Response to reviewer Ian Enting on "Time-scale dependence of airborne fraction and underlying climate-carbon cycle feedbacks for weak perturbations in CMIP5 models"

Guilherme L. Torres Mendonça[1,2,3], Christian H. Reick[2], and Julia Pongratz[2,4]

[1]International Max Planck Research School on Earth System Modelling, Hamburg, Germany
[2]Max Planck Institute for Meteorology, Hamburg, Germany
[3]Universidade de São Paulo, São Paulo, Brazil
[4]Ludwig-Maxmillians-Universität München, Munich, Germany

Correspondence: Guilherme L. Torres Mendonça (guilherme.mendonca@mpimet.mpg.de)

We thank the reviewer for his careful comments. We reproduce the reviewer's remarks in bold, while setting our replies in italic.

This paper (hereafter denoted TM23) is suitable for publication. The authors may wish to consider the following comments. References cited below refer to those listed in the bibliography of TM23 or additional references listed below. Some of my points are, for convenience, illustrated by citing my own publications. This not in itself a suggestion that these papers should be cited, nor that they are the most appropriate references.

OVERVIEW

This paper considers feedbacks in the carbon cycle, expressing the gain 1/(1-f) from feedbacks in terms of the total feedback, f. A generic result for linear feedbacks is that the combined loop feedback from multiple feedbacks is the sum of the feedbacks so that linear feedback contributions can be partitioned or aggregated without restriction. The analysis is in terms of the alpha, beta, gamma description (Friedlingstein et al, 2003), where carbon cycle feedback, f, is partitioned into a concentration feedback, beta, and a radiative feedback alpha*gamma. Each of these is often further partitioned into Land and Ocean contributions (and may be further partitioned, cf Enting and Clisby 2019 appendix). The description by (Friedlingstein et al, 2003) is history-dependent. A scenario-independent form requires generalising each of alpha, beta, gamma to functions which can be combined by convolutions over time. These combinations take a simpler form as Laplace transforms. (In this regard, as in the study by Enting and Clisby (2019), Laplace transform expressions can be regarded as a compact expression for calculations that are actually performed in the time domain, analogous to the way that vector expressions for electromagnetic fields define expressions that are ultimately calculated using specific components). The paper uses results from the CMIP intercomparison to estimate the generalised alpha, beta, gamma (in each case partitioned into Land and Ocean) and combines them into a generalised airborne fraction.

We fully agree.

COMMENTS

Line 71. This notes characterising climate change in terms of a single global temperature change. This is the basis for "pattern scaling" which is often used in impact assessments (Mitchell 2003, which should be cited). However this is not what is done later (see comment on eqn 4,5).

We thank the reviewer for this literature hint. Indeed, the study by Timothy Mitchell is a careful analysis of the extent to which global temperature alone is characterizing climate. Nevertheless, the study refers only to climate physics (temperature, precipitation), while Friedlingstein et al. base their alpha-beta-gamma formalism on the even wider hypothesis that also in relation to the global carbon cycle it suffices to characterize climate by global temperature alone. This is indeed nontrivial because one might think that for the estimation of feedbacks involving the global carbon cycle a separate characterization of the water and nutrient resources of plants would be needed – but apparently at a global scale this seems not necessary. Interestingly, Mitchell also corroborates the linearity of the response and finds in particular a dependence of the linear relationship on the rate of temperature rise. This can be interpreted as dependence on the internal memory of the system, which once more indicates the need for a more general formulation of the response in terms of linear response functions. In the revised paper we will refer to the Mitchell paper.

At some point between lines 155 and 175, it could be worth combining all the terms into one equation and write down the original alpha, beta, gamma formalism for comparison Delta C [1+ beta +alpha * gamma] = integrated emissions.

Thank you for this suggestion. We also think that we could make the relation to the original alpha-beta-gamma formalism more obvious. We will do so in relation to Eqs. (7)-(10), which have close analogues in the original formalism.

Equations 2 and 3.

These have several issues created by working with separate land and ocean temperatures:

*** it contradicts the initial statement about using a single global temperature**

*** the numbers are going to differ from other work that has a single global alpha and absorbs the land-ocean differences into gamma**

Indeed we use separate values for ocean and land instead of a single global temperature. We feel that in this way processes are more adequately represented, because e.g. ocean carbon uptake depends on ocean temperatures alone, and not on global temperature that involves an admixture of land temperatures. Still, comparison of results with previous studies is possible by means of straightforward transformations where in addition to the sensitivities only the fractions of global area occupied by land and ocean are needed (see Appendix A below). We will add this to the revised text.

*** working with a single alpha simplifies the inclusion of other radiative forcing (CH4, volcanoes etc) which would be needed for possible future work. Even within the context of the present work, including these terms helps make the important point that the carbon-climate coupling amplifies these forcings by the same factor that applies to amplification of the CO2 response determined by the beta term (Gregory 2009, eqns 8a,b of Freidlingstein 2003).**

Maybe using a single global temperature would indeed simplify a future inclusion of other radiative forcings, but even in that case we would find it more adequate to introduce the practically more complicated but physically more meaningful formulation in terms of separate land and ocean temperatures. But to include other radiative forcings one would probably have to account for further feedbacks that complicate the situation anyway: of particular importance are the enhancement of CH_4 emissions *from permafrost regions and wetlands under enhanced temperatures, and the reduction in the lifetime of N_2O in a warmer climate induced by an accelerated Brewer-Dobson circulation (Kracher et al., 2016). This seems to be a whole project in itself that is beyond the scope of the present work.*

The results shown in panels c and f of figure 2, suggest that for most, but not all, models the results are consistent with the assumptions of pattern scaling, with the land response about twice the ocean response on all timescales. It would be interesting to analyse this in more detail than what can be gleaned from low resolution plots– eg a plot of the ratios of the two responses as a function of timescale.

Yes, ocean and land alpha sensitivities are closely linked: it is well known that by various mechanisms land temperatures rise faster than ocean temperatures by a factor of about 1.4-1.7 (Lee et al., 2021, section 4.5.1.1.1, and Fig. 1 below for CMIP5 and CMIP6 simulation data, and Eyring et al., 2021, Fig. 3.2b for observation data). Looking at the definition of the land and ocean alpha generalized sensitivities one sees that they must differ exactly by this factor. We will add a remark on this in the revised paper.

Eqn 6. Introducing CO2 concentrations (rather than CO2 content as originally done by Friedlingstein et al 2003) (and thus introducing the factor k) seems an unnecessary complication which hinders comparisons with other work. (Of course k is given by the mass of the atmosphere scaled by ratio of molecular weights).

Indeed the usage of k could be omitted by absorbing it in the definition of the sensitivities. But physical and biogeochemical carbon processes develop via CO2 concentration and not by atmospheric carbon mass. Therefore we prefer to stick to the physically more adequate distinction between CO2 concentration and atmospheric carbon mass in the definition of the involved quantities, even though the equations look mathematically less elegant. Moreover, we do not see why it should hinder comparison with previous studies: although Friedlingstein et al. (2003) initially worked with atmospheric carbon content when introducing their methodology, the units of their calculated sensitivities in this and subsequent publications (e.g. Friedlingstein et al., 2006; Arora et al., 2013; Canadell et al., 2021) are actually in agreement with our definition: beta is given in GtC/ppmv, gamma in GtC/K, and alpha in K/ppmv (Friedlingstein et al., 2003, Table 1).

Line 188 seems poor wording of the situation. You can work in the time domain (and in many cases do so), but you have to incorporate history and not just single times (which is what Oeschger and Heimann pointed out in 1983).

Thanks for the comment, indeed we could have been clearer – we meant that Laplace transforms make the whole formulation simpler, but the interpretation of resulting quantities harder. We will reformulate the sentence accordingly.

Circa line 295. At around this point it could be helpful to have one or two sentences summarising the key aspects of the RFI technique (and maybe a longer summary in the relevant appendix).

We agree.

Eqn 15, (and associated definitions). What this means is that chi is the CO2 impulse response function that is widely used in the definition of GWP and was the subject of an extensive intercomparisons by Joos et al (2013). This should be noted and Joos et al cited at this point.

Thank you for reminding us, we will follow your advice.

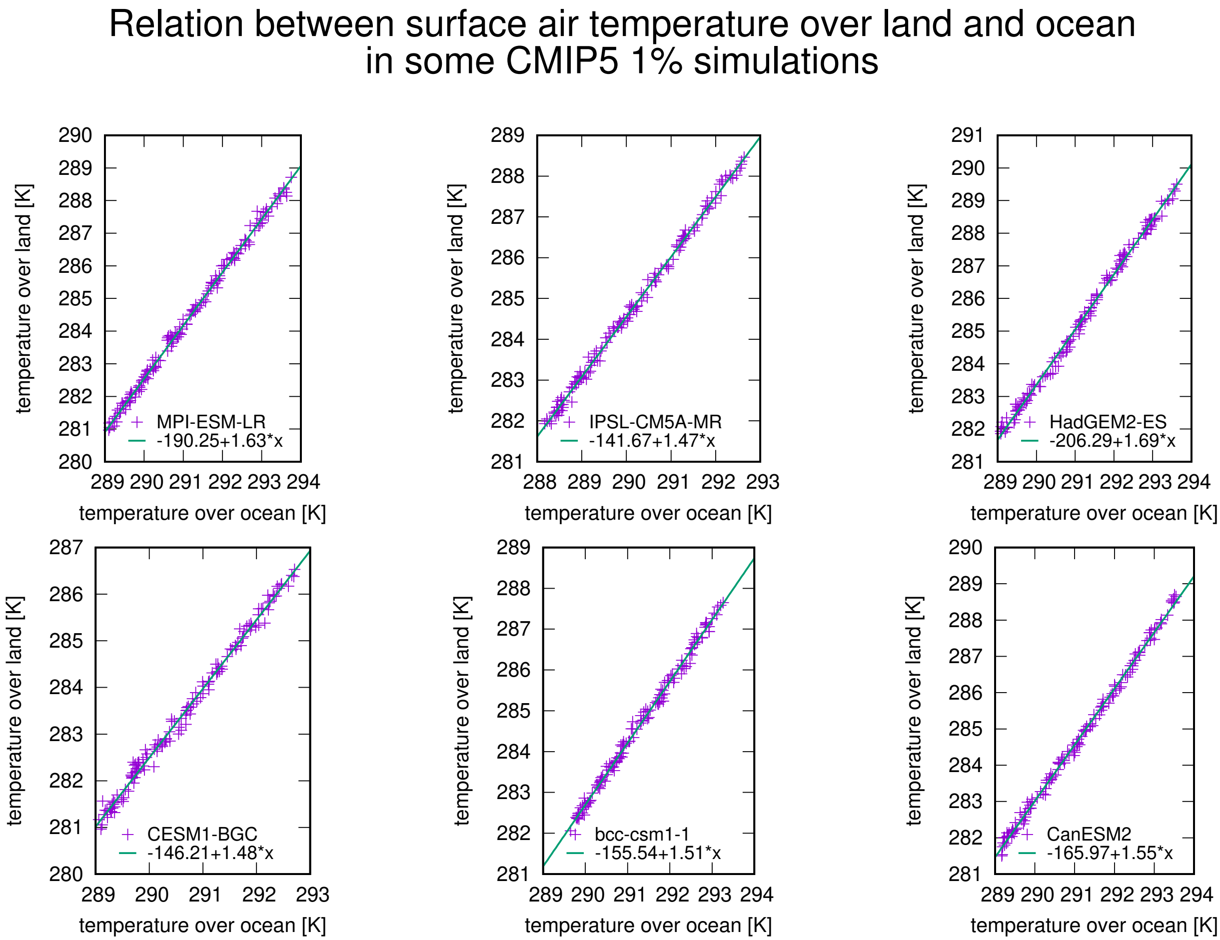

Figure 1. Annual mean land temperature as function of annual mean ocean temperature for various CMIP5 1% simulations. From the linear fits it is seen that the relation is rather linear and that land temperature rise is about a factor 1.5-1.7 times larger than ocean temperature rise. Noting that $\widetilde{\chi}^{(\mathrm{O})}_\alpha(p) = \Delta\widetilde{T}_{\mathrm{O}}(p)/\Delta\widetilde{c}(p)$ and $\widetilde{\chi}^{(\mathrm{L})}_\alpha(p) = \Delta\widetilde{T}_{\mathrm{L}}(p)/\Delta\widetilde{c}(p)$ these two generalized sensitivities differ by that factor.

Eqn 16, goes back at least to Enting (1990), as a Laplace transform. As a relation for growth at single time-scale it is implicit in the results of Oeschger et al 1980.

We will note this in the revised paper.

The overall response for CO2 is given by 1/p/(1+beta(p) +alpha(p) * gamma(p)) Enting (2009) suggested that models could give similar fits to 20th century changes (p approx 0.02) whether or not the gamma feedback was included, simply by changing beta (specific examples were given). While the CMIP data presented here do not give details of how the various models were calibrated, the results suggest that a similar inter-model flexibility appears here. Panels d and e of figure 2 suggest that on timescales of about 50 years, the models with smaller positive beta have smaller negative gamma.

This interpretation is supported by figure 6a, where the difference between the true AF spread and that from eqn (22) (which assumes that the spreads are independent), suggests that the spreads of beta and gamma are not independent.

Following Arora et al. (2013), we explain in the paper the joint occurrence of a smaller positive beta together with a smaller negative gamma found for NorESM1-ME and CESM1-BGC by the presence of nitrogen limitation in these models: ".. the coupling between nitrogen and carbon cycle weakens not only the biogeochemical but also the radiative response, because temperature-driven nitrogen remineralization enhances plant productivity, which counteracts the parallel carbon loss from the enhanced soil respiration in the warmer climate (see also Melillo et al., 2002; Thornton et al., 2009)" (lines 463-467). But if we understand it correctly, the reviewer suggests that there may be in general some sort of compensation effect between beta and gamma in each model so that models with large beta have also large gamma and vice-versa, which implies that a large model spread in beta would then correspond to a large spread in gamma. While this may indeed affect the accuracy of approximation (22) of the overall spread in airborne fraction by a sum of individual spreads from the contributing components – which depends also on smallness of these individual spreads –, we feel that this rough approximation is sufficient to convey our main message from this analysis, namely that the land biogeochemical feedback is dominating the spread in the airborne fraction, which is further supported by Fig 6b.

* **POTENTIAL FUTURE EXTENSIONS**

An indication of the quality of the work is the extent that it suggests potential future studies. Some possibilities (realising that such work may already be in progress) are: 1: Calculate the airborne fraction, dC/dt/E, as a function of time for various cases of RCP-SSP (Representative Concentration Profiles - Shared Socio-economic Pathways). Non-linearity will limit the accuracy, but the least affected will be the ones that are of most interest as likely to have the greatest change from near-constant airborne fraction. 2: Using the formalism to analyse the CMIP historical runs. These two extensions would require extending eqn (4,5) to include non-CO2 radiative forcing.

Thank you for these suggestions and reminding us that our current work is limited to idealized simulations where the only changing anthropogenic greenhouse gas is CO2 – we will add a note on this limitation in the discussion section of the paper. Indeed, application to historical simulations and RCP-SSPs would require an extension of the generalized alpha-beta-gamma formalism to include non-CO2 greenhouse gases. As pointed out above by the reviewer, one could follow here the works by Gregory et al. (2009) and Friedlingstein et al. (2003) to add those greenhouse gases as additional external forcing. But the real challenge would in our opinion be the inclusion of landuse change because in contrast to well-mixed greenhouse gases such as CO2 and methane, whose representation needs only global values, one had in the case of landuse change to account not only for its emissions, but also for its regional patterns that are different in different scenarios; these changes involve changes not only in regional surface properties (albedo, roughness), but also in the response characteristics of the regional biosphere whereby internal time scales are affected.

3: A more speculative possibility is the extension to response functions describing radiocarbon (C14). As noted by Enting and Clisby (2021) and Enting (2022), expressions for the responses to exponential forcing were described by Oeschger et al (1980). Oeschger et al also described corresponding responses for C14 perturbations and how these

relate to total carbon (see also Enting 1990). Since such responses to exponential forcing are the Laplace transforms of the impulse response functions (eg see eqn 2.11 of Enting 2022), the Oeschger et al results suggest the possibility of defining generalised sensitivities for C14. This would be of most interest in the analysis of historical trends.

Thank you for this interesting suggestion.

MINOR POINTS

Line 182: the PgC/ppm CO_2 should be in upright font, since these are not symbols representing mathematical variables.

Will be changed.

Similarly, throughout, the labels A, O, L should be in upright font.

Will be changed.

In the figure captions, it may be helpful to the reader if the symbol (and maybe number of defining equation) was included after the text description.

We will consider this suggestion to improve the intelligibility.

Note that actual (as opposed to CMIP model) human CO2 emissions include cement production and not just fuel use and also land use change and forestry.

Agreed. We will revise the text to clarify this.

With best regards,

Guilherme L. Torres Mendonça, Christian H. Reick and Julia Pongratz

Appendix A: Sensitivities transformations

In this appendix we show how from α and γ sensitivities defined using separate land and ocean temperatures one can compute their analogues defined by means of a single global temperature. Global temperature in a model is obtained by

$$\Delta T = \frac{\sum_i A_i \Delta T_i}{\sum_i A_i} = \frac{\sum_{i\in L} A_i \Delta T_i + \sum_{i\in O} A_i \Delta T_i}{\sum_{i\in L} A_i + \sum_{i\in O} A_i} = \frac{\sum_{i\in L} A_i \Delta T_i}{\sum_{i\in L} A_i}\frac{\sum_{i\in L} A_i}{\sum_i A_i} + \frac{\sum_{i\in O} A_i \Delta T_i}{\sum_{i\in O} A_i}\frac{\sum_{i\in O} A_i}{\sum_i A_i} =: \Delta T_L F_L + \Delta T_O F_O, \tag{A1}$$

where A_i and ΔT_i are the area and temperature of grid box i, $i \in L$ and $i \in O$ indicate sum over grid boxes on land/ocean, ΔT_L and ΔT_O are land/ocean temperatures, and F_L and F_O are the fractions of global area occupied by land and ocean.

Using a single global temperature, α is defined by

$$\Delta T = \alpha \Delta CO2. \tag{A2}$$

Using separate land and ocean temperatures one defines

$$\Delta T_L = \alpha_L \Delta CO2, \tag{A3}$$

$$\Delta T_O = \alpha_O \Delta CO2. \tag{A4}$$

Plugging (A1), (A3), (A4) into (A2) gives

$$\alpha = \alpha_L F_L + \alpha_O F_O. \tag{A5}$$

Taking a single global temperature, γ is defined by

$$\Delta C_X^{rad} = \gamma_X \Delta T, \tag{A6}$$

where X denotes the carbon response over land (L) or ocean (O).

Using separate land/ocean temperatures, γ can be defined by

$$\Delta C_X^{rad} = \gamma_X^* \Delta T_X. \tag{A7}$$

Inserting (A3)/(A4) and (A1) into (A7) gives

$$\gamma_X = \frac{\gamma_X^* \alpha_X}{F_L \alpha_L + F_O \alpha_O}. \tag{A8}$$

Since the Laplace-transformed formulation of the generalized framework is completely analogous to that of the original α-β-γ framework, (A5) and (A8) extend straightforwardly to the respective generalized sensitivities:

$$\widetilde{\chi}_\alpha = \widetilde{\chi}_\alpha^{(L)} F_L + \widetilde{\chi}_\alpha^{(O)} F_O, \tag{A9}$$

$$\widetilde{\chi}_\gamma^{(X)} = \frac{\widetilde{\chi}_\gamma^{(X,*)} \widetilde{\chi}_\alpha^{(X)}}{F_L \widetilde{\chi}_\alpha^{(L)} + F_O \widetilde{\chi}_\alpha^{(O)}}. \tag{A10}$$

References

Arora, V. K., Boer, G. J., Friedlingstein, P., Eby, M., Jones, C. D., Christian, J. R., Bonan, G., Bopp, L., Brovkin, V., Cadule, P., et al.: Carbon–concentration and carbon–climate feedbacks in CMIP5 Earth system models, Journal of Climate, 26, 5289–5314, 2013.

Canadell, J., Monteiro, P., Costa, M., Cotrim da Cunha, L., Cox, P., Eliseev, A., Henson, S., Ishii, M., Jaccard, S., Koven, C., Lohila, A., Patra, P., Piao, S., Rogelj, J., Syampungani, S., Zaehle, S., and Zickfeld, K.: Global Carbon and other Biogeochemical Cycles and Feedbacks, in: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 673—-816, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/9781009157896.007, 2021.

Eyring, V., Gillett, N., Achuta Rao, K., Barimalala, R., Barreiro Parrillo, M., Bellouin, N., Cassou, C., Durack, P., Kosaka, Y., McGregor, S., Min, S., Morgenstern, O., and Sun, Y.: Human Influence on the Climate System, p. 423–552, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/9781009157896.005, 2021.

Friedlingstein, P., Dufresne, J.-L., Cox, P., and Rayner, P.: How positive is the feedback between climate change and the carbon cycle?, Tellus B, 55, 692–700, 2003.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., et al.: Climate–carbon cycle feedback analysis: results from the C4MIP model intercomparison, Journal of climate, 19, 3337–3353, 2006.

Gregory, J. M., Jones, C., Cadule, P., and Friedlingstein, P.: Quantifying carbon cycle feedbacks, Journal of Climate, 22, 5232–5250, 2009.

Kracher, D., Reick, C. H., Manzini, E., Schultz, M. G., and Stein, O.: Climate change reduces warming potential of nitrous oxide by an enhanced Brewer-Dobson circulation, Geophysical research letters, 43, 5851–5859, 2016.

Lee, J.-Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J., Engelbrecht, F., Fischer, E., Fyfe, J., Jones, C., Maycock, A., Mutemi, J., Ndiaye, O., Panickal, S., and Zhou, T.: Future Global Climate: Scenario-Based Projections and Near-Term Information, p. 553–672, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/9781009157896.006, 2021.