How much CO_2 at 1.5C and 2C?

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Global warming of either 1.5°C or 2°C could occur at a wide range of CO_2 concentrations, due to uncertainties in climate sensitivity and the concentrations of other greenhouse gases. Climate change impacts studies need to account for this wide range to avoid either over or underestimating changes in crop yields and land and marine biodiversity.

As well as being a greenhouse gas, CO_2 also influences the environment through chemical and biological processes. An increase in the atmospheric concentration of CO_2 fertilizes enhances photosynthesis and plant water use efficiency, promoting additional vegetation growth which has been detected at the global scale over recent decades [1]. The extent of this CO_2 fertilization varies widely between species and hence can alter their ecological competitiveness [2], and can also reduce the nutrient content of food crops [3]. Elevated atmospheric CO_2 also results in CO_2 uptake by ocean waters, leading to reduced pH. Such ocean acidification impacts marine calcifying organisms such as corals and some species of zooplankton, reducing the production of biogenic calcium carbonate [4].

Risk assessments of the impacts of anthropogenic climate change on land and marine ecosystems and crop production therefore need to consider these additional impacts of rising CO_2 concentration in addition to the effects of radiatively-forced climate change. The strength of CO_2 fertilization as an offset to the effects of radiatively-forced climate change is a first-order uncertainty in projections of future impacts of climate change on global land ecosystems [5] and the role of elevated CO_2 in reducing plant transpiration is also identified as a major source of discrepancy between different projections of hydrological impacts of climate change [6]. Global economic models which project less severe impacts of climate change assume a strong influence of CO_2 fertilization on crop yields which results in an economic benefit of climate change on global-scale agriculture [7], in contrast to models that do not account for this process. A good understanding of the uncertainties in this impact are therefore crucial for assessing confidence in projections of climate change impacts on biodiversity, food supplies and economic wellbeing.

In particular, with the current major focus on the impacts of climate change at specific global warming levels (GWLs), particularly 1.5°C and 2°C above pre-industrial, it is important to consider how the impacts of these levels of climate change may be exacerbated or ameliorated by direct

CO_2 effects. Much effort is underway in studying and understanding the response of ecosystems to elevated CO_2 in controlled experiments, with techniques such as Free Air CO_2 Enrichment [8], and these studies are of high importance. However, the response to a given level of CO_2 is not the only uncertainty to consider when assessing the impacts of a given level of global warming. The CO_2 concentration that would accompany such a level of warming is itself a key factor.

Impacts studies invariably use one of three approaches: i) apply the CO_2 concentration that accompanies the model or models being used to simulate the climate as an input to the impacts model; (ii) ignore direct CO_2 impacts on the grounds that they are not well-quantified, or; (iii) perform pairs of simulations with and without CO_2 direct effects, again using the CO_2 concentration that accompanies the driving climate model. We propose that these approaches may be inadequate for covering the range of possibilities for direct CO_2 effects alongside the effects of climate change, and hence give too limited a view of the range and likelihood of outcomes.

There are two factors which determine the CO_2 concentration that could accompany a particular GWL. One concerns the nature of the forcing of the climate system, and the other concerns the response to this forcing.

The relative strength of radiative and biological effects of CO_2 will also depend on the response of the climate system to the net radiative forcing. The response of global temperatures to a given radiative forcing is routinely quantified in terms of both/either equilibrium climate sensitivity (ECS) and/or transient climate response (TCR). ECS is defined as the long-term increase in global mean temperatures once equilibrium has been reached following an instantaneous doubling of the CO_2 concentration relative to pre-industrial, and TCR is the instantaneous level of global warming at the time of passing doubled CO_2 in a scenario of ongoing CO_2 rise, often prescribed at a rate of 1% per year. If ECS or TCR are large, warming of 1.5°C and 2°C will be reached at relatively low levels of CO_2, so the direct impacts on photosynthesis, plant water use efficiency and ocean acidification will be relatively small. In contrast, these direct CO_2 effects could be more substantial at 1.5°C or 2°C if ECS and TCR are small.

Uncertainties in ECS and TCR have been systematically studied and quantified, and probability distribution functions (PDFs) providing estimates of their 'likely ranges' have long been a key outcome of the assessment reports of the Intergovernmental Panel on Climate Change. However, to date there has been no comparable systematic probabilistic assessment of implications of these uncertainties for the relative strength of the radiative and biological impacts of CO_2. To allow for such a systematic approach, we invert the PDF of TCR estimated from observational constraints in the IPCC 5th Assessment Report (AR5) [9], to create PDFs of CO_2 concentrations that would occur at global warming of 1.5C and 2C (Figure 1), if CO_2 were the only agent of radiative forcing (see Supplementary Information). The resulting observationally-constrained median estimates of CO_2 concentrations at 1.5°C and 2°C are 486.1ppm and 584.2 ppm respectively. The 5% to 95% ranges are 412.6 to 728.5ppm for 1.5°C, and 469.5 to 1001.9ppm for 2°C.

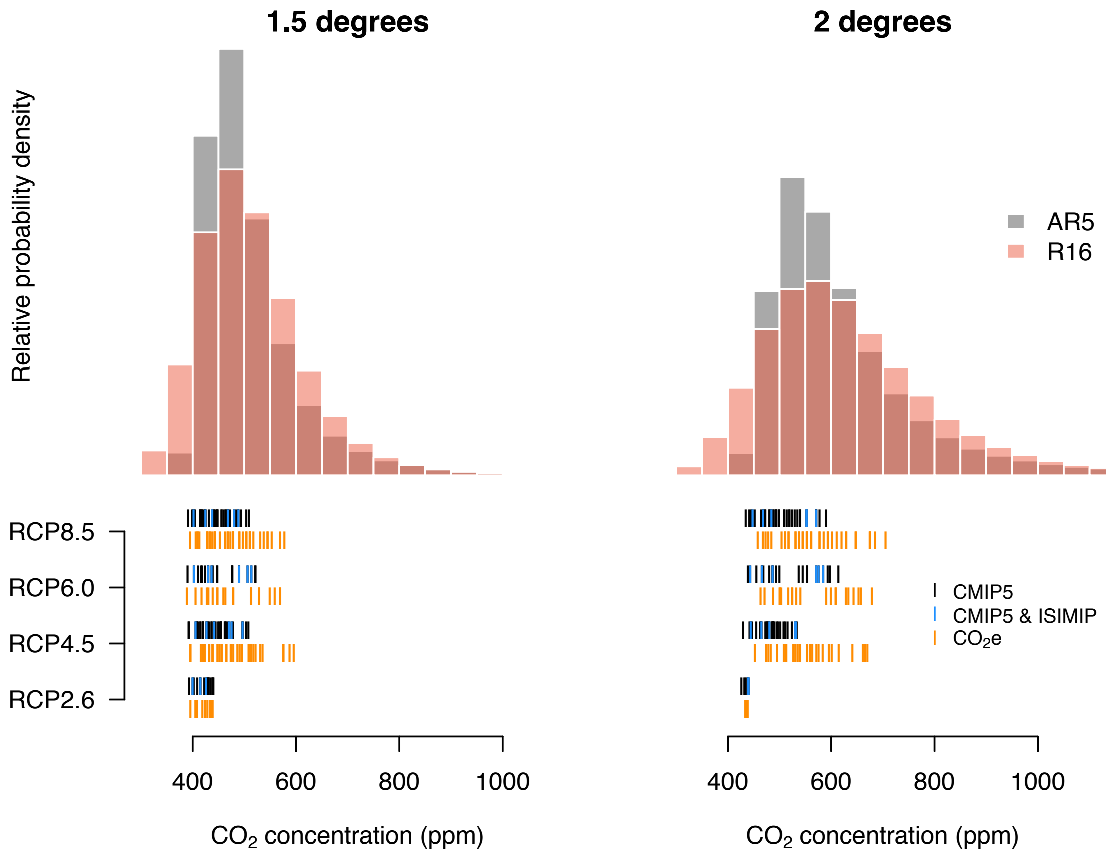

Figure 1. Probability distribution functions (PDFs) of CO_2 concentrations accompanying global warming of 1.5°C (left) and 2°C (right), based on observationally-based PDFs of transient climate response from the IPCC 5th Assessment Report (AR5) [9] and a reconciliation of observationally-based and model estimates (R16) [10]. Below the PDFs are shown the CO_2 concentrations at the time of passing 1.5°C and 2°C in the CMIP5 multi-model ensemble of climate simulations [10] for each of the Representative Concentration Pathways (RCPs) [11]. Blue lines show a subset of the CMIP5 models used for a widely-used set of climate change impacts projections from the Inter-Sectoral Impacts Model Intercomparison Project (ISIMIP) [12], and black lines show the remaining CMIP5 models. Also shown, in orange, are the equivalent CO_2 concentrations for the total effective radiative forcing from all agents in the CMP5 models for each RCP.

We applied the same approach to more recent PDF of TCR which reconciles observational constraints and model estimates [13], hereafter referred to as R16. From this, median estimates of CO_2 at 1.5°C and 2°C are 499.7 ppm and 606.1 ppm, with 5% to 95% ranges of 376.6 to 710 ppm for 1.5C and 415.6 to 969.8 ppm for 2°C. Notably, the latter range is larger than the difference between the CO_2 concentrations projected for 2100 by RCP8.5 and RCP2.6.

The median estimates based on R16 imply a slightly higher CO_2 concentration at either GWL compared to the AR5-based estimates, but in contrast the 5% to 95% ranges imply lower concentration from R16 compared to AR5. We note that the 5^{th} percentile of 376.6ppm for 1.5°C from R16 is lower than the estimated 2017 value of 406.75 ± 0.61 ppm.

The CO_2 concentrations at the time of passing 1.5°C and 2°C in the CMIP5 multi-model ensemble of climate projections span much smaller ranges than the above PDFs (Figure 1), and are towards the lower end of the distributions. For example, in the commonly-used scenario RCP8.5, the CO_2 concentrations at 2C span the 8^{th} to 46^{th} percentiles of the R16-based distribution. One reason for this is other sources of radiative forcing. While CO_2 provides the largest radiative forcing at present and in commonly-used future scenarios, other greenhouse gases provide a substantial additional forcing [14], and other forcing agents such as aerosols, solar irradiance and surface albedo change also exert either positive or negative radiative forcings.

At any GWL, therefore, the relative strength of the radiative and biological effects of CO_2 will depend on the proportion of the net positive radiative forcing provided by CO_2. An indication of this can be obtained by comparing the total effective radiative forcing of all forcing agents with that of CO_2 alone.

In the RCPs, the net effect of all non-CO_2 forcings is to increase the total effective radiative forcing (ERF) at any given level of actual CO_2 concentration (Figure 2) [14]. This means that at either GWL, the direct effects of CO_2 would be smaller than would be expected if CO_2 were the only forcing.

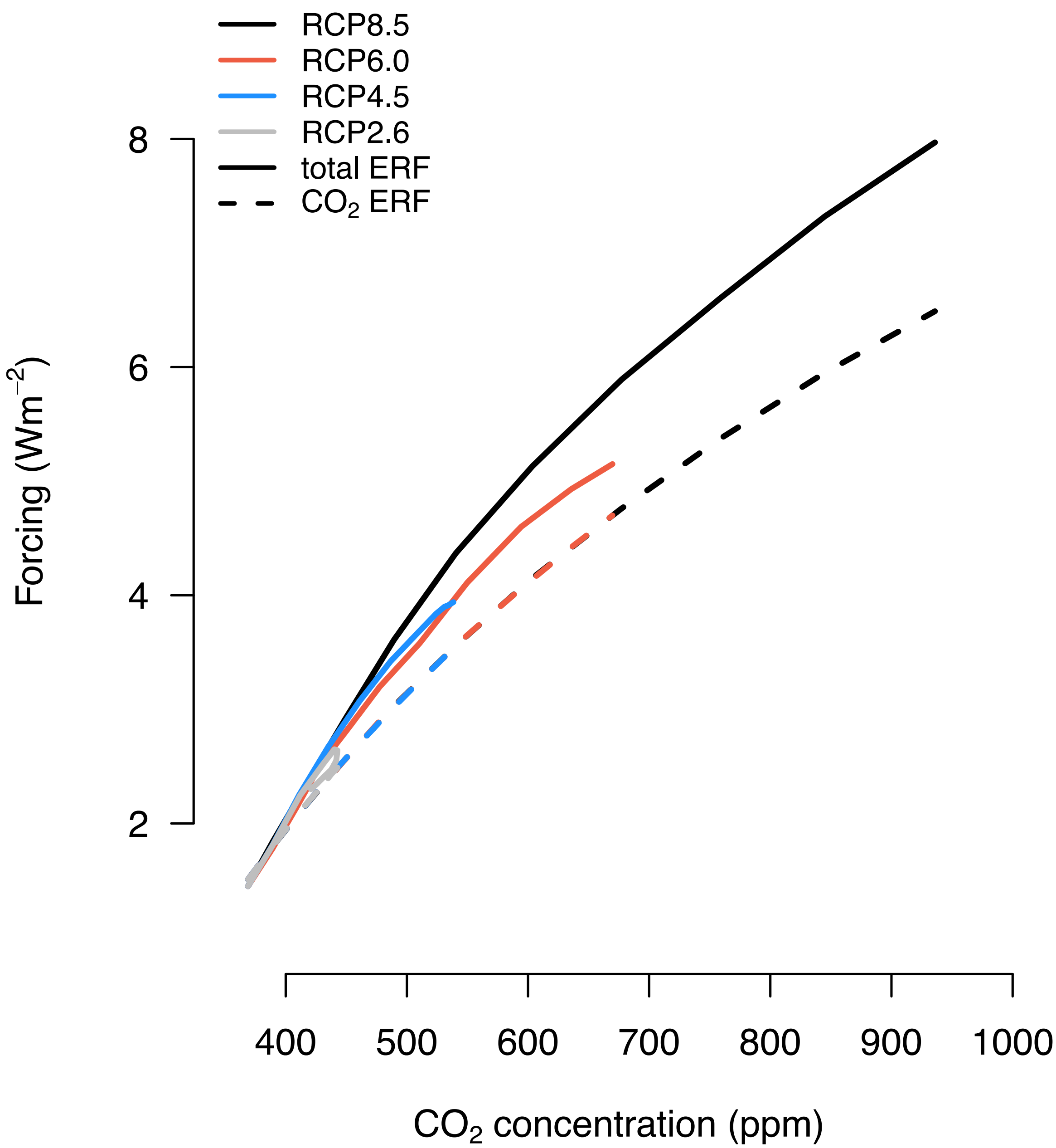

Figure 2. Radiative forcing vs. CO_2 concentration for CO_2 alone (dashed lines) and all forcings (solid lines), for all RCPs.

Hence, our PDFs should actually be considered as showing the probabilities of the equivalent CO_2 concentrations (CO_2eq), ie: the CO_2 concentrations that would give the same effective radiative forcing if CO_2 were the only forcing agent. The PDFs of actual CO_2 concentration for GWLs would be shifted to lower CO_2 concentrations when other forcings are in play.

An indication of the importance of this can be given by comparing the distributions of CO_2eq with those of actual CO_2 for the CMIP5 models (Figure 1). The range of CO_2eq at 2°C from RCP8.5 spans the 11^{th} to 73^{rd} percentile of the R16-based distribution, so covers a wider range than the actual CO_2 range. Nevertheless, the upper 27% of the R16-based distribution is not covered by the CMIP5 ensemble, so the ensemble does not account for the higher values of CO_2 that could accompany 2°C global warming. The range of possible strengths of direct effects of CO_2 on ocean acidification, photosynthesis and plant water use efficiency at 2°C (and also 1.5°C) could therefore extend to higher strengths than accounted for in studies which use the CMIP5 multi-model ensemble.

Comparison of CO_2 and CO_2eq concentration ranges within and across RCPs reveals other important points. In RCP2.6, the ranges of both quantities are constrained at the lower end of the AR5 and R16 distributions, because not all members of the ensemble reach these GWLs – those with lower TCR, which would have had higher CO_2 values for a given GWL, do not reach either 2°C alone or 1.5°C as well. In the other RCPs, the upper end of the CO_2eq range extends to higher concentrations for the higher-forcing RCPs, at least for 2°C. This reflects the lag in the temperature response to forcing. However, it should be noted that not all models were used with all RCPs, which may explain why this pattern is not seen at 1.5°C.

Moreover, the differences between RCPs are slightly different for the actual CO_2 – for example, in contrast to CO_2eq, for 2°C the upper end of the range for RCP8.5 Is lower than that for RCP6.0. This reflects the different mixes of greenhouse gases in the different RCPs – RCP8.5 has a relatively high proportion of non-CO_2 GHGs.

This analysis provides important context for studies assessing the impacts of climate change at 1.5°C and 2°C global warming using the CMIP5 multi-model ensemble or subsets of this. For CO_2 at 2°C, the 5-95% range based on models and observations is larger than the difference between RCP8.5 and RCP2.6 projections of CO_2 at 2100. Even when non-CO_2 forcing agents are accounted for, the full range of possible CO_2 concentrations for each GWL is not accounted for in the models alone, especially higher concentrations. The range of relative strengths of direct CO_2 effects on photosynthesis, plant water use efficiency and ocean acidification are not fully accounted for, even when the role of non-CO_2 forcings are taken into account. Moreover, the ensemble projections for different RCPs cover differ ranges of CO_2 at each GWL, due to the number of models either reaching those GWLs or being included in the ensemble at all, and the lag in temperature response. If the full set of effects of CO_2 on land and marine ecosystems and food production at 1.5°C and 2°C are to be assessed, for example in the IPCC Special Report on 1.5°C currently in preparation, a wider range of CO_2 concentrations for each level of global warming should be considered.

References

[1] Z. Zhu *et al.*, Greening of the Earth and its drivers. *Nature Climate change*, advance online publication (2016), doi:10.1038/nclimate3004.

[2] Phillips, O.L., Vasquez Martinez, R., Arroyo, L., Baker, T.R., Killeen, T., Lewis, S.L., Malhi, Y., Monteagudo Mendoza, A., Neill, D., Nunez Vargas, P., Alexiades, M., Ceron, C., Di Fiore, A., Erwin, T., Jardim, A., Palacios, W., Saldias, M. & Vincenti, B. (2002) Increasing dominance of large lianas in Amazonian forests. *Nature*, **418**, 770–774

[3] Myers, S. S., et al. (2014), Increasing CO_2 threatens human nutrition, *Nature*, **510**, 139–142

[4] Hoegh-Guldberg, O., P. J. Mumby, A. J. Hooten, R. S. Steneck, P. Greenfield, E. Gomez, C. D. Harvell, P. F. Sale, A. J. Edwards, K. Caldeira, N. Knowlton, C. M. Eakin, R. Iglesias-Prieto, N. Muthiga, R. H. Bradbury, A. Dubi, and M. E. Hatziolos. 2007. Coral reefs under rapid climate change and ocean acidification. *Science* 318:1737–1742

[5] Cox, P. et al. Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability. Nature 494, 341–344 (2013).

[6] R. A. Betts *et al.*, Climate and land use change impacts on global terrestrial ecosystems and river flows in the HadGEM2-ES Earth system model using the representative concentration pathways. *Biogeosciences* **12**, 1317 (2015)

[7] R.S.J. Tol, On the optimal control of carbon dioxide emissions: an application of FUND, Environ Model. Assess. 2 (1997) 151–163

[8] E. A. Ainsworth, S. P. Long, What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. *New Phytol*. 165, 351–372 (2005).

[9] Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari and X. Zhang, 2013: Detection and Attribution of Climate Change: from Global to Regional. In: Climate Change 2013: *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[10] Knutti, R. and Sedláček, J. (2013) Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change* 3, 369–373

[11] van Vuuren DP, Edmonds J, Kainuma MLT, Riahi K, Thomson A, Matsui T, Hurtt G, Lamarque J-F, Meinshausen M, Smith S, Grainer C, Rose S, Hibbard KA, Nakicenovic N, Krey V, Kram T (2011a). Representative concentration pathways: An overview. Climatic Change. doi:10.1007/s10584-011-0148-z

[12] Schleussner, C. F., T. K. Lissner, E. M. Fischer, J. Wohland, M. Perrette, A. Golly, J. Rogelj, K. Childers, J. Schewe, K. Frieler, M. Mengel, W. Hare and M. Schaeffer (2016). Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 degrees C and 2 degrees C. Earth System Dynamics 7(2): 327-351. doi:10.5194/esd-7-327-2016[13] M. Richardson, K. Cowtan, E. Hawkins, M. B. Stolpe, Reconciled climate response estimates from climate models and the energy budget of Earth. *Nat. Clim. Chang.* 6, 931–935 (2016). doi:10.1038/nclimate3066

[14] IPCC, 2013: Annex II: Climate System Scenario Tables [Prather, M., G. Flato, P. Friedlingstein, C. Jones, J.-F. Lamarque, H. Liao and P. Rasch (eds.)]. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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