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Determining CO_2 Airborne Fraction Trends with Uncertain Land Use Change Emission Records

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Abstract: Over the last decade, the concentration of carbon dioxide (CO_2) in the atmosphere has risen much more steeply than in the previous four. Recently, some have suggested that one cause for this is that the fraction of anthropogenically emitted CO_2 that contributes to annual increases in the atmospheric CO_2 concentration ("airborne fraction") is increasing. If so, this could have important implications for international climate policy and planetary carbon cycle science. Others have argued, however, that with similar assumptions and data but more careful consideration of uncertainties, no statistically significant (p=0.9) trend in airborne fraction can be detected. One source of uncertainty in the estimation of trend in the airborne fraction is uncertainty in the time history of land use change emissions of CO_2; we focus here on the consequences of this uncertainty. We use Monte Carlo techniques to estimate how large linear trends in land use change emissions would have to have been in order to yield a statistically significant increase or decrease in the airborne fraction over the past 50 years. We also show that, under the range of published assumptions, airborne fraction trends can be either positive or negative, but are not statistically significant. Uncertainty about historical land use change emissions alone prevents reliable detection of airborne fraction trend.

Keywords: Airborne Fraction, Carbon Cycle, Land Use Change, Fossil Fuel Emissions, Carbon Dioxide Emissions, Mauna Loa CO_2, CO_2 Sink, Trend, Uncertainty

Introduction

OVER THE PAST 50 years, the airborne fraction of anthropogenically emitted CO_2 has roughly equaled the fraction absorbed by natural land and ocean processes ("natural CO_2 sink"). That is, roughly half the estimated anthropogenic emissions have been taken up by the natural CO_2 sink. Any change in the efficiency of the planetary CO_2 sink could thus have a substantial effect on future atmospheric carbon dioxide concentrations. Detection of trend in the airborne fraction, regardless of the cause, could also have important climate carbon policy implications (see Solokow and Lam, 2007 for a discussion from the atmospheric CO_2 mitigation/stabilization perspective). Understanding airborne fraction behavior requires the use of a model of the global carbon cycle and involves many factors in addition to changes in the strength of the CO_2 sink[1]. But all such studies must begin with the best available information about airborne fraction variability and trend.

Recent efforts to estimate and explain the trend in the airborne fraction over the past 50 years have produced conflicting results. If there has been any multi-decadal trend in the airborne fraction, all studies agree that it is small in comparison to the observed levels of

[1] See Gloor et al. (2010) for a discussion of some different possible causes for changes in airborne fraction.

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interannual variability in the growth rate of atmospheric CO_2, which complicates its detection from the available historical observations and estimates of emissions.

The historical record of atmospheric CO_2 concentrations at Mauna Loa reveals a trend (21.6% increase between 1960 and 2008) and an annual cycle that is modulated by interannual variability. The interannual variability is substantially, but not exclusively associated with variations in the El Nino-Southern Oscillation (ENSO)-state of the tropical Pacific. Annual average changes in concentration illustrate the large range of year-to-year changes (ranging from ~0.7 to ~2.7ppmv/yr) despite relatively smoothly varying emissions from fossil fuel burning and cement production (Figure 1).

In order to study the airborne fraction it is also necessary to specify emissions from land use change (LUC) which account for up to 25% of total emissions (Denman et al., 2007). Unfortunately these emissions are substantially uncertain (Ramankutty et al., 2007).

Recently it has been claimed that there is a positive trend in the airborne fraction (AF) of CO_2 emissions, and that this trend indicates that the efficiency of the natural CO_2 sink has declined over the past 50 years (Canadell et al., 2007; Le Quéré et al., 2009). Raupach et al. (2008) has also claimed that there is a positive trend in the airborne fraction (at 90% confidence), but did not offer an explanation. Knorr (2009), however, considered the effects of several sources of uncertainty in the available atmospheric concentration and emissions data in a linear inverse model of the growth rate of atmospheric CO_2 concentration and concluded that there is no statistically significant trend in AF. Gloor et al. (2010), based on consideration of a simple linear model of the planetary carbon system, illustrate the importance of various factors in addition to changes in CO_2 sink efficiency for trend in AF. All these studies have agreed that understanding the behavior of AF is key to predicting future atmospheric CO_2 levels.

The above AF trend studies have all based their main conclusions on the same LUC emission estimate (Houghton, 2008), which has recently been substantially revised for the period since 2000 (Friedlingstein et al, 2010). Since even the character (e.g. long-term trend) of the time history of LUC emissions is uncertain (c.f. Grainger et al., 2008) it is difficult to know how much confidence can be placed on results based primarily on a single estimate. Because of the uncertainty in LUC emissions, which we summarize based on recently published estimates, and the broad importance that verification of a substantial long-term trend in AF could have for international climate policy and global carbon cycle science, we take another look at the uncertainty in estimating AF resulting from uncertain LUC emissions. Specifically, we determine how large positive and negative trends in LUC emissions would have to be, and how well would we have to be able to measure them, to infer statistically significant AF trends (>90% confidence), given our present knowledge of the growth rate of atmospheric CO_2 and the dominant sources of anthropogenic emissions. This can be set up as a straightforward calculation, using the Monte Carlo methods described below. We show that land use change emission uncertainty makes AF trend detection very difficult.

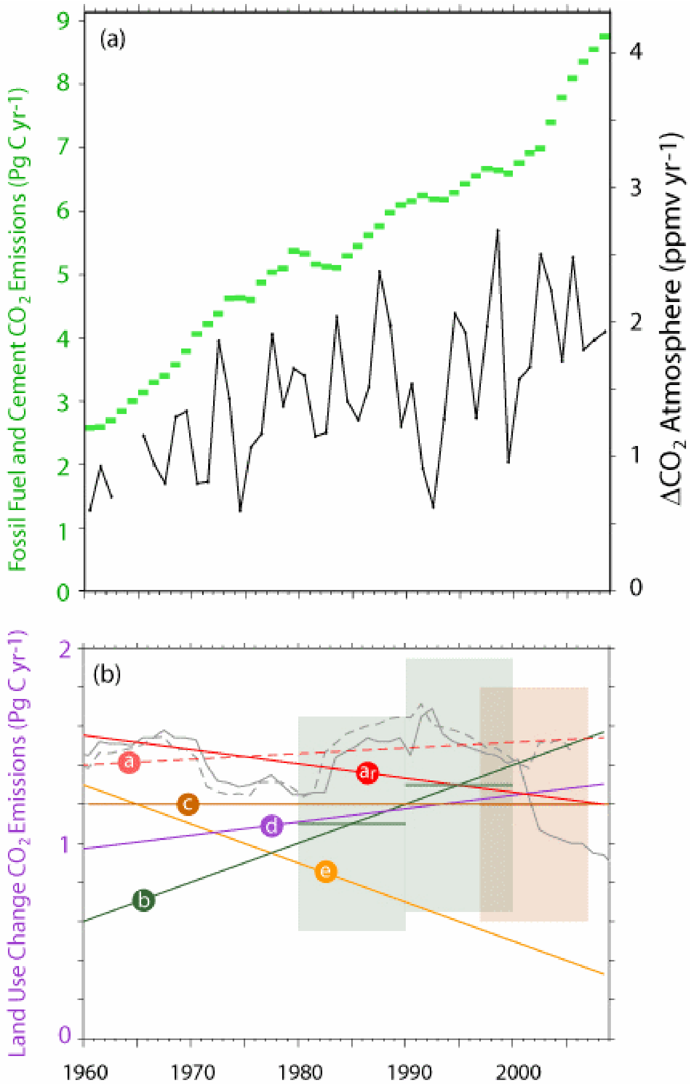

Figure 1: a) Annual emissions from fossil fuel burning and cement production (green bars) and the annual growth rate of atmospheric carbon dioxide concentration (ΔCO_2) at the Mauna Loa site (black curve). b) Houghton (2008) and Friedlingstein et al. (2010) land use change emissions (dashed and solid gray curves, respectively) and the best estimates and 50% uncertainty levels (shading) for Van Der Werf et al. (2009) WGI-Type (green lines and shading) and WGIII-Type (brown line and shading) decadal averages. Lines (a), (a_r), (b), (c), (d) and (e) are linear fits to previously published land use change emission estimates (See text.)

Airborne Fraction Model

The model of airborne fraction behavior used here resolves the effects of two types of land use emission uncertainty. The first ("scenario uncertainty'') explores the effects of using different linear land use emission scenarios with trends and magnitudes that are within the range of currently published estimates (see van der Werf et al., 2009 for a current list). Inclusion of the second ("measurement uncertainty") allows us to estimate, for a given assumed linear land use emission scenario, the effects that specified levels of uncertainty in CO_2 emissions have on our ability to reliably determine AF trend.

Our model for airborne fraction,

$$AF = \frac{\Delta CO2}{FE + LUCE} \qquad (1)$$

depends upon annual averages (since 1960) of the atmospheric CO_2 growth rate (ΔCO_2), fossil fuel and cement emissions (FE), which increases from about 2.6 to 8.7 Pg C yr^{-1} between 1960 and 2008 (see Fig. 1), and the assumed linear form of land use change emissions (LUCE). Once LUCE is specified, AF trend statistical significance is determined by Monte Carlo methods using a first-order-autoregressive (AR1) model to represent the variability seen in the de-trended historical AF time series. In this case, the AR1 parameters used are determined mainly from the standard deviation and 1yr-lagged-autocorrelation of the estimated historical AF time series [see Chap. 4 of Chatfield (2004) for more details on the fitting procedure used herein]. Then, large numbers (here $N=10^6$) of synthetic AF time series are generated randomly, and the distribution of the resulting synthetic AF trends is compared to the trend seen in the estimated historical AF time series to determine the null-hypothesis likelihood that the observed trend can be explained just by the shorter-term (interannual), stationary-type (i.e. no long-term trend) variability that is produced by this synthetic AR1 model. This approach was chosen here to facilitate comparison with the previous studies that have argued that there is a trend in AF based on results from this same type of trend statistical significance test (c.f. Canadell et al., 2007; Raupach et al., 2008; Le Quéré et al., 2009). It is useful to note that, as described to this point, the range of synthetic trends produced by the AR1 model depends only on the amount of interannual variability in the estimated AF record, which is due mainly to the interannual variability in the growth rate of atmospheric CO_2 (see Fig. 1a). That is, the effects of uncertainties in the historical emission records, other than those that result from specifying different LUC emission scenarios, have not yet been resolved. To resolve the effects of any annually-averaged measurement errors that might exist in a given LUC emission scenario, we here also include an "measurement uncertainty" (ε), such that,

$$LU = m * t + b + \varepsilon(t) \qquad (2)$$

where m is LU trend, b is a constant, t is time in years, and ε is a random normal variable with standard deviation σ_ε. Within our Monte Carlo procedure, the parameters m, b and σ_ε are varied systematically to determine their effects on AF trend. In practice, ε is propagated through Eqn. (1) and represented by a second Monte Carlo process so that the effects of using different LUC emission scenarios (i.e. different pairs of *m* and *b* values) can be determined independently from the effects of specifying different LUC emission measurement uncertainties (ε).

Data Summary

The monthly Mauna Loa CO_2 data used here was derived from *in situ* air samples by Keeling et al. (2008) and is available at http://scrippsco2.ucsd.edu/data/in_situ_co2/monthly_mlo.csv. Here, monthly data was first filtered with a 12 month running mean filter. The annual rate of increase of CO_2 was then determined from the difference between subsequent January 1st values. All values with a full 24 months of coverage between the differencing periods were used. Years with missing data (i.e. 1958 and 1964) were excluded.

Throughout the analysis described here we use fossil fuel and cement production CO_2 emission estimates provided by Marland et al. (2011). These are available at http://cdiac.ornl.gov/ftp/ndp030/global.1751_2008.ems

Results

The Monte Carlo results (Fig. 2) show, for example, that if LUC emissions are taken to have a 1990s mean of 1.3 Pg C yr^{-1} (as suggested by van der Werf et al., 2009), LUC emission trend must be substantially greater than ~+0.02 Pg C^{-2} or less than ~-0.02 Pg C^{-2} for AF trend to be statistically significant.

We find also that LUC emission scenarios with relatively larger average values and negative trends tend to produce more positive AF trends, whereas LUC emission scenarios with smaller average values and positive trends produce negative AF trends. This is consistent with the effects of LUC emission trend and magnitude perturbations considered by Raupach et al. (2008). It also means that one cannot simultaneously believe that recent LUC emissions have increased exponentially (a possibility suggested by Section 2.5.2 of the IPCC Fourth Assessment Report, which claims that tropical deforestation rates have increased exponentially since about 1960), and that the airborne fraction is increasing. We have explored the possibility of large recent increases in LUC emission with scenarios of the form LUCE = $p + q \times t^2$ (Eqn. 3), where p and q are constants and t is the number of years since 1960. Assuming a 1990s LUC emission mean of 1.3 Pg C yr^{-1} and perfect knowledge of LUC emissions, AF trends start to be negative and significant at q>0.53. Scenarios of this form and 1990s mean value cannot produce AF trends that are positive and significant at the 90% level.

The contour lines in Figure 2 show how well our observing system needs to be capable of measuring annual anthropogenic CO_2 emissions to infer significant AF trends. For reference, the range of the contours shown in Figure 2 was determined by the range of linear LUC emission scenarios that fit inside the 1980s and 1990s average uncertainty bounds suggested by van der Werf et al. (2009) and shown by the green-shaded boxes in Figure 1. A wide range of 1960-2008 LUC emission scenario trends are consistent with these bounds, yielding a wide range of tolerable (AF trend with >90% confidence) σ_ε values. Extremes in ε correspond to the types of LUC emission scenarios described above (large magnitude with negative trends; small magnitude with positive trends). In the area between the blue and red zero contours in Figure 2, significant AF trend will not be obtained, even with perfect knowledge of emissions, because the interannual variability in AF is too large.

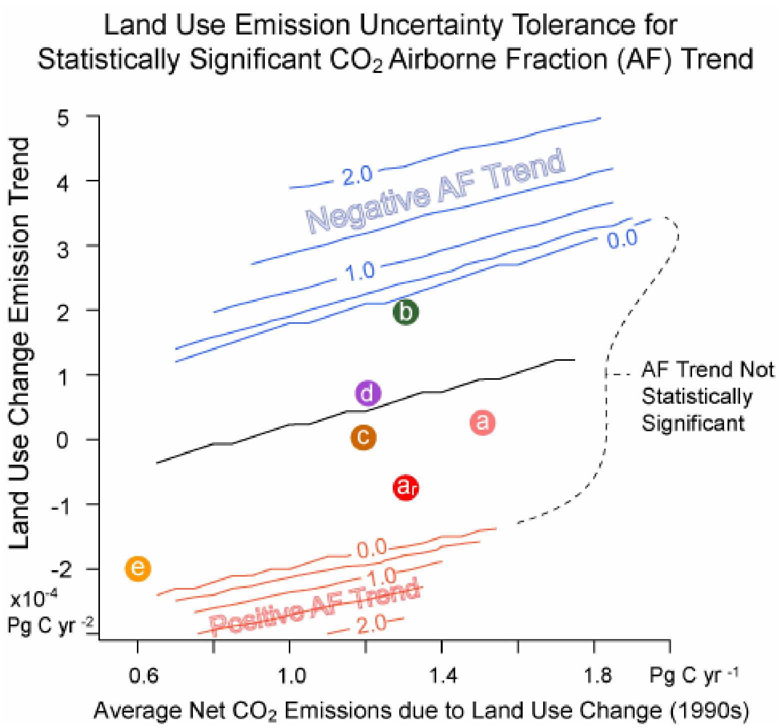

Figure 2: Annual uncertainty tolerances (Pg C yr^{-1}) on land use change (LUC) emission estimates needed to infer statistically significant airborne fraction trends over the period 1960-2008. LUC scenario emission averages over the period 1990-1999 are shown on the X-axis. Scenario trends are shown on the Y-axis. Points (a), (a_r), (b), (c), (d) and (e) show the locations of the best-linear-fits to the previously published estimates of land use change emissions described in the text and shown in Figure 1. Contour lengths are set by the WGI-type 50% uncertainty bounds on land use emissions in the 1980s and 1990s

It is useful to compare current estimates of LUC emissions within the framework of these results. For this purpose, we have plotted points (trend and 1990s-average values) corresponding to the LUC emission estimates discussed recently by van der Werf et al. (2009), including linear fits to; (a) the United Nations Food and Agriculture Organization (FAO)-bookkeeping-type estimate (from Houghton, 2008) that is used by Knorr (2009), Gloor et al. (2010) and Canadell et al. (2007), (b) the updated IPCC Fourth Assessment Report Working Group I-type (WGI) 1980s and 1990s averages from van der Werf et al. (2009), (c) a zero-LUC emission-slope scenario held at the updated 1997 to 2006 WGIII-type average, and (d) a fit to the three updated decadal averages (periods 1980-1989, 1990-1999 and 1997-2006) discussed by van der Werf et al. (2009). In addition to these four scenarios, we also consider scenario (e), from a linear fit to the model-based LUC emission estimates described by Shevliakova et al. (2009) since these represent the negative LUC emission trend extreme considered in supplementary work by Le Quéré et al. (2009).

Our finding is that the range of these five scenarios leads to both positive and negative AF trends, but none that are statistically significant. Thus, even if one of these LUC emission scenarios came to be accepted as precisely correct, no statistically significant AF trend would be detectable at this time due to the levels of interannual variability seen in the ΔCO_2 record.

Based on a more recent FAO report, the 2001-2009 period bookkeeping-type LUC emission estimates, upon which scenario (a) is based, have recently been revised to a have a 2001-2009 average of about 1 Pg C yr^{-1} (Friedlingstein et al. , 2010), which is down by about 0.5 Pg C yr^{-1} from the values previously reported for this time. We have also considered scenario based on this revised bookkeeping estimate (a_r). It suggests negative, rather than positive LUC emission trend in the time since 1960, but still yields an AF trend that is not statistically significant according to the methods used here.

The model can also be used to look at what happens if AF interannual variability is reduced by removing some of the interannual variability seen in the ΔCO_2 record. For example, if the interannual variability of ΔCO_2 is reduced by half (an amount possibly connected to ENSO variability based on correlations found in preliminary work of ~0.7 between ΔCO_2 and standard ENSO indices), scenarios (b) and (e) yield AF trends that still have opposite signs, but are statistically significant, provided that σ_ε is <0.85 Pg C yr^{-1}on an annual basis throughout the record. In the case of the more recently revised bookkeeping-type LUC emission scenario (a_r), this requirement tightens to σ_ε<0.35 Pg C yr^{-1}. It is unlikely, however, that we are currently able to estimate LUC emissions this accurately. For example, a (standard) error of 0.65 Pg C yr^{-1}on the estimated 1990-1999 LU average of 1.3 Pg C yr^{-1} (c.f. van der Werf et al., 2009) suggests σ_ε= 1.9 Pg C yr^{-1}on the annual basis in which ε is implemented in the model used here.

We also looked at what happens when interannual variability in LUC emission, and uncertainties in FE and ΔCO_2 are included in the model, and found that while effects from these uncertainties, especially about ΔCO_2, are not necessarily negligible, they are secondary to those caused by uncertainty in LUC emission trend. For example, the statistical significance of the AF trends yielded by the six LUC emission scenarios (assuming perfect knowledge of AF) were little changed when the interannual variability seen in the bookkeeping-type LUC emission estimate (Houghton, 2008) was added to them (< 4% difference in the five AF trend statistical significances; none changed sign; all still below the 90% confidence level). Adding uncertainty in FE equal to 6% of its yearly value (as estimated by Friedlingstein et al., 2010) also had only moderate effects on the AF trend statistical significances (<3% difference), while adding uncertainty in ΔCO_2 equal to 0.3 ppmv/yr (based on information provided by P. Tans and R. Keeling[2]) had a somewhat larger effect (up to 8% of the original value).

Discussion and Conclusions

The behavior of the airborne fraction of CO_2 emissions (AF) under changing atmospheric CO_2 concentration and changing planetary environmental conditions is important to know if future atmospheric concentrations are to be reliably projected under different emission scenarios. Despite some claims that the AF has increased recently, this study joins a previous one that indicates that the null hypothesis should remain that no AF trend has been detected over the past 50 years. We have shown that uncertainty in the historical behavior of CO_2 emissions resulting from land use change (LUC) emissions is, on its own, sufficient to prevent

[2] available at http://www.esrl.noaa.gov/gmd/ccgg/trends and http://scrippsco2.ucsd.edu/, respectively

reliable detection of AF trend. The importance of the range of uncertainty in LUC emissions in carbon cycle studies has not, in view of these results, received adequate attention.

Only if the time history of LUC emission were substantially different from the published scenarios would an AF trend be detectable at present. Both the average emission over the last 50 years and the emission trend factor into producing a detectable AF trend. Our results show that a LUC emission scenario with a larger average magnitude and stronger negative trend will produce a stronger positive AF trend, and a LUC emission scenario with a smaller average magnitude and stronger positive trend will produce a stronger negative AF trend. Overall, however, AF trend is more sensitive to LUC emission trend than magnitude (see Fig. 2).

What quantitative characteristics would a LUC emission scenario have to have to yield a statistically significant AF trend over the last 50 years? A scenario with zero LUC emission trend must have a 50 year average value larger than 2.650 Pg C yr^{-1} to produce a statistically significant (>90%) positive, or less than -0.150 Pg C yr^{-1} to produce a statistically significant negative AF trend. These average values are far outside the current range of LUC emission estimates. Scenarios with an average 1990s emission of 1.57 Pg C yr^{-1}, which is the Houghton (2008) value, must have a positive (negative) LUC emission trend > +0.031 (< -0.012) Pg C yr^{-2} to produce a statistically significant negative (positive) trend in AF. The most recently published bookkeeping-type LU scenario (Friedlingstein et al. 2010) yields a best-fit-linear AF trend of 0.0012 (Pg/Pg) per year. If this trend is correct and persists, duration would yield statistical significance at 90% confidence in 18 years, provided we can confirm such a trend by attaining nearly perfect knowledge of the historical record of CO_2 emissions by then. However, unless LUC emission scenario uncertainty can be eliminated and LUC emission trends are larger than present estimates, even the sign of AF trend will remain uncertain over the coming decade.

Knorr (2009) has also noted that the historical record does not reveal statistically significant AF trend over the last fifty years. What is striking here is that LUC emission uncertainty alone, particularly uncertainty about LUC emission trend, is sufficient to prevent reliable AF trend detection. Many previous studies (Knorr et al., 2009; Canadell, 2007, Gloor et al., 2010) have been based primarily on the Houghton (2008) LUC emission estimate. Our work indicates that it would be unwise at this point to attribute significance to results based on work that assumes any particular land use change emission scenario.

The existence of a trend in AF would have important implications for international carbon policy and planning, as well as for carbon cycle science. It is important that work continues to seek an understanding of the global carbon cycle and its mechanisms of variability and change. We hope that this work will ensure that future research will fully respect the importance of uncertainty about land use change emissions.

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