973 (2013).
8. Abram, N. J. *et al*. Early onset of industrial-era warming across the oceans and continents. *Nature* **536**, 411–418 (2016).
9. Mann, M. E. False hope. *Sci. Am.* **310**, 78–81 (2014).
10. Hartmann, D. J. *et al*. in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al*.) 159–254 (IPCC, Cambridge Univ. Press, 2013).
11. Mann, M. E. *et al*. Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proc. Natl Acad. Sci. USA* **105**, 13252–13257 (2008).
12. Ahmed, M. *et al*. Continental-scale temperature variability during the past two millennia. *Nat. Geosci.* **6**, 339–346 (2013).
13. Masson-Delmotte, V. *et al*. in *Climate Change 2013: The Physical Science Basis* 383–464 (IPCC, Cambridge Univ. Press, 2013).
14. Hasselmann, K. Stochastic climate models Part I. Theory. *Tellus* **28**, 473–485 (1976).
15. Schurer, A. P., Tett, S. F. B. & Hegerl, G. C. Small influence of solar variability on climate over the past millennium. *Nat. Geosci.* **7**, 104–108 (2014).
16. Taylor, K. E., Stouffer, R. J. & Meehl, G. A. An overview of CMIP5 and the experiment design. *Bull. Am. Meteorol. Soc.* **93**, 485–498 (2012).
17. Cowtan, K. *et al*. Robust comparison of climate models with observations using blended land air and ocean sea surface temperatures. *Geophys. Res. Lett.* **42**, 6526–6534 (2015).
18. Joshi, M., Hawkins, E., Sutton, R., Lowe, J. & Frame, D. Projections of when temperature change will exceed 2 °C above pre-industrial levels. *Nat. Clim. Change* **1**, 407–412 (2011).
19. Cowtan, K. & Way, R. G. Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. *Q. J. R. Meteorol. Soc.* **140**, 1935–1944 (2014).
20. Hansen, J., Ruedy, R., Sato, M. & Lo, K. Global surface temperature change. *Rev. Geophys.* **48**, RG4004 (2010).
21. Morice, C. P., Kennedy, J. J., Rayner, N. A. & Jones, P. D. Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: the HadCRUT4 data set. *J. Geophys. Res.* **117**, D08101 (2012).
22. Hawkins, E., Sutton, R., Hawkins, E. & Sutton, R. Connecting climate model projections of global temperature change with the real world. *Bull. Am. Meteorol. Soc.* **97**, 963–980 (2016).
23. Schurer, A. P., Hegerl, G. C., Mann, M. E., Tett, S. F. B. & Phipps, S. J. Separating forced from chaotic climate variability over the past millennium. *J. Clim.* **26**, 6954–6973 (2013).
24. Mann, M. E., Rutherford, S., Schurer, A., Tett, S. F. B. & Fuentes, J. D. Discrepancies between the modeled and proxy-reconstructed response to volcanic forcing over the past millennium: implications and possible mechanisms. *J. Geophys. Res.* **118**, 7617–7627 (2013).
25. D' Arrigo, R., Wilson, R. & Anchukaitis, K. J. Volcanic cooling signal in tree ring temperature records for the past millennium. *J. Geophys. Res.* **118**, 9000–9010 (2013).
26. Carslaw, K. S. *et al*. Large contribution of natural aerosols to uncertainty in indirect forcing. *Nature* **503**, 67–71 (2013).
27. Jones, G. S., Stott, P. A. & Mitchell, J. F. B. Uncertainties in the attribution of greenhouse gas warming and implications for climate prediction. *J. Geophys. Res.* **121**, 6969–6992 (2016).
28. Stevens, B. Rethinking the lower bound on aerosol radiative forcing. *J. Clim.* **28**, 4794–4819 (2015).
29. Pongratz, J., Reick, C., Raddatz, T. & Claussen, M. A reconstruction of global agricultural areas and land cover for the last millennium. *Glob. Biogeochem. Cycles* **22**, GB3018 (2008).
30. Kaplan, J. O. *et al*. Holocene carbon emissions as a result of anthropogenic land cover change. *Holocene* **21**, 775–791 (2010).

Acknowledgements

Author contributions

A.P.S. and M.E.M. conceived the initial idea. A.P.S. performed the analysis. All authors contributed to the writing, methodology and analysis strategy.

Additional information

Competing financial interests

The authors declare no competing financial interests.

Methods

To investigate global mean temperatures during the historic and future period, we use CMIP5 model projections for the three RCP scenarios (RCP2.6, RCP4.5 and RCP8.5), with anomalies taken over the period 1986–2005. Modelled surface temperature values are used, calculated from a blend of SATs and sea surface temperatures following Cowtan et al.[17] for total global coverage. Previously, analyses have typically used just global SATs[2]. Our choice to use blended temperatures is motivated by the current use of blended observational data sets, which will probably be those used to determine whether a temperature threshold has been reached.

To estimate the temperature change since pre-industrial (TEMP$_{\text{pre-industrial}}$), we follow equation (1):

$$\text{TEMP}_{\text{pre-industrial}} = \text{TEMP}_{1986-2005} + \text{PRE} + \text{IND} \qquad (1)$$

where blended temperature since a true pre-industrial baseline (TEMP$_{\text{pre-industrial}}$) is calculated by first taking anomalies from 1986–2005 (TEMP$_{1986-2005}$), adding values for observed warming from 1850–1900 to 1986–2005 (IND) and then an estimate for the difference between 1850–1900 and the true pre-industrial baseline (PRE). The IPCC AR5 report estimated a warming of 0.61° for IND, based on the HadCRUT4 data set[10]. Given that we are calculating global mean temperature with full coverage, we instead use an estimate calculated using the Cowtan and Way[19] observational data set that has used the same data as HadCRUT4 but has been infilled using kriging. This gives a value of 0.65 °C. To account for the uncertainty in IND, we calculate an estimate from the 100 published ensemble members[19]. HadCRUT4 and Cowtan and Way show less warming over this period then several other data sets[20,31]; for example, in the Berkeley Earth global land and sea data[32] it is 0.71 °C (ref. 6). Using different observational data sets could therefore result in earlier threshold exceedances.

To estimate values for PRE we use model simulations from seven different models (see Supplementary Information for more details) and calculate global temperature as a blend of SAT and sea surface temperature following Cowtan and colleagues[17]. We use model simulations that have been forced with all available forcings and those that consider only single forcings at a time. To calculate values of 100-year mean temperatures we use all possible model simulations. A distribution for all of the 100-year values within the period 1401–1800 is calculated using all available model simulation (see Supplementary Tables 2–4 for more details). Models providing multiple ensemble members are weighted down so that each model contributes equally to the distribution. The final distribution is then calculated using kernel density estimation.

To determine the sensitivity of our results to the way that the pre-industrial anomalies are calculated, we modify equation (1):

$$\text{TEMP}_{\text{pre-industrial}} = \text{TEMP}_{1861-1900} + \text{PRE} + \text{Tdiff} \qquad (2)$$

Here TEMP$_{\text{pre-industrial}}$ is calculated from model simulations with anomalies from 1861 to 1900 (note that 1861 was used as a start date rather than 1850 because some model simulations start only in 1861). Similar to equation (1) we add PRE, which is the temperature difference from pre-industrial to 1850–1900. To account for the slight difference between the model simulations anomaly period (1861–1900) and the period for which PRE applies (1850–1900) we add on a factor, Tdiff, which is the observed temperature difference between 1861–1900 and 1850–1900, accounting for observational uncertainty, in the same way as for IND in equation (1). We favour the first method (equation (1)) because we consider observed warming from 1850–1900 to be more reliable in observations than in models, due to uncertainties in radiative forcing and the models response to them. Our conclusions are not particularly sensitive to this choice (see Supplementary Information).

The likelihood for the mean temperature in 2080–2100 above a pre-industrial background for each of the RCP scenarios is calculated from the full blended global mean temperature for each model simulation. By accounting for the observational uncertainty in IND we calculate a likelihood distribution for each model simulation. To combine these distributions into one joint distribution, a weighted mean over all available model simulations is calculated, where the weights are set to account for the number of ensemble members each model has, so that each model counts equally. The median and 5–95% range is then calculated from the resultant distribution as is the likelihood of temperatures exceeding the 1.5 °C and 2 °C limits.

To estimate the threshold crossing times, first the global annual mean temperatures are smoothed by a 5-year running mean and for every year a joint probability distribution is calculated from each individual model simulation, accounting for observational uncertainty in IND. A threshold is said to have been crossed in the first year when 50% of the model distribution (weighted by number of ensemble members) is above the limit.

Data availability. The authors declare that all data that support the findings in the main article are available. Code and date for the blended temperatures are available via K. Cowtan (http://www-users.york.ac.uk/~kdc3/papers/robust2015). All model data are publicly accessible via the Earth System Grid Federation node (http://pcmdi9.llnl.gov), with the exception of the last millennium simulations from HadCM3 accessible at http://browse.ceda.ac.uk/browse/badc/euroclim500), CSIRO-Mk3L (https://www.ncdc.noaa.gov/paleo-search/study/16337) and CESM-CAM5 (http://www.cesm.ucar.edu/projects/community-projects/LME). The rest of the code and further data are available on the University of Edinburgh datashare (http://datashare.is.ed.ac.uk/handle/10283/2720) with the identifier http://dx.doi.org/10.7488/ds/2092. All other data and code that support the figures in the Supplementary Information are available from the corresponding author on request.

References

31. Karl, T. R. et al. Possible artifacts of data biases in the recent global surface warming hiatus. *Science* **348,** 1469–1472 (2015).
32. Rohde, R. et al. A new estimate of the average earth surface land temperature spanning 1753 to 2011. *Geoinform. Geostat. Overv.* **1,** 1000101 (2013).