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Halfway to doubling of CO₂ radiative forcing

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The “double CO₂” experiment has become a standard experiment in climate science, and a convenient way of comparing the sensitivity of different climate models. Double CO₂ was first used by Arrhenius¹ in the 19th century and in the classic paper by Manabe and Wetherald², published 50 years ago, which marked the start of the modern era of climate modeling. Doubling CO₂ 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 CO₂³⁻⁵, 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 CO₂ since pre-industrial times in terms of radiative forcing, but not in concentration.

The greenhouse effect due to change in CO₂ – 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 years⁶. Due to this relationship between radiative forcing and CO₂ concentration, the radiative forcing due to a doubling of CO₂ is approximately independent of background levels. A doubling of CO₂ is estimated by IPCC to cause a radiative forcing of 3.7 W m⁻². Recent detailed radiative transfer calculations arrived at a similar estimate⁷. The uncertainties are small for the radiative forcing due to CO₂; uncertainties associated with spectroscopic parameters that underpin forcing calculations are estimated to be less than 1% in a recent study⁸, with overall uncertainties assessed to be 10%⁶ (with 90% confidence). Forcing estimates of doubling of CO₂ from global climate models have the same best estimate as the IPCC value⁶, 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 CO₂ abundance in 2016 was 403 ppm according to global observations⁹ which is less than 50% higher than the pre-industrial CO₂ concentration of 278 ppm. However, due to the logarithmic forcing relationship, a halfway to doubling of CO₂, 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 CO₂ concentration is 417 ppm and will be reached before 2025 with current CO₂ growth rates. Hence, at CO₂ concentrations between of 393 and 417 ppm we are more than a halfway to CO₂ 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 CO₂, including other atmospheric gases and aerosols and changes to the land surface⁶. Increases in concentrations of well-mixed greenhouse gases (WMGHGs) other than CO₂ (notably CH₄, N₂O and halocarbons) contribute to a stronger greenhouse effect. The combined radiative forcing from all WMGHGs is 3.1 W m⁻² in 2015 (Figure 1b) and hence in CO₂-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 CH₄ forcing from 0.48 (the value in IPCC fifth assessment⁶) to 0.61 W m⁻². This increase is, in radiative forcing terms, close to the increase in CO₂ concentration over the 5 year period from 2010 to 2015. Consequently, we estimate that total WMGHG radiative forcing will be equivalent to doubling of CO₂, with present growth rates, by around 2030 Figure 1b). This is almost 5 years earlier than is estimated without the update to the CH₄ 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 CO₂-only forcing, but aerosols add uncertainty⁶. Nevertheless, in terms of radiative forcing we are more than half way to a doubling of CO₂.
Figure 1: Radiative forcing due to CO₂ and all well-mixed greenhouse gases (WMGHG). a, The CO₂ radiative forcing shown as a function of its global-mean abundance calculated using the IPCC forcing expressions⁶. Dotted lines are for a 50% increase in concentration (vertical) and radiative forcing (horizontal). b, Radiative forcing for all WMGHGs using the IPCC forcing expressions⁶, except for CH₄ where a stronger forcing, based on recent detailed calculations, is used⁷. Historical values are based on observed concentrations. Radiative forcing for CO₂, N₂O and halocarbons for the 2000-2010 period and future scenarios are from IPCC¹⁰. CH₄ concentrations are from IPCC¹⁰. For year 2015 the global annual mean concentrations of CO₂, CH₄ and N₂O are from NOAA⁹, and for halocarbons the relative increase since 2010 are from the Arctic Zeppelin observatory. Preliminary data for 2016 is included⁹, which may be subject to small changes. Growth in WMGHG radiative forcing in the 2010-2016 period is 0.04 W m⁻² yr⁻¹; the asterix shows the date at which the total WMGHG forcing equals a CO₂ doubling by extrapolating this trend.
6 Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,
8 V. Bex and P.M. Midgley (Cambridge University Press, Cambridge, United Kingdom and New
10 Myhre, G. et al. in Climate Change 2013: The Physical Science Basis. Contribution of Working
11 Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,
12 edited by T. F. Stocker et al. (Cambridge University Press, Cambridge, United Kingdom and New
15 (2016).
19 Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,
20 edited by T. F. Stocker et al. (Cambridge University Press, Cambridge, United Kingdom and New