The Seasons, Global Temperature, and Precession
Author(s): David J. Thomson
Source: *Science*, New Series, Vol. 268, No. 5207 (Apr. 7, 1995), pp. 59-68
Published by: American Association for the Advancement of Science
Stable URL: http://www.jstor.org/stable/2886492
Accessed: 11/04/2009 11:36

RESEARCH ARTICLE

The Seasons, Global Temperature, and Precession

David J. Thomson

Analysis of instrumental temperature records beginning in 1659 shows that in much of the world the dominant frequency of the seasons is one cycle per anomalistic year (the time from perihelion to perihelion, 365.25964 days), not one cycle per tropical year (the time from equinox to equinox, 365.24220 days), and that the timing of the annual temperature cycle is controlled by perihelion. The assumption that the seasons were timed by the equinoxes has caused many statistical analyses of climate data to be badly biased. Coherence between changes in the amplitude of the annual cycle and those in the average temperature show that between 1854 and 1922 there were small temperature variations, probably of solar origin. Since 1922, the phase of the Northern Hemisphere coherence between these quantities switched from 0° to 180° and implies that solar variability cannot be the sole cause of the increasing temperature over the last century. About 1940, the phase patterns of the previous 300 years began to change and now appear to be changing at an unprecedented rate. The average change in phase is now coherent with the logarithm of atmospheric CO_2 concentration.

Efforts to detect the effects of the increasing quantities of carbon dioxide and other so-called greenhouse gases on the Earth's climate have relied on a few carefully compiled series that represent regional or global average temperature departures from a seasonal average. In constructing these series great care has been taken to correct for changes in instrumentation, station locations, elevation, urbanization, and myriad similar effects. Although all (*1–3*) these compilations show that the average surface air temperature has increased by about 0.6°C during the last century, they also show that the warming is much larger in winter than in summer. This and other uncertainties about the range of natural variations to be expected in average temperature, particularly from solar variability, has caused attribution of the observed warming to the greenhouse effect to remain controversial (*4–6*).

In this paper I give an analysis of the statistical structure of temperature time series with emphasis on the frequency band around 1 cycle per year, that is the annual or seasonal cycle. Because these seasonal variations often cause more than 90 percent of the variance of a temperature record, careful analysis of the seasonal cycle can help to resolve such controversies.

Earth's orbit and seasonal radiation. The Earth has an elliptical orbit that changes slowly with time, and the eccentricity of the orbit and the orientation of the Earth's axis of rotation on the ecliptic control the amount of radiation received from the sun at a given latitude and date (*7–9*). On historical time scales, the obvious periodic recurrence time of the seasons and the length of the day are defined by the tropical year, the 365.24220 days from equinox to equinox (*10*). The insolation at a particular latitude has the period of the tropical year. The data used here, monthly average temperatures, are organized according to the Gregorian civil calendar. This calendar was designed to stay synchronized with the equinoxes, and over its full 400-year cycle of intercalations, the average calendar year of 365.2425 days is a remarkably accurate approximation to the tropical year. Because of this, subtraction of the seasonal cycle from the temperature records has not been questioned. This viewpoint was strengthened by the argument that, although direct radiation at a given latitude changes on the time scale of the Quaternary ice ages, the classical insolation formulas show that the major effect of orbital change in northern temperate latitudes during the last few hundred years should be a slight cooling and that the phase of insolation is almost constant when measured from the equinox. Moreover, the shortest of the major cycles, the 26,000 years required for a complete precession cycle, is so long compared to the length of the instrumental series that it was thought that such residual effects could be safely ignored.

The total amount of radiation received by the Earth at a given time also varies periodically, but the period is not the tropical year of the equinoxes but rather the time from perihelion to perihelion, or the anomalistic year, currently 365.25964 days. Because Earth's orbit is not very eccentric, the change in total radiation received over a year is small, and the change in average blackbody temperature from perihelion to aphelion is only about 2.1°C. Nonetheless, if atmospheric transport of heat were instantaneous and perfectly efficient, local insolation effects would be irrelevant, and all that could be learned from a temperature series would be the eccentricity of the orbit and the longitude of perihelion. Thus the annual cycle contains at least two major components, the tropical and anomalistic years, that differ by only one in about 26,000 years (*11*) and should be expected to interact. Because the effects of precession are clear in the paleoclimate record, the interaction is intense. In the theory of frequency-modulated communications systems (*13*) there is a well-known "capture effect" in which the observed phase of such a system is largely controlled by the stronger of the two components. Because albedo primarily effects the radiation or tropical year component, whereas topography alters the transport or anomalistic year part, and volcanic activity might change either, there is no obvious reason to expect either frequency to be uniformly dominant.

In addition to celestial mechanics and the paleoclimate record, there are other climate observations implying that the seasonal cycle is complicated. Hansen and Lebedeff (*2*) and Kuo *et al.* (*14*) showed "bumps" in the spectrum of deseasonalized temperature records around 1 cycle per year and Kuo *et al.* discussed modulation effects there. The variance in winter is larger than in summer, showing that a cyclostationary (periodically correlated) (*15*) process provides a better model of climate data than does a stationary process. This observation implies that there must be coherent energy at frequencies separated by 1 cycle per year. Finally, there is the seasonal dependence in temperature trends (*4, 16*).

Data analysis. To investigate the interaction of these two seasonal components and related effects, I write the dominant component of the annual seasonal temperature cycle as

$$T(t) = A(t)\cos[2\pi t + \theta(t)] \qquad (1)$$

where t is the time in Gregorian calendar years, $A(t)$ is the amplitude, and the phase, $\theta(t)$, describes the timing of the seasons. Using monthly average temperature records (*17*), both from individual stations and hemispheric averages, I estimate their amplitude and phase by complex demodulation (*18, 19*). When a time series contains significant energy in specific frequency bands, as here in the vicinity of the annual cycle, a preferred method of analysis is complex demodulation about which Tukey (*20*) wrote: "It has to be tried out on actual data before its incisiveness and power is adequately appreciated."

For a temperature record $x(t)$ complex

The author is at AT&T Bell Labs, Murray Hill, NJ 07974, USA.

demodulation estimates the amplitude and phase by forming

$$y(t) = h(t) * \{x(t)e^{-i2\pi ft}\}$$

$$= \sum_{j=0}^{N-1} h(j)\, x(t-j)\, e^{-i2\pi f(t-j)} \qquad (2)$$

where the effect of $e^{-i2\pi ft}$ is to shift components of $x(t)$ at frequency f to the origin, $*$ represents convolution, and $\{h(t),\ t = 0, N-1\}$ is the impulse response of a suitably chosen low-pass filter. From the complex demodulate $y(t)$, the amplitude is estimated by

$$A(t) \approx 2|y(t)| \qquad (3a)$$

the phase by

$$\theta(t) \approx \arctan\frac{Im\{y(t)\}}{Re\{y(t)\}} \qquad (3b)$$

and the annual cycle by $2Re\{e^{+i2\pi ft}\ y(t)\}$. For most (*21*) of the results here $h(t)$ has been a zero-order Slepian sequence (*22, 23*), $v_n^{(0)}(N, W)$, with the block length, determined by N, set between 5 and 20 years with the bandwidth, W typically set at $N W = 1$ or 2. This simple filter has excellent band limiting properties, linear phase, and no overshoots or Gibb's ripples, but has the disadvantage that the output is shorter than the input by $N - 1$ samples. However, it is not well suited for extracting the wideband signals used in coherence calculations. I used projection filters (*24, 25*) for these calculations and as checks on the others.

In this analysis I usually took the center frequency f to be 1 cycle per tropical, or Gregorian calendar, year. If the annual cycle of the data being analyzed varies at this frequency then, except for noise, the phase $\theta(t)$ should be constant. If, on the other hand, the frequency in the data is different from that assumed, the phase will have a linear trend in time with a slope equal to the frequency difference. Regression on phase is a standard method for making precision frequency estimates (*26*). These estimates are unbiased and their variance, which is inversely proportional to the cube of the length of the series, can achieve the Cramér-Rao bound for minimum variance estimation (*27*). This accuracy is sufficient to discriminate between the frequencies of the tropical and anomalistic year in historical temperature records.

Many of the temperature data sets have some missing data. I interpolated the data through gaps by taking midmeans for the same month from a few years on both sides of the gap. There are also numerous outliners associated with volcanic eruptions and probably transcription errors and so forth. Reanalysis of the data using adaptations of the robust methods developed in (*28, 29*) gives the same conclusions as the nonrobust estimates. To allow for the serial correlations present in all climate data, I used multiple-window methods (*30–33*) and computed tolerances using multiple-window jackknife methods (*34*). Statistical properties of phase estimates are known (*35, 36*).

The Central England series. The "Central England" temperature series was compiled by Manley (*37*) for 1659 to 1973 and has been recently updated (*38*). The early part of the series, up to about 1772, is slightly noisier than the later parts. This record was not deseasonalized, and although the design (or lack) of earlier thermometer screens may have caused a slight exaggeration of the amplitude of the annual cycle, there appears to be no reason that it should change the phase (*39*).

In the early record, Fig. 1, the most striking feature in the phase is an apparent step in 1752. Before September 1752, England used the Julian calendar and, although Manley gives the dates in the Gregorian calendar, he noted that some of the earlier data were only available as weekly averages, Sundays excluded. Thus the 3° phase discontinuity in 1752 is an expected result of shifting the dates of the early data by 2 weeks rather than by 11 days. If this offset in September 1752 is accounted for, the predominant feature of the phase is the steady drift with respect to the tropical year. From 1659 to 1940 the estimated slope is 51.1 arc seconds per year. This value is close to the general precession constant of 50″.256/year. The multiple-window standard deviation of the slope (*14, 40*) is 6″.82/year. Thus a test for constant phase has a t statistic of 7.49 and, with 14 df, is rejected above the 99.999 percent significance level. Thus, this trend shows that the frequency is not 1 cycle per tropical year (*41*), but is consistent with 1 cycle per anomalistic year, a completely unexpected result. Finally, it is obvious from Fig. 1 that, around 1940, the character of the phase altered, and during

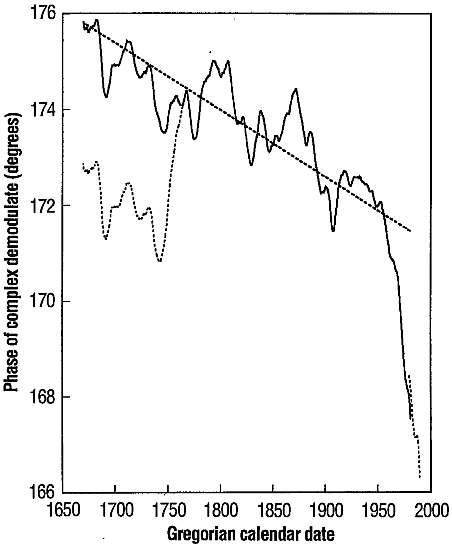


Fig. 1. The phase of the Central England series from 1659 to 1990 from a filter of bandwidth 1/22 years. The dotted portion before September 1752 shows the offset in phase of 3° before correction for the change from Julian to Gregorian calendars. The detectability of this 3-day offset in monthly data implies that the data quality is good. The straight line has the general precession constant as a slope. The dotted line at the lower right shows the phase from a filter of bandwidth 0.1 cycle per year from 1980 to 1990. The phase observed after 1940 would not have been easily predicted from that observed in the preceding 300 years.

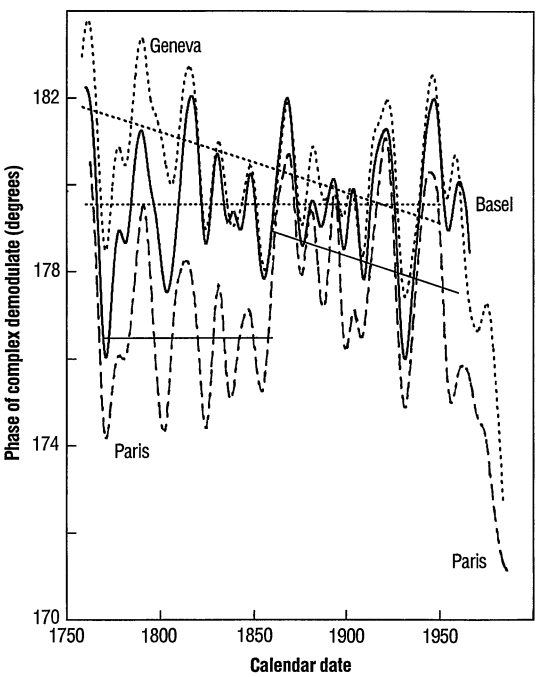


Fig. 2. Phase of the annual cycle for Geneva (Cointrin) (top, short dashes), Basel (Binningen) (solid line), and Paris (Le Bourget) (long dashes). Although most of the short-term detailed structure is highly coherent between the three, the trends are different, with Geneva having followed precession, Basel the equinoxes, and Paris having switched from equinoxes to precession about 1860. The filter was a Slepian sequence of 10 years duration and bandwidth 0.2 cycle per year.

the last 50 years has changed more than in the preceding 300 years.

Other individual temperature series. Long temperature records from Edinburgh, New Haven, Toronto, and numerous other locations exhibit similar effects. Although the tendency for the precession signal to capture the phase is common and apparently dominant, at many locations the phase of the climate does follow the tropical year. Apparently, local topography, heat storage, albedo, or the like can cause even nearby stations to differ.

For example, although Geneva and Basel are only 200 kilometers apart, the phase at Geneva followed precession, whereas at Basel the phase remained nearly constant until mid-century (*42*) (Fig. 2). Thus temperature at Basel follows the tropical year and Geneva the anomalistic. On the other hand, Paris appears to have switched between the two about 1860. This phase jump also occurred simultaneously in many European records including Milan and Stockholm. Tests of the binary hypothesis of constant phase versus precession applied in the two intervals (*43*) 1760 to 1860 and 1860 to 1960 shows that constant phase was the norm in the former interval and precession in the latter. This phase discontinuity appears to be an example of the capture effect. Furthermore, the phase in Paris has changed by more than 8 days (*44*) since 1950. The phase at DeBilt is similar to the phase at Paris.

Figure 3 shows phases derived from an 11-year filter for four tropical stations and for several in the North American west. Of the tropical stations, Apia, Samoa, exhibits the largest phase change that I have observed, nearly 38 days. Apia is in the region strongly influenced by the Southern Oscillation (El Niño). Among others, the 3-week phase change at San Francisco, and the 2-week phase change at Darwin may be related. The phases plotted for western North America are typical. In these and many other stations, the recent phase change exceeds 1 week. The current phase anomaly in this region exceeds the previous large phase excursion of the late 1920s and early 1930s by 50 percent or so.

I also analyzed a group of individual station records, mostly from the Northern Hemisphere. These consisted of all the records from the data set NDP-041 (*45*) that were longer than 100 years, had less than 5 percent missing data, and ended in 1990. I filled gaps by taking monthly mid-means using valid data within 3 years of the gap, so a few stations with gaps near the ends of the record were excluded. The resulting data set consisted of 222 station records, 188 above 23°N, 16 from the tropics, and 18 below 23°S. In the 50 or more years before 1940, the median and 80 percent mid-mean phase slope of all 222 records were −49″.4/year and −50″.8/year, respectively, close to the general precession constant. The small number of stations and low median amplitudes of 4.9°C and 2.9°C in the south and tropics, give poorer estimates of phase slope in the south and tropics than in the north. Nonetheless, both appear to be consistent with precession instead of constant phase. Thus, even though there are many locations like Basel where the phase follows the equinoxes, the average phase appears to be dominated by the average insolation and to follow perihelion.

In the 50 years since 1940, however, the median and 80% mid-mean became +92″.7/year and +94″.2/year, a 7σ change. In addition to the change in average phase slope, the variances in the post-1940 interval are 2.4 times the variances for the same stations before 1940. Part of this increase is from the low variance of a few long data records in the early part of the calculation. To remove this bias, I compared the same stations over the 45-year intervals 1895 to 1940 and 1940 to 1985 and found that the variance has still increased in the later period by more than a factor of 2 (*46*). In both these variance calculations, I excluded the extreme positive and negative 10 percent of the phases and so the comparisons are between the middle 80 percent of the stations in both time intervals.

Phase slopes for Northern temperate stations before 1940 (Fig. 4) are relatively tightly clustered and have a mode near −50″/year. The median is −44″/year, and the 10 percent trimmed mean is −42″/year, about what would be expected from a mixture. Both the ordinary standard deviation and Winsorized scale (a robust estimate of standard deviation) are near 153″/year, and there is a hint that the distribution is slightly trimodal.

After 1940, the distribution of phase slopes obviously changed; the median became +107″/year, the 10 percent trimmed mean was +113″/year, and the Winsorized scale increased to 242″/year. The standardized fourth moment increased from 5.52 to 7.42, showing that the distribution flattened, and the central mode shifted by

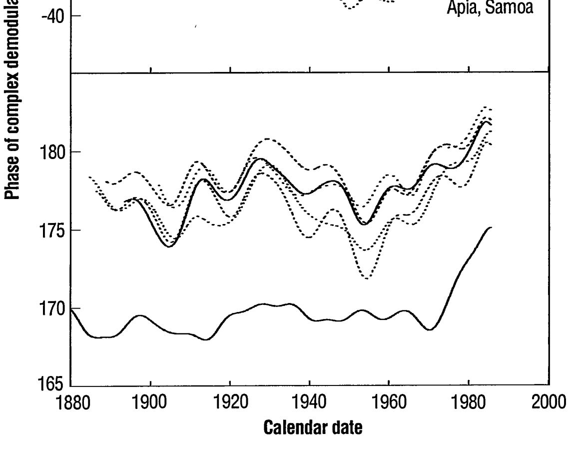


Fig. 3. (**Top**) Tropical stations: Madagascar; Brisbane; Apia, Samoa; and offset by 180°, San Juan, Puerto Rico. The phase in Apia has changed by over 5 weeks and in San Juan by 3 weeks. (**Bottom**) Stations from the western United States and Canada. The bottom solid line is Marquette, Michigan, and those in the upper group are Banff, Calgary, Edmonton, Alberta, Williston, North Dakota, and Kalispell, Montana.

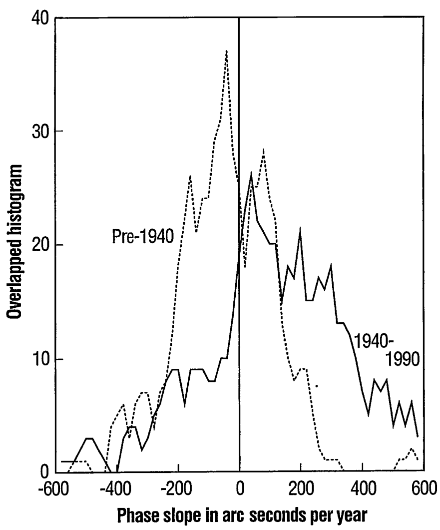


Fig. 4. Histograms of phase slopes of 188 Northern Hemisphere stations above 23°N before 1940 (dotted) and 1940 to 1990 (solid). The average has shifted and the variance has doubled.

about 250″/year. Thus the phase of the annual cycle has not only changed on average but has become more variable than it was before 1940.

Hemispheric average temperature series. Analysis of the Jones and Wigley Northern Hemispheric land plus marine average temperature series (*1*) exhibits a similar pattern as the individual stations. Because the individual component series making up the average series had been deseasonalized, I first added the average climatology (*47*) back in to the series (*48*), then demodulated it as above. In the Northern Hemisphere (Fig. 5), phase followed precession until about 1940, when the trend reversed and returned to approximately the value it had in 1850. In contrast, before 1940 the apparent phase slope of the Southern Hemisphere Jones-Wigley land plus marine average was closer to zero than to the precession constant, so climate in the Southern Hemisphere may have followed the tropical year. However, the slope of the hemispheric average, ~−5″/year, is much less than that of the average, −120″ ± 42″/year of the 18 long Southern Hemisphere records discussed above. In addition, the change in the Southern Hemisphere (Fig. 6) is much less than the change in the Northern Hemisphere after 1940.

The enhanced sensitivity of the phase in the Northern Hemisphere can be understood in terms of the direct insolation and transport components of the temperature at a given location. In the Northern Hemisphere, summer solstice (maximum insolation) occurs on 22 June whereas, currently, perihelion (maximum total incoming radiation) is on 3 January, so omitting transport time, the two components are 172° out of phase and thus nearly cancel. Consequently, slight perturbations on either component can change the resultant disproportionally. In the Southern Hemisphere the opposite situation prevails and, because perihelion occurs in the antipodal summer, the two vector components are currently misaligned by only 8° so a slight change in either does not change the phase of the resultant nearly as much as in the north.

To test this pattern, I fitted the complex demodulates, Eq. 2, from 1854 to 1940 with both the tropical and anomalistic year components

$$\hat{y}(t) \approx C\, e^{i2\pi f_T t} + D\, e^{i2\pi f_A t} \qquad (4)$$

with f_T and f_A as their respective frequencies (*49*). The estimated coefficients of Eq. 4 from analysis of the Jones-Wigley Hemispheric series (Fig. 7) largely cancel each other in the Northern Hemisphere, whereas they are nearly in phase in the Southern, as suggested above. Moreover, the residuals from this fit are small and show no systematic seasonal dependence of trend.

Seasonal dependence of temperature trends. Several workers (*4, 16*) have recognized that linear trends in temperature anomaly series during the last century show a strong seasonal dependence. As a specific example, if one fits simple linear strand to the January data in the Hansen-Wilson (*2*) Northern Hemisphere series, the slope is 1.05°C per century, whereas, when the same operation is done for the July data, the slope is only 0.37°C per century. Most of this seasonal dependence can be accounted for as an artifact of the deseasonalizing procedure used to generate the anomaly series. The essence of the deseasonalizing procedure is to average all the January data in a reference period, subtract it from all the January data in the series, and likewise for the other 11 months. Thus it subtracts a mean value function that has a period of exactly 1 year from the data.

As shown above, the phase of the annual cycle had a linear trend of about 50 arc seconds per year. This precessional signal, combined with the deseasonalizing procedure, leads to biases in the estimates of monthly trends in temperature data. To see why, consider an idealized temperature variation

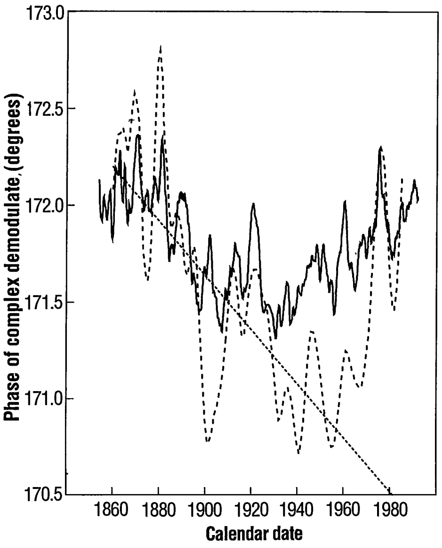


Fig. 5. Phase of the Jones-Wigley Northern Hemisphere land plus marine average temperature (solid). A projection filter of bandwidth 0.5 cycle per year was used. The dashed line is the average phase for the 156 individual stations at latitudes above 23°N. Stations were selected for length and data quality, not uniformity of coverage, so their phase is more variable than that of the Jones-Wigley series. Because phase demodulation is nonlinear, phase of the average is not expected to equal the average of the phases. The marine component may also help to stabilize the Jones-Wigley series. The dotted line shows the slope corresponding to the general precession constant. In the Jones-Wigley series, phase clearly followed precession from 1860 to about 1920.

$$T(t) = A\cos[2\pi t + \theta_0 + \phi(t)] \qquad (5)$$

where θ_0 is the average phase, and $\phi(t)$ is the drift in phase about the average. Subtract an average climatology with an exact 1-year period

$$C(t) = A\cos[2\pi t + \theta_0] \qquad (6)$$

where both the amplitude and average phase are correct and the only error is in ignoring $\phi(t)$. For small $\phi(t)$, the anomaly, $R(t) = T(t) - C(t)$ is approximately

$$R(t) \approx -A\phi(t)\sin[2\pi t + \theta_0] \qquad (7)$$

When $\phi(t)$ has a linear trend, as above, the anomaly series will have a seasonally dependent linear trend.

In the Northern Hemisphere the annual cycle has an average amplitude $\bar{A}$ of about 6.7°C, so the monthly slope should vary by ±0.16°C per century from the frequency difference alone. The median amplitude of the 188 northern station records considered above, 12.3°C, would give a range of slopes of ±0.29°C per century. Compared to the average temperature slope observed over the last century, about 0.65°C per century, this is a large error (*52*). In the Northern Hemisphere the phase θ_0 is near 180°, so Eq. 7 gives a positive slope in spring and negative in the fall. The data in Fig. 8 show that the seasonal change in slope arises mostly from the assumption that the frequency of the temperature cycle is the same as that of the insolation cycle. Thus it appears that the seasonal changes in slope are related not to global warming but to precession. This result supports Lindzen's

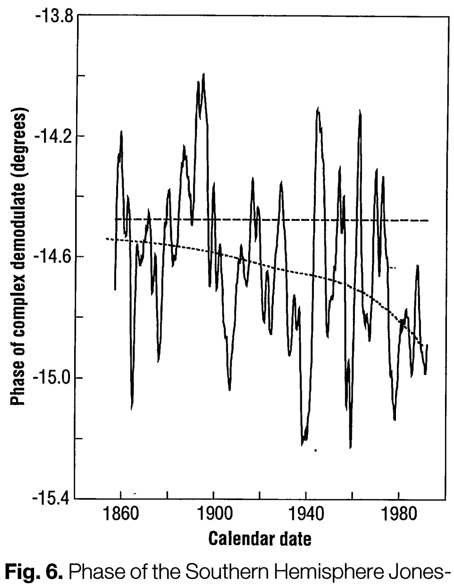


Fig. 6. Phase of the Southern Hemisphere Jones-Wigley land plus marine average temperature series. Unlike the Northern Hemisphere, the average phase may have been timed by the equinoxes. The dashed line shows constant phase and a fit with log of atmospheric CO_2 levels.

argument (*4*) that these seasonal effects are not a direct global warming signal.

There are additional problems with statistical analyses in which the annual cycle is subtracted. First, seasonal differences in trends have been used to argue for specific hypotheses for polar regions where the amplitude of the annual cycle can be large (*4*). For example, at Verhojansk (67.55°N 133.38°E), a station used in generating the histogram shown in Fig. 4, monthly average temperatures have ranged from −55.4° to 19.9°C, and the amplitude was about 32°C. Thus, slope errors computed there will be five times those of the hemispheric averages. Second, for the most part, temperature anomaly series are based on a 1951 to 1980 reference period. During this interval, phase was beginning to depart markedly from its pre-1940 patterns and, in many locations, at rates much greater than 50″/year. Using the above simple argument with a random phase instead of the simple offset implied by precession implies that errors in individual records could be several times that given above. In particular, applying the same argument to the reference period when the average slope may have shifted by about +200″/year implies that spurious seasonal slopes could exceed ±1°C per century for recent parts of the anomaly series, and several times that in polar regions. One major effect of this spurious component is to inflate the variance of the average unnecessarily. Clearly, many perceived regional differences based on seasonal trends may be unreliable. These arguments do not mean that there are no real seasonal differences in trend, but simply implies that reliable detection of them requires careful analysis. The amplitudes and phases of harmonics of the annual cycle are also shifting rapidly. In particular the amplitude of the 2 cycles per year harmonic is increasing, and the phase at some locations has changed by 180°. Thus the shape of the seasonal cycle is changing along with the amplitude. In consideration of this remarkable sensitivity of the estimated seasonal slopes to subtle differences in the length of the year, the process of deseasonalizing temperature records must be more complicated than current practice, and at a minimum, precession must be included.

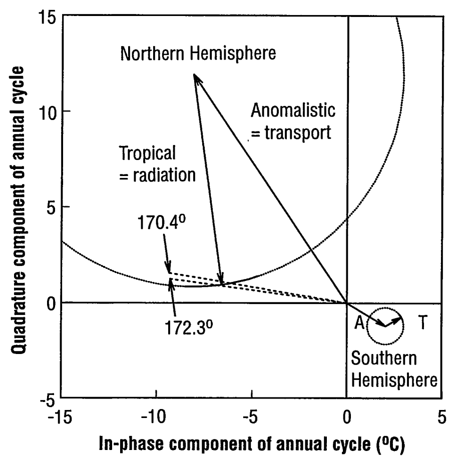


Fig. 7. Vector representation of the coefficients of the anomalistic and tropical year components of the annual cycle of the Jones-Wigley hemispheric series. The fit was made on the epoch 1854 to 1942. In the Northern Hemisphere the two components largely cancel, so that slight perturbations of either can change the vector sum disproportionally. The two resultant vectors labeled 170.4 and 172.3 degrees correspond to that obtained by extrapolating the fit shown in Fig. 5 and the observed phase in 1990 and show how a slight relative change in the radiation component can cause a large change in phase. Because the amplitude of the annual cycle is low, accuracy of the Southern Hemisphere estimates is low. The circles centered on the tips of the transport components have the magnitude of the radiation component as radius; the pattern rotates around the origin once per anomalistic year.

Amplitude of the annual cycle and solar variability. A large uncertainty in the interpretation of temperature records comes from our lack of knowledge about solar variability. Recent measurements (*53, 54*) show that the solar irradiance changes during the solar cycle, but, over the time that precision measurements have been available, these changes have been about one part per thousand, too small to cause the observed changes in temperature. These changes in solar luminosity are smaller than those observed (*55*) in stars whose composition and age are thought to be similar to the sun's. Foucal (*56*) showed that these larger solar variations would be incompatible with the ^{14}C and ^{10}Be records.

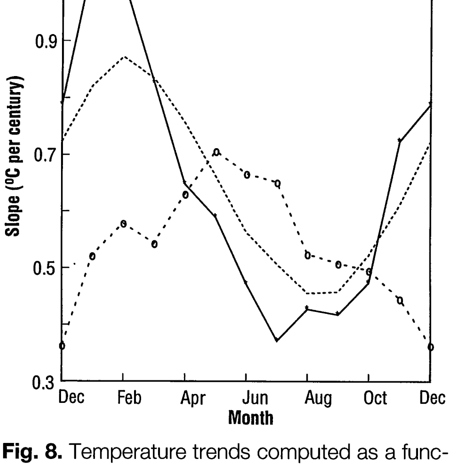


Fig. 8. Temperature trends computed as a function of month for the Hansen-Wilson Northern Hemisphere average temperature (solid) and the expected trend resulting from precession, Eq. 7, (dotted). The dashed line marked with open circles shows the monthly trends for the Southern Hemisphere. Effects of both frequency offsets and more than one harmonic are visible. This suggests that the phase of the temperature cycle in the south followed precession in agreement with the average for individual Southern Hemisphere stations, and the fit in Fig. 7.

Friis-Christensen and Lassen (*57*), recently proposed that if the period of the sunspot cycle were used as a proxy for the solar constant, then almost all the long-term variability in the instrumental temperature series, including the trend of the last century, could be explained. This hypothesis was somewhat suspect because, first, there are many possible nonlinear transformations of time-series and no physical reason was known for the effect and, second and more seriously, the Southern Hemisphere temperature does not show the 1940 to 1970 cooling observed in the Northern Hemisphere that the hypothesis attributes to solar variability. An independent test of their hypothesis is possible because all the insolation formulae (*9, 58*) contain the solar irradiance, S_o, as a direct multiplier. Thus, if S_o varies as a function of time, it should induce coherent changes on the average temperature and on the amplitude of the annual cycle.

There are, however, other possible sources of coherent changes between the low-frequency and annual cycle components such as El Niño or albedo feedback, and these must be distinguished from solar effects. El Niño effects occur in well-defined frequency bands, and so are not easily confused with the hypothesized low-frequency solar variations. Albedo feedback occurs at similar low frequencies, but experiments with increased atmospheric CO_2 concentrations in general circulation models (*59*) imply that the low-frequency phase of the coherence from albedo feedback should be 180°, whereas for solar forcing this phase should be in-phase, or 0°.

To test between the solar and CO_2 albedo feedback hypotheses, I first used projection filters (*25*) to extract two nonoverlapping frequency bands from the Jones-Wigley Northern Hemisphere series, $x(t)$. The first of these was the low-pass, real-valued signal $\bar{x}(t) = \bar{y}(t|0)$, from the frequency range (−0.5, +0.5) cycle per year. The series $\bar{x}(t)$ is a measure of the average temperature. The second extract was a band-pass signal $\bar{y}(t|1)$, from the frequencey range (+0.5, +1.5) cycle per year, which includes the annual cycle. The magnitude of the band-pass signal, $A(t) = |\bar{y}(t|1)|$ is an estimate of the amplitude of seasonal variation. I then looked for coherent variation between $\bar{x}(t)$ and $A(t)$. To estimate these coherences I used multiple-window methods (*14, 23, 30*) with the bandwidth large enough to accommodate the hypothesized range of frequency variations. Because I am testing the hypothesis that changes in solar luminosity are changing both the average and amplitude coherently (and are responsible for the observed trend in average temperature), I only removed averages, but not trends, before this calculation.

One feature in the Northern Hemisphere amplitude (Fig. 9) is the decrease in level attributed to improved thermometer screens introduced around 1880; otherwise there are small oscillatory variations. The amplitude of the annual cycle, $A(t)$, does not show the 1940 to 1970 cooling apparent in the average temperature series, and from about 1920 to present the amplitude has been slowly decreasing. The low-frequency average temperature was roughly constant from 1854 to 1920, but since then, has increased episodically. In the Southern Hemisphere (Fig. 10) the increase in average temperature has a more uniform character than in the Northern Hemisphere. The amplitude of the annual cycle, although only about 3.05°C, has a trend of −0.027°C per century.

In the early part, 1854 to 1923, of the Jones-Wigley Northern Hemisphere record $\bar{x}(t)$ and $A(t)$ are moderately coherent with each other, $A(t)$ and Wolf sunspot numbers are highly coherent, and both these coherences are in-phase (Fig. 11). There is also coherent variation at several discrete frequencies that suggests solar variations and El Niño effects. The phase of the coherence (Fig. 11, upper right) has a linear trend showing an average time-delay of about 4.3 years (60). There is also reasonable coherence (not shown) between the sunspots and average, also in-phase. In the last half of the series, 1923 to 1991, coherence between the average and amplitude is high, and the phase stays close to 180°C, independent of frequency. At low frequencies this squared coherence is high, about 0.7, and significant above the 99.8 percent point; its 180° phase implies that albedo feedback, not solar variations, is the cause. Analysis of the Southern Hemisphere Jones-Wigley series give similar results (in-phase in the first half, 180° phase in the last half), with indecisive significance levels (*61*).

Similar coherences between the amplitude of the Central England annual cycle and the sunspot numbers from 1752 to 1950 are higher than those from the early part of the Northern Hemisphere series, and the phase of the coherence shows that modulation of the annual cycle leads the average temperature by about 2.3 years, perhaps the transport time of the Gulf Stream.

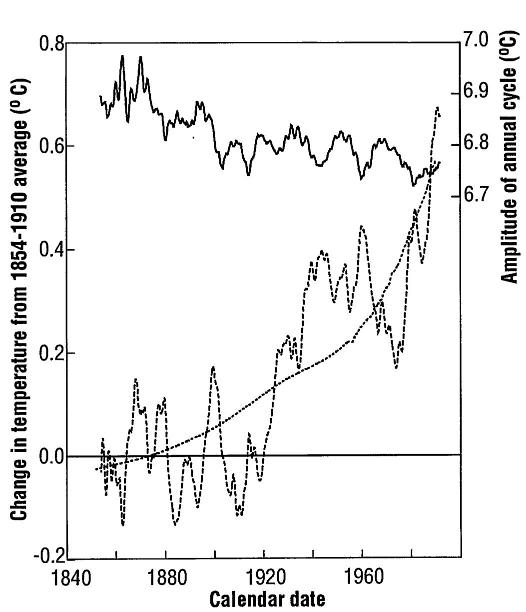
From these coherence estimates, I conclude that solar variability (*63*) causes small fluctuations in temperature on decade time scales, consistent with recent satellite measurements, but is at most a minor factor in the increase in average temperature observed over the last century. The decreasing slope of the amplitude in the annual cycle observed since 1900 implies that either solar output has been decreasing, or that albedo feedback is already occurring. In either case, the worldwide increase in average temperature may be larger than previously recognized.

The sudden increase in average temperature about 1923, which is obvious in Fig. 9, is accompanied by abrupt phase changes of more than 5° on the annual cycle at 35 of the 222 stations used above (see Fig. 5). Changes on the second harmonic are more dramatic, with 98 locations changing phase more than 30°, 20 of these by more than 90°, and 5 by about 180°. This suggests that the episodic temperature increases may be caused by a switch in ocean or atmospheric circulation, consistent with a phase capture.

CO_2 and changes in the annual cycle. The analysis above showed that phase characteristics changed suddenly about 1940 in many long series. Numerous causes for changes in the recent climate have been considered (*16, 64*). The leading contenders are changes in the sun's luminosity and the increasing atmospheric concentration of CO_2 caused by burning fossil fuels.

To test the hypothesis that atmospheric CO_2 concentration is responsible for the changes on the annual cycle, I regressed Eq. 4 on the (+0.5, +1.5) cycles per year complex demodulates from 1854 to 1940 and computed the partial residuals (*66*) on both the tropical year component, $R_T(t) = y(t) - \hat{C}e^{i2\pi f_T t}$ and on the anomalistic year $R_A(t) = y(t) - \hat{D}e^{i2\pi f_A t}$ for the entire time span. A plot of the estimated amplitude of the tropical year partial residual $|R_T(t)|$ (not shown) has a rapid increase in amplitude after mid-century as its predominant feature. The shape of the increase, moreover, resembles the long-term trend in atmospheric CO_2 levels. The anomalistic year residual, $|R_A(t)|$ shows comparatively little change. Because the tropical year component is the one primarily responding (*67*) to direct radiative forcing and the greenhouse effect is fundamentally a modification of the radiative transfer process, I interpret this change in partial residuals to be consistent with the hypothesis that greenhouse forcing is present.

My attempts to estimate the effect of CO_2 on the amplitude, $A(t)$ gave estimates showing that doubling CO_2 decreases the amplitude of the annual cycle between 0.18° and 0.46°C, consistent with albedo feedback. Before systematic measurements (*68*) of atmospheric CO_2 began in 1958, the quality of the CO_2 record is marginal for time scales of a few years. The irregular and



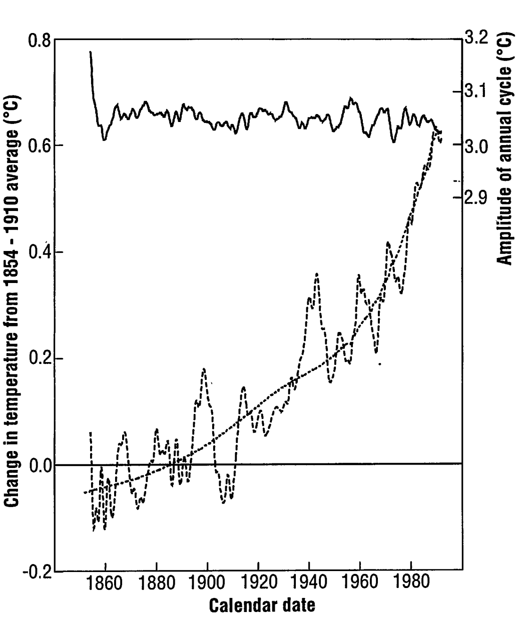


Fig. 9 (left). Amplitude of the annual cycle and low-pass extracts from the Jones-Wigley Northern Hemisphere series. The low-pass filtered part is plotted as changes from the 1854 to 1910 average. Projection filters with a bandwidth of 0.5 cycle per year were used to compute both. Note that, unlike the low-pass part, or average, the amplitude of the annual cycle (right-hand scale) has been decreasing, arguing against solar variability as the cause of the increasing average temperature. The dotted line shows a least-squares fit to the low-pass extract by regressing on the logarithm of atmospheric CO_2 concentration and a constant. **Fig. 10 (right).** Southern Hemisphere equivalent of Fig. 9. The first few years have low spatial coverage so the rapid changes before 1860 are probably unreliable.

sparse samples make estimating transfer functions from the early CO_2 record difficult (69). This, combined with the numerical difficulties in separating the closely spaced frequency components, and particularly the problems with early thermometer screens, are responsible for the large uncertainty in the estimate. Despite this uncertainty, continuation of a decreasing trend in amplitude may imply a problem: As the magnitudes of the two components of the annual cycle approach each other, slight perturbations in either (from volcanic activity, changes in albedo, and so forth) may make rapid transitions between their phases easier (*70*).

Estimates of the effects of atmospheric CO_2 levels on the phase $\theta(t)$ were more satisfactory. Although the same data are used, the changes in phase are relatively larger than those in the amplitude of the annual cycle, separate estimates of both frequency components are not needed, and the lack of thermometer screens is almost irrelevant. Using ordinary least-squares, I fitted the change in phase of the Jones-Wigley Northern Hemisphere series from precession (Fig. 12) using only a constant and the $\log_2$ of the atmospheric CO_2 levels. The agreement is visually good at low frequencies. However, such simple fits do not give a valid significance test in time series. The magnitude-squared coherence (MSC) (Fig. 13) between the phase change and $\log_2 CO_2$ is 0.96 at low frequencies, significance of 8 σ. Even though the early part of the CO_2 record is of marginal quality and has likely been over-smoothed, MSC in the El Niño band is also about 0.5, with a corresponding significance level of about 99%. The phase change in the Southern Hemisphere is also significant.

To summarize these and similar tests, I obtained time series representing various climate forcings; perturbations from an elliptic orbit, El Niño, volcanic activity (*71*), stratospheric aerosols (*72*), and solar variability. I computed coherence between each of these and the low-pass, $\bar{x}(t)$, amplitude $A(t)$, and phase $\theta(t)$ of the band-pass extract of the Jones-Wigley temperature series. All of these climate forcing signals explain some of the observed changes in the temperature series. However, only CO_2 is significantly coherent with the observed recent large changes in phase and average temperature.

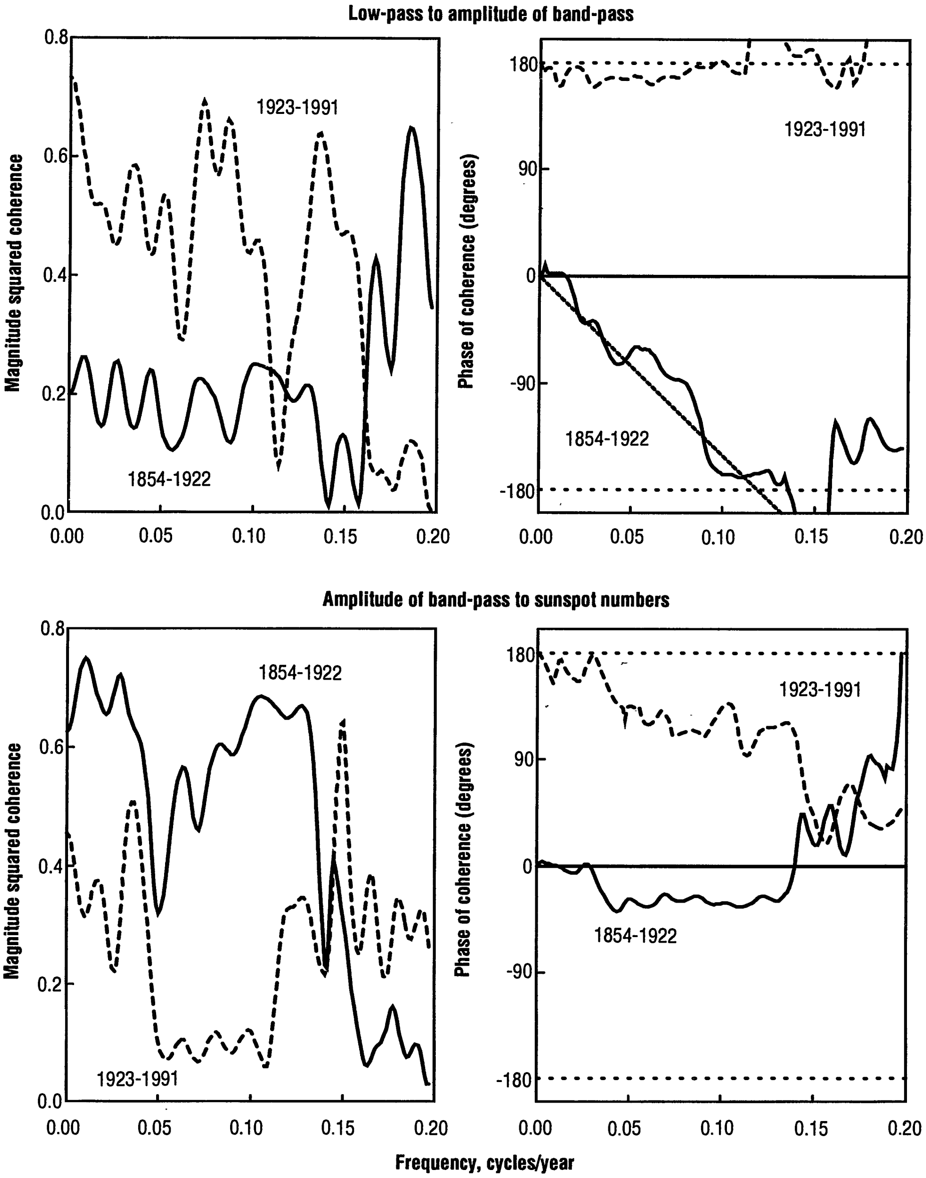


Fig. 11. Coherence tests for solar variability. The upper pair of plots are estimates of the magnitude-squared coherence and phase between the low-pass filtered data and the amplitude of the annual cycle for the Jones-Wigley extracts shown in Fig. 9. The solid line is for the first half of the series, 1854 to 1922. The coherence is only moderately significant. At low frequencies changes in the average are in phase with those in the amplitude, arguing for solar forcing. As shown by the dotted line on the phase plot, changes in the average lag those in the amplitude by about 4.2 years. The dashed line shows the same calculation for 1923 to 1991; the coherence is stronger and the phase is near 180 degrees across the band, as predicted for albedo feedback. The lower panels show similar coherence tests between the amplitude of the annual cycle and the sunspot numbers for the same two intervals. In the early data the coherence is large and nearly in-phase, but in the last half of the record the coherence has dropped and the phase reversed arguing that the solar modulation seen in the first half of the record is being overwhelmed by albedo feedback.

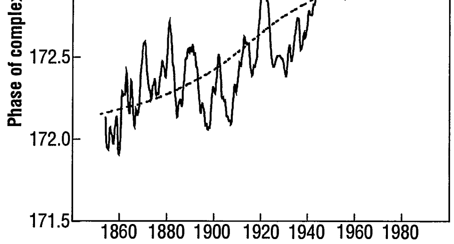


Fig. 12. Phase of the Jones-Wigley Northern Hemisphere land plus marine temperature series, Fig. 5, after a linear offset 50″.256. (t − 1854) from precession has been added. It is thus an estimate of deviation of the phase from the trend in Fig. 5 that was observed in the early part of the record. The dashed line is a least-squares fit to the phase regressed on the logarithm of atmospheric CO_2 levels and a constant. For a significance test, see Fig. 13.

Incidental observations and speculations. The analysis I have given does not cover the entire globe. Because the anomalistic and tropical years are so close in frequency, long series are needed to tell one from the other. Also, tropical regions with a weak annual cycle do not have as well-determined phases as the temperate zones. Finally, some stations seem to have much greater intrinsic variability than others, whether from various global oscillations (*73, 74*) or, perhaps, proximity to the auroral regions.

The increasing phase observed after 1940 for the Northern Hemisphere average seen in Fig. 5, clearly does not hold at all locations, and many records, as in Figs. 1 to 4, show that the phase is decreasing rapidly. Taylor-series arguments imply that this phase divergence must be accompanied by increasing temperature gradients in spring and autumn when the average temperature is changing rapidly. These may be related to the perceived increasing variability of the climate. The phase changes observed in northwestern Europe seem to have a different source than those for the hemispheric average. These possibly may reflect changes in the Gulf Stream. The most obvious natural explanation of the observed changes, termination of the Holocene, seems to be incompatible with the change in Northern Hemisphere average phase and the increasing average temperature.

While the influence of orbital changes on the climate on the time scale of the Pleistocene are well documented (*8, 12*), the exact mechanisms for coupling changes in the Earth's orbit into the climate system are debated (*75*). Also, while most of the dominant frequencies predicted by celestial mechanics (*9, 58, 76*) are accurately reproduced by analysis of long climate series (*23*) the paleoclimate record contains much evidence (*77*) for rapid variations at rates much higher than predicted by the Milankovitch theory. This study raises the possibility that eccentricity may have a larger, and different, effect than previously thought, and that the relative magnitudes of average and direct insolation may be critical in determining climate. It may be that climate behaves in a simple manner only when eccentricity is low or, possibly, when the tropical and anomalistic years are in reasonable phase alignment. Is it possible that the capture effect, perhaps triggered by solar forcing, may be responsible for some of the abrupt transitions seen in the climate record?

The decade-scale fluctuations in the phase (Figs. 1 to 3) need to be further understood. In the Central England series, the MSC between the phase fluctuations and the sunspot numbers reaches 0.8 (significance level ~ 99.8%) at periods near 30 years. This corresponds to the phase drift of ~12° per year in the coherence between amplitude changes and sunspot numbers (*14*) and suggests that phase change is primary and the observed amplitude effect a derivative term. These 30-year modulations may be detected in many long temperature records and, as estimates of the period seem suspiciously close to one-third of the 104-year Suess period (*31*), the connections to Suess wiggles noted (*42*) also needs further study. Is this phase modulation related to total solar irradiance, energetic particles (*78, 79*), changes in ultraviolet irradiance (*53*), or something else?

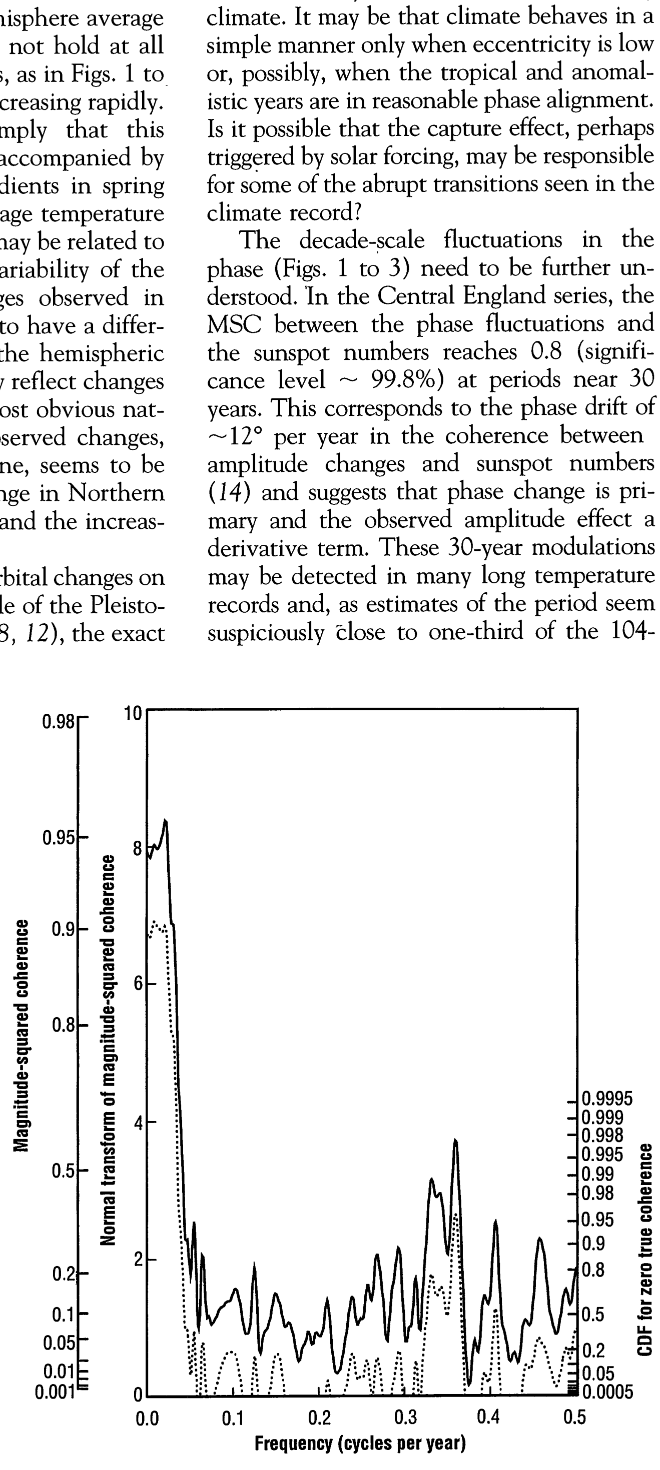


Fig. 13. Magnitude-squared coherence (outer left scale) between the phase of the Jones-Wigley Northern Hemisphere annual cycle and the logarithm of Keeling's atmospheric CO_2 series from 1854 to 1991. A multiple-window method with a time-bandwidth product of 4.5 and 8 windows was used. The right scale shows the cumulative probability distribution for independent series. The inner left scale is a $\tanh^{-1}$ transform to normal units. The dotted line is one jackknife standard deviation down from the estimate; with Gaussian data the spacing should be 1 unit on the normal scale. Coherence is high in the El Niño band, around 0.35 cycle per year, and exceptionally so near 0.02 cycle per year.

Summary and implications. These results have several implications for climate research. First, orbital effects cannot be ignored in the analysis of contemporary climate time-series. Anomaly series used in climate research that have been deseasonalized by subtracting monthly averages need to be recomputed. The best method for doing this is not obvious (*49*). Similarly, conclusions based on perceived seasonal differences in temperature trends need to be reexamined. It is possible that suitable information can be extracted from the modulations on the annual cycle and its harmonics in temperature series. Second, attempts might be made to find a greenhouse fingerprint by matching observations and the outputs of general circulation models that explicitly include the evolution of Earth's orbit. Third, significant efforts must be made to understand the consequences of the annual temperature cycle following precession rather than the equinoxes, and of the capture effect.

These results also involve the greenhouse effect. First, the effects of increasing greenhouse gases may be worse than previously thought. Removal of the precessional seasonal-dependent trend from the temperature series increases the statistical significance in the general increase in temperature. This seasonal dependence in trend had been used to argue against the influence of greenhouse warming, and this argument is now void. Second, simple solar variation is not a statistically viable explanation for the increase in average temperature. Indeed, the evidence on the annual cycle would argue for either decreasing solar luminosity over the last few decades, or, equally serious, induced changes in albedo. If true, this might explain why the observed greenhouse warming has been less than many models predict and less than would be expected from paleoclimate evidence. Third, the rate of change in the timing of the seasons in the Northern Hemisphere is without precedent in the instrumental data records.

Finally, given the importance of a stable seasonal cycle for biological processes (*80*) and the problems that late springs or early frosts cause for agriculture, an unpredictable phase in the climate may be a more serious problem to society than changes in the amplitude of the annual cycle or even of the average temperature.

REFERENCES AND NOTES

1. P. D. Jones, *J. Climate* **7**, 1794 (1994).
2. J. Hansen and S. Lebedeff, *J. Geophys. Res.* **92**, 13345 (1987).

3. K. Ya. Vinnikov, P. Ya. Groisman, K. M. Lugina, *J. Climate* **3**, 662 (1990).
4. R. S. Lindzen, *Bull. Am. Meteorol. Soc.* **71**, (1990).
5. S. H. Schneider, *Science* **263**, 341 (1994).
6. R. A. Kerr, *ibid.* **267**, 612 (1995).
7. J. Croll, *Philos. Mag.* **33**, 119 (1867).
8. A. Berger, J. Imbrie, J. Hays, G. Kulka, B. Saltzman, Eds., *Milankovitch and Climate, Vol. I, II* (Reidel, Dordrecht, 1984).
9. J. Laskar, F. Joutel, F. Boudin, *Astron. Astrophys.* **270**, 522 (1993).
10. B. L. Gurnette and R. v. d. R. Wooley, *Explanatory Supplement to the Astronomical Ephemeris* (Her Majesty's Stationary Office, London, 1961).
11. The motions are complicated and contain many periodic terms in addition to the secular ones. See chapter 7 of (*12*). Strictly speaking, the frequency difference being measured is not the simple difference between the tropical and anomalistic years, but the combination of changes in the longitude of perihelion, the vernal equinox, lunisolar, and planetary precession terms, all summarized as general precession.
12. T. J. Crowley and G. R. North, *Paleoclimatology*, (Oxford Univ. Press, Oxford, 1991).
13. M. Schwartz, W. R. Bennett, S. Stein, *Communications Systems and Techniques* (McGraw-Hill, New York, 1966).
14. C. Kuo, C. R. Lindberg, D. J. Thomson, *Nature* **343**, 709 (1990). Reprinted in *Coherence and Time Delay Estimation*, G. C. Carter, Ed. (IEEE Press, New York, 1993), pp. 395–400.
15. H. Ogura, *IEEE Trans. Inf. Theory* **IT-17**, 143 (1971).
16. J. T. Houghton, G. J. Jenkins, J. J. Ephraums, Eds., *Climate Change The IPCC Scientific Assessment* (Cambridge Univ. Press, Cambridge, 1990).
17. For most of the calculations I have ignored the variable lengths of the months and treated the data as being equally spaced at a time step of one-twelfth year. A Taylor's series expansion in the difference between the true and approximate monthly dates gives a high-frequency noise term that is small over the frequency ranges plotted here. See L. Shaw, *IEEE Trans. Audio Electroacoust.* **AU-19**, 24 (1971). As a check, I rewrote several of the programs using exact Julian day numbers for the middle of the months and centered the filters exactly on the tropical year. Graphically, the results are indistinguishable.
18. P. Bloomfield, *Fourier Analysis of Time Series: An Introduction* (Wiley, New York, 1976).
19. T. Hasan, in *Handbook of Statistics*, D. R. Brillinger and P. R. Krishnaiah, Eds. (North-Holland, Amsterdam, 1983), vol. 3, pp. 125–156.
20. J. W. Tukey, *Technometrics* **3**, 191 (1961). Reprinted, in *The Collected Works of J. W. Tukey, I*, D. R. Brillinger, Ed (Wadsworth, Belmont, CA, 1984).
21. The annual cycle is usually so dominant that even a simple, unwindowed Fourier transform is adequate (but not recommended) to extract the phase and amplitude characteristics.
22. D. Slepian, *Bell System Tech. J.* **57**, 1371 (1978).
23. D. J. [illegible]*ilos. Trans. R. Soc. London Ser. A.* **332**
24. D. J. Thomson, *Proc. IEEE Seventh SP Workshop on Statistical Signal and Array Processing*, 39 (1994).
25. Projection filters (*24*) use the optimality properties of the discrete prolate spheroidal sequences, or Slepian sequences (*22, 23*), to isolate a narrow-band signal, minimize leakage from signals at other frequencies, and to provide statistical diagnostics on the filtering operation. Expand the part of a discrete-time process $x(t)$ in the frequency band $(f - W, f + W)$ and the interval $[b, b + N - 1]$ on a basis of the Slepian sequences $\nu_n^{(k)}(N, W)$ using the eigencoefficients

$$y_k(f, b) = \sum_{n=0}^{N-1} x(b+n) e^{-i2\pi f(b+n)} \nu_n^{(k)}(N, W) \qquad (8)$$

for $k = 0, 1, \ldots, K = [2NW] - 1$. Using the completeness and orthonormality properties of these sequences, reconstruct the complex baseband analytic process at time t by forming

$$\hat{y}(t, \mid f, b) = \sum_{k=0}^{K-1} y_k(f,b)\, \nu_{t-b}^{(k)}(N, W) \qquad (9)$$

and note that for each t there are N such estimates beginning with $b = t + 1 - N$ and ending with $b = t$. While the individual estimates suffer from Gibb's ripples, they may be averaged over base positions to form

$$\bar{y}(t \mid f) = \sum_{b=t+1-N}^{t} \hat{y}(t \mid f, b) \qquad (10)$$

a narrow band representation that covers the entire time span available although with slightly poorer accuracy at the ends of the series than in the center where all N overlapping expansions are available. The averaging greatly reduces the Gibb's ripples, and they may be eliminated by use of the inverse theory described in J. Park, *Statics in the Environmental and Earth Sciences*, A. T. Walden and P. Guttorp, Eds. (Arnold, London, 1992), chap. 10. Typically, both the eigencoefficients, Eq. 8, and the different reconstructions averaged in Eq. 10 are weighted, and in the filters I used, the procedure was iterated and a form of coherent sidelobe cancellation was used. In addition to giving an output series that is the same length as the input, differences between the different reconstructions (Eq. 9) may be used, in a form of resampling, to monitor the reliability of the results.
26. J. A. Barnes, *Proc. IEEE* **54**, 207 (1966).
27. S. A. Tretter, *IEEE Trans. Inf. Theory* **IT-31**, 832 (1985). The double line case is covered in H. Ge and D. W. Tufts, *IEEE Trans. Signal Process.* **41**, 1982 (1993).
28. B. Kleiner, R. D. Martin, D. J. Thomson, *J. Royal Statist. Soc.* **B-41**, 313 (1979).
29. A. D. Chave, D. J. Thomson, M. E. Ander, *J. Geophys. Res.* **92**, 638 (1987).
30. D. J. Thomson, *Proc. IEEE* **70**, 1055 (1982).
31. D. J. Thomson, *Philos. Trans. R. Soc. London Ser. A.* **330**, 601 (1990); in *The Earth's Climate and Variability of the Sun over Recent Millennia*, J.-C. Pecker and S. K. Runcorn, Eds. (The Royal Society, London, 1990), pp. 203-218.
32. L. I. Tauxe, *Rev. Geophys.* **31**, 319 (1993).
33. D. B. Percival and A. T. Walden, *Spectral Analysis for Physical Applications: Multitaper and Conventional Univariate Techniques* (Cambridge Univ. Press, Cambridge, 1993).
34. D. J. Thomson and A. D. Chave, in *Advances in Spectrum Analysis*, S. Haykin, Ed. (Prentice-Hall, Englewood Cliffs, NJ, 1991), chap. 2.
35. S. O. Rice, *Bell System Tech. J.* **27**, 109 (1948).
36. D. Middleton, *Statistical Communication Theory* (McGraw Hill, New York, 1960).
37. G. Manley, *Q. J. R. Meteorol. Soc.* **100**, 389 (1974).
38. D. E. Parker, T. P. Legg, C. K. Folland, *Int. J. Climatol.* **12**, 317 (1992).
39. Note that FM receivers commonly discard amplitude information entirely by hard limiting, and that accurate amplitudes are not required for accurate phase estimation.
40. The estimated standard deviation of the Central England series, 6″.82/year, is considerably higher than expected from measurement noise. The standard deviation of a frequency estimate made from a signal $A\cos(2\pi ft + \theta)$ with no other close frequency components embedded in white Gaussian noise of variance σ^2 is $Var\{\hat{f}\} = (12\Delta T\sigma^2)/(\pi^2 A^2 T^3)$ where T is the total observation and ΔT the sampling time. See D. C. Rife and R. Boorstyn, *Bell System Tech. J.* **55**, 1389 (1970). For the Central England series, uncorrelated errors with a large standard deviation of 0.25°C imply a frequency standard deviation of 1″.96/year. This discrepancy is discussed later in the text. Note that the variance from the 330-year Central England series is less than the ensemble variance from 30 independent century-long records.
41. The small difference in equilibrium temperature between perihelion and aphelion appears superficially too small to control phase at the latitudes of Northern Europe where changes in insolation are large. Insolation changes in the polar regions are even larger than in England, but atmospheric transport of energy clearly maintains the minimum temperature well above the 3 K big bang background temperature. For the Central England series monthly averages of blackbody temperatures from the insolation formulae range from 114.1 to 302.1 K. The monthly climatology, however, ranges only from 275.8 to 289.1 K, so heat transport dominates direct insolation.
42. Although the phase trends are different at the three locations, the remarkable coherence between decade-scale phase variations is not what one expects to find in noise. Preliminary analysis of these fluctuations suggests that solar effects both at the usual sunspot cycle periods and also at frequencies normally associated with the ^{14}C Suess wiggles (*31*) may be present.
43. The early part of the Paris record seems to be quite noisy, possibly a result of the large Icelandic volcanic eruptions noted in H. H. Lamb, *Philos. Trans. R. Soc. London* **266**, 425 (1970).
44. Because 360 ≈ 365, I frequently refer to phase changes in degrees or days interchangeably. The calculations are done in degrees.
45. T. A. Boden, D. P. Kaiser, R. J. Sepanski, F. W. Stoss, *Trends '93: A Compendium of Data on Global Change Publ. ORNL/CDIAC-65* (Oak Ridge National Laboratory, Oak Ridge, TN 1994).
46. In these calculations the filter (Eq. 2) had a 10-year span, so the 1895 to 1940 phase trend includes temperature data from 1890 to 1945, while the 1940 to 1985 trend includes data from 1935 to 1990.
47. The average climatologies for the Jones-Wigley hemispheric series were provided by P. D. Jones, personal communication.
48. The anomaly series was directly demodulated and the Fourier coefficient of the climatology added to the result. With linear filters the result is identical to adding the climatology directly to the anomaly and filtering; with adaptive weighting, better sidelobe suppression is obtained.
49. Examination of the numerical analysis (*50*) and parameter estimation (*51*) literature shows that simply fitting a temperature record by least squares using an approximation such as

$$X(t) = a + b\,t + c\cos(2\pi f_T t + \theta_T) + d\cos(2\pi f_A t + \theta_A)$$

(where f_T and f_A are the frequencies of the tropical and anomalsitic years) is ill-conditioned. One method that appears to work reasonably for this problem is the following: First, frequencies around +1 cycle per year are isolated with the use of a projection filter. Second, I assume that the response to the forcing at the two frequencies is linear, Eq. 4. Third, I define $\omega_o = \pi(f_T + f_A)$ so Eq. 4 may be written

$$Z(t) \approx e^{i\omega_o t}[C'\cos(\delta\, t) + D'\sin(\delta\, t)] \qquad (11)$$

where $\delta = \pi(f_T - f_A)$. If the time origin is taken at the center of the series, the two terms are orthogonal, and the filter output fits reasonably. (Because δ is small, the cosine and sine terms are approximatley 1 and $\delta\, t$ respectively). C' and D' can be found by robustified least-squares and hence give $C = ½(C' - iD')$ for the tropical year and $D = ½(C' + iD')$ as the coefficient describing the anomalsitic year dependency. A second approach would be to use the seasonal dependence in slope to extract the two amplitudes. This could be more easily applied in series with long stretches of missing data. However, at best, deseasonalizing is a tricky and fundamentally ill-conditioned operation so that real changes in seasonal characteristics may be easily confused with the frequency offset.
50. C. L. Lawson and R. J. Hanson, *Solving Least Squares Problems* (Prentice-Hall, Englewood Cliffs, NJ, 1974).
51. G. A. F. Seber, *Linear Regression Analysis* (Wiley, New York, 1977).
52. Temperature variations are more complicated than given by Eq. 5, but if further terms of the trigonometric series are included, the effect of the frequency offset on the kth harmonic scales by a factor of k.
53. J. Lean (chair), *Solar Influences on Global Change* (National Research Council, Washington, DC, 1994).
54. J. Lean, *Reconstructions of Past Solar Variability*, in *Climate Variations and Forcing Mechanisms of the Last 2,000 Years*, P. Jones, J. Jouzel, R. Bradley, Eds. (*NATO ASI Ser.*, Riedel, Dordrecht, in press).

55. S. Balunias and R. Jastrow, *Nature* **348**, 520 (1990).
56. P. Foucal, *Science* **264**, 238 (1994); *ibid.* **266**, 1072 (1994).
57. E. Friis-Christensen and K. Lassen, *ibid.* **254**, 698 (1991).
58. A. Berger and M. F. Loutre, *Quat. Sci. Rev.* **10**, 297 (1991).
59. S. Manabe and R. J. Stouffer, *J. Geophys. Res.* **85**, 5529 (1980).
60 A linear phase slope in coherence implies a simple time delay.
61. Perhaps because of the large ratio of ocean to land areas in the Southern Hemisphere, and the large thermal inertia of the oceans, time delays appear to be much larger than in the Northern Hemisphere, so the coherence estimates are unreliable. The disagreement between the phase of the Southern Hemisphere average temperature and the average of phase slopes from individual long records may have the same cause. It is often claimed that historical temperature data are just noise, or worse. I argue that temperature records that are that good enough to distinguish a few arc seconds per year deserve more respect. Science requires that the differences between signals and noise be well understood (*62*) and, with climate data, this does not yet appear to be accomplished.
62. A. A. Penzias and R. W. Wilson, *Astrophys J.* **142**, 419 (1965).
63. Statistical analysis of climate time-series has received dismissive treatment (*64*) with the change in the Lake Victoria record (*65*) often used as a specific example of their failings. The change in the Lake Victoria record appears to coincide with the rapid increase in average temperature visible about 1923 in Fig. 7, and the probable increase in albedo feedback shown above. Thus I suggest that a more reasonable interpretation of this example is that the statistics were showing what they should have shown, and that the failure was in not recognizing a major shift in the climate system.
64. J. T. Houghton, B. A. Callander, S. K. Varney, *Climate Change 1992*, (Cambridge Univ. Press, Cambridge, 1992).
65. J. A. Eddy, in *Weather and Climate Responses to Solar Variations*, B. M. McCormac, Ed. (Univ. of Colorado Press, Boulder, 1983), chap. 1.
66. C. L. Mallows, *Technometrics* **28**, 313 (1986).
67. In a broad sense, water vapor is the most important greenhouse gas and, because the tropical atmosphere contains much water and the polar atmosphere little, increases in atmospheric CO_2 levels are expected to have proportionally greater influence away from the tropics than in them. Other things being equal, the energy available for atmospheric and ocean transport is proportional to surface area, and as half the world's area is at latitudes less than 30°, the transport, or anomalsitic year, component of temperature should be less sensitive to atmospheric CO_2 levels than is direct radiation at higher latitudes.
68. C. D. Keeling *et al.*, in *Aspects of Climate Variability in the Pacific and the Western Americas*, D. H. Peterson, Ed. (American Geophysical Union, Washington, DC, 1989), pp. 165–363.
69. See the discussion surrounding figures 33 and 34 and table A.6 of (*68*). Equivalent CO_2 data from T. M. L. Wigley and S. C. B. Raper [*Nature* **357**, 293 (1992)]; cases I and M were also tried, but the residuals were slightly larger those from (*68*).
70. S. O. Rice, in *Time Series Analysis*, M. Rosenblatt, Ed. (Wiley, New York, 1963), chap. 25.
71. A. R. Solow, *J. Am Statist. Assoc.* **86**, 49 (1991).
72. M. Sato *et al.*, *J. Geophys. Res.* **98**, 22987 (1993).
73. M. E. Mann and J. Park, *Geophys. Res. Lett.* **20**, 1055 (1994).
74. ———, *J. Geophys. Res.* **99**, 25819 (1994).
75. J. Imbrie *et al.*, *Paleooceanography* **8**, 699 (1993).
76. T. R. Quinn, S. Tremaine, M. Duncan, *Astrohys. J.* **101**, 2287 (1991).
77. G. C. Bond and R. Lotti, *Science* **267**, 1005 (1995).
78. L. B. Callis *et al.*, *J. Geophys. Res.* **96**, 2921, 2939 (1991).
79. C. R. Lindberg, *Abstr. Am. Assoc. Adv. Sci. Ann. Meeting* **29** (1995).
80. Phase stability may be important when, for example, a species reproductive cycle is synchronized by light and reproductive efficiency depends on temperature or vice-versa. Similar problems occur if one member of a symbiotic pair is timed by light, the other by temperature. The increasing amplitudes of the second and third harmonics may, by causing a double season, also imply a very serious problem. Thus, for example, plants come into bloom during a prolonged January thaw, only to be frozen shortly afterwards.
81. I thank P. D. Jones for data, discussions, and supplying the climatologies for his average temperature series. E. M. Standish provided the planetary ephemeris and H. Coffee the solar data. U.S. government agencies, NGDC, GISS, and ORNL have provided data. C. R. Lindberg and I knew (circa 1990) that there was a serious problem with standard deseasonalizing procedures, but had not identified the source. J. B. Kruskal, R. McPherson, C. G. Maclennan, J. Park, L. J. Lanzerotti, C. D. Keeling, M.-L. Thomson, T. E. Graedel, and particularly J. C. Lagarias gave valuable comments.

4 January 1995; accepted 3 March 1995.