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The 2010-15 anomaly in the Southern Hemisphere baseline CO$_2$

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Abstract

The CO$_2$ measured in baseline air collected over three decades from six Southern Hemisphere sites spanning 70° of latitude uniformly indicate an 11 PgC anomaly between 2010 and 2015. The anomaly, in annually averaged residuals from the smooth increase due to the cumulative total of long lived anthropogenic emissions, exceeds uptake expected from modelled sinks. It also departs from long term lagged correlations with ENSO indices. Air-surface exchange is of insufficient magnitude, abruptness, and persistence to explain the anomaly. Overestimation in the 3-4 PgC year$^{-1}$ interhemispheric flux of fossil emissions is implied. The anomaly trails the GFC, whose impact is complicated by anomalous within-NH and interhemispheric mixing. Resumption of atmospheric behaviour more consistent with emission estimates coincides with improved national emissions accounting at COP21. There is relevance to top-down air-surface flux estimates, for example, recent conflicting transport model estimates of Chinese emission trends or El Niño induced emissions.

Introduction

Development in atmospheric CO$_2$ monitoring involves dichotomy between methods focussing on verification of annual national emission estimates and those more directly informing global climate and ocean chemistry anthropogenic impacts. The first requires increased density of monitoring sites, at a cost of increased degrees of freedom in interpretative models. The second requires selection of few sites providing data with high precision and maximum spatial representation and is the approach used in this article.

The CSIRO Global Atmospheric Sampling LABoratory (GASLAB) methods and data, with focus on the key baseline sites Kennaook/Cape Grim (CGO, 41°S) and Mauna Loa (MLO, 20°N), are documented elsewhere$^1$. In summary, since 1992:

- Dry, pressurized baseline air is collected in glass flasks from 11 globally distributed sites, most in the Southern Hemisphere (SH).
- Extended lifetimes of frequently accessed CO$_2$ reference and calibration standards ensure high precision maintained at <0.05 μmol mol$^{-1}$ (ppm) in interannual variation.
- Baseline integrity is monitored by hourly Radon-222 at CGO, and since 2004 at MLO.
- Air is also measured for CO$_2$ stable isotopes δ$^{13}$C (δ) and δ$^{18}$O, as well as CO, CH$_4$, N$_2$O and H$_2$.

The CGO and MLO individual flask CO$_2$ (C) measurements are replotted in Figure 1, where the conservative quantity δ.C$^{2-4}$ is used to represent stable carbon isotope ratio (δ) behaviour.
The simplicity in temporal behaviour indicates a small number of dominant influences. The diverging quadratic fits (Supplementary Information S1) are attributed primarily to the accumulation of long-lived\textsuperscript{5,6} anthropogenic emissions. With \~{}95\% emitted in the Northern Hemisphere (NH), the Southern Hemisphere (SH) experiences the anthropogenic emissions mixed globally. Note that estimated globally, terrestrial biosphere exchange\textsuperscript{7} only marginally reduces the three-decade industrial changes. The standard deviation (SD) of individual flask C residuals around a conventional 80-day smooth curve\textsuperscript{8} (that captures the seasonality) is 0.16 ppm at CGO and 0.47 ppm at MLO. The quadratic 55.7 ppm 1992-2020 C change at CGO occurs when the global reported anthropogenic emissions since 1959 total 236 PgC\textsuperscript{9}, on average requiring 4.24 PgC of the emissions to change the SH atmosphere by 1 ppm.

Converting the measured CGO background mole fraction (ppm C in dry air) to atmospheric mass, the SH trend provides a precise lower limit to the increase in global atmosphere CO\textsubscript{2} content, from 724 to 838 PgC. The inverted $\delta^13C$ quadratic is consistent with the cumulative total being of fossil fuel emission origin but with its $\delta$\textsuperscript{13}C~\textasciitilde{}\textasciitilde{}27 \%\textsubscript{o} isotopically equilibrated to $\sim{}$13 \%\textsubscript{o}\textsuperscript{1} predominantly by gross turnover with ocean surface layer dissolved inorganic carbon (DIC) at $\delta$\textsuperscript{13}C\textasciitilde{}+1 \%\textsubscript{o}\textsuperscript{10} which is released to the atmosphere with $\delta$\textsuperscript{13}C\textasciitilde{}$\sim{}$7 \%\textsubscript{o}\textsuperscript{11} (Supplementary Information S2). Compared to the atmosphere which has accumulated
anthropogenic CO$_2$ over recent centuries, the ocean, over millennia, has accumulated around 50 times
more carbon as DIC$^{12}$. On the timescales of relevance here, around 900 PgC of the DIC in the ocean
surface layer$^{12}$ is available for equilibration with the atmosphere. The -7 ‰ isotopic labelling of ocean
emissions is more effective in reducing the -27 ‰ accumulated fossil emission label than emissions
from C3 photosynthesising plants with $\delta$~27 ‰ (which marginally reduce the equilibrated value in
the NH) or C4 plants with $\delta$~12 ‰ (sufficiently close to the equilibrated value to have little effect on
annual timeframes or longer$^{13,14}$).

Residuals from Hemisphere Backgrounds

Global carbon budgets generally associate atmospheric CO$_2$ growth rate with net air-surface exchange fluxes. The CO$_2$ annual growth rate is typically obtained by differentiation of a 650-day smoothing spline$^8$ through data at each site and used to distinguish seasonal and interannual variation. Seeking higher time resolution and more independent description of the interannual spatial differences, we use residuals from the intrinsically smooth cumulative fossil fuel induced quadratic fit to CGO and MLO 1992-2021 baseline CO$_2$ measurements. Covariation of these residuals with significant exchange fluxes are explored. Using the CGO data, the Standard deviation (SD) of residuals from the quadratic is 0.58 ppm, almost entirely the result of the regular seasonal cycle with SD 0.41 ppm and (with seasonality suppressed by annual averaging) a quasi-regular 2-4 year annual variation, also with a SD of 0.41 ppm.

In contrast, at MLO the SD in residuals from the MLO quadratic (with large seasonality due to temperature-driven forest exchange) is 2.4 ppm.

Figure 2: Annual residuals from CGO (Southern Hemisphere, blue) and MLO (Northern Hemisphere, red) quadratics for 8 GASLAB sites (latitudes included in legends) with multi-decadal records. C residuals are dark (left axes) and $\delta$C residuals light (right axes) in each hemisphere. Shading on C curves indicate anomalies that generally exceed excursions in bracketing interannual variation. The size of subtracted mean C differences are indicated in legends. No normalisation is made to $\delta$C plots.
Figure 2 shows SH residuals from the CGO quadratics, and NH residuals from MLO quadratics, from 80 GASLAB sites with multi-decade continuity. To address occasional data gaps and variations in sample frequency, annual averages are obtained from monthly data using the 80-day smoothing spline. Without the 650-day smoothing conventionally used to determine trends, these data retain near-annual time resolution.

In Figure 2, SH residuals exhibit no linear trend compared to CGO, while ALT shows no obvious linear trend compared to MLO, confirming that CGO and MLO provide useful baselines for their respective hemispheres. Mean C offsets of 0.89 ppm at CFA in the SH and 1.13 ppm at ALT in the NH reflect the mean latitudinal gradient, which is linked to the latitudinal distribution of industrial emissions but moderated in the NH by rectification of the large regular NH terrestrial biosphere CO₂ seasonal cycle interacting with less regular N-S atmospheric transport seasonal variation (discussed below).

The persistence of SH C residuals excursions that fall below the range of bracketing interannual variation, identifies the 2010-2015 anomaly (shaded). In the anomaly period, all six SH residual responses are statistically indistinguishable, dipping to -1 ppm in 2012. There are corresponding negative excursions at MLO and ALT (at 84°N) but starting earlier, similar to the SH at ALT, but only marginally anomalous at around -0.4 ppm at MLO. Away from the 2010-2015 anomaly period (also away from 1992-93 at MLO), interannual variations in C residuals show similar phase and amplitude globally, generally consistent with an equatorial origin. We point out that the 1997-1998 El Niños correspond to record wildfire emissions over the 3-decade period, and 1999-2002 correspond to unusually strong and persistent La Niña activity, neither making a strong impact in Figure 2.

The slope of $\delta^13C$ versus C for the annually averaged CGO (SH) C and $\delta^13C$ residuals is $-18.11 \pm 0.15 \text{‰}$, more positive than for $\sim$-27 % C3 forests emissions, but more negative than can be explained by savannah $\sim$-12 % C4 photosynthesis. This indicates a significant C3 terrestrial photosynthesis contribution to the equatorial interannual variation in C residuals. The slope is not significantly changed if 2010-2015 data (explored below for variable transport of fossil emissions from the north) are removed. (Note: GASLAB isotope data exhibit less scatter than that from other networks when applied to MLO and CGO $\delta^13C$ differences).

The mean $\delta^13C$ offset for ALT is 50 ‰ ppm per ppm offset, while that at CFA it is 6 ‰ ppm per ppm offset, indicating much greater isotopic equilibration with oceans in the multi-decadal Southern Hemisphere values.

To confirm the quadratics are not unduly influenced by selection of period, fits to data from 1980-2020 and 1992-2020 were compared (using CSIRO CGO in situ and NOAA MLO monthly average flask data). Yearly averaged C residuals remained within 0.1 ppm.
Interannual Variation (IAV) in Residuals

There is a broad consensus between top down inversions and more recent compilations of surface fluxes, that IAV in the global carbon cycle is the result of climate variation influencing equatorial terrestrial vegetation, in particular on semi-arid ecosystems featuring C4 photosynthesis. The normalised IAV in the GASLAB C data is compared to equatorial climate forcing in Figure 3(a) and to global carbon budget modelled terrestrial and ocean IAV in Figure 3(b), where the IAV in C residuals are corrected for the mean SOI forcing.

The CGO C residual IAV is taken to represent the whole SH (including CFA minus 0.89 ppm), while in the NH, 1.13 ppm is subtracted from ALT annual means. Overall, these data indicate that ±1 PgC of equatorial interannual surface variation results in ~±0.5 ppm in C residuals globally, i.e. requiring ~ 2 PgC ppm$^{-1}$. The greater sensitivity, compared to the 4.24 PgC ppm$^{-1}$ SH change due to NH Fossil emissions, is attributed to the vertical convection of the near-equatorial emissions and their N and S mixing at altitude, minimizing removal by surface sinks. This limited surface exchange would also mean that isotope equilibration is less for the near-equatorial emission isotopic signals.

In Figure 3(a), the C residuals annual variation in the SH, also at MLO and at ALT, are compared to the annual variations the Southern Oscillation Index (SOI, inverted and plotted at year plus 1). Table 1 shows the significant correlation ($r$~0.6) between each site’s lagged C residual plot and -SOI(y+1) (or

Figure 3(a) compares the annual C residuals in ppm at CGO (blue), MLO (red dash), and ALT (purple dot) on the left axis, with ENSO variation, using negative SOI plotted at year+1 (right axis, black). In Figure 3(b) the mean SOI variation defined by the relationship at CGO is subtracted from all three C residual plots (left axis) and compared to interannual variability in global terrestrial (green) and ocean (light blue) fluxes.
the Nino34(y+1), not shown), using data from 1995 to avoid possible influence due to the 1991
Pinatubo volcanic explosion.

**Table 1**: Correlation coefficients of actual and lagged by 1 year C residuals at CGO and MLO with ENSO indices, SOI (inverted) and Nin3.4 (NOAA, 2021)

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<th></th>
<th>r from 1995</th>
<th>y</th>
<th>(y+1)</th>
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<td>0.62</td>
<td>-0.08</td>
<td>0.51</td>
<td></td>
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<tr>
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<td>0.64</td>
<td>-0.22</td>
<td>0.64</td>
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In Figure 3(b), the delayed carbon variation, due to the equatorial ENSO climate forcing of the terrestrial biosphere, is suppressed by adjusting the residuals based on the slope ± standard error, (0.334 ± 0.087), of a linear regression through CGO C residuals versus -SOI(y+1). This adjustment emphasizes the anomalies. The large negative anomalies in 1993-1994 are much larger at MLO compared to CGO and insignificant at ALT. In contrast the 2010-2015 period shows ALT and CGO anomalies large but barely significant at MLO.

The 1993-1994 anomaly is attributed elsewhere to the Pinatubo volcanic explosion at 18°N, at a similar latitude to MLO. The isotopic data suggest a significant terrestrial influence via the photosynthetic stimulation of light scattered by particulate matter, as well as uptake due to ocean cooling. We also note the absence of negative residuals in 2019-2020, providing no evidence for a reported reduction in emissions accompanying the COVID-19 pandemic, as reported elsewhere.

For a perspective on the 2010-2015 anomaly, the IAV in the modelled global and terrestrial biosphere exchange variation (using residuals from a quadratic fit) is shown on the right axis of Figure 3(b). It demonstrates the volatility of the terrestrial exchange compared to that with oceans, and thus the improbability of the oceans contributing to the SH 2010-2015 anomaly. Slow ocean uptake is due to the chemical buffering of atmosphere-ocean CO2 exchange described by the Revelle Factor, which is the ratio of the proportional changes in atmosphere \( \delta_{pCO_2}/pCO_2 \) and ocean \( \delta_{DIC/DIC} \). A typical ratio is 10-11, with the stability of the DIC reflecting its large historic accumulation. The consequent relatively slow ocean uptake is inconsistent with the sudden onset and recovery of the 2010-15 anomaly, while the isotopic data of Figure 2 also exclude a SH oceanic sink of sufficient magnitude.

(Note: If marine biota obtain the bulk of their carbon from the abundant DIC there will be little immediate impact on atmospheric CO2). Remaining possibilities for the SH anomaly are a SH terrestrial sink or a reduction in the 3-4 PgC yr\(^{-1}\) of fossil emissions transported from the NH.

A combination of top-down inversions coupled with comprehensive satellite and surface observations reported an exceptionally large land carbon sink anomaly in 2011, of which more than half was attributed to Australia. After the mean -SOI correction, it likely makes a modest contribution to the extended apparent sink in that year and was transient, recovering quickly by 2012-13. (Their identification of similar sink behaviour in 2001 does correspond to a modest drop and 1-2 year
recovery in C residuals in Figure 3(b) and serves as an indication of the possible magnitude of the 2011
biosphere extra contribution.)

We note in passing that the subtraction of a lagged C residual response to SOI substantially removes
interannual variation in the CGO (SH) record, however a significant 2 to 4-year variation persists at
MLO and ALT. The persisting Northern Hemisphere variation, showing larger amplitude at ALT
compared to MLO, exhibits a weak direct (not lagged) correlation with -SOI (r~0.2). This correlation
also exists with the δ¹⁸O in the CO₂ of these samples. The δ¹⁸O have been linked to ENSO forcing of
the equatorial hydrological cycle but are relatively insensitive to net carbon transfers²⁶. During the
2010-2015 anomaly in the CO₂ residuals, the δ¹⁸O (not shown) continue to track the ENSO indices¹,
strengthening the inference that the Cres anomaly is not climate related but due to industrial
emissions from the NH.

We conclude that a reduction in NH fossil emissions provides the most likely cause of the SH anomaly.
Using the observed 4.24 PgC ppm⁻¹ to describe the sensitivity of SH C residuals to NH anthropogenic
emissions, the negative CGO ppm anomalies in Figure 3(b) between 2010 and 2015 total -2.7 ppm,
converting to -11.5 PgC.

An obstacle to this explanation is the absence of a similar reduction in the MLO C residuals, which are
located closer to the NH industrial emissions. Our explanation for this inconsistent MLO behaviour
involves unusual atmospheric mixing and IH exchange around 2010.

Latitudinal gradients

To address the near absence of a 2010-2015 anomaly in the MLO C residuals, Figure 4 shows three
decade mean C residuals from the CGO quadratic of Figure 1, using the 8 GASLAB sites plus 22 (mainly
NH) sites from the NOAA flask network plotted as a function of latitude (site identification and
residuals are provided in supplementary information S3). Where there is co-monitoring, there is
general agreement between the laboratories.

Figure 4: Annual average C residuals of NOAA sites (red circles) from the GASLAB Southern Hemisphere CGO quadratic as a
function of latitude (sites are identified in Supplementary Information S3). GASLAB C residuals are in blue. The dashed red
line is a schematic representing a lower envelope of NOAA Northern Hemisphere data.
Significance is attached to the lower envelope of the NH residuals described by a dashed red line, as indicating NH sites least affected by regional emissions. Background sites less than 30°N have lower residuals than the NH average, while sites above the Arctic Circle (66°N) are higher. The low latitude sites are in a region where the largest flux removing fossil emissions from the NH operates. This is via mean NH to SH transport by the Hadley Circulation in the upper troposphere, particularly over the Pacific sector, and through turbulent eddy transport caused by Rossby wave propagation and breaking in the regions of the upper tropospheric westerly ducts, most notably over the Pacific. Thus, lower mean values are unsurprising. The high Arctic values, despite sparse industrial or biospheric activity in the region, indicate greater NH South to North mixing in winter when the mid-latitude boreal forests are near peak respiration. Both processes are subject to variation in transport.

**Transport variation**

The $u_{\text{duct}}$ index for the Pacific Westerly Duct to describe eddy exchange between hemispheres was introduced to link the unprecedented boreal winter-spring jump in $C_{\text{MLO}}$-$C_{\text{CGO}}$ in 2009-2010\textsuperscript{16}, (a dynamical rather than surface C exchange explanation was reinforced by there being similar impact on other atmospheric trace species). Subsequently, $\omega_{300}$ and $v_{200}$ indices were introduced to describe the late boreal spring and summer-autumn IH exchange via mean or Hadley Cell transport in 2015, 2016\textsuperscript{27}. The indices are re-examined in Figure 5, which also includes the NAO index indicating changes of N-S mixing within the NH, with increased intra-hemispheric mixing in the asymmetric negative phase of the NAO.
The sign of IH exchange indices is selected so that increased IH mixing is upwards and decreased IH mixing is downwards in Figure 5. The 6 month averaging interval in interhemispheric transport indices is chosen to emphasize seasonal differences in hemispheric CO$_2$ partial pressure difference, which drive the CO$_2$ exchange. The mean MLO-CGO values are 4.77 ± 0.69 ppm in December to May and 1.82 ± 0.55 ppm June to November.

**Figure 5(a):** Interhemispheric exchange indices $u_{\text{duct}}$ (Dec-May, blue, eddy, left axis) and $-\omega_{300}$ (Jun-Nov, orange, Hadley, right axis), with up indicating more IH exchange and **Figure 5(b)** $-v_{200}$ (Jun-Nov, orange dot, Hadley, left axis). Also, in 5(b) the within-hemisphere -NAO (annual, black, left axis) shows N->S exchange.

In Figure 5(a), eddy IH exchange index, $u_{\text{duct}}$, is reduced at times of the 1998, 2010 and 2016 El Niños. In 2010 the El Niño is the result of mid-Pacific rather than Eastern-Pacific sea surface temperature changes and is also associated with an extreme northerly excursion of the Inter Tropical Convergence Zone (ITCZ). These unusual factors both act to increase the accumulation of NH anthropogenic emissions at MLO by reducing the large nearby interhemispheric flux and temporarily restricting the NH anthropogenic emissions to a smaller hemispheric volume. This is reinforced by extreme within-NH mixing indicated by the extreme negative phase of NAO in Fig. 5(b), relatively reducing the Figure 4 Arctic CO$_2$ levels (ALT) and increasing the NH low-latitude levels.

Extremely low Hadley interhemispheric exchange existed in 2009 (the extreme lows in $-\omega_{300}$ and $-v_{200}$ in Figure 5), during in the recovery phase of the 2007-2008 Global Financial Crisis(GFC) emissions reduction, immediately followed by reduced eddy exchange. Subsequently, there was the unusually strong 2011 La Niña sink, mostly expressed in the SH sub-tropics. Allowing for a minor contribution to SH residual reduction in 2011, transport irregularities provide a consistent description of non-ENSO variation in residuals in Figure 3(b) before 2012.

We speculate that around this time the overestimation of reported anthropogenic emissions commenced. The relatively stable persistence of the anomaly through to 2015 may be influenced by the large opposing trends in IH exchange indices $u_{\text{duct}}$ and $\omega_{300}$ from 2012 to 2016, depending on
which one dominates IH exchange, for example if the magnitude of the overestimation increases, the
atmospheric impact may be stabilized by the reducing IH eddy transfer.

Discussion

The CO$_2$ anomaly period is bracketed by the 2007-2009 GFC plus reduced interhemispheric exchange
in 2010, and the COP21 Conference of Parties Paris Agreement in 2015. COP21 called for “Intended
Nationally Determined Contributions” to greenhouse emissions reductions. Methodologies to
estimate and integrate national global emissions were more variable and less developed during the
anomaly period and possible commercial/political influences, perhaps anticipating a requirement to
demonstrate future reductions, were more difficult to detect.

In contrast, the global total of the mainly NH emissions is quite accurately reflected in vigorously mixed
high southern latitudes. Several innovations in CO$_2$ measurement, calibration, and verification, also in
the verification of sample air mass history, that have operated consistently since 1992$^1$, mean that
CO$_2$ measurement and sampling uncertainty is insignificant (with measurement precision of annual
means around 0.05 ppm).

Large differences in estimates of the Chinese terrestrial sink in period 2010 to 2016, obtained using
inverse modelling techniques, have been attributed to different atmospheric chemistry transport
models$^{29,30,31}$. This period includes the 2.7 ppm anomaly from 2010 to 2015, measured over 70° of SH
latitude and attributed here to underestimation of global fossil emissions. The inversion studies
employing underestimated fossil emissions will result in overestimated terrestrial sinks. Furthermore,
the sensitivity to transport models in the inversion studies may well reflect their inability to capture
the volatility of interhemispheric exchange indicated by the indices shown in Figure 5.

An earlier atmospheric inversion study$^{32}$ had suggested a 1.4 PgC year$^{-1}$ overestimation by East Asian
CO$_2$ emissions or increase in the land sink in the decade from 2001 (total 11.4 PgC), based on a scaled
2002-2012 inversion of methane emissions. Their Figure 5 attributes much of the decadal trend in
emissions CO$_2$ flux to a jump in 2010-2012 data, which we associate with the anomaly onset.

Also, it is clear from Figure 5, that there are significant changes in IH transport following the major El
Niños, making their top-down flux estimates critically dependent on high-time resolution model
transport veracity.

This study suggests that the ability of trace gas transport models to reproduce the observed Southern
Hemisphere 2010-2015 anomaly, in both baseline CO$_2$ and its stable carbon isotopes, provides a
critical evaluation of their interhemispheric transport simulation and for estimated global (NH)
anthropogenic carbon emission changes.
Data availability.

Meteorological data are available from the NOAA/ESRL web site: [http://www.esrl.noaa.gov/psd/](http://www.esrl.noaa.gov/psd/) and [https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/nino34.long.anom.data](https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/nino34.long.anom.data). Trace gas data are obtained from WDCGG (World Data Centre for Greenhouse Gases), 2022. [https://gaw.kishou.go.jp](https://gaw.kishou.go.jp)
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References


Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- NCC230423SupplementaryInformation1.pdf