

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

Article

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

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11 The “double CO<sub>2</sub>” experiment has become a standard experiment in climate science, and a convenient  
12 way of comparing the sensitivity of different climate models. Double CO<sub>2</sub> was first used by Arrhenius<sup>1</sup> in  
13 the 19<sup>th</sup> century and in the classic paper by Manabe and Wetherald<sup>2</sup>, published 50 years ago, which  
14 marked the start of the modern era of climate modeling. Doubling CO<sub>2</sub> now has an iconic role in climate  
15 research. The equilibrium climate sensitivity (ECS) is defined as the global-mean surface temperature  
16 change resulting from a doubling of CO<sub>2</sub><sup>3-5</sup>, which is a headline result in Intergovernmental Panel on  
17 Climate Change (IPCC) assessments. In its most recent assessment IPCC concluded that the ECS “is likely  
18 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  
19 times in terms of radiative forcing, but not in concentration.

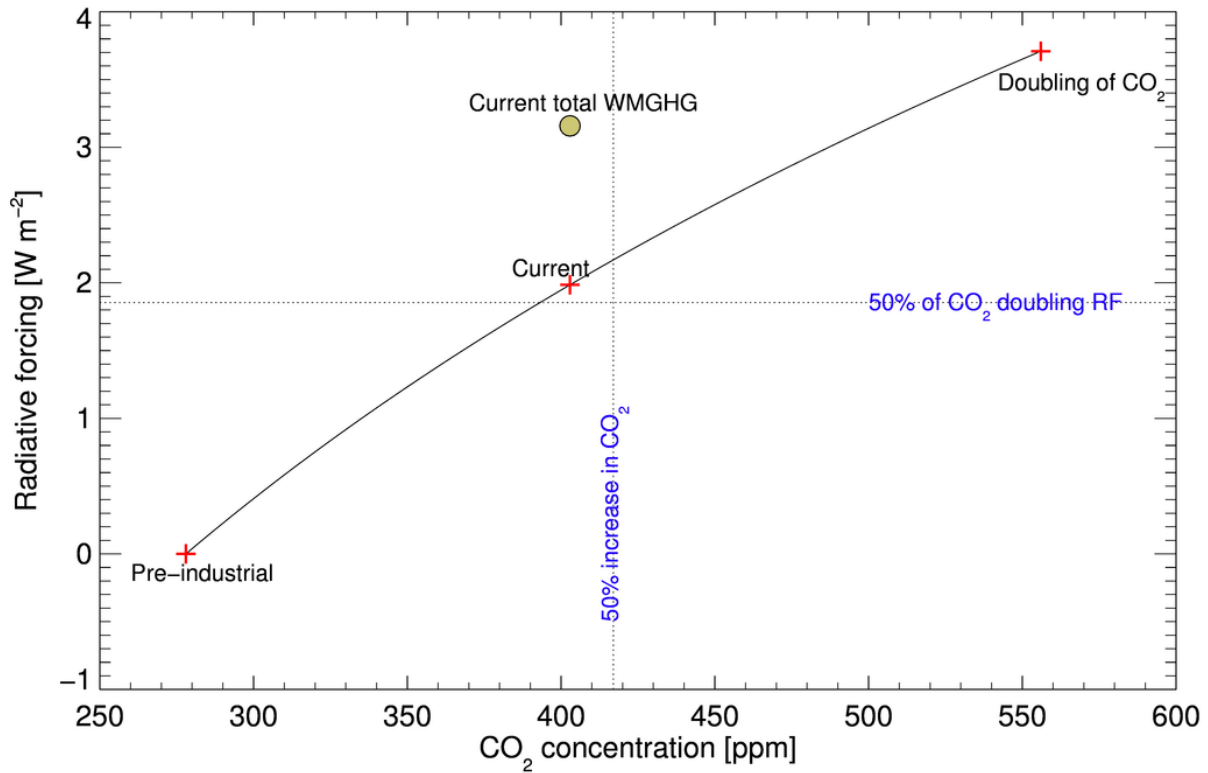
20 The greenhouse effect due to change in CO<sub>2</sub> – quantified using calculations of radiative forcing – follows,  
21 to a good approximation, a logarithmic dependence on the ambient concentration in the atmosphere  
22 over the last 1000 years<sup>6</sup>. Due to this relationship between radiative forcing and CO<sub>2</sub> concentration, the  
23 radiative forcing due to a doubling of CO<sub>2</sub> is approximately independent of background levels. A  
24 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  
25 transfer calculations arrived at a similar estimate<sup>7</sup>. The uncertainties are small for the radiative forcing  
26 due to CO<sub>2</sub>; uncertainties associated with spectroscopic parameters that underpin forcing calculations  
27 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  
28 90% confidence). Forcing estimates of doubling of CO<sub>2</sub> from global climate models have the same best  
29 estimate as the IPCC value<sup>6</sup>, even though these models include rapid atmospheric adjustments, which  
30 modify the forcing calculated using a radiative transfer model.

31 It is timely to assess where we are now, relative to a doubling. The global-mean CO<sub>2</sub> abundance in 2016  
32 was 403 ppm according to global observations<sup>9</sup> which is less than 50% higher than the pre-industrial CO<sub>2</sub>  
33 concentration of 278 ppm. However, due to the logarithmic forcing relationship, a halfway to doubling  
34 of CO<sub>2</sub>, in terms of radiative forcing, has now been reached. Figure 1a illustrates that this halfway point  
35 happened at 393 ppm, which was reached in 2012. A halfway to doubling in the CO<sub>2</sub> concentration is  
36 417 ppm and will be reached before 2025 with current CO<sub>2</sub> growth rates. Hence, at CO<sub>2</sub> concentrations  
37 between of 393 and 417 ppm we are more than a halfway to CO<sub>2</sub> doubling in radiative forcing, but not in  
38 concentration (Figure 1a).

39 Climate change over the industrial era is caused by several anthropogenic climate drivers in addition to  
40 CO<sub>2</sub>, including other atmospheric gases and aerosols and changes to the land surface<sup>6</sup>. Increases in  
41 concentrations of well-mixed greenhouse gases (WMGHGs) other than CO<sub>2</sub> (notably CH<sub>4</sub>, N<sub>2</sub>O and  
42 halocarbons) contribute to a stronger greenhouse effect. The combined radiative forcing from all  
43 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  
44 to a doubling. This value includes a recent estimate of methane's radiative forcing which incorporated  
45 its absorption of solar radiation; this update resulted in an increase in the 1750-2011 CH<sub>4</sub> forcing from  
46 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,  
47 close to the increase in CO<sub>2</sub> concentration over the 5 year period from 2010 to 2015. Consequently, we  
48 estimate that total WMGHG radiative forcing will be equivalent to doubling of CO<sub>2</sub>, with present growth  
49 rates, by around 2030 (Figure 1b). This is almost 5 years earlier than is estimated without the update to  
50 the CH<sub>4</sub> forcing. Aerosols generally cool the Earth and have historically countered much of this additional  
51 WMGHG forcing. The total anthropogenic forcing is expected to be close to the CO<sub>2</sub>-only forcing, but  
52 aerosols add uncertainty<sup>6</sup>. Nevertheless, in terms of radiative forcing we are more than half way to a  
53 doubling of CO<sub>2</sub>.

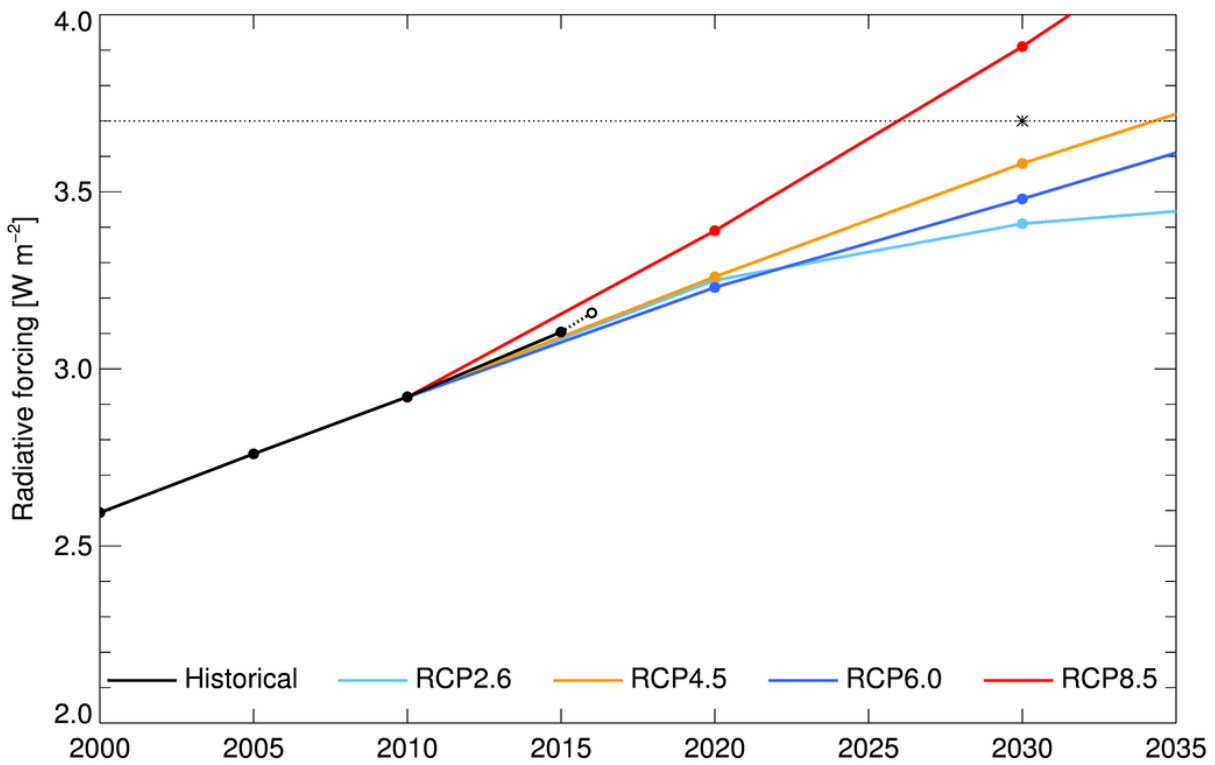
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77 **Figure 1:** Radiative forcing due to CO<sub>2</sub> and all well-mixed greenhouse gases (WMGHG). **a,** The CO<sub>2</sub>  
78 radiative forcing shown as a function of its global-mean abundance calculated using the IPCC forcing  
79 expressions<sup>6</sup>. Dotted lines are for a 50% increase in concentration (vertical) and radiative forcing  
80 (horizontal). **b,** Radiative forcing for all WMGHGs using the IPCC forcing expressions<sup>6</sup>, except for CH<sub>4</sub>  
81 where a stronger forcing, based on recent detailed calculations, is used<sup>7</sup>. Historical values are based on  
82 observed concentrations. Radiative forcing for CO<sub>2</sub>, N<sub>2</sub>O and halocarbons for the 2000-2010 period and  
83 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  
84 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  
85 since 2010 are from the Arctic Zeppelin observatory. Preliminary data for 2016 is included<sup>9</sup>, which may  
86 be subject to small changes. Growth in WMGHG radiative forcing in the 2010-2016 period is 0.04 W m<sup>-2</sup>  
87 yr<sup>-1</sup>; the asterisk shows the date at which the total WMGHG forcing equals a CO<sub>2</sub> doubling by  
88 extrapolating this trend.

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