Instability and atmospheric CO_2 anomalies in the recent global carbon cycle

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Abstract
A major instability occurred in the recent global carbon cycle. It manifests as a major CO_2 anomaly between 2009 and 2015 that is clearly seen in the residuals from generalized exponential growth, or equivalent quadratic curves through Taylor expansion, or 10-year running means. Our findings contradict recent assertions of the stability of the recent global carbon cycle based on growth rate analysis. Our analysis highlights the methodological problems of attempting to determine systematic anomalies in the carbon cycle based on annual tendency growth rates where the anomaly is hidden in plain sight.

Independent verification of reported fossil fuel emissions remains a critical component in tracking progress towards the reduction targets formalized in the Paris Agreement on Climate Change.

Conflicting conclusions, on the stability of the recent global carbon cycle, were reached by the Birner at al. article "Surprising stability of recent carbon cycling enables improved fossil fuel emission verification"[1] and our "Systematic anomalies in the recent global atmospheric CO_2 concentrations"[2].

Factors that distinguish the studies are:

- The reliance on CO_2 growth rates to constrain complex models of the carbon cycle[1], compared to measured annual variation in background CO_2 concentration[2].
- Summing growth rate derived air-surface fluxes from around 200 individual locations to arrive at a global response[1], compared to tracking concentration changes in a large, well-mixed Southern Hemisphere (SH) volume of the atmosphere most remote from the predominantly Northern Hemisphere (NH) fossil fuel emissions and terrestrial biosphere changes[2].

We note that the Birner et al.[1] growth rate approach is consistent with that used in the regularly updated global budgets in Global Carbon Project (GCP)[3] and the UN Intergovernmental Panel on Climate Change (IPCC)[4] reports. Similar trace gas modelling is conducted more widely, for example in the Atmospheric Tracer Transport Model Intercomparison Project[5].

This comment includes two figures, updated from reference **2** to 2024. Fig. 1 identifies pertinent details on the 2009-2015 anomaly from generalized exponential growth or, broadly equivalent, 10-year running mean[2]. Fig. 2 demonstrates why the widely employed growth rate-based studies have failed to report the systematic concentration anomalies

In Fig.1, hemispheric concentration variation is represented by Mauna Loa (MLO) and Cape Grim (CGO) residuals from 3-decade smooth curves representing the increase due to fossil emissions, ~95% of which are released at NH mid latitudes (Appendix). Apart from the obvious persisting low concentrations, pertinent factors that distinguish the anomaly from the rest of the 3-decade record, include:

- There is markedly less scatter in the annual MLOres – CGOres difference within the anomaly period. Between 2010 and 2014 the value is 0.27±0.06 ppm. After the 1991 Pinatubo volcanic explosion, with influence that persists to ~1994, the mean (MLOres – CGOres) concentration variation is -0.01±0.20 ppm. If the anomaly period is excluded the scatter is similar, -0.05±0.18 ppm. The anomaly corresponds to the largest multi-year difference between the MLO and CGO step plots.

- After Pinatubo, the CGO step plot departs significantly from the overall correlation with the previous year's negative SOI index (-SOI*), while the MLO demonstrates a similar relationship.
- The anomaly exhibits fossil fuel isotopic labelling which is much stronger than the decadal fossil fuel labelling.

Birner et al.'s[1] verification of the modelled carbon cycle effectively relies on averaging the MLO and SPO concentrations to represent global behaviour. This is essentially equivalent to the dashed purple curve in Fig.1, which reduces the significance of the MLO and CGO anomaly difference[2].

In Fig.2, annual differencing of annual concentrations is employed with MLO and CGO data. This is the method used by Birner et al.[1]; as we have previously demonstrated[2], there is no detectable difference between variation in the annually averaged concentrations using CGO or SPO data.

The 2009-2015 anomaly of Fig.1 is not visually or statistically evident in the Fig. 2 growth rate plot. The fundamental reason for the failure of growth rates to accurately represent concentration or carbon amount, are detailed in supplement S4 of reference **2**. It stems from growth rates being the derivative of concentrations whereas concentrations are the integral of growth rates.

Discussion

Our analysis highlights the methodological problems of attempting to determine systematic anomalies in the carbon cycle based on annual tendency growth rates where the anomaly is hidden in plain sight. This issue has previously been noted in studies of atmospheric instability[6], atmospheric teleconnection patterns[7,8], ensemble perturbations, and errors in seasonal prediction[9] and dynamical system theory and chaos[10]. For example, high impact phenomena like the boreal spring predictability barrier that occurs in April is seen in the equivalent of residual anomalies but not in the peak growth rates which occur in December (see Figure 2 of reference **9**). This issue is further detailed in Supplement S4 of reference **2**.

An important distinction between concentration and growth rates is that concentrations are more directly and precisely related to climate forcing and ocean acidification.

It is also relevant that both total atmospheric emissions variation, and terrestrial biosphere exchange, occur primarily in the NH mid-latitudes. The expansion of fossil emissions across the Intertropical Convergence Zone is governed by seasonality in the NH terrestrial biosphere coinciding with sub-annual variation in inter-hemispheric transport[11,12]. It is the second largest flux in an annual carbon budget and dominates air-surface exchange in the SH[3]. It cannot be adequately represented by long term averaging of CO_2 interhemispheric difference or using different trace gas species, methods that are frequently employed in global carbon cycle studies.

Birner et al.[1], "assuming constant dynamics", fail to detect the anomaly. However, it is significant that the anomaly coincides with unprecedented anomalies in NCEP upper tropospheric winds that induce the large scale interhemispheric exchange[2]. The reduction in concentration during the 2009-2015 anomaly is consistent with reduced anthropogenic emissions following the 2008 Global Financial Crisis (GFC)[2]. The expression of the GFC in the atmosphere is complicated by the reduction in the large interhemispheric flux, enhancing MLO concentrations and reducing CGO values. Our data suggests that the decrease in economic activity, translating into reduced anthropogenic fossil emissions, persists through to 2015 (reference **2**, Fig. 4(b)).

There are further measurements supporting the fact that the variation in Southern Hemisphere baseline data is largely determined by CO_2 transported from the Northern Hemisphere. These include a decade of ~monthly aircraft profiling of CO_2 above Cape Grim (AIA) to 8km altitude in baseline conditions. Interpretation of the profile data[13] was focused on similar profiles from the NH and exclusively interprets every profile in terms of air-surface exchange. But the absence of seasonality in the AIA profiles indicates an absence of significant terrestrial sinks. The NH origin of the SH variation is strongly supported by stable carbon isotopes also measured in the AIA samples. There is strong anti-correlation between CO_2 and $d^{13}CO_2$ in the upper troposphere and an effective absence of correlation near the surface. The seasonal timing of the upper troposphere correlation is also significant, occurring between July and November[14]**.** This is at a time of the largest hemispheric CO_2 partial pressure difference[15] and a maximum interhemispheric transport, occurring above the Intertropical Convergence Zone[12]. The upper troposphere CO_2 anticorrelation with $d^{13}CO_2$ is consistent with transport of fossil emissions from the NH and the absence of correlation at the surface is consistent with the dominating influence of isotopic equilibration with SH ocean dissolved inorganic carbon.

Reinterpretation of highly cited papers based on growth rate analysis (e.g. reference **16**) is recommended. Also, emphasizing the wider relevance, the SH uniform CO_2 variations[2] of NH origin suggest that recent oceanographic studies using CO_2 growth inversions to estimate Southern Ocean CO_2 removal (e.g. Gruber et al.[17]), require reinterpretation.

***Figure 1**: Interannual variation in CO_2 concentration at MLO (red dotted step), CGO (blue step) and the average of MLO and CGO (purple, dashed graph) on the left axis. Negative Southern Oscillation Index from the previous year (-SOI*, black graph) is plotted on the right axis. In the respective hemispheres, concentration variations are expressed as the residuals from 3-decade quadratic increase due to fossil emissions. The green ellipse encloses the 2009-2015 anomaly.*

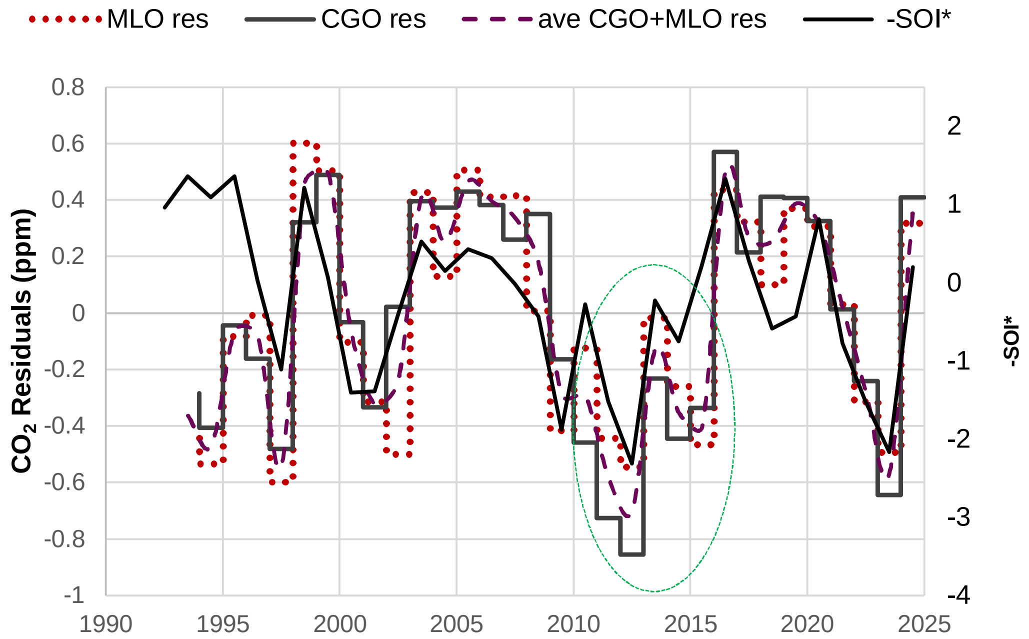
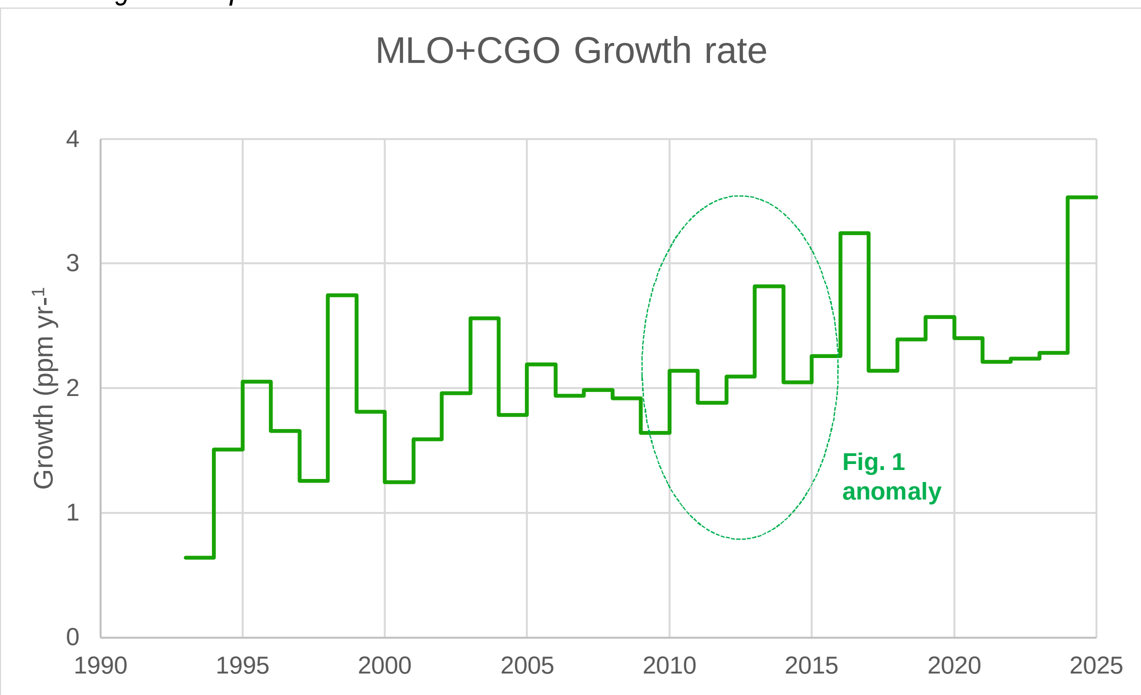


***Figure 2**: Failure of annual tendency growth rates to register the concentration anomaly in Fig.1 during the time of the green ellipse.*



Appendix

The terms background, or baseline, are used here to describe measurements in samples of air collected in conditions that minimize terrestrial and industrial influence and maximize spatial representation. Mass changes are simply calculated from the CO_2 mixing ratio in dry air. Measurements of baseline annual CO_2 samples by both CSIRO and NOAA, have demonstrated uniform interannual variation over more than 70° of extra-tropical Southern latitude[2]. The large-scale atmospheric behaviour is closely characterized using data from GAW primary baseline sites: Mauna Loa in the Northern Hemisphere and Cape Grim in the Southern Hemisphere.

These factors highlight the unique role that Cape Grim (CGO, 41°S, 141°E) data can play in monitoring changes in anthropogenic forcing of climate and ocean acidification. The station is jointly managed by the Australian Bureau of Meteorology (logistics and meteorology) and CSIRO (trace gas and aerosol measurement). There is extensive scientific involvement by other, mainly international, agencies. The site provides the best demonstration of the Southern Hemisphere highly systematic CO_2 variation of Northern hemisphere origin. Distinguishing features include high baseline sample frequency of ~50 samples yr^{-1} collected at extremely high wind speeds of 13 ± 5 ms^{-1}, from 240° ± 24° from North, with superior CO_2 precision (<0.05 ppm). The site is accessible at short notice, with real time access to data. There is extensive verification of air mass history (>50 trace gases including hourly Rn^{222} from 1992) & aerosol parameter monitoring, and with back trajectories verifying negligible terrestrial or industrial exchange (reference **2**, Supplement S1).

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