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Importance of the Pre-Industrial Baseline in Determining the Likelihood of Exceeding the Paris Limits

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During the Paris Conference of December 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"[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 scenarios RCP2.6 and RCP4.5 the probability of exceeding the temperature 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 the strongest mitigation scenario, 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 stabilisation are similarly highly dependent on the pre-industrial baseline. For stabilisation at 2°C, allowable emissions decrease by as much as 40% when earlier than 19th 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-18th century[4,5] the late-19th 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[9,6]. However very few instrumental measurements of temperature exist, prior to the 19th 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[11,12,13,14], 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]. In this article, 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 1861-2100. We employ a global blend of simulated sea surface temperatures and surface air temperature (SATs)[17] **(**Figure 1). In contrast to other studies which just use SATs[18,2], this allows the most rigorous and unbiased comparison to current blended observational datasets[19,20,21], which we have assumed will be those used to determine if a temperature threshold has been reached in the future. Following the approach of Joshi et al[18] we first calculate anomalies from 1986-2005 (as used by IPCC AR5[2,3]), 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 based on 5-year annual mean temperatures (see methods), in order to avoid temporary early threshold exceedances due to internal variability, such as that linked to large El-Nino events.

If we assume 1850-1900 can be used as a pre-industrial baseline (i.e. 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[2]**.** This is because the use of blended temperatures instead of global mean SATs results in about 4-10% less warming[17] (see supplement). Note that these estimates rely on the model spread encapsulating the true response, and uncertainties would be somewhat larger if the 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-19th century is to a "true" pre-industrial baseline. We concentrate on the period 1401-1800, as it pre-dates the major anthropogenic increase in GHGs, coincides with a diverse range of natural (volcanic and solar) forcing[5] and is a period where reconstructions agree reasonably well with each other, and with model simulations[13,23] and are based on the most data[13,11]. This therefore 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 different segments of the period 1401-1800 found to be cooler than the late-19th 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 16th century, are of comparable warmth to the late-19th century, while other periods have a multi-model mean nearly 0.2°C cooler.

Simulations from 3 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 subinterval 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 1401-1800 from each of the 7 models (see methods; fig S7 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 17th-19th centuries. Also, the magnitude of past solar forcing is uncertain, although most likely small[15,5], as are estimates of early industrial aerosols and land use. Hence, the true uncertainties are almost certainly larger than shown in figure 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 supplement 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 Ages (LIA) is largely anthropogenic in origin. As the cause of the LIA 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 18th and 19th GHG concentration increase[4]. Implicit in estimating pre-industrial temperatures based on GHGs alone is also the assumption that the late-19th 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-19th 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)[6] (see fig 3) which was based on choosing a relatively low volcanic period, namely 1720-1800. 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. In particular, periods during the medieval climate anomaly at the start of the last millennium, may have warmer temperatures than the late-19th century, particularly in the 11th and 12th century. In models this is due to a combination of orbital forcing and solar forcing with reduced volcanic forcing (figure S6) and this variability 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 (i.e. 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 Figure 3&4. The results highlight the particular importance of the definition of pre-industrial temperature to the exceedance probabilities 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-19th 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-19th 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-19th century warming is assumed.

It is possible to weight model projections based on the agreement between the models simulated past temperatures and observed temperature. Results where each model is weighted based on its agreement with observations from 1865-2005 are shown in the supplement (figs S11-13). 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 likelihood 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* which 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 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 accordingly. The IPCC estimated that that there is a 50% probability 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 820GTC. Given that the IPCC estimates that 515GTC had been emitted up until 2011 (since 1870) this leaves 305GTC 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 60GTC 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-19th 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 which appear contradictory, being reached by different studies and to allow for a more clearly defined framework for policymakers and stakeholders[6].

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Contributions:

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

Methods

In order 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 calculated from a blend of SATs and SSTs following *Cowtan et al 2015*[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 datasets, which will likely be those used to determine if a temperature threshold has been reached.

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

$$TEMP_{pre\text{-}industrial} = TEMP_{1986\text{-}2005} + PRE + IND \quad (1)$$

Where blended temperature since a true-preindustrial baseline ($TEMP_{pre\text{-}industrial}$), is calculated by first taking anomalies from 1986-2005 ($TEMP_{1986\text{-}2005}$), 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-preindustrial baseline (PRE). The IPCC AR5 report estimated a warming of 0.61°for IND, based on the HadCRUT4 dataset[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 dataset which 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 datasets[20,31], for example in the Berkeley Earth global land and sea data[32] it is 0.71°C[6]. Using different observational datasets could therefore result in earlier threshold exceedances.

To estimate values for PRE we use model simulations from seven different models (see supplement for more details) and calculate global temperature as a blend of surface air temperature and sea surface temperature following *Cowtan et al 2015*[17]. We use model simulations which have been forced with all available forcings and those which only consider single forcings at a time. To calculate values of 100 year mean temperatures we use all available model simulations. A distribution for all the 100-year values within the period 1401-1800 is calculated using all available model simulation (see supplement tables S2-4 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:

$$TEMP_{pre\text{-}industrial} = TEMP_{1861\text{-}1900} + PRE + Tdiff \quad (2)$$

Here $TEMP_{pre\text{-}industrial}$ is calculated from model simulations with anomalies from 1861-1900 (note that 1861 was used as a start date rather than 1850 because some model simulations only start in 1861). Similar to eqn. 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 Eqn. 1. We favour the first method (Eqn. 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 supplement).

The probability 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 probability 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 probability 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.

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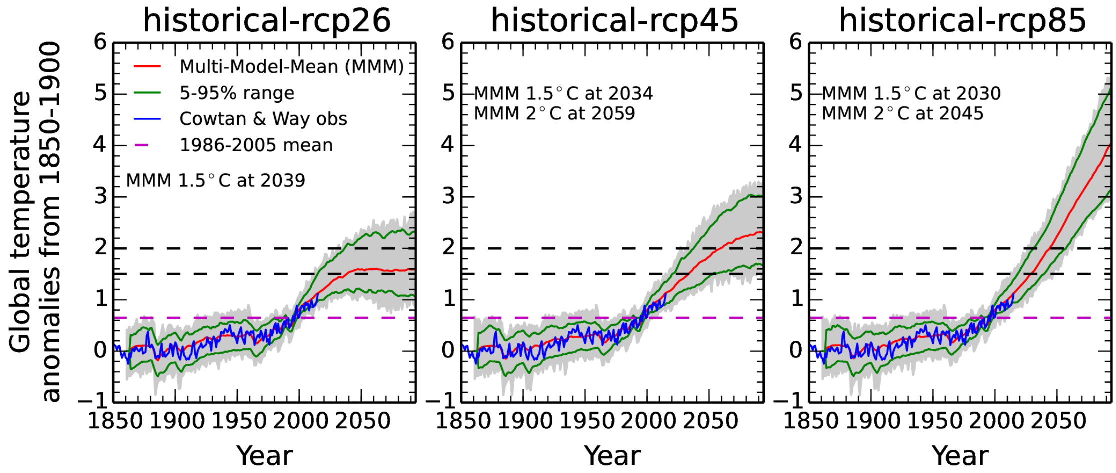

Fig 1 – Historical data and future projections for global mean temperature. Annual global mean temperature for observations[17] (blue) and model simulation range (grey), anomalies first calculated for 1986-2005 and then observed warming since 1850-1900 (0.65[17] – purple dashed line) has been added. Model mean (red) and 5-95% range (green) of the likelihood distribution from the model simulations smoothed by a 5-year running mean. Year when the median of the model distribution relative to 1850-1900 crosses the 1.5°C and 2°C thresholds are given in text.

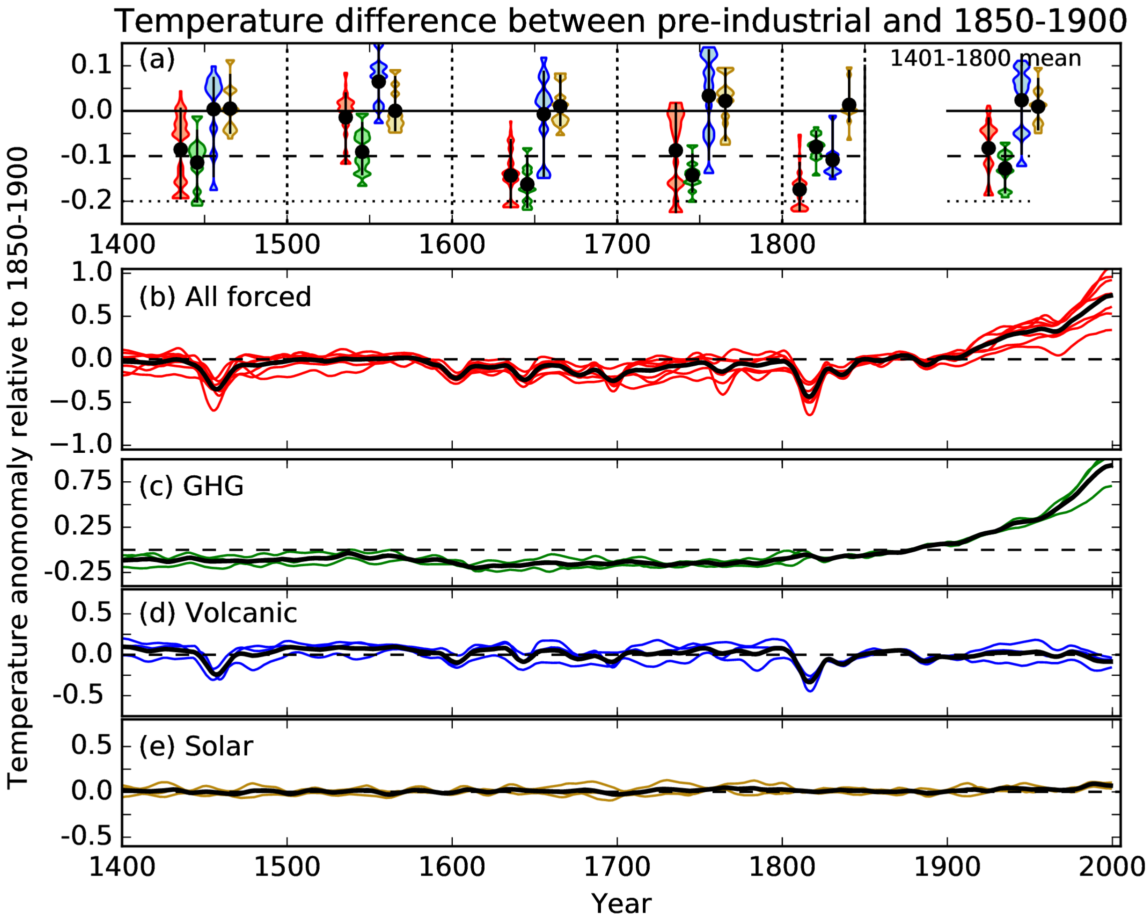

Fig 2. Model simulated difference in global mean temperature between different pre-industrial periods and 1850-1900. a) Range of ensemble means for different models, and for different forcing combinations (model mean: circle, model range: bar) model distribution fitted with a Kernel Density Estimate - red: All forcings combined; green: greenhouse gas forcing only, blue: volcanic forcing only, brown: solar forcing only. Differences refer to the mean of the period enclosed by the dotted lines; except on far right where they are means for the full period 1401-1800 (relative to 1850 to 1900). b)-e) Model means for different forcing combinations, colours ensemble means for individual models, black line – mean over all models.

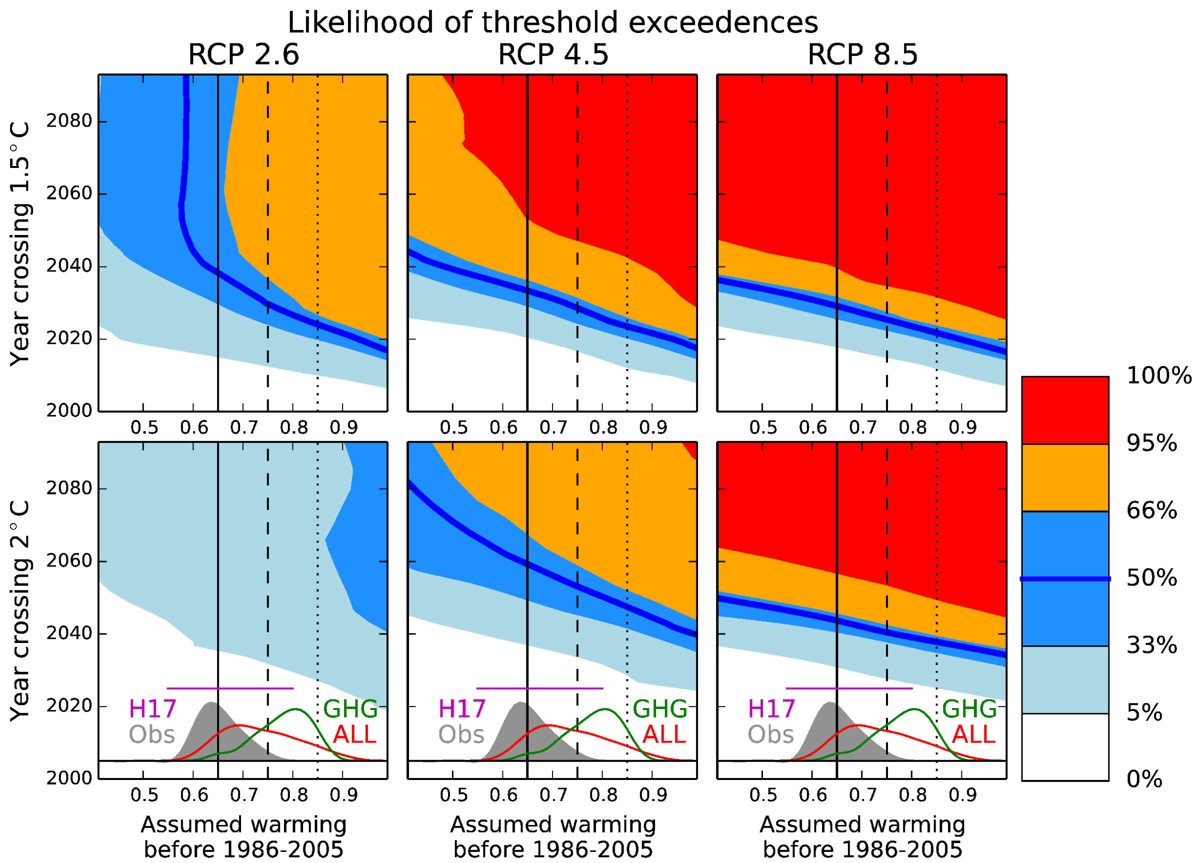

Fig 3 – Probability of exceeding temperature threshold for different assumed preindustrial baselines. Probabilities for exceeding a particular global mean temperature threshold in any given year are given [%], smoothed by a 30-year Lowess filter for clarity (un-filtered version in supplement). Vertical 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 only (green), the purple line shows the equivalent 1720-1800 temperature range estimated by Hawkins et al[8].

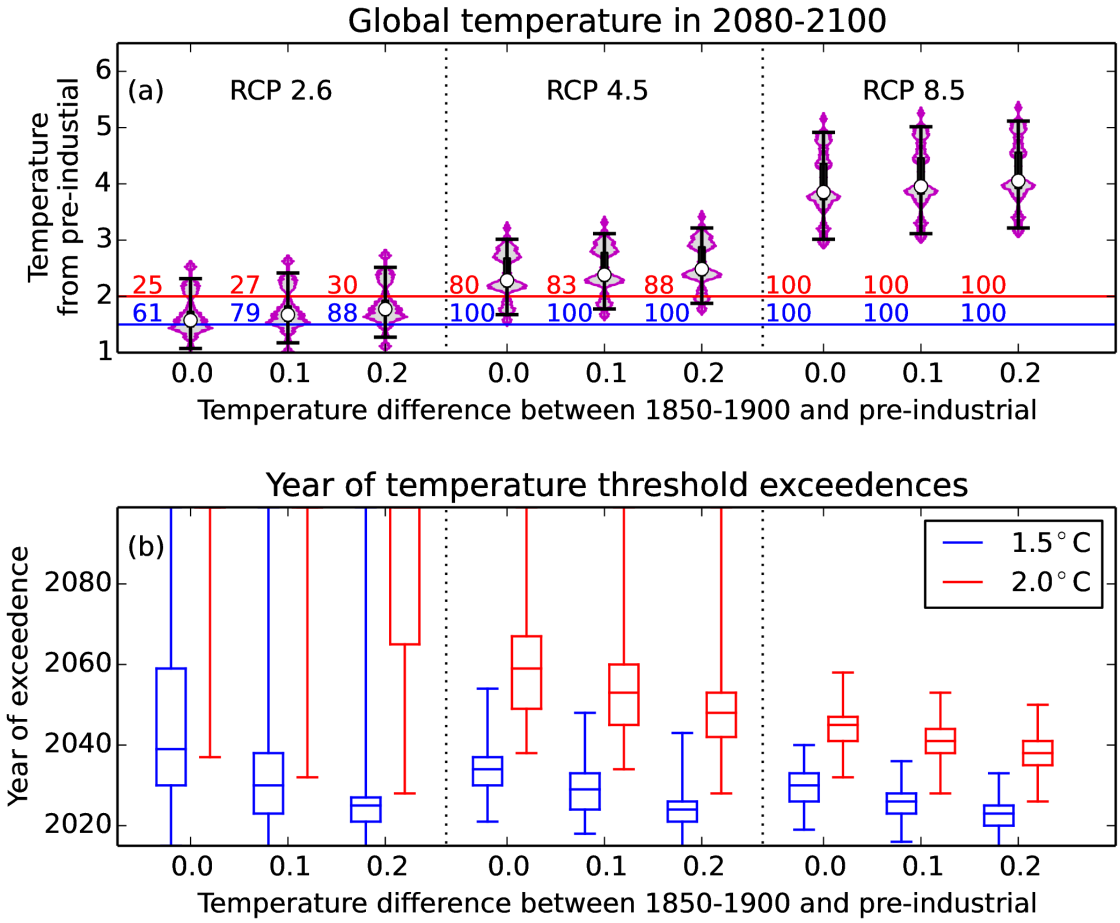

Figure 4 – Probability distributions for mean temperatures and time of threshold exceedence. Probability distribution: Model distribution (violin plot, purple line), 33-66% range (thick black line) 5-95% range (whiskers) and median value (white circle). a) Model temperature projections. Text gives probability 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).