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Declining uncertainty in transient climate response as CO₂ dominates future climate change

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Carbon dioxide (CO₂) has been the largest contributor to radiative forcing and surface temperature change over the industrial era but other anthropogenic drivers have had a significant role^{1,2}. The large uncertainty in the total forcing makes it difficult to derive climate sensitivity from historical observations³⁻⁷. Based on data from Intergovernmental Panel of Climate Change (IPCC) reports, we show that the evolution of increased anthropogenic forcing and its reduced relative uncertainty between the Fourth and Fifth Assessment Reports^{1,8} can be expected to continue into the future, driven by the greater ease of reducing air pollution than CO₂ emissions, long lifetime of CO₂, and hence a stronger dominance of CO₂ forcing. Here we present, using a statistical model, that the relative uncertainty in anthropogenic forcing of more than 40% quoted in the latest IPCC report for 2011 will be reduced by almost half by 2030, even without further improvement in scientific understanding. Absolute forcing uncertainty will also decline for the first time assuming projected decreases in aerosols occur. Other factors being equal, this stronger constraint on forcing will bring a significant reduction in the uncertainty of observation-

27 *based estimates of transient climate response, with a 50% reduction in its uncertainty range*
28 *expected by 2030.*

29

30 Equilibrium climate sensitivity (ECS) and transient climate response (TCR) are two key
31 measures that are used to evaluate how much the world might warm. TCR, which corresponds
32 to the warming at the time of a doubling CO₂ in a 1%- per-year CO₂ increase scenario, is
33 more policy-relevant than ECS to gauge the strength of climate change over coming decades.
34 Although there is high confidence in the human contribution to climate change, current IPCC
35 estimates of TCR show a large uncertainty range of 1.0 to 2.5 °C (5-95% confidence interval)
36 for a doubling of CO₂ (ref. ²), which translates into an equivalent range of 0.27 to 0.68
37 °C (W m⁻²)⁻¹ for the normalized definition of TCR that we adopt in this paper. Different
38 methods and data sets have been used to derive estimates of TCR. Observation-based studies
39 analyze the historical temperature record combined with information on the radiative forcing
40 (RF)⁵. The high uncertainty in historical RF is the main contributor to the uncertainty in the
41 estimate of TCR and ECS through such methods^{4,6}. Recent studies have shown that
42 uncertainties in climate sensitivity will be reduced in the future based on longer available time
43 series of surface temperature⁹. Here, we show that narrowing the uncertainty in RF can have a
44 larger effect on the diagnosed TCR uncertainty.

45

46 Recently the IPCC 5th Assessment Report assessed historical RF and its uncertainty¹. In this
47 paper we evaluate how uncertainty estimates have evolved between IPCC reports and
48 estimate how we expect uncertainty estimates in RF to change in the future. We then evaluate
49 the consequences of these trends on future uncertainty in diagnosing TCR from the available
50 temperature observations record.

51 Climate change can be driven by a wide range of emitted compounds as well as by physical
52 and chemical processes^{1,8}. The increase in well-mixed greenhouse gas abundances leads to a
53 documented RF with small relative uncertainty ($\approx 10\%$) with all uncertainties presented here
54 covering 5-95% ranges and all relative uncertainties given as half the 5-95% relative ranges
55 unless otherwise stated. However, several of these greenhouse gases affect atmospheric
56 chemistry leading to indirect effects that add to the RF uncertainty¹⁰⁻¹². The positive RF from
57 greenhouse gas increases since pre-industrial time has partly been counteracted by an overall
58 negative RF by anthropogenic aerosols¹³⁻¹⁶; however the scattering and absorbing effects of
59 atmospheric aerosols, including the component due to aerosol-cloud interactions, have
60 uncertainties¹⁷ that are much larger ($\sim 100\%$ relative uncertainty) than those associated with
61 CO₂ (see Supplementary Figure 1).

62 In the two most recent IPCC assessment reports (AR4 and AR5) best estimates for
63 anthropogenic RF, together with their uncertainties, have been provided^{1,8}. Similar estimates
64 have been provided for earlier IPCC assessments^{18,19}. The changes in RF estimates and their
65 uncertainties between the reports are combinations of evolution in our scientific
66 understanding and temporal change of the forcing agents between the RF evaluation years.
67 Forcing estimates in the IPCC assessment are based on observations and modelling, and
68 estimates constrained from observed climate change^{20,21} are ignored.

69 Relative to pre-industrial (1750) the total anthropogenic RF in AR5 (for year 2011) is larger
70 than in AR4 (for year 2005) and TAR (for year 1998) and Figure 1 shows that further
71 increases are expected under two extreme Representative Concentration Pathways (RCPs) for
72 2030 (see Methods). This increased total anthropogenic forcing from TAR and AR4 to AR5 is
73 due to increases in greenhouse gases as well as increased scientific evidence for a less
74 negative aerosol forcing¹. In AR5 more aerosol processes are included in the forcing estimates

75 (allowing for rapid adjustments in the atmosphere) relative to previous IPCC assessments,
76 which resulted in a less negative RF estimate (-0.9 (-1.9 to -0.1) W m⁻² in AR5 versus -1.2 (-
77 2.4 to -0.6) W m⁻²). Importantly, the relative uncertainty is reduced from TAR and AR4 to
78 AR5 as shown in the right panel of Figure 1. Projections using the RCPs indicate that this
79 reduction will continue and, by 2030, the relative uncertainty in the total anthropogenic RF
80 will be approximately halved relative to the latest IPCC assessments assuming no change in
81 the scientific understanding of the forcing mechanisms (based on RCP2.6 and RCP8.5).
82 Despite improvements in understanding, individual RF uncertainties changed relatively little
83 between the assessment reports; yet the relative uncertainty in total RF has narrowed and can
84 be expected to exhibit an even stronger decrease by 2030.

85 The main cause of reduction in the relative uncertainty of the total RF is due to the increasing
86 share of the CO₂ contribution to the total as shown in Figure 2. In the last decades of the 20th
87 century, non-CO₂ greenhouse gases made substantial contributions to the total, with rapid RF
88 increases, while aerosols offset part of the greenhouse gas RF. The first decade in this century
89 and projections for the next few decades show limited RF changes for non-CO₂ greenhouse
90 gases and a decrease in the offsetting negative aerosol forcing combined with an enhancement
91 in the CO₂ RF. This dramatic change in the relative RF contributions is due to fairly stable or
92 declining recent and projected emissions of short-lived aerosols and aerosol precursors and
93 most non-CO₂ GHGs, in contrast with continuous increases in CO₂ emissions²² coupled with
94 its long lifetime. The forcing due to aerosols including their influence on clouds is better
95 understood and quantified than in AR4, but uncertainties remain large¹⁷. Over the last two
96 decades, there has been a large change in the distribution of aerosols, linked to reduced
97 anthropogenic emissions in Europe and North America and increased emissions over South

98 and East Asia. These opposite trends over the last decades are expected to more-or-less
99 balance each other in terms of global mean RF^{1,23}.

100 Figure 3 illustrates the time evolution of forcing used in this paper and its standard deviation.
101 A maximum in the standard deviation (and hence absolute uncertainty) was reached around
102 2011 and is expected to decline further despite the increase in forcing. This leads to continued
103 reduction in the relative uncertainty which, based on AR5 estimates, has been declining since
104 about 1970. Figure 3 clearly shows how the reduction in relative uncertainty is caused by the
105 increasing dominance of CO₂ in the total RF. Overall, the combination of enhanced CO₂
106 forcing and weak magnitude of the non-CO₂ and aerosols forcing both contributed to the
107 recent reduction in uncertainty in anthropogenic forcing and likewise for the trend in the
108 coming decades. Whereas the change in the relative uncertainty in the anthropogenic forcing
109 from AR4 to AR5 is a combination of larger CO₂ domination and improved quantification of
110 the aerosol forcing, estimated further change by 2030 is solely due to a change in atmospheric
111 abundances and no assumed change in scientific understanding about the individual drivers of
112 climate change.

113 In the following we take the trends in anthropogenic RF estimates described above and
114 examine their implications for estimating TCR from the historical record. TCR, when derived
115 from historical observations or simulations relates the temperature change (ΔT) and the RF at
116 a given time as follows:

$$117 \quad \text{TCR} = \Delta T / \text{RF} \quad (1)$$

118 The method used to estimate TCR here is similar to that used in recent studies⁶. Note that in
119 the above equation TCR is expressed per unit of RF rather than for a doubling of CO₂
120 abundance. It assumes quasi linear changes in ΔT and RF over a chosen time period. Often

121 TCR is assumed to be similar for all climate forcing mechanisms, although this may not
122 be the case²⁴ (see further discussion below and in the Supplementary Material). It may also
123 depend on the rate of change of forcing²⁵, which introduces a further small uncertainty term
124 not accounted for here. The relative uncertainty in TCR ($d \text{ TCR} / \text{TCR}$), where d refers to half
125 the uncertainty of the 5-95% uncertainty range, is shown in Figure 4a for RF relative
126 uncertainties for AR4, AR5 and two RCPs for 2030 as a function of temperature change using
127 the Monte Carlo simulations described and discussed in the Methods and Supplementary
128 Material. Figure 4a shows that the relative uncertainty in TCR for the two RCPs is about half
129 that found for AR5 data. The uncertainties related to temperature decrease as the temperature
130 change increases, as can be seen for the two RCPs. However, the contribution from
131 temperature uncertainties is less than 10% of the change in the relative uncertainty in TCR
132 between AR5 and the RCPs for 2030, emphasizing that changes in the RF uncertainties are
133 the dominant cause of the differences between AR5 and the RCPs for 2030.

134 The difference in RF uncertainty between AR4, AR5 and the two RCPs for 2030 translates
135 into a large difference in the 5-95% uncertainty range of the TCR for AR5 present-day
136 temperature changes and best estimate RF as shown in the inset in Figure 4. The only
137 difference in these ranges in TCR is caused by the declining uncertainty in RF. The better
138 quantification of RF has the largest impact on the upper range of the derived TCR in absolute
139 terms. Upper ranges of TCR are associated with low values of RF for which the lower bound
140 of the aerosol RF is particularly relevant. A relatively symmetric distribution of RF leads to
141 more asymmetric shape of the distribution of TCR⁷. The two RCPs uncertainty estimates in
142 2030 provide rather similar uncertainty ranges for TCR. The AR5 likely range of TCR can be
143 reduced by about 50% based on climate data from two additional decades solely due to
144 expected RF trends without further improvements in understanding (subject to continued

145 availability of global surface temperature observations), see inset in Figure 4b. The absolute
146 change in TCR is more dependent on temperature changes than the relative change in TCR.
147 Figure 4b shows that the absolute range in TCR will be at least 25% lower than the AR5
148 range over the RCP8.5 temperature ranges for 2030. For small temperature changes, the
149 absolute uncertainty in TCR will see a greater reduction than the relative uncertainty in TCR
150 between AR5 and the RCP for 2030 (up to 56%).

151 Including an enhanced response to forcing in the Northern Hemisphere extratropics²⁴ would
152 increase the uncertainty in present-day TCR calculations, but would lead to an even greater
153 narrowing of the TCR uncertainty moving to 2030 RCP conditions (see Supplementary Figure
154 2). The combination of air quality policies, the Montreal Protocol, trends in emission of
155 climate related compounds, and most importantly the differentiated lifetime of the compounds
156 suggests that the current evolution is likely to continue over the next few decades. Our
157 findings illustrate that the stronger domination of CO₂ RF over the other forcing terms leads
158 to a better quantification of TCR.

159 A better quantification of TCR will have a pronounced impact on the probability distribution
160 of estimates of the amount of permissible CO₂ emissions for a given temperature target, e.g
161 the 2 °C target agreed to under the UNFCCC. Currently these emissions are highly uncertain²⁶,
162 but the expected CO₂ domination will bring about (by itself) a better quantification of TCR
163 and future projections of climate change.

164

165

166 **Methods**

167 All forcing values and their uncertainties used for figures and analysis are given in the IPCC
168 AR5 in chapter text, supplementary or annex^{1,27}, except for one case as described below for

169 RCP2.6. The time evolution of historical and future RF is also from IPCC AR5. Projections
170 for 2030 are based on the two most extreme RCPs, namely RCP2.6 and RCP8.5²⁸. These two
171 RCP represent lower and upper projections over the next decades, respectively in terms of
172 CO₂ emissions and to some extent other climate relevant species. The development over the
173 last decade is closest to RCP8.5 in terms of CO₂ emissions. Other emission scenarios based
174 on realistic development until 2030 have little impact on our findings. AR5 forcing estimates
175 for aerosols and contrail induced cirrus include rapid adjustments and thus use the effective
176 radiative forcing concept^{1,17}, whereas in AR4 and previous IPCC reports rapid adjustments
177 were not quantified. This makes some of the forcing estimates not entirely comparable, but
178 allowing for the difference in treatment of rapid adjustment is the most consistent method for
179 the aerosols between the IPCC reports. Forcing estimates for the two RCPs and AR5 are
180 derived consistently with the same forcing concept and relative uncertainty for the individual
181 drivers. The combined forcing from ozone and stratospheric water vapour in Figure 1 has a
182 small change in the relative uncertainty between AR5 and the RCPs caused solely by
183 abundance changes. The best estimate of the total anthropogenic RF for the various IPCC
184 reports and the two RCPs is calculated based on the sum of the best estimate of each
185 component. The range of the total anthropogenic RF is derived from the square root of the
186 sum of the square of the upper and lower range deviation from the best estimate for the
187 individual component. This allows for a consistent treatment of the best estimate and range,
188 but may differ slightly from the report values in previous IPCC reports. The best estimate and
189 uncertainty ranges for the two RCPs for 2030 are derived consistently with AR5 estimates,
190 where the only change in estimate arise from atmospheric compositional change. Aerosols RF
191 for RCP2.6 is not provided in the IPCC AR5 annex²⁷ and is derived based on the difference in
192 aerosol forcing from 2010 to 2030 as derived from one model (OsloCTM2)²⁹ and thus also

193 made consistent with the AR5 estimate. The main source of the time evolution of historical
194 and future forcing of aerosols and ozone for IPCC AR5 was a multi-model study³⁰.
195 The time series of uncertainty used in Figure 3 are derived from a Monte-Carlo method, based
196 on converting IPCC AR5 uncertainty ranges in RF for 2011 into fractional error PDFs. We
197 then sample these to generate plausible RF time series.
198 For the calculations of changes in uncertainties in TCR probability distribution functions
199 (PDFs) of TCR from PDFs of temperature change and RF is derived using a Monte Carlo
200 random sampling approach. The values adopted to derive the PDFs are given in
201 Supplementary Table 1. Supplementary Figure 3 shows PDFs of TCR derived in this way
202 from PDFs of RF and temperature change. The 5-95% interval is derived from the PDFs of
203 TCR.
204 Relative uncertainties are given as half the 5-95% relative ranges. In Figure 4 the full 5-95%
205 relative range is added to the relative uncertainty. In Figure 1 the relative uncertainties are
206 calculated as half the 5-95% confidence range, divided by the best estimate.

207 **Figure 1:** Anthropogenic forcing for four phases of IPCC reports and two RCPs. Aerosols,
208 ozone and stratospheric water vapour, well-mixed greenhouse gases (WMGHG), land use
209 change and total forcing are given for SAR (1750-1993), TAR (1750-1998), AR4 (1750-
210 2005) and AR5 (1750-2011)) and two RCPs for 2030. . All the forcing values are based on
211 best estimates reported in the IPCC reports, but with a consistent approach to calculate the
212 total forcing which may differ slightly from reported values (see Methods). In SAR land use
213 change was not estimated and thus not included in the total. Further, the RF of a given CO₂
214 concentration was estimated to be 15% higher in SAR compared to the recent IPCC reports,
215 adding 0.24 Wm⁻² to the total RF quoted in SAR. Estimate for AR5 and the two RCPs for
216 2030 includes rapid adjustments in the RF, whereas these have not been quantified earlier in
217 SAR, TAR, and AR4. The probability density function for SAR and TAR are based on
218 Boucher and Haywood¹⁹ and their simulation C1.5. The relative uncertainties are shown in the
219 right panel. All uncertainty ranges correspond to 5-95% confidence intervals with relative
220 uncertainties given as half the 5-95% relative range.

221

222

223 **Figure 2:** Decadal RF change between 1970 and 2010 and for 2020 to 2030 for two RCPs.
224 The forcing is given for 1970 to 1980, 1980 to 1990, 1990 to 2000, and 2000 to 2010 and for
225 2020 to 2030 based on IPCC AR5 forcing values (see Methods). RF for ozone includes
226 changes in the troposphere as well as in the stratosphere. Other WMGHG includes CH₄, N₂O
227 and halocarbons. All process associated with aerosol-radiation and aerosol-cloud interactions
228 taken into account in the IPCC assessments are included for aerosol, except black carbon on
229 snow. Consistent treatment is applied for RCPs for 2030 and AR5. Forcing mechanisms other
230 than those shown in the figure are small (see Supplementary Information).

231

232

233 **Figure 3:** Time evolution in RF and standard deviation in RF. RF for total anthropogenic,
234 CO₂, the combined non-CO₂ greenhouse gases (GHG) such as CH₄, N₂O, halocarbons, ozone,
235 and stratospheric water vapour, the others such as land use changes, black carbon on snow
236 and ice, and contrails, and finally aerosols over the period 1850 and 2030 (a); the time
237 evolution of the standard deviation of RF (b) and the ratio of the standard deviation of RF to
238 the total RF (c). All the time evolutions of forcing are taken from IPCC AR5 (see Methods).
239 RCP8.5 and RCP2.6 are shown with solid and dashed lines, respectively.

240

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243

244 **Figure 4:** The relative a) and absolute b) uncertainty in TCR for the indicated conditions as a
245 function of temperature change. The results are based on Monte Carlo simulations of the PDF
246 of TCR as a function of temperature change and relative uncertainty in RF for AR4, AR5, and
247 RCP2.6 and RCP8.5 for 2030 (see methods for source of RF values). The uncertainties in RF
248 for the two RCPs are based on the scientific knowledge in AR5 and projected abundance
249 changes. Observed temperature changes and their uncertainties from AR4 and AR5 are
250 adopted in the calculations of the relative uncertainty in TCR, whereas for RCP2.6 and
251 RCP8.5 results are shown for CMIP5 simulated temperature changes. The absolute
252 uncertainty in temperature change for 2030 is assumed to be same as in AR5. The relative
253 uncertainties and best estimates of TCR are shown as horizontal lines with ranges shown for
254 lower and upper bound of the relative uncertainty in TCR and TCR (lines for AR4 and AR5
255 whereas bands for the two RCPs for 2030). The inset shows the TCR and the uncertainty
256 range from Equation 1 for temperature changes and RF at the time of AR5 but with different
257 relative uncertainty in RF from AR4, AR5, and RCP2.6 and RCP8.5 for 2030. The diamond
258 symbol shows the TCR with the best estimate RF and is thus constant to illustrate solely the
259 difference in relative uncertainty in RF.

260

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346

347 **Author contributions**

348 GM, FMB, DS initiated the study with additional contribution on the design on the study from

349 PF and OB. GM, OB, FMB, PF, and DS performed the analysis and wrote the paper.

350









