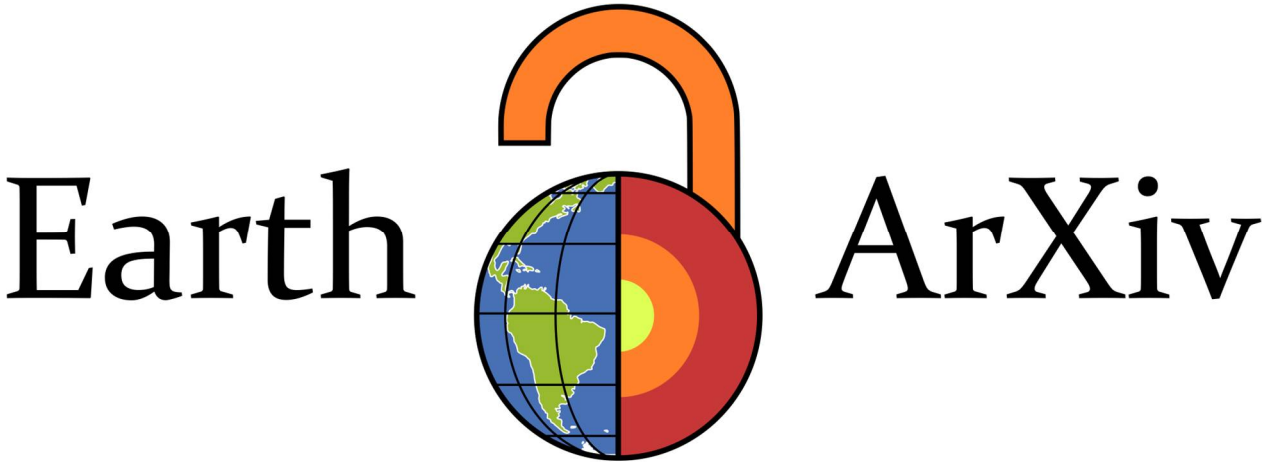




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This, version 2 of our non-peer reviewed manuscript, has also been submitted for publication to the peer review journal Nature Climate Change, Matters Arising. The earlier version 1 of this EarthArXiv submission has slightly different content as may any subsequent versions. If accepted for publication, the final version of this manuscript will be available via the 'Peer-reviewed Publication DOI' link on the right-hand side of this webpage. Please feel free to contact Jorgen Frederiksen; we welcome feedback.

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# Instability and atmospheric $CO_2$ anomalies in the recent global carbon cycle

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Key words: $CO_2$ anomalies, carbon cycle, instability, $CO_2$ transport, fossil fuel.

ARISING FROM: B. Birner et al. Nature Climate Change https://doi:10.1038/s41558-023-01761-x

## 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.

## The Controversy

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.

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], reach conflicting conclusions about the stability of the recent global carbon cycle. The controversy has direct relevance to verification of the anthropogenic emissions that influence climate.

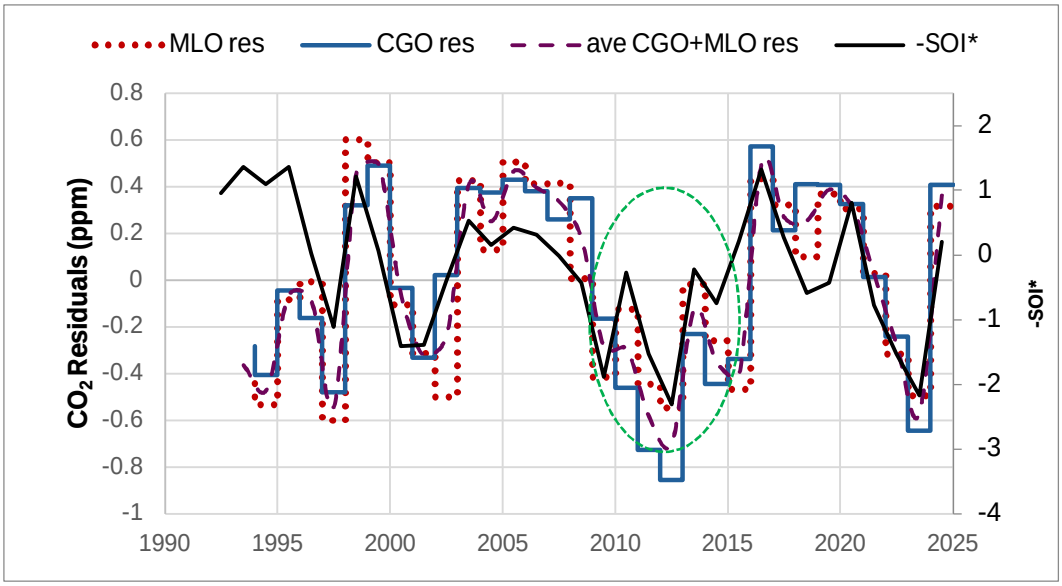
Factors that distinguish the two studies are:

- Birner et als.[1] assumption of constant dynamical processes compared with our observations that the extraordinary 2009 to 2015 anomaly in $CO_2$ amount is bracketed by unprecedented changes in interhemispheric exchange[2].
- Their reliance on $CO_2$ growth rates to constrain complex models of the carbon cycle[1] compared with our measured variation in $CO_2$ concentration[2].
- Their summing growth rate derived air-surface fluxes from around 200 individual locations to arrive at a global response[1]. This is compared with our tracking concentration changes in a large, well-mixed Southern Hemisphere (SH) volume of the atmosphere which is most remote from the predominantly Northern Hemisphere (NH) fossil fuel emissions and terrestrial biosphere changes[2]. Integration is achieved by atmospheric mixing.
- Their conclusion on the surprising stability of the recent global carbon cycle[1] compared with our observation of a classical instability leading to the unparalleled 2009 to 2015 anomaly in $CO_2$ amount[2].

This comment includes two figures in the main text and one in the Appendix, 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.

***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*

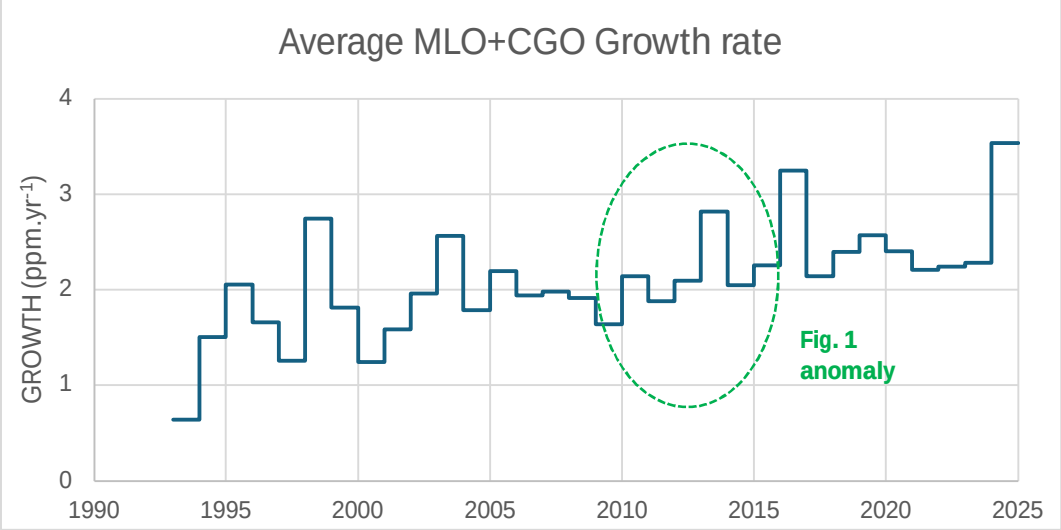
*the right axis. In the respective hemispheres, concentration variations are expressed as the residuals from 3-decade quadratic increase due to fossil emissions. The green ellipse encloses the 2009-2015 anomaly.*




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[3] (differences in the hemisphere representative concentrations are shown in Appendix). Apart from the obvious persisting low concentrations, pertinent factors that distinguish the anomaly from the rest of the 3-decade record, include:

- The $CO_2$ anomaly corresponds to the largest multi-year difference between the MLO and CGO step plots.
- After a Pinatubo response, the most significant multi-year feature is the departure of the CGO $CO_2$ step plot from the overall correlation with the previous year's negative Southern Oscillation Index (-SOI*). The reduction in CGO concentration, while MLO retains a similar relationship with SOI, is consistent with a reduction in interhemispheric transport.
- There is markedly less scatter in the annual MLOres – CGOres $CO_2$ 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 -at 0.01±0.20 ppm. (If the anomaly period is excluded the scatter is similar, -0.05±0.18 ppm.)
- The atmospheric $^{13}C/^{12}C$ ratio in $CO_2$ is represented by $\delta^{13}C \approx -8‰$ in annual averaged values. The smooth long-term increase in fossil emissions with $\delta^{13}C \approx -27$ ‰ is accompanied by a smooth decrease of $\delta^{13}C \approx -13$ ‰ (supplement S1 of reference 2) in annually averaged values. This is due primarily to gross flux isotopic equilibration with ocean DIC, releasing $\delta^{13}C=-7$ ‰ to the atmosphere. The 2010-2015 anomalous reduction in annual concentration is characterised by $\delta^{13}C$ values of -27 ‰ at MLO and -19 ‰ at CGO, consistent with the opportunity for air-surface isotopic equilibration and relative exposure to terrestrial fluxes in the respective locations[2].
- Birner et al.'s[1] verification of the modelled carbon cycle effectively relies on averaging the MLO and SPO $CO_2$ 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].

***Figure 2**: Annual growth rates based on the average of MLO plus GCO $CO_2$ showing annual tendency growth rates to fail to clearly register the concentration anomaly in Fig.1 during the time of the green ellipse.*




In Fig.2, annual growth rates are calculated by differencing of the average of the MLO plus CGO $CO_2$ annual concentrations. 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 the SPO data used by Birner et al.[1].

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[4], atmospheric teleconnection patterns[5,6], ensemble perturbations, and errors in seasonal prediction[7] and dynamical system theory and chaos[8]. 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 $CO_2$ concentration and growth rates is that concentrations are more directly and precisely related to climate forcing and ocean acidification.

It is also pertinent 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[9,10]. 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 important 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. Note that our data suggest that the decrease in economic activity, translating into reduced anthropogenic fossil emissions, persists through to 2015 (reference 2, Figure 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[11] was focussed on similar profiles from the NH and exclusively interprets every profile in terms of air-surface exchange. But the absence of seasonality in the overall 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 $\delta^{13}CO_2$ 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[12]**.** This is at a time of the largest hemispheric $CO_2$ partial pressure difference[13] and a maximum interhemispheric transport, occurring above the Intertropical Convergence Zone[10]. The upper troposphere $CO_2$ versus $\delta^{13}CO_2$ correlation 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.

The atmospheric dynamics during the anomaly period of 2009 to 2015 was far from constant, a fact which Birner et al.[1] assumed was a reasonable assumption for their analysis, but transport underwent some of the most dramatic changes.

The signal of instability (Figure A1) and systematic anomalous behaviour (Figure 1) are clearly seen in the baseline $CO_2$ data and conflict with Birner et als.[1] conclusion on the surprising stability of the recent global carbon cycle.

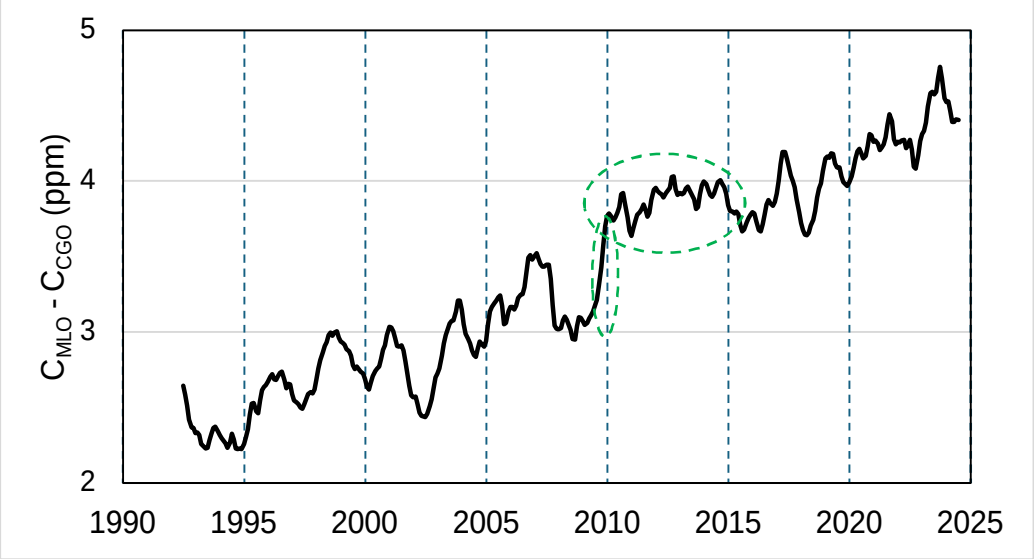
As a consequence of our study[2], we have reinterpreted some of our highly cited papers, based on growth rate analysis, specifically reference 14, with the primary cause now being changes in the Southern Oscillation Index. Also, emphasizing a wider relevance, the SH uniform $CO_2$ variations[2] of NH origin suggest that recent oceanographic studies using $CO_2$ growth inversions to estimate Southern Ocean $CO_2$ removal (e.g. Gruber et al.[15]), require reinterpretation.

The Birner et al. 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)[16] reports. The failure of these updates to detect the anomalous behaviour in $CO_2$ background concentrations compromises their effectiveness in advising on global climate change. Additional analysis of systematic variations in annual residual carbon amount provides opportunities for improved advice.

### *Appendix*

The 2009 to 2015 anomaly can be seen in the monthly raw data for the MLO minus CGO $CO_2$ difference and more easily from the corresponding monthly perturbation to the average annual cycle of $CO_2$. The anomaly and the classical instability of the carbon cycle with the rapid growth between 2009 and 2010 followed by the flattening or saturation to 2015 is very evident in the 12-month running means shown in Figure A1.

***Figure A1****: The 12-month running mean of MLO – CGO $CO_2$. Ellipses highlight the classical instability and the 2009–2015 $CO_2$ anomaly period.*




The terms background, or baseline, are used here to describe measurements in samples of air collected in conditions that minimise terrestrial and industrial influence and maximise 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 characterised 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).

## References


1. Birner, B., Rödenbeck, C., Dohner, J. L. *et al.* Surprising stability of recent global carbon cycling enables improved fossil fuel emission verification. *Nat. Clim. Chang.* 13**,** 961–966, 2023. https://www.nature.com/articles/s41558-023-01761-x
2. Francey R.J. and Frederiksen J.S. Systematic anomalies in the recent global atmospheric $CO_2$ concentration. *PLOS Clim* 4(8), e0000682, 2025. https://doi.org/10.1371/journal.pclm.0000682
3. Friedlingstein, P., Jones, M. W., O'Sullivan, M. *et al.*, Global Carbon Budget 2021. *Earth Syst. Sci. Data Discuss.,* 14, 1917–2005, 2022. https://doi.org/10.5194/essd–14–1917–2022
4. Frederiksen JS, Branstator G. Seasonal and intraseasonal variability of large scale barotropic modes. *J Atmos Sci*. 58, 50–69, 2001. https://doi.org/10.1175/1520–0469(2001)058<0050:SAIVOL>2.0.CO;2

5. Frederiksen JS, Branstator G. Seasonal variability of teleconnection patterns. *J Atmos Sci.,* 82, 1346–1365, 2005. https://doi.org/10.1175/JAS3405.1

6. Hannachi A. *Patterns Identification and Data Mining in Weather and Climate*. 2021, Springer Nature, Switzerland, AG. https://doi.org/10.1007/978–3–030–67073–3

7. Frederiksen JS, Frederiksen CS, Osbrough SL. Seasonal ensemble prediction with a coupled ocean-atmosphere model. *Aust Meteor. Oceanograph. Journal*, 59, 53-66, 2020. http://www.bom.gov.au/jshess/docs/2010/jfrederiksen.pdf

8. Frederiksen JS. Covariant Lyapunov Vectors and Finite–Time Normal Modes for Geophysical Fluid Dynamical Systems. *Entropy*, 25, 244, 2023. https://doi.org/10.3390/e25020244

9. Bowman, K. P., Cohen, P. J., Interhemispheric exchange by seasonal modulation of the Hadley circulation. *J. Atmos. Sci.,* 1997, 54, 2045–2059. https://doi.org/10.1175/1520-0469(1997)054<2045:IEBSMO>2.0.CO;2

10. Frederiksen, J.S. and Francey, R.J., Unprecedented strength of Hadley circulation in 2015–2016 impacts on $CO_2$ interhemispheric difference. *Atmos. Chem. Phys.*, 18, 14837–14850, 2018. https://doi.org/10.5194/acp-18-14837-2018

11. Stephens et al. Weak Northern and Strong Tropical Land Carbon Uptake from Vertical Profiles of Atmospheric $CO_2$. *Science,* 319,1732-1735, 2007. https://www.sciencemag.org/ doi:10.1126/science.1137004

12. Langenfelds, R.L.L., Studies of the global carbon cycle using atmospheric oxygen and associated tracers. Ph.D. thesis, University of Tasmania, pp. 248-262, 2002.

13. Francey, R. J. and Frederiksen, J. S., The 2009–2010 step in atmospheric $CO_2$ interhemispheric difference. *Biogeosciences*, 13, 873–885, 2016. https://doi.org/10.5194/bg-13-873-2016

14. Francey, R., Trudinger, C., van der Schoot, M. *et al.* Atmospheric verification of anthropogenic $CO_2$ emission trends. *Nature Clim. Change,* 3, 520–524, 2013. https://doi.org/10.1038/nclimate1817

15. Gruber, N., Bakker, D. C. E., DeVries, T., Gregor, L., Hauck, Landschützer, P., McKinley, G. A., Müller J. D., Trends and variability in the ocean carbon sink. *Nature Reviews Earth & Environment*, 4, 119–134, 2023. https://www.nature.com/articles/s43017-022-00381-x

16. https://www.ipcc.ch/reports