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# Halfway to doubling of CO<sub>2</sub> radiative forcing

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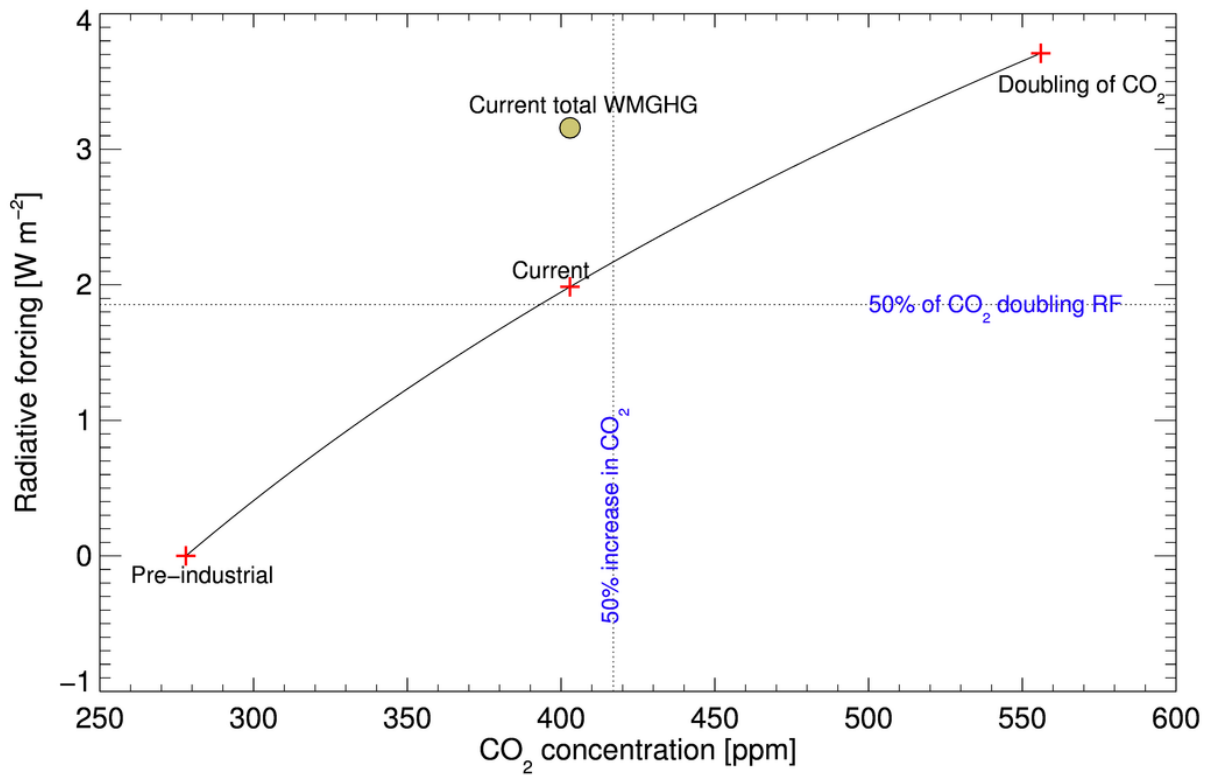
The “double CO<sub>2</sub>” experiment has become a standard experiment in climate science, and a convenient way of comparing the sensitivity of different climate models. Double CO<sub>2</sub> was first used by Arrhenius<sup>1</sup> in the 19<sup>th</sup> century and in the classic paper by Manabe and Wetherald<sup>2</sup>, published 50 years ago, which marked the start of the modern era of climate modeling. Doubling CO<sub>2</sub> now has an iconic role in climate research. The equilibrium climate sensitivity (ECS) is defined as the global-mean surface temperature change resulting from a doubling of CO<sub>2</sub><sup>3-5</sup>, which is a headline result in Intergovernmental Panel on Climate Change (IPCC) assessments. In its most recent assessment IPCC concluded that the ECS “is likely in the range 1.5 to 4.5°C”. We show that we are now halfway to doubling of CO<sub>2</sub> since pre-industrial times in terms of radiative forcing, but not in concentration.

The greenhouse effect due to change in CO<sub>2</sub> – quantified using calculations of radiative forcing – follows, to a good approximation, a logarithmic dependence on the ambient concentration in the atmosphere over the last 1000 years<sup>6</sup>. Due to this relationship between radiative forcing and CO<sub>2</sub> concentration, the radiative forcing due to a doubling of CO<sub>2</sub> is approximately independent of background levels. A doubling of CO<sub>2</sub> is estimated by IPCC to cause a radiative forcing of 3.7 W m<sup>-2</sup>. Recent detailed radiative transfer calculations arrived at a similar estimate<sup>7</sup>. The uncertainties are small for the radiative forcing due to CO<sub>2</sub>; uncertainties associated with spectroscopic parameters that underpin forcing calculations are estimated to be less than 1% in a recent study<sup>8</sup>, with overall uncertainties assessed to be 10%<sup>6</sup> (with 90% confidence). Forcing estimates of doubling of CO<sub>2</sub> from global climate models have the same best estimate as the IPCC value<sup>6</sup>, even though these models include rapid atmospheric adjustments, which modify the forcing calculated using a radiative transfer model.

It is timely to assess where we are now, relative to a doubling. The global-mean CO<sub>2</sub> abundance in 2016 was 403 ppm according to global observations<sup>9</sup> which is less than 50% higher than the pre-industrial CO<sub>2</sub> concentration of 278 ppm. However, due to the logarithmic forcing relationship, a halfway to doubling of CO<sub>2</sub>, in terms of radiative forcing, has now been reached. Figure 1a illustrates that this halfway point happened at 393 ppm, which was reached in 2012. A halfway to doubling in the CO<sub>2</sub> concentration is 417 ppm and will be reached before 2025 with current CO<sub>2</sub> growth rates. Hence, at CO<sub>2</sub> concentrations between of 393 and 417 ppm we are more than a halfway to CO<sub>2</sub> doubling in radiative forcing, but not in concentration (Figure 1a).

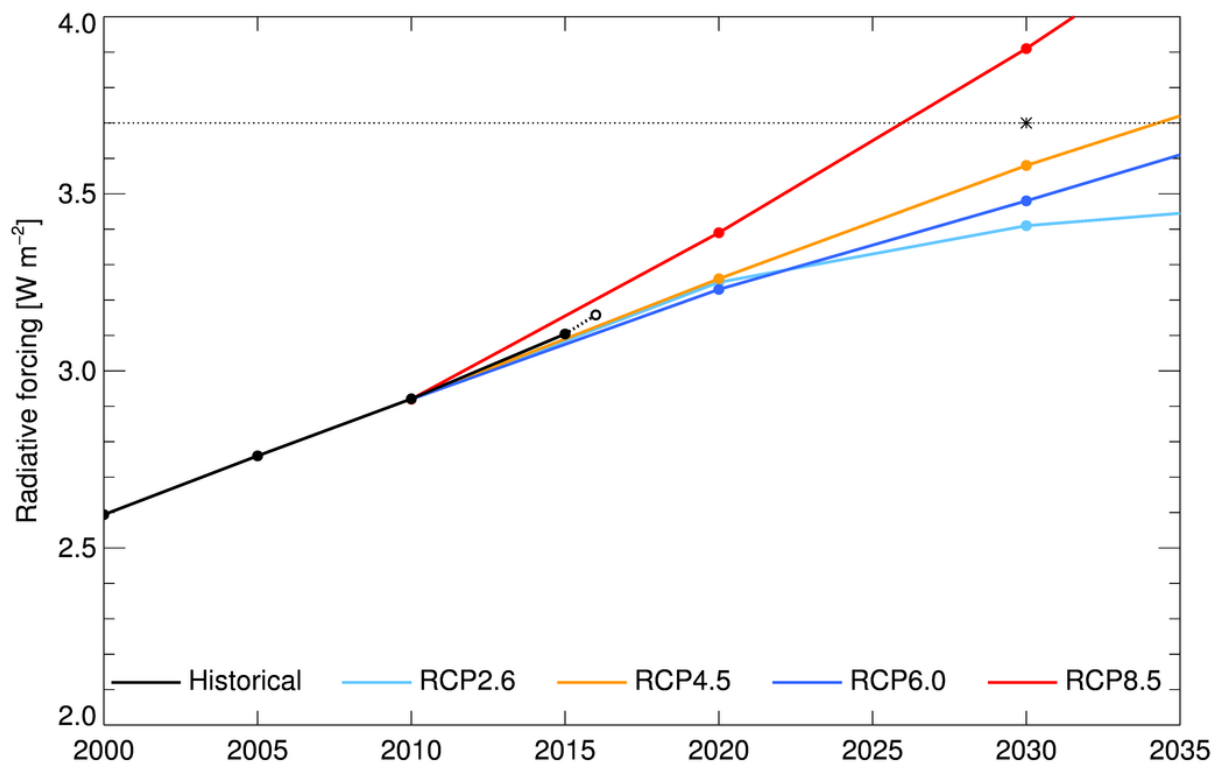
Climate change over the industrial era is caused by several anthropogenic climate drivers in addition to CO<sub>2</sub>, including other atmospheric gases and aerosols and changes to the land surface<sup>6</sup>. Increases in concentrations of well-mixed greenhouse gases (WMGHGs) other than CO<sub>2</sub> (notably CH<sub>4</sub>, N<sub>2</sub>O and halocarbons) contribute to a stronger greenhouse effect. The combined radiative forcing from all WMGHGs is 3.1 W m<sup>-2</sup> in 2015 (Figure 1b) and hence in CO<sub>2</sub>-equivalent forcing terms, is 84% of the way to a doubling. This value includes a recent estimate of methane's radiative forcing which incorporated its absorption of solar radiation; this update resulted in an increase in the 1750-2011 CH<sub>4</sub> forcing from 0.48 (the value in IPCC fifth assessment<sup>6</sup>) to 0.61 W m<sup>-2</sup> <sup>7</sup>. This increase is, in radiative forcing terms, close to the increase in CO<sub>2</sub> concentration over the 5 year period from 2010 to 2015. Consequently, we estimate that total WMGHG radiative forcing will be equivalent to doubling of CO<sub>2</sub>, with present growth rates, by around 2030 (Figure 1b). This is almost 5 years earlier than is estimated without the update to the CH<sub>4</sub> forcing. Aerosols generally cool the Earth and have historically countered much of this additional WMGHG forcing. The total anthropogenic forcing is expected to be close to the CO<sub>2</sub>-only forcing, but aerosols add uncertainty<sup>6</sup>. Nevertheless, in terms of radiative forcing we are more than half way to a doubling of CO<sub>2</sub>.

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**Figure 1:** Radiative forcing due to CO<sub>2</sub> and all well-mixed greenhouse gases (WMGHG). **a**, The CO<sub>2</sub> radiative forcing shown as a function of its global-mean abundance calculated using the IPCC forcing expressions<sup>6</sup>. Dotted lines are for a 50% increase in concentration (vertical) and radiative forcing (horizontal). **b**, Radiative forcing for all WMGHGs using the IPCC forcing expressions<sup>6</sup>, except for CH<sub>4</sub> where a stronger forcing, based on recent detailed calculations, is used<sup>7</sup>. Historical values are based on observed concentrations. Radiative forcing for CO<sub>2</sub>, N<sub>2</sub>O and halocarbons for the 2000-2010 period and future scenarios are from IPCC<sup>10</sup>. CH<sub>4</sub> concentrations are from IPCC<sup>10</sup>. For year 2015 the global annual mean concentrations of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O are from NOAA<sup>9</sup>, and for halocarbons the relative increase since 2010 are from the Arctic Zeppelin observatory. Preliminary data for 2016 is included<sup>9</sup>, which may be subject to small changes. Growth in WMGHG radiative forcing in the 2010-2016 period is 0.04 W m<sup>-2</sup> yr<sup>-1</sup>; the asterisk shows the date at which the total WMGHG forcing equals a CO<sub>2</sub> doubling by extrapolating this trend.

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