INFLUENCES OF VARIOUS FORCING VARIABLES ON GLOBAL ENERGY BALANCE DURING THE PERIOD OF INTENSIVE INSTRUMENTAL OBSERVATION (1958-1987) AND THEIR IMPLICATIONS FOR PALEOCLIMATE

By: JOEL GUNN

1991. Joel Gunn. Influences of Various Forcing Variables on Global Energy Balance During the Period of Intensive Instrumental Observation (1953-1987) and Their Implications for Paleoclimate. *Climatic Change* 19:393-420.

Abstract:
Consistent, accurate, and numerous measures of global scale atmospheric variables have been collected since about 1958. A time series of 30 years duration was assembled to investigate contributing factors to the global energy balance. The El Nino-Southern Oscillation (ENSO), CO_2 changes, and variation in solar energy output account for a quarter or more each of the variability in global energy balance. Upper atmospheric aerosols contribute, but less significantly and in a more complex way. The analysis suggests a hypothesis that has hearing on global climatic stability. Global climate fortuitously passed through a shift from a warmer NH to a warmer SH during the study period. The ENSO appears to act as a hemispheric energy balancing mechanism. There were significant changes in global atmospheric function when the hemispheric energy balance shifted in favor of the Southern Hemisphere about 1966. When applied to past climates, hemispheric dominance of global climate and related patterns of periodic stability could explain the rise and fall of some complex hierarchical social systems.

Article:
Introduction
The years 1958 to 1987 were highly varied with respect to global climate and intensively observed by various surface and space based instruments. This 30 year time series is of sufficient duration to provide a sample of adequate length for statistical analysis. The great accuracy and thorough nature of the observations provides a basis for verification of long suspected relationships in the atmospheric system, and generation of hypotheses to be investigated by further research in modeling global climate, general circulation models, the retrodiction and prediction of climate, and the study of social impacts of global climatic change.

This paper pursues two objectives. The first is to discover the extent of regulation of the global energy balance by independent and quasi-independent forcing variables at the astronomical and global scales. The global energy balance (GEB, the difference between incoming solar radiation and outgoing energy radiated by the Earth (Budyko, 1977)) is measured as the average seasonal and annual temperature of atmosphere (Angell and Korshover, 1983). The analysis of the forcing variables and their effect on GEB suggests an important change in atmospheric and oceanic processes following 1966. The second objective is to examine evidence of similar transitions in the past. They appear to have implications for human impacts of climate change which have heretofore gone unnoticed.

The study illustrates new insights which can be gained from the interdisciplinary treatment of cultural change in the context of now much studied teleconnections between the climatic events in various parts of the world. Much more could be and will be done with the data than has been attempted in this article. Since it is intended for an interdisciplinary audience, the analysis methods are as uninvolved as possible but adequate. The only assumption that is made is some understanding of the purpose of regression. The calculation of regression coefficients between variables, in the presence of au idea or model about their relationships, provides measures of cause-and-effect and statistical estimates of the significance of those relationships given the sample sizes.

The Amount of GEB Variation Since 1958 and Its Potential Uses

Thanks to the thermodynamic character of the earth's fluid envelope (Budyko 1958, 1974, 1977; Kasting et al., 1988), the global energy balance is correlated with the pattern of currents in the atmosphere and oceans. The currents in turn dictate the distribution -if temperature and moisture on the earth's surface. The GEB is therefore a useful index for a number of purposes, including modeling of past and future climates and estimating regional climatic changes.

The amount of variability of annual GEB in the decades between 1958 and 1987 was found by Angell and Korshover (1983; Kerr, 1985) to be about 1 °C. That can be compared roughly to the last 1000 years. Bergthorsson (I 969) estimated a two degree C. variation in Icelandic temperatures since the 10th century AD. The Little Climate Optimum (AD 900-1250) was warmer than the present century. Episodes of the Little Ice Age (AD 1250-1900) were colder. If Icelandic annual temperatures are assumed to approximate the average annual temperature of the Northern Hemisphere (Bryson and Murray, 1977: 47-53, see Schneider and Londer 1984: 269ff for other measures), the 1958-1987 GEB variations range over approximately the middle half of that of the last 1000 years. The variation of the GEB since 1957 may provide important information on the processes of past climatic variation, but in much greater detail than they can be observed in the distant past.

Furthermore, the atmosphere was in a transient rather than an equilibrium state during the study period. The disequilibrium should expose the relationships between forcing variables and GEB to analysis of cause-and-effect by regression.

The transcience of increasing GEB levels, apparently caused by humans adding CO_2 and other trace gases to the atmosphere, has become a matter of global concern. While not detracting from the urgency of the global warming problem, it should also be noted that global warming provides a laboratory for studying the processes of climatic change. It is equally likely that the study of past climates, some of which were warmer and changed with equal rapidity as currently being experienced, will provide answers to some of the questions being asked about future conditions.

Potential Causes of Late 20th Century GEB Variation

The greater the range of causal forces active between 1958 and 1987, the more likely it is to represent the variety of forces acting to alter the GEB in the past. Fortunately there were numerous potential sources of variation in the GEB during the study period.

1. Solar energy output variation was measured (Willson et at., 1981, 1986) which presumably changed the amount of incoming energy.
2. Volcanic eruptions injected debris into the upper atmosphere blocking incoming radiation (Rampino and Self 1984).
3. There were several El Niño-Southern Oscillation (ENSO) events (Rasmus- son, 1985). While ENSO does not change the amount of energy in the system, it does restructure timing of the movement of energy from low to high latitudes (Ropelewski and !pert. 1986). Energy stored in the equatorial oceans is in-
   dependent of the atmosphere because the atmosphere has little ability to remove excess heat from the ocean within five degrees latitude of the equator. The ENSO is therefore an independent oceanic process until warm water is released to higher latitudes where the energy can be picked up by the atmosphere. There will be more on this later.
4. Finally, a substantial increase in carbon dioxide and other trace gases in the atmosphere was recorded (Keeling, 1978).

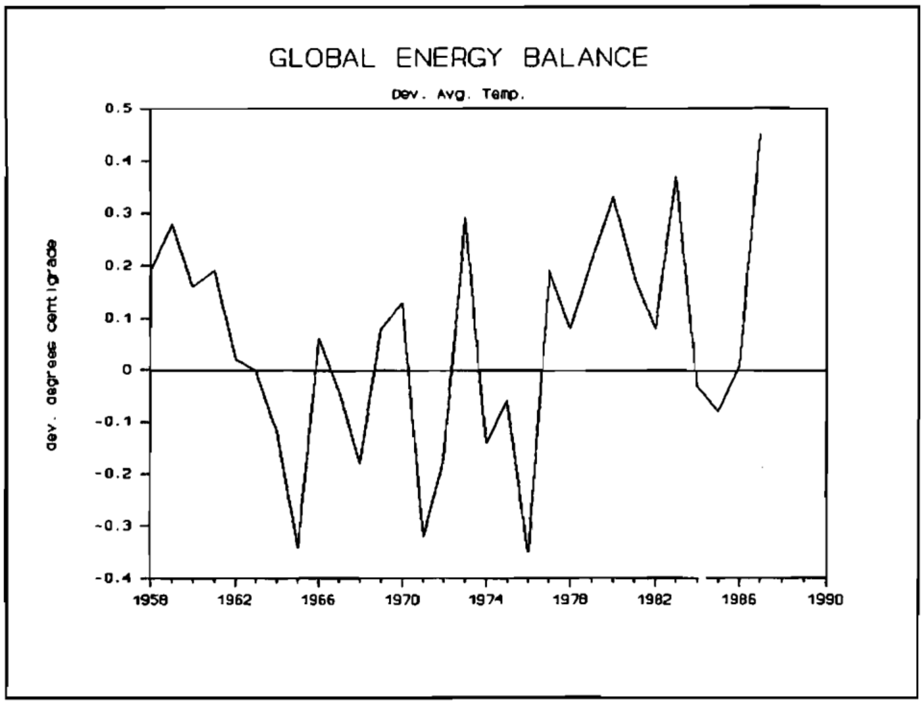
This list of forcing variables is probably a minimal but adequate set of radiation balance controls. As a first approximation, the objective was to identify enough major system contributors so that the majority of the variance would he accounted for (the minority of the variance would be in the error term). In most of the analyses this list of forcing variables accounts for more than 60% of the variation in global energy balance. Gilliland (1982) used a similar suite of variables.

Estimators of Global Energy Balance and Forcing Variables

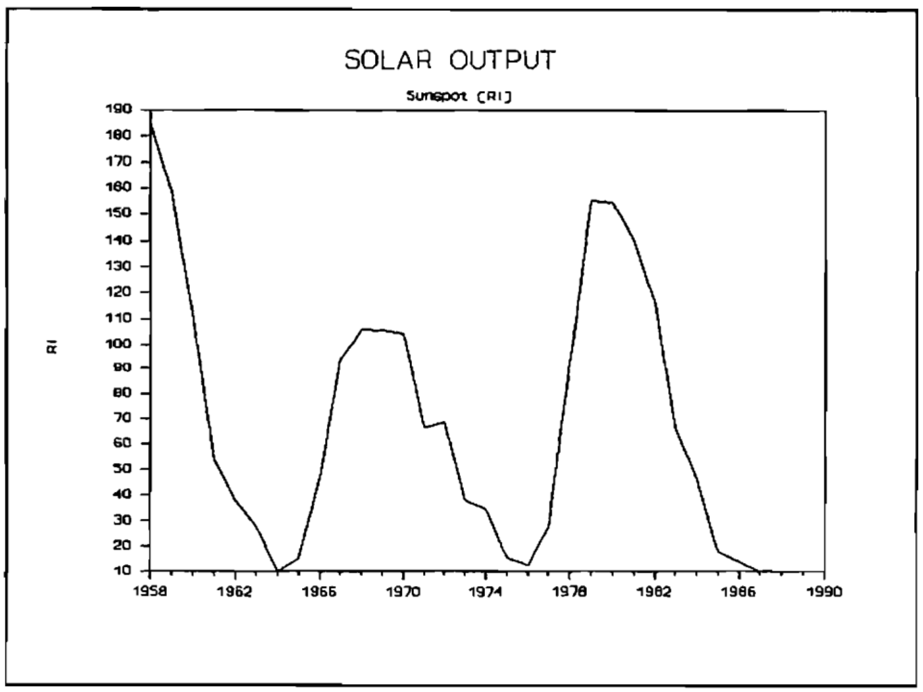
A globally integrated estimate of GEB, and measures of the four major forcing variables identified in the previous section were used. The source and character of each estimator is discussed in this section.

The Global Energy Balance

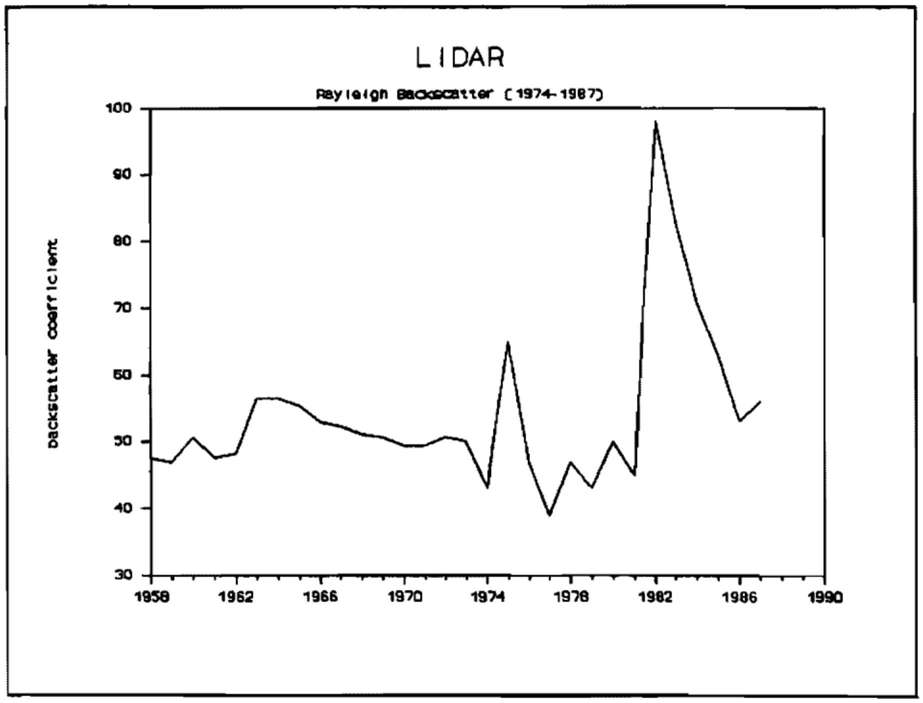
In 1956 a program of launching balloons with weather observation instruments (radiosonde) was instituted around the world. Balloons were lofted twice daily at 00h00 UTC and 121100 UTC and sometimes rose to a hundred thousand feet or more. During their ascent they measured temperature, humidity, pressure, and


GLOBAL ENERGY BALANCE
Dev. Avg. Temp.
dev. degrees centigrade
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
1958
1962
1966
1970
1974
1978
1982
1986
1990

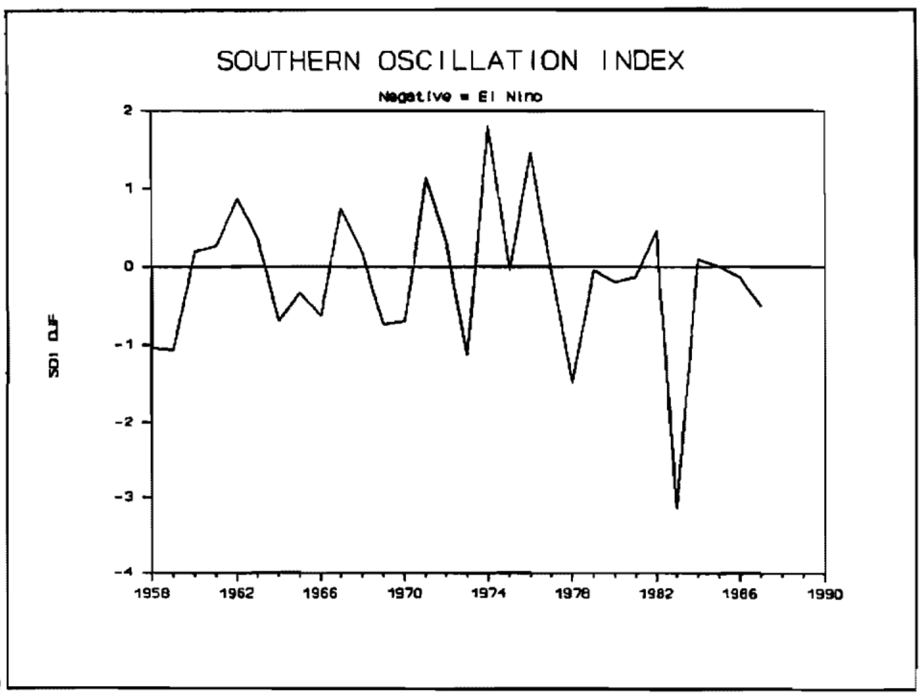
(a)


SOLAR OUTPUT
Sunspot (RI)
RI
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
1958
1962
1966
1970
1974
1978
1982
1986
1990

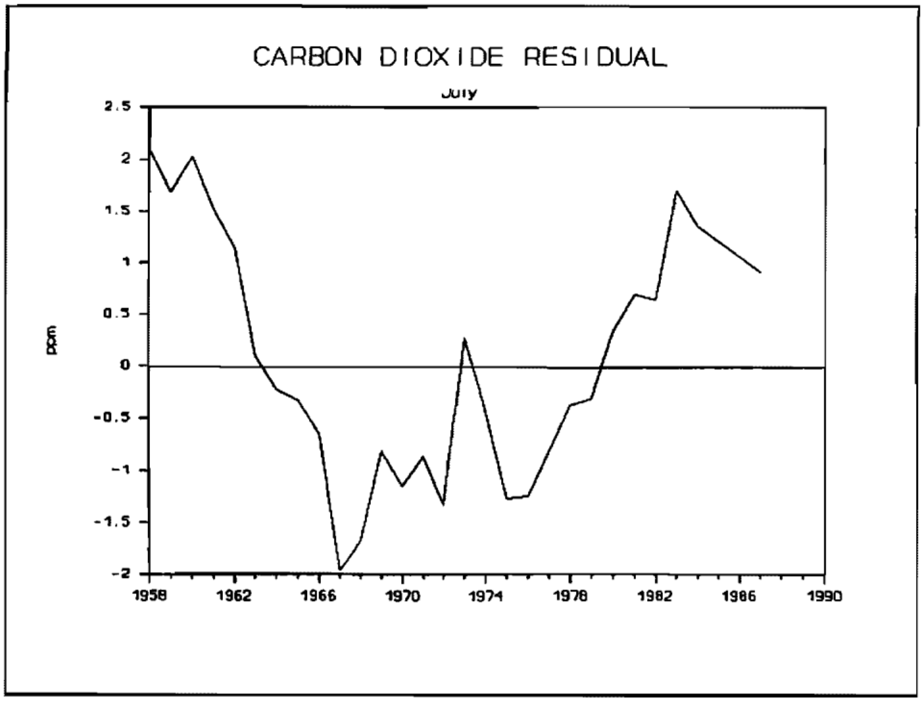
(b)


LIDAR
Rayleigh Backscatter (1974-1987)
backscatter coefficient
100
90
80
70
60
50
40
30
1958
1962
1966
1970
1974
1978
1982
1986
1990

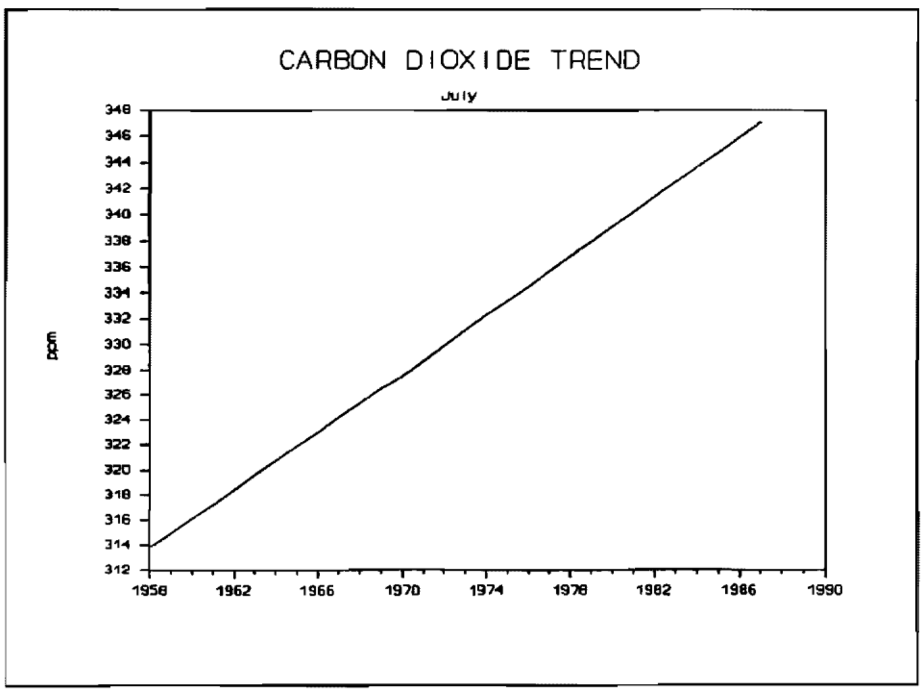
(c)


SOUTHERN OSCILLATION INDEX
Negative = El Nino
SOI DJF
2
1
0
-1
-2
-3
-4
1958
1962
1966
1970
1974
1978
1982
1986
1990

(d)



(c)



(f)

Fig. 1. Time series for (a) global energy balance, (b) solar output, (c) atmospheric debris, (d) Southern Oscillation Index, and July carbon dioxide broken down into (e) long term trend, primarily of anthropogenic origin, and (f) residual fluctuations. See the text for explanations and sources.

winds, and transmitted the data back to receivers on the surface. These data have been reduced to estimates of global energy balance by Angell and Korshover (1983). They published a series of articles (1975, 1978, 1983, 1984) tracing changes in the GEB.

Angell and Korshover's data were assembled from 63 stations around the world selected to represent all latitudes from pole-to-pole. Station deviations were calculated from a 1958-1970 mean. The station deviations were composed from surface temperature in degrees centrigrade, and the 850-300 mb and 300-100 mb thicknesses converted to degrees centigrade by a hydrostatic equation. The three values were weighted 15, 55 and 20 respectively.

These data were thought to provide a thorough measurement of the total energy resident in the atmosphere, i.e. the global energy balance. As such they were a carrier of whatever climatic change signal was active in the earth system: oceans and land in addition to the atmosphere. Furthermore they were a carrier of appropriate time scale to study climatic change for a period of 30 years. Deep ocean temperatures respond to forcing in decades while land surfaces respond in days. The atmosphere is influenced both by land and ocean but responds to forcing in about a month (Rampino and Self 1984). The Angell and Korshover deviations were an integrated measure of the climatic status of the system.

The variability of GEB is demonstrated in Figure 2. It is a histogram of the annual global temperature variations. For convenience of reference, frequency modes in the distribution have been labelled 'hot', 'warm', 'cool', and 'cold'. Since cool years are the most frequent, the climate of the study period overall would be characterized as 'cool'. A globally 'cold' climate such as the Little Ice Age (AD 1250-1900) would have a preponderance of cold years. 'Hot' GEB years were probably analogous to hotter Holocene episodes such as the Little Climate Optimum (AD 900— I 250).

The 30 year time series of global energy balance is plotted as cumulative deviations in Figure 3. Cumulative deviations accomplish the smoothing of time series without obscuring abruptness or gradualness of significant changes, extreme events, exact year of an abrupt event, or existence and precise duration of clusters of extreme years (Bell, 1981: 271). The cumulative deviations reveal that the years before 1963 and after 1977 tend to be warmer and less variable, while the intervening years are cooler and more variable.

TABLE I: Key to global energy data labels

SM	Greater Solar Maxima
Sm	Lesser Solar Maxima
Ni	El Niño-Southern Oscillation (ENSO)
Ag	Mount Agung eruption (Lesser Sunda Is. 17 Apr 1963)
Ch	El Chichon eruption (Mexico, March-April 1982)
Ru	Ruiz eruption (Columbia November 1985)
Nu	Maximum of atmospheric nuclear weapons testing
Si	The year of the very unusual winter 1976, the Siberian Express

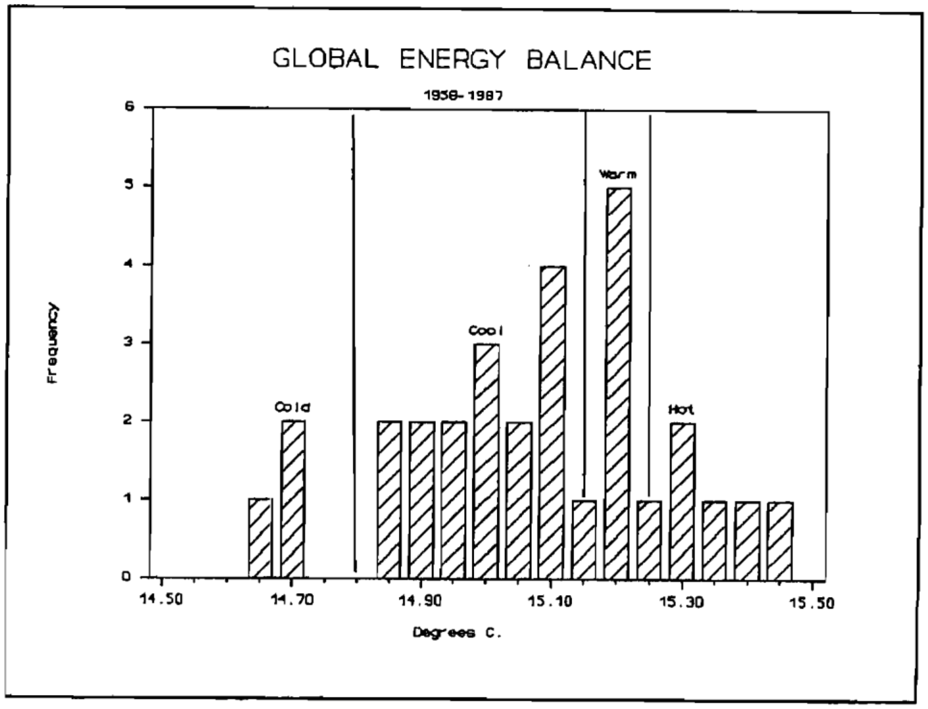


Fig. 2. Histogram of annual global energy balance for the period 1958–1987 (data supplied by J. Angell, Air Resources Laboratory, Rockville, MD).

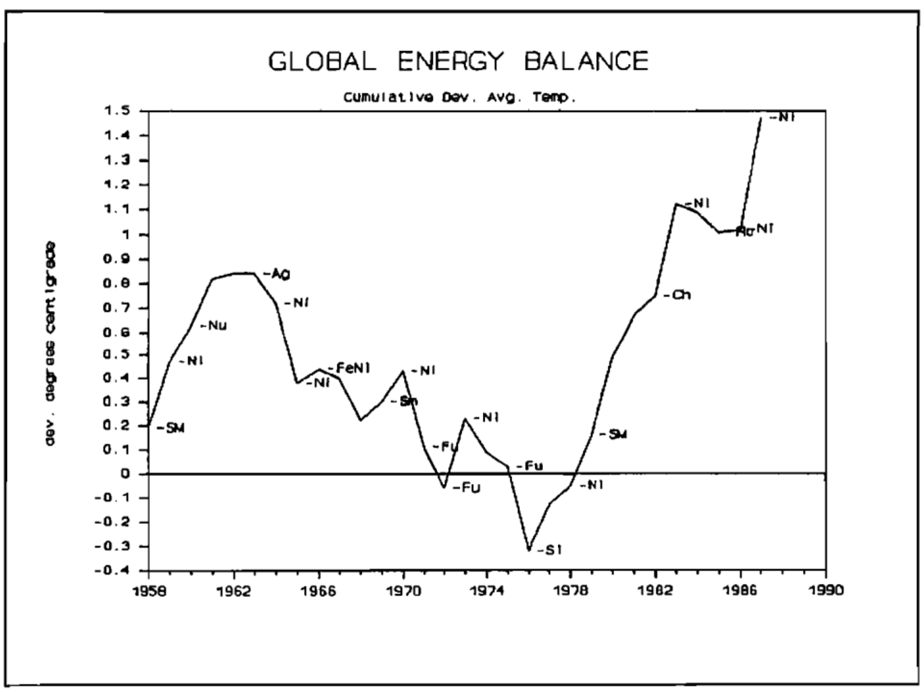


Fig. 3. Global energy balance cumulative deviations for 1958–1987. The meanings of the data labels are listed in Table I (data from J. Angell).

Solar Radiation and GEB

A satellite was launched in 1980 to measure the energy output of the sun. Analysis of the data determined that solar energy output varies from day-to-day and that sunspot numbers are a reasonable measure of that variation (Willson et al, 1981, 1986) for a portion of the spectral emissions. There are other effective measures of solar energy output, but annual average sunspot numbers were used. Their selection anticipates historical studies as the sunspot numbers have been observed consistently since 1749 at Zurich, Switzerland, and so can be used to extend knowledge of solar variation into the past. Values used were mean annual International Sunspot Numbers (R_1) published in January 1987 *Solar-Geophysical Data: Prompt Reports* (p. 11).

The relationship between solar radiation and climate has been long debated. Despite continuing controversy, numerous articles have appeared in the solar-terrestrial literature in the last few years with statistically convincing results linking variations in solar output with specific atmospheric functions and even geophysical phenomena. Nastrom and Belmont (1980) demonstrated that the speed of the jet stream correlates with sunspots. Labitzke and Van Loon (1988) have found a correlation between 2800 MHz solar output (which is highly correlated with sunspots) and high latitude temperatures. Droughts in the western US have been linked to

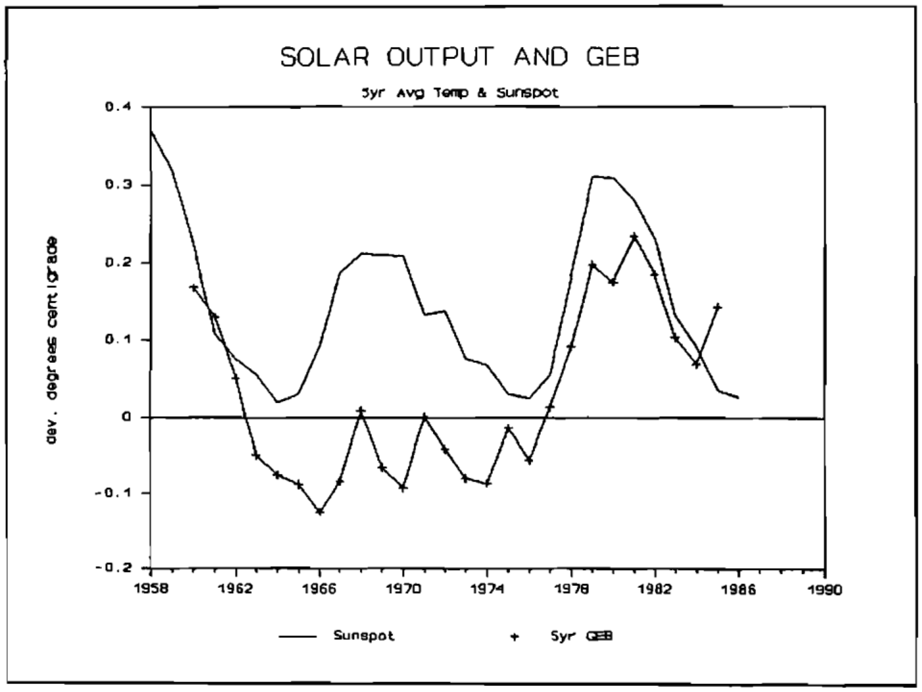


Fig. 4. Five year running average of global energy balance 1957–1987 (Angell and Korshover, 1984) and sunspots (R_i, *Solar-Geophysical Data: Prompt Reports*, November 1986).

sunspot numbers (Mitchell et al.. 1979; Stockton el al., 1985), especially the 22 year Hale Cycle. It appears that the mechanism of the Hale solar cycle has been identified (Wilson et al, 1988). and perhaps the ultimate causes (Landscheidt 1987).

The trend of the GEB curve follows the 22 year Hale Cycle (Figure 4). The GEB time series is smoothed with a five year running average. The running average hides the approximately five year ENSO signal and exposes signals in GEB response greater than five years. The cumulative deviations (Figure 3) indicate that GEB maintained positive movements for three years after the greater maxima (-SM) of the Hale Cycle.

Volcanism and the GEB

Lamb (1970), Schneider and Mass (1975), Pollack et al (1976), Bryson and Goodman (1980), Stommel and Stommel (1979) and many others have argued that eruptions which inject debris into the stratosphere influence GEB. In fact, many studies argue that this is the most potent of the currently active forcing variables (Gunn, 1982). Following a relative cessation of volcanism in the early 20th century, several events were observed during the study period.

The best recorded and studied was the El Chichon (Mexico, March-April 1982) eruption (Rampino and Self, 1984). Satellites recorded the dispersion of the cloud of debris as it girded the globe. Balloons were lofted from Laramie, Wyoming, to collect specimens of debris (SEAN Bulletin 1986). Surfaee-based laser radars (lidar) measured the details of quantity and elevation of the debris in Virginia, Japan, Germany and at Mauna Loa, Hawaii (SEAN *Bulletin* 1987).

In this analysis integrated lidar backscatter from the Mauna Loa observatory (I 9°32'N, 155°35'W, 3400 m MSL) is used. Annual values of non-Rayleigh backscattering coefficient integrated over 300 m intervals for 16-33 km (Robinson and DeFoor 1988; DeLuisi et al., 1984) were read from a 1974-1987 graph (Robinson and DeFoor. 1988, all Mauna Loa data can now be obtained from National Geophysical Data Center, NOAA, NESDIS E/GC4, 325 Broadway, Boulder CO 80303.) Annual values were based on multiple monthly observations, usually between 3 and 20 (DeLuisi et al., 1984). Values before 1974 were determined by least squares estimate from solar radiation transmission measured at Mauna Loa (Robinson and DeFoor, 1988). The estimate was calculated on the overlap between 1974 and I 985, and the equation applied to the 1958-1973 transmission data.

There have been thirteen eruptions which are thought to have injected aerosols into the upper atmosphere since lidar measurement began on Mauna Loa in 1974. The result has been a substantial increase in background stratospheric aerosols (Robinson and DeFoor, 1988). The two largest eruptions, Agung (Lesser Sunda Is, 17 April 1963) and El Chichon (Mexico March-April 1982, Rampino and Self 1984, Angell and Korshover 1984), precipitated decreases in the GEB (Figure 3a). The effect of El Chichon is somewhat obscured by a subsequent hot year which was coincident with a major solar maximum.

El Niño-Southern Oscillation and the GEB

Satellite and surface measures were made of the vast and relatively unknown tropical Pacific. They revealed the structure of the El Niño-Southern Oscillation phenomenon which periodically brings warm water to the eastern Pacific, as well as an extended array of teleconnected regional weather to near and distant parts of the globe.

Once ignored as a tropical peculiarity, the Pacific ENSO has become an important topic of research in the last few years, and is now considered to be a major global climatic controlling mechanism (Rasmusson, 1985). In fact, it appears that the ENSO effect is so powerful that climate modeling is not possible without it. There are both antecedent teleconnections to ENSO, in Eurasian snows (Barnett et al, 1988), and myriad succeeding conditions around the world (Rasmusson, 1985; Nicholls, 1987), and in North America (Ropelewski and Halpert, I 986).

The southern oscillation index provides an estimate of the ENSO effects (Rasmussen, 1985. *Climate Diagnostics Bulletin* March 1986 and subsequent issues). In this study the indices for December, January, and February were averaged to form an estimate of ENSO activity since it tends to maximize in the months following Christmas. The index is a measure of the intensity of an ENSO event by means of atmospheric pressure in the central and western Pacific. (Calculation of the southern oscillation index is discussed in the *Climate Diagnostics Bulletin* March, 1986). ENSO is in progress when the index is negative.

Several ENSOs occurred during the study period, but as with volcanism, there is an extraordinary specimen of ENSO for investigation. The El Chichon eruption was followed by the grandest ENSO event of the century, and perhaps in the last 450 years (Woodman, cited in Rasmussen, 1985), which produced wide ranging (teleconnected) atmospheric and human impacts (Glantz et al, 1987).

The Pacific is a potent factor in world climate because of its vast area and the ability of water to accumulate energy efficiently. The Pacific stores so much energy that it is a quasi-independent global climate forcing mechanism itself. It acts as an oscillator or capacitor to global energy balance. Teleconnections from Pacific-originated climatic events are being investigated as a means of predicting climate over large portions of world (Nicholls, 1987).

Atmospheric Carbon Dioxide

Finally, the amount of carbon dioxide and other trace gases in the atmosphere was carefully monitored from Mauna Loa Observatory. July 15 measures in parts per million were used. Observations were taken continuous by nondispersive infrared CO_2 analyzers (Keeling, 1978). A NH summer month was selected because it is the time of the year when NH biota are maximally actively drawing down CO_2. The CO_2 observations were separated into a least squares trend (Figure 2e) and a residual (Figure 2f) or short term fluctuations (R^2 = 0.99). The trend is probably produced by progressive anthropogenic pollution for the most part. The short term fluctuations vary with the GEB and are probably largely natural. The notable negative inflection following 1973, however, reflects reduction of pollution following the OPEC oil crisis.

During and since the Pleistocene there have been natural changes in the CO2 levels in the atmosphere (Neftel et al., 1982). In the last century there has been an approximately 25% increase in CO-, which is attributed to human sources (Sehneider, 1987). Humans have taken a position with the sun as an independent controller of GEB by releasing atmospheric pollutants. The question of the effects of humans taking a place 'with the sun' rather than in the sun' is an important one. However, there have been equivalent events in the past caused by volcanic eruptions.

Global Forcing Variables as a Multicausal System Controlling GEB
This section is concerned with the problem of whether the proposed forcing variables measurably affect the GEB. Two tests were conducted. The first was one way analysis of variance (abbreviated ANOVA, a form of regression, Blalock, 1972: 317ff, Wilkinson, 1988: 484ff) which tests the significance of differences in forcing variable means by categories of GEB climates (see Figure 2). The second test was multiple linear regression which treats all of the variables as an interaetive system. Each method has advantages, and the two together complement and check each other. ANOVA will show simple but powerful relationships between GEB and the individual forcing variables. Since ANOVA utilizes nominal categories as the independent variable, non-linear relationships will be revealed. The ANOVA provides a conservative check on the regressions for curvilinear relationships.

Multiple linear regression will be used to investigate complex relationships between all of the forcing variables treated simultaneously. In a complex multi- causal system, statistical analysis of relations between individual forcing variables and GEB, (such as the ANOVAs) should be viewed with caution. The unincluded variables all appear in the residuals as unaccounted for variance. Unless the included variable accounts for a very large proportion of variance by itself, a low percentage of variance accounted for automatically results, and an insignificant F-statistic, even though the variable may be making a reasonably important contribution to GEB variations, Analysis as a multivariable system partials the forcing variables (removes mutual or redundant influences), eliminates various masking conditions (Blalock 1972: 443ff, see Labitzkc and Van Loon (1988) for an interesting example of masking), and shows the contribution each makes to the whole system.

TABLE II: Analysis of Variance statistics on global energy (split into four categories, hot, warm, cool, and cold climate, see Figure 2) relations to forcing variables

	One way analyses of variance (ANOVA)			
	R	R^2	F-value	p
Solar	0.48	0.23	2.6	0.074
Lidar	0.34	0.12	1.1	0.353
ENSO	0.58	0.33	4.3	0.013
CO_2 Residual	0.55	0.31	3.8	0.022
CO_2 Trend	0.26	0.07	0.6	0.613

ANOVA
Analyses of variance were calculated between individual forcing variables and GEB (Table 11). The GEB was categorized into four classes, 'hot', 'warm', 'cool', and 'cold', as discussed above (Figure 2). ENSO, CO_2 Residual, and solar output were powerful enough to emerge for the multicausal system. ENSO and CO_2 each account for about a third of the movement of the GEB, while solar output accounts for about a quarter of the variance in GEB. The relatively significant F-values (<0.1) serve to demonstrate that the relations are real rather than merely an artifact of chance, autocorrelation, or apparent rather than real differences in scale. The low

significance of atmospheric debris (lidar) and CO_2 does not mean that they were not active in the system, but that their relations to global energy balance may he more complex, curvilinear or masked correlations. The fact that the five analyses add up to more than 100% of variance in GEB accounted for indicates some spurious correlation and the need for partialing. Both unmasking and partialing were accomplished by multiple linear regression (Blalock, 1972: 443ff).

Multiple Linear Regression

Three multiple regression analyses are shown in Table III. Standardized regression coefficients and percents of variance were calculated to provide global and hemispheric perspectives. All regressions were of the form:

$$\mathrm{GEB} = a + b_1\,\mathrm{Solar} + b_2\,\mathrm{Lidar} + b_3\,\mathrm{ENSO} + b_4\,\mathrm{CO_2\ Residual} + b_5\,\mathrm{CO_2\ Trend},$$

where 'a' is a constant term and'$b_1 b_5$- are regression coefficients. In Table III standardized regression coefficients are presented for relative comparisons of contributions.

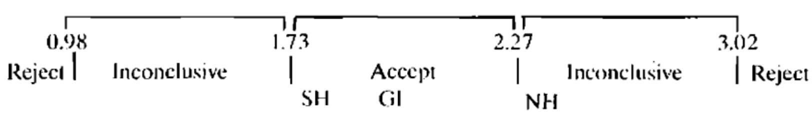
The global analysis (Table III; 1) provides a point of comparison for the other two analyses, an analysis of all space and all time in the study interval. The global regression equation is significant at $p < 0.001$. The five variables included in the

TABLE III: Global and hemispheric multiple linear regression analyses of GEB and forcing variables: constants (Const), standardized regression coefficients (Solar, Lidar, ENSO, CO_2 Residual and Trend, with students t probabilities under each), percent of variance in GEB accounted for (%Var), standard error (StdEr), F-value (F), and probability (p), and Durbin-Watson statistic (D-W)

Const	Standardized – Regression Coefficients –					%Var		StdEr	F	p	D-W
	Solar	Lidar	ENSO	Resid	Trend						
1. Global											
−1.37	0.37	−0.28	−0.35	0.38	0.22	0.63	0.14	8.2	<0.001	1.97	−0.04
p =	0.01	0.04	0.02	<0.01	0.10						
2. Southern Hemisphere											
−3.56	0.42	−0.32	−0.27	0.30	0.50	0.67	0.14	9.9	<0.001	1.77	0.06
p =	<0.01	0.02	0.05	0.03	<0.01						
3. Northern Hemisphere											
0.90	0.23	−0.18	−0.43	0.42	−0.11	0.63	0.16	8.0	<0.001	2.31	−0.19
p =	0.11	0.19	<0.01	<0.01	0.40						

Key: Solar – R_z, *Solar-Geophysical Data: Prompt Reports*, Jan 87, #509: 11.
Lidar – Integrated non-Rayleigh backscatter coefficient from Mauna Loa, *SEAN Bulletin* **12 (9)**, 11. Before 1974 values were determined by least squares estimate atmospheric transmission (Robinson and DeFoor, 1988).
ENSO – Southern Oscillation Index, *Climate Diagnostics Bulletin*, Mar 86 and subsequent issues. Negative values indicate an active ENSO.
Resid/Trend – Carbon dioxide measured at Mauna Loa on 15th of the July, data supplied by C. Keeling, Scripps. Least squares residuals were used for Residual values; Trend is the long term increase in CO_2, expected values.

Durbin-Watson Test for Serial Correlation
H_0: error terms are serially independent.
Critical Values for 95% Confidence Levels
(30 cases, 5 parameters, Rao 1971: 122, 228)



SH = Southern Hemisphere, Gl = Globe, NH = Northern Hemisphere

equation account for 63% of the variance, so the goal of accounting for the majority of the variance in GEB was achieved. (There is some curvilinear relationship between GEB and the lidar measurement as well as the CO_2 Trend. Polynomial terms yield a better R^2 but not a better corrected R^2. if theoretical explanations can be found for these relationships, future analyses should be directed at this problem.) The Durbin-Watson statistic (Rao and Miller, 1971: 122-123) indicates that the residuals are serially independent (see Appendix for residual plots and discussion).

Students t probabilities under each standardized regression coefficient in Table III indicate the statistical significance of each forcing variable coefficient. CO_2 Trend was least active at the global scale but short term CO_2 Residual variations Were most influential on GEB.

Comparing the hemisphere analyses (Table 111; 2, 3) to the global analysis (1) shows some interesting shifts of emphasis.

(1) The SH is more influenced by solar energy. This is reasonable since it has more ocean to store incoming radiation.
(2) The NH is more influenced by the ENSO than the SH. This supports the hemispheric balance model (see below); as the NH differs from the SH, the ENSO injects heat into the NH to balance it.

(3) Atmospheric debris (lidar) is not an effective predictor of GEB in the NH at the temporal and spatial scale of this analysis. This is contrary to qualitative observations (Rampino and Self 1984, Goodman 1987) and should be given future attention. There is, however, measurable effect on the SH.
(4) The SH is strongly influenced by the long term trend toward increasing CO_2; the NH responds to short term flux in CO_2. This supports the inference made in point 1, that the southern oceans were storing the heat accumulated by increased CO_2. It also implies that CO_2 greenhouse effect is not yet pervasive enough to affect the whole world on a sustained basis, only the SH.

The percent of variance accounted for changes from analysis to analysis. The NH has the lowest accounted for variance. In the NH either there were additional variables active, or there is measurement error in the variables used, or both. The most likely source of unspecified variables is in the point-location of the aerosol measures taken at Mauna Loa. The aerosols were not evenly distributed over the globe at any one time (SEAN, various since 1983). There also appear to be differential effects between high and low latitude volcanos (Goodman, 1987) which need to be investigated and accounted for. A second likely source of error is in the lack of correlation between El Nino and the southern oscillation index (Deser and Wallace. 1987).

A Systemic Change in the Global Climate: The 1966 Threshold and Hemispheric Dominance of Global Climate

Having established a set of relationships between forcing variables and GEB, this section attempts to take advantage of the transient nature of the 1958-1987 climate to suggest the character of some global climatic processes and their implications for interpreting past climatic changes. Observing more extreme climates in the Holocene in the context of this model will illuminate them, assist in predicting the effects of global warming.

In 1966 the hemispheric energy balance shifted in favor of the Southern Hemisphere (Figure 5). It has been known for some time that the NH and SH behave differently with respect to their average temperatures (Angell and Korshover.

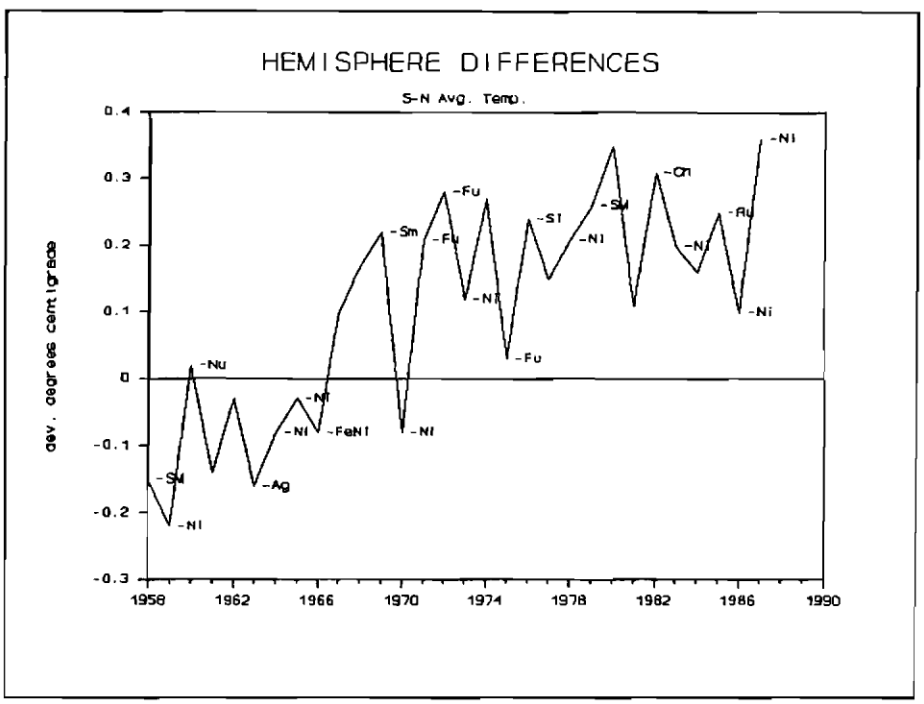


Fig. 5. Average annual temperature of Southern Hemisphere minus Northern Hemisphere (data from J. Angell).

1975). Figure 5 shows the SH subtracted from the NH. Until 1966 the SH was generally cooler than the NH. After 1966 the SH became noticeably warmer than the NH.

The physiography of the two hemispheres suggests the meaning of this divergence. The NH, being the more terrestrial hemisphere, responds rapidly to external forcing of its average temperature. The SH, being the hemisphere of water, responds slowly because it stores energy in its vast oceans. Notice that in the year following solar maxima the hemispheric energy balance is driven toward the NH (down), as would he expected in response to increased incident heat on NH terrestrial surfaces.

The shift in hemispheric energy balances indicates a fundamental change in global climate in 1966. Comparing the regression analyses suggests a shift from an early system state dominated by incident heating and driven by the NH process as they quickly responded to solar energy variation and volcanism. The later system state is one of accumulating heat, a process dominated by the SH. Since, once established in 1966, the trend dominates solar cycles and the global temperature nadir of 1976, it appears that the accumulating heat balance of the SH became more important than the periodic phenomena in the global climate system.

Even though the hemispheric balance threshold appears to have been crossed in 1966, a secure trend in SH temperatures was not established until 1976. Figure 6 is

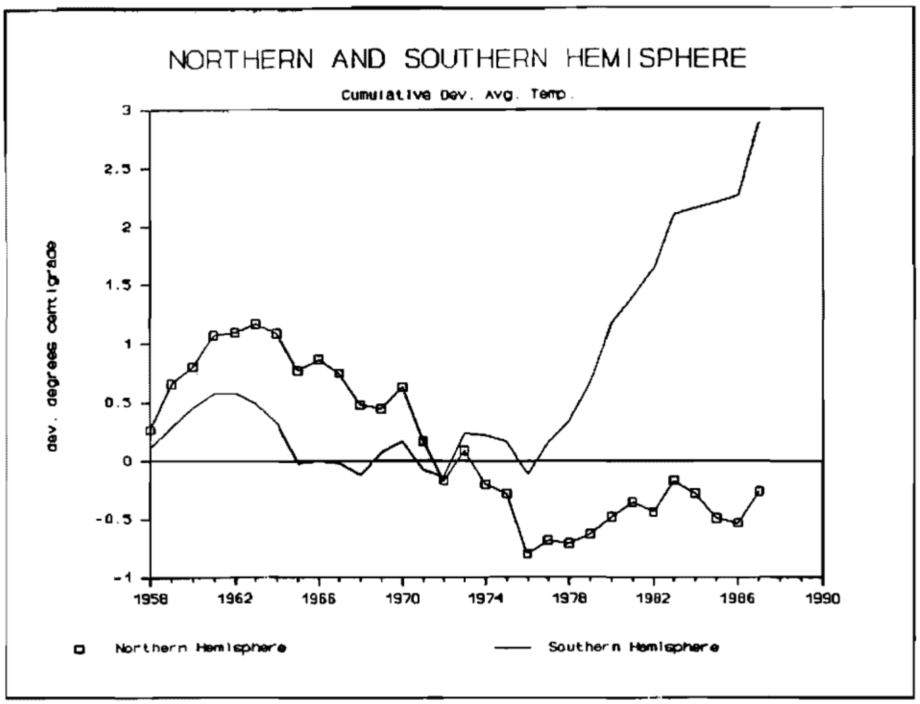


Fig. 6. Cumulative deviations for the Northern Hemisphere and Southern Hemisphere.

the cumulative deviations for the hemispheres. Their histories are clearly inverse. Before 1976 the SH shows a random walk in response to various perturbations. After 1976 it displays a monotonic increase in temperature. The cumulative SH effects were quite large and account for Jones, Wigley and Wright's (1986) finding three of the hottest five years in the last century in the 1980s.

The NH cools through the early period following the 1963 Mount Agung eruption. After 1976 it assumes a random walk pattern. This again indicates that the now-warmed SH is dominating late-period climatic processes. The ten year lag from the 1966 threshold to the 1976 accumulation trend changeover between hemispheres suggests a ten year lag in ocean warming. This is a hypothesis that needs to be examined as the rate of change in the oceans and their influence on the atmosphere is still an unresolved but very important question relative to global climatic stability.

The Hemispheric Balance Hypothesis: ENSO as a Hemispheric Energy Balancing Mechanism

Perhaps the most important information that this analysis offers is that the ENSO serves a twofold purpose: one, as was previously thought, to dispel heat from the tropical Pacific, and secondly, a previously undetermined temperature equalization function between the hemispheres.

The idea that ENSO dispels heat from the equatorial Pacifie was recently proposed by Cane and Zebiak (1985, Graham and White 1988: 1296, discuss the reasons for the success of the Cane and Zebiak model and compare it to others). Their model correctly predicted the 1986-1987 ENSO event (Kerr, 1986b, Climate Diagnostic Bulletin, various 1986). Hurricanes also dispel excess heat from the tropics. The hurricane process picks up great amounts of energy from the ocean surfaces and propels it poleward as sensible or latent heat (Barry and Chorley, 1968; Henderson-Sellers and Robinson, 1986). Hurricanes, however, can only form outside five degrees latitude because Coriolis Force is too weak at the equator to initiate spin (Wendland, 1977).

Since hurricanes cannot form, inside five degrees latitude, which students of ENSO call the 'wave guide' (Rasmusson, 1985: 175), the ENSO process performs this function. Cane and Zebiak (1985) developed a physical model of the Pacific basin ENSO which assumes that following an ENSO the waveguide energy reservoir is empty. (ENSO-like phenomena also appear in the Atlantic (Philander, 1986) and Indian (Flohn, 1 988) Oceans). As years pass, energy accumulates. When the water inside the wave-guide is above average temperature, and the normal late summer and fall (NH) changes in ocean currents occur along the west coast of South America, a stronger than usual flow of water eastward along the equator begins. This water splits at equatorial South America and flows poleward along the North and South American coasts. The ENSO of 1982-1983 was so powerful that it interrupted weather and ocean ecology all the way from Alaska to southern Chile (Rasmusson, 1985; Fiedler I984). Terrestrial impacts were even more widespread (Glantz et al., 1987).

That the ENSO acts secondarily to equalize temperatures between the hemispheres is suggested by this data analysis. In Figure 5 all cases of ENSO were associated with a reduction in the temperature discrepancy between hemispheres either in the year during or immediately after the event. In the Cane and Zebiak (1985) model of ENSO the warm tropical waters flow first to the east along the equator and then poleward along the shores of the Americas. It seems possible that, in addition to dispelling energy from within the wave-guide, the ENSO evens the distribution of energy between the hemispheres by splitting the heated waters proportional to the temperature differential between the hemispheres.

Support for this hypothesis resides in the history of development of ENSOs during the study period. Before the 1982-1983 event, ENSO was thought to be a predominantly SH phenomenon. This was because the SH-dominated global climate pattern had not yet fully developed. Casey et al. (1988) report a particular type of 'weak' ENSO in 1964 in the San Diego Basin. However, the appearance of 'strong' ENSO effects in the NH in 1982-1983 and the coincident reduction of difference between the temperature of the hemispheres (Figure 5), suggests that the waters split in proportion to the temperatures between the hemispheres that had developed by 1982. The effect was to equalize the hemispheric differences. Also, the 1964 ENSO produced an equalization in the opposite direction toward the SH.

Implementation of Forcing Variables in Pre-instrumental Periods

Since this paper is concerned with refined insights into climates of the past through the study of current conditions, the question may arise as to whether the same system of variables could be studied in pre-instrumental periods. No attempt will be made to demonstrate applications to paleoclimate as this has been done elsewhere (Gunn, 1990; Gunn and Crumley, 1989). However, means of implementing the model can he discussed briefly. The forcing variables can be measured by any number of pre-instrumental climatic proxy measures in the Holocene. For example, Eddy (1977, 1986) points out that solar activity can be traced into the past 8000 years by various means, among them radiocarbon date corrections. Solar activity variation is reflected in atmospheric radiocarbon because solar activity modulates cosmic ray flux, which in turn generates C_{14}.

Volcanism can he traced through the Holocene by at least two means. Bryson and Goodman (1980) constructed an index of volcanism to 40,000 BP from radiocarbon dates and utilized it in a Late Quaternary projection of the

GEB (Bryson, 1986). A similar experiment by Gunn (1985, 1987a, b, 1990) has shown favorable results. Also, ice cores arc a rich source of annual data on the status of global atmospheric forcing variables. Volcanism is reflected in ice varve acidity (Hammer, Clausen, and Dansgaard 1980). Atmospheric CO_2 is measured from air bubbles in Arctic and Antarctic ice caps (Neftel et at, 1982). The prehistoric effects of ENSO appear in the Quelccaya Ice Cap (Thompson et at; 1984, Thompson et al., 1986) and in the anoxic San Diego Basin (Casey et al., 1988).

Cyclicity in astronomical variables is thought to affect the GEB. The GEB can be projected into the past on a long term basis by orbital functions (Kukla, 1975; Davis, 1984; Davis and Sellers, 1986; Kutzbach and Guetter, 1986). Gunn (1985) and Bryson (1986) refine these projections by subtracting a volcanism index from precessional forcing of the radiation balance. Shorter term variations can be modeled using a function of center of mass of the solar system as a GEB driver (Landscheidt, 1987).

The ENSO Hemispheric Balancing Mechanism in History and Prehistory

If GEB levels were known from the past, and particularly during periods of transition from cool to hot global energy balance, the foregoing model could become a productive tool for synergistically refining chronologies of past climates from current events. Several efforts are being made to generate such GEB equivalents. In general, however, the GEB of the Holocene has been known for some time and can be used here. The Middle Holocene (4500-750(1 BP) was mostly hotter than the present century. The Late Holocene (after 4500 BP) was variable but generally as cool or cooler than the present century.

If the hemispheric balancing mechanism is functional as a long term process, the evidence for it should appear in prehistory. Studying it should be very enlightening

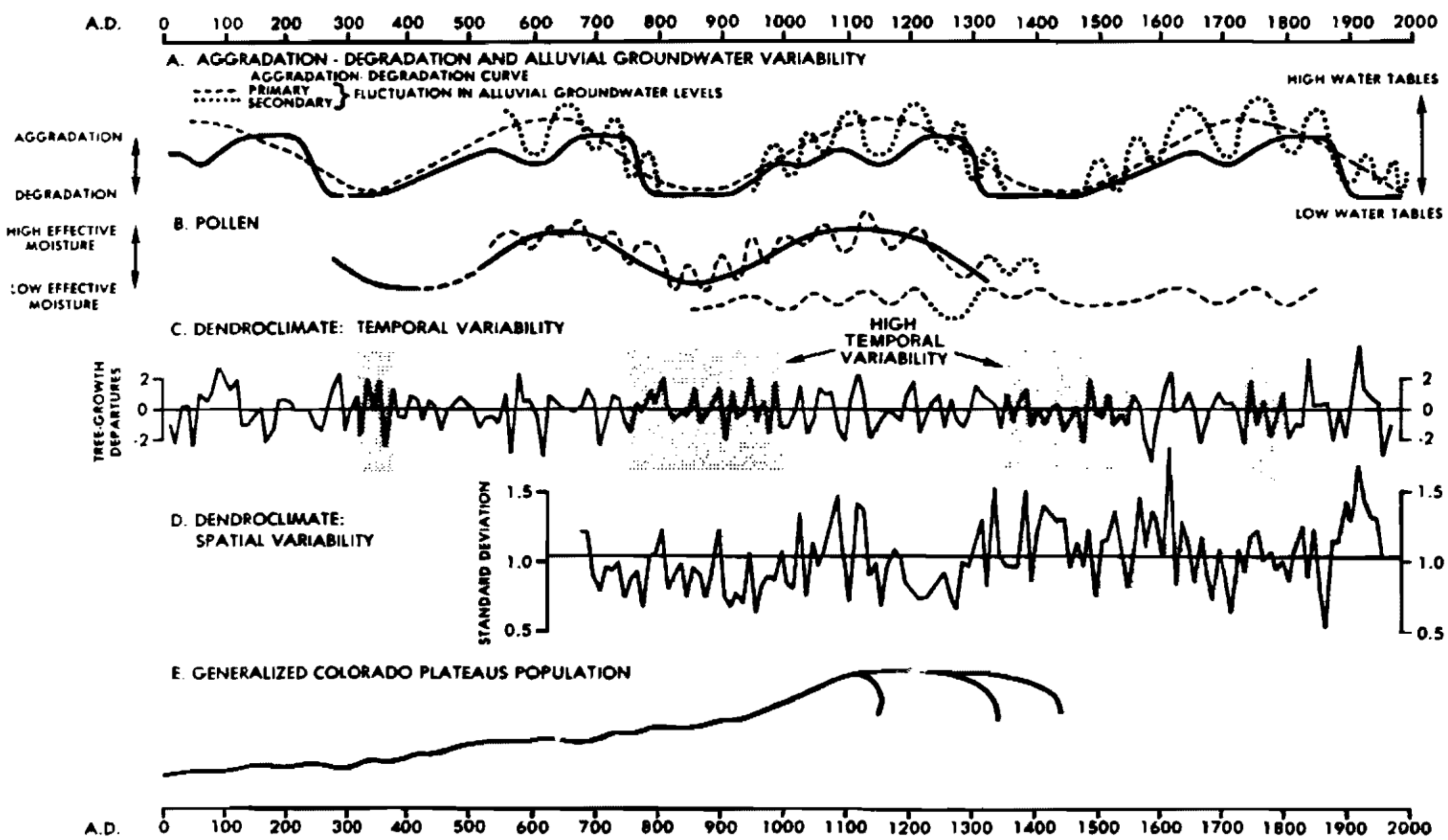


Fig. 7. Periods of unstable climate in the Southwestern United States (Dean *et al.*, 1985).

as to how the transfer mechanism changes with GEB boundary conditons. Two sources of data are currently available.

(1) Pleistocene and Holocene sea core data are being analyzed from anoxic (varved) sediments in the San Diego Basin of California (Casey el al., 1988) which are marked by ENSOs. The appearance of strong ENSO in the record will be indicative of a SH dominated global climate, and show when the ENSO teleconnections can be expected to be effective in other parts of the world. This will in turn be verifiable through regional paleoclimatic chronologies.
(2) Rollins el al. (1986) report that from 11k-5k BP the water along the Peruvian coast which now experiences the alternating cold and warm of ENSO (5-1(1 S. Lat.) was continually warm The Pampas las Salinas site (ibid 5-8) has an ecologically diverse molluscan fauna indicating a stable habitat. It dates between 50005500 BR is now 5 km from the Pacific because of tectonic uplift, and is 500 km south of where the faunal assemblage would be found now in permanently warm tropical water. This suggests that during the Early and Middle Holocene there was enough warming of the wave-guide so that there was the equivalent of a continual state of ENSO, that is to say a permanent, stable, warm equatorial Pacific off Peru. A moister on-shore fauna and flora support this (see DeVries 1987 for additional evidence and alternative views).

It was only with lower GEB levels in the Late Holocene that the ENSO became an episodic phenomenon. Rollins et at (1986: 8-11) report nine tectonically uplifted ridges which they attribute to very large ENSOs. The amplitude of the ridges indicates the magnitude of ENSOs diminished from 5000-4500 BP (ibid 8). This suggests a lessening of the amplitude of the ENSO as GEB cooled. In the perspective of the hemispheric dominance model, this indicates that as warm, SH dominated conditions transitioned to cool NH dominated conditions, the size of the ENSOs declined. Evidence should also be found to indicate smaller northward infusions of warmer water, e.g., in the San Diego Basin.

The hemispheric balance hypothesis of ENSO could be further checked in modern times by using satellite data to determine if the amount of heat transport to one or the other hemispheres is proportional to the difference in temperature between the hemispheres. if it bears further confirmation, the ENSO would join ocean and atmospheric poleward circulation as part of an array of mechanisms for equalizing the global distribution of energy.

Discussion

This analysis suggests that:

(1) There is forcing of the GEB by independent and quasi-independent variables in the solar system and earth system (by ANOVA and regression).
(2) As the GEB changes, global atmospheric/oceanic processes rebalance the effects of the forcing variables (Figure 5), and the consequent periodicity of global climatic instabilities. From the range of experience in the period of intensive instrumental observation, and during globally warm intervals of the Holocene, three states can be inferred.
    a) Low GEB (less than the 1958-1970 mean): The episodic phenomena, predominantly solar cycles of 22 and 83 years, and possibly others, determine the quasi-periods. Aerosols may be negatively correlated with the solar cycles (Landscheidt, 1987).
    b) Middle GEB (greater than the 1958-1970 mean): The episodic phenomena are dominated by ENSO. This results in approximately five year quasi-periods.
    c) High GEB (greater than the 1958— 1986 experience): All episodic forces are damped by SH dominance and a generally warmed world.

These states parallel with DeVries' (1987) suggestion of a somewhat more complex range of four regimes, and are probably a subset of DeVries' model.

Very strong ENSO events have been detected in Peruvian sediments. They suggest several things about the model.

(1) Very strong events are found around 500 BC and AD 1100 (Quinn et al., 1988: 14, 449). These dates are during the Roman Empire and Little Climatic Optima respectively. They are therefore ENSO events associated with periods of generally recognized global warming. The question arises as to whether there is only one very strong ENSO event with each warming. There were also very strong ENSOs in the 1520s and 1920s (Quinn et al., 1988), which were also periods of global warming (Bergthorsson, 1969).

(2) There were multiple, very strong ENSOs in the Middle Holocene (Wells, 1988). Is this a problem for this model, or does it just reflect variable long term climate in the Middle Holocene with several warmings through the SH-NH threshold? (see Gunn (1990) for a discussion of Middle Holocene global climatic variation).

From the perspective of prehistory and history a global stability factor could be very important. For example, the ENSOs in the 1980s generated a cycle of about two years of drought alternating with three years of moisture in the Southeastern United States. Parry (1978) suggests that one crop failure in five is the maximum tolerance level of subsistence farmers. The Middle GEB level with its five year periodicity could therefore be expected to cause problems. at least for cultures based on subsistence agriculture, and probably for more technologically complex societies.

In the Southwestern United States, which is one of the best studied areas with respect to climate and culture in prehistory, Dean et al. (1985, Figure 7) report that the climate (tree rings) varies from stable to unstable over periods of hundreds of years. The stable phases encourage sustained cultural development and the unstable phases clearly do not. From a global climatic perspective, high energy budget phases such as the Little Climate Optimum (about 900-1250, Williams and Wigley, 1983) are associated with stable climate while unstable regional climates were associated with cooler GEB phases, the 1300s for example. This analysis suggests that the terrestrial Northern Hemisphere at low GEB is the source of the instability, while a high GEB world dominated by Southern Hemispheric processes should be inherently more stable. The transitional phase between the two would he viciously unstable.

Such a model of interaction between global climate and regional culture change explains why populous and/or complex civilizations tend to he associated with global thermal optima (Anasazi in the Southwest, but also the Roman Empire, Hopewell, High Medieval Europe, Kingdom of Ghana, Mississippian), while periods of shift away from populous and/or complex hierarchical systems were associated with cooling, especially episodes of volcanism. (An exceptional case is the Maya Lowlands, Gunn and Adams, 1981; Folan et al., 1983.) This of course is an important hypothesis for regional archaeologists, geographers and historians to document.

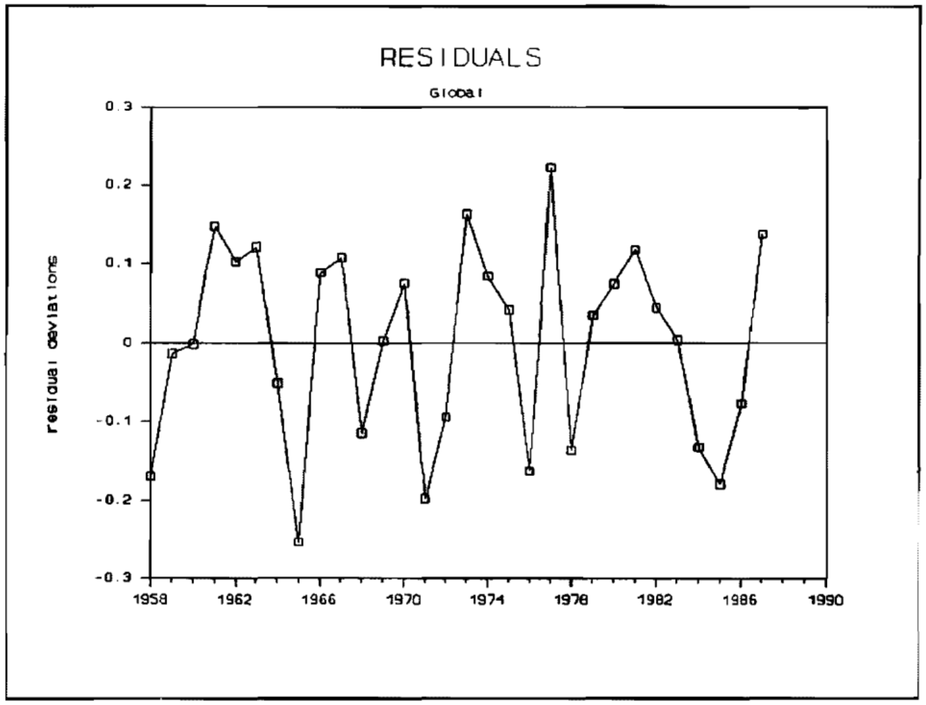
Conclusions

The effort of data collecting, particularly since the International Geophysical Year in 1957, is beginning to pay dividends in terms of understanding global climate. This paper has examined an aspect of global climate on the basis of a short term (30 years) but highly accurate data set. The data are fortuitously transient and at a GEB level which may register a mechanism which conditions stability in the global climate, the ENSO. There are those who will object to using an interval of time as short as 30 years to model the variation in Holocene climate. The primary counter argument is changing boundary conditions imposed by orbital forcing, deep ocean temperatures, and ice volume. It may be that these circumstances advise application of the model to the Late and Middle Holocene when boundary conditions were most like those at present. In the Early Holoeene the seasonal distribution of insolation due to orbital parameters (Davis, 1984), ice volume, and ocean temperatures varied from the present. However, a 20-year based model for eastern France correctly retrodicts hydrological conditions in the Early Holocene (Gunn and Crumley, I 989). This suggests that, at least in part, the GEB level is of predominant importance, less so the contributing factors to the GEB. Another example of this is that GCMs predict drought in middle North America with global warming whether it is forced by insolation or CO, warming (Schneider, 1987. Wigley et al., 1980). Presumably desirable refinements would result from a better understanding of the origins of GEB levels. Such refinements are likely to come from advanced atmospheric and ocean circulation models (Schneider, 1987: 78) and analysis of longer term data sets. Such second order approximations would he most welcome.

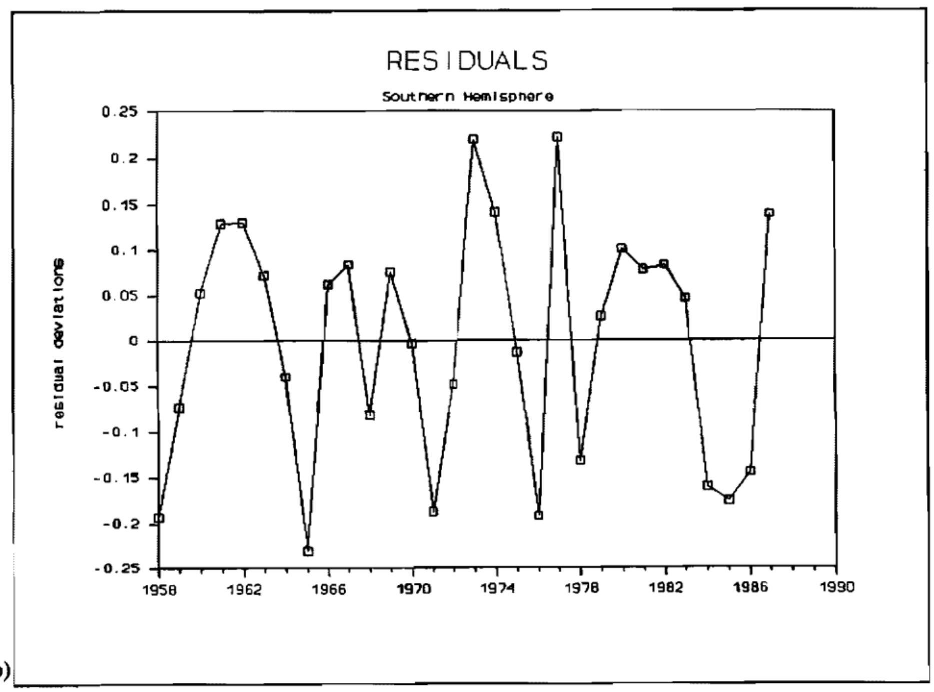
Acknowledgements
David Burney, Carole Crumley, Vance Holliday, and Brian Goodman read and commented on the drafts. The article benefited from the suggestions of three anonymous reviewers.

Appendix

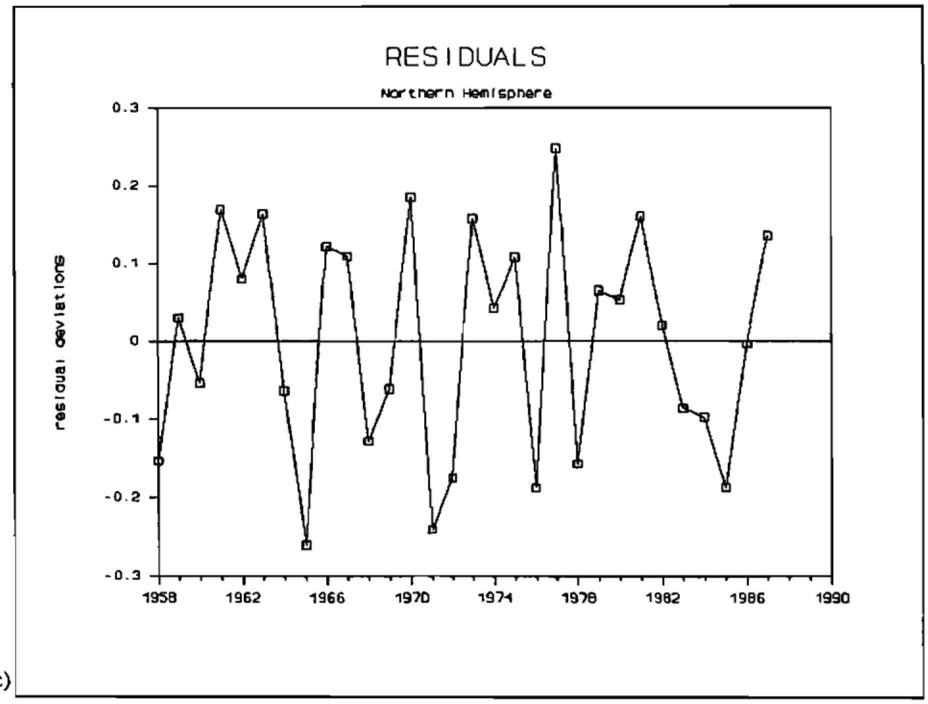
Residual plots for equations in Table III, (a) global, (b) Southern Hemisphere, (c) Northern Hemisphere.



(a)



(b)



(c)

References

Angell, J. K. and Korshover, J.: 1975, 'Estimate of the Global Change in Tropospheric Temperature Between 1958 and 1973', *Monthly Weather Review* 103, 1007-1012.
Angell, J. K. and Korshover 1:1978, 'Global Temperature Variation, Surface-100 mb: An Update into 1977', *Monthly Weather Review* 106, 755-770.
Angell. J. K. and Korshover, J.: 1983, 'Global Temperature Variations in the Troposphere and Stratosphere. 1958-1982', *Monthly Weather Review* 901-921.
Angell, J. K. and Korshover, J.: 1984, 'Comparison of Tropospheric Temperatures Following Agung and El Chichon Volcanic Eruptions'. *Monthly Weather Review* 112 (7), 1457-1463.
Barnett. T. P., Dumenil, L., Schlese, U., Roeckner. E.: 1988, 'The Effect of Eurasian Snow Cover on Global Climate', *Science* 239.504-507.
Barry, R. G, and Chorley, R. J.: 1968, *Atmosphere, Weather and Climate,* Third Edition, Methuen & Co., Lid, London.
Bell, B.: 1981. 'Analysis of Viticultural Data by Cumulative Deviations', in R. Rotberg and T. Rabb (eds.), *Climate and History,* Princeton University Press, Princeton NJ.
Bergthorsson. P.: 1969, 'An Estimate of Drift Ice and Temperature in Iceland in 1.000 Years', *Jokull (Journal of the Icelandic Glaciological Society)* 19, 94-101.
Blalock. H. M.: 1972, *Social Statistics*, McGraw-Hill, New York.
Bryson, R. A.: 1986, 'Late Quaternary Volcanic Modulation of Milankovitch Climate Forcing, Paper presented at the Symposium on *Mechanisms of Climate and Culture Change,* J. Gunn and A. Paulsen, organizers, annual conference of the American Anthropological Association, Philadelphia, to appear in *The Anthropological Implications of Climatic Change.* J. Gunn and A. Paulsen, eds.. submitted for review
Bryson, R. A.: 1987, *Civilization and Rapid Climate Change,* Edinburgh 870904, Manuscript.
Bryson, R. A. and Goodman, 13. M.: 1980, 'Volcanic Activity and Climatic Changes', *Science* 207, 1041-1044.
Bryson, R. A. and Goodman, B. M.: 1986, .Milankovitch and Global Ice Volume Simulation', *Theoretical and Applied Climatology* 37, 22-28.
Budyko, M. 1.: 1958. *The Heat Balance of the Earth's Surface,* Nina Steponova, trans.. U.S. Weather Bureau. Washington, D.C.
Budyko, N1. I.: 1974, *Climate and Life,* Academic Press, New York.

Budyko, M. I.: 1977. *Global Ecology,* English translation 1980. Progress Publishers. Moscow.
Cane. Ni. A. and Zebiak, S. E.: 1985, 'A Theory for El Nino and the Southern Oscillation', *Science* 228, 1085-1087.
Casey. R. E., Weinheimer, A., and Nelson. C. O.: 1988, 'Different Kinds of California El Ninos, from Recent and Fossil Records of the Southern California Sea', *Proceedings of the Pacific* AAA, 6 (1). 22.
Davis. 0.: 1984. ¯Multiple Thermal Maxima During the Holocene'. *Science* 225, 617-619.
Davis. 0. and Sellers. W. I).: 1986, 'The Effects of Insolation on the History of the Arizona Monsoon', Paper presented in the symposium on Mechanisms of Climate and Culture Change, J. Gunn and A. Paulsen, organizers. American Anthropological Association Conference, Philadelphia. to appear *in The Anthropological Implications of Climatic Change, J.* Gunn and A. Paulsen (eds.), submitted for review.
Dean, .1. S., Euler, R. C., Gumerman. G. J., Plug. E. Hevly, R. H., and Karlstrom, T. N. V.: 1985. `Human Behavior. Demography. and Paleoenvironment on the Colorado Plateaus'. American *Antiquarian* 50 (3), 537-555.
DeLuisi, J., DeFoor. T., Coulson, K., Fernald, F. and Thorne, K.: 1984, *Lidar Observations of Straw- spheric Aerosol over Manna Loa Obervatory:* 1974-1981. NOAA Data Report BERL ARL-4. Air Resources Laboratory, Rockville. MD.
Deser, C. and Wallace. J. M.: 1987, 'El Nino Events and Their Relation to the Southern Oscillation: 1925-1986, *Journal of Geophysical Research* 92 (C13), 14,189-14.196.
DeVries. T. J.: 1987, 'A Review of Geological Evidence for Ancient El Nino Activity in Peru, *Jonrnal of Geophysical Research* 92 (C13), 14,471-14,479.
Eddy, J. A.: 1977, "Hie Case of the Missing Sunspots', .*Scientific American* 236 (5), 80-92.
Eddy, J. A.: 1986. 'Solar History and Human Affairs, Paper presented at the Symposium on *Mechanisms of (innate and Culture Cbange.* J. Gunn and A. Paulsen, organizers, annual conference of the American Anthropological Association, Philadelphia, to appear in *The Anthropological Implications of Climatic Change, J.* Ciunn and A. Paulsen, (eds.). submitted for review.
Fiedler, P.1984, 'Satellite Observations of the 1982-1983 El Niño Along the U.S. Pacific Coast', *Science* 224. 1251-1254.
Flohn, H.: 1988, 'East African Rains of 1961/62 and the Abrupt Change of the White Nile Discharge'. *Paleoecology of Africa* pp. 3-18.
Folan, W. J., Gunn, J., Eaton. J. D., and Patch, R. W.: 1983. 'Paleoclimatological Patterning in Southern Mesoamerica, *Journal of Field Archaeology 10,* 453-468.
Gilliland, R. L.: 1982, 'Solar, Volcanic and CO, Forcing of Recent Climatic Changes', *Climatic Change* 4,111-131.
Glantz, M.. Katz, R., and Krenz, M.. (eds.): 1987, *The Societal Impacts Associated with the 1982-83 Worldwide Climate Anomalies,* Environmental and Societal Impacts Group, NCAR and UNEP.
Goodman, B. M.: 1987, 'The Climatic Influence of Volcanic Activity'. to appear in J. Gunn and A. Paulsen, (eds.), *The* Anthropological *Implications of Climatic Change.* submitted for review.
Graham, N. E. and White. W. B.: 1988, 'The El Niño Cycle: A Natural Oscillator of the Pacific Ocean - Atmosphere System', *Science* 240. 1293-I 302.
Gunn. J.: 1982, 'Analysis of Modern Climate Data', in G. Mute and J. Gunn (eds.). *A Snub' of Laze Quarternary Environments and truly Man Along she Tombigbee River, Alabama and Mississippi,* National Park Service, Atlanta. pp. 2-19 to 2-26.
Gunn, J.: 1985. *'Chino& *aim, 3.02, Modeling Climate/Culture Change, Users Guide,* ECS Corp. San Antonio TX.
Gunn, J.: I 987a, 'Mobility Patterns in Central Texas'. in J. Fox (ed.), *Aboriginal Cenral Texas: Culture Change along the Central Tetras Ecotone, submitted* for review.
Gunn, J.: 1987b, 'Middle¯PeCos Culture Sequence and Holocene Climate, in N. M. S. Tularosa and P. Katz (eds.), *Advances in Middle Pecos Archaeology.* Proceedings of the Middle Pecos Symposium. at the 4th Jornada Mogollon Conference, Bureau of Reclamation. Southwest Region, Amarillo TX.
Gunn, J.: 1990, *Regional Climates of Texas: Global Climatic Change in Landscape Perspective,* in preparation.
Gunn, J. and Adams. R. E. W.: 1981, 'Climatic Change, Culture, and Civilization in North America, *World Archaeology* 13 (l), 85-100.

Gunn, J. and Crumley, C. L.: 1989, 'Global Energy Balance and Regional Hydrology: A Burgundian Case Study', *Discussion Reports*, European Conference on Landscape Ecological Impacts of Climatic Change, The Netherlands' Ministry of Housing, Physical Planning and Environment, Lunteren, The Netherlands.
Hammer, C. U., Clausen, H. B., and Dansgaard.1980. 'Greenland Ice Sheet Evidence of Post-Glacial Volcanism and Its Climatic Impact˙. *Nature* 288, 230-235.
Henderson-Selle•s, A. and Robinson, P. J.: 1986. *Contemporary Climatology* Longman Scientific & Technical, and John Wiley and Sons, Inc., New York.
Jones, P. D., Wigley, T. M. L., and Wright. P. B.: 1986, 'Global Temperature Variations Between 1861 and 1984', *Nature* 322,430-434.
Kasting. J. E,O. B., and Pollack..J. B.: 1988. 'How Climate Evolved on the Terrestrial Planets', *Scientific American* 258. 90-97.
Keeling, *C.* D.: 1978, ''Hie Influence of Mauna Loa Observatory on the Development of Atmospheric CO, Research'. Scripps Institution of Oceanography, Anniversary Volume.
Kerr, R. A.: 1985, 'Wild String of Winters Confirmed', *Science* 227, 504-505.
Kerr, R. A.: 1986a, 'Greenhouse Warming Still Coming', .*Science* 232, 573-574.
Kerr, R. A.: 1986b. 'Another Try at Forecasting El Nino, *Science* 232, 155.
Kukla, Ci. J.: 1975. 'Missing Link Between Milankovitch and Climate, *Nacre* 253, 600-603. Kutzbaeh, J. E. and (inciter, P. J.: 1986, 'The Influence of Changing Orbital Parameters and Surface Boundary Conditions on Climate Simulations for the Past 18.000 years', *Journal of Atmospheric Research* 43 (16): 1726-1759.
Labitzke, K. and van Loon, H.: 1988, 'Associations Between the 11-year Solar Cycle, the OBO and the Atmosphere. Part I: the Troposphere and Stratosphere in the Northern Hemisphere in Winter'. *Journal of Atmospheric and Terrestrial Physics* 50 (3): 197-206.
Lamb, H.11.: 1970, 'Volcanic Dust in the Atmosphere: with its Chronology and Assessment of its Meteorological Significance', *Philosopbical Transactions of the Royal Society of London* 266: 425533.
Landscheidt, T.: 1987. ¯Long-Range Forecasts of Solar Cycles and Climate Change', in M. Rampino. J. Sanders, W. Newman, and L. Konigsson (eds.). *Climate: History, Periodicity. and Predictability.* Van Nostrand Reinhold Company. New York. pp. 421-445.
Mitchell. J. M., Jr., Stockton, C. W., and Mao, D. M.: 1979, ¯Evidence of a 22-Year Rhythm of Drought in the Western United States Related to the Hale Solar Cycle Since the 17th Century, in B. McCormac and T. Seliga *(ells.), ,Solar-Terrestrial Influences on Weather and Climate,* Kluwer Acad. Publ., Dordrecht, Holland.
Nast rom, G. D. and Belmont. A. D.: 1980, 'Evidence for a Solar Cycle Signal in Tropospheric Winds', *Journal of Geophyhsical Research* 85, 443-452.
Nebel, A., Oeschger, H., Schwander,Stauffer, B., and Zumbrunn, R.: 1982, 'Ice Core Sample Measurements Give Atmospheric CO, Content During the Past 40,000 yr, *Nature* 295, 220-223.
Nicholls, N.: 1987, 'The El Niño/Southern Oscillation Phenomenon, in *The Societal Impacts Associated with the* /982-83 *Worldwide Climate Anomalies*, Environmental and Societal Impacts Group. NCAR and UNEP.
Parry, S. G. 11.: 1978. *Climatic Cbange Agriculture and Settlement*, Dawson-Archon Books, Folkstone. Kent, England.
Philander, G. H.: 1986, 'Unusual Conditions in the Tropical Atlantic Ocean in *1984', ;Nacre* 322, 236-238.
Pollack, J. B., 'Mon, 0. B.. Sagan, C., Summers, A., Baldwin. 13.. and Van Camp. W.: 1976, 'Volcanic Explosions and Climatic Change: A Theoretical Assessment', *Animal of Geophysical Research* 81 (6), 1071-1083.
Quinn. W. H.. Neal. V T., and Antunez de Mayolo, S. E.: 1987, 'El Niño Occurrences Over the Past Four and a Half Centuries'. *Journal of Geophysical Research* 92 (C I3), 14,449-14,461.
Rampino, Ni. R. and Self. S.: 1984, 'The Atmospheric Effects of El Chichon', *Scientific American* 251 (1), 48-57.
Rao, P. and LeRoy Miller, R.: 1971, *Applied Econometrics*, Wadsworth Publishing Co., Belmont CA.
Rasmusson, E. M.: 1985, El Niño and Variations in Climate'. *American Scientist* 73. 168-177. Robinson. E. and DeFoor, T. E.: 1988, 'Stratospheric Aerosol Conditions Over Manua Loa During Recent Quiescent Volcanic Periods', in P Hobbs and P. McCormick (eds.). *Proceedings of the International Union of Geodesy and Geophysics.*

Rollins, H. B.. Richardson, J. B., and Sandweiss. D. H.: 1986, 'The Birth of El Nino: Geoarchaeological Evidence and Implications', *Geoarchaeology* I (1), 3-15.
Ropelewski, C. F. and Halpert. M. S.: 1986, 'North American Precipitation and Temperature Patterns Associated with the El Niño/Southern Oscillation, (ENSO)', *Monthly Weather Review* 114, 23522362.
Schneider, S.1987, 'Climate Modeling, *Scientific American* 256, 72-80.
Schneider, S. H. and Londer, R.: 1984. *The Coevolution of Climate and Life.* Sierra Club Books, San Francisco.
Schneider, S. H. and Mass, C.: 1975, 'Volcanic Dust, Sunspots, and Temperature Trends'. *Science* 190 (4216), 741-746.
SEAN Bulletin: 1984, 'Atmospheric Effects'. *SEAN (Scientific Event Alert Network) Bulletin* 9 (8), 16. SEAN Bulletin: 1986, 'Atmospheric Effects', *SEAN (Scientific Event Alert Network) Bulletin* 11 (5), 20. SEAN Bulletin: 1987, 'Atmospheric Effects', *SEAN (Sciennfic Event A lert Network) Bulletin* 12 (9), II. Stockton, C. W., Boggess. W. R., and Meko, D. M.: 1985, 'Climate and Tree Rings', in A. Hecht (ed.), *Paleoclimate Analysis and Modeling,* John Wiley & Sons, New York.
Stommel. H. and Stommel, F.: 1979, 'The Year Without a Summer, *Scientific American* 240 (6), 176186.
Thompson, 1.. G., Mosley-Thompson, E., Arnao, B. M.: 1984. 'El Niño-Southern Oscillation Events Recorded in the Stratigraphy of the Tropical Quelccaya Ice Cap, Peru', *Science* 226, 50-52. Thompson, L. G., Davis, M., and Mosley Thompson, E.: 1987, A 1500 Year Tropical Ice Core Record of Climate: Potential Relationships to Man in the Andes, Paper presented at the Symposium on *Mechanisms of Climate and Culture Change,* J. Gunn and A. Paulsen, organizers, annual conference of the American Anthropological Association, Philadelphia, to appear in *The Anthropological Implications of Climatic Change.* J. Gunn and A. Paulsen (eds.). submitted for review.
Wells, L. E.: 1987, 'An Alluvial Record of El Niño Events from Northern Coastal Peru', *Journal of Geophysical Research* 92 (C 13), 14,463-14.470.
Wendland, W. M.: 1977, 'Tropical Storm Frequencies Related to Sea Surface Temperature', *Journal of Applied Meteorology* 16, 477-48I.
Wigley, 'I'. M. L.. Jones. P D., and Kelly, P. M.: 1980, 'Scenario for a Warm, High-CO, World'. *Nature* 283, 17-21.
Wilkinson, L.: 1988, *Systat: The System for Statistics,* Systat Inc.. Evanston IL.
Williams, L. D. and Wigley, T. M. L.: 1983, 'A Comparison of Evidence for Late Holocene Summer Temperature Variations in the Northern I Hemisphere', *Quaternary Research* 20, 286-307.
Willson, R. C. Gulkis, S., Janssen, Ni., Hudson, H. S., and Chapman, G. A.: 1981. 'Observations on Solar Irradiance Variability, *Science* 211, 700-702.
Willson, R. C., Hudson. H. S., Frohlich, C., and Brusa, R. W.: 1986, 'Long-Term Downward Trend in Total Solar Irradiance' Science 234, 1114-1117.
Wilson, P. R.. Altrock. R. C., Harvey, K. L., Martin, S. F.. and Snodgrass, H. B.: 1988. 'The Extended Solar Activity Cycle, *Natnre* 333, 748-750.