Response to comment by Corinne Le Quéré on our study 'What can be learned about carbon cycle climate feedbacks from CO_2 airborne fraction?'

Corinne Le Quéré raises the question of where our simple land vegetation 'model' fits in with her modelling result that global vegetation models respond differently to a warming climate compared to a constant climate (Le Quéré et al. 2009). Specifically in a warming climate land vegetation models take up less carbon from approximately 1970 onwards (see below). As a consequence the implied airborne fraction differs for the two simulation scenarios. Corinne Le Quéré also asks two questions: (1) what trend in the efficiency of the land carbon sink, with sink efficiency defined as in our study, would correspond to the difference in the land carbon uptake in the two Le Quéré et al. (2009) model simulations, and (2) whether the climate effect would be detectable at a statistically significantly level. We will try to address these questions here briefly, in addition to the most important question, (3) which of the models is closest to observations and what are the implications for a potential feedback between carbon cycle and climate.

Corinne Le Quéré has provided us with the global atmosphere to land and atmosphere to ocean carbon fluxes, $F_{at>ld}$ and $F_{at>oc}$ respectively for constant and changing climate, which were discussed in Le Quéré et al. (2009). The atmosphere to land fluxes are calculated as the mean of the simulation results from 5 models. For our analysis we calculate the temporal rate of change of atmospheric carbon, dC/dt, from her ensemble mean fluxes as

$$\frac{dC}{dt} = FF + LU - F_{at\rightarrow oc} - F_{at\rightarrow ld}$$

where FF is fossil fuel carbon emissions from Marland et al. 2006, updated by Boden et al. 2009, and LU is carbon emissions to the atmosphere due to land use change from Houghton et al. 2007. Similarly we calculate the airborne fraction, AF, as

$$AF \equiv \frac{\frac{dC}{dt}}{FF + LU} = \frac{FF + LU - F_{at\rightarrow oc} - F_{at\rightarrow ld}}{FF + LU} = 1 - \frac{F_{at\rightarrow oc} + F_{at\rightarrow ld}}{FF + LU}$$

We address the first question in figure 1, where we show a calculation of the atmosphere to land carbon flux predicted by our simple linear model as

$$F_{at\rightarrow ld} = \frac{\Delta C}{\tau_{ld}}$$

with $\Delta C(t) \equiv C(t) - C(1765)$. The main results are (i) that the simple linear vegetation model prediction lies between the two Le Quéré et al. (2009) sets of model simulations with changing climate versus constant climate (as expected), and it is qualitatively similar to both, (ii) that the inter-annual variability of the simulation using a changing climate is much larger compared to the constant climate simulation, and (iii) that the 1972-1979 period does not seem to be realistic in the simulation with climate change. This is in agreement with the conclusions of Le Quéré et al. (2009). In the following we therefore exclude this period from our analysis.

We address the second point raised by Corinne Le Quéré in figure 2. The slope of AF of the simulation results based on a changing climate is nearly zero whereas with constant climate it is negative. As a consequence the slope of the difference $AF_{changing\ clim} - AF_{const\ clim}$ is positive. The value of this slope is similar to the slope we predicted for a sink efficiency change of 50\% over approximately 50 years based on Eq. (3) of our study (section 5). We found that such a slope would be detectable at the 90 \% significance level over a 50 year period (section 5). It would not be detectable at this significance level if based on a 27 year period only.

We finally address the third question in figure 3, which is 'which of the models comes closest to observations? and what are the implications for a potential carbon cycle climate feedback?'

We view the temporal rate of change of atmospheric carbon, dC/dt, as the most suitable observational constraint for this purpose because, in contrast to AF, it does not involve anthropogenic flux estimates. For the reasons mentioned above we focus here on the 1980-2007 period. We notice first that the simulation results based on a constant climate and our simple model predictions are quite similar, while they both differ from the changing climate simulation predictions. Specifically the simulations based on a changing and constant climate over- and under- predict dC/dt, respectively. Neither of the two simulation types are confirmed in full by the observations.

Since the simple-model / constant climate simulations under-predict somewhat the observations we may ask ourselves to what extent this could be indicative of a climate feedback signature and whether it would be detectable given the data.

If we first interpret the difference between observed and simple-model / constant climate simulation predictions entirely as a climate response signal, then the magnitude of the signal is approximately half the magnitude of the difference between climate change and constant climate simulations. The implied signal in the slope of AF would then likely similarly be approximately half of the difference of the slope in AF between climate change and constant climate simulations shown in Figure 2. Such a signal, if due to a 50 \% change in sink efficiency, would not be detectable at a significant level over the 50 year period considered and even less detectable over a period of 27 years.

We may analyze the differences between the simulations a bit further to understand what causes the over-/under-prediction events, specifically whether they are caused by a changing climate alone or partially caused by extrinsic non-anthropogenic forcings (volcanic eruptions, climate oscillations). In the latter case they should be removed when estimating the difference between simulations and observations for the purpose of sink efficiency detection. Two main features in the 1980-2007 period are indeed known to be due to extrinsic, non-anthropogenic forcings: the increased land carbon uptake associated with the Pinatubo eruption and the Indonesian peat burning pulse signature. If we omit these two events, the main difference between observed and simple model prediction is the 2002/3 event which our analysis based on AF has already lead us to interpret as a possibly non-linear climate response feedback event. Other than this event the remaining differences are small. We would also like to reiterate that the 'noise' in this detection problem is actually greater than what we used in our analysis. Additional variance which should be taken into account in a proper signal/noise analysis, is the variance across the different simulations, and the variance in anthropogenic emissions estimates, particularly those associated with land use change. Finally we should not forget model limitations per se which cause biases.

It is interesting to analyze a bit further why the simulations with and without changing climate differ. There are four remaining events / signatures when the climate change versus simple linear model / constant climate simulations differ: 1983, 1987, 1994/95 and 2002/3. Climate change simulations over-predict the associated changes in atmospheric carbon, and constant climate change simulations under-predict changes in atmospheric carbon. All of these events coincide with El Niño phases (or at least positive El Niño index phases) of the El Niño Southern Oscillation. The difference in the simulation results is thus related to the specific El Niño response of these models.

Overall we conclude first that our simple model is not that far off from either of the two simulations which Corinne Le Quéré asked us to analyze supporting the credibility of our original analysis, and secondly that the difference between atmospheric concentration observations and constant climate simulations is currently too small to statistically robustly infer a decrease in carbon sink efficiencies.

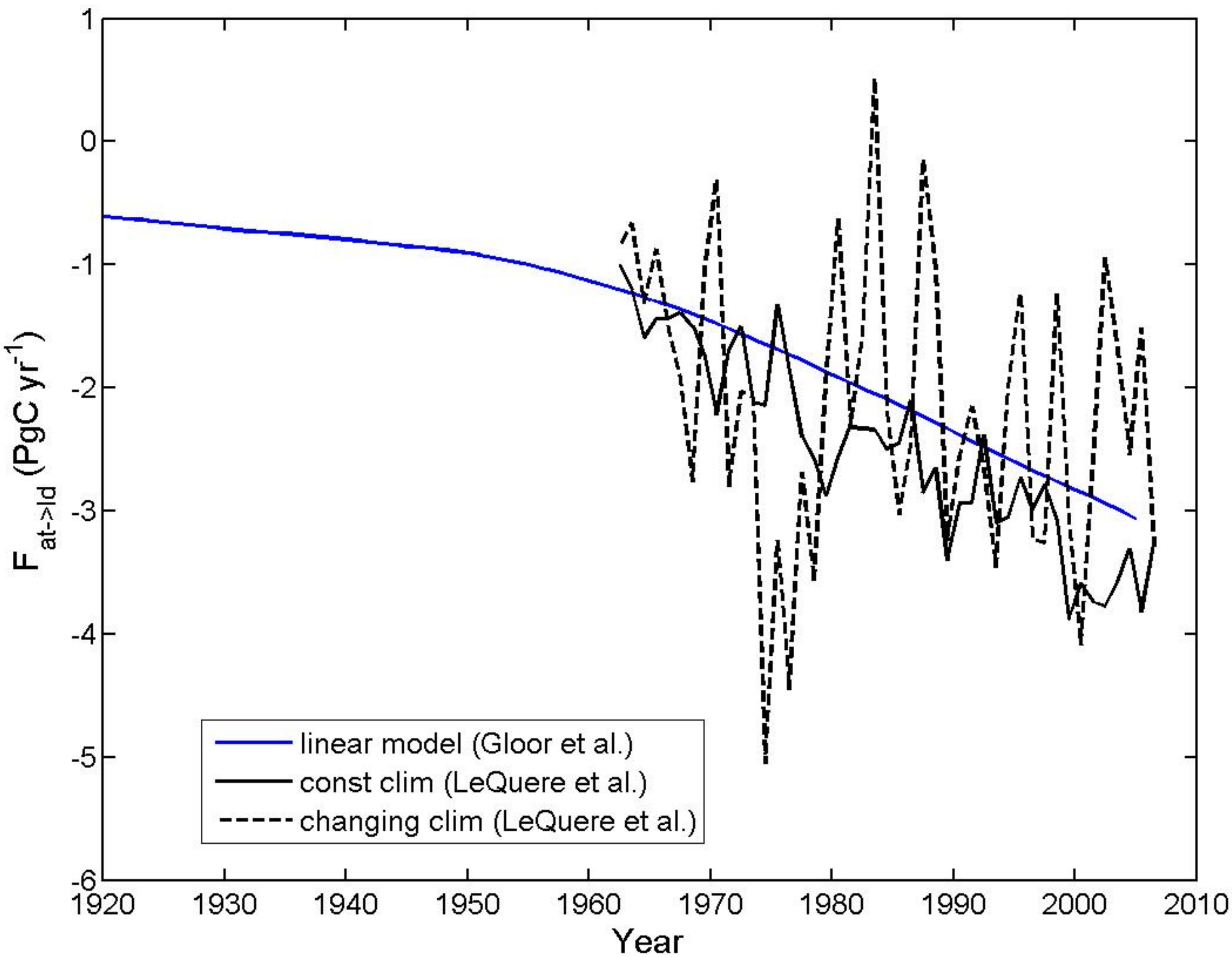
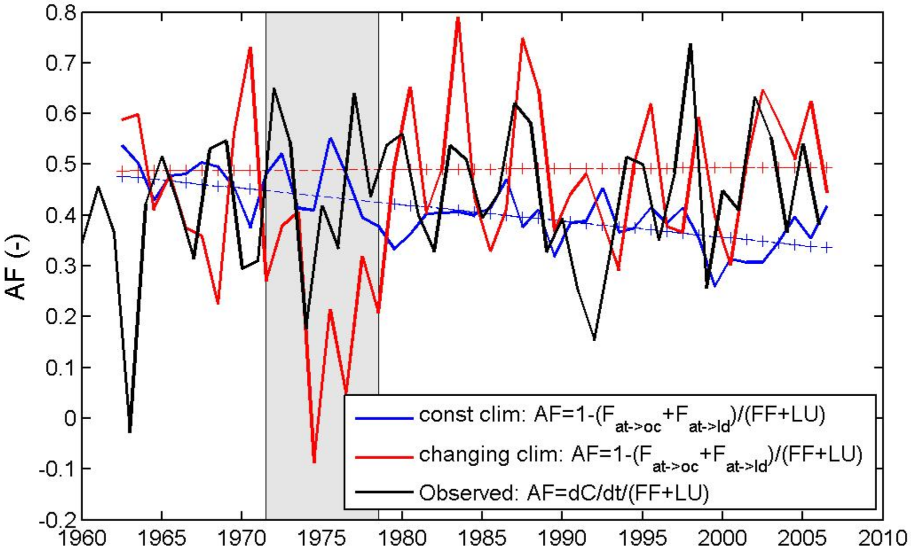


Figure 1 Comparison of atmosphere to land carbon flux predictions of the simulations reported in Le Quéré et al. (2009) and the simple linear model of our study.


AF (-)
const clim: AF=1-(F_at->oc+F_at->ld)/(FF+LU)
changing clim: AF=1-(F_at->oc+F_at->ld)/(FF+LU)
Observed: AF=dC/dt/(FF+LU)

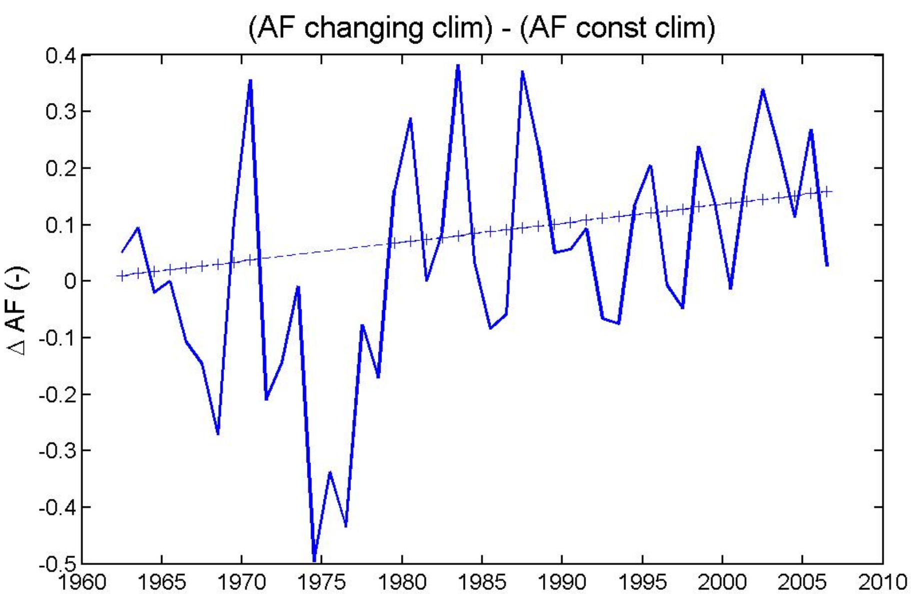

(AF changing clim) - (AF const clim)
Δ AF (-)

Figure 2 (a) AF and linear trend of AF implied by simulations of ocean and land carbon uptake with and without changing climate from LeQuéré et al. 2009. To calculate the trends we have excluded the simulation data from the interval indicated by light shading.

(b) Difference of $AF_{changing\ clim}$-$AF_{const\ clim}$ for simulations using a changing versus a non-changing climate.

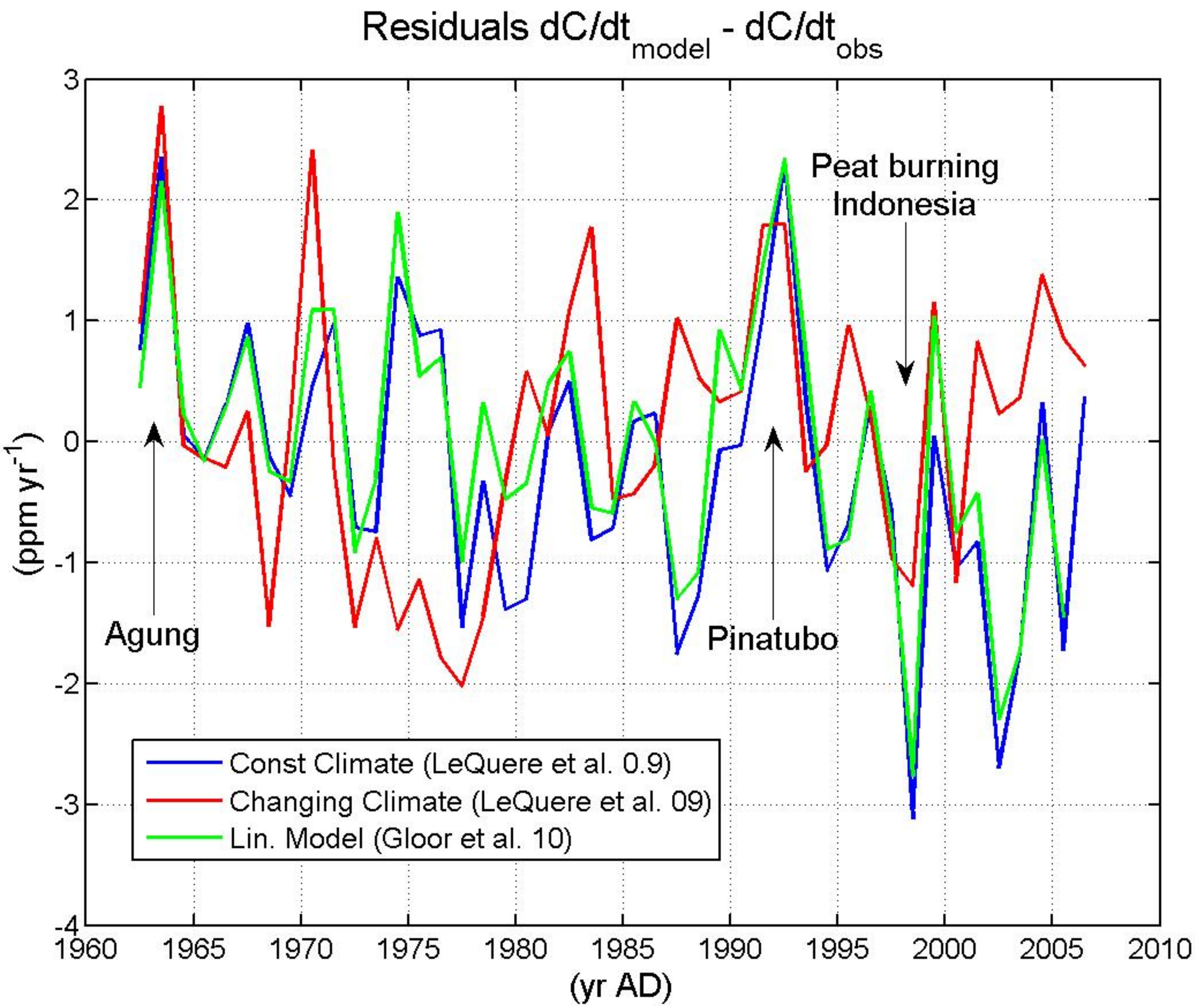


Figure 3 Observed and simulated accumulation rate of carbon in the atmosphere over approximately the last 5 decades.

References

Le Quéré, C., Raupach, M. R., Canadell, J. G., Marland, G. et al.:
Trends in the sources and sinks of carbon dioxide, Nature Geoscience, 2, 831 - 836, doi:10.1038/ngeo689, 2009.

Boden, T. A., Marland, G., and Andres, R. J.: Global, regional, and national CO_2 emissions, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, 2009.

Marland, G., Boden, T. A. and Andres, R. J.: Global, regional, and
national CO_2 emissions. Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U. S. Department of Energy, Oak Ridge, Tenn., U.S.A, 2006.

Houghton, R. A.: Balancing the global carbon budget, Ann. Rev. Earth Plan. Sc., 35, 313-347, 2007.