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TIME SERIES ANALYSES OF GLOBAL CHANGE DATA

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Abstract

The hypothesis that statistical analyses of historical time series data can be used to separate the influences of natural variations from anthropogenic sources on global climate change is tested. Point, regional, national, and global temperature data are analyzed. Trend analyses for the period 1901–1987 suggest mean annual temperatures increased (in °C per century) globally at the rate of about 0·5, in the USA at about 0·3, in the south-western USA desert region at about 1·2, and at the Walnut Gulch Experimental Watershed in south-eastern Arizona at about 0·8. However, the rates of temperature change are not constant but vary within the 87-year period. Serial correlation and spectral density analysis of the temperature time series showed weak periodicities at various frequencies. The only common periodicity among the temperature series is an apparent cycle of about 43 years. The temperature time series were correlated with the Wolf sunspot index, atmospheric CO_2 *concentrations interpolated from the Siple ice core data, and atmospheric* CO_2 *concentration data from Mauna Loa measurements. Correlation analysis of temperature data with concurrent data on atmospheric* CO_2 *concentrations and the Wolf sunspot index support previously reported significant correlation over the 1901–1987 period. Correlation analysis between temperature, atmospheric* CO_2 *concentration, and the Wolf sunspot index for the shorter period, 1958–1987, when continuous Mauna Loa* CO_2 *data are available, suggest significant correlation between global warming and atmospheric* CO_2 *concentrations but no significant correlation between global warming and the Wolf sunspot index. This may be because the Wolf sunspot index apparently increased from 1901 until about 1960 and then decreased thereafter, while global warming apparently continued to increase through 1987. Correlation of sunspot activity with global warming may be spurious but additional analyses are required to test this hypothesis. Given the inconclusive correlation between temperature and solar activity, the significant intercorrelation between time, temperature, and atmospheric* CO_2 *concentrations, and the suggestion of weak periodicity in the temperature data, additional research is needed to separate the anthropogenic component from the natural variability in temperature when assessing local, regional, and global warming trends.*

Keywords: time series analysis, global climate change, temperature, Wolf sunspot index, atmospheric carbon dioxide concentration.

INTRODUCTION

One of the main limitations in projecting future trends in global climate is our limited ability to separate natural variations in weather and climate from those variations and trends which may be anthropogenic. The former source of variations may be entirely random or may be more or less related to other phenomena such as linkages between solar activity and climate change (e.g. see Hoyt, 1979*a* for an example using statistics of solar activity and Pittock, 1978 for a critical review), and ocean circulations and climate change (Ghil & Vautard, 1991). The latter source is usually attributed to the greenhouse gases, particularly increases in atmospheric carbon dioxide concentration, affecting global warming (e.g. see Schneider, 1975; Williams, 1978; Hoyt, 1979*b*; Kuo *et al.*, 1990 and Silver & DeFries, 1990). Statistical analyses of time series that may indicate global climate change have been described and reviewed (Vautard & Ghil, 1989; Elsner & Tsonis, 1991).

We hypothesize that statistical analyses of historical time series data can be used to separate the influences of natural variations from anthropogenic sources on global climate change and call this the hypothesis of separability. As a first examination of this hypothesis we analyze point, regional, and global temperature data and sunspot data using a variety of statistical procedures. The objective of the analyses is to provide a preliminary test of the above hypothesis using temperature data as a subset of the larger body of global change data.

As we use statistical techniques, no assertions of causality are made, rather we examine the temporal structure of temperature time series over various spatial scales. We also relate these time series to atmospheric carbon dioxide concentration, as a measure of the greenhouse effect, and to the Wolf sunspot number, as an index of solar activity. The strengths of the statistical relationships among time, temperature, atmospheric carbon dioxide concentration, and sunspots are then interpreted as supporting or refuting the basic hypothesis of separability.

MATERIALS AND METHODS

The data bases

Data for these analyses, except as noted, are from the Carbon Dioxide Information Analysis Center

(CDIAC), Oak Ridge National Laboratory. Specifically, the publication is entitled '*Trends '90: A Compendium of Data on Global Change*' and is cited herein as *Trends '90* or Boden *et al.* (1990). Citations of the Principal Investigators providing the data follow the format as recommended on page xiii of Boden *et al.* (1990).

Global temperature anomalies (GTA) for the period 1901–1987 are from Hansen and Lebedeff (1990) and were calculated from the 1951–1980 normalizing period using the following procedure. Temperature differences between neighboring stations were calculated and combined to form estimates of temperature changes for grids, latitudinal zones, the northern and southern hemispheres, and the globe (see Hansen & Lebedeff, 1987 for a description of the procedures used).

Mean annual temperature data averaged over the USA and 23 regions within the USA including the Southern Desert Region are from Karl *et al.* (1990) and were corrected for missing data, instrument changes, and urban effects as specified by Karl *et al.* (1988).

Mean annual temperature data for the Tombstone, Arizona station on the Walnut Gulch Experimental Watershed (see Renard, 1970 for a description of this experimental watershed and global change research facility) are from data compilations made by Green and Sellers (1964), Sellers and Hill (1974), and Climatological Records published by NOAA through 1987 (United States Department of Commerce, 1973–1987).

The Wolf sunspot data (see Bray & Loughhead, 1964 for detailed description and history of observations) for 1901–1981 are from Hoyt (1985) and for 1982–1987 are from McKinnon, J. (1992, pers. comm.).

Carbon dioxide data are from *Trends '90* with appropriate interpolations and estimation of missing data accomplished by the authors. Annual atmospheric concentrations (in ppmv) of CO_2 from 1959 to 1963 and 1965 to 1987 are from Keeling and Whorf (1990). Missing values for 1958 and 1964 were estimated by the authors as 315·2 and 320·0, respectively. A regression equation for annual CO_2 concentration vs time for 1959 (t = 2 years) to 1970 (t = 13 years) was derived as follows

$$CO_2 = 314{\cdot}4 + 0{\cdot}7948t \qquad (1)$$

with $N = 11$ and $R^2 = 0{\cdot}986$. Equation (1) was then used with $t = 1$ for the 1958 estimate of 315·2 and $t = 7$ for the 1964 estimate of 320·0.

Annual atmospheric carbon dioxide concentrations (ppmv) for the period 1901–1957 were based on Siple ice core data (Neftel, *et al.*, 1990 and Friedli *et al.*, 1986) for atmospheric CO_2 concentration data for the years of: 1878, 1887, 1899, 1903, 1905, 1909, 1915, 1921, 1927, 1935, 1943 and 1953. Annual values for the missing years of data were interpolated by the authors using the following procedures.

For 1901 to 1915 the seven data points from 1878 ($t = -22$ years) to 1915 (t = 15 years) were used to derive the following regression equation

$$CO_2 = 295{\cdot}9 + 0{\cdot}27t \qquad (2)$$

with $N = 7$ and $R^2 = 0{\cdot}94$ Equation (2) was then used to estimate annual CO_2 atmospheric concentration values for the missing years between 1901 and 1915.

For 1916 to 1953 the six data points from 1915 (t = 15 years) to 1953 (t = 53 years) were used to derive the following regression equation

$$CO_2 = 295{\cdot}9 + 0{\cdot}31t \qquad (3)$$

with $N = 6$ and $R^2 = 0{\cdot}96$. Equation (3) was used to estimate annual CO_2 atmospheric concentration values for the missing years between 1916 and 1953.

For 1954 to 1957, linear interpolation was used between values of 312·7 in 1953 and 315·2 in 1958 to estimate CO_2 annual atmospheric concentration data for the missing years of 1954, 1955, 1956 and 1957.

The data described above were used to define two data sets, the 'short record' is from 1958 to 1987 when continuous atmospheric carbon dioxide concentration data were measured at Mauna Loa. The 'long record' is from 1901 to 1987 when the interpolated data from the Siple ice cores were used to estimate atmospheric carbon dioxide concentrations from 1901 to 1957 and the Mauna Loa data were used for 1958 to 1987.

Time series analyses

Trend analysis used here is accomplished by using linear regression with the variable of interest, i.e. mean annual temperature, as the dependent variable and $t = 1,2, \ldots, N$, the time in years as the independent variable. The regression intercept is the value of the dependent variable at the beginning of the time series and the regression slope is the linear rate of change in the dependent variable with time. The primary goodness of fit statistic used is the coefficient of determination, R^2, defined as the proportion of variance explained as an improvement over that portion explained by the mean of the dependent variable.

Serial correlation analysis is used to examine the correlation structure with time as the dependent variable. If the series of N observations on the dependent variable are denoted as $x_1, x_2, \ldots, x_N$, then we can define a lag k as $k = 0,1,2, \ldots, M$, where $M = N/2$ if N is even and $M = (N - 1)/2$ if N is odd. The series of M correlation coefficients r_k then form the autocorrelation function for the time series.

The spectral density function is calculated as the Fourier transform of the autocorrelation function and is a measure of how much of the variance of the dependent variable is explained by harmonics at frequencies from $f = 0{\cdot}0$ to $f = 0{\cdot}5$. The period or cycle corresponding to a particular frequency f is then calculated as $T = 1/f$. The spectral density function is used herein to examine the historical time series for periodic or cyclical behavior.

In summary, time series analyses used herein are (1) linear trend analysis to test for linear trends with time, (2) serial correlation analysis to test for dependency with time at various lags and to calculate (3) the spectral density function which may indicate significant periods or cycles.

Table 1. Summary of time series analyses of global, national, regional, and point time series data for the period 1958–1987

Data	Trend analysis			Apparent periodicity (years)	
	a	*b*	R^2	Raw data	Without linear trend
GTA	−0·09	0·008 7[a]	0·24	Inf,[b] 30	None
USA Temp.	11·3	0·010 3	0·08	3	3
S. Des. Temp.	17·2	0·024 8[c]	0.15	Inf, 30, 15	30,15
Tombstone Temp.	17·5	−0·003 0	0·01	None	None
CO_2	311·7	1·15[a]	0·98	Inf, 30	Inf, 30, 15
Wolf SS	88·8	−1·10	0·03	11	11

[a] Linear trend with time in years, significant at the 1% level.
[b] Infinite (Inf) period suggests a trend throughout the entire 30 years of data.
[c] Linear trend with time in years, significant at the 5% level.

Regression analysis

Linear regression analysis is used to examine the relationships between historical time series. The procedure is to regress dependent variables, such as temperature, on independent variables representing natural sources of variations (i.e. sunspot data) and anthropogenic sources (i.e. CO_2 data) to test the hypothesis of separability.

RESULTS

Analysis of the short record, 1958–1987, *N* = 30

Results of time series analyses for the short record are summarized in Table 1, where: (1) GTA is global temperature anomaly in °C; (2) USA Temp. is mean annual temperature in °C for the continental United States; (3) S. Des. Temp. is mean annual temperature in °C for the Southern Desert Region of the USA; (4) Tombstone Temp. is mean annual temperature in °C for the Tombstone, Arizona station representing the Walnut Gulch Experimental Watershed; (5) CO_2 is annual atmospheric carbon dioxide concentration in ppmv, and (6) Wolf SS is the dimensionless Wolf sunspot index.

Notice that there are statistically significant increases in GTA, S. Des. Temp., and CO_2. The USA Temp., Tombstone Temp., and Wolf SS show no significant trends with time. Notice also that there are no consistent periodicities among the six time series and that the Wolf SS has the characteristic 11 year cycle.

A partial correlation matrix for the six variables in Table 1 and time in years is shown in Table 2. There is significant intercorrelation among all of the temperature data, except Tombstone Temp., and with CO_2 and time. There is no significant correlation between the Wolf SS and any of the other variables.

In Table 2, GTA was strongly correlated with CO_2. Regression of GTA on CO_2 explained 30% of the variance in GTA for the 30 year period, 1958–1987. The GTA estimated from CO_2 data is shown in Fig. 1 relative to GTA data.

Analysis of the long record, 1901–1987, *N* = 87

Time series analyses for the long record are summarized in Table 3. With these data, GTA, S. Des. Temp., Tombstone Temp., CO_2, and Wolf SS all show significant linear trends with time. Moreover, there is a common periodicity with a cycle of about 43 years in

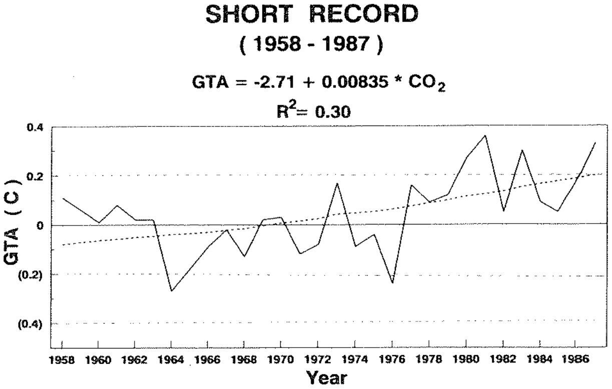

Fig. 1. Observed and fitted global temperature anomalies for 1985–1987 using CO_2 as the independent variable. ——, GTA observed; -----, GTA fitted.

Table 2. Partial correlation matrix for global, national, regional, and point time series data for the period 1958–1987

	GTA	USA Temp.	S. Des. Temp.	Tombstone Temp.	CO_2	Wolf SS	Time
GTA	1·00	0·56[a]	0·71[a]	0·33	0·55[a]	0·34	0·49[a]
USA Temp.	0·56[a]	1·00	0·55[a]	0·37[b]	0·33	−0·15	0·28
S. Des. Temp.	0·71[a]	0·55[a]	1·00	0·51[a]	0·46[a]	0·32	0·39[b]
Tombstone Temp.	0·33	0·37[b]	0·51[a]	1·00	−0·03	0·17	−0·07
CO_2	0·55[a]	0·33	0·46[a]	−0·03	1·00	−0·17	0·99[a]
Wolf SS	0·34	−0·15	0·32	0·17	−0·17	1·00	−0·19
Time	0·49[a]	0·28	0·39[b]	−0·07	0·99[a]	−0·19	1·00

[a] Significant at the 1% level.
[b] Significant at the 5% level.

Table 3. Summary of time series analysis of global, national, regional, and point time series data for the period 1901–1987

Data	Trend analysis			Apparent periodicity (years)	
	a	*b*	R^2	Raw data	Without linear trend
GTA	−0·24	0·0045[a]	0·39	Inf,[b] 86, 43	Inf, 86, 43
USA Temp.	11·4	0·0028	0·03	Inf, 86, 43, 7, 2·5	86, 43, 7
S. Des. Temp.	16·7	0·0122[a]	0·29	Inf, 86, 43, 29, 22	43, 29, 22, 4
Tombstone Temp.	17·0	0·0082[a]	0·14	Inf, 86, 43, 29, 9	86, 43, 9
CO_2	290·3	0·52[a]	0·90	Inf, 86	Inf, 86, 43, 29
Wolf SS	34·0	0·56[a]	0·09	Inf, 86, 11	11

[a] Linear trend with time in years, significant at the 1% level.
[b] Infinite (Inf) period suggests a trend throughout the entire 30 years of data.

Table 4. Partial correlation matrix for global, national, regional, and point time series data for the period 1901–1987

	GTA	USA Temp.	S. Des. Temp.	Tombstone Temp.	CO_2	Wolf SS	Time
GTA	1·00	0·47[a]	0·53[a]	0·35[a]	0·57[a]	0·29[a]	0·62[a]
USA Temp.	0·47[a]	1·00	0·42[a]	0·34[a]	0·12	−0·09	0·16
S. Des. Temp.	0·53[a]	0·42[a]	1·00	0·53[a]	0·56[a]	0·27	0·54[b]
Tombstone Temp.	0·35	0·34[a]	0·53[a]	1·00	0·27[b]	0·17	0·37[a]
CO_2	0.57[a]	0·12	0·56[a]	0·27[b]	1·00	0·22[b]	0·95[a]
Wolf SS	0·29[a]	−0·09	0·27[b]	0·17	0·22[b]	1·00	0·30[a]
Time	0·62[a]	0·16	0·54[a]	0·37[a]	0·95[a]	0·30[a]	1·00

[a] Significant at the 1% level.
[b] Significant at the 5% level.

the temperature and CO_2 time series and a unique, but characteristic for sunspot data, 11 year cycle in the Wolf SS data.

A partial correlation matrix for the long record is shown in Table 4. There is significant correlation between GTA and all the other variables and significant correlation between time and CO_2 and all variables except USA Temp.

In Table 4, GTA was strongly correlated with time and this relationship is shown in Fig. 2. Regression on time explained 39% of the variance in GTA for the 87 year period, 1901–1987. A nearly equal correlation was found between GTA and CO_2. Regression of GTA on CO_2 explained 33% of the variance in GTA for the 87 year period, 1901–1987. GTA estimated from CO_2 data is shown for the 1901–1987 period in Fig. 3.

DISCUSSION

To reconcile discrepancies between results from analysis of the short record and the long record, it is instructive to compare time series for GTA, CO_2, and Wolf SS for the entire long record, 1901–1987. Global warming data (GTA) and the fitted trend line are shown in Fig. 2. Notice the general warming trend from about 1920 until the mid-1950s, a period of apparent cooling from the mid-1950s to the mid-1970s, and the current period of apparent rapid warming from the mid-1970s to 1987. Over the entire record, there is a significant average warming trend of about 0·45 °C per century. However, it would be possible to select specific periods of 10–20 years in length from this 87 year record where one could infer increases, decreases, or no change at all.

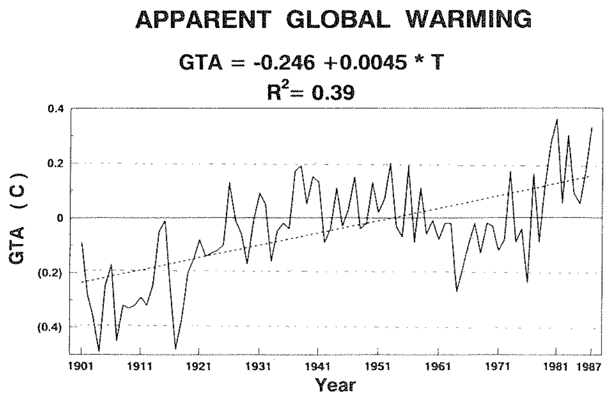

Fig. 2. Observed and fitted global temperature anomalies using time as the independent variable. ——, GTA observed; -----, GTA fitted.

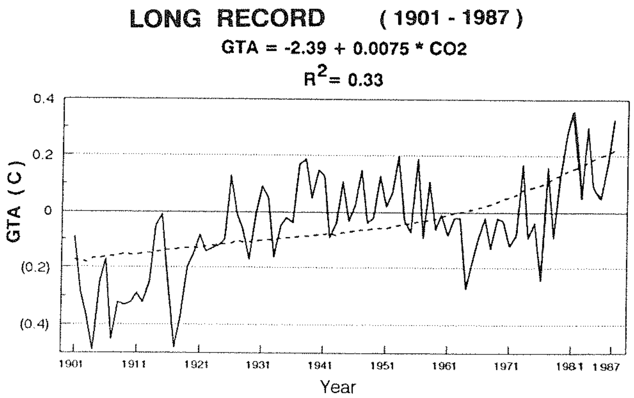

Fig. 3. Observed and fitted global temperature anomalies using CO_2 as the independent variable. ——, GTA observed; -----, GTA fitted.

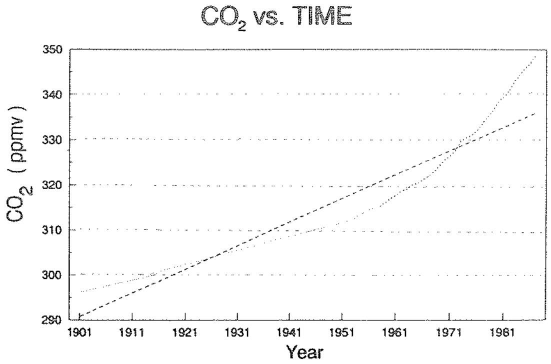

Fig. 4. Observed and fitted atmospheric CO_2 concentration data using time as the independent variable. ·······, CO_2 interpolated; -----, CO_2 measured; ——, CO_2 fitted.

The time series for CO_2 is shown in Fig. 4. Notice that the rate of increase during the 50 year period from 1901 through about 1950 was approximately linear and that there is an accelerating rate of increase from about 1950 to 1987. Over the entire 87 year period, the linear model is an inappropriate model to describe increases in CO_2 with time.

Wolf sunspot data for 1901 to 1987 are shown in Fig. 5. Notice the periodic behavior with a cycle of about 11 years, the apparent increase in magnitude of the peaks from 1901 to about 1960, and the apparent decrease from about 1960 to 1987. Correlation of Wolf SS with global warming exhibits a positive relationship for the entire period of record (Table 4) but not for the short record (Table 2). The reasons for this are apparent in Figs 2 and 5. Both Wolf SS and GTA increased over the entire 1901–1987 period, GTA apparently continued to increase over the period 1960–1987 while the magnitude of the peak Wolf SS apparently decreased over the period 1960–1987. Therefore, the correlation of the Wolf SS with global warming may be spurious depending upon the portion of the record examined. This finding is illustrated in Fig. 6. Notice that there are 10–20 year periods where the Wolf SS can be used to fit the GTA data but that overall using Wolf SS as an independent variable in the regression equation results in a poor fit (R^2 = 0·09).

In contrast, CO_2 concentration was highly correlated with GTA in the short record (Table 2) and in the long record (Table 4). The reasons for this are apparent in Tables 2 and 4 where CO_2 and time are highly intercorrelated and in Figs. 2 and 3 where regression on CO_2 produces nearly as much precision in fitting (R^2 = 0·33) the GTA data as does regression on time (R^2 = 0·39).

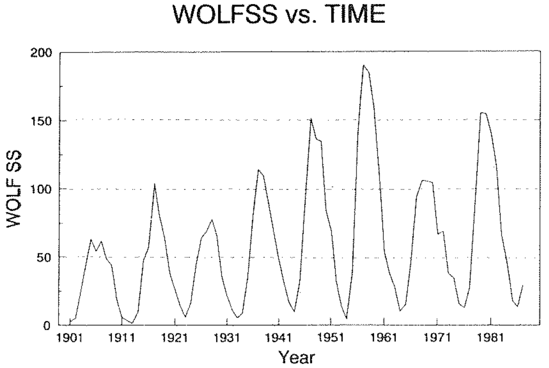

Fig. 5. Observed Wolf sunspot data. ——, Wolf SS.

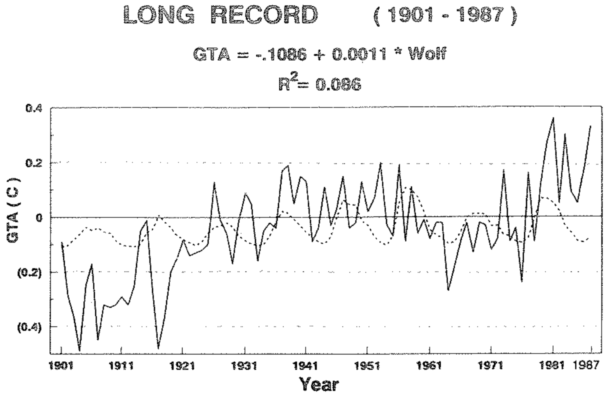

Fig. 6. Observed and fitted global temperature anomalies using Wolf SS as the independent variable. ——, GTA observed; -----, GTA fitted.

CONCLUSIONS

Correlation of sunspot data with global warming may be spurious. Additional analyses using longer record periods and alternative variables describing solar activity and sunspots will be needed to test this hypothesis.

Using procedures described herein, we may be able to statistically test the hypothesis of separability. Repeated acceptance (in the statistical sense) of this hypothesis would lend support to our efforts to separate natural from anthropogenic factors affecting global warming. If successful, these statistical methods would provide a useful adjunct to Global Circulation Model predictions.

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