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A re-evaluation of the coherence between global-average atmospheric CO_2 and temperatures at interannual time scales

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[1] Frequency-dependent coherence between atmospheric CO_2 and historical temperatures reveals climate feedbacks within Earth's carbon cycle. Coherence between interannual fluctuations in global-average temperature and atmospheric CO_2 has changed over time. Since 1979, at Mauna Loa and other observation sites, interannual coherence exhibits a 90° phase lag that suggests a direct correlation between temperatures and the time-derivative of CO_2. The coherence transition can be explained if the response time of CO_2 to a global temperature fluctuation has lengthened from 6 months to at least 15 months. A longer response time may reflect saturation of the oceanic carbon sink, but a transient shift in ocean circulation may play a role. Coherent annual-cycle fluctuations in CO_2 and temperature are evident in the 1958–1988 time series, but not since 1979. Coherence of interannual CO_2 variations with gridpoint temperature anomalies are strongest in the tropical oceans.

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1. Introduction

[2] Statistical correlations between atmospheric carbon dioxide and global temperatures have been found on multiple time scales. Simple autoregressive prediction filters that utilize CO_2, CO_2-proxy and solar-variability time series show that a handful of free parameters can explain well the secular progression of 20th-century temperatures [*Thomson*, 1997; *Kaufmann and Stern*, 1997; *Tol and de Vos*, 1998; *Stern and Kaufmann*, 2000]. On interannual time scales, carbon-cycle feedbacks are evident in correlation analyses that show CO_2 fluctuation to lag several months behind correlated fluctuations in global temperatures [*Kuo et al.*, 1990; *Martin et al.*, 1994; *Dettinger and Ghil*, 1998; *Adams and Piovesan*, 2005]. The earliest study [*Kuo et al.*, 1990] used spectral coherence statistics to correlate CO_2 and temperature, but most later studies use time-domain correlations, some statistical, some visual [see *Keeling et al.*, 1995, *Braswell et al.*, 1997; *Langenfelds et al.*, 2002; *Lintner*, 2002; *Buermann et al.*, 2007].

[3] The synoptic view afforded by global-scale measurements remains valuable. *Kuo et al.* [1990] correlated global temperature with a 30-year record of monthly CO_2 observations at Mauna Loa, Hawaii [*Keeling*, 2008]. 20 additional years of data is now available from Mauna Loa and the largely coeval South Pole CO_2 time series. A global network of stations [*GLOBALVIEW-CO2*, 2008; *Masarie and Tans*, 1995], now provides time series as long as the Mauna Loa series originally analyzed by *Kuo et al.* [1990]. It seems timely to ask whether the spectral correlations reported in the 1990s have persisted.

[4] *Martin et al.* [1994] cited ENSO to explain the interannual phase lead of global and hemispheric temperature relative to Mauna Loa CO_2. *Dettinger and Ghil* [1998] used Singular Spectrum Analysis to find correlations between CO_2 fluctuations and tropical SST. Interannual variability in the North Atlantic oceanic carbon sink has been observed to fluctuate with SST [*Gruber et al.*, 2002]. The importance of the terrestrial biosphere as a carbon sink [*Houghton*, 2007] has encouraged some researchers to seek its correlations with CO_2 variability [*Keeling et al.*, 1996; *Dargaville et al.*, 2002; *Buermann et al.*, 2007]. Temperature fluctuations are a crude proxy for carbon-cycle fluctuations, but influence many relevant physical and biospheric processes. In this spirit we have applied an extension of *Kuo et al.*'s [1990] coherence estimator to the geographically gridded Hadley Centre temperature anomaly data set to investigate which portions of the globe have experienced temperature fluctuations that cohere significantly with the CO_2 time series.

2. Data and Methods

[5] We obtained monthly data for atmospheric CO_2 concentrations at Mauna Loa, Hawaii and South Pole [*Keeling et al.*, 2009]. The Mauna Loa and South Pole CO_2 time series are continuous since 1958 and 1965, respectively; we analyze South Pole data since 1979. The GlobalView data product [*GLOBALVIEW-CO2*, 2008; *Masarie and Tans*, 1995] provides quasi-weekly CO_2 data (48 samples/yr) for individual stations of a global network. We use the GlobalView series from Barrow, Alaska, because its remote location should reflect global-average CO_2 values.

[6] We used the HadCrut3 globally gridded monthly temperature anomaly data set [*Brohan et al.*, 2006], as well as the global- and hemisphere-average monthly temperature-anomaly data sets (http://www.cru.uea.ac.uk/cru/data/). We interpolated linearly any data gaps of three months or fewer at individual gridpoints. The 1958–2008 Mauna Loa data series could be correlated against 1194 gridpoints, and the 1979–2007 data series could be correlated against 1316 gridpoints. We restored the 1961–1990-average yearly cycle to the temperature data to facilitate comparison with the CO_2 time series, which contain the annual cycle.

[7] Along with multiple-taper spectrum estimates [*Thomson*, 1982], we compute coherence $C(f)$, which meas-

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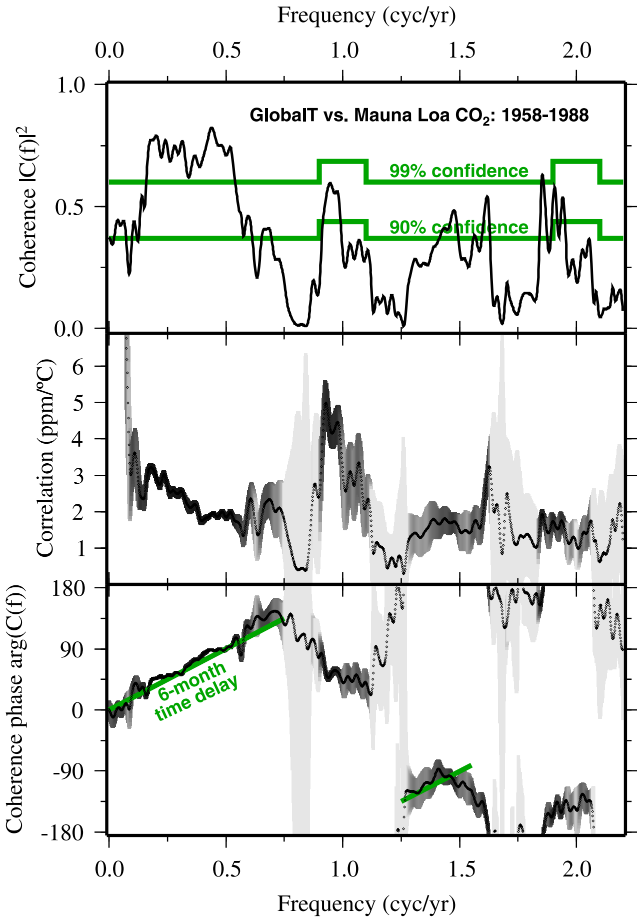

Figure 1. Coherence $C(f)$ for 1958–1988 between global-average temperatures and atmospheric CO$_2$ concentration measured at Mauna Loa, Hawaii. (top) $|C(f)|^2$ plotted with reference to the 90% and 99% confidence levels for nonrandomness. Coherence is based on 2 and 10 degrees of freedom with 6 Slepian tapers with time-bandwidth product p = 3.6. The confidence thresholds are higher near the annual and semiannual cycles, which have been fitted for and removed. (middle) Correlation transfer function, expressed in ppm/° C. Formal uncertainties are indicated by shading, with lighter grey for larger uncertainty. (bottom) Coherence phase arg($C(f)$), with uncertainties. Green line is the phase ramp for a 6-month delay of CO$_2$ relative to temperature at interannual periods.

ures the extent to which two time series vary in tandem near frequency f [*Kuo et al.*, 1990; *Park and Levin*, 2000]. We describe algorithm details in the auxiliary material, which also provides a SCILAB script that computes and plots several simple coherence relationships between time series.[1]

[8] Both temperature and CO$_2$ time series have significant autoregressive memory and red spectra. We prewhiten all time series with a simple one-month first-difference. For each time interval considered, we remove the mean of the first-differenced series (which removes any original trend), fit for periodic components at f = 1 and f = 2 cyc/yr and subtract them. For the 1958–2008 data series below, we choose p = 6 and K = 10 Slepian tapers for spectrum estimation, so that the estimation half-bandwidth Δf = 0.12 cyc/yr. For 30-yr data series, p = 3.6 and K = 6 Slepian tapers achieve the same Δf, but with weaker statistical constraints.

3. Results

[9] Our estimate of $C(f)$ between Hadley-Centre global-average temperature and CO$_2$-concentration at Mauna Loa USA over 1958–1988 (Figure 1) agrees largely with *Kuo et al.* [1990], but coherence over 1979–2008 differs significantly (Figure 2). For 1958–1988 $|C(f)|^2$ exceeds the 99% confidence level for nonrandomness over $0.2 < f < 0.6$ cyc/yr, breaches the 90% confidence level for non-periodic variability near $f = 1$ cyc/yr, and breaches the 90% confidence level within $1.25 < f < 2.0$ cyc/yr. For 1979–2008 $|C(f)|^2$ exceeds 99% confidence over a narrower low-frequency bandpass and breaches 90% confidence modestly near $f = 2.0$ cyc/yr. A more telling comparison involves arg($C(f)$). During 1958–1988 a linear phase ramp mimics the effect of a 6-month delay in CO$_2$ fluctuations relative to those in global ΔT. *Kuo et al.* [1990] reported a 5-month delay; the discrepancy might relate to updates in the

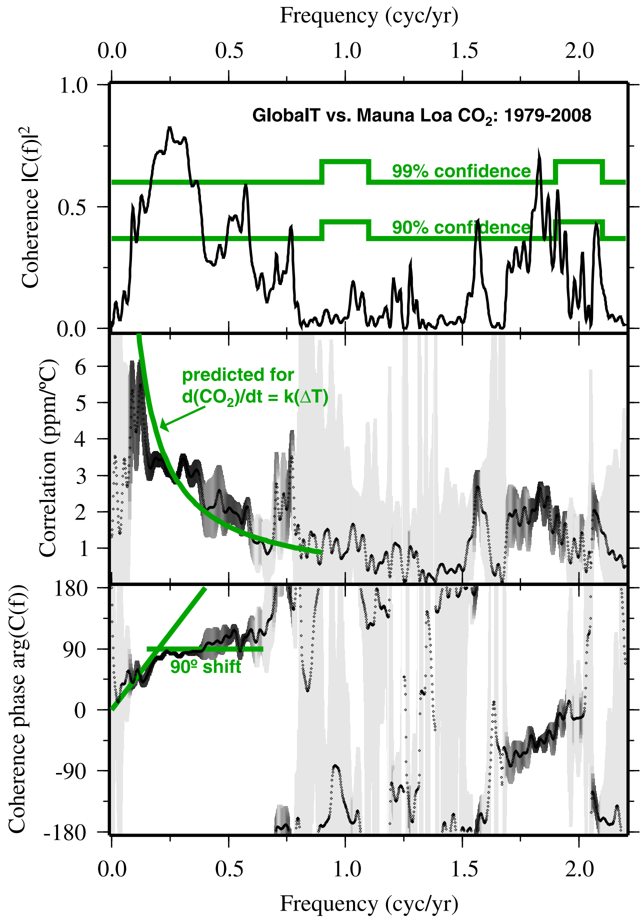

Figure 2. Coherence $C(f)$ for 1979–2008 between global-average temperatures and atmospheric CO$_2$ concentration measured at Mauna Loa, Hawaii. Plotting conventions identical to Figure 1.

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[1] Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2009gl040975. Other auxiliary material files are in the HTML.

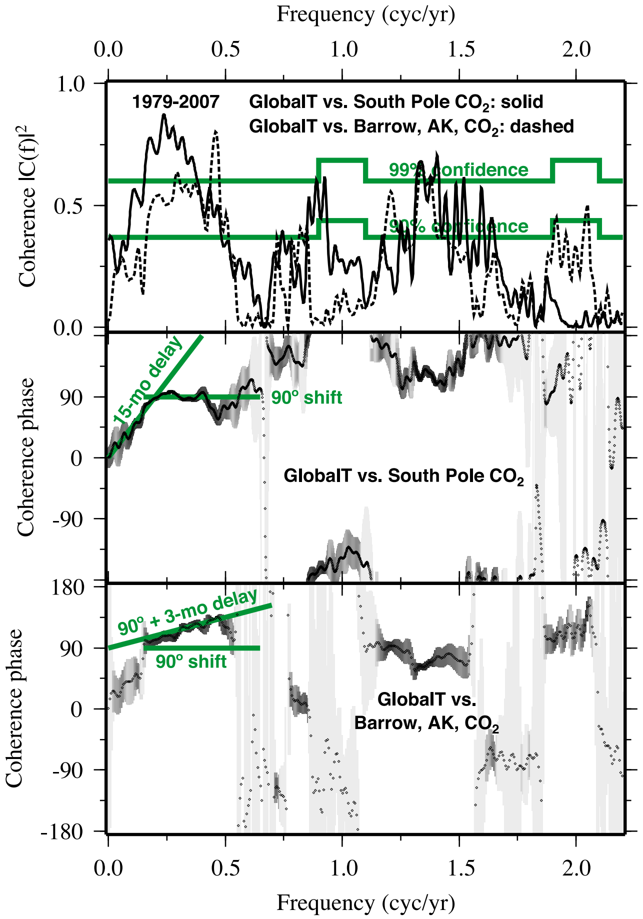


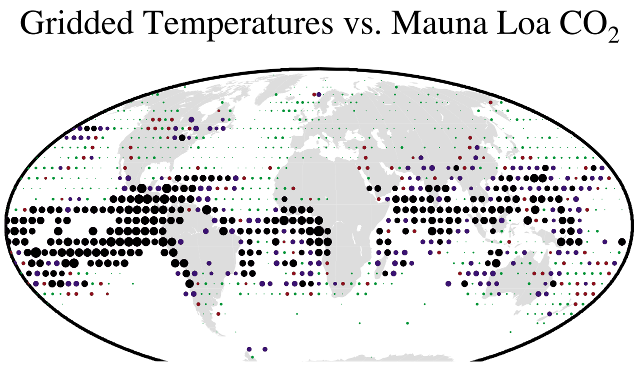
Figure 3. Coherence $C(f)$ for 1979–2008 between global-average temperatures and atmospheric CO_2 concentration measured at South Pole and Barrow, Alaska. (top) Squared coherence $|C(f)|^2$ plotted with frequency f. (middle) Coherence phase arg $C(f)$ for South Pole, with uncertainties. The green lines indicate (1) a 90° phase shift of CO_2 relative to temperature at interannual frequencies, and (2) a phase ramp for a 15-month delay of CO_2 relative to temperature. (bottom) Coherence phase arg $C(f)$ for Barrow, with uncertainties. The green lines indicate (1) a 90° phase shift of CO_2 relative to temperature at interannual frequencies, and (2) a 90° phase shift plus a 3-month delay.

historical SST dataset [*Brohan et al.*, 2006]. During 1979–2008 the interannual arg($C(f)$) $\sim$ 90° where $|C(f)|^2$ is significant, i.e., a constant phase rather than a phase ramp.

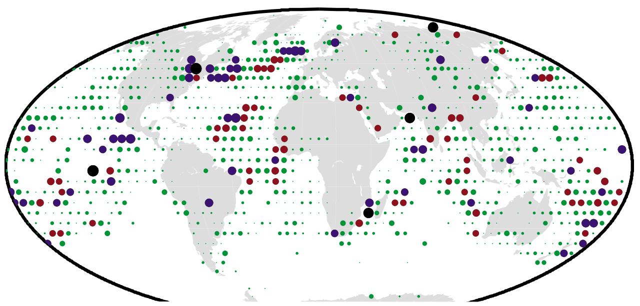
[10] Coherence since 1979 between global-average ΔT and CO_2 data from South Pole and Barrow, Alaska, confirms coherence at Mauna Loa, with some adjustments for atmospheric transport (Figure 3). Interannual arg($C(f)$) = 90° at South Pole, similar to Mauna Loa, and displays higher coherence and smaller transfer function $H(f)$ (not shown): 2.5 ppm/° C versus 3 ppm/° C at f = 0.25 cyc/yr. This suggests rapid, but incomplete, mixing of CO_2 in the Southern Hemisphere. At Barrow, arg($C(f)$) follows a 90° shift plus a ramp consistent with a 3-month transport from the tropics to the boreal Northern Hemisphere.

[11] We seek mechanisms for the temperature-CO_2 relationship by correlating the 1958–2008 Mauna Loa CO_2 time series with ΔT time series from individual gridpoints in the Hadley Centre data set. At f = 0.25 cyc/yr (Figure 4, top), significant $|C(f)|^2$ is evident throughout the tropical oceans, and is weak in most other regions. Separate analyses for the 1958–1988 for Mauna Loa and 1979–2008 time periods for Mauna Loa, South Pole and Barrow confirm the primacy of the tropical-ocean gridpoints. Many extra-tropical ocean gridpoints exhibit coherence with Mauna Loa CO_2 at $\geq$90% confidence for nonrandomness, but few in both time periods. Low interannual coherence with CO_2 is found in continental interiors, downplaying land-based carbon-cycle feedbacks linked primarily to local ΔT, e.g., permafrost melting.

[12] Annual-cycle variability ($f \sim 1$ cyc/yr) in Mauna Loa CO_2 also changes in the latter part of the 20th century. During 1958–1988, annual-cycle fluctuations are large, and $|C(f)|^2$ is marginally significant, with transfer function $|H(f)|$ = 3–4 ppm/° C (Figure 1). During 1979–2008, annual-cycle variability is no larger than the background spectrum, coherence with global-average temperature is weak, and the transfer function is minimal ($|H(f)| \sim 1$ ppm/° C). Coherence with gridpoint temperature series at f = 1.0 cyc/yr during 1958–1988 is scattered (Figure 4, bottom). Significant coherence is largely absent from tropical-ocean gridpoints, and a cluster of high-$C(f)$ gridpoints exist in NE



Coherence at f=0.25 cyc/yr (1958-2008)



Coherence at f=1.00 cyc/yr (1958-1988)

Figure 4. (top) Squared coherence $|C(f)|^2$ at f = 0.25 cyc/yr for 1958–2008 between Hadley Centre gridded surface temperatures and Mauna Loa atmospheric CO_2. (bottom) $|C(f)|^2$ at f = 1.00 cyc/yr (after removal of the annual cycle) for 1958–1988 between gridded surface temperatures and the CO_2 time series. In both plots, symbol size scales with $|C(f)|^2$, and color indicates statistical confidence for nonrandomness: green, $\leq$90%; red, >90%; blue, >95%, black, >99%.

North America and the North Atlantic. During 1979–2008 significant gridpoint coherence with Mauna Loa CO_2 at f = 1 cyc/yr occurs also in the North Atlantic (not shown), but coherence with global-average temperature is weak. These results suggest a change in the efficacy of the North Atlantic carbon sink [e.g., *Schuster et al.*, 2009].

4. Discussion

[13] Interannual $\arg(C(f)) > 0$ suggests that CO_2 fluctuations are caused by fluctuations ΔT in global temperature. The correlation coefficient is 2–3 ppm/° C for interannual periods. If Earth climate warms by 3°C for a doubling of preindustrial CO_2, the predicted greenhouse feedback for a global-average ΔT = 1°C ENSO fluctuation would be less than 0.05°C, that is, <5% feedback.

[14] We hypothesize that the 90° phase shift during 1979–2008 relates to a simple physical mechanism. Warmer water can hold less dissolved CO_2, so that one expects a rise in SST to correlate with a decrease in the rate of CO_2-uptake by the surface ocean. Correlation of one stochastic process with the time-derivative of a second process implies $\arg(C(f)) = 90°$. The relation $d(CO_2)/dt = k\Delta T(t)$, with constant k, predicts the transfer function $H(f) \sim f^{-1}$ (Figure 2). A physical model for interannual coherence during 1958–1988 is less simple, because $\arg(C(f))$ suggests that atmospheric CO_2 adjusted to global ΔT within 6 months, regardless of the time scale. A SCILAB script in the auxiliary material illustrates these relationships.

[15] We hypothesize that changes in $C(f)$ in our study relate to a shift in the global carbon exchange between atmosphere and ocean. If this exchange is close to its steady state value, a modest fluctuation in global-average SST can be accommodated within a fixed time frame. If the atmospheric and oceanic carbon reservoirs are far out of balance, an interannual ΔT will reach its peak and reverse sign before atmospheric CO_2 fully adjusts. Because coherence during 1979–2008 peaks at ENSO frequencies $f > 0.2$, this hypothesis implies that the adjustment time of atmospheric CO_2 to oceanic SST fluctuations has grown to 15 months or longer. Because there is currently a net uptake of anthropogenic CO_2 by the world ocean [*Houghton*, 2007], our hypothesis implies that human activities have lately outpaced the ocean's capacity for absorbing carbon, a conclusion supported by inverse carbon-cycle models [*Le Quere et al.*, 2007; *Schuster et al.*, 2009]. The size of the carbon-cycle shift suggested by our study is likely associated with a change in ocean-atmosphere dynamics [e.g., *Feely et al.*, 2006], rather than gradual saturation of the ocean carbon sink. The change in quasi-annual coherence also suggests a dynamical shift.

[16] This study does not imply that the terrestrial biosphere is unimportant to interannual CO_2 fluctuations, but does suggest that its influence is not expressed linearly via continental ΔT. Several factors may dampen interannual coherence. Interannual climate variability couples primarily via atmosphere-ocean interactions, such as ENSO. Terrestrial carbon uptake may vary more with precipitation than ΔT, e.g., *McPhaden et al.* [2006] proposes that drought-induced fires in the tropics cause the phase lag between CO_2 and ENSO. Terrestrial carbon exchanges are seasonal. Testing continental ΔT against CO_2, *Buermann et al.* [2007] applied summer-only and winter-only comparisons in the time domain, and failed to find correlations as widespread as the simple coherences with year-round ΔT we estimate in the tropical-ocean (Figure 4).

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