Response to Referees' Comments

Peter Rayner

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Before addressing the referees' comments we need to point out an error in some figures and data. A programming error meant that the $\delta^{13}CO_2$ data had not been properly included. This most seriously affects Table 2. To quantify the effect we replicate the structure of Table 2 for the regional fluxes but showing the differences between the corrected and erroneous versions. We use the corrected versions of the uncertainties although these hardly change from the original version.

$\delta^{13}CO_2$ is modelled by assuming weak prior knowledge on the isotopic disequilibrium flux and its first derivative (Rayner et al., 1999; Rayner, 2001). This means that differences in the long-term first and second derivatives of $\delta^{13}CO_2$ will be absorbed by these variables. There is also relatively little $\delta^{13}CO_2$ data available from the one network we use. Thus it is unsurprising that the differences demonstrated in the table are slight, certainly smaller than the uncertainties. Thus we believe the error has no material impact on the results of the paper.

We thank the three anonymous referees for their comments which have allowed us to clarify various points in the paper. There are two points made by more than one referee. We address these first then deal point by point with the comments of each referee. We place referees' comments in typewriter font and our responses in Roman.

Table 1: Errors in land and ocean β values from the inversion for northern extratropics, tropics and southern extratropics for the periods 1992–2012 and 2002–2012.

Flux	1992–2012		2002–2012	
	β (yr^{-1}	uncertainty (yr^{-1}	β (yr^{-1})	uncertainty (yr^{-1})
northern land	-0.000	0.004	0.005	0.012
northern ocean	0.001	0.002	-0.003	0.005
tropical land	-0.001	0.008	0.002	0.021
tropical ocean	0.001	0.003	-0.001	0.006
southern land	-0.001	0.006	0.003	0.016
southern ocean	0.001	0.003	-0.004	0.006

Common Points

Here we paraphrase the referees' comments and refer back to them in the detailed responses.

`Expand on the comparison with gloor et al., (2010)`

This is a good point. the purposes of the two papers are a little different. We have expanded on the difference between the papers in the introduction and model description. We also removed the comment in the abstract comparing the two simple models since this is, indeed, covered by Gloor et al. (2010). We have also noted the conclusion of a possible increase in response, a different result from Gloor et al. (2010).

`the assumption of independent errors in the Global Carbon Project data is unjustified and threatens the paper's conclusions.`

We thank the reviewers for pointing this out. Because our analysis depends on trends in various terms the most likely type of error (positive temporal correlation) would actually increase the significance of the results. We now point this out in an extra paragraph in section 2.

The only case where this is not true is the calculation of the error in α in Section 2. We now bracket this uncertainty by assuming either independence (the default) or perfect correlation so that the assumed 5% error in the annual fossil fuel flux propagates directly into the sum. We also describe this case in Section 2.

Comments from Anonymous Referee 1

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This manuscript presents an interesting study into decadal
trends in the strength of carbon cycle feedbacks, extending
the approach applied in previous publications by a decomposition
of global tendencies into regional and seasonal components.
The methodology and its application to inversions and ecosystem
models is interesting as it allows a different way of looking
at existing simulations.  As pointed out for the global analysis,
for which longer data records are available, shorter-term results
may not point at robust tendencies.  The question remains if
this lesson of caution doesnt also apply to the inverse model
and vegetation model results, which are evaluated over shorter
periods.  Whether or not robust, the ideas presented in this
work are definitely worth publishing.  Below are a list of
corrections and suggestions that will hopefully facilitate
the reading, and a few scientific issues that require some
further attention.
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General Comments

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Although the focus of the paper is on trends in the carbon
cycle response to its forcing, the mean sensitivities that
are derived deserve some attention also.  The absence of a
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weakening in the oceanic response is quite significant in light of a few others studies, as is discussed. However, the mean values that are derived for the sensitivity of the ocean seem rather small, which calls for an explanation also. At least an effort should have been made to compare the numbers with Gloor et al, 2010.

We have added a paragraph to the discussion making this comparison. We point out that the comparison is difficult since Gloor et al. (2010) do not include the constant term in their regression (compare their Equation 2 with our Equation 5). Both approaches are perfectly valid for the different aims of the two papers.

SPECIFIC COMMENTS

Abstract, line 11: also suggests a similarity with the previously sentence, which is not the case.

"Also" deleted.

Footnote 1: But if policy decisions change the long-term mean flux (due to some new infrastructure becoming functional) then the corresponding source may be constant, rather than constantly growing. This is different for a policy decision that causes the infrastructure to evolve in time. In that case the flux may integrate a single political decision, but otherwise not.

This seems a misreading of the footnote. It says that policy choices will add or subtract anthropogenic sources and these sources will probably last a long time. Put mathematically, each decision on a new infrastructure is a pulse in source space, and the lifetime of that pulse is often long. The point is not critical for this paper though so we deleted the footnote.

Eq.7: If M and q both represent burdens of carbon or CO2 in the atmosphere, then why not use the same parameter? They are not defined exactly the same, but this seems to make the equation unnecessarily complicated.

An excellent idea. We have changed this throughout and changed some text around Eqs. 5 and 6 to reflect this.

Page 9926, line 8: J=q i.o. 1/q

J here is meant to be a column matrix so we think the current form is correct. If it is being mistaken for a fraction we should discuss with copy editors how to clarify this within the house style.

Page 9926: Please mention briefly what dM/dt is based on.

We do not understand why this request should be made for one term in the budget (probably the best known) and not the others. We have added a paragraph in Section 3 summarizing the data sources.

Page 9927: How realistic is it to assume independence of annual estimates of F_{anthro}? The 1% seems quite optimistic. I wonder if it is supported by the size of the fit residuals.

See response to common points above.

Page 9927, line 5-10: Are these results shown somewhere?

We have added an extra figure to show them explicitly.

Page 9927: The large uncertainty in beta i.o. The large beta value

No, we really are referring to the value here not its uncertainty.

Page 9927: the mean residual of the fit i.o. the residuals of the fit

Corrected.

Page 9928, line 2: What is the meaning of disjoint in this context? That the corre- sponding processes are independent? This doesnt necessarily hold for a seasonal decomposition.

We mean that fluxes can be decomposed into a sum, we have made this explicit.

Page 9928, line 1-10: It is not directly clear which regression problem you solve in this case (in terms of J and y). I suppose you start now from equation 6 where $y = F_{\mathrm{ocean}}$ for solving beta-ocean, and $y = F_{\mathrm{land}}$ for solving beta-land?

Correct. We have made this explicit now.

Page 9928: How do you get 6 periods of 11 years for the period 1960 to 2010?

We calculate β for 11-year periods starting in every possible year of the study period. We now explain this explicitly on the previous page where the technique is first used for the global response.

Page 9929, line 510: Why is this best compared without the fossil component? Any difference between the GCP and CCAM fossil fuel prior would be mapped to the non- fossil component. The main requirement is that the model reproduces the observed trend in CO2, right?

No, testing that the model reproduces the overall trend in CO_2 only tests that our inversion scheme conserves mass (not a trivial test but not one we should inflict on the reader). That the components we're interested in follow the GCP after the inversion has made adjustments to the fossil and dealt with the interannually invariant prior is a tougher test. We note that reviewer 3 didn't think it was nearly tough enough.

Page 9930, line 13: aliased into the calculated beta io aliased into errors in calculated beta

Corrected.

Page 9932, line 25: What is the reason for using a different region definition for the inversion and the biosphere model?

The main reason is the calculation of posterior uncertainties for fluxes. These form an input into Eq. 9 where we calculate the uncertainty on our diagnostics. The posterior flux uncertainties can be calculated for groups of regions but it is extremely difficult to map these back onto precise geographic boundaries. Given the large and systematic differences between inversion and terrestrial model results it is hard to imagine the small differences in regions playing much of a role.

Page 9932, line 25 ...: Earlier it was mentioned that LUC drives beta in the tropics. Then to properly interpret the results of LPJ it is necessary to know if its LUC in recent years resembles that of GCP.

There are a couple of meanings of the word "drive" in play here. There is the physical sense in which land uptake is partly a response to LUC. Hopefully those processes are mirrored in the terrestrial biosphere models we use. Attribution of uptake to LUC is difficult, usually requiring parallel model runs with and without LUC. In our case, LUC is one of many forcings not dependent on concentration but which might masquerade as a first-order process. We mention other such forcings in the second paragraph of the discussion and have added LUC to the list.

For the inversion results, LUC has a more direct effect. Inversions solve for the net fux, so to produce the uptake flux compatible with the biosphere models we must subtract the LUC contribution. Thus part of the structure of the uptake estimates from the inversion comes from the GCP estimate of LUC. In this sense it is not necessary that GCP and (for example) LPJ LUC estimates are the same. The best way to clarify this point is to add LUC to the list of forcings as already described.

Page 9933, line 14: Since part of the paper deals with CCAM it would be better to specify model here as an ecosystem model.

Done.

TECHNICAL CORRECTIONS

Abstract, line 11: Terrestrial models i.o. terrestrial models

Corrected.

Page 9926, line This io this

Corrected.

Comments from Referee 2

General comments

As this work relies on an analysis framework developed by Gloor et al. [2010], a clearer distinction in the abstract and introduction between the two studies would help highlight the novel contributions of the current study.

See responses to common points.

Additionally, some discussion of how the Global responses results (Section 3) compare to the previous study may be useful

See response to general comments from Referee 1.

Regarding the amplitude of the residuals with time. A figure showing these values may be useful.

Added in response to request from Referee 1.

Detailed Comments

Abstract, lines 3–6, This text seems to be stating a conclusion already found by Gloor et al. [2010]. The authors should try to make the distinction more clear.

We have removed the comment.

Page 9921, lines 27–28, but for different purposes. Clearly state different purposes.

We have added a summary point here and note that the use of the diagnostic is explained in more detail two paragraphs later.

Page 9926, line 9, How does that constant term manifest itself in the above equations?

We have added a reference to Eq. 5 where this is demonstrated.

Page 9926, line 22, How does this 0.95 Pg C yr-1 value get used in the analysis? Is it added to R?

In fact we use it in $\mathbf{R}$. We have made this explicit in the relevant sentence. This also led us to note an error in Eq. 10. It was missing a power -1. We have corrected this.

Page 9927, line 4, I understand why mathematically assuming independence of the annual uncertainties allows for a cleaner and computationally cheaper solution but would inflating this value make sense because this assumption is likely over optimistic, e.g. errors are likely correlated because accounting methods and hence errors from year to year are similar.

See response to Referee 1.

Page 9927, line 7–9, What does the increase in the amplitudes of the residuals imply? Could a plot be useful here?

We have added a plot and the point is elaborated on P9934.

Page 9934, line 5–8, It seems this method would also be useful in comparing bottom- up and top-down methods to estimate CO2 flux. While intercomparisons would also prove to be useful within modeling arenas, the difference in the regional responses between the inversions and terrestrial models shown here again highlight the contrast between methods to estimate carbon exchange.

Indeed, we note this in the last sentence in the discussions.

Technical Comments

Abstract, line 11, capitalize t in Terrestrial

Done.

Page 9922, line 5, insert the after since the early 2000s,

Done.

Page 9926, line 9, capitalize t in This is. . .

Done.

Comments from Referee 3

Overall comments

Rayner et al. are revisiting an analysis done by Gloor et al. (2010) which looks at trends in the airborne fraction of anthropogenic emissions. Changing trends in this simple model might imply that natural sinks (and sources) are not responding in a linear way to the exponential rise in CO2. Gloor et al. (2010) were mainly concerned with the global changes in anthropogenic fluxes and changes in CO2 mole fraction where they felt the errors (uncertainties) in the temporal change in mole fraction and fossil fuel flux were small. They suggested that land use change adds a complexity because it has a much larger uncertainty. The land use change not only adds uncertainty to the calculation but it also prolongs the spin up time needed to get meaningful results from this simple model construct.

We thank the referee for prompting another reread of Gloor et al. (2010); it is a very fine paper. The reread, though, revealed even less in common between the papers than I remembered. Gloor et al. (2010) is predominantly concerned with findings about the airborne fraction of some preceding studies. They use a version of the β model to analyze the airborne fraction. There is little analysis of variations in β itself and no decomposition by space and time. We did have one clear overlap with Gloor et al. (2010), a comment in the abstract on drivers in changes of α. We have removed this.

Rayner et al. takes the Gloor et al (2010) study one step further by looking at both seasonal and regional trends in airborne fraction where they note, in particular, that the terrestrial uptake in the terrestrial northern hemisphere summer has been much higher in the last decade. Rayner also suggests in this paper that this "first-order" model approach is potentially useful for evaluating models response to climate change which begs the question why build the model in the first place.

Overall, the idea that the uptake in the terrestrial northern hemisphere summer is in- creasing is fascinating. However, this paper does little to bring the reader up to speed so that they might understand why this might be a legitimate approach or what the pit- falls of this analysis might be. Simply taking the time to describe uncertainties carefully described by Gloor et al. (2010) or the details of the Rayner et al. (2008) inversion or the data from Le Qur et al. (2013) would be very helpful. In the case of the Gloor et al. (2010) analysis it would also be helpful to not only describe the uncertainties that are so carefully analyzed in Gloor et al (2010) but also describe what this paper has done differently. Many places throughout the text need more clarification to help the reader

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truly evaluate the merits of this simplifying approach to understand
the high uncertainties of the regional and seasonal analysis.
In its present form, I cannot recom- mend this paper for publication
because it does not adequately describe the problem, technique
used or the results in clear and concise way.
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The referee raises a common but difficult point. How much background from previous work is necessary to evaluate a new paper and should this background be treated by referencing or in precis? The task is to provide the reader what they need as efficiently as possible. One can't decide this balance as a generality and equally it is hard to respond to such a general critique. The referee does state a couple of points in their specific comments where enlargement would help and we have responded to these.

Specific comments

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9920 line 7  first order model first introduced here but needs
to be defined more clearly.  From here the term is used sometime
but not always.  It would be helpful if this was more consistent.
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An excellent suggestion, we have changed most occurrences of "first-order" to "linear" and used the name "β-model" to refer to it.

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9920  line 9  What is meant by their
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We have changed this to "flux".

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9920 line 17  Problematic because.  it is problematic because
temperature .  .  ..  I read this sentence multiple times and
still have no idea what it is saying.
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We have changed the sentence to "It is problematic since temperature responds to accumulated radiative forcing and radiative forcing by long-lived greenhouse gases is driven by accumulated sources."

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9920 line 22  inherently fascinating for whom?
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I'm not sure what the referee is asking us to do here. Should we add a string of references?

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9920 first two paragraphs need to reworked and simplified
to help reader appreciate what the author clearly excited about.
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There's not much guidance in this comment. Neither of the other two referees commented that the abstract was a poor summary of the paper.

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9921 line 5 such changes be specific
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"such changes" refers to the previous sentence. I think this is standard English usage but have changed it to "these changes" which is perhaps clearer.

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9921 line 29 different purpose?  specify
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This point is common to all referees and we have expanded on the different intentions of the two papers.

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9922 line 18 CO2 forcing of the response from other drivers.
Do you mean the other drivers might be a response to CO2 forcing?
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No, we make no comment on the nature of the other drivers.

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9922 line 26 is section 4 applying the same diagnostics
to inverse estimates at regional levels?
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Yes, we have made this explicit.

9925 line 17. full range of flux estimates available in. . .. Not sure what this statement means.

We have clarified this to say we have not applied our diagnostics to the ensembles of results gathered by intercomparisons.

9926 line 22 this maybe mean-squared residuals.

I think the referee is referring to "this value". I don't see an ambiguity there so I'm not sure what the referee is asking us to correct.

9927 line 3 assuming independence of annual values what is the reason for assum- ing this? show reference

Instead of an examination of uncertainties in anthropogenic fluxes we note that the assumption we have made is the most conservative possible for the β model and have discussed the implications for the α model.

9927 line 9 interannual variability has been used . . . . Can you say what Cox and Wang found out?

We come back to that point in the discussion. Here we only need to motivate the presentation of the figure.

9927 line 17 larger [value] occurring

We have reworded the sentence.

9927 line 22 with the large error bar a result of the large interannual variability . . . the large error bars are a result of large . . .

We have split the sentence and reworded.

9927 line 25 The change in trend over that time is approaching significance but is not robust. What is this supposed to mean? Why should I believe either the long term beta or the short term beta?

It is not the task of statistical tests to tell people what they are supposed to believe, that's a task for decision theory. We have provided a series of statements of probability about the results. If these are inadequate we need to know why. We have explained the tests we use a little more fully.

9928 line 8 We obtain =0.010 0.001yr for ocean and =0.0060.002yr for land. Interesting that the land values have a longer response time than ocean.

Yes, an interesting point but for another paper.

9928 line 9 This suggests we should increase the land uncertainty to . . .. Please explain

We have elaborated the reason by pointing out the difference between the assumed and actual magnitudes of the residuals.

9928 line 23 We can apply similar diagnostics to inverse estimates of fluxes. Can you be explicit. Not clear how you are using inversion flux estimates or why?

We have made this explicit.

9929 line 1 age since more stations now meet the 70ment. I see reference but simply explaining what you mean by 70might be helpful as it is I would have to read the paper to even guess at what this might mean.

This is a specific example of the general point raised by the referee on background from other papers. It is one of only two specific examples they note. We address this by describing the criterion explicitly.

`9929 line 8 We are here interested. . .. Edit.`

Done.

`9929 line 9 we adjust the mean fluxes to be equal. Equal to each other? Please specify.`

We have expanded this and added an explanation of why it will have no effect on the calculated β.

`9929 line 13 Next we can ask whether the GCP and inversion agree on the land-ocean . . .. Explain why these are independent estimates or why this is a sufficient test.`

We have added a sentence pointing out the independence of the estimates.

`9929 line 14 The groupings taken from Gurney et al.(2002) rather than a latitudinal separation. Why is this?`

We have added a sentence explaining the need to calculate posterior uncertainty from the inversion correctly.

`9930 Line 14. mean flux noted by Jacobson. Explain`

We have added a comment on uncertainty correlations in Jacobson et al. (2007).

`9931 Line 6 and probably do not. This is speculation.`

No, it is a paraphrase of the findings of Piao et al. (2008).

`9931 Line 14 sum of assimilation. Be consistent in terminology.`

changed to "production".

`9932 line 25 complex TRANSCOM boundaries used in the inversion here the bound- ary for inversion is refered to as TRANSCOM with no reference yet above Gurney is referenced with no explanation.`

We have changed "transcom" to a reference to Gurney et al. (2002).

`9931 line 22 reasonable way to summarize the behaviour of the large-scale carbon cycle we can also apply it to models. Not sure why you would not just sum up appropriate fluxes in the model. I agree that comparing this to a data driven estimate might be better however one has to be careful because the anthropogenic fluxes in a model might be the same so you are not really learning anything. I must be missing something.`

There seem to be a couple of points here. One is a general comment on the utility of simple model diagnostics. Defending their use is beyond the scope of this reply or the article. I hope it is sufficient to say they are a common choice whenever complex models must be compared to each other or different estimates. I don't understand the comment on the anthropogenic fluxes since the terrestrial models don't use these.

`9933 line 12 deepening of growing flux minimum. How about increasing.`

"increasing minimum" is an ambiguous phrase, "deepening" is not.

`9933 line 13 strongly implicating concentration changes. Not clear what is being implicated.`

We have made this explicit.

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9933 line 18 it is in a benign direction.  Who decides what
is good and bad?
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We have replaced this language with “mitigate and exacerbate”.

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9934 line 24.  Models.  Do you mean forward models?
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Terrestrial ecosystem models, we have made this explicit.

References

Gloor, M., Sarmiento, J. L., and Gruber, N.: What can be learned about carbon cycle climate feedbacks from the CO_2 airborne fraction?, Atmospheric Chemistry and Physics, 10, 7739–7751, doi:10.5194/acp-10-7739-2010, URL http://www.atmos-chem-phys.net/10/7739/2010/, 2010.

Gurney, K. R., Law, R. M., Denning, A. S., Rayner, P. J., Baker, D., Bousquet, P., Bruhwiler, L., Chen, Y.-H., Ciais, P., Fan, S., Fung, I. Y., Gloor, M., Heimann, M., Higuchi, K., John, J., Maki, T., Maksyutov, S., Masarie, K., Peylin, P., Prather, M., Pak, B. C., Randerson, J., Sarmiento, J., Taguchi, S., Takahashi, T., and Yuen, C.-W.: Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models, Nature, 415, 626–630, 2002.

Jacobson, A. R., Mikaloff Fletcher, S. E., Gruber, N., Sarmiento, J. L., and Gloor, M.: A joint atmosphere-ocean inversion for surface fluxes of carbon dioxide: 2. Regional results, glob. Biogeochem. cyc., 21, GB1020, doi:10.1029/2006GB002703, 2007.

Piao, S., Ciais, P., Friedlingstein, P., Peylin, P., Reichstein, M., Luyssaert, S., Margolis, H., Fang, J., Barr7, A., Chen, A., Grelle, A., Hollinger, D. Y., Laurila, T., Lindroth, A., Richardson, A. D., and Vesala, . T.: Net carbon dioxide losses of northern ecosystems in response to autumn warming, Nature, 451, 49–52, doi:10.1038/nature06444, 2008.

Rayner, P.: Atmospheric perspectives on the ocean carbon cycle, in: Global biogeochemical cycles in the climate system, edited by Schulze, E. D., Harrison, S. P., Heimann, M., Holland, E. A., Lloyd, J., Prentice, I. C., and Schimel, D., pp. 285–294, Academic Press, San Diego, 2001.

Rayner, P. J., Enting, I. G., Francey, R. J., and Langenfelds, R. L.: Reconstructing the recent carbon cycle from atmospheric CO_2, $\delta^{13}C$ and O_2/N_2 observations, Tellus, 51B, 213–232, 1999.

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Recent changes in the global and regional carbon cycle: analysis of first-order diagnostics

P. J. Rayner[1], A. Stavert[2], M. Scholze[3], A. Ahlstrom[3], C. E. Allison[2], and R. M. Law[2]

[1]School of Earth Sciences, University of Melbourne, Melbourne, Australia
[2]CSIRO Oceans and Atmosphere flagship, Melbourne, Australia
[3]Dept. of Physical Geography and Ecosystem Science, Lund University, Sweden

Correspondence to: P. J. Rayner (prayner@unimelb.edu.au)

Kurzfassung

We analyze global and regional changes in CO_2 fluxes using two simple models, an airborne fraction of anthropogenic emissions and a linear relationship with CO_2 concentrations. We show that both models are able to fit the ~~nonanthropogenic~~ non-anthropogenic (hereafter natural) flux over the length of the atmospheric concentration record~~and that departures in the airborne fraction model are largely due to departures from exponential growth of emissions~~. Analysis of the ~~first-order~~ linear model (including its uncertainties) suggests no significant ~~change~~ decrease in the response of the natural carbon cycle. Recent data points rather to an increase. We apply the same ~~first-order~~ linear diagnostic to fluxes from atmospheric inversions. ~~Their~~ Flux responses show clear regional and seasonal patterns driven by terrestrial uptake in the northern summer. Ocean fluxes show little or no ~~first-order response. terrestrial models also~~ linear response. Terrestrial models show clear responses, agreeing globally with the inversion responses, however the spatial structure is quite different, with dominant responses in the tropics rather than the northern extratropics.

1 Einleitung

The interplay of various timescales in anthropogenically forced climate change is both problematic and fascinating. It is problematic since temperature responses integrate radiative forcing and radiative forcing by greenhouse gases integrates sources. Thus changes in source processes can, if sustained, drive surprisingly large changes in the trajectory of temperature. [1]

For the most important greenhouse gas, CO_2, this double integration gives a respectable utility to an inherently fascinating question: Are there changes in the underlying processes of the carbon cycle? The utility comes from the natural carbon cycle's role in mitigating the anthropogenic perturbation by absorbing about half the anthropogenic input of carbon to the atmo-

[1] ~~The problem is even worse since the long lifetime of much industrial infrastructure means source processes integrate policy choices.~~

sphere (Le Quéré et al., 2013). Optimal policy response relies on projections of this uptake so changes in the natural carbon cycle have direct policy implications.

We have had conceptual models for ~~such~~ these changes for many years. For the ocean these are predominantly changes in chemical buffering (Revelle and Suess, 1957) and changes in physical circulation (Sarmiento et al., 1998). For terrestrial uptake there are many countervailing factors at work such as extension of the high latitude growing season (Zhou et al., 2001; Piao et al., 2008) and the varied responses of terrestrial ecosystems to changes in temperature and rainfall. Cox et al. (2000) combined many of these responses into a reasonably complete model of the earth system and projected a strong reduction in carbon uptake with the land becoming a net source around 2050. Friedlingstein et al. (2006) showed that this was one of many possible responses. Such studies naturally prompted observational tests of the important processes such as the reaction of the Amazon forest to drying (Saleska et al., 2003). Several studies have suggested sink saturation or reduction in various regions such as Schuster and Watson (2007) for the North Atlantic, Le Quéré et al. (2007) for the Southern Ocean and Nabuurs et al. (2013) for European forests.

Meanwhile the 5-decade record of atmospheric CO_2 raises the possibility of detecting changes in the results of these processes directly. This was first taken up by Canadell et al. (2007) who suggested that sinks were saturating, at least relative to emissions. This was made more explicit by Raupach et al. (2008) who attempted to isolate the anthropogenic and natural contributions to long-term changes in CO_2 growth-rate. The statistical significance of the trends noted by (Canadell et al., 2007) and Raupach et al. (2008) was challenged by Knorr (2009). Gloor et al. (2010) also pointed out difficulties in interpreting changes in the relationship between emissions and growth-rate in terms of the response of the system. They used a linear perturbation model and developed diagnostics of the airborne fraction from it. We will use the same model but~~for different purposes~~, rather than diagnosing the behaviour of a yet simpler model (airborne fraction) we will use it to diagnose the behaviour of inferred or modelled fluxes from more complex systems.

Along with this controversy over long-term changes in the sink efficiency, different questions have emerged on more recent changes. Sarmiento et al. (2010) used a combination of the atmospheric growth-rate, anthropogenic inputs and an ocean model to posit an abrupt change in the terrestrial uptake around 1988. Francey et al. (2010) and Francey et al. (2013) pointed out that, since the early 2000s, the growth-rate of atmospheric CO_2 had failed to keep pace with the acceleration in reported fossil fuel use. Their conclusion was to question the timing of this acceleration.[1]

To provide context for subsequent discussions, Fig. 1 plots the history of anthropogenic carbon fluxes and the growth-rate in atmospheric CO_2. It also shows the predicted growth-rate from two simple models to be discussed later. Data is taken from Le Quéré et al. (2013). We see a clear increase in anthropogenic fluxes and a much noisier increase in the atmospheric growth-rate. We also see an increasing divergence between these curves, connoting an increasing uptake. This uptake is a response to a range of perturbations, atmospheric CO_2 itself, nutrient input, land management and land-use change and doubtless many others. Here we analyze this uptake as a simple linear response to CO_2 concentration. We use CO_2 concentration as a surrogate for forcings with a similar time course, that is we do not attempt to separate CO_2 forcing of the response from other drivers. Rather we ask whether there has been significant departure from this ~~first-order~~ linear response evident in recent years. Further we analyze regional contributions to this ~~first-order~~ linear response. This provides a simple diagnostic of model responses which can be compared with inverse estimates of regional fluxes. Our focus is on the change of uptake rather than its mean value. Such analysis of trends requires reasonably long records and is hence less certain at regional than global scales.

The outline of the paper is as follows: Sect. 2 describes the simple diagnostics we use and the data. Section 3 analyzes the global record in terms of this diagnostic. Section 4 applies the same diagnostic to regional fluxes from inverse estimates while Sect. 5 applies it to terrestrial models. Section 6 points out some of the caveats and implications in the preceding analysis and Sect. 7 summarizes the main points.

[1]Some confusion has arisen between the two discussions of changes in airborne fraction. In general they address different time-scales.

2 Methods and tools

2.1 Defining the carbon budget

Our aim is to analyze the response of parts of the carbon budget to changes in forcing. We must therefore define which terms of the carbon budget we consider. We start with the decomposition used by the Global Carbon Project (GCP) (Le Quéré et al., 2013)

$$\frac{\partial M}{\partial t} = F_{\mathrm{fossil}} + F_{\mathrm{LUC}} - F_{\mathrm{land}} - F_{\mathrm{ocean}} \tag{1}$$

Where M is the mass of carbon in the atmosphere, F_{LUC} is the flux due to land-use change (LUC) and all other fluxes have their usual meanings. Throughout the paper we will talk of uptakes by land and ocean so we have not followed the usual convention of writing fluxes with a single direction (towards the atmosphere or surface).

We will also frequently combine the two anthropogenic fluxes as

$$F_{\mathrm{anthro}} = F_{\mathrm{fossil}} + F_{\mathrm{LUC}} \tag{2}$$

Some terms in Eq. (1) are ambiguous, especially the partition between F_{LUC} and F_{land}. This point is discussed by Enting et al. (2012). When discussing global budgets we will follow the GCP definitions. The atmospheric inversion studies we draw on do not separate these two fluxes. Globally we will correct F_{land} by F_{LUC} from the GCP. When we consider regional budgets we will ascribe changes in the combined flux to F_{land} and discuss the implications of this approximation.

2.2 Two models

We follow Gloor et al. (2010) in using two models for the change in atmospheric CO_2 concentration in response to anthropogenic inputs. The provenance of these two models and the relationship between them is thoroughly described by Gloor et al. (2010) so we will only summarize them here.

2.2.1 Airborne fraction model

This expresses the change in the atmospheric mass of carbon as

$$\frac{\partial M}{\partial t} = \alpha F_{\text{anthro}} \tag{3}$$

where α is known as the airborne fraction.[2] Combining this with Eq. (1) we see

$$F_{\text{land}} + F_{\text{ocean}} = (1-\alpha) F_{\text{anthro}} \tag{4}$$

It is important to remember that Eq. (4) represents a relationship following from mass conservation rather than a causal relationship between anthropogenic inputs and contemporaneous uptakes. It is hard to conceive a mechanism that would link the three fluxes in Eq. (4).

2.2.2 The β-model

An alternative to the airborne fraction model is to parameterize CO_2 uptakes as a linear function of CO_2 concentration or, equivalently, CO_2 mass (Gloor et al., 2010). Thus we write

$$F_{\text{land}} + F_{\text{ocean}} = \beta(q - qM - M_0) \tag{5}$$

where q is the concentration M is the mass of CO_2 and q_0 in the atmosphere and M_0 is the background or equilibrium mass of CO_2 concentrationin the atmosphere. Given the near-equilibrium of the preindustrial carbon cycle evident from the data of Etheridge et al. (1996) and Francey et al. (1999) we often use the preindustrial value of q for $q_0 M$ for M_0. With our focus in this paper on changes rather than mean values we are not interested in q_0 M_0 so we simplify Eq. (5) to

$$\left[F_{\text{land}} + F_{\text{ocean}} = \beta qM + F_0 \right] \tag{6}$$

[2]Airborne fraction can also be quoted relative to F_{fossil}

If instead of concentration we use units of PgC for q, β has units of yr^{-1} and plays the role of an inverse residence time for excess carbon against the processes of land and ocean uptake.

Substituting Eq. (6) into Eq. (1) yields

$$\frac{\partial M}{\partial t} = F_{\text{anthro}} - \beta q M - F_0 \tag{7}$$

With independent data available on F_{anthro} , M and q and M it is possible to estimate β and F_0 using standard statistical techniques such as linear regression. Below we apply this technique to flux estimates at several scales and from several sources. Although we consider some aspects of uncertainty in the calculation we have not attempted to cover the full range of flux estimates available in , for example, model or inversion intercomparisons applied our diagnostics to the ensembles of results available in intercomparisons of forward or inverse models.

3 Global responses

In this section we compare the behaviour of the two models introduced in Sect. 2.2. We use the data from the Global Carbon Project (Le Quéré et al., 2013) to estimate α from Eq. (3) and β from Eq. (6). Data in Le Quéré et al. (2013) comes from many sources. M (and consequently $\frac{\partial M}{\partial t}$) come from concentration measurements of CO_2 at South Pole and Mauna Loa before 1980 and a range of marine boundary layer sites thereafter. F_{fossil} is derived from inventories from the Carbon Dioxide Information Analysis Center. F_{LUC} and F_{ocean} come from a combination of inventories and models. F_{land} is derived as a residual.

We use the standard maximum likelihood least squares formulation so that

$$\boldsymbol{x} = \mathbf{K}\mathbf{J}^{\mathrm{T}}\mathbf{R}^{-1}\boldsymbol{y} \tag{8}$$

where $\boldsymbol{x}$ is the vector of unknowns we seek, $\boldsymbol{y}$ the data, $\mathbf{J}$ the Jacobian matrix mapping $\boldsymbol{x}$ to $\boldsymbol{y}$ and $\mathbf{R}$ the uncertainty covariance for $\boldsymbol{y}$. $\mathbf{K}$ is given by

$$\mathbf{K} = [\mathbf{J}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{J}]^{-1} \tag{9}$$

After some simplification the uncertainty covariance for $\boldsymbol{x}$ is given by

$$\mathbf{C}(\boldsymbol{x}) = \mathbf{K}^{-1} \tag{10}$$

For the α-model $\mathbf{J} = F_{\text{anthro}}$ and $\boldsymbol{y} = \frac{\partial M}{\partial t}$ while for the β-model ~~$\mathbf{J} = \frac{1}{q}$~~ $\mathbf{J} = \frac{1}{M}$ and $\boldsymbol{y} = F_{\text{anthro}} - \frac{\partial M}{\partial t}$. For the β-model we include a constant term in the inversion ~~, this~~ (see Eq. 5). This is mathematically the uptake when ~~$q = 0$~~ $M = 0$. Physically it represents uptakes which do not vary with ~~q~~ M, e.g. those caused by reforestation. It also contributes to the mean uptake over a period. We stress that we are not here concerned with the mean uptake over the whole or part of the study period.

For $\mathbf{R}$ there are two contributions, data uncertainties and modelling errors. The uncertainties in $\boldsymbol{y}$ are quoted in Le Quéré et al. (2013) as 5 % for F_{fossil}, $0.5\,\text{Pg C yr}^{-1}$ for F_{LUC} and 0.7 or $0.2\,\text{Pg C yr}^{-1}$ for $\frac{\partial M}{\partial t}$ before or after 1970. We add these quadratically. Growth-rate uncertainty dominates before 1970 while F_{LUC} is the largest contributor later. The root mean square value of the uncertainty is $0.69\,\text{Pg C yr}^{-1}$. The errors due to the simplicity of the models can only be calculated once we have performed the fit.

Le Quéré et al. (2013) did not give clear guidance on temporal correlation for their uncertainties. The most likely form for these is positive temporal correlation arising from systematic errors in reporting or biogeochemical models. Our analysis is concerned with trends, that is of year-to-year differences. Positive temporal correlations will increase the significance of these trends. Thus we make the conservative assumption of temporal independence. The one case where this is not true we will treat explicitly.

Figure 1 also shows the observed and predicted atmospheric growth-rate from the two models. The regression solutions give $\alpha = 0.45$ and $\beta = 0.016\,\text{yr}^{-1}$. The two models produce mean-square residuals of $0.95\,\text{Pg C yr}^{-1}$. Thus we use this value as the uncertainty $\mathbf{R}$ for the dependent variable in the regression for the β-model. It yields a 1σ uncertainty of $0.002\,\text{yr}^{-1}$. Calculating the uncertainty of α is more difficult since the most uncertain term is the Jacobian. We can approximate it by noting that the relationship between F_{anthro} and $\frac{\partial M}{\partial t}$ can be integrated to give $M_{\text{final}} - M_{\text{initial}} = \alpha \sum F_{\text{anthro}}$. The total change of CO_2 mass in the atmosphere is constrained by the initial and final concentration uncertainties and these concentrations are very well known. Thus the percentage error in α is the percentage error in $\sum F_{\text{anthro}}$. The uncertainty in $\sum F_{\text{anthro}}$ can be calculated directly by quadratically summing the annual uncertainties (assuming independence of the annual values) for the limiting cases of complete independence and perfect temporal correlation. For the independent case we sum uncertainties quadratically to give 4.3 Pg C of a total of 372 Pg C, or about 1 % uncertainty. The uncertainty in For the case of perfect correlation the 5 % uncertainty in annual values translates to a 5 % uncertainty in the total. Thus the uncertainty in α is hence about lies between 1 % and 5 %.

Figure 2 shows the residuals from the α and β models from Figure 1. The two models produce similar residuals. Both residuals are driven by short-term changes in the atmospheric growth-rate and arise from the failure of these simple integrated models to reproduce such changes. One striking similarity is the increase in the amplitude of the residuals with time. The amplitudes grow by 60 % from the first to the second half of the period. The interannual variability has been used by Cox et al. (2013) and Wang et al. (2014) to assess the sensitivity of the carbon cycle to forcing.

By construction, β provides an optimal fit to the time course of $\frac{\partial M}{\partial t}$ but this does not mean it is optimal throughout. We can ask whether different periods suggest different magnitudes for the first-order responseβ. Here we focus on the 11 year period 2002–2012. We repeat the calculationfor the first-order response obtaining a value , obtaining $\beta = 0.057 \pm 0.018\,\text{yr}^{-1}$. This is much larger but much more uncertain than the overall value of $\beta = 0.016 \pm 0.002\,\text{yr}^{-1}$. The large β value is a direct result of the negative trend in the residuals evident from 2002. The difference can be considered statistically significant with a 5 % probability of such a value or larger a larger value occurring by chance over this period. It is , however, not robust. Repeating We can also ask whether it is robust, that is how sensitive is the result to our choice of period. We repeat the analysis for every 11 year period in the record (i.e starting with 1959, 1960 etc). This yields 6 values greater than $0.057\,\text{yr}^{-1}$.

We can also ask whether the residuals mean residual of the fit of the β-model are is significantly different from 0. The mean residual for 2002–2012 is $-0.07 \pm 0.27\,\text{Pg C yr}^{-1}$with the . The large error bar is a result of the large interannual variability. In summary, the mean CO_2 uptake over the last decade is not significantly different from that predicted by a first-order linear response to concentration. The change in trend over that time is approaching significance but is not robust. Let us now analyze some spatially resolved estimates of fluxes to try to attribute the behaviour over the full period and more recently.

3.1 Land and ocean contributions

One very useful property of Eq. (6) is thatit can be decomposed as $\beta = \beta_1 + \beta_2 + \ldots$ provided that the processes represented by the different β_i are disjoint, if we can decompose fluxes as $F = F_1 + F_2 + \ldots$ we can decompose the corresponding β values as $\beta = \beta_1 + \beta_2 + \ldots$. We will show decompositions into land or ocean, by latitude band and by season. In each case we replace $\boldsymbol{y}$ in Eq. 8 with the corresponding flux.

First we calculate β for land and ocean separately using the values and uncertainties from Le Quéré et al. (2013). The uncertainties are 0.5 Pg C yr^{-1} for the ocean and 0.8 Pg C yr^{-1} for the land. We obtain $\beta = 0.010 \pm 0.001\,\text{yr}^{-1}$ for ocean and $\beta = 0.006 \pm 0.002\,\text{yr}^{-1}$ for land. The root mean square residuals are 0.18 Pg C yr^{-1} for ocean and 0.96 Pg C yr^{-1} for land. This The calculated residuals for land have larger magnitude than assumed which suggests we should increase the land β uncertainty to 0.003 yr^{-1}.

Figure 3 shows the GCP estimates and the linear fits. When analyzing these we must remember that the GCP land estimate is calculated as a residual from Eq. (1). The relatively small residuals from the ocean fit and the additive form of the β decomposition, imply that the residuals in the land uptake resemble those in the total uptake.

Again considering the period 2002–2012 we obtain 0.047 yr^{-1} for land and 0.01 yr^{-1} for ocean. As with the total uptake, there are 6 periods of 11 years with larger β for the land while the ocean value is at the mean and median for the set of 11 year periods. Thus even when accounting for the different interannual variability of each environment the relative changes in the land flux are much larger than for the ocean. Changes in land uptake explain all the increase in total uptake over 2002–2012 but this change cannot be regarded as robust.

4 Diagnostics for inversions

We can apply similar diagnostics to inverse estimates of fluxes . These also allow us further decompose land and ocean fluxes into their regional contribution and calculate the related β to attribute regional contributions to trends. We Regional flux estimates can come either from atmospheric inversions or models. In this section we use an update of the CCAM inversion used in Peylin et al. (2013) which extended the study of Rayner et al. (2008). The update extends the study period from 1992–2012. This allows expanded station coverage since more stations now meet the Rayner et al. (2008) required that stations must report measurements during 70temporal coverage requirement imposed by Rayner et al. (2008) . Some stations are also lost. % of months in their study period in order to be included. We apply the same criterion but the different study period means the network will be different from that of Rayner et al. (2008) . The $^{13}CO_2$ records are also extended to 2012. Calculations for the data uncertainties are as in Rayner et al. (2008). We use only the CCAM model from the earlier study.

Before we can trust the inversion to identify regional changes we verify its ability to match the atmospheric growth-rate. This is best done by comparing the net, non-fossil flux. For the GCP this is the sum of the LUC, land and ocean fluxes while for the inversion it is the annual mean, non-fossil flux. We are here interested in variability so we adjust the GCP and inverse mean fluxes to be equal for plotting purposes. The inclusion of the constant term in Eq. 5 means this will have no effect on the calculated β. Figure 4 shows the results for the GCP and inversion. As we would hope we see good agreement for both short and long term variability. We stress that this is a necessary but not sufficient condition for successful regionalization of trends.

Next we can ask whether the GCP and inversion agree on the land-ocean division of recent sink changes. Table 1 presents the results for the inversion and GCP budget for the periods 1992–2012 and 2002–2012. For comparison we calculate the net land flux for the GCP as the difference between LUC and land uptake. Similarly we calculate the uncertainty here from the residual budget between the growth rate, fossil fuel flux and ocean uptake. Most β values agree to within their uncertainties. We see general agreement on the predominance of land over ocean responses and the much stronger response over 2002–2012. Thus, as far as we can tell from independent evidence, the inversion is partitioning reasonably the first order linear responses of land and ocean. We stress that this was not preordained since the ocean models which control the trend in land-ocean partition for the GCP estimates do not inform the inversion. We can proceed to discuss the regional form of these responses.

Figure 5 shows the estimated flux and fit from the β model for land and ocean and northern extratropics, tropics and southern extratropics separately. The groupings are taken from Gurney et al. (2002) rather than a latitudinal separation. This allows us to calculate the uncertainty of the regional fluxes correctly. The uncertainties used in the β-model fit are the generated annual uncertainties from the posterior covariance of the inversion. Results of the fit are shown in Table 2 for 1992–2012 and 2002–2012. Both Fig. 5 and Table 2 show strong spatial patterns in the first-order linear response of uptake.

As one might expect from the small global β for the ocean, most ocean regions show weak response and, given their uncertainties, none could be reliably distinguished from 0. One exception is the southern extratropical ocean for 2002–2012. The large uncertainties counsel caution but the apparent increase in the response does not support findings of long-term reductions in uptake (e.g. Le Quere et al., 2009). This is in line with the results of Law et al. (2008).

For land, there is a strong positive response of uptake in the northern extratropics and near cancellation between the tropics and southern extratropics. The tropics shows a large negative β over the whole period. The tropical β depends strongly on the changes in F_{LUC}. This is particularly evident for 2002–2012 where the increase in β is coincident with a sharp downward trend in F_{LUC}. Any error in trends of F_{LUC} will be aliased into errors in the calculated β. The dipole in response between the tropics and southern extratropics raises the possibility of highly uncertain responses with strong error correlations. This was certainly the case for the mean flux noted by Jacobson et al. (2007) who reported large uncertainty correlations between these regions in atmospheric inversions.

The response with the largest signal-noise occurs in the northern extratropical land. The response is large over the whole period and much larger for 2002–2012 where it dominates the global signal. The increase in relative uncertainty as we move to smaller regions precludes a more detailed spatial examination of the signal. The results suggest that, notwithstanding the cautionary finding of Piao et al. (2008), the strong trend in greenness (e.g. Zhou et al., 2001; Xu et al., 2013) has made a strong imprint on the pattern of CO_2 uptake.

We can further decompose the β for the northern extratropical land into the positive and negative components of the flux. The growing season net flux (GSNF) is defined as the sum of all the negative (uptake) components over a year. We further define the quiescent season net flux (QSNF) as the sum of all the positive (source) fluxes. The annual uptake can be decomposed as annual flux = GSNF − QSNF and thus β can be decomposed as

$$\beta_{\text{annual}} = \beta_{\text{GSNF}} - \beta_{\text{QSNF}} \tag{11}$$

The term $\beta_{\text{GSNF}} + \beta_{\text{QSNF}}$ reflects a change in the integrated amplitude of the seasonal flux and hence to a likely change in the seasonal amplitude of concentration. These changes in amplitude have been noted by Keeling et al. (1995) and Graven et al. (2013) in surface and airborne measurements in the Northern Hemisphere. Roughly paraphrased, the argument of Piao et al. (2008) is that near cancellation between β_{GSNF} and β_{QSNF} means that changes in amplitude need not (and probably do not) correspond to changes in net flux.

Temporally decomposed β values for northern and southern extratropical land are also listed in Table 2. As might be expected, the uncertainties on seasonal fluxes are considerably larger than their annual means so again some caution is suggested in interpretting these values. We see a large ~~first-order~~ response in the GSNF but not in the QSNF. We can hence say that the response in net flux is due to the productive part of the year but it is still a step to say the response is related to production since atmospheric inversions sense only the net flux which is always ~~a sum of assimilation~~ the difference between production and respiration. One further clue to the likely driver is given by a similar analysis for the maximum uptake in each year. The uncertainties are even larger here but we do see similar increases for the maximum as for the GSNF. This suggests that it is the productivity which mediates the ~~first-order~~ linear response in the net flux and its change over time and that this change in productivity is the likeliest cause of the increasing annual uptake in the northern extratropics.

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5 An example of model responses

If the ~~first-order~~ linear diagnostic is a reasonable way to summarize the behaviour of the large-scale carbon cycle we can also apply it to models. This has the further advantage that we can create process diagnostics the same way. As examples, we analyze the ~~first-order~~ linear response of the LPJ-GUESS model (Smith et al., 2001) and the LPJ model (Sitch et al., 2003). LPJ combines mechanistic treatment of terrestrial ecosystem structure (vegetation composition, biomass) and function (energy absorption, carbon cycling). Vegetation dynamics are updated annually based on the productivity, disturbance, mortality, and establishment of nine plant functional types (PFTs). Modelled potential vegetation cover (including C3-/C4-plant distribution) depends on competition and climate history. LPJ-GUESS' process formulation of plant physiology and ecosystem biogeochemistry is similar to LPJ. However, in contrast to the area-based representation of vegetation structure and dynamics for mean individual plant types of LPJ, LPJ-GUESS employs a more detailed scheme that distinguishes woody plant type individuals (cohorts) and represents patch-scale heterogeneity. LPJ-GUESS explicitly models resource competition (light and water) and subsequent growth between woody plant type individuals on a number of replicate patches. Similar to LPJ, herbaceous under-storey (simulated using the grass PFT) is modelled, but individuals are not distinguished. While the LPJ simulation used here represents potential natural vegetation, LPJ-GUESS takes into account present day landuse by accounting for croplands and pastures as grass PFT using the 2005 cropland and pasture map from the Hyde 3.1 database (Klein Goldewijk et al., 2011). Both LPJ and LPJ-GUESS use fixed land cover so we fit the β-model to the output directly rather than correcting with F_{LUC}.

First we compare the global fluxes for the two models with F_{land} from the GCP. Figure 6 shows the three fluxes with means adjusted to agree with F_{land}. We see that LPJ agreement is poor for the first half of the period but improves considerably after 1980. The two models do comparably well in this period.

We have fluxes computed until 2011 for LPJ and 2010 for LPJ-GUESS so we analyze the longest possible period for each model for the closest comparison with the inversion. The β values for land in the northern semi-hemisphere, tropics and southern semi-hemisphere are listed in Table 3. We note that we cut the regions at 30° here rather than the more complex TRANSCOM boundaries boundaries from Gurney et al. (2002) used in the inversion. We see reasonable agreement for the global β for the whole period but only LPJ shows the dramatic increase in the second half of the period.

The regional structure of the first-order linear response in both models is quite different from that suggested by the inversions. Model responses are dominated by the tropics as is the intensification in response in the last decade. This strong positive response is offset by smaller negative responses in the extratropics. The inversion suggests positive responses in the extratropics (especially the north) with ambiguous response in the tropics.

6 Discussion

It is tempting to compare our β values with those of Gloor et al. (2010) . The important difference is that Gloor et al. (2010) do not include a constant term in their linear model (their Eq. 2) while we do. This means their value of β (τ_S in their formulation) will attempt to fit the mean value of uptake while ours will not. Given the likely role of other processes in uptake we would expect that our β value would underestimate mean uptake if used without the mean term. This, indeed, is the case with a mean uptake for 1959–2010 of 2.3 yr^{-1} compared to the GCP value of 3.8 yr^{-1}. Gloor et al. (2010) predict an uptake of 3.5 yr^{-1}. We stress that the formulation of Gloor et al. (2010) is valid for their purposes but that our focus made it important to separate the mean and trends.

We have analysed the CO_2 uptake throughout as a first-order linear response to concentration. We have not, however, proposed a causal link with CO_2 concentration itself since there are many other variables (most importantly timeand temperature e.g. time, temperature and LUC) which are highly colinear with CO_2 concentration. The record, especially of regionally resolved fluxes, is not long enough compared to the various exponential doubling times of emission and concentration to allow a clear separation between linear and exponential changes. The evidence from the inversion of a deepening of the growing season flux minimum does suggest a role for productivity, more strongly implicating concentration changes. Given the mechanistic link between productivity and concentration this does suggest increasing concentration changes have contributed to increased land uptake. The two ecosystem models we studied are too dissimilar in their responses to the inversion to use them as a diagnostic of the inferred flux behaviour.

The results for the most recent decade suggest a strong, but not yet robust increase in the first-order linear response. It suggests that if there is a change in carbon-cycle behaviour, it is in a benign direction direction to mitigate rather than exacerbate climate change. We note the much weaker response of tropical uptake and the sensitivity of our result to F_{LUC} estimates.

Finally, the first-order linear diagnostic suggests an interesting interpretation for the recent result of Wang et al. (2014). They noted a large increase in the interannual variability of the terrestrial carbon cycle over the second half of the GCP period. We noted the same thing when considering the residuals from our first-order linear fit. While it is tempting to interpret this increase as an increase in the climate sensitivity of the carbon cycle it seems equally possible that it is a constant modulation of a more strongly forced process. As an analogy we may consider a container with a tap at the bottom which is being randomly opened and closed. The variation in flow will increase as the height of water in the container increases even if the variation in the tap is unchanged. A weakness in this argument is the difference between the location of peak variability (usually located in the tropical land) and the dominant first-order response (located by the inversion in the extratropics).

The calculations in this paper are mainly exemplary. We have made little attempt yet to see how robust the findings are across different terrestrial models and inverse systems. The first of these is relatively easy, aided by several intercomparisons which collect model output. The specification of uncertainty is difficult for models however. For inversions the difficulty is to isolate the components of the flux which are legitimate targets for these diagnostics. F_{LUC} is often included in inverse models as part of the prior flux and it must be separated. Similarly, with an in-house inversion system it is possible to calculate uncertainty on the same scale as the flux estimates while this information is often not available for data from intercomparisons such as that of Peylin et al. (2013). That said, these diagnostics do seem a simple way of summarizing longer-term behaviour of any flux estimate. It will be interesting to see if the finding of Baker et al. (2006) that interannual variability in flux is more robust across the model ensemble than the mean flux also holds for these long-term changes.

7 Fazit

We have characterized the global and regional response of the carbon cycle as a ~~first-order~~ linear response to CO_2 concentration (or any colinear variable). We have seen that this fit works as well as the airborne fraction model with the advantage that it can be decomposed by time and space. We see an increase in the ~~first-order~~ linear global response in recent years dominated by land. Inverse flux estimates show a similar response and locate it in the northern extratropics and the growing season. ~~Models~~ Terrestrial ecosystem models show a similar global response but, by contrast, locate it in the tropics.

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Literatur

Baker, D. F., Law, R. M., Gurney, K. R., Rayner, P., Peylin, P., Denning, A. S., Bousquet, P., Bruhwiler, L., Chen, Y.-H., Ciais, P., Fung, I. Y., Heimann, M., John, J., Maki, T., Maksyutov, S., Masarie, K., Prather, M., Pak, B., Taguchi, S., and Zhu, Z.: TransCom 3 inversion intercomparison: impact of transport model errors on the interannual variability of regional CO_2 fluxes, 1988–2003, Global Biogeochem. Cy., 20, GB1002, doi:10.1029/2004GB002439, 2006.

Canadell, J. G., Le Quéré, C., Raupach, M. R., Field, C. B., Buitenhuis, E. T., Ciais, P., Conway, T. J., Gillett, N. P., Houghton, R. A., and Marland, G.: Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks, P. Natl. Acad. Sci. USA, 104, 18866–18870, doi:10.1073/pnas.0702737104, 2007.

Cox, P. D., Betts, R. A., Jones, C. D., Spall, S. A., and Totterdell, I. J.: Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model, Nature, 408, 184–187, 2000.

Cox, P. M., Pearson, D., Booth, B. B., Friedlingstein, P., Huntingford, C., Jones, C. D., and Luke, C. M.: Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability, Nature, 494, 341–344, 2013.

Enting, I. G., Rayner, P. J., and Ciais, P.: Carbon Cycle Uncertainty in REgional Carbon Cycle Assessment and Processes (RECCAP), Biogeosciences, 9, 2889–2904, doi:10.5194/bg-9-2889-2012, 2012.

Etheridge, D. M., Steele, L. P., Langenfelds, R. L., Francey, R. J., Barnola, J. M., and Morgan, V. I.: Natural and anthropogenic changes in atmospheric CO_2 over the last 1000 years from air in Antarctic ice and firn, J. Geophys. Res., 101D, 4115–4128, 1996.

Francey, R. J., Allison, C. E., Etheridge, D. M., Trudinger, C. M., Enting, I. G., Leuenberger, M., Langenfelds, R. L., Michel, E., and Steele, L. P.: A 1000-year high precision record of δ^{13}C in atmospheric CO_2, Tellus B, 51, 170–193, 1999.

Francey, R. J., Trudinger, C. M., Van Der Schoot, M., Krummel, P. B., Steele, L. P., and Langenfelds, R. L.: Differences between trends in atmospheric CO_2 and the reported trends in anthropogenic CO_2 emissions, Tellus B, 62, 316–328, doi:10.1111/j.1600-0889.2010.00472.x, 2010.

Francey, R. J., Trudinger, C. M., van der Schoot, M., Law, R. M., Krummel, P. B., Langenfelds, R. L., Paul Steele, L., Allison, C. E., Stavert, A. R., Andres, R. J., and Rodenbeck, C.: Atmospheric verification of anthropogenic CO_2 emission trends, Nature Clim. Change, 3, 520–524, doi:10.1038/nclimate1817, 2013.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Doney, S., Eby, M., Fung, I., Govindasamy, B., 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., Thompson, S., Weaver, A. J., Yoshikawa, C., and Zeng, N.: Climate -carbon cycle feedback analysis, results from the C4MIP model intercomparison, J. Climate, 19, 3737–3753, 2006.

Gloor, M., Sarmiento, J. L., and Gruber, N.: What can be learned about carbon cycle climate feedbacks from the CO_2 airborne fraction?, Atmos. Chem. Phys., 10, 7739–7751, doi:10.5194/acp-10-7739-2010, 2010.

Graven, H. D., Keeling, R. F., Piper, S. C., Patra, P. K., Stephens, B. B., Wofsy, S. C., Welp, L. R., Sweeney, C., Tans, P. P., Kelley, J. J., Daube, B. C., Kort, E. A., Santoni, G. W., and Bent, J. D.: Enhanced seasonal exchange of CO_2 by northern ecosystems since 1960, Science, 341, 1085–1089, doi:10.1126/science.1239207, 2013.

Gurney, K. R., Law, R. M., Denning, A. S., Rayner, P. J., Baker, D., Bousquet, P., Bruhwiler, L., Chen, Y.-H., Ciais, P., Fan, S., Fung, I. Y., Gloor, M., Heimann, M., Higuchi, K., John, J., Maki, T., Maksyutov, S., Masarie, K., Peylin, P., Prather, M., Pak, B. C., Randerson, J., Sarmiento, J., Taguchi, S.,

Takahashi, T., and Yuen, C.-W.: Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models, Nature, 415, 626–630, 2002.
Jacobson, A. R., Mikaloff Fletcher, S. E., Gruber, N., Sarmiento, J. L., and Gloor, M.: A joint atmosphere–ocean inversion for surface fluxes of carbon dioxide: 2. Regional results, Global Biogeochem. Cy., 21, GB1020, doi:10.1029/2006GB002703, 2007.
Keeling, C. D., Whorf, T. P., Wahlen, M., and van der Plicht, J.: Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980, Nature, 375, 666–670, 1995.
Klein Goldewijk, K., Beusen, A., van Drecht, G., and de Vos, M.: The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years, Global Ecol. Biogeogr., 20, 73–86, doi:10.1111/j.1466-8238.2010.00587.x, 2011.
Knorr, W.: Is the airborne fraction of anthropogenic CO_2 emissions increasing?, Geophys. Res. Lett., 36, L21710, doi:10.1029/2009GL040613, 2009.
Law, R. M., Matear, R. J., and Francey, R. J.: Comment on "Saturation of the Southern Ocean CO_2 Sink Due to Recent Climate Change", Science, 319, 570, doi:10.1126/science.1149077, 2008.
Le Quéré, C., Rödenbeck, C., Buitenhuis, E. T., Conway, T. J., Langenfelds, R., Gomez, A., Labuschagne, C., Ramonet, M., Nakazawa, T., Metzl, N., Gillett, N., and Heimann, M.: Saturation of the Southern Ocean CO_2 sink due to recent climate change, Science, 316, 1735–1738, doi:10.1126/science.1136188, 2007.
Le Quéré, C., Peters, G. P., Andres, R. J., Andrew, R. M., Boden, T. A., Ciais, P., Friedlingstein, P., Houghton, R. A., Marland, G., Moriarty, R., Sitch, S., Tans, P., Arneth, A., Arvanitis, A., Bakker, D. C. E., Bopp, L., Canadell, J. G., Chini, L. P., Doney, S. C., Harper, A., Harris, I., House, J. I., Jain, A. K., Jones, S. D., Kato, E., Keeling, R. F., Klein Goldewijk, K., Körtzinger, A., Koven, C., Lefèvre, N., Maignan, F., Omar, A., Ono, T., Park, G.-H., Pfeil, B., Poulter, B., Raupach, M. R., Regnier, P., Rödenbeck, C., Saito, S., Schwinger, J., Segschneider, J., Stocker, B. D., Takahashi, T., Tilbrook, B., van Heuven, S., Viovy, N., Wanninkhof, R., Wiltshire, A., and Zaehle, S.: Global carbon budget 2013, Earth Syst. Sci. Data, 6, 235–263, doi:10.5194/essd-6-235-2014, 2014.
Le Quere, C., Raupach, M. R., Canadell, J. G., Marland, G., Bopp, L., Ciais, P., Conway, T. J., Doney, S. C., Feely, R. A., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R. A., House, J. I., Huntingford, C., Levy, P. E., Lomas, M. R., Majkut, J., Metzl, N., Ometto, J. P., Peters, G. P., Prentice, I. C., Randerson, J. T., Running, S. W., Sarmiento, J. L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., van der Werf, G. R., and Woodward, F. I.: Trends in the sources and sinks of carbon dioxide, Nat. Geosci., 2, 831–836, doi:10.1038/ngeo689, 2009.

Nabuurs, G.-J., Lindner, M., Verkerk, P. J., Gunia, K., Deda, P., Michalak, R., and Grassi, G.: First signs of carbon sink saturation in European forest biomass, Nature Clim. Change, 3, 792–796, doi:10.1038/nclimate1853,2013.

Peylin, P., Law, R. M., Gurney, K. R., Chevallier, F., Jacobson, A. R., Maki, T., Niwa, Y., Patra, P. K., Peters, W., Rayner, P. J., Rödenbeck, C., van der Laan-Luijkx, I. T., and Zhang, X.: Global atmospheric carbon budget: results from an ensemble of atmospheric CO_2 inversions, Biogeosciences, 10, 6699–6720, doi:10.5194/bg-10-6699-2013, 2013.

Piao, S., Ciais, P., Friedlingstein, P., Peylin, P., Reichstein, M., Luyssaert, S., Margolis, H., Fang, J., Barr, A., Chen, A., Grelle, A., Hollinger, D. Y., Laurila, T., Lindroth, A., Richardson, A. D., and Vesala, T.: Net carbon dioxide losses of northern ecosystems in response to autumn warming, Nature, 451, 49–52, doi:10.1038/nature06444, 2008.

Raupach, M. R., Canadell, J. G., and Le Quéré, C.: Anthropogenic and biophysical contributions to increasing atmospheric CO_2 growth rate and airborne fraction, Biogeosciences, 5, 1601–1613, doi:10.5194/bg-5-1601-2008, 2008.

Rayner, P. J., Law, R. M., Allison, C. E., Francey, R. J., and Pickett-Heaps, C.: The interannual variability of the global carbon cycle (1992–2005) inferred by inversion of atmospheric CO_2 and $\delta^{13}CO_2$ measurements, Global Biogeochem. Cy., 22, GB3008, doi:10.1029/2007GB003068, 2008.

Revelle, R. and Suess, H. E.: Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO_2 during the past decades, Tellus, 9, 18–27, 1957.

Saleska, S. R., Miller, S. D., Matross, D. M., Goulden, M. L., Wofsy, S. C., da Rocha, H. R., de Camargo, P. B., Crill, P., Daube, B. C., de Freitas, H. C., Hutyra, L., Keller, M., Kirchhoff, V., Menton, M., Munger, J. W., Pyle, E. H., Rice, A. H., and Silva, H.: Carbon in Amazon forests: unexpected seasonal fluxes and disturbance-induced losses, Science, 302, 1554–1557, 2003.

Sarmiento, J. L., Hughes, T. M. C., Stouffer, R. J., and Manabe, S.: Simulated response of the ocean carbon cycle to anthropogenic climate warming, Nature, 393, 245–249, 1998.

Sarmiento, J. L., Gloor, M., Gruber, N., Beaulieu, C., Jacobson, A. R., Mikaloff Fletcher, S. E., Pacala, S., and Rodgers, K.: Trends and regional distributions of land and ocean carbon sinks, Biogeosciences, 7, 2351–2367, doi:10.5194/bg-7-2351-2010, 2010.

Schuster, U. and Watson, A. J.: A variable and decreasing sink for atmospheric CO_2 in the North Atlantic, J. Geophys. Res., 112, C11006, doi:10.1029/2006JC003941, 2007.

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K., and Venevsky, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, Glob. Change Biol., 9, 161–185, doi:10.1046/j.1365-2486.2003.00569.x, 2003.

Smith, B., Prentice, I. C., and Sykes, M. T.: Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space, Global Ecol. Biogeogr., 10, 621–637, doi:10.1046/j.1466-822X.2001.t01-1-00256.x, 2001.

Tarantola, A.: Inverse Problem Theory and Methods for Model Parameter Estimation, SIAM, (ISBN 0-89871-572-5), 2004.

Wang, X., Piao, S., Ciais, P., Friedlingstein, P., Myneni, R. B., Cox, P., Heimann, M., Miller, J., Peng, S., Wang, T., Yang, H., and Chen, A.: A two-fold increase of carbon cycle sensitivity to tropical temperature variations, Nature, 506, 212–215, 2014.

Xu, L., Myneni, R., Chapin, F., Callaghan, T., Pinzon, J., Tucker, C., Zhu, Z., Bi, J., Ciais, P., Tommervik, H., Euskirchen, E., Forbes, B., Piao, S., Anderson, B., Ganguly, S., Nemani, R., Goetz, S., Beck, P., Bunn, A., Cao, C., and Stroeve, J.: Temperature and vegetation seasonality diminishment over northern lands, Nat. Clim. Change, 3, 581–586, doi:10.1038/nclimate1836, 2013.

Zhou, L. M., Tucker, C. J., Kaufmann, R. K., Stayback, D., Shabanov, N. V., and Myneni, R. B.: Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999, J. Geophys. Res.-Atmos., 106, 20069–20083, 2001.

Tabelle 1. Land and ocean β values from the GCP budget and inversion for the periods 1992–2012 and 2002–2012.

Flux	1992–2012		2002–2012	
	$\beta\,\mathrm{yr}^{-1}$	uncertainty yr^{-1}	$\beta\,\mathrm{yr}^{-1}$	uncertainty yr^{-1}
Inversion Land	0.025	0.007	0.050	0.017
GCP Land	0.017	0.005	0.056	0.015
Inversion Ocean	0.003	0.005	0.014	0.012
GCP Ocean	0.008	0.005	0.009	0.011

Tabelle 2. Land and ocean β values from the inversion for northern extratropics, tropics and southern extratropics for the periods 1992–2012 and 2002–2012.

Flux	1992–2012 $\beta\,\mathrm{yr}^{-1}$	uncertainty yr^{-1}	2002–2012 $\beta\,\mathrm{yr}^{-1}$	uncertaintyyr^{-1}
northern land	~~0.016~~ 0.015	0.005	~~0.031~~ 0.037	0.012
northern ocean	0.002	0.002	~~0.001~~ −0.004	0.005
tropical land	−~~0.013~~ 0.014	0.008	~~−~~0.002	0.021
tropical ocean	0.001	0.003	0.002	~~0.007~~0.006
southern land	~~0.010~~ 0.009	0.007	~~0.014~~ 0.017	0.016
southern ocean	0.001	0.003	~~0.011~~ 0.007	~~0.008~~ 0.007
Northern GSNF	~~0.015~~ 0.014	~~0.028~~ 0.027	~~0.030~~ 0.034	~~0.070~~ 0.069
Northern QSNF	−~~0.000~~ 0.001	0.009	−~~0.002~~ 0.003	0.024
Southern GSNF	~~0.008~~ 0.010	~~0.024~~ 0.023	~~0.012~~ 0.014	0.060
Southern QSNF	−~~0.003~~ 0.002	~~0.017~~ 0.015	−~~0.002~~ 0.003	~~0.042~~0.039
Northern max	~~0.016~~ 0.013	0.027	~~0.035~~ 0.037	0.067
f Southern max	~~0.012~~ 0.007	0.027	~~0.019~~ 0.018	0.067

Tabelle 3. Global and regional β values for the LPJ and LPJ-GUESS models along with the GCP Land estimates.

Flux	1992–2010/11		2002–2010/11	
	$\beta\,\mathrm{yr}^{-1}$	uncertainty yr^{-1}	$\beta\,\mathrm{yr}^{-1}$	uncertainty yr^{-1}
LPJ Global	0.020	0.020	0.139	0.055
LPJ-GUESS Global	0.020	0.020	0.051	0.063
GCP Land	0.015	0.020	0.13	0.055
LPJ Northern	−0.010	0.020	−0.014	0.055
LPJ-GUESS Northern	−0.001	0.022	0.010	0.064
LPJ Tropics	0.038	0.020	0.140	0.055
LPJ-GUESS Tropics	0.032	0.022	0.066	0.064
LPJ South	−0.004	0.020	0.027	0.055
LPJ-GUESS South	−0.005	0.022	−0.000	0.064

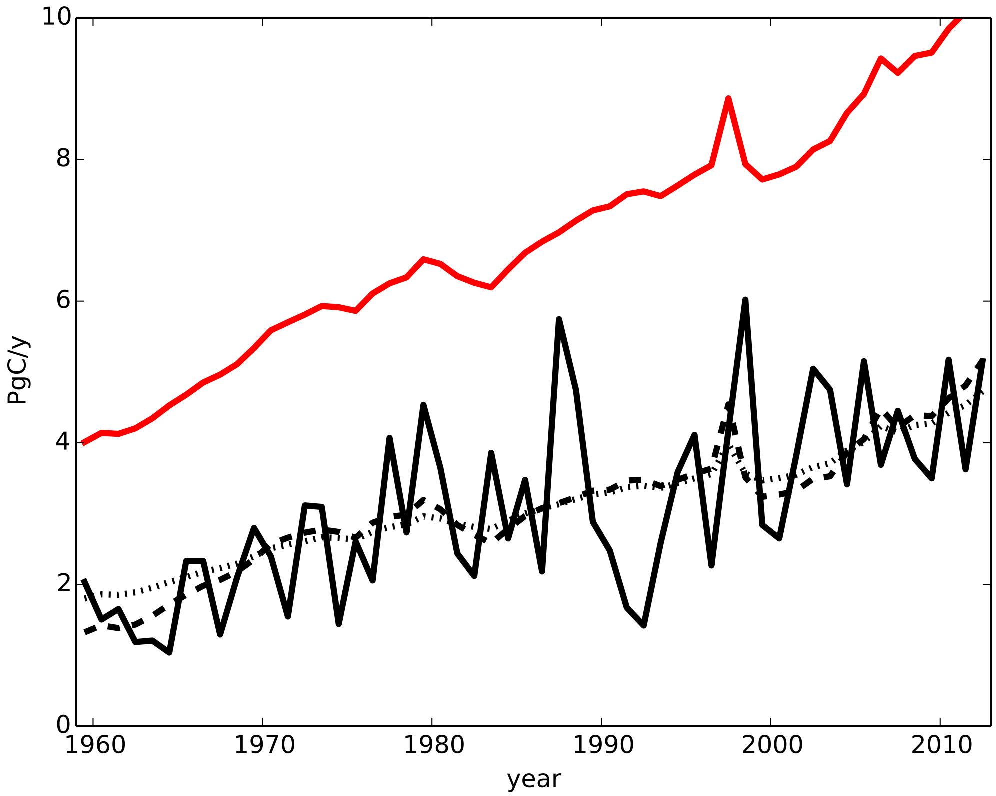

Abb. 1. Anthropogenic inputs (red) and atmospheric growth rate (black) from Le Quéré et al. (2013). Anthropogenic inputs include both fossil and land-use. The dotted line shows the predicted atmospheric growth-rate from the airborne fraction model while the dashed line shows the growth-rate from the β-model.

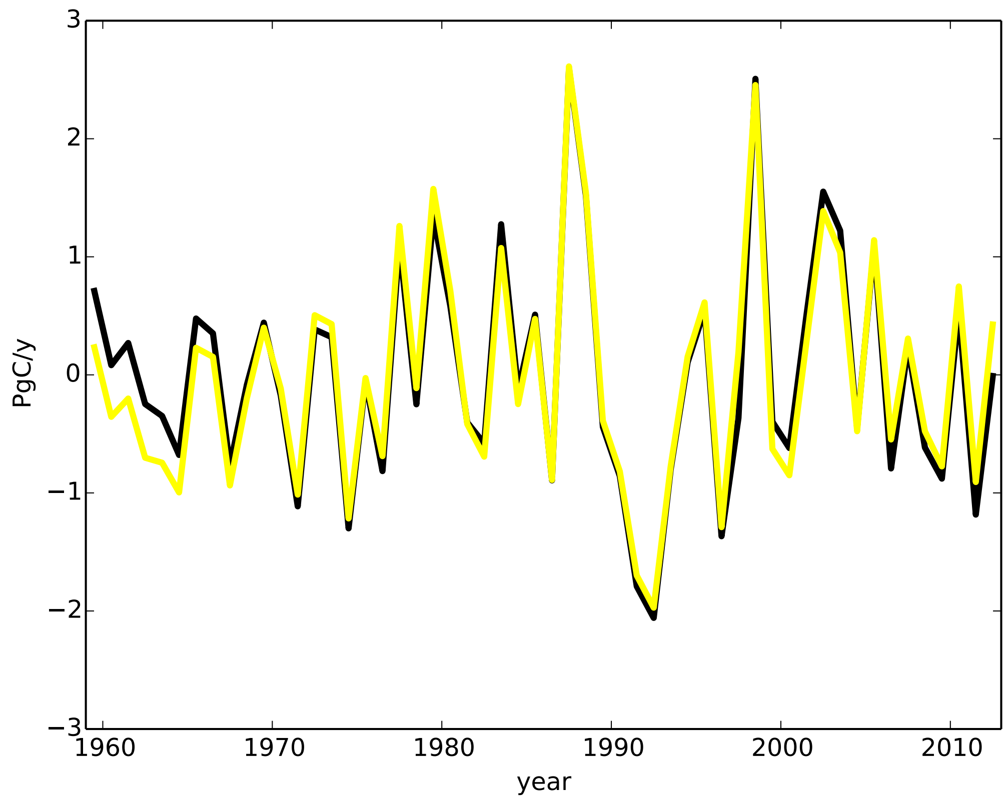

Abb. 2. ~~Ocean uptake~~ Residuals in the growth rate (~~blue~~observed − predicted) for the α model (black) and ~~land uptake~~ β model (~~green~~black)~~in~~ .~~Dashed lines are estimates from Le Quéré et al. (2013) while the solid lines are predictions from the first-order model.~~

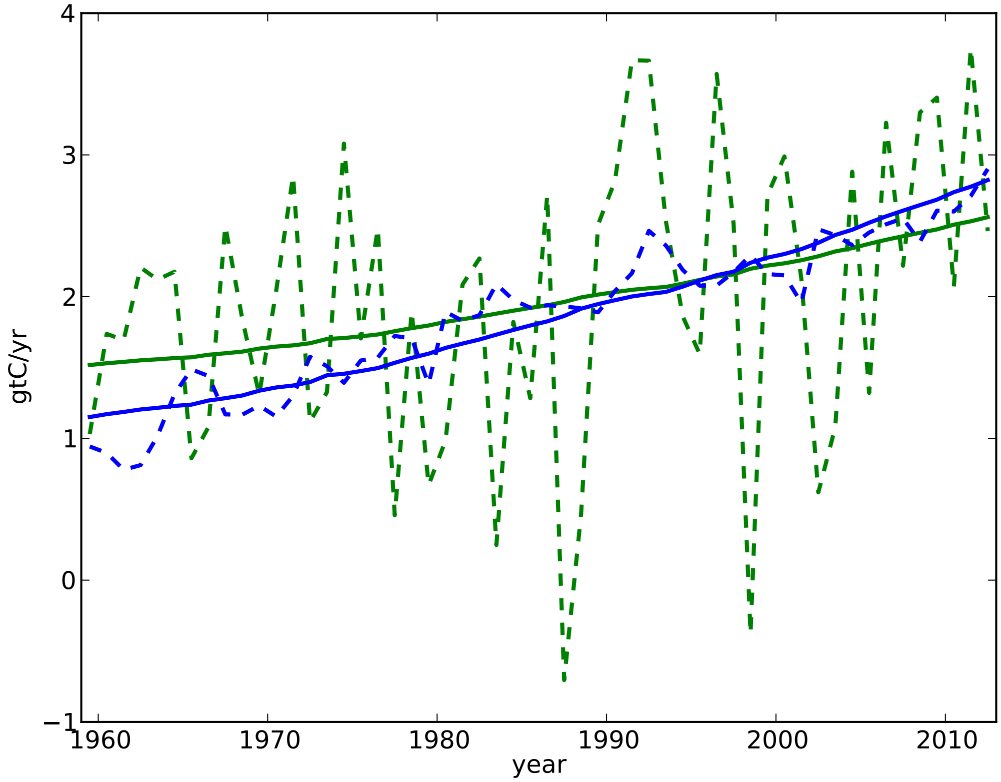

Abb. 3. Ocean uptake (blue) and land uptake (green) in $\mathrm{Pg\,C\,yr^{-1}}$. Dashed lines are estimates from Le Quéré et al. (2013) while the solid lines are predictions from the β model.

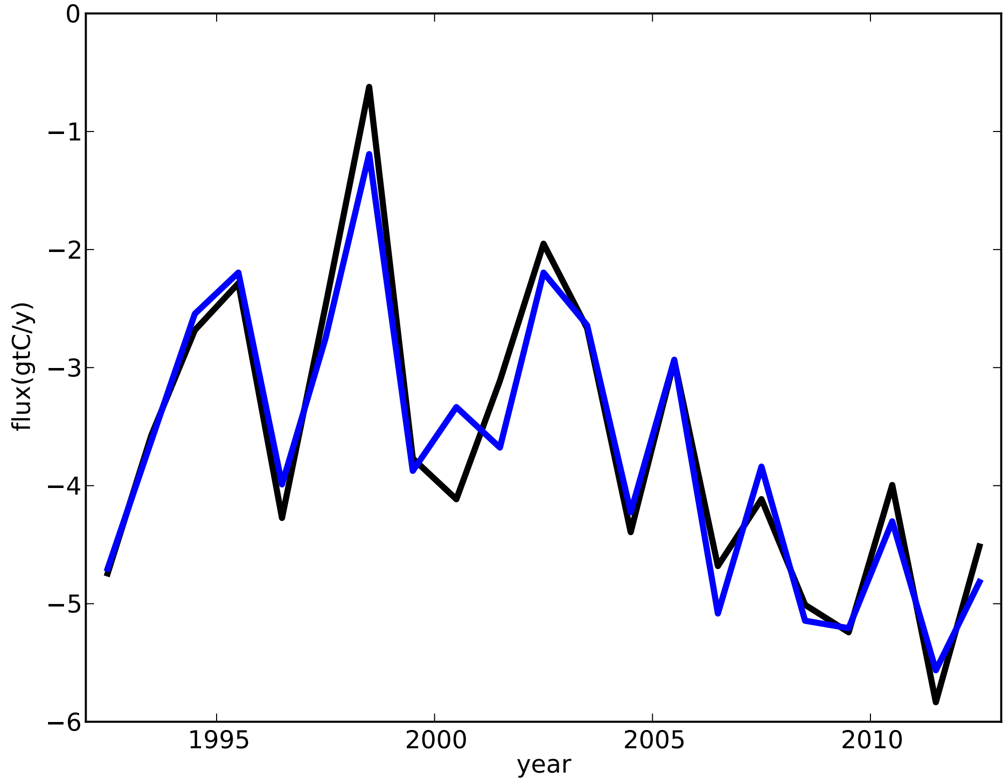

Abb. 4. Net uptake from Le Quéré et al. (2013) (black) and from the inversion (blue). Means over the period have been adjusted to be equal.

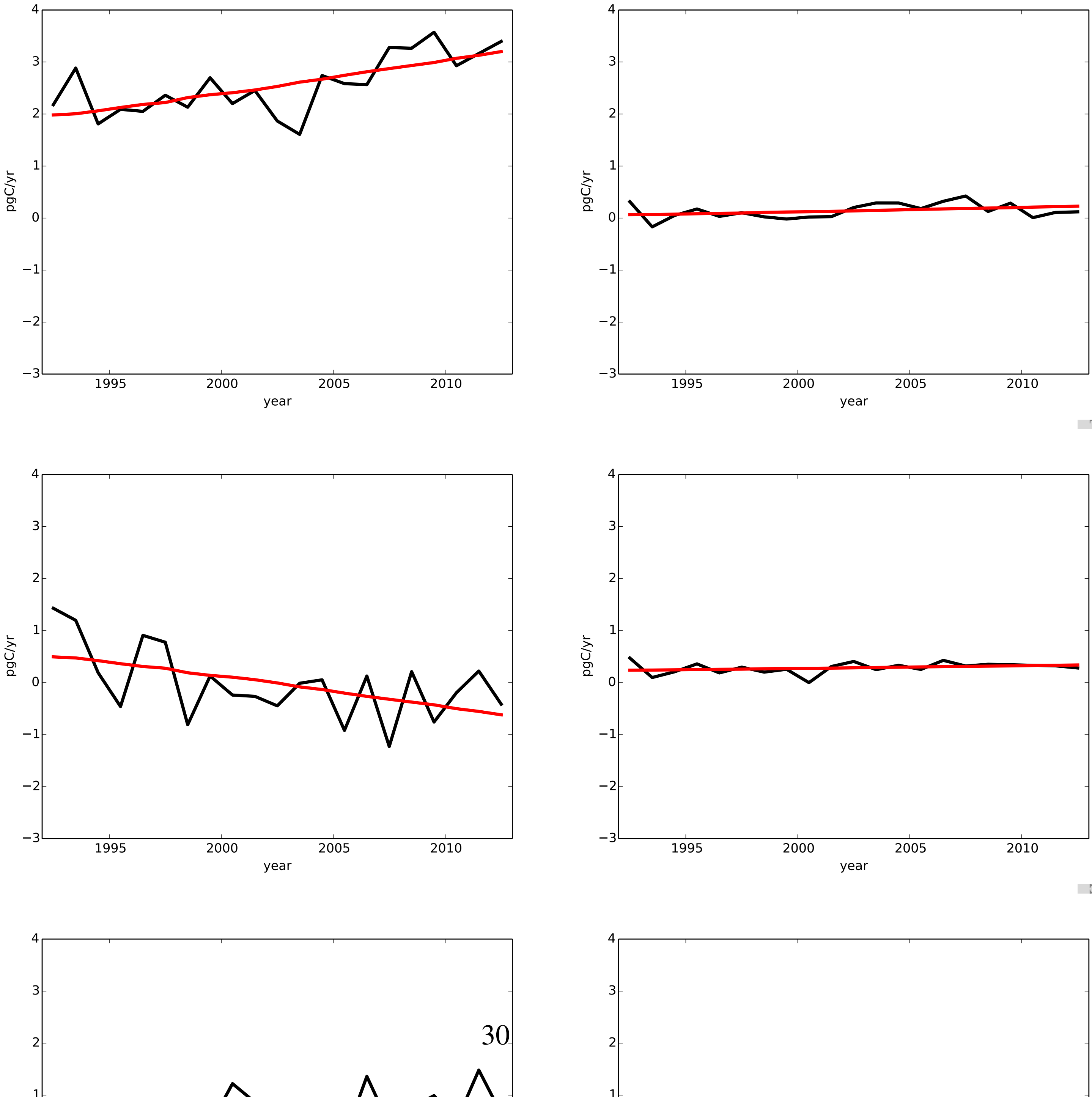
pgC/yr
year
4
3
2
1
0
−1
−2
−3
1995
2000
2005
2010

Abb. 5. Estimated uptake from inversion (black) and ~~first-order~~ β-model fit (red) for the north (top row), tropics (middle) and south (bottom) with land on the left and ocean on the right.

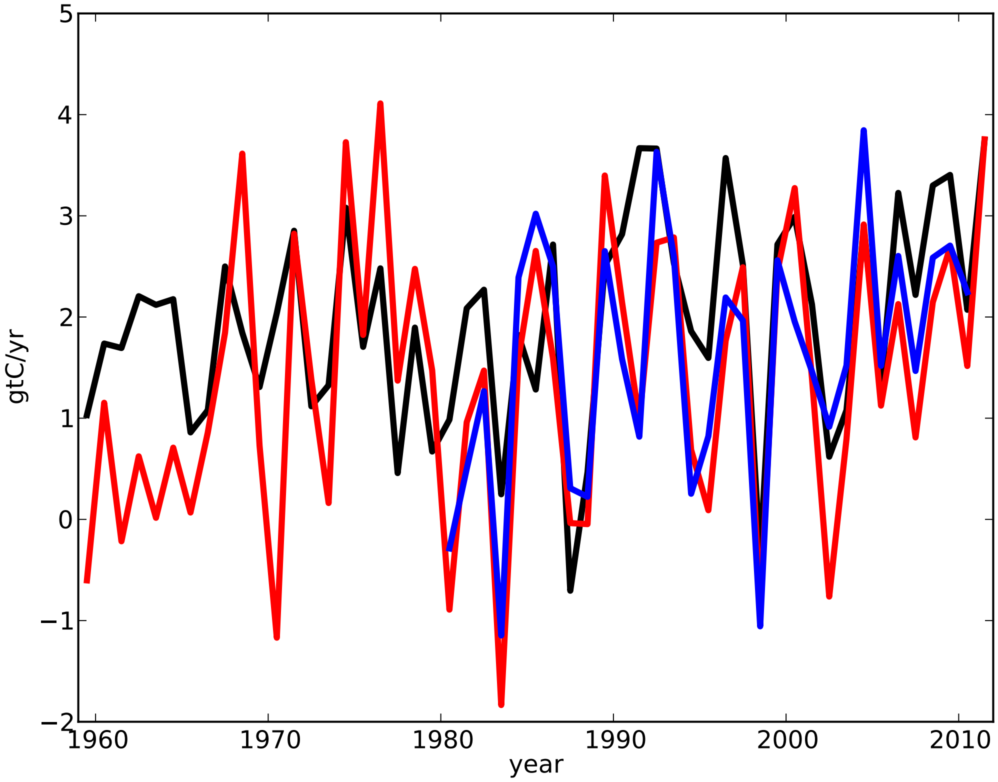

Abb. 6. Terrestrial uptakes from Le Quéré et al. (2013) (black), LPJ (red) and LPJ-GUESS (blue). Means have been adjusted to give equal uptake over the whole period.