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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