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TIME SERIES PROPERTIES OF GLOBAL CLIMATE VARIABLES: DETECTION AND ATTRIBUTION OF CLIMATE CHANGE

by

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Time Series Properties of Global Climate Variables:

Detection and Attribution of Climate Change[1]

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ABSTRACT

Several time series investigations of global climate change have been published, but the time series properties of the variables has received little attention with a few exceptions in the case of global temperature series. We focus on the presence or absence of stochastic trends. We use three different tests to determine the presence of stochastic trends in a selected group of global climate change data for the longest time series available. The test results indicate that the radiative forcing due to changes in the atmospheric concentrations of CO_2, CH_4, CFCs, and N_2O, emissions of SO_X, CO_2, CH_4, and CFCs and solar irradiance contain a unit root while most tests indicate that temperature does not. The concentration of stratospheric sulfate aerosols emitted by volcanoes is stationary. The radiative forcing variables cannot be aggregated into a deterministic trend which might explain the changes in temperature. Taken at face value our statistical tests would indicate that climate change has taken place over the last 140 years but that this is not due to anthropogenic forcing. However, the noisiness of the temperature series makes it difficult for the univariate tests we use to detect the presence of a stochastic trend. We demonstrate that multivariate cointegration analysis can attribute the observed climate change directly to natural and anthropogenic forcing factors in a statistically significant manner between 1860 and 1994

1. INTRODUCTION

Several direct empirical [2] time series investigations of global climate change have been published (e.g. Lane *et al*. 1994; Kuo *et al*. 1990; Thomson 1995; Schönwiese 1994; Tol and de Vos 1993; Tol 1994; Lean *et al*. 1995) but the time series properties of the variables have received little attention with a a few notable exceptions in the case of global temperature series (Bloomfield 1992; Bloomfield and Nychka 1992; Woodward and Gray 1993 1995). In particular, it is important to determine whether the time series contain a stochastic trend, which is termed a unit root. The presence or absence of unit roots in these time series may call into question the interpretations given to some previous results and implies that cointegration analysis can be used to investigate the relations among variables.

This paper explores the time series properties of variables thought to influence global climate and their implications for the relation among global temperature, and radiative forcing due to solar irradiance, sulfate aerosols, and the atmospheric concentration of radiatively active gases, and their emissions of trace gasses. The results would appear to indicate that there is no meaningful relationship between radiative forcing and temperature in the observed data. However, the ability of the univariate tests to detect a stochastic trend in a series depends on the signal to noise ratio of the series. Temperature is a particularly "noisy" series. We use the Johansen cointegration procedure as a multivariate version of the unit root tests. This procedure detects a stochastic trend that we can attribute to radiative forcing variables. Section 2 describes the classification of time series variables according to the presence of a stochastic trend and the concept of cointegration. Section 3 describes the methods used to detect the presence of a stochastic trend. The results of the tests are described in section 4. Section 5 describes the implications of these results for both past statistical analyses of climate change and future investigations. Section 6 uses cointegration analysis to attribute the observed climate change to anthropogenic and natural forcing factors.

2. UNIT ROOTS AND COINTEGRATION

Time series can be characterized in many ways. We focus on the presence or absence of trends in the time series. There are two types of trends - deterministic trends and stochastic trends. A stochastic trend is a random walk process that may or may not contain deterministic or stochastic drift. A time series that contains a random walk process is termed a unit root process.

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[2] These studies directly investigate the relations between observed time series in contrast to studies that attempt to find correlations between climate model outputs and observations. See Santer *et al*. (1996b) for details of the latter class of studies.

The presence or absence of a random walk process can be illustrated by the parameters associated with the following model of time series y:

$$y_t \quad = \quad \mu + \rho y_{t-1} + \beta t + \varepsilon_t \tag{1}$$

in which μ is a constant, ε_t is a stationary but possibly autocorrelated random error process with mean zero, ρ is the autoregressive parameter, and t is a deterministic time trend. If ρ is less than 1, the effects of shocks introduced via the error term ε_t fade over time. If β is zero, the variable y has a constant mean and therefore is stationary. This type of stationary process is termed ‘levels stationary’. If β is not equal to zero, the mean of y is nonconstant and therefore y is nonstationary. However, subtraction of βt from both sides of (1) would result in a stationary process. Therefore, y is said to be ‘trend stationary’.

The time series properties of y change if $\rho = 1$ and $\beta = 0$ in equation (1). Under these conditions, the variable y is a random walk. The random walk may also have a deterministic drift term ($\mu \quad 0$). In either case, the mean of the series is nonconstant and therefore the series is nonstationary. Differencing yields a stationary model and so the process is said to be integrated of order one or I(1). Correspondingly, stationary and trend stationary processes are said to be integrated of order zero or I(0). A random walk process with a drift term that is a stochastic trend and must be differenced twice to achieve stationarity is referred to as an I(2) process.

Integration implies that y shows no particular tendency to return to its mean and that shocks to the variable are "remembered." Their effects do not die out over time. A large part of the recent econometric time series literature deals with estimation and inference in the presence of such so called "unit roots" and testing for the presence of nonstationarity of this type (see Enders 1995; Hamilton 1994). Three standard tests for integration are described in the next section.

The random walk components of integrated processes are referred to as stochastic trends. Linear combinations of integrated process also are integrated. Therefore, unless two integrated time series variables share a common stochastic trend, the residual from a regression of one of the variables on the other will be non-stationary. This violates the classical conditions for a linear regression. Such a regression is known as a spurious regression (Granger and Newbold 1974). The critical levels for t and F statistics for restrictions on the regression coefficients are much higher than under the classical conditions. This might suggest to the naïve investigator that a significant relationship exists among the variables when none exists. When there are more than two I(1) processes, if any of the series contains a stochastic trend that is not also present in at least one of the other series linear combinations of the series will also be integrated.

A vector of variables is said to cointegrate if stochastic trends present in the series are shared (Engle and Granger 1987). Under these conditions, there exists a linear combination(s) of the variables that acts to zero out the stochastic trend and leaves a stationary residual. For example if ε_t is a stationary process (possibly with nonzero mean):

$$\beta' z_t = \varepsilon_t \tag{2}$$

then the vector of random variables z cointegrates. β is termed a cointegrating vector. When there is more than one shared stochastic trend there are also more than one unique (orthogonal) cointegrating vectors. The cointegration residual ε_t can be interpreted as the disequilibrium from a stable long-run equilibrium relationship among the variables z.

A large literature now discusses tests for cointegration and estimating cointegrated models (for surveys see Hamilton 1994; Enders 1995; Dickey and Rossana 1994; Johansen 1988; Johansen and Juselius 1990). A simple way to test the hypothesis of non-cointegration (Engle and Granger 1987) is to estimate a linear regression of one variable on the others using ordinary least squares (OLS). The residuals from the regression are then tested for integration. When there is more than one stochastic trend is present the estimated cointegrating vector will be a linear combination of all the unique cointegrating vectors. This does not affect the validity of the hypothesis test that there are shared stochastic trends. The causal ordering among the variables can be investigated using a priori information and hypothesis tests about cointegration among subgroups of variables. Multivariate maximum likelihood techniques have been developed (Johansen 1988; Johansen and Juselius 1990) which can be used to test for the number of shared stochastic trends and estimate, multiple cointegrating vectors using linear techniques. The Johansen procedure estimates the parameters of the cointegrating vectors jointly with parameters that model short-run adjustment of the endogenous variables to exogenous shocks and the remaining long-run disequilibrium. More details are given in section 6.

Given the presence of cointegration, hypothesis tests about individual regression coefficients have the standard distributions. The basic purpose of cointegration analysis can be described by comparison with other techniques. Classical regression analysis is used to estimate the partial correlations between variables. Coherence analysis is used to find shared cycles among stationary variables. Cointegration analysis is used in a similar way to find shared stochastic trends among nonstationary variables.

This literature has the following implications for time series analysis of global climate change data:

1. The presence of integrated series would mean that standard regression inference techniques need to be modified to account for this potential violation of the classical assumptions.

2. Shocks to integrated processes tend to persist rather than returning to equilibrium. This would need to be taken into account when forecasting or projecting climate change.
3. If there is causality from variables that contain unit root processes to other variables then the unit root signals from each of the driving variables must be present in the driven variable. Another way of stating this is that the group of driving and driven variables must cointegrate. This is a potential method for detecting and attributing climate change.

Woodward and Gray (1995) used a unit root test, the Dickey-Fuller test, to characterize the time series properties of three different global temperature time series. They find that the series could be adequately modeled as a random walk with no drift. They point out the implications of this result in terms of 1. above, noting that the Bloomfield and Nychka (1992) test for a deterministic trend in the temperature series suffered from the "spurious regression" problem. In terms of 2. above they argue that the absence of a deterministic trend or drift component in temperature would mean that the current upward trend in temperature was accidental and could just as easily be reversed in the future. However, they do not raise issue 3. above. If a random walk is present in the temperature series this might not be accidental and could be the product of forcing by another variable that also contains a stochastic trend.

3. UNIT ROOT TESTS

To test for the presence of stochastic trends, we use three standard tests (Dickey and Fuller 1979 1981; Phillips and Perron 1988; Schmidt and Phillips 1992) The Dickey-Fuller (Dickey and Fuller 1979 1981) and Phillips-Perron (Phillips and Perron 1988) methodologies test the same hypotheses and the test statistics have the same distribution but they use different approaches to deal with serial correlation. The null hypothesis is that the data contain a unit root. This hypothesis is tested in the context of three different maintained hypotheses or models concerning the alternative hypothesis. These differ according to the presence of an intercept and/or deterministic trend. For the Dickey-Fuller test the three models are:

$$\Delta y_t = \alpha + \beta t + \gamma y_{t-1} + \sum_{i=1}^{p} \delta_i \Delta y_{t-i} + \varepsilon_t \qquad \text{(Model I)} \qquad (3)$$

$$\Delta y_t = \alpha + \gamma y_{t-1} + \sum_{i=1}^{p} \delta_i \Delta y_{t-i} + \varepsilon_t \qquad \text{(Model II)} \qquad (4)$$

$$\Delta y_t = \gamma y_{t-1} + \sum_{i=1}^{p} \delta_i \Delta y_{t-i} + \varepsilon_t \qquad \text{(Model III)} \qquad (5)$$

Tests also are carried out on the parameters α and β. The purpose of the lagged variables is to provide a correction for serial correlation that may be present. When lagged dependent variables are included in the regression, the test is known as the Augmented Dickey-Fuller Test (ADF). We choose the number of lags p using the Akaike Information Criterion. In Model I the null is that y is a random walk with drift while the alternative hypothesis is that y is a trend stationary variable. In Model II the null is that y is a driftless random walk vs. a stationary process with mean α. Model III is a more powerful test for a unit root when the null is a random walk with no drift and the alternative is a stationary process with mean zero.

The test for a unit root is given by $H_0: \gamma = 0$. If the series is I(0), $\gamma < 0$. The critical values for the t statistic associated with γ in models I (Indicated by τ_τ in Table 1), II(τ_μ), and III(τ) at the 5% level are: -3.45, -2.89, and -1.95 respectively; and at the 10% level: -3.15, -2.58, and -1.61. Values of the t statistic for γ more negative than this critical value reject $\gamma = 0$, indicating that the series is I(0) and vice versa. $\tau_{\alpha\tau}$, $\tau_{\beta\tau}$, and $\tau_{\alpha\mu}$ are test statistics (critical levels at the 5% level are: 3.11, 2.79, and 2.54) for the exclusion of the respective deterministic components under the maintained hypothesis that there is a unit root present. ϕ_3 is the test statistic (critical level at the 5% level: 6.49; at the 10% level: 5.47) for the joint exclusion of γ and β in Model I. ϕ_2 is the test statistic (critical level at the 5% level: 4.88) for the joint exclusion of γ, α, and β in Model I. ϕ_1 is the test statistic (critical level at the 5% level: 4.71; at the 10% level: 3.86) for the joint exclusion of γ and α in Model II.

The Phillips-Perron test (Table 2) uses the same three models as the Dickey-Fuller tests but utilizes a nonparametric correction for serial correlation developed by Newey and West (1987) in place of the lagged dependent variables used in the ADF. We choose the truncation lag for this nonparametric correction with the automated bandwidth estimator that uses the Bartlett kernel (Andrews 1991). We use the same nonparametric correction in the Schmidt-Phillips test. The nonparametric correction is more versatile than the lagged values of the dependent variable with regard to the forms of serial correlation it can deal with. The $T\gamma$ statistics are the product of the number of observations and the parameter γ in equations (3, 4 , 5). This has a nonstandard distribution tabulated in Fuller (1976) and reproduced in Hamilton (1994). The critical levels at the 5% level are: -20.7 (Model I), -13.7 (Model II), -7.9 (Model III).

The model used in the Schmidt-Phillips test (Schmidt and Phillips, 1992) is given by equation (6):

$$\Delta y_t \quad = \quad \alpha + \phi S_{t-1} + \varepsilon_t \tag{6}$$

where S_t is a residual calculated as follows:

$$S_t \quad = \quad y_t - y_1 - \text{mean}(\Delta y_t)(t-1) \tag{7}$$

The null hypothesis is that y is I(1) while the alternative is that it is trend stationary. The statistic ρ (Table 3) is calculated as: $\rho = T\phi$. Critical values are -17.05 at the 5% level and -14.6 at the 10% level. Values more negative than these critical values indicate that the series is trend stationary or I(0). τ is the t statistic for ϕ in equation (6). Critical values are -3.06 at the 5% level and -2.77 at the 10% level. Values more negative than these critical values indicate that the series is trend stationary or I(0). The statistics $Z\tau$ and $Z\rho$ embody corrections for serial correlation and are tested against the critical values for τ and ρ given above.

4. RESULTS OF UNIT ROOT TESTS

We use the three tests described above to determine the presence of stochastic trends in a selected group of global climate change data for the longest time series available. The length of each time series is noted in Table 4. These data include three time series for temperature (northern and southern hemisphere, global), the solar irradiance series compiled by Lean *et al*. (1995), radiative forcing due to changes in the atmospheric concentrations of CO_2, CH_4, CFC's, and Nitrous Oxide, radiative forcing due to stratospheric sulfates, anthropogenic emissions of CO_2, CH_4, CFC's and the radiative forcing associated with anthropogenic emissions of SO_X. The atmospheric concentration of gases are transformed to reflect standard radiative forcing formulae (Shine *et al*. 1991, Wigley and Raper 1992; Kattenberg *et al*. 1996). The emissions series for carbon dioxide and methane are not transformed. Data sources and their transformations are described in Appendix I.

Anthropogenic sulfate concentrations are not examined separately from emissions because the short life span of tropospheric sulfate aerosols implies that atmospheric concentrations parallel emissions (Alkezweeny, 1995; Jonas *et al*., 1995). We do not look at ice core records of sulfate aerosols such as that from the Greenland ice core analyzed by Mayewski *et al*. (1990). Ice cores reflect atmospheric concentrations over regions far from the sources of emission, and the stratospheric sulfate signal from volcanic eruptions dominates the record. However, there is a fairly strong correlation between the two series (Stern and Kaufmann, 1996b).

Casual inspection and anecdote suggest that global climate change data are nonstationary. The series for anthropogenic trace gases and sulfur emissions probably all are I(1). The series trend strongly, are fairly smooth, and the slope of the trend changes occasionally, all of which is typical of I(1) or I(2) variables. Many of the emission and concentration variables are influenced by economic activity such as GDP or energy use, which are suspected to be I(1) (Nelson and Plosser 1982; Yu and Jin 1992). From a physical perspective, CO_2, CH_4 and CFC’s have relatively long lifespans in the atmosphere, which implies that pulses of these gases from anthropogenic activity remain for long periods. Stratospheric sulfates would be expected to be stationary because volcanic eruptions occur at random and their effects are known to die out quickly (Sato *et al.* 1993). Solar irradiance might be either I(0) or I(1). The picture for temperature is far less clear. The time series is trending but the graph (Figure 1) cuts across a deterministic linear regression line repeatedly, which hints that it could be a trend stationary variable.

Results of the Dickey-Fuller test (Table 1) indicate that northern hemisphere (nhem) and global (globl) temperatures are unit root processes while southern hemisphere temperatures (shem) are trend stationary. All three time series are close to the critical threshold at the 5 percent level of significance. Carbon dioxide is I(2) while methane and nitrous oxide are I(1). But there is a linear trend in the nitrous oxide first differences and therefore a quadratic trend in the levels of the series. Therefore on the basis of an I(1) series being defined as having stationary differences this is not an I(1) series. Based on the Dickey-Fuller test on the undifferenced series the CFCs would appear to be trend stationary. However, their first differences are I(1) which indicates that the order of integration of the series is greater than one. Tests on the second difference of these series (not reported) reinforces the conclusion that they are I(2). Solar irradiance (sun) is I(1). Stratospheric sulfates for the global aggregate and means for the region north of 30 N, between 30 N and 30 S, and south of 30 S (ssgl, ssnh, and sssh) all are stationary. Anthropogenic emissions of CO_2, CH_4, CFC's and SO_X all are I(1). The SOx radiative forcing series is I(1).

Results of the Phillips-Perron test indicate that all the temperature series are trend stationary. Radiative forcing of CO_2, CH_4, and N_2O are I(1) while radiative forcing of CFC11 and CFC12 are I(2). But again the CO_2 first difference results are not clear-cut. The τ_μ test results in a rejection of the null of a unit root and acceptance of levels stationarity but the τ test results in acceptance of the unit root hypothesis. Solar irradiance is I(1). Stratospheric sulfates are levels stationary. All the emissions series are I(1). Similar interpretations are indicated by the results from the Schmidt-Phillips test (Table 3). The principal difference is that CFC emissions series are I(2). The results of all three tests are summarized in Table 4.

5. DISCUSSION

The time series properties of climate change data have several important implications about the relation among temperature, radiative forcing, and human activity, and previous attempts to establish this relation using standard regression techniques. These relate to implications 1, 2, and 3 in section 2 above. First we contrast our results with Woodward and Gray (1995). This is related to both 1 and 2 in terms of which statistical techniques are appropriate for testing for a trend in the temperature series and whether such an apparent trend will persist. Second we examine the implications for possible relations among forcing variables and temperature. This relates to implication 3. Finally we look at the implications for previous statistical studies of the temperature-radiative forcing relationship. This relates to implication 1.

a. Implications for Detecting Climate Change

Woodward and Gray (1995) use the results from the Dickey-Fuller test suite to argue that the three global temperature series were well-represented by a random walk without drift. Our results (Table 1) confirm this finding. Under model 1 we find a unit root in globl. The tests for the presence of drift and or trend terms cannot reject the null hypothesis (no trend or drift). The same result is found using model 2. Model 3 also indicates a unit root. However, for southern hemisphere temperatures a unit root is rejected in model 1 and under the assumption of the presence of a unit root the absence of a deterministic trend is rejected (which would imply a quadratic trend in the data. ϕ_3 rejects the joint hypothesis of a unit root with a random walk at the 10% level. But the the hypothesis of a random walk with no drift would be more difficult to reject (ϕ_2). Clearly, this is a borderline case.

The Phillips-Perron test clearly indicates that the global series is trend stationary. Under model 1 both the joint hypothesis tests for the random walk with drift and driftless random walk are rejected. Under the assumption that there is a unit root we would, though, be able to accept that there is no drift but reject that there is no quadratic trend. A unit root is rejected in both the other models as well. The Schmidt-Phillips test is not appropriate for this question as it has trend stationarity as the only alternative hypothesis.

Therefore, we conclude that more sophisticated tests indicate that there is a deterministic trend present in the temperature series. This may not be the whole story as we discuss in the next section.

b. Implications for Potential Relations between Radiative Forcing and Temperature

The test results indicate that the radiative forcing due to the atmospheric concentrations and emissions of CO_2 and CH_4, are I(1) as are anthropogenic emissions of SO_x. CFCs and their emissions appear to be I(2). Therefore all the anthropogenic variables, and those known to have a strong direct anthropogenic influence, are strongly integrated. Temperature however, is found to be a trend stationary variable by all tests except in the Dickey-Fuller test, which finds northern hemisphere temperatures to be unit root at a borderline level of significance but southern hemisphere temperatures to be stationary. The simplest conclusion that can be drawn from these results is that the trace gases and sulfate emissions do not drive temperature. This might seem to be strong evidence in favor of the hypothesis that human activity has not influenced temperature. However, other hypotheses might be examined:

1. Total radiative forcing might be an I(0) trend stationary aggregate, which would then be the cause of the linear trend present in temperature. This could be the case if the series for the trace gasses and sulfate emissions and/or solar irradiance share the same stochastic trends.

2. The unit root tests might fail to detect the presence of a unit root that is present in the temperature series. The null hypothesis of the tests used in this paper is the presence of a

unit root. Therefore this would mean that the probability of type I error is greater than indicated by the nominal significance level. But unit root tests are notorious for their low power in rejecting the null hypothesis of nonstationarity i.e. the probability of type 2 error is high if the null is incorrect. Therefore, this might seem to be unlikely.

We test hypothesis I by means of the Engle-Granger (1987) cointegration technique. There are four subhypotheses that we consider [3]:

1a. the I(0) aggregate is composed of the trace gasses
1b. the I(0) aggregate is composed of the trace gasses and SO_x
1c. the I(0) aggregate is composed of the trace gasses and Sun
1d. the I(0) aggregate is composed of the trace gasses, SO_x, and Sun

The meaning of these hypotheses is illustrated by the following. If we accept hypothesis 1a this would mean that solar irradiance (sun) and tropospheric sulfates (SO_x) have no effect on temperature and that the five gasses share stochastic trends (in practice there could be up to four such trends). Accepting 1d, for instance, would mean that all the variables have an effect on temperature and share trends. On *a priori* grounds SO_x and Sun cannot share a stochastic trend. However, they can each share a trend with the gas series.

To test hypothesis 1a, we aggregate the gas series using standard radiative forcing formulae (Shine *et al*. 1991; Kattenberg *et al*. 1996). We then apply the Dickey-Fuller and Phillips-Perron tests to the time series. To test hypotheses 1b through 1d, we remove the time trend from each of the variables because a cointegrating vector estimated using OLS is not consistent when the time trend is used as a regressor (Hamilton 1994). We achieve this by removing the mean of the first difference multiplied by the time trend from each series. We then regress each of the radiative forcing variables on the remaining variables and a constant and test the residual for a unit root using the augmented Dickey Fuller and Phillips-Ouliaris (1990) procedures. This is not a maximum likelihood procedure therefore, regression results vary according to the dependent variable. The critical levels for the rejection of the null hypothesis (no cointegration) for Hypothesis 1a are -3.37 and -3.20 at the 5% significance level respectively, Hypotheses 1b and 1c at a 5% significance level is -3.77 and at the 10% level -3.58 (Hamilton 1994). The critical levels for Hypothesis 1d are -4.11 and -3.96 respectively. The cointegrating Durbin-Watson statistic is the Durbin-Watson statistic for first order residual correlation in the cointegrating regression. The critical levels are given by Engle and Granger (1987). The critical value for the 5% significance level is 0.386 and for the 10% significance level is 0.322. The results are presented in Table 5. Neither the Dickey-Fuller nor the Phillips-Perron test

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[3] Other subhypotheses are possible, but there seems no a priori reason to assume that carbon dioxide say has an effect on temperature while methane does not.

shows any sign of cointegration regardless of which variable the cointegrating vector is normalized on and which hypothesis is tested. Likewise the cointegrating Durbin-Watson test indicates no cointegration in any of the regressions.

Instead, we argue that hypothesis (2) is not an unlikely case. The global temperature series is fairly noisy (Figure 1). The Dickey Fuller and other unit root tests tend to reject the null too often when the data generating process (DGP) is a random walk with noise and the noise is large compared to the signal. The larger the signal to noise ratio, the higher the probability of a type I error. Enders (1995) and Hamilton (1994) both discuss this point. The model considered by Hamilton is:

$$y_t = \mu + \theta A_{t-1} + \varepsilon_t \tag{8}$$

$$A_t = A_{t-1} + \varepsilon_t \tag{9}$$

As θ approaches 0, the probability of type I error increases. This result is confirmed using Monte Carlo simulations reported by Schwert (1989), Phillips and Perron (1988), and Kim and Schmidt (1990).

Enders (1995) considers the more general model:

$$y_t = \mu + A_t + \eta_t \tag{10}$$

$$A_t = A_{t-1} + \varepsilon_t \tag{11}$$

where the noise term in (10) η_t, is not necessarily identical with that in (11), σ_η^2 is the variance of η, and σ_ε^2 is the variance of ε. In a finite sample, increasing the signal to noise ratio $\sigma_\eta^2/\sigma_\varepsilon^2$ increases the probability that the test will indicate that y_t is trend stationary--a type I error.

Equations (10) and (11) are a reasonable model of the temperature time series. Atmospheric temperature itself probably is not a unit root process. Rather, it is probably a stationary process that is driven by unit root processes such as ocean heat and radiative forcing and subject to considerable noise. Given that we do not know the true data generating process for temperature, (even if we did, we do not know the signal to noise ratio), there is good reason to believe that the standard unit root tests cannot tell us unambiguously whether the temperature series contains a unit root process. Therefore, alternative techniques are needed to investigate this hypothesis. In section 6 below we use the Johansen cointegration procedure to that end.

c. Implications for Previous Studies

The possibility that atmospheric temperature could contain a stochastic trend preserves the possibility that temperature is related to I(1) variables in tables 1 - 4 such as solar irradiance and the radiative forcing of individual gases. But the presence of stochastic trends invalidates many of the statistical inferences regarding the relation among these variables that are described in previous analyses.

The two main classes of techniques that have been used are regression analysis in the time domain and spectral approaches in the frequency domain. Regression-based studies generally estimate a single OLS regression equation is estimated and provide few diagnostic statistics are provided through which readers can evaluate the adequacy of the estimated regressions in light of possible nonstationarity. Most of the regression models also suffer from omitted variable bias because they exclude many variables that affect solar energy input or radiative forcing. Some models specify carbon dioxide as the only determinant of temperature while other models include other greenhouse gases (e.g. CFC's, methane), and other determinants of the heat balance (e.g. aerosols, solar activity). The presence of unit roots in variables also has implications for spectral analyses. We highlight some of the best of these two types of studies to indicate the problems involved. Tol and de Vos (1993) and Tol (1994) are examples of the regression approach. Kuo *et al.* (1990) is an example of the spectral approach.

Tol and de Vos (1993) and Tol (1994) carry out a more sophisticated regression analysis. Their preferred model is presented in equation (1) of Tol (1994)

$$y_t = a_0 + a_1 y_{t-1} + a_2 \gamma_t + a_3 s_{t-1} + a_4 v_t + a_5 v_{t-1} + a_6 v_{t-2} + a_7 e_t + a_8 e_{t-1} + a_9 t \qquad (13)$$

in which y is global mean temperature, v is a dust veil indicator, s is the sunspot number, e is an index of the influence of the El Niño Southern Oscillation, and γ is greenhouse gas concentrations (measured in CO_2 equivalents) transformed by a second order Almon distributed lag with 40 lags and zero restrictions at both sides. The time period used is 1870 to 1991. The model is more general and more reasonable than the Schönwiese (1994) model on several counts. In particular, lagged values of y are included and rather than assuming that the full impact greenhouse gases is transmitted in a single a twenty year lag, the response is spread over a forty year period. Tol and de Vos test this model against a Schönwiese type model and find that it has superior performance. The trend variable is intended to pick up any exogenous trend in the climate. They also find that the inclusion or exclusion of the trend variable strongly affects the significance of the greenhouse gases' coefficient, though this is less important when they place a Bayesian prior on a_9 based on the prehistorical record of natural temperature variability. If temperature is nonstationary, this time trend is used inappropriately. The constant would model any linear drift in temperature, while a time trend would model a quadratic drift.

Tol and de Vos (1993) find that greenhouse gases affect global temperature with a high degree of significance, and that a simple bivariate Sims (1972) test indicates greenhouse gases ‘Granger cause’ temperature. The estimated expected response of temperature to a doubling of CO_2 is in the order of 2.5^{o}K.

Tol and de Vos' (1993) model has several shortcomings. The model of the impact of greenhouse gases on temperature is arbitrary. No feedback is allowed from temperature to gas concentrations. Their methodology tends to move from specific to general rather than vice-versa, that is the maintained hypothesis is a specific one rather than at the greatest degree of generality (see Cuthbertson *et al*., 1992; Harvey, 1990). No allowance is made for possible saturation effects as greenhouse gases accumulate or for the interaction between the individual gases in their effect on total radiative forcing of the atmosphere. No tests are made for cointegration and no adjustments are made to inferential procedures in the absence of such cointegration.

Kuo et al. (1990) devote much greater attention to the dynamic structure of the time series and to the validity of test statistics. However, their analysis is not multivariate. They use a multiple window technique that makes efficient use of short time series to examine CO_2 from 1958 to 1988 and the global temperature time series from 1880 to 1988. They find that both time series have significantly positive trends. Coherence tests over the period 1958 to 1988 on data decomposed into a parametric trend and a non-parametric residual and show that removing a deterministic trend from the CO_2 and temperature data results in fairly stationary residuals. These residuals exhibit coherence at a confidence level exceeding 98% over much of the frequencies below 0.6 cycles per year. Not only are the trend components of both series increasing, but the residuals of the two series are coherent with high confidence throughout the low frequency band.

An analysis of the phase of coherence suggests that CO_2 lags temperature by five months, which suggests the presence of Granger causality (though this term is not used by the authors) from temperature to CO_2. As described by the authors, this conclusion is very tentative. They caution that their method for generating correlations can generate misleading results regarding causality and that this lack of reliability is compounded by the short sample.

The CO_2 residuals spectrum is very strong at zero frequency. This raises the possibility that the residuals are not stationary and that removing a deterministic trend is not appropriate. It is equally possible that the time series is difference stationary rather than trend stationary. Without evidence regarding the nature of the data generating process, serious errors may occur if the trend is removed using an inappropriate method (Enders, 1995). This may limit confidence in the results of Kuo *et al*. (1990).

Though the authors also show that variations in the annual cycle are correlated with the sunspot number, in general, interpretation of the results is limited by the omission of variables other than carbon dioxide. During the sample period, there are significant changes in the atmospheric concentration of several greenhouse gases such as CFC's and methane. In addition, there is a significant change in the atmosphere's albedo due to atmospheric aerosols from both anthropogenic and natural sources. Indeed, the authors admit that a more complete analysis would include the effects of other variables that affect the heat balance.

6. COINTEGRATION USING THE JOHANSEN METHOD

The univariate tests described in sections 3 and 4 above test the null hypothesis of a unit root in a time series without information from other variables that may impart the stochastic trend. In contrast, the Johansen procedure tests the null of stationarity or trend stationarity when the variable in question is conditioned on the first differences of other relevant nonstationary variables. These variables may reduce the noise described in section 5 and increasing the power of the test. Conventionally the Johansen procedure is carried out on a vector of variables which is modelled as an autoregression on all it elements - a vector autoregression model. We perform these tests on a "partial system" with only one dependent variable - global temperature. This precludes feedbacks such as from temperature to carbon dioxide concentrations and therefore our model can be considered to be a reduced form model.

The first step in performing the cointegration analysis is to choose the lag length to be used in the partial system. To do so, we model temperature in terms of its own lagged values and the lagged and current values of other variables of interest. These variables are aggregate radiative forcing from trace gasses, rftg; the radiative forcing of solar irradiance, sun; radiative forcing by sulfur emissions, rfsox; and radiative forcing by stratospheric sulfates, rfssgl. Different lag lengths are tested and an optimal or adequate lag length selected. We find that 2 lags is sufficient to model the temperature series. The Ljung-Box test statistic for general serial correlation (33 lags cutoff point) is 13.170 ($p = 1.00$). Lagrange multiplier statistics for first order and fourth order serial correlation are 3.328 ($p = 0.07$), and 0.206 ($p = 0.65$) respectively, while the test statistic for residual normality (Hansen and Juselius, 1995) is 3.501 ($p = 0.17$).

The model is then reformulated using the error correction representation:

$$\Delta y_t = \mu + \pi_{11} \Delta y_{t-1} + \sum_{i=2}^{5} \sum_{j=0}^{1} \pi_{ij} \Delta z_{t-i} + \alpha \beta' z_{t-1} + \varepsilon_t \qquad (14)$$

where y is temperature and z is the six dimensional vector [y, rftg, sun, rfsox, rfssgl, time]. α is a scalar and β a $7 \infty 1$ vector. β is the cointegrating vector. β_1 is normalized to unity so that represents the rate at which temperature adjusts to disequilibrium. Stratospheric sulfates clearly are stationary therefore β_5 was a priori restricted to zero. α represents the proportion of disequilibrium $\beta' z_{t-1}$ between current temperature and its long-run equilibrium which is eliminated each period. The vector π represents the short-run dynamics of adjustment of temperature to exogenous shocks. i sums over explanatory variables, while j sums over time lags. The R^2 statistic for this formulation of the model is 0.367.

The companion matrix is given by:

$$A = \begin{bmatrix} A_1 & A_2 \\ 1 & 0 \end{bmatrix} \tag{15}$$

where the A_i are the coefficients on temperature lagged one and two periods in the model in levels form - before transformation to the error correction representation. The eigenvalues of this matrix can tell us whether the variables in the model cointegrate. The modulus of the two eigenvalues is 0.2668 (one real root and one complex root). Therefore, cointegration occurs, as no unit roots remain. Values of 0.9 and above can be interpreted as indicating a lack of cointegration. In full systems where some dependent variables are exogenous the number of unit roots in this matrix can be tested with the number of unit roots equal to the number of exogenous variables and the number of cointegrating vectors given by the dimension of the dependent vector minus the number of unit roots.

Next, we investigate whether temperature can be represented by a trend stationary process. This is tested by restricting all elements of β to zero except the coefficients for temperature and the time trend. The test statistic is distributed as chi-square with three degrees of freedom. The calculated value is 18.85 which is clearly significant, and indicates that temperature contains a unit root. The test statistic for the exclusion of the time trend from the cointegration space is 7.57 which is chi-square with one degree of freedom, and indicates that the time trend is appropriate. Test statistics for the exclusion of the other variables from the cointegration relationship are: rftg 8.44, p = 0.00; sun 10.36, p = 0.00; rfsox 9.72, p = 0.00. These values reject the null, which indicates that all of these variables contribute towards the stochastic trend in temperature. This result allows us to attribute temperature change directly to changes in radiative forcing that are associated with anthropogenic activity in a statistically rigorous fashion.

To further test the conformity of the model to theory we carried out further tests. The radiative forcing of solar activity, greenhouse gases, and tropospheric sulfates are measured in the same units, watts per meter square therefore, the coefficients associated with these variables should be equal in the absence of mismeasurement of the radiative forcing effect of the different gasses (especially ozone depletion) or feedbacks of carbon dioxide on vegetation. We carried out tests for the equality of the coefficients of these three variables but these restrictions are rejected ($\chi^2(2) = 9.88$, p = 0.01). A joint restriction to equalize the coefficients of solar irradiance and tropospheric sulfates also is rejected ($\chi^2(1) = 7.57$, p = 0.01). A restriction for equality of the trace gas and solar irradiance coefficients is accepted ($\chi^2(1) = 2.13$, p = 0.13). These results suggest that the negative radiative forcing of tropospheric sulfates could have been underestimated. This is possible given the great uncertainty about the atmospheric concentration of tropospheric sulfates and their effect on radiative forcing.

The estimated cointegration vector, the adjustment factor α, and the coefficients of the short-run dynamics are given in Table 6. The size of the coefficients associated with greenhouse gases is consistent with other estimates for temperature sensitivity. The coefficient implies that doubling the atmospheric concentration of carbon dioxide would increase global temperature by about 2.0^{o} C. This climate sensitivity is consistent with the results generated by simple climate models, which indicate a temperature sensitivity of about 2.5^{o} C is best able to reproduce the historical temperature record (Wigley et al., in press). The estimate is higher than other statistical estimates of climate sensitivity (Bloomfield, 1992).

In spite of these strengths, the model does not account satisfactorily for all aspects of temperature change satisfactorily. The adjustment factor α is -.59. Although this value is statistically significant and has the correct sign, it is probably too large. It implies that temperature adjusts to 59% of the disequilibrium between it and its long-run equilibrium each year. This rate of adjustment is too rapid based on our current understanding of the climate system. Equally troubling, the coefficients associated with the short-run effects of stratospheric sulfates are statistically insignificant. This is confirmed by a joint exclusion test (p = 0.66). The implied time trend is 0.8 C per century. Again this rate seems too high. It would imply that the effects of trace gasses and solar irradiance roughly balance the cooling due to sulfates.

These inconsistencies do not disqualify the result that global temperature, solar activity, and the radiative forcing of greenhouse gases and tropospheric sulfates cointegrate. Rather, these results indicate that the model is probably incomplete. For example, the simple model ignores the possibility that temperature feed back on the atmospheric concentration of carbon dioxide and methane, and that there may be feedbacks among the gases. Omitting these effects clearly would bias the results, such as overstating the rate of adjustment. The dynamics of adjustment also may be more complex than can be modeled using this simple cointegration model because the univariate tests indicate that some variables may be integrated of order two.

7. CONCLUSIONS

A relation between temperature, solar irradiance, and the radiative forcing of CO_2, CH_4, CFC's, and SO_2 is possible only if the temperature data contain a stochastic rather than a deterministic trend. Even though univariate tests indicate that temperature data are stationary around a deterministic trend, there is good reason to believe that the probability of type I error is in this case greater than that indicated by the nominal significance levels of the tabulated distributions for these tests. Therefore standard tests may fail to detect the stochastic trend the temperature data. Taken at face value our statistical tests would indicate, in contrast to Woodward and Gray (1995) that climate change has taken place over the last 140 years but that this is not due to anthropogenic forcing. The presence of stochastic trends in most of the relevant time series means that caution is needed in interpreting the results of previous studies that ignore the implications of unit roots for statistical inference. However, application of the Johansen cointegration procedure finds that in the presence of relevant nonstationary variables, temperature cannot be adequately described by a deterministic trend and stationary noise. Rather, there is a stochastic trend present in the temperature series and this trend can be attributed to the effects of trace gasses, solar irradiance, and tropospheric sulfate aerosols. The results of the Johansen procedure provide the most statistically rigorous and statistically direct attribution of temperature change to anthropogenic activity to date.

APPENDIX I: DATA SOURCES

We have assembled an annual time series data set for the period 1854 to the present for the variables described below.

Temperature

We examine three temperature indicators - global mean annual temperature, and series for the northern and southern hemispheres separately. These data have not been adjusted for ENSO. These data are available from (Jones *et al*., 1994).

Carbon Dioxide

Data for direct observations for the atmospheric concentration of carbon dioxide are available from the Mauna Loa observatory starting in 1958. Prior to 1958, we used data from the Law Dome DE08 and DE08-2 ice cores (Etheridge *et al*. 1996). We interpolated the missing years using a natural cubic spline and two years of the Mauna Loa data (Keeling and Whorf 1994) to provide the endpoint. The data set can be updated in a consistent manner based on annual observations from Mauna Loa.

Data on global CO_2 emissions from fossil fuels between 1860 and 1949 are available in Keeling (1994). This series is extended into 1950-1991 by Marland *et al*. (1994). These data also include information on emissions from cement production. Data on emissions from biota from 1860 through the present are available from Houghton *et al*. (1983) and recent updates (and revisions) are available from CDIAC to 1990. In order to utilize the observations on other variables available for later dates we estimated emissions from biota for 1991-4. We did this by assuming the same rate of growth in emissions from 1991 on as in 1990 for all individual world regions and then aggregating over the nine regions. We updated estimates of emissions from fossil fuels for 1993-94 using data on global energy consumption from EIA (1996) and assuming that emissions from gas flaring declined by 1.7% per annum and that emissions from cement production rose by 2.5% per annum. The estimated emissions are: 1993: 6128.7 million tonnes C; 1994: 6230.9. Radiative forcing in Wm^{-2} is given by $6.3\ln(C_t / C_{1860})$ where C is in ppmv.

Methane

Indirect observations for the atmospheric concentration of methane are available from the Law Dome ice core (Etheridge *et al*. 1994). These data are available starting in 1841 and end in 1978. Observations are not available for every year and some years have multiple observations. We use a cubic spline to generate a consistent set of annual observations. Data for 1981 to 1991 are from Khalil and Rasmussen (1994). For 1992 they are the based on the mean percentage increase in the Dlugoklenchy *et al*. (1994) global series. For 1993-1994 they are based on the ALE/GAGE data downloaded from CDIAC and described in Prinn *et al*. (1995). Accounting for the effects of tropospheric ozone and stratospheric water vapor due to methane (Kattenberg *et al*., 1996) and the overlap with nitrous oxide, we calculate that radiative forcing is given by approximately 0.0387 $(M_t - M_{1860})$ where M is in ppbv.

Methane emissions are from Stern and Kaufmann (1996a). We updated our emissions series from 1993 to 1994. The estimate for 1994 is 378.6 million tonnes. This is up 3.5 million tonnes on the previous year. Estimates for some earlier years were also adjusted. Updated estimates are available at: http://cres.anu.edu.au/~dstern/datasite.html

CFC's

Direct observations for the atmospheric concentration of CFC-11 and CFC-12 are available starting in 1978. Prather *et al*. (1987), have generated estimates for years prior to 1978 based on historical emissions and a general model of atmospheric mixing. As the Prather *et al*. series is based on Adrigole in Ireland we used the Elkins *et al*. (1994) northern hemisphere series to update the series to 1992 from 1978. Including the radiative forcing due to ozone depletion (Kattenberg *et al*., 1996, Wigley and Raper, 1992) gives the following formulae:

CFC-11 $\quad 0.22\ y - 0.0552\ (3y)^{1.7}$

CFC-12 $\quad 0.28\ z - 0.0552\ (2z)^{1.7}$

where y and z are in parts per billion.

Historical data on emissions are available from 1932 to 1992 (AFEAS, 1994). Emissions were zero prior to 1938. We adjust these to reflect unreported emissions as described in AFEAS (1994). We assume that growth rates of these unreported emissions were constant between the three nodes.

Nitrous Oxide

Data from 1978 to the present are a weighted average of the stations in the ALE/GAGE network (Prinn *et al*., 1990; Prinn *et al*., 1995). Pre-1978 is based on data from the H15 Antarctica ice core reported in Machida *et al*. (1995). We discard a number of observations based on the fit with the Battle *et al*. (1996) firn data and fitted a cubic spline to the remaining data. Radiative forcing is assumed to be 0.1325 $(N_t - N_{1860})$ where N is in ppbv. The coefficient is reduced from 0.14 to account for the overlap with methane.

Aerosols

We use estimates of stratospheric aerosols from Sato *et al*. (1993). The radiative forcing due to these emissions has been estimated by L. D. Harvey (personal communication).

We use estimates of anthropogenic emissions of SOx rather than ice core records of tropospheric sulfate aerosol densities. We generated these estimates by updating the estimates of Dignon and Hameed (1989) and Hameed and Dignon (1992). The estimates are documented and presented in Stern and Kaufmann (1996b) and can be downloaded via the World Wide Web as described above. Figure 2 illustrates the time series for sulfur emissions. The main recent development has been a downturn in emissions following the collapse of the Eastern European economies, the recession of the early 1990s, and continuing cutbacks in emissions in Western Europe in the context of acid rain abatement. This trend may again be reversing as economic growth picks up. Though Dignon and Hameed's technique now appears somewhat primitive, annual historical inventories with global coverage are at the time of writing still in the process of construction. Radiative forcing is assumed to be $-.3\ (S_t / S_{1990})\ -.8\ \ln(1 + S_t/42) / \ln(1 + S_{1990}/42)$ where S is in megatonnes (Kattenberg *et al.*, 1996; Wigley and Raper, 1992).

Solar Activity

The effect of solar activity on the planetary heat balance is represented using the index of solar irradiance assembled by Lean *et al*. (1995). Radiative forcing is linear in irradiance and equal to .175 times the change in irradiance (Shine *et al*., 1991)

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Table 1 Dickey Fuller Statistics

		Model 1					Model 2			Model 3	
Variables	Lags	τ_τ	$\tau_{\alpha\tau}$	$\tau_{\beta\tau}$	ϕ_3	ϕ_2	τ_μ	$\tau_{\alpha\mu}$	ϕ_1	τ	Unit Root
nhem	3	-2.81	-2.43	2.55	4.16	3.07	-1.32	-0.02	1.30	-1.62	yes
Δnhem	3	**-9.68**	-0.16	0.73	**46.89**	**31.28**	**-9.67**	1.06	**46.82**	**-9.62**	no
shem	2	**-3.47**	-3.20	**3.20**	6.14	4.38	-1.38	-0.43	1.36	-1.60	no
Δshem	2	**-10.15**	0.00	0.54	**51.56**	**34.37**	**-10.17**	1.02	**51.68**	**-10.11**	no
globl	3	-2.82	-2.58	2.72	4.19	3.20	-0.96	0.15	1.05	-1.45	yes
Δglobl	4	**-7.92**	-0.07	0.78	**31.37**	**20.92**	**-7.90**	1.35	**31.17**	**-7.75**	no
CO2	3	0.87	0.22	0.14	3.14	2.91	2.51	0.65	**4.39**	2.90	yes
ΔCO2	2	-2.69	-0.54	2.37	3.86	2.74	-1.43	1.53	1.25	-0.40	yes
CH4	4	-0.73	-1.08	1.93	5.46	**7.68**	2.65	1.66	**9.46**	3.99	yes
ΔCH4	3	**-6.94**	-0.91	**3.37**	**24.09**	**16.06**	**-5.84**	**3.30**	**17.06**	**-4.65**	no
CFC11	2	**-4.73**	-3.89	**4.06**	**13.14**	**8.94**	-2.71	2.21	3.87	-1.62	?
ΔCFC11	4	-2.24	0.45	-0.19	2.77	1.85	-2.37	1.75	2.82	-1.56	yes
CFC12	2	**-3.73**	-2.25	2.39	**10.84**	**7.74**	**-3.83**	1.77	**8.03**	**-3.53**	?
ΔCFC12	1	1.10	2.60	-2.44	3.61	2.45	-1.07	1.04	0.63	-0.41	yes
N2O	5	0.68	-0.38	0.88	4.36	4.34	2.82	1.01	**6.14**	3.35	yes
ΔN2O	4	**-3.92**	-1.26	**2.93**	**7.71**	**5.21**	-2.54	1.99	3.32	-1.62	?
sun	5	-2.58	2.58	2.61	3.63	2.71	-0.64	0.64	0.62	0.91	yes
Δsun	2	**-7.62**	-0.28	0.54	**29.00**	**19.38**	**-7.62**	0.41	**29.08**	**-7.64**	no
ssGL	2	**-4.91**	-1.09	-0.71	**12.06**	**8.04**	**-4.87**	**-2.96**	**11.86**	**-3.76**	no
ssN	1	**-6.62**	-2.01	-0.04	**21.94**	**14.63**	**-6.65**	**-3.75**	**22.11**	**-5.24**	no
ssT	2	**-4.94**	-0.76	-0.97	**12.25**	**8.17**	**-4.85**	-2.80	**11.78**	**-3.87**	no
ssS	2	**-4.75**	-0.86	-0.70	**11.34**	**7.56**	**-4.72**	-2.65	**11.14**	**-3.82**	no
SOx	1	-2.19	0.36	-2.25	2.54	**7.31**	0.12	-2.19	**8.17**	3.35	yes
ΔSOx	1	**-8.39**	-1.69	-0.64	**35.22**	**23.48**	**-8.39**	-4.40	**35.18**	**-6.68**	no
eCO2	3	-0.38	-1.09	1.90	4.20	**4.92**	2.16	0.81	**5.45**	3.21	yes
ΔeCO2	2	**-9.03**	-1.36	**4.11**	**40.78**	**27.19**	**-7.58**	**4.07**	**28.73**	**-6.04**	no
eCH4	3	0.11	-0.78	1.57	4.64	4.83	2.59	-0.56	**5.94**	3.41	yes
ΔeCH4	2	**-4.13**	-0.77	**3.08**	**8.57**	**5.73**	-2.68	2.21	3.61	-1.50	no
eCFC11	1	-2.19	-1.57	1.70	2.85	1.96	-1.64	1.50	1.43	-0.77	yes
ΔeCFC11	1	-3.06	0.93	-0.86	4.81	3.22	**-2.99**	0.65	4.48	**-2.94**	no
eCFC12	2	-1.69	-1.28	1.41	1.63	1.49	-1.11	1.56	1.22	0.04	yes
ΔeCFC12	1	-3.33	0.73	-0.57	5.64	3.77	**-3.33**	1.09	**5.56**	**-3.14**	no

$\tau_\tau, \tau_\mu, \tau$	$\gamma = 0$	ϕ_3	$\gamma = \beta = 0$
$\tau_{\alpha\tau}, \tau_{\alpha\mu}$	$\alpha = 0$ given $\gamma = 0$	ϕ_2	$\alpha = \gamma = \beta = 0$
$\tau_{\beta\tau}$	$\beta = 0$ given $\gamma = 0$	ϕ_1	$\alpha = \gamma = 0$

Figures in bold indicate that the statistic is significant at the 5% level. All variables with the exception of CO2, CH4, and CFC emissions in terms of radiative forcing

Table 2 Phillips-Perron Tests

		Model 1						Model 2				Model 3		
Variables	Lags	$T\gamma_\tau$	τ_τ	$\tau_{\alpha\tau}$	$\tau_{\beta\tau}$	ϕ_3	ϕ_2	$T\gamma_\mu$	τ_μ	$\tau_{\alpha\mu}$	ϕ_1	$T\gamma$	τ	Unit Root
nhem	0	**-54.8**	**-5.64**	-1.37	**3.98**	**15.96**	**10.75**	**-29.5**	**-3.80**	-1.37	**7.37**	**-24.3**	**-3.58**	No
Δnhem	0	**-164**	**-14.7**	0.61	0.47	**108.3**	**72.25**	**-163**	**-14.76**	0.61	**109**	**-163**	**-14.8**	No
shem	0	**-52.4**	**-5.61**	-1.77	**4.49**	**15.74**	**10.62**	**-19.7**	**-3.14**	-1.77	**5.11**	**-11.9**	**-2.64**	No
Δshem	1	**-153**	**-14.0**	0.67	0.21	**98.39**	**65.60**	**-153**	**-14.08**	0.67	**99.14**	**-153**	**-14.1**	No
globl	0	**-49.8**	**-5.34**	-1.34	**4.25**	**14.33**	**9.72**	**-19.8**	**-3.06**	-1.34	**4.89**	**-14.6**	**-2.82**	No
Δglobl	1	**-152**	**-13.7**	0.72	0.35	**93.53**	**62.37**	**-152**	**-13.72**	0.72	**94.15**	**-152**	**-13.7**	No
CO2	8	3.03	2.83	1.02	-0.22	**31.00**	**59.22**	2.80	7.73	1.02	**85.69**	3.08	12.80	Yes
ΔCO2	0	**-41.1**	**-4.79**	2.52	**3.62**	**11.57**	**7.80**	**-19.7**	**-3.03**	**2.52**	**4.73**	-8.04	-1.73	No
CH4	5	-1.41	-0.67	1.90	1.54	3.98	**10.91**	1.64	2.38	1.90	**15.29**	2.55	4.93	Yes
ΔCH4	2	**-78.8**	**-7.45**	2.95	1.77	**27.77**	**18.51**	**-74.6**	**-7.20**	**2.95**	**25.90**	**-62.6**	**-6.39**	No
CFC11	0	0.55	0.38	**4.79**	-0.64	**0.61**	**15.10**	-0.33	-0.91	**4.79**	**22.75**	1.05	3.90	Yes
ΔCFC11	0	-1.70	-0.99	0.52	-2.12	2.58	1.72	-1.41	-0.79	0.52	0.32	-0.76	-0.61	Yes
CFC12	1	-3.35	-3.15	**3.97**	**4.04**	**12.89**	**46.10**	0.81	2.43	3.97	**39.18**	1.77	6.28	Yes
ΔCFC12	0	-1.98	-0.61	1.34	-0.87	1.48	1.00	-3.74	-1.49	1.34	1.13	-0.96	-0.67	Yes
N2O	5	1.82	1.20	1.24	0.81	15.02	**25.5**	2.96	5.45	1.10	**38.41**	3.38	8.55	Yes
ΔN2O	1	**-72.3**	**-7.09**	**5.07**	**4.34**	**25.2**	**16.8**	**-41.4**	**-4.97**	**3.28**	**12.42**	**-22.2**	**-3.36**	No
sun	7	-14.3	-2.80	1.30	-0.72	3.96	2.73	-3.66	-1.30	1.30	0.99	0.00	0.55	Yes
Δsun	2	**-66.8**	**-6.37**	0.25	-0.01	**20.31**	**13.54**	**-66.8**	**-6.39**	0.25	**20.45**	**-66.6**	**-6.41**	No
ssGL	3	**-44.4**	**-5.12**	-2.69	-0.41	**13.1**	**8.74**	**-44.1**	**-5.12**	-2.68	**13.11**	**-31.3**	**-4.22**	No
ssN	2	**-57.5**	**-5.95**	-3.13	0.12	**17.7**	**11.8**	**-57.5**	**-5.97**	-3.15	**17.84**	**-40.3**	**-4.86**	No
ssT	3	**-45.4**	**-5.18**	-2.57	-0.66	**13.4**	**8.94**	**-44.5**	**-5.15**	-2.53	**13.24**	**-33.2**	**-4.35**	No
ssS	3	**-44.6**	**-5.13**	-2.45	-0.43	**13.2**	**8.77**	**-44.2**	**-5.13**	-2.44	**13.14**	**-33.7**	**-4.39**	No
SOx	2	-6.92	-1.95	-2.43	-1.97	1.95	**9.17**	0.00	-0.01	-2.43	**11.90**	1.33	4.01	Yes
ΔSOx	0	**-104**	**-9.35**	-4.01	-0.30	**43.75**	**29.16**	**-104**	**-9.38**	-4.01	**44.03**	**-85.1**	**-8.01**	No
eCO2	3	-0.07	-0.06	0.81	2.02	**10.80**	**21.96**	2.09	4.03	0.81	**28.74**	2.42	7.53	Yes
ΔeCO2	0	**-97.7**	**-8.87**	**4.09**	**3.96**	**39.31**	**26.21**	**-78.2**	**-7.50**	**4.09**	**28.11**	**-55.4**	**-5.92**	No
eCH4	2	0.87	1.10	-1.39	1.55	**30.21**	**77.51**	2.04	7.51	-1.39	**112**	1.70	14.53	Yes
ΔeCH4	0	**-99.6**	**-8.97**	**4.68**	**5.46**	**40.26**	**26.84**	**-62.1**	**-6.40**	**4.68**	**20.52**	**-29.5**	**-4.05**	No
eCFC11	7	-1.92	-0.50	1.69	-0.25	0.97	1.00	-2.32	-1.39	1.69	1.43	-0.15	-0.13	Yes
ΔeCFC11	1	-14.0	-2.74	0.45	-1.16	3.86	2.59	-12.7	-2.53	0.45	3.23	**-12.0**	**-2.51**	No
eCFC12	9	-3.39	-0.84	1.77	0.26	0.85	1.17	-1.75	-1.23	1.77	1.60	0.15	0.15	Yes
ΔeCFC12	2	-13.9	-2.70	0.67	-1.03	3.77	2.52	-13.2	-2.58	0.67	3.34	**-11.9**	**-2.49**	No

$\tau_\tau, \tau_\mu, \tau$	$\gamma = 0$	ϕ_3	$\gamma = \beta = 0$
$\tau_{\alpha\tau}, \tau_{\alpha\mu}$	$\alpha = 0$ given $\gamma = 0$	ϕ_2	$\alpha = \gamma = \beta = 0$
$\tau_{\beta\tau}$	$\beta = 0$ given $\gamma = 0$	ϕ_1	$\alpha = \gamma = 0$

Figures in bold indicate that the statistic is significant at the 5% level. All variables with the exception of CO2, CH4, and CFC emissions in terms of radiative forcing

Table 3 Schmidt-Phillips Tests

Variable	Lags	τ	$Z\tau$	ρ	$Z\rho$	Unit root
nhem	1	**-4.15**	**-4.03**	**-31.12**	**-29.34**	no
Δnhem	1	**-7.64**	**-7.50**	**-83.26**	**-80.09**	no
shem	0	**-6.03**	**-6.03**	**-58.39**	**-58.39**	no
Δshem	1	**-14.08**	**-13.47**	**-165.13**	**-151.00**	yes
globl	0	**-4.40**	**-4.40**	**-34.43**	**-34.43**	no
Δglobl	1	**-6.48**	**-6.36**	**-65.34**	**-62.87**	no
CO2	8	-0.42	-0.84	-0.36	-1.42	yes
ΔCO2	1	**-4.76**	**-4.60**	**-39.53**	**-36.85**	no
CH4	5	-0.96	-1.00	-1.86	-2.02	yes
ΔCH4	2	**-6.85**	**-6.78**	**-71.07**	**-69.63**	yes
CFC11	11	-0.45	-1.30	-0.42	-3.50	yes
ΔCFC11	1	-0.87	-0.90	-1.56	-1.64	yes
CFC12	11	-0.41	-1.09	-0.35	-2.45	yes
ΔCFC12	4	-1.32	-1.10	-3.52	-2.43	yes
N2O	5	-0.52	-0.82	-0.54	-1.37	no
ΔN2O	2	**-7.39**	**-6.99**	**-79.42**	**-70.96**	yes
sun	8	-2.26	-2.16	-10.03	-9.10	yes
Δsun	2	**-6.16**	**-6.61**	**-60.31**	**-69.35**	no
ssGL	3	**-5.41**	**-5.38**	**-48.95**	**-48.41**	no
ssN	2	**-6.10**	**-6.24**	**-59.47**	**-62.31**	no
ssT	3	**-5.44**	**-5.42**	**-49.43**	**-49.01**	no
ssS	3	**-5.38**	**-5.36**	**-48.60**	**-48.18**	no
SOx	2	-1.39	-1.51	-3.87	-4.54	yes
ΔSOx	0	**-9.71**	**-9.71**	**-111.29**	**-111.29**	no
eCO2	3	-0.53	-0.63	-0.57	-0.80	yes
ΔeCO2	0	**-8.90**	**-8.90**	**-100.21**	**-100.21**	no
eCH4	2	-0.43	-0.48	-0.37	-0.46	yes
ΔeCH4	0	**-8.05**	**-8.05**	**-87.97**	**-87.97**	no
eCFC11	9	-0.79	-1.30	-1.28	-3.45	yes
ΔeCFC11	2	-2.73	-2.93	-13.53	-15.55	yes
eCFC12	11	-0.72	-1.30	-1.07	-3.49	yes
ΔeCFC12	2	-2.64	-2.90	-12.83	-15.53	yes

See text for details of test statistics

Figures in bold indicate that the statistic is significant at the 5% level. All variables with the exception of CO2, CH4, and CFC emissions in terms of radiative forcing

Table 4. Summary of Unit Root Tests			
Variable and Sample Period	Dickey-Fuller	Phillips-Perron	Schmidt-Phillips
nhem 1854-1995	I(1)	I(0)	I(0)
shem 1854-1995	I(0)	I(0)	I(0)
globl 1854-1995	I(1)	I(0)	I(0)
CO2 1854-1995	I(2)	I(1)	I(1)
CH4 1854-1995	I(1)	I(1)	I(1)
CFC11 1938-1994	I(2)	I(2)	I(2)
CFC12 1932-1994	I(2)	I(2)	I(2)
N2O 1854-1995	I(1) to I(2)	I(1)	I(1)
sun 1860-1994	I(1)	I(1)	I(1)
ssGL 1854-1995	I(0)	I(0)	I(0)
ssN 1854-1995	I(0)	I(0)	I(0)
ssT 1854-1995	I(0)	I(0)	I(0)
ssS 1854-1995	I(0)	I(0)	I(0)
SOx 1860-1994	I(1)	I(1)	I(1)
eCO2 1860-1994	I(1)	I(1)	I(1)
eCH4 1860-1994	I(1)	I(1)	I(1)
eCFC11 1938-1992	I(1)	I(1)	I(2)
eCFC12 1932-1992	I(1)	I(1)	I(2)

Table 5. Cointegration Tests

	Hypothesis 1A			Hypothesis 1B			Hypothesis 1C			Hypothesis 1D		
Dependent Variable	DW	DF	PO	DW	DF	PO	DW	DF	PO	DW	DF	PO
Trace gasses	n.a.	-1.13	-0.82	0.02	-0.89	-0.74	0.01	-1.07	-0.78	0.02	-0.91	-0.93
SOx				0.07	-1.77	-1.62				0.08	-1.92	-1.86
Sun							0.13	-1.70	-2.30	0.14	-2.03	-2.73

DW is the cointegrating Durbin-Watson test statistic

DF is the Dickey Fuller cointegration test statistic

PO is the Phillips-Ouliaris cointegration test statistic

Figures in bold are significant at the 5% level

Table 6. Johansen Procedure		
	Coefficient	Standard error
Cointegrating vector β		
Temperature	1.000	0
Trace gasses	-0.458	.089
Solar irradiance	-0.458	.089
Tropospheric sulfates	-1.448	.369
Time trend	-0.008	.002
Loading factor α		
	-0.590	0.093
Short run coefficients π		
ΔTemperature(t-1)	0.065	0.085
Δrftg(t)	2.693	0.842
Δrftg(t-1)	-1.453	0.866
Δsun(t)	0.019	0.317
Δsun(t-1)	0.037	0.319
Δrfsox(t)	1.189	0.553
Δrfsox(t-1)	-1.027	0.547
Δrfssgl(t)	-0.00	0.044
Δrfssgl(t-1)	0.007	0.016
Constant	-0.156	0.027

Figure 1

Global Temperature 1854-1995

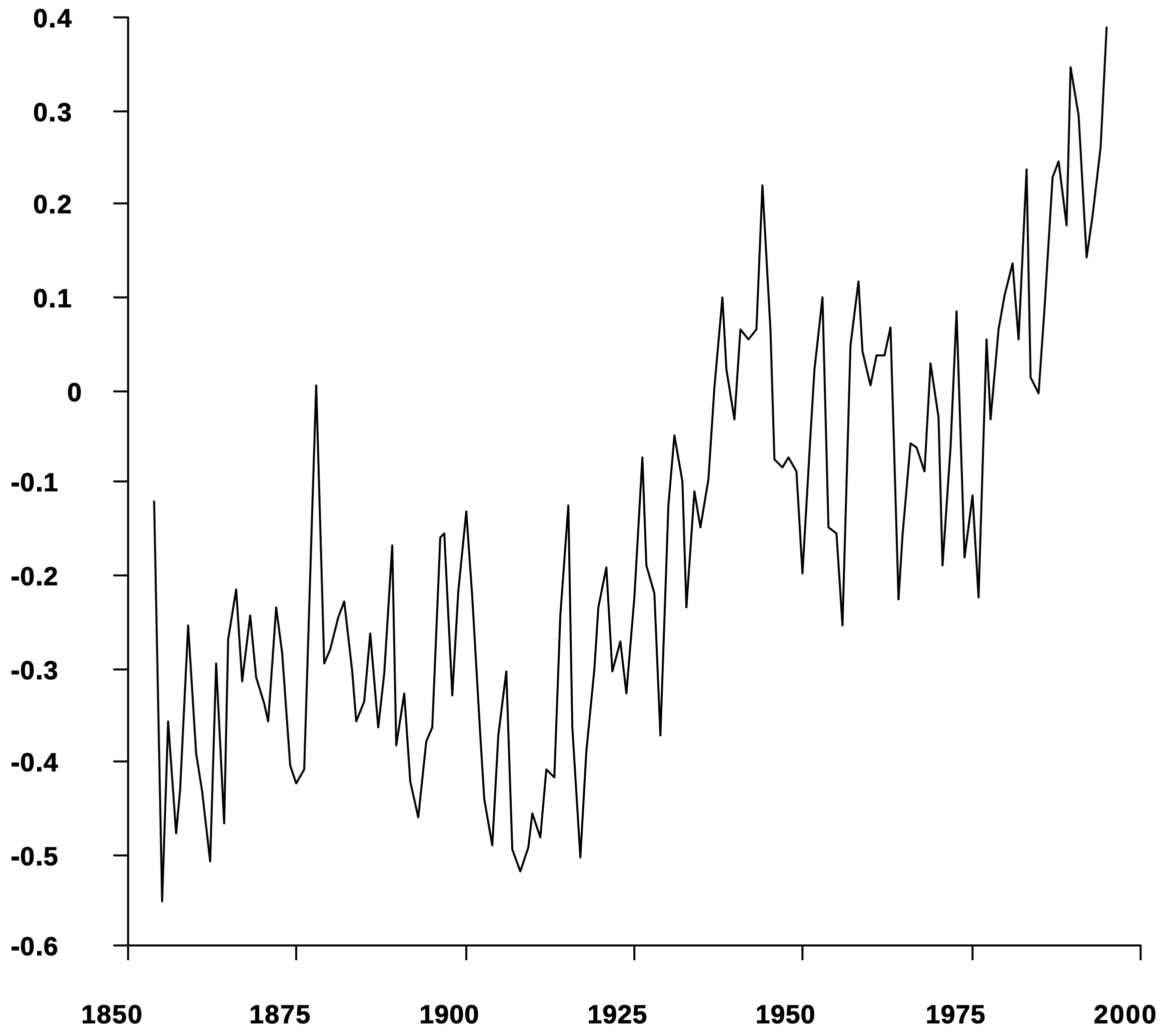

Figure 2

World SOx Emissions 1860-1994