MONTHLY CHANGES IN THE INTRANNUAL CYCLE OF ATMOSPHERIC CARBON DIOXIDE AT MAUNA LOA

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ABSTRACT

I investigate monthly changes in the intrannual cycle of atmospheric CO_2 at Mauna Loa, Hawaii using econometric techniques that are designed to detect seasonal changes in economic time series. Consistent with previous efforts, the results identify a change in the intrannual cycle in spring (April). The results also uncover a new result—a change in the intrannual cycle in fall (October). In April, the rise in atmospheric CO_2 steepens over time. During October, the downturn in atmospheric CO_2 increases over time. These monthly changes appear unrelated to commonly measured patterns of atmospheric circulation, which suggests that they may be caused by changes in the flow of carbon between the atmosphere and terrestrial biota or ocean.

INTRODUCTION

Nearly fifty years of measurements identify several changes in the atmospheric concentration of carbon dioxide; an increase over time, an intrannual cycle, and interannual changes in the intrannual cycle. Between 1959 and 2004, the atmospheric concentration of carbon dioxide at Mauna Loa increased from 316 ppm to 377 ppm. Most of this increase is associated with the combustion of fossil fuels and anthropogenic changes in land-use (Conway et al., 1994; Keeling et al., 1995; Houghton, 2000; Marland et al., 2001; Prentice et al., 2001). Within each year, the atmospheric concentration of carbon dioxide rises and falls through an intrannual cycle, with the amplitude increasing with latitude (Keeling et al., 1996). The intrannual cycle is attributed to seasonal changes in the balance between photosynthesis and respiration in the terrestrial biota (Keeling et al., 1996; Francey et al., 1995; Morimoto et al., 2000). The intrannual cycle changes from year to year, with a general increase in amplitude over time and changes in monthly values (Keeling et al., 1996; Dettinger and Gil, 1998).

Several analyses focus on interannual changes in the intrannual cycle of atmospheric CO_2. Keeling et al., (1996) find that the amplitude of the intrannual cycle has increased most rapidly at high latitudes and that the phasing has advanced by about seven days. Based on correlations between these changes and temperature, Keeling et al., (1996) argue that these observations are associated with temperature-driven changes in the terrestrial biota, specifically an earlier spring.

Dettinger and Ghil (1998) use singular-spectrum analysis to analyze monthly patterns at both Mauna Loa and the South Pole. They identify several months in which the intrannual cycle changes. Based on their timing and correlations with other time series, Dettinger and Ghil (1998) write that these changes seem to be associated with tropical processes, especially sea-surface temperature. Nonetheless, these correlations cannot be used to differentiate among possible causal variables, such as sea surface temperature, oceanic circulation, or changes in biotic activity.

Interannual changes in the intrannual cycle are attributed to changes in; (1) atmospheric circulation, (2) the flow of carbon between the atmosphere and ocean, and/or (3) the flow of carbon between the atmosphere and the terrestrial biota. The potential importance of atmospheric circulation is highlighted by Higuchi et al., (2002), who argue that historical shifts in atmospheric circulation can cause annual variations in the amplitude of atmospheric CO_2 that are similar to those observed at Mauna Loa and Point Barrow. Muryama et al., (2004) find that interannual changes in atmospheric circulation disrupt the link between biotic changes and measurements taken at distant stations.

Bridging the link between atmospheric and oceanic circulation, a correlation between atmospheric concentrations of carbon dioxide and El Nino Southern Oscillation events (ENSO) is first noted by Bacastow (1976) and is confirmed by Wignuth et al., (1994), Keeling et al., (1995) and Kaufmann et al., (2006). The relative importance of oceanic and atmospheric circulation in the effect of ENSO events on atmospheric CO_2 is uncertain. Wignuth et al., (1994) suggest that changes in sea surface temperature may be responsible for correlations between ENSO events and atmospheric CO_2. Other analysts argue that changes in terrestrial vegetation generate the correlation between ENSO events and atmospheric CO_2 (e.g. Ciais et al., 1995; Francey et al., 1995; Zeng et al., 2005). Siegenthaler (1990) suggests that ENSO events weaken the monsoon, which reduces carbon uptake by the terrestrial biota. Yang and Wang (2000) argue for the importance of clouds, which reduce solar radiation and may suppress photosynthetic rates. Rayner et al., (1999) argue for both ocean and terrestrial factors—oceanic changes generate negative anomalies while terrestrial responses generate positive anomalies.

Vegetation affects the intrannual cycle of atmospheric carbon dioxide via several mechanisms that include a fertilization effect due to the increased concentration of atmospheric CO_2 (Kolmaier et al., 1989), seasonal shifts in the phasing of photosynthesis and respiration (Chapin et al., 1996), and/or changes in the length or intensity of the growing season at mid and high latitudes (Myneni et al., 1997).

Many of these mechanisms may be linked to changes in climate. Changes in temperature and precipitation have the potential to affect the intrannual cycle by extending the growing season and/or increasing summer greenness (Zhou et al., 2001). To date, there is no agreement about which factor if either predominates. Several analysts argue for the importance of longer growing seasons. Tanja et al., (2003) find that the start of photosynthesis in the spring is correlated with air temperature. Keyser et al., (2000) find that higher spring temperatures elongate the growing season and increase net primary production by up to 20 percent for sites in Alaska. Hollinger et al., (2004) find that the quantity of carbon stored by spruce forests in Maine (USA) is related positively to warmer spring and falls. This effect is simulated by Randerson et al., (1999), who find a correlation between spring temperatures and early season net ecosystem uptake. Churkina et al., (2005) suggest a linear relationship between annual net ecosystem exchange and the carbon uptake period.

Other analyses point to the importance of summer conditions, especially soil moisture, which may decline due to higher summer temperatures and/or reduced precipitation. For example, Zhou et al., (2003) find that summer precipitation has a measurable effect on interannual variations in satellite measures of surface greenness. Consistent with this result, White and Nemani (2003) find that precipitation during the growing season has a greater effect on net ecosystem exchange than the length of the growing season. Correlations between tree rings and NDVI in June and July (as opposed to months in spring or fall) seem to suggest the importance of a greener summer (Kaufmann et al., 2004). Angert et al., (2005) ague that drier summers suppress carbon uptake.

Nor is the effect of climate limited to vegetation—soil carbon pools also may respond to changes in climate (Trumbore et al., 1996). Studies of heterotrophic respiration find that the period of soil thaw (Goulden et al., 1998) and heterotrophic respiration (Shibistova et al., 2002) are very sensitive to temperature. The duration of these temperature effects on soil respiration are uncertain—some analysts argue that acclimatization reduces the effect of temperature over time (e.g. Luo et al., 2001). Yet others argue that carbon flows from mineral soils are relatively unaffected by temperature (e.g. Giardina and Ryan, 2000).

Here, I use statistical techniques to identify the month(s) in which the intrannual cycle of atmospheric CO_2 at Mauna Loa, Hawaii changes. Consistent with previous efforts, the results identify a change in the intrannual cycle in spring (April). The results also uncover a new result—a change in the intrannual cycle in fall (October). Additional results indicate that the timing of these changes is not caused solely by commonly recognized patterns of atmospheric circulation, such as ENSO events. This suggests that interannual changes in the intrannual cycle are caused by changes in the flow of carbon between the atmosphere and terrestrial biota or ocean, but identifying the causal mechanism(s) requires additional analyses.

Methodology

To identify the month(s) in which the intrannual cycle of atmospheric CO_2 changes, I use a statistical methodology that is designed to detect seasonal changes in economic time series (Canova and Hansen, 1995). Following their methodology, I proceed in three steps. First, I crate a stationary time series of anomalies for the atmospheric concentration of carbon dioxide at Mauna Loa by removing the year-to-year increases from monthly observations. In the second step, these observations are used as the dependent variable in a statistical model that specifies monthly categorical variables as explanatory variables. In the third step, regression errors are analyzed to test whether the regression coefficients for monthly categorical variables are stable over time.

Monthly concentrations (ppm) of carbon dioxide at Mauna Loa, Hawaii (19 32’N 155 35’W) are compiled by Keeling and Whorf (2003). To separate changes in the timing of the intrannual cycle from year-to-year increases associated with fossil fuel combustion and deforestation, to solve the problem of nonstationarity described by Lintner (2002), and to satisfy the statistical methodology’s requirement that the time series be stationary, monthly observations are measured relative to the mean value for each waxing and waning phase of the intrannual cycle. Anomalies are calculated as follows:

$$Y_t = CO_{2m} - (TROUGH_{t-1}+PEAK_t)/2 \quad \text{If Month m before peak in year t} \quad (1)$$

$$Y_t = CO_{2m} - (PEAK_t + TROUGH_t)/2 \quad \text{If Month m between peak and trough} \quad (2)$$

$$Y_t = CO_{2m} - (PEAK_t + TROUGH_{t+1})/2 \quad \text{If Month m after peak in year t} \quad (3)$$

in which Y is the monthly anomaly for the atmospheric concentration of carbon dioxide for month m, PEAK is the largest monthly observation for the atmospheric concentration of CO_2 in year t (usually in March or April), and TROUGH is the smallest monthly observation for the atmospheric concentration of CO_2 in year t (usually September or October).

Equations 1-3 generate a time series of monthly values that fluctuate around zero. (Figure 1). The absolute difference between the peak and trough represents the amplitude of the waxing or waning portion of the intrannual cycle. This time series is stationary, as indicated by F statistics ($\pi/2 = 38.7$, $2\pi/3 = 24.1$, $\pi/3=21.9$, $5\pi/3 = 34.9$, $\pi/6 = 13.6$) developed by Beaulieu and Miron (1993).

The intrannual pattern in the anomalies for atmospheric CO_2 is quantified by estimating equation (7):

$$Y_m = \sum_{i=1}^{s} \beta_i Y_{m-i} + \sum_{i=1}^{12} \gamma_i Mon_i + e_t \qquad (4)$$

in which Mon are categorical variables that represent each of the twelve months (the variable equals one when the dependent variable corresponds to that month, it is zero otherwise), β and γ are regression coefficients that are estimated using ordinary least squares, and e is the regression error. The number of lags (s) is chosen using a likelihood ratio statistic (Sims, 1980). For the purpose of detecting changes in the intrannual cycle, equation (4) is equivalent to fitting a trigonometric specification (Canova and Hansen, 1995). Equation (4) specifies lagged values of the dependent variable to account for serial correlation—an innovation during one month may "carry over" to change the intrannual cycle during the following month(s).

Regression coefficients associated with the categorical variables (γ_i) represent the pattern of the intrannual cycle. To identify months in which the intrannual cycle changes in a statistically significant fashion, the regression coefficients (γ_i) are tested to determine whether they are stable over the sample period. If the regression coefficients for individual months do not change over the sample period, the monthly pattern is said to be stable. The monthly pattern is said to change in a given month if the regression coefficient for that month is unstable over the sample period.

To evaluate whether the regression coefficient for an individual month (γ_i) is stable over the sample period, I use a test statistic that is designed to detect changes in the seasonality of economic times series (Canova and Hansen, 1995). To calculate this test statistic, regression errors (e) from equation (4) are compiled by month. This process generates a time series of regression errors for January, regression errors for February…. regression errors for December. For example, the January regression errors between 1965 and 2004 are given in figure 2(a), the February regression errors between 1965 and 2004 are given in Figure 2(b), etc.

Each of the times series of monthly regression errors is used to calculate a test statistic (L_a) that is given by:

$$L_a = \frac{\sum_{j=1}^{T}(\sum_{t=1}^{j} e_{t)})^2}{T^2 \sum_{k=-m}^{m} w(k/m)1/T\sum_{i} e_{i+k}e_i} \qquad (5)$$

in which e is a time series of the regression residuals from equation (4) for an individual month, T is the number of observations for that month, and W(k/m)l is an optimal weighting function that corresponds the Bartlett window (Andrews, 1991). Calculating the test statistic requires a continuous time series, therefore L_a is calculated using residuals for the longest period for which data are available, January 1965 through 2004. The Mauna Loa record is missing observations for February through April, 1964.

As described by Canova and Hansen (1996), L_a is essentially the statistic developed by Kwiatowski et al., (1992). The null hypothesis of the test statistic L_a is that the regression coefficient is stable. This null hypothesis is evaluated against the generalized Von Mises distribution with one degree of freedom (monthly coefficients are tested individually). Values of (L_a) that reject the null hypothesis indicate that the regression coefficient for that month is unstable. Such a result indicates that the intrannual pattern "changes" during that month. This change would be indicated by a general increase/decrease in the time series of regression errors.

Results

The monthly frequency of the sample period from January 1965 October 2004 generates 477 observations. Based on the econometric "rule of thumb" of $T^{1/3}$, a maximum lag length of eight months is considered for estimating equation (4). The Sims likelihood ratio test rejects a restriction that would reduce the lag length from four lags to five lags ($\chi2(1) = 10.27$, $p < .01$). A restriction that would reduce the lag length from six lags to five lags is just shy of the five percent threshold ($\chi2(1) = 3.73$, $p < .06$), nonetheless, equation (4) is estimated using four lags. The results described below do not change significantly if six lags are used to estimate equation (4).

The large r^2 (0.98) indicates that equation (4) is able to account for most of the variation in the intrannual cycle. The coefficients associated with nine of the twelve monthly categorical variables (γ_i) are statistically different from zero (Table 1), which indicates that the statistical model is able to quantify the "average" monthly pattern. The exceptions are January, July, and December. These months often correspond to the midpoint for the waning and waxing phase of the intrannual cycle. As such, the anomaly for these months are close to zero hence the value for γ is not statistically distinguishable from zero. Coefficients (β_i) associated with the lagged dependent variable are statistically different from zero (Table 1). This indicates that innovations in the intrannual cycle persist. But the value associated with the previous month ($\beta_1 = 0.49$) indicates that innovations decay quickly.

The test statistic L_a identifies months during both the waxing and waning phase of the intrannual cycle for atmospheric CO_2 in which the monthly pattern changes (Table 1). For April, August, and October, L_a rejects the null hypothesis that the regression coefficient (γ_i) is stable at the five percent level (Table 1). For other months, the test statistic fails to reject the null hypothesis, even at the ten percent level.

Additional information about changes in the monthly pattern can be gleaned from movements in the regression errors. The regression errors for April (Figure 2(d)) tend to increase over the sample period while the regression errors for the August (Figure 2(h) and October (Figure 2(j)) tend to decrease over the sample period. The increase in the April regression error indicates that equation (4) tends to underpredict April anomalies later in the sample period. This systematic error indicates that size of the April rise relative to the mean tends to increase over time. Conversely, the decrease in the August and October regression errors over the sample period indicates that equation (4) tends to overpredict August and October CO_2 anomalies later in the sample period. This systematic error indicates that size of the drawdown relative to the amplitude tends to increase over time.

These results are relatively insensitive to a variety of assumptions. The significance level of L_a changes little as the window used in equation (5) is lengthened or shortened. Nor do changes in the sample period used to estimate equation (4) affect the timing and direction of changes in the monthly pattern for April and October. For these months, calculating L_a from regression errors estimated with observations through 2000 or 1995 rejects the null hypothesis at $p < .05$ (Table 1). If equation (4) is estimated with data from 1959-2004 and the regression errors from 1965-2004 are used to calculate L_a, the test statistic rejects the null hypothesis at the five percent level for April and October, but the significance level of the test statistic for the August regression coefficient (γ_8) drops to the ten percent level. Similarly, the significance level of the test statistic for August regression coefficient (γ_8) drops to the ten percent level if the sample period used to estimate equation (4) is truncated in 2000 or 1995 (Table 1). Instead, there is some evidence for changes in the intrannual cycle during September (1965-2000) or July (1965-1995).

Discussion

Instability, as indicated by values of the L_a statistic that reject the null hypothesis, identify a month in which the intrannual cycle changes over the sample period. Overall, the results presented above indicate that the intrannual cycle of atmospheric carbon dioxide at Mauna Loa changes in spring (April) and Fall (October).

As described previously, changes in the intrannual cycle are attributed to (1) changes in atmospheric circulation, (2) changes in the flow of carbon between the atmosphere and terrestrial biota, or (3) changes in the flow of carbon between the atmosphere and the ocean. Of these three possible mechanisms, the role of changes in atmospheric circulation can be investigated further using the methodology developed here. To investigate the effect of changes in atmospheric circulation on the intrannual cycle of atmospheric carbon dioxide at Mauna Loa, indices of monthly circulation are included in equation (4) as follows:

$$Y_m = \sum_{i=1}^{s} \beta_i Y_{m-i} + \sum_{i=1}^{12} \gamma_i Mon_i + \sum_{i=0}^{s} \delta_i Index_{m-i} + e_t \qquad (6)$$

in which Index is a monthly index for a commonly measured pattern of atmospheric circulation, such as the Southern Oscillation Index (Allen et al., 1991), the Northern Atlantic Oscillation (Hurrel, 1995), the Western Pacific Oscillation (Climate Prediction Center, 2005), the Eastern Pacific Oscillation (Climate Prediction Center, 2005), or the Pacific Decadal Oscillation (Zhang et al., 1997). Regression errors from equation (6) are used to calculate the test statistics (L_a) using equation (5).

Including an index for atmospheric circulation in equation (6) can have one of three effects on the statistical results. If the pattern of atmospheric circulation represented by the index has no effect on the intrannual cycle of atmospheric carbon dioxide, the regression coefficients associated with Index (δ) will be statistically indistinguishable from zero. In this case, the regression errors in equation (6) will change little relative to those for equation (4). Under these conditions, values of L_a will not change significantly, nor will conclusions about the timing of changes in the intrannual cycle. Together, these results would indicate that the timing of changes in the intrannual cycle of atmospheric carbon dioxide is not associated with the pattern of atmospheric circulation represented by Index.

Alternatively, the regression coefficients associated with Index (δ) could be statistically different from zero, which would indicate that the pattern of atmospheric circulation represented by the index has a statistically measurable effect on the atmospheric concentration of carbon dioxide at Mauna Loa. This effect could either strengthen or overturn results regarding the timing of changes in the intrannual cycle. The results generated using the regression errors from equation (6) could strengthen results generated using the regression errors from equation (4) if the pattern of atmospheric circulation represented by the index acts as “noise” to obfuscate change associated with the flow of carbon between the atmosphere and ocean and/or terrestrial biota. Under these conditions, including the index in equation (6) removes noise associated with the pattern of atmospheric circulation, which makes it easier for the methodology to detect the signal associated with monthly changes in the intrannual cycle generated by either the terrestrial biota or atmospheric circulation.

Alternatively, including the index in equation (6) could overturn the results generated using the regression errors from equation (4) if the pattern of atmospheric circulation represented by the index is responsible for the monthly changes in the intrannual cycle of atmospheric carbon dioxide identified by L_a. In this case, including Index in equation (6) eliminates the systematic pattern in the monthly regression errors such that the value of L_a no longer rejects the null hypothesis. Under these conditions, changes in atmospheric circulation as represented by the index would be responsible for monthly changes in the intrannual cycle of atmospheric carbon dioxide.

Regression results for equation (6) indicate that the Eastern Pacific Index (EPI) does not have a statistically measurable effect ($p < .05$) on the anomalies for the atmospheric concentration of carbon dioxide at Mauna Loa (Table 2). Consistent with this lack of effect, the statistical significance for monthly values of L_a reported in Table 2 do not change slightly relative to those for equation (7) reported in Table 1 (the significance of L_a for August drops to the 10 percent level).

Conversely, one or more current or lagged values of the index for the southern oscillation (SOI), the North Atlantic Oscillation (NAO), Western Pacific oscillation (WPI), and Pacific Decal Oscillation (PO) have a statistically measurable effect on the atmospheric concentration of carbon dioxide at Mauna Loa (Table 2). Despite this effect, the resultant values for L_a generally are consistent with the original results. The monthly pattern of atmospheric carbon dioxide changes ($p < .05$) in April and October. As before, the significance level changes little as the window used to calculate L_a is lengthened or shortened. This indicates that changes in atmospheric circulation associated with the southern oscillation, the North Atlantic Oscillation, Western Pacific oscillation, and Pacific Decal Oscillation introduce noise that obfuscates the monthly changes in the annual cycle of atmospheric carbon dioxide at Mauna Loa, but do not cause the on-going monthly changes in the intrannual cycle.

That changes in atmospheric circulation do not appear responsible for changes in the intrannual cycle is not too surprising. Higuchi et al., (2002) find that historical shifts in atmospheric circulation can cause annual variations in amplitude that are similar to those observed at Mauna Loa, but these shifts do account for changes in the phasing of the cycle identified here.

Conclusion

The inability to relate the timing of changes in the intrannual cycle of atmospheric carbon dioxide at Mauna Loa to atmospheric circulation increases the likelihood that changes in the flow of carbon dioxide between the atmosphere and terrestrial biota or ocean are responsible. Mechanism(s) associated with these flows tend to be temporally and spatially heterogeneous. That is, rates of carbon uptake by terrestrial vegetation tend to be greatest in some biomes at certain times of the year. As such, their effect cannot be investigated using the methodology used here.

Nonetheless, the general trend in Figures 2(d) and 2(h) are suggestive. The general increase in the April regression errors suggests that the rate at which carbon flows into the atmosphere rises over time due to increases in heterotrophic respiration. The importance of respiration relative to photosynthesis may not too surprising given the sensitivity of heterotrophic respiration to temperature and the relatively low rate of net primary production in early spring. Similarly, the general decrease in the October regression errors suggests that longer growing seasons may be increasing the amount of carbon dioxide pulled from atmosphere and/or slowing the rate at which carbon flows from the biota to the atmosphere.

To investigate the effect of changes in the flow of carbon dioxide between the atmosphere and terrestrial vegetation or oceans, further research will use the notion of Granger causality to examine the statistical ordering of spatial and temporal changes in proxies for terrestrial vegetation, aquatic biotic activity, or oceanic circulation, relative to station measures of atmospheric carbon dioxide. These results may be able to identify locations and periods when changes in biotic activity or oceanic circulation generate changes in station measures of atmospheric carbon dioxide and the physical mechanisms that drive these changes.

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Table 1
Regression results for equations 4 and 5

	Sample Period							
	1965-2004		1959-2004		1965-2000		1965-1995	
	$\gamma, \delta, \beta^{\dagger}$	$L_a^{\#}$	$\gamma, \delta, \beta^{\dagger}$	$L_a^{\#}$	$\gamma, \delta, \beta^{\dagger}$	$L_a^{\#}$	$\gamma, \delta, \beta^{\dagger}$	$L_a^{\#}$
January (γ_1)	1.9E-1	.22	2.7E-1^{+}	0.21	1.8E-1	.19	2.0E-2	.07
February (γ_2)	4.2E-1**	.18	2.7E-1^{+}	.13	4.1E-1	.13	2.7E-1^{+}	.13
March (γ_3)	1.0**	.20	7.2E-1**	.14	1.1	.31	9.7E-1**	.21
April (γ_4)	2.1**	.67*	1.7**	.61*	2.0	.61*	2.0*	.54*
May (γ_{45})	1.5**	.10	1.3**	.08	1.4	.10	1.5*	.25
June (γ_6)	1.1**	.14	1.0**	.16	1.1	.12	1.1*	.10
July (γ_7)	5.5E-2	.29	9.8E-2	.22	6.2E-2	.24	1.5E-1	.55*
August (γ_8)	-1.1**	.47*	-9.7E-1**	.41^{+}	-1.0	.29	-9.3E-1**	.33
September (γ_9)	-1.9**	.36	-1.6**	.30	-1.9	.56*	-1. 8**	.41^{+}
October (γ_{10})	-1.5**	.72*	-1.2**	.68	-1.5	.64*	-1.4**	.53*
November (γ_{11})	-5.2E-1**	.30	-2.3E-1^{+}	.34	-5.0E-1	.34	-5.6E-1**	.14
December (γ_{12})	3.5E-3	.33	2.1E-1^{+}	.34	-8.3E-3	.25	1.3E-1	.06
Y_{t-1} (β_1)	4.9E-1**		4.9E-1**		5.1E-1		4.7E-1**	
Y_{t-2} (β_2)	-3.1E-2		-3.7E-2		-3.4E-2		9.4E-3	
Y_{t-3} (β_3)	2.7E-2		8.6E-3		1.1E-2		-2.3E-2	
Y_{t-4} (β_4)	-1.5-1**		-1.1E-1*		1.3E-1		-1.6E-1**	
Y_{t-5} (β_5)			-2.9E-2					
Y_{t-6} (β_6)			-9.7E-2**					

[†] Significance level for a t test of the null hypothesis the regression coefficient is zero. Standard error calculated using a heteroscedactic and autocorrelation consistent estimator (Newey and West, 1987).

[#] Critical values for the Von Mises distribution with one degree of freedom are 0.47 (5 %), 0.398 (7.5%), 0.353 (10%), and 0.243 (20%) (Canova and Hansen, 1995). Lag length is six..

Test statistics reject the null hypothesis at the: **1%, *5%, +10% level.

Dates refer to the period over which equation 1 is estimated. The L_a statistic is calculated from 1965 through the end date of the sample period.

Table 2
Results that include patterns of atmospheric circulation (equations 5 & 6)

	Time Series used for index									
	SOI		NAO		EPI		WPI		PDO	
	$\gamma, \delta, \beta^{\dagger}$	$L_a^{\#}$	$\gamma, \delta, \beta^{\dagger}$	$L_a^{\#}$	$\gamma, \delta, \beta^{\dagger}$	$L_a^{\#}$	$\gamma, \delta, \beta^{\dagger}$	$L_a^{\#}$	$\gamma, \delta, \beta^{\dagger}$	$L_a^{\#}$
Jan (γ_1)	3.2E-1*	.18	2.7E-1^{+}	.24	2.5E-1	.18	2.9E-1^{+}	.16	3.3E-1*	.18
Feb (γ_2)	2.4E-1*	.11	3.3E-1^{+}	.26	3.1E-1^{+}	.10	3.8E-1*	.09	3.8E-1*	.10
March (γ_3)	7.6E-1**	.13	8.0E-1**	.19	8.2E-1^{++}	.11	8.8E-1**	.17	8.3E-1**	.19
April (γ_4)	1.7**	.63*	1.8**	.47*	1.9^{++}	.57*	1.9**	.62*	1.8**	.60*
May (γ_{45})	1.3**	.10	1.3**	.15	1.4^{++}	.10	1.3**	.07	1.3**	.13
June (γ_6)	1.1**	.18	1.1**	.21	1.1^{++}	.20	1.1**	.17	1.0**	.12
July (γ_7)	9.9E-2	.19	9.8E-2	.22	1.0E-1	.24	8.5E-2	.17	8.0E-2	.21
Aug (γ_8)	-9.9E-1*	.39^{+}	-9.8E-1**	.31	-1.0^{++}	.44^{+}	-1.0**	.35^{+}	-1.0**	.44^{+}
Sept (γ_9)	-1.7*	.29	-1.7**	.30	-1.8^{++}	.30	-1.8**	.39*	-1.8**	.33
Oct (γ_{10})	-1.3**	.70*	-1.3**	.54*	-1.4^{++}	.69*	-1.4**	.59*	-1.4**	.68*
Nov (γ_{11})	-2.6E-1^{+}	.31	-3.3E-1*	.32	-3.9E-1^{++}	.28	-3.7E-1*	.32	-2.9E-1*	.33
Dec (γ_{12})	2.5E-1^{+}	.35^{+}	1.9E-1	.31	1.4E-1	.34	1.7E-1	.33	2.3E-1*	.38^{+}
Y_{t-1} (β_1)	4.6E-1**		4.8E-1**		4.8E-1^{++}		4.8E-1**		4.8E-1**	
Y_{t-2} (β_2)	-3.0E-2		-4.9E-2		-4.4E-2		-3.3E-2		-3.8E-2	
Y_{t-3} (β_3)	3.5E-2		4.7E-2		4.6E-2		2.3E-2		4.1E-2	
Y_{t-4} (β_4)	-1.2E-1*		-1.4E-1*		-1.2E-1^{+}		-1.2E-1*		-1.3E-1*	
Y_{t-5} (β_5)	-3.1E-2		-5.8E-3		-1.5E-2		7.0E-3		-8.3E-3	
Y_{t-6} (β_6)	-9.5E-2*		-1.1E-1^{+}		-1.1E-2^{+}		-7.6E-1*		-9.1E-2*	
Y_{t-7} (β_7)			2.1E-2		5.2E-2					
I_t (β_0)	-1.4E-2		-1.4E-2^{+}		-5.4E-3		4.8E-2**		-2.0E-2	
I_{t-1} (β_1)	7.3E-3		9.7E-3		-3.3E-3		-1.7E-2		4.4E-2	
I_{t-2} (β_2)	2.0E-2		-6.6E-3		1.2E-2		4.6E-3		-1.7E-2	
I_{t-3} (β_3)	2.8E-2		1.3E-1		9.8E-3		1.7E-2		1.0E-3	
I_{t-4} (β_4)	8.3E-3		-2.8E-3		1.4E-2		7.8E-3		-7.7E-2*	
I_{t-5} (β_5)	-3.3E-2*		2.2E-3		-3.0E-2^{+}		1.2E-3		5.4E-2*	
I_{t-6} (β_6)	-1.3E-2		-6.6E-3		-1.9E-3		-1.9E-2		1.1E-2	
I_{t-7} (β_7)			-2.3E-2**		-2.4E-2^{+}					

[†] Significance level for a t test of the null hypothesis the regression coefficient is zero. Standard error calculated using a heteroscedactic and autocorrelation consistent estimator (Newey and West, 1987).

[#] Critical values for the Von Mises distribution with one degree of freedom are 0.47 (5 %), 0.398 (7.5%), 0.353 (10%), and 0.243 (20%) (Canova and Hansen, 1995). Lag length is six..

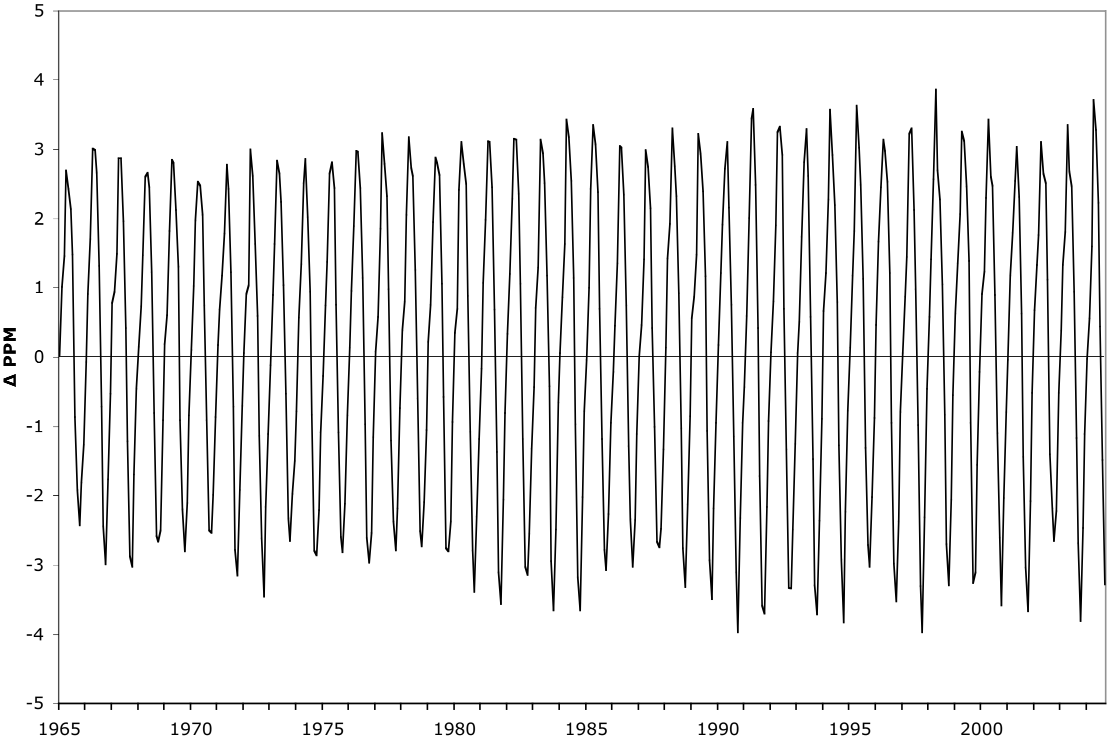
Test statistics reject the null hypothesis at the: **1%, *5%, +10% level.

Figure Caption

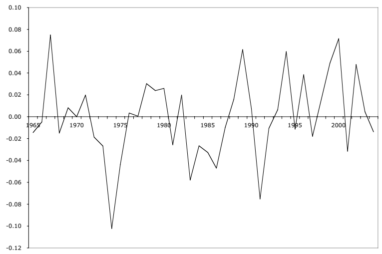
Figure 1 Monthly anomalies for the atmospheric concentration of carbon dioxide at Mauna Loa between January 1965 and October 2004 as calculated by equations (1-3).

Figure 2(a) residuals from equation (4) for January **(b)** as in 1(a) but for February, **(c)** March, **(d)** April, **(e)** May, **(f)** June, **(g)** July, **(h)** August, **(i)** September, **(j)** October, **(k)** November, **(l)** December.

Figure 1



(a)



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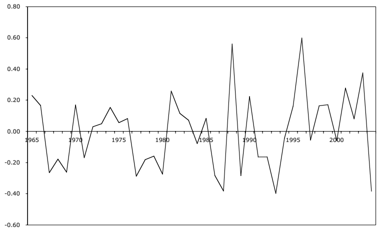

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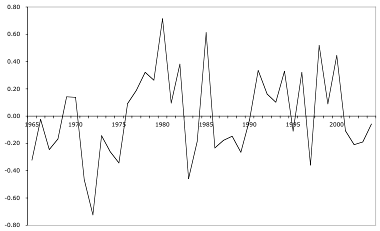

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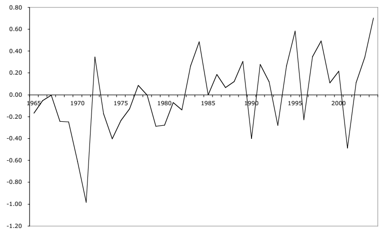

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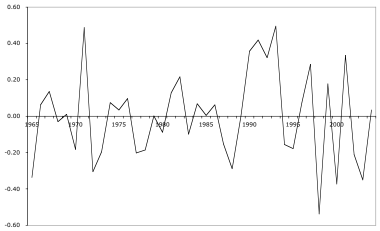

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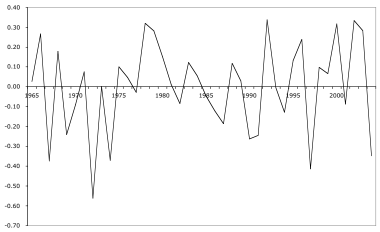

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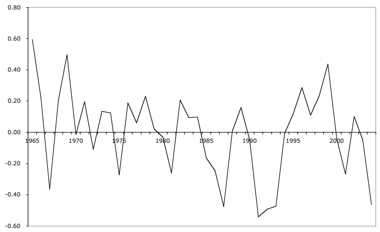

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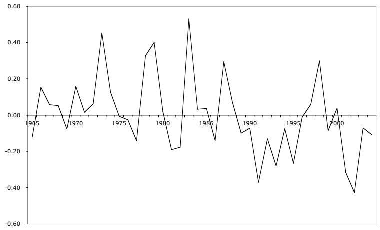
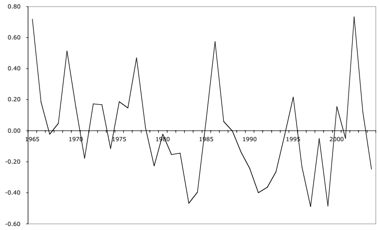
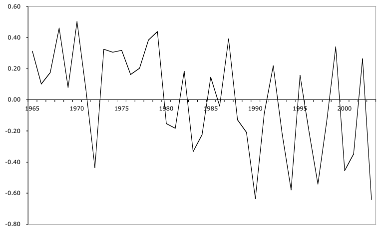


(i)



(j)



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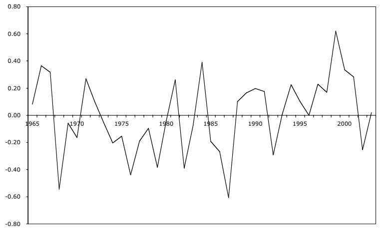

(l)