CORRESPONDENCE:

Anthropogenic CO_2 emissions

To the Editor — Francey *et al.*[1] use atmospheric CO_2 measurements to infer an underestimation in 1994–2007 emissions. Here we show that this inference depends on an unrealistic assumption of CO_2 sinks and that atmospheric CO_2 measurements are not inconsistent with global CO_2 emission inventory data[2] over the past two decades, given the observational uncertainties.

The mass balance for atmospheric CO_2 is $dC/dt = FF + LUC - \text{sinks}$, where dC/dt is atmospheric CO_2 accumulation, FF and LUC are emissions from fossil fuels and land-use change, respectively, and sinks include the uptake of CO_2 by both land and ocean reservoirs. Inference of FF emissions from dC/dt therefore also requires information about sinks and LUC emissions.

Francey *et al.*[1] compared FF + LUC with dC/dt, suppressing interannual variability (IAV) by the removal of El Niño–Southern Oscillation- and volcanic-correlated components. They compared trends from 1990 to 2011 in FF + LUC and dC/dt – IAV by using an offset of 5.3 Pg C yr^{-1} to bring the two quantities together (black and red lines in the upper panel of Fig. 1, reproducing their Fig. 3). The area between these lines accounts for their proposed cumulative underestimation (~9 Pg C) of 1994–2007 emissions.

This method implicitly assumes that, averaged from 1990 to 2011 and with IAV removed, sinks are constant at 5.3 Pg C yr^{-1}. In contrast, observational and modelling evidence[3,4] and theoretical understanding[5,6] of the contemporary carbon cycle all show that sinks cannot be arbitrarily assumed to be constant. The blue line in the upper panel of Fig. 1 extends the assumption of constant sinks back in time to 1958, demonstrating an unrealistic discrepancy with emissions data.

A simple way to infer emissions from atmospheric measurements would be to assume a constant airborne fraction, $AF = (dC/dt)/(FF + LUC)$, of about 0.44 over the past 60 years[3]. A constant AF would imply that sinks increase proportionally with emissions. The assumption of a constant AF has no general mechanistic basis[6] but is in fair agreement with available observations, notwithstanding discussion[3,4,7] of the question of small trends in the AF. In fact, a constant AF is proposed by Francey *et al.*[1]. The result, shown by the blue and red lines in the lower panel of Fig. 1, removes most of the discrepancy between atmospheric CO_2 measurements and emissions data asserted by Francey *et al.*[1].

A better approach is to use estimates of the land and ocean sinks from an ensemble of carbon cycle models[3,8]. These estimates incorporate the effects of rising CO_2, climate change and variability in sinks from El Niño–Southern Oscillation, volcanic activity and other influences. The result (green line in the lower panel of Fig. 1) explains most of the remaining discrepancy.

With these more realistic representations of CO_2 sinks, and given the remaining uncertainties, atmospheric measurements provide no evidence that CO_2 emissions data are significantly in error. From 1990 to 2011, average mismatches (AF- or model-based estimate minus emissions data) are very small (< 0.1 Pg C yr^{-1} in magnitude), with no clear temporal pattern. The surge in reported global FF emissions since 2000 is also fully consistent with a simultaneous surge in global economic activity and a shift in energy mix towards coal[9,10].

There are uncertainties in global emissions inventories, especially for FF in China[11] and LUC globally[3]. We agree

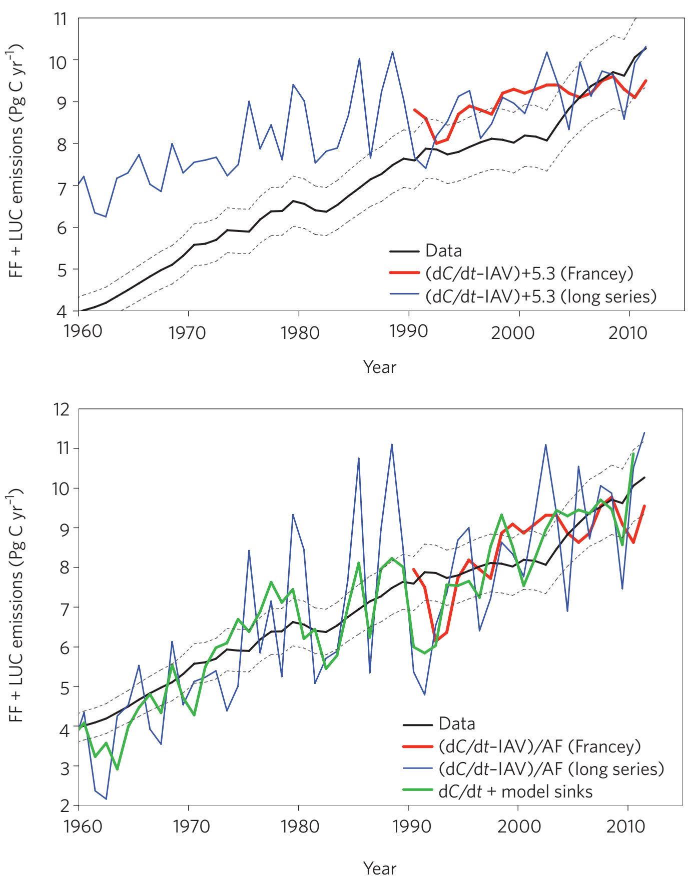

Figure 1 | Inferences of FF + LUC emissions from atmospheric CO_2 growth-rate data. The solid black line in both panels shows FF + LUC emission inventory data[2,8], with indicative uncertainty of one standard deviation (±9%; dashed black line). The upper panel applies the method of Francey *et al.*[1], comparing the data with estimates from atmospheric concentrations derived by displacing dC/dt – IAV by 5.3 Pg C yr^{-1}; red and blue lines use dC/dt – IAV from Francey *et al.*[1] (available for 1990–2011) and from a longer series[12,8], respectively. The lower panel compares emissions data with AF-based estimates from atmospheric concentrations, using the same series for dC/dt – IAV as the upper panel (red and blue lines). Also shown is an emissions estimate derived by adding model-based estimates[8] of land and ocean CO_2 sinks to observed dC/dt (green line).

with Francey *et al.*[1] that atmospheric measurements have a critical role in reducing these uncertainties, but argue that they need to be combined with observations of land- and ocean-carbon fluxes and pools, to provide numerous constraints on carbon cycle models and understanding. ❐

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Francey *et al.* reply — In the context of atmospheric verification of anthropogenic CO_2 emissions, Raupach *et al.*[1] demonstrate consistency in the global carbon budget since 1960 whereas our Article[2] demonstrates inconsistency between changes in reported emissions and atmospheric CO_2 since 1990.

Figure 3 of our Article demonstrated this inconsistency between the two largest and most precisely determined terms in the global carbon budget. If the curves represent global trends, then the changing difference represents variation in sinks to maintain global mass balance. We estimated a magnitude for the difference between the curves at ~9 Pg C between 1994 and 2005, obtained by overlapping the curves during a recent four-year period of unusually quiet natural interannual variability (IAV). We make no previous assumptions about sink changes on timeframes of longer than three to five years (that is, those considered when suppressing natural variability in the atmospheric record).

A previous study[3] speculated that the differences between atmospheric and emission trends might be due to an underestimation of emissions rather than sink adjustments, a possibility enhanced by the absence of an atmospheric response to sudden changes in reported emissions. To explore implied sink behaviour we used (in Fig. 4 and Supplementary Fig. S7)[2] inversion modelling with two emission scenarios, that is, assuming reported emission trends are correct, or assuming atmospheric growth trends better reflect actual emission trends. Although there is some ambiguity between Northern Hemisphere emissions and terrestrial uptake[2] that compromises a quantitative allocation, 'realistic' temporal changes in the global sink were obtained for both cases. Post-1990 decadal changes in the Northern Hemisphere terrestrial sink (the main sink responding to emission scenarios) are less for the atmospheric trend case.

In contrast to our approach[2], significant assumptions about the constancy of sink processes underpin suggestions both by Raupach *et al.*[1] (using airborne fraction, AF, or an ensemble of sink process models) and the previous study using these data[3] (with a box model calibrated against ice-core data, with no IAV and considerably greater CO_2 signal-to-noise than is possible with briefer modern records. Incidentally, this did support an emissions underestimate of similar magnitude to the 1994–2005 trend anomaly).

Regarding AF, this is a statistical construct with no clear understanding of the processes involved in maintaining a near-constant value since the beginning of direct atmospheric measurements. This makes application to a different period risky, particularly if processes are changing as a result of environmental change. Similarly, the problem with using an ensemble of process models to estimate trends in natural sinks is the absence of bottom-up information of sufficient quality to verify global trends in modelled ocean or terrestrial processes on timeframes greater than around five years. Agreement between such models possibly says as much about similarity in model parameterizations (for example, to describe seasonality) as about globally significant real-world processes on longer timeframes.

In the context of emission verification, a more serious difference from Raupach *et al.* is evident when comparing their $(dC/dt - IAV)/AF$ (Francey) and $(dC/dt - IAV)/AF$ (long series) where AF is constant. We refer to marked differences in remnant IAV. Global budget consistency is statistically easier to achieve with larger remnant IAV, whereas our detection of differences in atmospheric and emission trends is aided by smaller remnant IAV. Our smaller variability is mainly due to two factors, more careful selection of CO_2 data to maximize spatial representativeness and five-year smoothing to further suppress remnant IAV.

The interpretation of the recent inconsistencies in terms of an emission underestimate is prompted mainly by the absence of a dC/dt response corresponding to unprecedented changes in the dominant term in the global budget, fossil fuel CO_2 emissions. The absence of change around 2000 in the north–south interhemispheric concentration gradient (which responds much more quickly and sensitively than dC/dt to Northern Hemisphere emission changes, as evidenced in 2010) further strengthens that argument.

Finally, a recent time series of satellite-derived measurements of NO_2 concentrations over the Chinese region[4] provides independent evidence that CO_2 emissions between 1996 and 2008 increased more smoothly than suggested by emission inventories. NO_2 is produced during fossil fuel combustion and observations of the relatively short-lived atmospheric NO_2 reflect the spatial and temporal structure of emission fields in much more detail than similar CO_2 observations. The sharp change in Chinese emissions seen in reported regional (and consequently global) CO_2 emissions around 2000 is not detected in the NO_2 time series, in our global CO_2 growth-rate data, or (unlike in 2010) in CO_2 interhemispheric differences. ❐

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