

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

Article

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1 **Importance of the Pre-Industrial Baseline in Determining the Likelihood of** 2 **Exceeding the Paris Limits**

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10 **During the Paris Conference of December 2015, nations of the world strengthened the United**
11 **Nations Framework Convention on Climate Change by agreeing to holding “the increase in the**
12 **global average temperature to well below 2°C above pre-industrial levels and pursuing efforts**
13 **to limit the temperature increase to 1.5°C”¹. However, “pre-industrial” was not defined. Here**
14 **we investigate the implications of different choices of the pre-industrial baseline on the**
15 **likelihood of exceeding these two temperature thresholds. We find that for scenarios RCP2.6**
16 **and RCP4.5 the probability of exceeding the temperature thresholds and timing of exceedance**
17 **is highly dependent on the pre-industrial baseline, for example the probability of crossing 1.5°C**
18 **by the end of the century under the strongest mitigation scenario, RCP2.6, varies from 61% to**
19 **88% depending on how the baseline is defined. In contrast, in the scenario with no mitigation,**
20 **RCP8.5, both thresholds will almost certainly be exceeded by the middle of the century with the**
21 **definition of the pre-industrial baseline of less importance. Allowable carbon emissions for**
22 **threshold stabilisation are similarly highly dependent on the pre-industrial baseline. For**
23 **stabilisation at 2°C, allowable emissions decrease by as much as 40% when earlier than 19th**
24 **century climates are considered as a baseline.**

25 In the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the
26 likelihood of global mean temperatures exceeding 1.5°C and 2°C above 1850-1900 levels was
27 estimated^{2,3}. No estimates were provided, however, for a true “pre-industrial” baseline in this context.
28 Given that the industrial revolution and concomitant increase in greenhouse gases (GHG) was well
29 underway by the late-18th century^{4,5} the late-19th century temperatures do not provide an accurate
30 “pre-industrial” baseline as specified by the Paris agreement¹. Unfortunately, the estimation of pre-
31 industrial temperature is far from straightforward⁶. GHG concentrations have been increasing since
32 industrialization began around 1750, and are likely to have impacted global temperatures^{7,8}.
33 Consequently, estimates of a temperature baseline prior to the industrial revolution would be
34 desirable^{9,6}. However very few instrumental measurements of temperature exist, prior to the 19th
35 century, and these are concentrated in the Northern Hemisphere¹⁰. To further complicate matters,
36 natural fluctuations in global temperature are ever-present, leading to multi-decadal and longer-term
37 changes throughout the last-millennium^{11,12,13,14}, implying that there is no single value for pre-
38 industrial global mean temperature. Some of this variability is linked to natural forcings, particularly
39 volcanic eruptions, and variations in GHG concentration, such as the small drop in 1600^{5,15}. In this
40 article, we estimate probabilities for exceeding key temperature thresholds, under different emission
41 scenarios, including the impact of differing assumptions regarding the pre-industrial temperature
42 baseline.

43 To determine the effect of the pre-industrial baseline on the probability of exceeding projected
44 temperature thresholds, we use model simulations performed as part of the Coupled Model
45 Intercomparison Project Phase 5 (CMIP5)¹⁶. We use historical simulations and projections from three

46 different future representative concentration pathways (RCPs), namely: RCP2.6, RCP4.5 and RCP8.5
47 to calculate continuous global temperature time series from 1861-2100. We employ a global blend of
48 simulated sea surface temperatures and surface air temperature (SATs)¹⁷ (Figure 1). In contrast to
49 other studies which just use SATs^{18,2}, this allows the most rigorous and unbiased comparison to
50 current blended observational datasets^{19,20,21}, which we have assumed will be those used to determine
51 if a temperature threshold has been reached in the future. Following the approach of Joshi et al¹⁸ we
52 first calculate anomalies from 1986-2005 (as used by IPCC AR5^{2,3}), and add an estimate of the
53 difference between this period and pre-industrial. To estimate the latter, we combine warming over
54 the 1850-2005 period, calculated from observations, with an estimate of warming prior to 1850.
55 Similar analyses have been found to be particularly sensitive to the choice of anomaly period²², and
56 we choose this method because tying projections to more recent observations will reduce the impact
57 of the uncertainty in past radiative forcing, since we do not rely on modelled warming prior to 1986.
58 We define threshold exceedance based on 5-year annual mean temperatures (see methods), in order to
59 avoid temporary early threshold exceedances due to internal variability, such as that linked to large
60 El-Nino events.

61 If we assume 1850-1900 can be used as a pre-industrial baseline (i.e. warming before 1850-1900 has
62 been negligible) it is almost certain that 2°C will be exceeded in the high future emissions scenario
63 (RCP8.5), very likely by the middle of the century (p=0.85), with a median estimate of a 3.9°C
64 increase by the end of the century (Fig. 1). In the scenario with moderate mitigation (RCP4.5) it is still
65 unlikely that the temperature increase can be limited to below 2°C (p<0.2), with a median estimate
66 warming of 2.3°C by the end of the century. It is only in the pathway with strong mitigation
67 (RCP2.6) where preventing a temperature rise above 2°C becomes probable (p=0.75) and holding
68 temperatures below 1.5°C possible (p=0.40). These projected temperatures are slightly lower than
69 those presented in IPCC AR5². This is because the use of blended temperatures instead of global
70 mean SATs results in about 4-10% less warming¹⁷ (see supplement). Note that these estimates rely on
71 the model spread encapsulating the true response, and uncertainties would be somewhat larger if the
72 uncertainty in transient climate response beyond the model range was included².

73 How large an impact could choosing a pre-industrial period before 1850-1900 have on these
74 probabilities, given the observed fluctuations in temperature throughout the last millennium and
75 beyond? A number of model simulations now exist covering the last millennium and these can be
76 used to calculate global temperatures over different periods between 1401 and 1850, to determine how
77 much warmer (or colder) the late-19th century is to a “true” pre-industrial baseline. We concentrate on
78 the period 1401-1800, as it pre-dates the major anthropogenic increase in GHGs, coincides with a
79 diverse range of natural (volcanic and solar) forcing⁵ and is a period where reconstructions agree
80 reasonably well with each other, and with model simulations^{13,23} and are based on the most data^{13,11}.
81 This therefore leads to greater confidence in the model simulations. In addition, it is also the period
82 where we have most model data and further back in time orbital forcing begins to diverge from that of
83 present day, making earlier periods less suitable.

84 In total, spatially complete blended global temperatures from 23 simulations, from 7 different models,
85 were analysed with the means of each model for different segments of the period 1401-1800 found to
86 be cooler than the late-19th century baseline (1850-1900) by 0.03°C to 0.19°C (multi-model mean of
87 0.09°C, fig 2b). In these simulations, and in temperature reconstructions of the past millennium^{11,12},
88 there is considerable centennial variability. Some periods, such as the 16th century, are of comparable
89 warmth to the late-19th century, while other periods have a multi-model mean nearly 0.2°C cooler.

90 Simulations from 3 models run with single-forcings (fig 2c-e) show that the major cause of variations
91 in pre-industrial temperature between centuries is a varying frequency of volcanic eruptions; with a
92 consistent cooling due to lower CO₂ levels and a smaller solar influence consistent with a small
93 attributed response to solar forcing over the Northern Hemisphere¹⁵. Choosing any particular sub-

94 interval over the past millennium to define pre-industrial temperatures thus involves a certain level of
95 subjectivity. To quantify this we calculate a combined distribution of 100-year periods from 1401-
96 1800 from each of the 7 models (see methods; fig S7 and fig 3), resulting in a 5-95% range of -0.02 to
97 0.21°C. Several studies have identified that the cooling response to very large volcanic eruptions in
98 model simulations exceeds the response estimated in many proxy temperature reconstructions^{7,13}.
99 While there is ongoing debate in the literature over the cause^{24,25}, this remains a source of uncertainty
100 when analysing model simulations during the volcanically active 17th-19th centuries. Also, the
101 magnitude of past solar forcing is uncertain, although most likely small^{15,5}, as are estimates of early
102 industrial aerosols and land use. Hence, the true uncertainties are almost certainly larger than shown
103 in figure 2.

104 Another way to approach the question of an appropriate pre-industrial baseline is to ignore natural
105 forced variability and consider how much warmer 1850-1900 is due to just anthropogenic forcing. To
106 estimate this we use climate models driven only with changes in GHG concentrations (fig 2c). The
107 calculated mean difference between 1850-1900 and the period 1401-1800 in different models ranges
108 from 0.10 to 0.18 °C (multi-model mean 0.13 °C, see supplement for more details), with some
109 dependence on the period analysed due to the dip in GHGs in 1600. This yields an estimate of
110 warming to 1850-1900 with a 5-95% range of 0.02 to 0.20°C. This approach, however, assumes that
111 the increase in CO₂ since the Little Ice Ages (LIA) is largely anthropogenic in origin. As the cause of
112 the LIA CO₂ drop is unknown, this is far from clear, although supported by a previous modelling
113 study that found only a small contribution from natural forcings to the 18th and 19th GHG
114 concentration increase⁴. Implicit in estimating pre-industrial temperatures based on GHGs alone is
115 also the assumption that the late-19th century experienced “typical” natural forcings, since we are not
116 accounting for differences in natural forcing. It also does not account for changes in other potential
117 anthropogenic forcings, particularly a cooling from early anthropogenic aerosols, which could have
118 been substantial²⁶ but is highly uncertain^{27,28}, as is a potential radiative effect of early land-use
119 change^{29,30}.

120 The estimates obtained above, suggest that depending on the definition of pre-industrial and the model
121 used, the late-19th century could provide a reasonable estimate of the pre-industrial temperature
122 baseline or alternatively this choice could underestimate the true warming since pre-industrial by as
123 much as 0.2°C. This is a slightly higher range than that calculated by Hawkins et al (H17)⁶ (see fig 3)
124 which was based on choosing a relatively low volcanic period, namely 1720-1800. It should be noted
125 that these values are specific to the period 1401-1800 and the range of possible pre-industrial
126 temperatures is likely to increase if periods further back in time are analysed. In particular, periods
127 during the medieval climate anomaly at the start of the last millennium, may have warmer
128 temperatures than the late-19th century, particularly in the 11th and 12th century. In models this is due
129 to a combination of orbital forcing and solar forcing with reduced volcanic forcing (figure S6) and
130 this variability should increase even more further back in time¹¹.

131 To calculate the effect that our new estimated range of additional warming since pre-industrial could
132 have on the likelihood of crossing key (i.e. 1.5°C and 2°C) thresholds under different scenarios, we
133 re-calculate the probabilities with a wide, but plausible range of additional pre-industrial warming,
134 covered by our 5-95% distributions (approximately 0 to 0.2°C), with results shown in Figure 3&4.
135 The results highlight the particular importance of the definition of pre-industrial temperature to the
136 exceedance probabilities for the strong mitigation scenario RCP2.6. For this scenario the probability
137 of exceeding the 1.5°C threshold increases from 61% to 88% if the late-19th century is assumed to be
138 0.2°C warmer than the true pre-industrial. The probability of exceeding 2°C increases from 25% to
139 30% under RCP2.6 and from 80% to 88% under RCP4.5. The choice of pre-industrial period also
140 effects the time of threshold crossing with the greater assumed pre-late-19th century warming leading
141 to earlier reaching of thresholds (Fig 4). This effect is larger under scenarios with more mitigation
142 because the associated rate of temperature change is smaller (Fig 3). For RCP4.5, for example, the

143 year in which the 50% probability for 2°C warming is crossed is reduced from 2059 to 2048 if 0.2°C
144 of pre-late-19th century warming is assumed.

145 It is possible to weight model projections based on the agreement between the models simulated past
146 temperatures and observed temperature. Results where each model is weighted based on its agreement
147 with observations from 1865-2005 are shown in the supplement (figs S11-13). The probability of
148 avoiding 1.5°C and the importance of the pre-industrial baseline is unaffected by the weighting.
149 Weighting does however reduce the uncertainty of the projections, and thus the likelihood of avoiding
150 2°C in both the RCP2.6 and RCP4.5 scenarios is reduced.

151 The relatively small early warming can also have dramatic impacts on cumulative carbon budgets. In
152 the most recent IPCC report² the total carbon budget allowed to avoid exceeding 1.5°C and 2°C was
153 given as the amount of carbon emissions *since 1870* which would lead to a warming relative to an
154 *1861-1880 baseline*. If we assume linearity these values will still hold for temperature increases
155 relative to a true pre-industrial baseline provided that the carbon emissions are also re-calculated from
156 a true pre-industrial period. If instead we wish to keep temperature beneath a threshold relative to a
157 *pre-industrial baseline* but use the existing estimates for carbon emissions *since 1870*, then the carbon
158 budget must be lowered accordingly. The IPCC estimated that that there is a 50% probability of
159 keeping temperature to a 2°C threshold (relative to 1861-1880) if 1210 GTC is emitted since 1870²
160 (which equates to 605 GTC per degree warming). If non-CO₂ forcings, are also taken into account,
161 under the RCP2.6 scenario, the allowed emissions of carbon reduce further to 820GTC. Given that the
162 IPCC estimates that 515GTC had been emitted up until 2011 (since 1870) this leaves 305GTC still to
163 be emitted. But, assuming linearity, if a warming of 0.1°C had already occurred due to CO₂ increases
164 by 1861-1880, then around 60GTC of the budget would have already been used. This corresponds to
165 roughly 20% of the budget still remaining (in 2011), and approximately 40% if the early warming was
166 as much as 0.2°C. The corresponding fractions of the remaining budget are likely to be even larger for
167 a 1.5°C target.

168 Despite remaining uncertainties there are at least two robust implications of our findings. Firstly,
169 mitigation targets based on the use of a late-19th century baseline are probably overly optimistic and
170 potentially substantially underestimate the reductions in carbon emissions necessary to avoid 1.5°C or
171 2°C warming of the planet relative to pre-industrial. Secondly, while pre-industrial temperature
172 remains poorly defined, a range of different answers can be calculated for the estimated likelihood of
173 global temperatures reaching certain temperature values. We would therefore recommend that a
174 consensus be reached as to what is meant by pre-industrial temperatures to reduce the chance of
175 conclusions which appear contradictory, being reached by different studies and to allow for a more
176 clearly defined framework for policymakers and stakeholders⁶.

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261 **Contributions:**

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

264

265 **Methods**

266 In order to investigate global mean temperatures during the historic and future period, we use CMIP5
267 model projections for the three RCP scenarios (RCP2.6, RCP4.5 and RCP8.5), with anomalies taken
268 over the period 1986-2005. Modelled surface temperature values are calculated from a blend of SATs
269 and SSTs following *Cowtan et al 2015*¹⁷ for total global coverage. Previously, analyses have typically
270 used just global SATs². Our choice to use blended temperatures is motivated by the current use of
271 blended observational datasets, which will likely be those used to determine if a temperature threshold
272 has been reached.

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

274
$$TEMP_{pre-industrial} = TEMP_{1986-2005} + PRE + IND \quad (1)$$

275 Where blended temperature since a true-preindustrial baseline ($TEMP_{pre-industrial}$), is calculated by first
276 taking anomalies from 1986-2005 ($TEMP_{1986-2005}$), adding values for observed warming from 1850-
277 1900 to 1986-2005 (IND) and then an estimate for the difference between 1850-1900 and the true-
278 preindustrial baseline (PRE). The IPCC AR5 report estimated a warming of 0.61°C for IND, based on
279 the HadCRUT4 dataset¹⁰. Given that we are calculating global mean temperature with full coverage
280 we instead use an estimate calculated using the Cowtan and Way¹⁹ observational dataset which has
281 used the same data as HadCRUT4 but has been infilled using kriging. This gives a value of 0.65°C.
282 To account for the uncertainty in IND, we calculate an estimate from the 100 published ensemble
283 members¹⁹. HadCRUT4 and Cowtan and Way show less warming over this period than several other
284 datasets^{20,31}, for example in the Berkeley Earth global land and sea data³² it is 0.71°C⁶. Using different
285 observational datasets could therefore result in earlier threshold exceedances.

286 To estimate values for PRE we use model simulations from seven different models (see supplement
287 for more details) and calculate global temperature as a blend of surface air temperature and sea
288 surface temperature following *Cowtan et al 2015*¹⁷. We use model simulations which have been
289 forced with all available forcings and those which only consider single forcings at a time. To calculate
290 values of 100 year mean temperatures we use all available model simulations. A distribution for all
291 the 100-year values within the period 1401-1800 is calculated using all available model simulation
292 (see supplement tables S2-4 for more details). Models providing multiple ensemble members are
293 weighted down so that each model contributes equally to the distribution. The final distribution is then
294 calculated using kernel density estimation.

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

297
$$TEMP_{pre-industrial} = TEMP_{1861-1900} + PRE + Tdiff \quad (2)$$

298 Here $TEMP_{pre-industrial}$ is calculated from model simulations with anomalies from 1861-1900 (note that
299 1861 was used as a start date rather than 1850 because some model simulations only start in 1861).
300 Similar to eqn. 1 we add PRE, which is the temperature difference from pre-industrial to 1850-1900.
301 To account for the slight difference between the model simulations anomaly period (1861-1900) and
302 the period for which PRE applies (1850-1900) we add on a factor, Tdiff, which is the observed
303 temperature difference between 1861-1900 and 1850-1900, accounting for observational uncertainty,
304 in the same way as for IND in Eqn. 1. We favour the first method (Eqn. 1) because we consider
305 observed warming from 1850-1900 to be more reliable in observations than in models, due to
306 uncertainties in radiative forcing and the models response to them. Our conclusions are not
307 particularly sensitive to this choice (see supplement).

308 The probability for the mean temperature in 2080-2100 above a pre-industrial background for each of
309 the RCP scenarios is calculated from the full blended global mean temperature for each model

310 simulation. By accounting for the observational uncertainty in IND we calculate a probability
311 distribution for each model simulation. To combine these distributions into one joint-distribution a
312 weighted mean over all available model simulations is calculated, where the weights are set to
313 account for the number of ensemble members each model has, so that each model counts equally. The
314 median and 5-95% range is then calculated from the resultant distribution as is the probability of
315 temperatures exceeding the 1.5°C and 2°C limits.

316 To estimate the threshold crossing times, first the global annual mean temperatures are smoothed by a
317 5-year running mean and for every year a joint probability distribution is calculated from each
318 individual model simulation, accounting for observational uncertainty in IND. A threshold is said to
319 have been crossed in the first year when 50% of the model distribution (weighted by number of
320 ensemble members) is above the limit.

321

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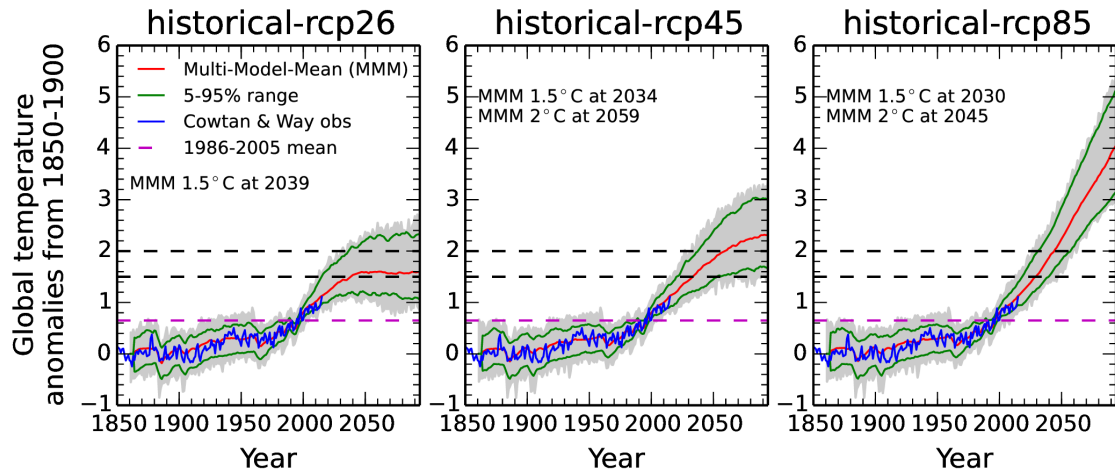


Fig 1 – Historical data and future projections for global mean temperature. Annual global mean temperature for observations¹⁷ (blue) and model simulation range (grey), anomalies first calculated for 1986-2005 and then observed warming since 1850-1900 (0.65¹⁷ – purple dashed line) has been added. Model 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.

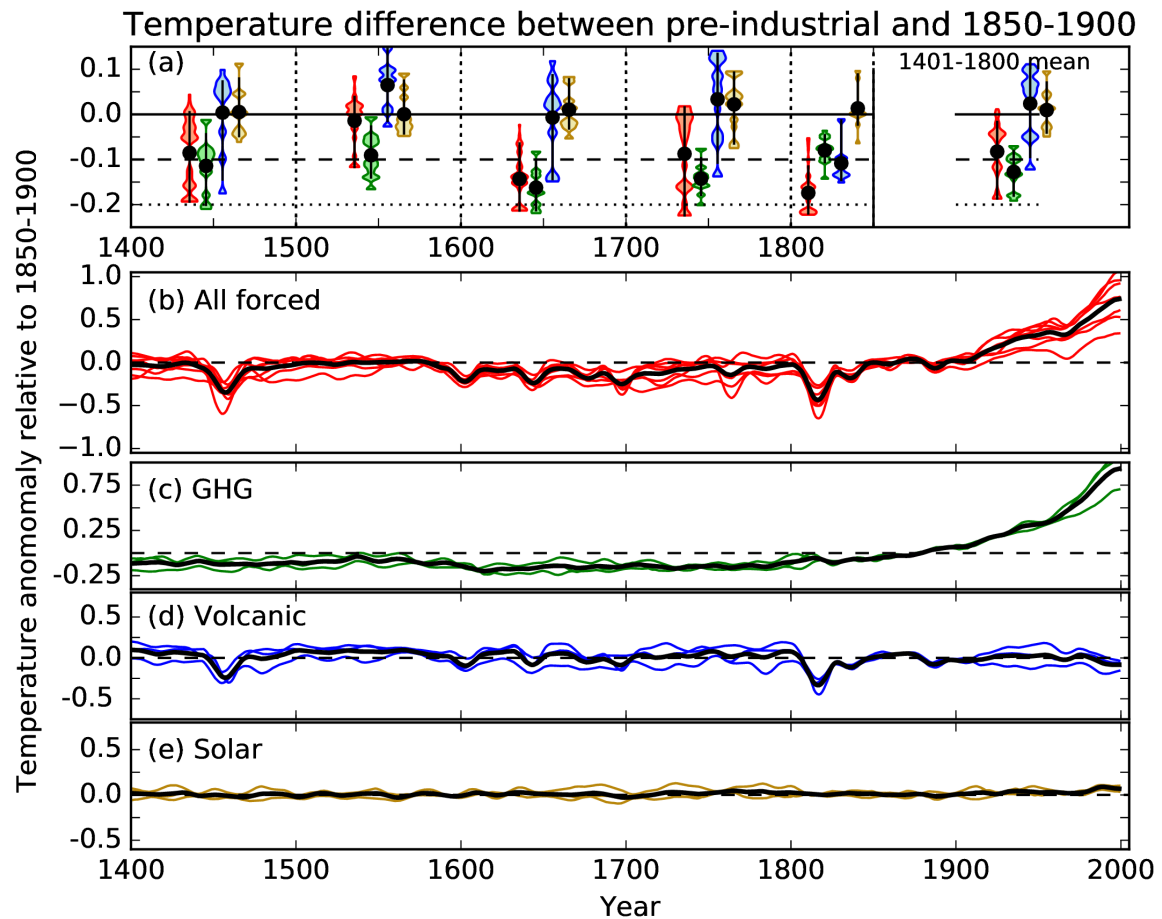


Fig 2. Model simulated difference in global mean temperature between different pre-industrial periods and 1850-1900. a) Range of ensemble means for different models, and for different forcing combinations (model mean: circle, model range: bar) model distribution fitted with a Kernel Density Estimate - 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.

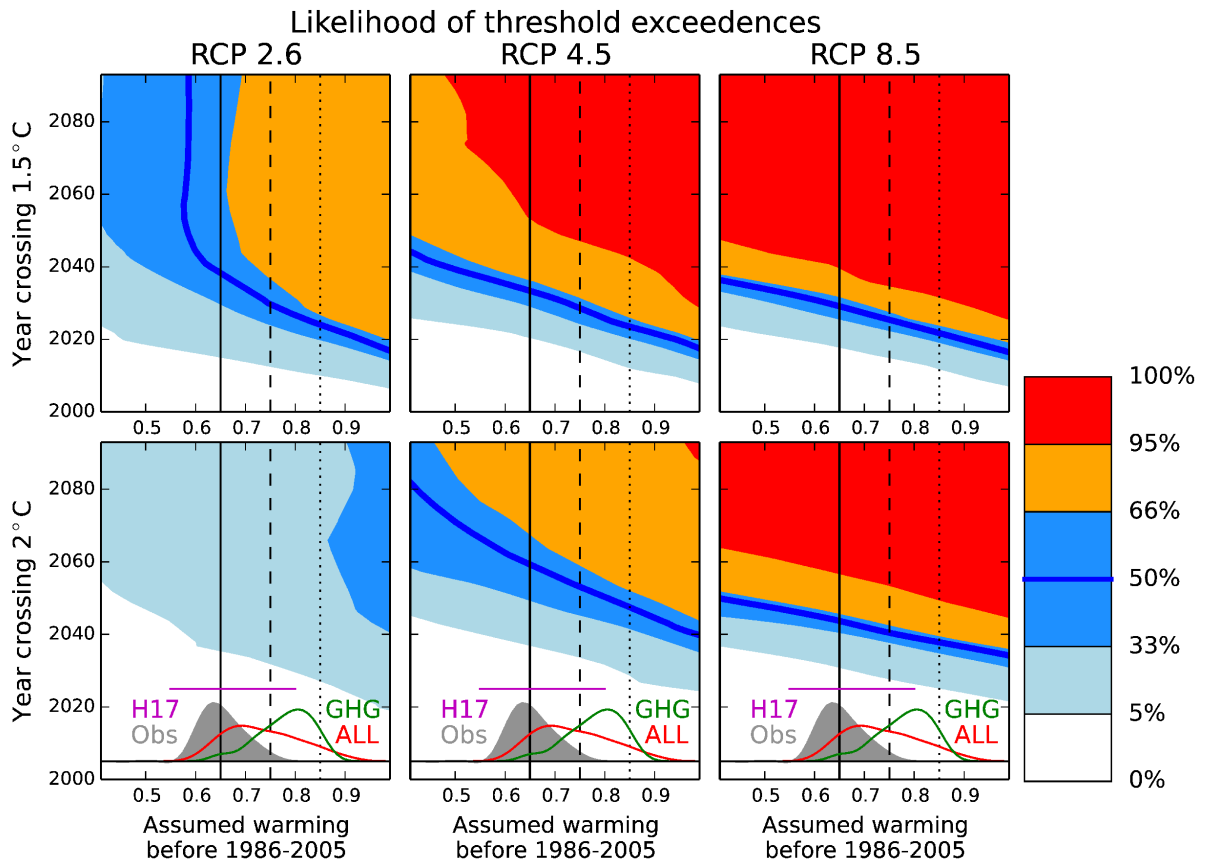


Fig 3 – Probability of exceeding temperature threshold for different assumed preindustrial baselines. Probabilities for exceeding a particular global mean temperature threshold in any given year are given [%], smoothed by a 30-year Lowess filter for clarity (un-filtered version in supplement). Vertical 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 al⁸.

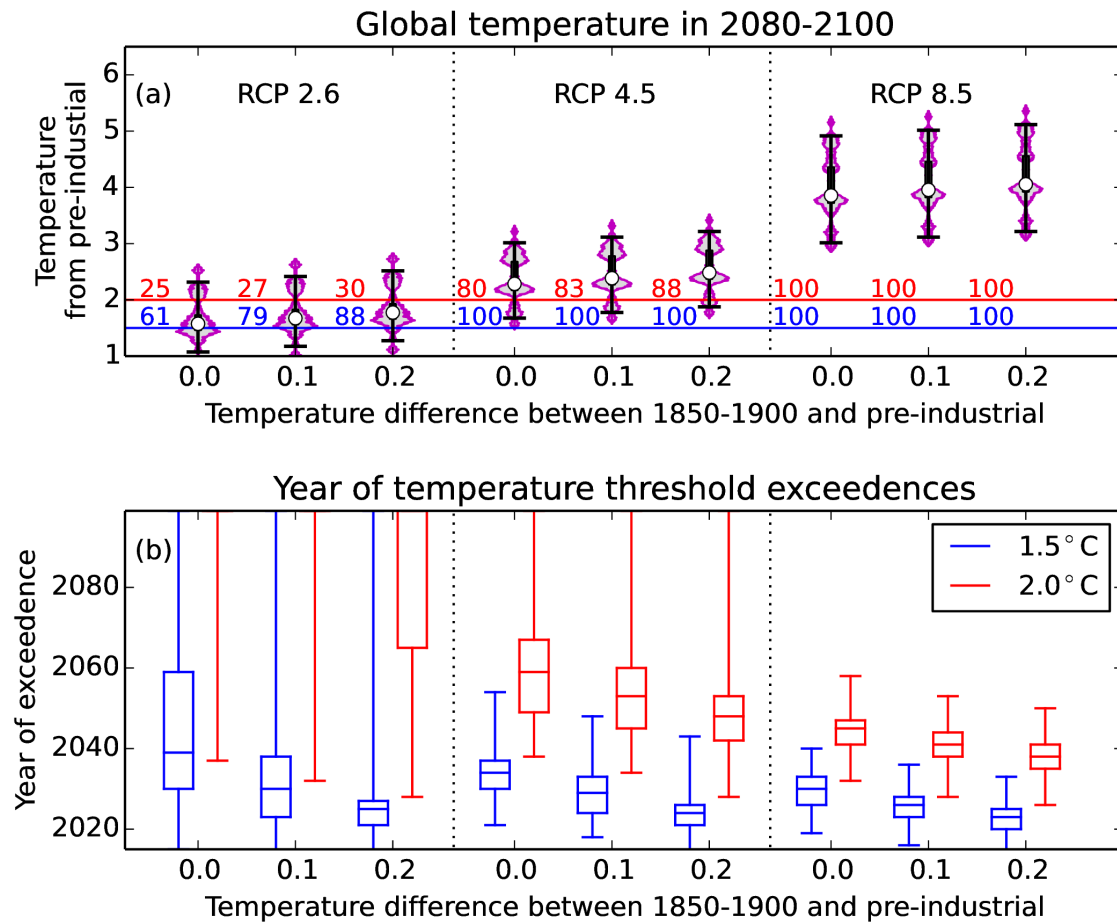


Figure 4 – Probability distributions for mean temperatures and time of threshold exceedence. Probability distribution: Model distribution (violin plot, purple line), 33-66% range (thick black line) 5-95% range (whiskers) and median value (white circle). a) Model temperature projections. Text gives probability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