The atmospheric CO_2 airborne fraction and carbon cycle feedbacks

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1. Introduction

The five decades of the Mauna Loa record of atmospheric CO_2 have been instrumental in much increased understanding of the functioning of the global carbon cycle. One important result is the remarkable fact that the airborne fraction of CO_2 (i.e. the fraction of anthropogenic emissions which remain in the atmosphere) has remained almost constant on multi-year timescales throughout the last 50 years.

It is now widely predicted by complex climate-carbon cycle models that future climate change will significantly affect the ability of the natural carbon cycle (both terrestrial and marine) to take up anthropogenic carbon (Cox et al., 2000; Friedlingstein et al., 2006). However, the constancy of the observed airborne fraction has been seen as evidence that climate is not yet affecting these processes – in other words we are not yet seeing a "climate-carbon cycle feedback". Is this a correct inference?

Here we attempt to show that although climate feedbacks will certainly alter the airborne fraction from what it would have been in the absence of climate change, the two concepts are not the same.

A constant airborne fraction does not imply an absence of climate feedback on carbon uptake

and likewise

A change in the airborne fraction does not necessarily imply a climate feedback on the carbon cycle

We show that the constant airborne fraction is not a fundamental property of the carbon cycle, but results from the particular time history of anthropogenic emissions. Understanding how the airborne fraction has behaved in response to the emissions history will allow better projections of it in a future, changing, climate.

2. The airborne fraction, *AF*

The airborne fraction, AF, is defined as the fraction of anthropogenic carbon emissions which remain in the atmosphere after natural processes have absorbed some of them.

$$AF = \frac{\Delta CO_2}{E}$$

- high AF means more impact from carbon emissions (i.e. this could be seen as a "bad thing").
- low AF means relatively less impact from the same emissions (i.e. good).

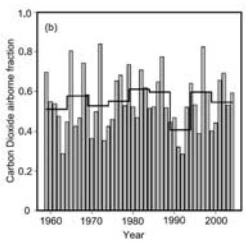
The AF is sometimes defined in terms of purely fossil fuel emissions (as in the IPCC Fourth Assessment Report), and sometimes in terms of total anthropogenic emissions (i.e. fossil plus land-use change, as in Canadell et al., 2007).

Understanding the behaviour of the AF, and being able to predict its future is a central aim of climate-carbon cycle research. It is vital to being able to understand the link between human emissions activity and future CO_2 levels (and hence climate change). The AF can be seen as an important "bridge" between climate science and climate mitigation policy.

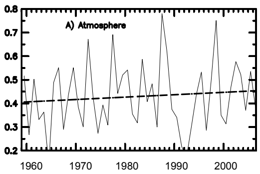
3. AF behaviour

The airborne fraction (AF) has remained remarkably constant over the last five decades since observations of CO_2 began at Mauna Loa 50 years ago.

Jones & Cox (2005) calculated the AF as a constant 42%. In a recent paper, Canadell et al (2007) calculate that it has risen from 40% in 1960 to 45% at present, with a statistically significant trend of 0.25±0.21 % per year.



IPCC AR4, chapter 7, figure 7.4.



Canadell et al. (2007)

Bare in mind, however, that this change is hard to assess due to the small magnitude of the trend, the large interannual variability and also significant uncertainty in the historical record of emissions – particularly from the land-use change component (which cannot be measured directly, but is estimated from a book-keeping approach).

4. Interpretation

What does a constant or rising Airborne Fraction mean?

It is commonly assumed that:
- no change in airborne fraction implies no change in the carbon cycle.
This is not true.

It is also commonly assumed that:
- if AF is rising, this implies we've detected a climate feedback on the carbon cycle.
This is also not true.

In reality, the AF depends not only on this years emissions and natural fluxes, but the time history of the carbon cycle, which in itself depends on the time history of the emissions. A different rate of emissions will imply different response of AF. This is true regardless of any feedbacks from climate.

As an example, consider a very simple conceptual model, where any CO_2 above preindustrial levels has a constant lifetime, τ, in the atmosphere (unaffected at all by climate), and is driven by emissions, E:

$$\frac{dCO_2}{dt} = E - \frac{(CO_2 - 280)}{\tau}$$

In this simple model, we see that an exponential rise of emissions leads to a constant AF (after recovery from the initial shock). Figure 1 shows that AF then remains constant until 2100 if emissions continue to rise exponentially.

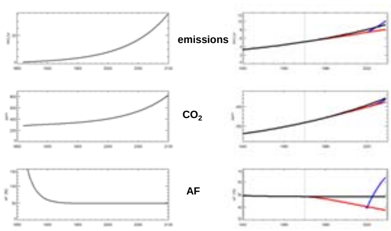


Figure 1. Exponential carbon emissions leads to constant airborne fraction

Figure 2. Sub- or super-exponential emissions lead to decreasing (increasing) airborne fraction

Figure 2, however, shows what happens if emissions do not rise at the same exponential rate. The black line shows exponential emissions rise of 1.5% p.a. until 2010 as in figure 1. The red line shows the effect of a linear increase in emissions since 1970 – although atmospheric CO_2 is not drastically different, the AF drops markedly.

The blue line now shows what happens if, at 2000, emissions begin to rise exponentially again, but now at 3.5% p.a., in line with the estimate of Canadell et al. (2007). There is a very strong increase in AF from 40% to 60% in a decade. Remember, here there is no climate effect at all – we can see large changes in AF simply from different emissions history.

In reality of course, CO_2 does not have a single, well-defined lifetime in the atmosphere, but that does not change the simple conclusion that AF depends on the emissions history.

5. What do complex models show?

Canadell et al (2007) claim that the coupled climate-carbon cycle models in the C4MIP project (Friedlingstein et al 2006) do not show a late 20th century upwards trend in AF. This is true. But why?

Figure 3 shows the observed upwards trend in AF of 0.25±0.21 % per year. The figure also shows the same trend from 1960 to 2006 simulated by the 11 C4MIP models both *with* ("coupled") and *without* ("uncoupled") the effects of climate change. The models almost invariably fail to show this recent trend, and it is important to understand why.

Maybe the models are not sensitive enough to climate change, and that the climate-carbon cycle feedback is stronger than even the most sensitive of these models predicts. But all of these models do show a future increase in AF due to climate change – it is unlikely, given the strong feedbacks shown by some of them, that all are under-sensitive to climate change. It is possible that they do not show all the mechanisms required, such as weakened Southern Ocean uptake as observed by Le Quere et al. (2007).

It could also be a response of the system to the rate of change of emissions. Figure 4 shows the year-on-year percentage increase in emissions used to drive the C4MIP models for the contemporary period. The red line shows the decade-average values discussed by Canadell et al. of 1.3% per year in the 1990s and 3.3% per year since 2000. It is clear that more recent emissions have risen much faster than expected in the emissions scenario used in C4MIP.

The expected impact of this sudden recent increase in emissions rise would be to increase the AF (see figure 2). It is our hypothesis that this rise has contributed to the recent upwards trend in AF.

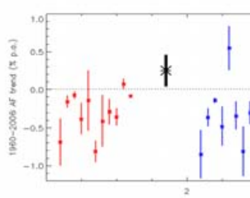


Figure 3 – C4MIP coupled (red) and uncoupled (blue) AF trends from 1960 to 2006. Observed trend (black) from Canadell et al (2007).

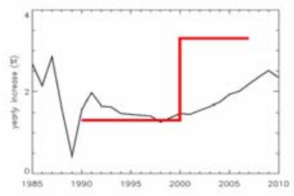


Figure 4 – year-on-year percent rise in emissions used in C4MIP (black) and actual from Canadell et al (red). Recent emissions have risen much faster than expected.

Conclusions

- **AF is a key property of the carbon cycle for climate policy. It is vital that we monitor it and understand changes in it.**
- **50 years of Mauna Loa data gives us a hugely valuable resource to improve our insight into AF.**
- **Climate WILL affect AF - but so do other factors, such as time history of emissions.**
  - **Constant AF is not a fundamental property of the carbon cycle.**
- **Constant AF should not be assumed to mean "no change in carbon cycle functioning".**
  - **Changing AF should not be assumed to mean "we can see the climate feedback".**
- **The Mauna Loa record is in danger of being misinterpreted. The interactions between emissions history and the climate effect need more research to be able to disentangle them correctly.**

References

Canadell et al., 2007. Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proceedings of the National Academy of Sciences (PNAS), 10.1073/pnas.0702737104

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

Friedlingstein, P. et al., 2006. Climate-carbon cycle feedback analysis, results from the C4MIP model intercomparison. J. Clim. 19, 3337-3353

Jones, C.D. and Cox, P.M., 2005. On the significance of Atmospheric CO_2 growth-rate anomalies in 2002-03 Geophys. Res. Lett. 32.

Le Quere et al., 2007. Saturation of the Southern Ocean CO_2 sink due to recent climate change. Science.

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