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

Reply to referee report number 1

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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. We have also prepared a Supplementary Material file with results of further analyses. We elaborate further in our answers below.

1.1 Comment 1

1.1.1 Referee comment

First, this study comes after almost a decade-long research (Knorr (2009), Gloor et al. (2010), and Ballantyne et al. (2015)) on the detection of the changes in AF or sink efficiency and does not provide new findings (e.g., results are in the line of Raupach 2014). Yet this work merits to be acknowledged because it is the first to my knowledge to investigate this long debate on the stationarity of the AF or SF variations. Here the authors confirm that there is no non-stationnarity in AF and SF using GCP2018 data (from 1959 to 2017). Therefore, I am wondering if it is not the real outcomes of the study ? I mean once the stationarity of the variance is proved, the state space system loses some interest. The potential caveats as suggested by Gloor et al 2010 are removed and thus a simple linear model can be used to estimate trends in AF and SF. Standard statistics can be then used to detect if the signal (the trends) is larger than the noise (the variability).

1.1.2 Answer

Thank you for raising these important points. In our approach, stationarity or non-stationarity is a *finding* rather than an *assumption*. We agree with the referee that stationarity of the AF and negative linear trending in the sink rate are the main results, *ex post*. However, *a priori*, we have formulated a statistical dynamic model that allows for both, non-stationary and stationary processes for y_t and for linear as well as stochastic trending behavior. In the paper, below equation (7), we show that the solution to the difference equation (7) leads to a deterministic time trend when the iid Gaussian random variable η_t is zero (effectively when its variance is zero, that is $\sigma_\eta^2 = 0$). In this case, the time series is *trend-stationary* and the dynamic process for y_t does not exhibit a unit-root (which is the case for a *difference-stationary* time series). Since σ_η^2 is estimated using the observations for y_t, we can only conclude *ex post* that the time series is trend-stationary. Without the estimation of our state-space model, we could not have arrived at this conclusion.

Our main findings can be summarized as follows. (a) We find no statistical evidence of an increasing airborne fraction, while we do find statistical evidence for a decreasing sink rate. (b) While the findings (a) have also been reported elsewhere, most notably in Raupach et al. (2014), our statistical model does not make any a priori assumptions regarding the stationarity or non-stationary of the series and regarding deterministic or stochastic behaviour of the trends. These findings are thus *results*, as opposed to assumptions, of our approach. Furthermore, we find that we need to estimate our model on *all* the data from the global carbon budget jointly to reach the findings (a).

In the joint estimation, we take all data into account, that is the time series for AF and SR as defined on page 3 of the paper, but also the additional data obtained by assuming that the carbon budget is balanced, which we explain on page 4 of the paper. (Note that we follow the sink rate definition of Raupach (2013) and Raupach et al. (2014), with concentrations in the denominator, not emissions. The sink rate (SR) in our paper is thus not the complement of the airborne fraction.) More specifically, when analyzing the sink fraction, for example, we can opt for either one or both of the two time series:

$$k_S^{(1)} = \frac{S_t^O + S_t^L}{C_t},$$

$$k_S^{(2)} = \frac{E_t - G_t}{C_t},$$

where we exploit the carbon budget equation to obtain $k_S^{(2)}$:

$$E_t = G_t + S_t^O + S_t^L + B_t^{IM}.$$

The budget imbalance B_t^{IM} is a zero-mean noise sequence that represents the measurement errors in the other variables of the carbon budget (Le Quéré et al., 2018). In Table 3 of the main paper we report the results when we estimate our state-space model on $k_S^{(1)}$ and $k_S^{(2)}$ separately. In Table 4 and Figure 2 of the main paper we report the results when we estimate the state-space model on $k_S^{(1)}$ and $k_S^{(2)}$ jointly. It is a feature of the state-space model that it allows for alternative measurements for the same object of interest.

In the Supplemental Material file, we have included Figure 1 that presents the extracted the latent trends, T_t in equation (7), from the separate analysis, and Figure 2 that presents the extracted comment trend T_t from the joint analysis. (This is a replication of Figure 2 in the main paper.) The extraction method is based on the filtering and smoothing approach as discussed in the main paper. The various extracted trends illustrate our points as argued above: in the separate analysis, we obtain (slightly) time-varying stochastic trends, whereas in the joint analysis, we obtain a deterministic linear trend with a significantly negative slope (compare Panel B of Table 4 in the main paper). We have found similar results for the AF series, which we include in the Supplemental Material file.

Figure 1. Univariate estimation of time-varying trend for sink rate, k_S.

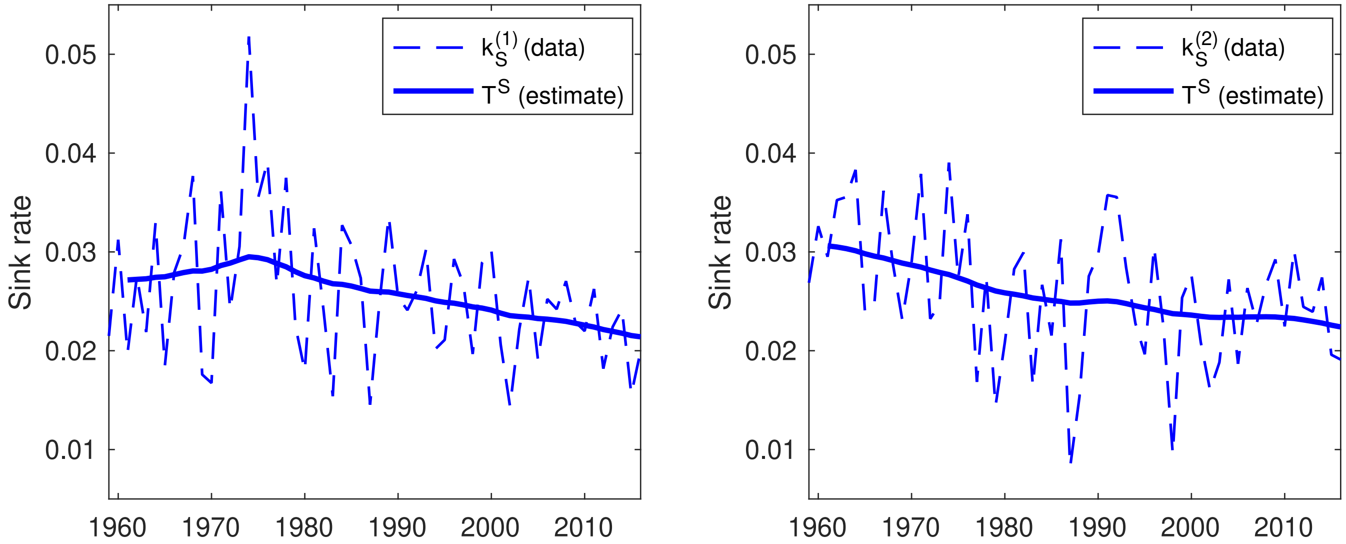
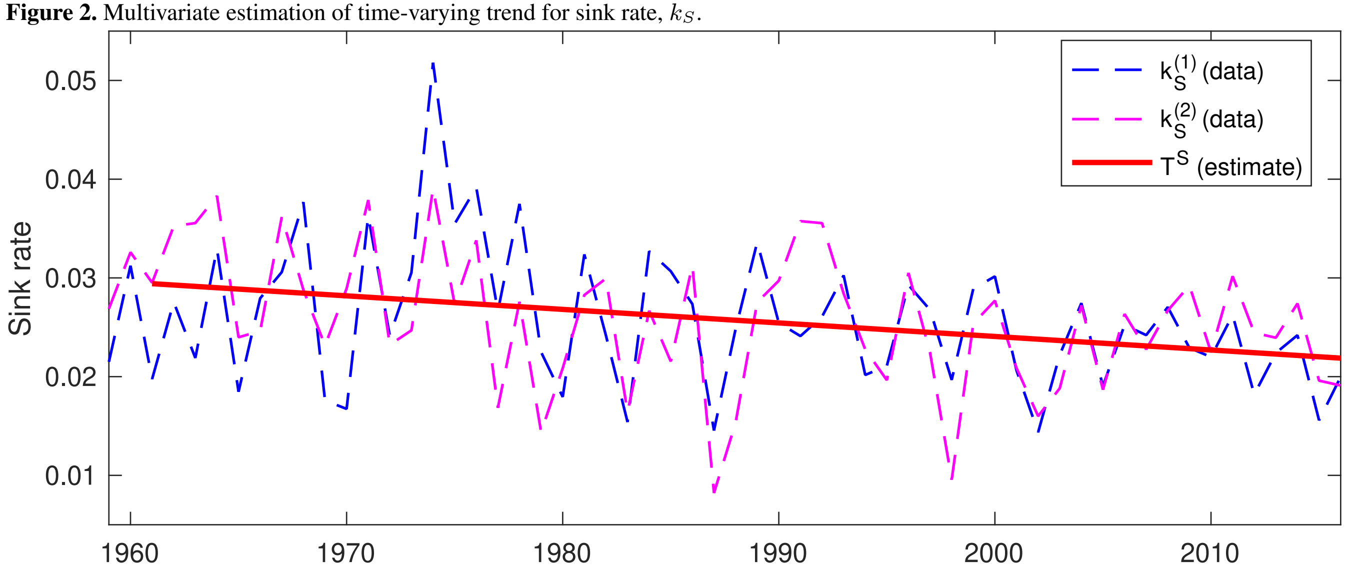


Figure 2. Multivariate estimation of time-varying trend for sink rate, k_S.



1.1.3 Plan to change paper in response

We will paraphrase the explanations of the AF and SR definitions in Section 2 to show the contribution of the state-space model in the context more crisply.

We will include Figure 1 and the corresponding results for the AF in the Supplementary Material.

1.2 Comment 2

1.2.1 Referee comment

The second major comment concerns the attribution of the decreasing sink to the land carbon sink. Regarding the shape of the land C sink, we may be interested to test since how many years the land sink has started to decrease. To further this comment, I think that several test of the length of the data and the influence of the sampling are missing in the manuscript. We need to see how far this approach is robust when using, for example, 5-year average data (removing ENSO and volcanoes influence).

1.2.2 Answer

The referee raises two interesting questions; we treat them one-by-one.

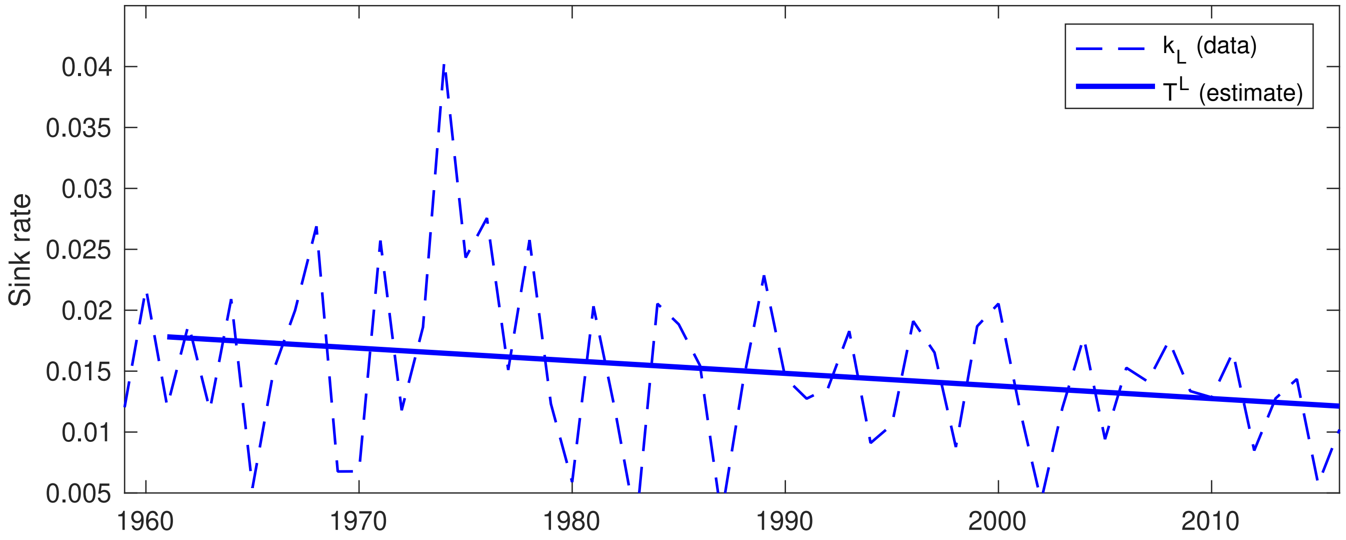
(i) With respect to the land sink rate, we are treating it as a fraction: the ratio of flux in land sink over CO_2 concentration in the atmosphere. The land sink flux itself, S_t^L, is increasing over time but the land sink rate, $k_{L,t} = S_t^L / C_t$, shows evidence of a decreasing trend. Our paper shows (Figure 2 in this reply) that if we sum up ocean and land sink and use both time series for this object, $k_S^{(1)}$ and $k_S^{(2)}$, jointly, we obtain a significantly negatively sloping deterministic trend. We can of course also consider $k_S^{(1)}$ and $k_S^{(2)}$ separately. The result is shown in Figure 1 of this reply. From the left panel of this figure, one might argue that the negative trend started in the mid 1970s. The right panel, which shows $k_S^{(2)}$, however, does not display such a kink. Finally, we can consider the land sink rate, k_L, individually. The result is shown in Figure 3 of this reply. We obtain a deterministic trend with an insignificant negative slope, cf. Table 5 of the main paper.

(ii) We have estimated the state-space model on 5-year average data in order to reduce the impact of effects such as ENSO, volcanic eruptions, and the like. The state-space model estimated on annual data is also capable of accounting for these effects, since it treats them as additive noise in the measurement equation. Repeating the analysis based on 5-year average data, however, provides a way to verify our estimation results and conclusions. (We also considered 2-, 3-, and 4-year averages, with similar results.)

We calculate 5-year non-overlapping averages in order to avoid introducing serial correlation into the time series. Running (i.e., overlapping) averages would necessitate specifying a model to capture this serial correlation, and we think this is a relatively bigger disadvantage than the reduction in the sample size that we incur from non-overlapping averages. Since we have 58 years of data, we calculate an average of the first three years followed by 5-year averages, resulting in 12 observations. The findings from estimating the state-space model on these time series of averages confirm those reported in the main paper: In the joint estimation, we find no statistical evidence of a trend in the airborne fraction (with a p-value of 0.32138), and we do find statistical evidence of a decreasing trend in the sink rate (with a p-value of 0.00064). Of course, the residual diagnostics for these short time series are not as convincing as those presented in the main paper. The extracted trends from these joint analyses are presented in Figures 4 (airborne fraction) and 5 (sink rate) in this reply. Incidentally, some analyses in earlier studies were based on running averages; we discuss these briefly in the Discussion section of the main paper (P13 L10).

We emphasize two points in this context: (1) The state-space model is advantageous in this exercise, since it allows to incorporate the alternative time series for both, AF and SR, which is particularly useful when the sample period is short. (2) The main finding from annual data prevails: In the separate analyses, the trends are estimated as stochastic. Only in the joint analysis do we obtain a deterministic trend and statistical significance for the sink rate.

Figure 3. Univariate estimation of time-varying trend for land sink rate, k_L.



1.2.3 Plan to change paper in response

- (i) We will include the separate analysis of the land sink rate (k_L) in the Supplementary Material. For completeness, we also submit the ocean sink rate (k_O) to the same analysis in the Supplementary Material.
- (ii) We will include the estimation results based on 5-year averages in the Supplementary Material and briefly discuss these findings in the main paper as well, with a reference to the Supplementary Material for further details. We will emphasize that the findings of the paper are robust to averaging of the data.

Figure 4. Multivariate estimation of time-varying trend for AF. Data: 5-year averages (no overlap)

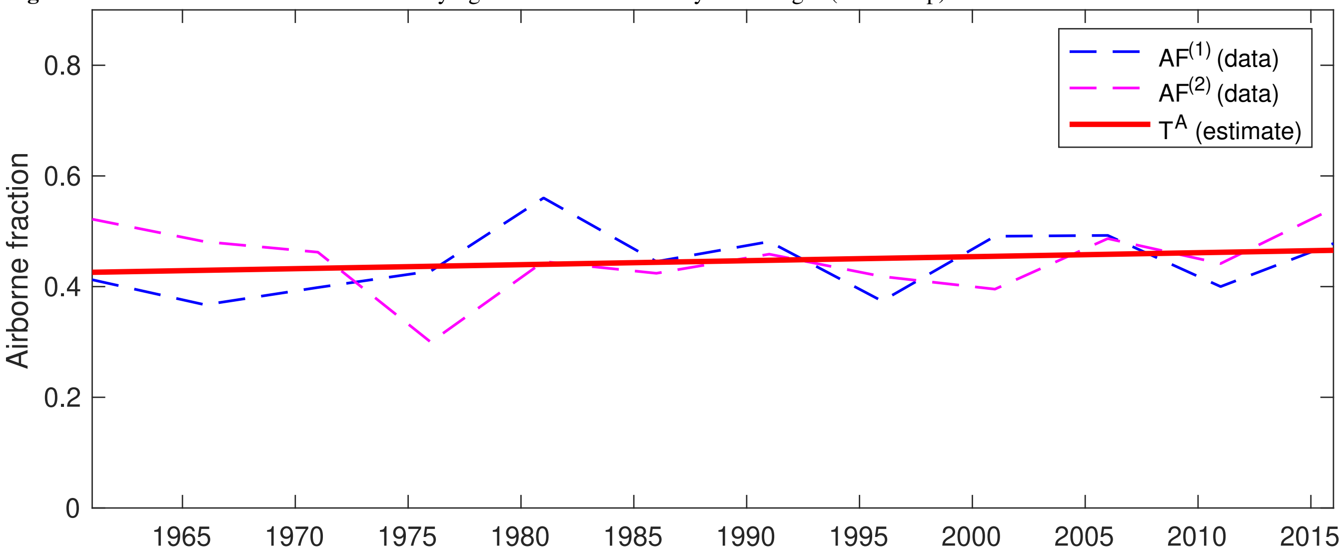
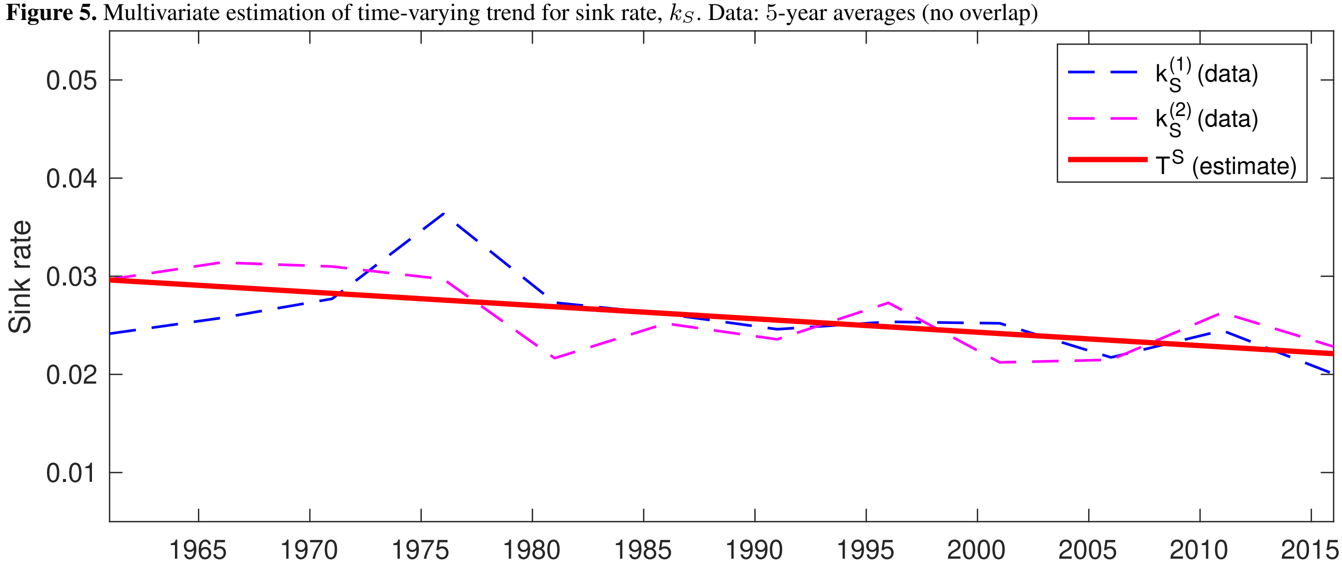


Figure 5. Multivariate estimation of time-varying trend for sink rate, k_S. Data: 5-year averages (no overlap)



1.3 Comment 3

1.3.1 Referee comment

My last major comment relates to the use of the "balanced" C budget whereas Le Quere et al. 2018 provides the Bim terms that could be used as a third entry in you model. I mean does the variance of Bim is steady in time or does it vary ? How far this terms correlates with AF and SF ? Do you fin a trends in Bim that could explain why the sink rate declines whereas the AF does ? I think all these discussions might consolidate the study.

1.3.2 Answer

Thank you for raising this point. By assuming that the carbon budget is balanced, we already include the B_t^{IM} data in the analysis. Specifically, the data on the budget imbalance enters as follows. For the case of the sink rate, the two time series employed are:

$$k_S^{(1)} = \frac{S_t^O + S_t^L}{C_t},$$
$$k_S^{(2)} = \frac{E_t - G_t}{C_t}.$$

Given the carbon budget equation, the latter expression can be written as

$$k_S^{(2)} = \frac{E_t - G_t}{C_t} = \frac{S_t^O + S_t^L + B_t^{IM}}{C_t} = k_S^{(1)} + \xi_t,$$

where

$$\xi_t = \frac{B_t^{IM}}{C_t},$$

can be regarded as an error term. This is the motivation for using the two time series $k_S^{(1)}$ and $k_S^{(2)}$ as data for the same underlying quantity, that is, the sink rate.

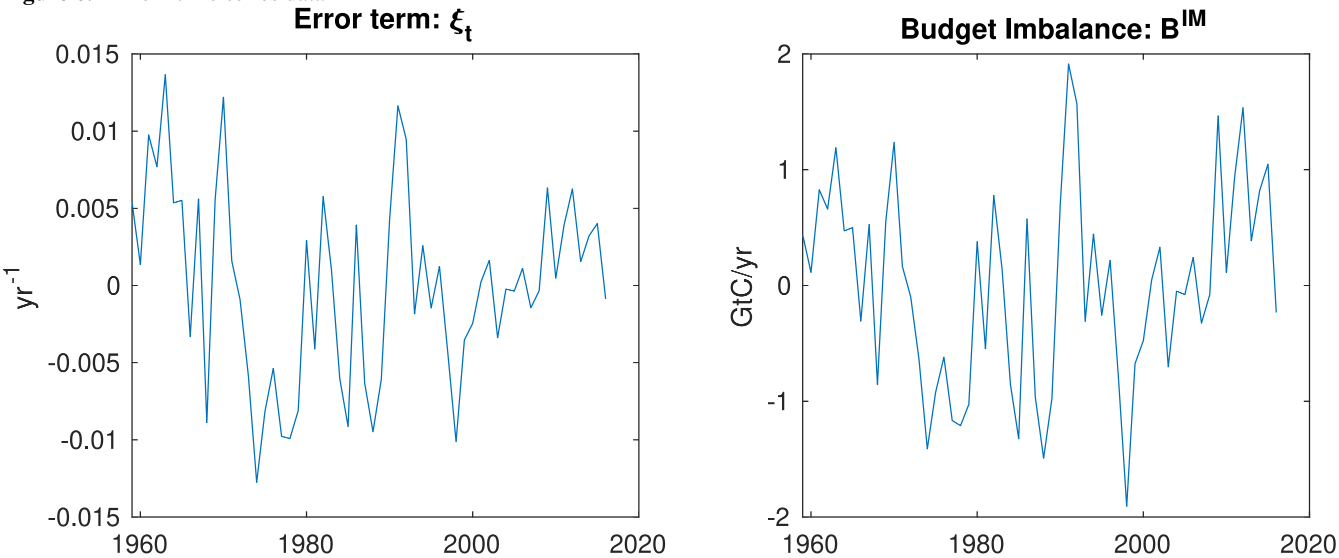
Figure 6 plots the time series of ξ_t (left plot) and B_t^{IM} (right plot). Both have a mean that is not significantly different from zero and follow stationary dynamics, albeit with some serial correlation.

In the joint state-space model, both $k_S^{(1)}$ and $k_S^{(2)}$ enter the measurement equation with an error term, and the residual diagnostics reported in the paper show that these error terms are well-behaved to such a degree that the statistical inference reported in the paper is valid.

1.3.3 Plan to change paper in response

We will include a discussion that relates the alternative measurements of the sink rate and AF to the budget imbalance, as explained above. When discussing residual diagnostics, we will point out the connection with the time series properties of the budget imbalance.

Figure 6. “Error” time series data



1.4 Specific comment: 1

1.4.1 Referee comment

P1 L4 what do you mean by “balanced carbon budget” ?

1.4.2 Answer

We mean that the sources of CO_2 should equal the sinks of CO_2, i.e., that the budget equation $E_t = G_t + S_t^L + S_t^O$ should hold (be “balanced”) at all times and that any departures from this equation are due to measurement errors in the data. Departures from the equation are captured by the budget imbalance term, B_t^{IM}. Hence, what we mean is that this term is, on average, zero. (This has indeed been the case historically, see Le Quéré et al., 2018).

1.4.3 Plan to change paper in response

We will rephrase the sentence in the paper to better capture our intended meaning.

1.5 Specific comment: 2

1.5.1 Referee comment

P1 L4 please clarify this sentence. It is unclear to me what object are you talking about

1.5.2 Answer

We are specifically referring to the airborne fraction and the sink rate. Also notice that we give an example in parentheses at the end of the sentence: “(for example, the airborne fraction)”.

1.5.3 Plan to change paper in response

We will rephrase the sentence in the paper to clearly identify the object we are referring to.

1.6 Specific comment: 3

1.6.1 Referee comment

P1 L6 please explain a bit further because a decrease in the sink should end up ultimately by a change in the AF

1.6.2 Answer

As explained in Section 8 of Gloor et al. (2010), it is not necessarily the case that a decrease in the sink rate implies an increase in the airborne fraction. We touch briefly on this in the Discussion section (P13 L 15). See also Raupach (2013).

The main point is that the airborne fraction is defined as $AF_t = G_t/E_t$, while the sink rate is defined as $k_{S,t} = S_t/C_t$. In other words, the normalizations of these time series are different, and they are not complements. Raupach et al. (2014) argue that the latter quantity is more appropriate as an object of study. However, due to the interest in the literature in both the sink rate as well as the airborne fraction, we have analyzed both quantities in the main paper. In the Discussion section we give some further arguments as to why the sink rate may be an easier object to analyze statistically than the airborne fraction (P13 L18).

1.6.3 Plan to change paper in response

We will add some clarifications on this in Section 2 of the main paper.

1.7 Specific comment: 4

1.7.1 Referee comment

P1 L13 please add the reference period over which this % are estimated + the reference publication

1.7.2 Answer

Thank you. We will do this in the revised version of the paper.

1.8 Specific comment: 5

1.8.1 Referee comment

P1 L18 you could acknowledge more recent studies here

1.8.2 Answer

Thanks for pointing this out, we will do so.

1.9 Specific comment: 6

1.9.1 Referee comment

P2 L5 anthropic = anthropogenic

1.9.2 Answer

Thank you. Corrected.

1.10 Specific comment: 7

1.10.1 Referee comment

P2 L7 you can remove "which we argue is well designed for the problem at hand"

1.10.2 Answer

Thank you. Removed.

1.11 Specific comment: 8

1.11.1 Referee comment

P3 L12-16 I think paragraph should be move above and better explain why you are working on the "balanced" hypothesis. The Bim remains small compared to the other terms for example ?

1.11.2 Answer

Thanks for pointing this out. We will clarify this in the revised version.

1.12 Specific comment: 9

1.12.1 Referee comment

P4 L2 could you further explain the meaning of "Using a simplifying linear specification ?

1.12.2 Answer

In Section 3 of Gloor et al. (2010), the variable $k_{S,t}$ is interpreted as a "sink efficiency". To see why this is, note that we can write (cf. Equation (3) in the main paper)

$$S_t^O + S_t^L = k_{S,t} \cdot C_t.$$

In other words, $k_{S,t}$ is the amount of CO_2 transferred into the sinks, for every unit of CO_2 in the atmosphere above pre-industrial levels (C_t). In this way, k_{S_t} gives an indication of the efficiency with which the carbon system transfers CO_2 to the sinks. See also Raupach (2013) Section 3.1 for a discussion of this "efficiency" interpretation.

1.12.3 Plan to change paper in response

We will change the paper to better reflect the above discussion and make our statement clearer.

1.13 Specific comment: 10

1.13.1 Referee comment

P6 L12-15 what about for a lower confidence threshold e.g., 90% do you get a better agreement ? why such a different in Beta estimates (one order of magnitude) ?

1.13.2 Answer

In Table 1 of the main paper, we indeed get two different estimates of β, namely 0.00109 and 0.00049. However, we notice that the standard deviations of the estimates are given by 0.00179 and 0.00203, respectively. It indicates that although the estimates are very different (by an order of magnitude, as pointed out by the referee), this difference is not statistically significant. The p-values are 0.5423 and 0.8084 respectively.

The p-values also give an answer to the second question: the estimates are not significant at a 90% level.

1.13.3 Plan to change paper in response

We will add the p-values to the main paper.

1.14 Specific comment: 11

1.14.1 Referee comment

P7 L14 please give the estimate of TtA ? besides I think there is a error in Eq 13 with the random noise epsilon. I read it as independent of time.

1.14.2 Answer

The estimate of T_t^A is shown in Figure 1 in the main paper (page 8). The estimates of the accompanying parameters are given in Table 2 (page 7 in the main paper).

We have indeed missed the subscript in Equation (13). Thank you for pointing this out.

1.14.3 Plan to change paper in response

A subscript “t” will be added to the error term in Equation (13), P7 L14.

1.15 Specific comment: 12

1.15.1 Referee comment

P10 L9-10 the last sentence requires further explanations.

1.15.2 Answer

Agreed. The forecasts we provide are implied by the model and can be computed within our state space approach. The forecasts for the next 25 years are displayed in Fig. 3 of the main paper and the downward trend is the result of a negative estimate of β as reported in Table 4. Under the current conditions, our forecast implies that it takes more than 25 years before the sink rate is below the value of 0.02.

1.15.3 Plan to change paper in response

In the main paper, we will expand the explanation along the lines given here.

1.16 Specific comment: 13

1.16.1 Referee comment

Figure 3 I don't know what these two panels show. They show the two metrics, correct ? Why giving the confidence interval for 1 sigma whereas most of the statistical test were conducted with a 95% confidence threshold ?

1.16.2 Answer

Correct and agreed. We will explain more carefully. We will also give 95% thresholds.

1.17 Specific comment: 14

1.17.1 Referee comment

P12 L15 this looks like trivial. I guess that a simple correlation between the SF and LF should lead to the same conclusion. . .

1.17.2 Answer

The wording of the sentence in the paper is somewhat unclear. What we meant to say is that the variation in the combined sink rate is mostly driven by the variation in the land sink rate. We will rephrase the paragraph to make the point clear.

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