Trend analysis of the airborne fraction and sink rate of anthropogenically released CO_2

Reply to referee report number 2

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1 Introduction

We thank the referee for the insightful comments and the supportive review. We will revise the paper in response to your comments, and we think that the paper will improve substantially as a result.

1.1 Comment 1

1.1.1 Referee comment

Firstly in the introduction the authors state: " a key question is whether the airborne fraction is increasing " but they do not say why. It would be good if they would add why this is so.

1.1.2 Answer

We will add some text in the paper explaining the importance and add some references to the literature such as Gloor et al. (2010), Raupach et al. (2014), Bacastow and Keeling (1979), Schimel et al. (2001).

1.2 Comment 2

1.2.1 Referee comment

Sentence just above - 24% and 31% - I would add a reference here - and possibly uncertainties - just for completeness.

1.2.2 Answer

We will add a reference to Le Quéré et al (2018). (We calculated these numbers from the GCB data.) Similar numbers have been reported elsewhere, e.g., Ballantyne et al. (2012).

1.3 Comment 3

1.3.1 Referee comment

When applying the Kalman filter the authors will need to initialize it. I may have missed it but if not it would be good if the authors would add this in the main text.

1.3.2 Answer

We use a diffuse initialisation of the Kalman Filter as outlined in Chapter 5 of Durbin and Koopman (2012). We will make this clear in the main text in Section 2.

1.4 Comment 3

1.4.1 Referee comment

Finally my comment - while all the results are sound - what the paper does not explain is the true reason for the decrease in sink rates - and thus it is not clear whether a decreasing sink rate is alarming or not. It would be nice if the authors could comment on that - but it is not a necessary condition.

Some earlier papers actually give a clue what the real reason may be.

1.4.2 Answer

Thank you for pointing this out. Raupach (2013) argue that a necessary condition for a constant sink rate is that emissions (E_t) grow exponentially. Hence, a decreasing sink rate could be the result of less-than-exponential growth in emissions.

Another explanation can be fertilisation/saturation of the sinks. To illustrate this, we focus on the land sink rate, since we find some evidence in the paper for a decreasing land sink rate. Recall that (Equation (5) in the main paper)

$$S_t^L = k_{L,t} \cdot C_t,$$

where $k_{L,t}$ is the land sink rate, S_t^L the land sink CO_2 flux, and C_t the amount of CO_2 in the atmosphere above pre-industrial levels. If the flux of CO_2 to the land sink was linear in C_t, then $k_{L,t}$ would be constant. Conversely, a decreasing $k_{L,t}$ implies that the efficiency with which the land sink absorbs CO_2 is decreasing. That is, the flux of CO_2 to the land sink is non-linear in C_t and this non-linearity is such that the efficiency is decreasing. This is in line with simulation results from climate cycle models (Friedlingstein et al., 2006).

We can illustrate how such non-linearities can arise. The precise relationship between S_t^L and C_t still alludes us but Bacastow and Keeling (1973) (p. 94) suggest that (in our notation):

$$S_t^L \approx \beta \log(1 + C_t/\mathcal{C}^0),$$

wherre $\mathcal{C}^0 = 591.30$ GtC is the amount of CO_2 in the atmosphere in pre-industrial times. Using this, we can deduce

$$\begin{aligned} S_t^L &\approx \beta \log(1 + C_t/\mathcal{C}^0) \\ &\approx \beta \frac{C_t}{\mathcal{C}^0} - \frac{1}{2}\beta \left(\frac{C_t}{\mathcal{C}^0}\right)^2. \end{aligned}$$

Now, if $\mathcal{C}^0$ is large as compared to C_t, this shows how a linear specification between S_t^L and C_t might be reasonable. However, once C_t becomes large as compared to $\mathcal{C}^0$, this shows how the the estimated sink rate can be found to be decreasing. To see this, use the above to write

$$S_t^L \approx k_{L,t} C_t,$$

where

$$k_{L,t} = \frac{\beta}{\mathcal{C}^0} - \frac{1}{2}\frac{\beta}{\mathcal{C}^0}\frac{C_t}{\mathcal{C}^0}$$

is decreasing in C_t. For example, we have $C_{1959} \approx 80$ GtC and $C_{2016} \approx 267$ GtC, resulting in $C_{1959}/\mathcal{C}^0 \approx 14\%$ and $C_{2016}/\mathcal{C}^0 \approx 45\%$.

1.4.3 Plan to change paper in response

We will add the references and the discussion to the main paper.

References

Bacastow, R. and Keeling, C. D.: Atmospheric Carbon Dioxide and radiocarbon in the natural cycle: II. Changes from A. D. 1700 to 2070 as deduced from a geochemical model, in: Carbon and the biosphere conference proceedings; Upton, New York, USA, 1973.

Bacastow, R. B. and Keeling, C. D.: Models to predict future atmospheric CO2 concentrations, in: Workshop on the global effects of carbon dioxide from fossil fuels, pp. 72–90, US Department of Energy, 1979.

Ballantyne, A. P., Alden, C. B., Miller, J. B., Tans, P. P., and White, J. W. C.: Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years, Nature, 488, 70 EP –, https://doi.org/10.1038/nature11299, 2012.

Durbin, J. and Koopman, S. J.: Time series analysis by state space methods, 38, Oxford University Press, 2012.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H. D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K.-G., Schnur, R., Strassmann, K., Weaver, A. J., Yoshikawa, C., and Zeng, N.: Climate–Carbon Cycle Feedback Analysis: Results from the C4MIP Model Intercomparison, Journal of Climate, 19, 3337–3353, https://doi.org/10.1175/JCLI3800.1, https://doi.org/10.1175/JCLI3800.1, 2006.

Gloor, M., Sarmienti, J. L., and Gruber, N.: What can be learned about carbon cycle climate feedbacks from the CO2 airborne fraction?, Atmospheric Chemistry and Physics, 10, 7739 – 7751, 2010.

Raupach, M. R.: The exponential eigenmodes of the carbon-climate sytem, and their implications for ratios of responses to forcings, Earth System Dynamics, 4, 31 – 49, 2013.

Raupach, M. R., Gloor, M., Sarmiento, J. L., Canadell, J. G., Frölicher, T. L., Gasser, T., Houghton, R. A., Le Quéré, C., and Trudinger, C. M.: The declining uptake rate of atmospheric CO_2 by land and ocean sinks, Biogeosciences, 11, 3453–3475, https://doi.org/10.5194/bg-11-3453-2014, https://www.biogeosciences.net/11/3453/2014/, 2014.

Schimel, D. S., House, J. I., Hibbard, K. A., Bousquet, P., Ciais, P., Peylin, P., Braswell, B. H., Apps, M. J., Baker, D., Bondeau, A., Canadell, J., Churkina, G., Cramer, W., Denning, A. S., Field, C. B., Friedlingstein, P., Goodale, C., Heimann, M., Houghton, R. A., Melillo, J. M., Moore III, B., Murdiyarso, D., Noble, I., Pacala, S. W., Prentice, I. C., Raupach, M. R., Rayner, P. J., Scholes, R. J., Steffen, W. L., and Wirth, C.: Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems, Nature, 414, 169 EP –, https://doi.org/10.1038/35102500, 2001.