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On the significance of atmospheric CO_2 growth rate anomalies in 2002–2003

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[1] We examine the facts behind the growth rate of atmospheric CO_2 in 2002 and 2003. Observations show consecutive increases of greater than 2 parts per million (ppmv) per year for the first time on the Mauna Loa record (which extends back to 1958). We use a statistical regression to show that increasing anthropogenic emissions and El Niño activity are able to account for variations in the CO_2 growth rate at Mauna Loa, aside from the anomalously low growth rates of 1992 and 1993 following the Pinatubo volcanic eruption, and the anomalously high growth rate of 2003. Increased forest fires in the northern hemisphere, consistent with remote-sensing and carbon monoxide measurements, seem likely to have contributed significantly to the 2003 anomaly. We hypothesise that the hot and dry Eurasian summer of 2003 led to an increase in forest fire emissions from Siberia, and may also have directly suppressed land-carbon uptake. Insofar as the 2003 Eurasian summer may have been a symptom of anthropogenic climate change, it is possible that the 2003 CO_2 growth rate anomaly is the first evidence of a positive climate-carbon cycle feedback. **Citation:** Jones, C. D., and P. M. Cox (2005), On the significance of atmospheric CO_2 growth rate anomalies in 2002–2003, *Geophys. Res. Lett.*, *32*, L14816, doi:10.1029/2005GL023027.

1. CO_2 Growth Rates in 2002 and 2003 at Mauna Loa

[2] Figure 1 shows atmospheric concentrations of CO_2, measured at the Mauna Loa Observatory in Hawaii [*Keeling and Whorf*, 2004]. Figure 1a shows the annual mean CO_2 concentration from 1960 to 2004 and Figure 1b shows the annual CO_2 growth rate, calculated as:

$$\Delta CO_2(yearN) = CO_2(N) - CO_2(N-1)$$

The calculated growth rate is centred on the beginning of the year, as it is formed by subtracting annual means which are centred on the middle of each year. Note that 2002 and 2003 are the first consecutive years to both exceed a growth rate of 2 ppmv yr^{-1}, which has sparked interest in these observations as a possible indication of accelerating climate change through carbon cycle feedbacks [e.g., *Cox et al.*, 2000].

[3] However, even in the absence of a change in the behaviour of the "natural" carbon cycle we expect the absolute CO_2 growth rate to increase with the upward trend in total anthropogenic CO_2 emissions. In the long-term (i.e., 10 years or more) the carbon cycle appears to be absorbing a fixed fraction of emissions, leaving the remainder in the atmosphere as the so-called "airborne fraction". The red line in Figure 1b shows the time series of 40% of anthropogenic CO_2 emissions. The assumption that 40% of these emissions remains in the atmosphere explains the upwards trend of CO_2 rises, but does not explain their inter-annual variability. Our choice of the value of 40% is explained in the next section, but it has long been known that the natural carbon cycle absorbs approximately half of the emissions [*Schimel et al.*, 1996].

[4] Emissions data for fossil fuel and cement manufacture up to 2000 are taken from *Marland et al.* [2003], while the 2001, 2002 and 2003 emissions are estimated assuming annual growth rates of 1.2%, 1.4 % and 1.4% respectively (J. Penman, personal communication) with emissions for 2004 kept equal to 2003. Net annual land-use emissions up to the year 2000 are taken from the *Houghton and Hackler* [2002] estimates. In the absence of estimates for 2001–2004 we assume fixed net land-use emissions from 2000. Our results are robust to our choice of extrapolation of anthropogenic emissions to 2004 – assuming no growth from 2000 levels or assuming 2% p.a. makes little difference to the resulting size of the CO_2 growth rate anomaly.

[5] A number of studies have shown previous anomalies in the CO_2 growth rate to be correlated with the El Niño–Southern Oscillation (ENSO). During the El Niño phase of ENSO large-areas of tropical land become dryer and warmer, leading to a net emission of CO_2 from the land to the atmosphere which amplifies the CO_2 growth rate due to anthropogenic emissions [see, e.g., *Keeling et al.*, 1995; *Jones et al.*, 2001; *Zeng et al.*, 2005; *Knorr et al.*, 2005]. The opposite happens during the La Niña phase leading to anomalously low CO_2 growth rates.

[6] The black line in Figure 1b shows the variation in the CO_2 growth rate anomaly about the long-term trend due to increasing anthropogenic emissions. This shows that 2002 is not an exceptional growth rate anomaly, and 2003 is only the 4th largest anomaly on record. However, the three larger anomalies in 1973, 1988 and 1998 are all associated with significant El Niño events.

[7] Figure 1c shows the Niño3 index for each year (i.e., the sea-surface temperature anomaly in the Eastern Pacific region defined by 150°W–90°W, 5°S–5°N, calculated from the HadISST data set [*Rayner et al.*, 2003]). Analysis of the monthly data suggests that the Niño3 index typically leads the CO_2 anomaly at Mauna Loa by about 3 months [*Jones et al.*, 2001], hence we use the mean annual Niño3 centred on October rather January. So the annual mean

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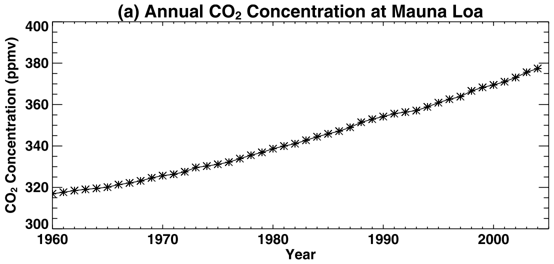
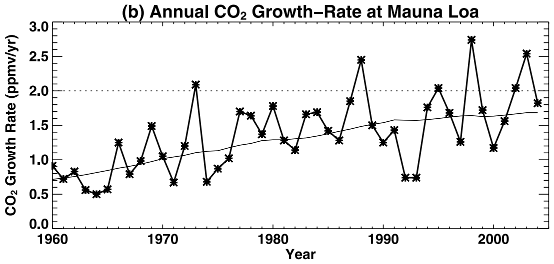

(a) Annual CO_2 Concentration at Mauna Loa


(b) Annual CO_2 Growth−Rate at Mauna Loa

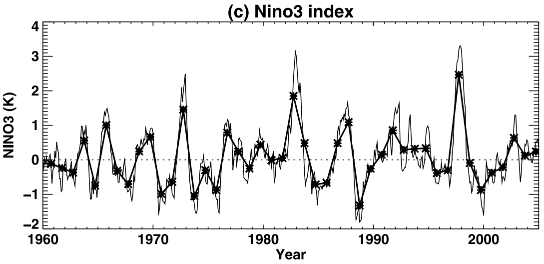

(c) Nino3 index

Figure 1. (a) annual mean CO_2 concentrations from Mauna Loa; (b) annual CO_2 growth rate (thick line) and 40% of total anthropogenic emissions (thin line). The horizontal dotted line marks 2 ppmv yr^{-1}: 2002 and 2003 are the first consecutive years above this level. (c) Monthly Niño3 index (thin line) and annual Niño3 index (April–March means; thick line). See color version of this figure in the HTML.

ENSO state which influences a given year's CO_2 rise is the mean ENSO state centred on the previous October. This processing has the additional advantage of making sure that ENSO events (which typically start towards the end of the calendar year and continue into the next year) are not "split" in two by inappropriate annual meaning starting in January.

[8] There is clear similarity between Figures 1b and 1c, with the positive CO_2 growth rate anomalies corresponding to El Niño events, and the negative growth rate anomalies corresponding to La Niña events. The largest positive CO_2 growth rate anomalies are coincident with large Niño3 values in 1973, 1988 and 1998. By contrast, the 2003 CO_2 growth rate anomaly follows a small Niño3 value suggesting a weak El Niño, and the Niño3 preceding the 2002 CO_2 rise is actually slightly negative.

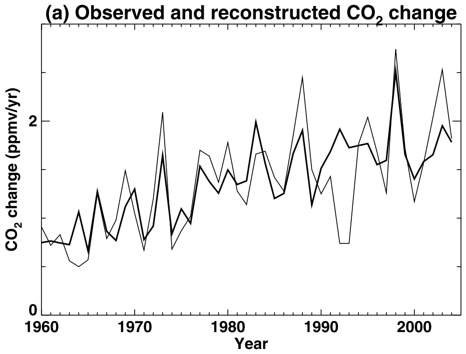
2. How Anomalous Were the 2002 and 2003 CO_2 Growth Rates?

[9] Here we investigate how anthropogenic emissions and ENSO activity combine to produce the observed changes in atmospheric CO_2. We regress the ΔCO_2 data simultaneously against anthropogenic emissions, ε, and the Niño3 index, N:

$$\Delta CO_2 = \alpha_1 + \alpha_2 N + \alpha_3 \varepsilon$$

This regression gives, $\alpha_1 = 0.08 \pm 0.47$ ppmv yr^{-1}, $\alpha_2 = 0.33 \pm 0.14$ ppmv yr^{-1} K^{-1}, $\alpha_3 = 0.40 \pm 0.14$. In other words, we get the expected positive correlation with Niño3 and find that in the long-term, 40% of emissions (from fossil fuel, cement and land-use change) remain airborne (as plotted in Figure 1b). Figure 2a shows the observed ΔCO_2 from Figure 1b and that reconstructed by our simple linear model based on anthropogenic emissions and Niño3 index.

[10] When these coefficients are used to calculate the extent to which each year's ΔCO_2 varies from that predicted by our linear model, several features emerge (Figure 2b). The most notable negative anomalies are 1992 and 1993 when the CO_2 growth rate was unusually low because of the climatic effects of the Mt. Pinatubo eruption in 1991 [*Jones and Cox*, 2001; *Lucht et al.*, 2002]. The low growth rate of 1964 is also coincident with a large volcanic eruption (Mt. Agung, 1963). The eruption of El Chichon in 1982 would similarly have caused a reduction in CO_2 growth rate but its coincidence with a large El Niño led to cancellation and a neutral ΔCO_2 value. 2003 has the largest positive anomaly


(a) Observed and reconstructed CO_2 change

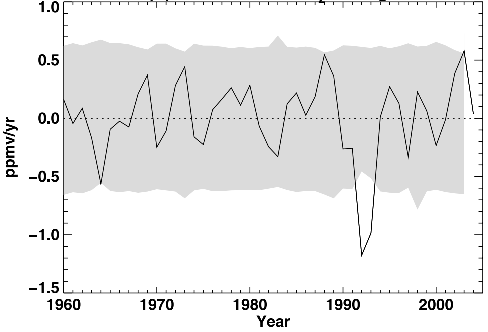

(b) Anomalous CO_2 change

Figure 2. (a) Reconstructed (thick line) and observed (thin line) rises in atmospheric CO_2 based on the linear model obtained by regressing CO_2 changes onto emissions and Niño3. (b) The anomalous CO_2 change – i.e., the difference between the curves in panel (a): positive values imply anomalously high CO_2 growth rate. The shaded bar represents levels of CO_2 change which may not be statistically significant. Anomalies outside the shading are significant at the 90% level. See color version of this figure in the HTML.

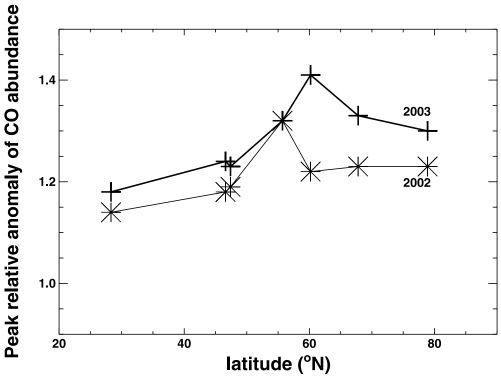


Figure 3. Anomalous carbon monoxide (CO) measurements (peak monthly value for 2002, 2003 divided by the mean from March 2000 to February 2002) from across Europe, displayed by latitude, for 2002 (thin line) and 2003 (thick line). Data from *Yurganov et al.* [2004]. See color version of this figure in the HTML.

and also the largest CO_2 growth rate for any year with a Niño3 value less than +1K.

[11] To quantify the statistical significance level of the 2003 anomaly, we build on the previous regression to add in a hypothesised extra process which operates for a single year:

$$\Delta CO_2 = \alpha_1 + \alpha_2 N + \alpha_3 \varepsilon + \alpha_4 \delta(y)$$

We apply the delta function, $\delta(y)$, to each year, y, in turn, and test the significance of the null hypothesis that this extra process is not operating in that year. In other words, the null hypothesis is that the ΔCO_2 can be explained purely in terms of the anthropogenic emissions, the Niño3 index and noise. If the null hypothesis is rejected statistically, then we can be confident that some other process is required to explain the ΔCO_2 for that year. The shaded region in Figure 2b shows the range of ΔCO_2 for which the null hypothesis is not rejected. Years whose ΔCO_2 lie outside this region have a 90% confidence that some other process is operating in that year. Low anomalies following the Pinatubo eruption show up very clearly (1992–1993), the other previously mentioned two volcanic years (1964 and 1983) also show low anomalies, although 1983 is not significantly so. 2003 is the only year to exhibit a high anomaly which is significant by this particular measure.

[12] It is possible that the volcanic signal is skewing the regression towards low ΔCO_2 values. We chose here to perform the initial analysis without any prior information, but to test the robustness of the statistics, the analysis was repeated twice – once with 1992 and 1993 excluded, and once where further "volcanic" years were also removed (i.e., 1963, 1964, 1982, 1983, 1992, 1993). In both cases, 2003 remained both the largest positive anomaly and the year with the greatest confidence that another process was operating to produce a positive anomaly.

[13] We also consider the robustness of the results to different measures of CO_2 rise and ENSO. We have checked that our use of annual mean CO_2 data to remove short-term variability does not influence our conclusions compared with use of a gliding mean of monthly data. Our choice of the Niño3 index as a measure of El Niño is due to it having the highest correlation with annual CO_2 variability. *Saith and Slingo* [2005] suggest that the 2003 El Niño SST anomalies formed further into the central Pacific than normal. Therefore we repeated our analysis using the Niño4 (150°E–150°W, 5°S–5°N) and Niño3.4 (170°W–120°W, 5°S–5°N) region SST anomalies and also the Southern Oscillation Index (the mean sea level pressure difference between Tahiti and Darwin). The different measures of ENSO each produce different years with the most significant positive anomaly: 2003 for Niño3, 1973 for Niño3.4, 1998 for Niño4 and 1988 for the SOI. In each case, 2003 shows an anomalously high CO_2 growth rate, but only for Niño3 does it exceed the 90% significance level. The sensitivity of the results to the measure of ENSO indicates that 2003 may not be the only year in the record which exhibits anomalous behaviour.

3. What Caused the 2002 and 2003 CO_2 Growth Rate Anomalies?

[14] We have shown that the 2003 ΔCO_2 was anomalously large given the size of the preceding El Niño, and that 2002 was larger than expected but not significantly so. It is unlikely that these anomalies can be explained by an abrupt increase in anthropogenic emissions, as the anomalies are much larger than annual increases in fossil fuel emissions. Most interannual variability in the CO_2 growth rate is attributable to variations in land-atmosphere CO_2 exchange with climate (e.g., associated with ENSO or volcanic perturbations), and the same is likely to be true for 2002 and 2003.

[15] There is good evidence of increased forest fires in Europe in 2002, and in Siberia in 2003 which could have contributed to increased CO_2 growth rates [*Balzter et al.*, 2005]. *Kovacs et al.* [2004] describe a correlation between Siberian fires and human activity, but the increase in 2003 forest fires is much greater than the increase in agricultural fires in that region. Hence it is likely that much, although not all, of the increased fire activity is in response to climatic rather than anthropogenic causes. *Balzter et al.* [2005] show how the fire activity is correlated with both large scale and regional scale climatic anomalies. Ground and space-based measurements of carbon monoxide are also consistent with large increases in biomass burning in 2002 and 2003 within the Northern Hemisphere [*Yurganov et al.*, 2004]. Figure 3 shows the carbon monoxide concentration anomaly for these years as a function of latitude. The anomaly for both years is significant, but the latitudinal peaks differ, consistent with mid-latitude fires in June–July 2002 and higher latitude fires in August–September 2003. Other trace gases (such as CH_4, H_2 and CH_3Cl) confirm the likelihood of increased Northern burning in 2003 [*Simmonds et al.*, 2005].

[16] An explanation in terms of Northern hemisphere fires is also supported by CO_2 and CO measurements in the southern hemisphere. We repeated our analysis using CO_2 data from the South Pole [*Keeling and Whorf*, 2004] and find positive, but less significant, growth rates for 2003. Also, there is no clear CO anomaly [*Francey*, 2005], despite high profile fires in Australia in January 2003. It is interesting to note that the other years which showed

anomalously large CO_2 increases (1973, 1988 and 1998) also show a greater increase in the northern hemisphere than the southern, but CO data is not available for these years to indicate whether they also experienced increased northern fire activity.

4. Conclusions

[17] 2002 and 2003 are the first two consecutive years on the Mauna Loa record to show atmospheric CO_2 growth rates of greater than 2 ppmv yr^{-1}. Although a long-term upward trend in CO_2 growth rate is to be expected because of the upward trend in anthropogenic CO_2 emissions, the 2002 and 2003 CO_2 growth rates cannot be explained by emission changes alone.

[18] However, most large positive CO_2 growth rate anomalies (such as in 1998), are preceded by strong El Niño signals, but the 2002 and 2003 CO_2 growth rates cannot be explained on this basis. We have shown that there is a high probability that some other process contributed to the 2003 ΔCO_2 anomaly.

[19] It is possible that the increased CO_2 release from Northern Hemisphere fires of 2002 and 2003 were driven by anomalous climatic conditions in these years (e.g., hot, dry summers). The dry European summer of 2003 also seems to have suppressed land carbon uptake, based on measurements from flux towers and model reconstructions [*Knorr et al.*, 2005; *Ciais et al.*, 2005]. These two mechanisms (i.e., increased fires and reduced land carbon uptake) are the most likely reasons for the 2002 and 2003 growth rates, but further analysis is required to fully attribute the changes.

[20] It has been hypothesised that a strong positive feedback between climate change and the carbon cycle may significantly accelerate global warming [*Cox et al.*, 2000; *Friedlingstein et al.*, 2001]. If this is true then as the climate warms we would expect to see an increase in the long-term fraction of emissions which remain airborne. If the anomalous 2003 rise in CO_2 was due to the hot conditions of that year which in turn may have been due to man-made global warming [*Stott et al.*, 2004] then might we be seeing the first signs of this positive feedback? Although it is clearly too early to detect a significant and persistent trend in the annual airborne fraction from the observed data, we cannot exclude this explanation as a possibility.

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