Combined Effects of Earth Orbit Perturbations and Solar Activity on Terrestrial Insolation. Part I: Sample Days and Annual Mean Values

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ABSTRACT

We combine calculated effects of short- and long-period orbital perturbations with modeled effects of recorded sunspot and facular activity to examine patterns of terrestrial insolation at selected latitudes in the Northern Hemisphere for the period 1874–1981. Here we consider systematic insolation effects at times of equinox and solstice and as annual means over the 108-year period. Solar activity is the more dominant term; it modulates global insolation at the period of the solar activity cycle with a maximum depletion, in years of maximum sunspot area, of about 0.1%. At high latitudes, where their effect is greatest, long-period orbital perturbations have driven annual mean insolation downward at a rate of about 0.05%/century. At middle and low latitudes this orbitally-induced, Milankovitch trend in annual mean insolation is positive and about 100 times smaller. Nutation of Earth's rotational axis induced by the gravitational pull of the moon adds a distinct modulation of 18.6-year period that significantly influences insolation at polar latitudes. Orbital perturbations by Jupiter and the inner planets add weaker modulation at shorter periods. The influence of orbital effects is to produce secular trends in combined insolation patterns that vary in amplitude, phase, and sign with latitude and time of year.

1. Introduction

The flux of solar thermal energy incident on any point at the top of the earth's atmosphere is a function of the solar constant S_0 and of instantaneous values of the sun–earth distance and the inclination of the earth's axis of rotation. Each of these parameters changes with time to modulate the latitudinal distribution of insolation.

One can readily calculate as a function of latitude the so-called astronomical variation of insolation using known variations in orbital parameters. A number of attempts have been made to replicate the effect of orbital factors on climate, both for the geological past (e.g., Sharaf and Budnikova, 1969; Hays *et al.*, 1976; Berger, 1978; Vulis and Monin, 1979) and on much shorter (one-year) time scales for the current epoch (Borisenkov *et al.*, 1983). In all of these studies it was assumed that there were no intrinsic variations in the output of the Sun itself; i.e., that S_0 is constant. Recent spaceborne measurements of the total solar irradiance have shown, however, that the so-called "solar constant" varies from day to day by as much as 0.3% as a result of modulation by sunspots and bright faculae (Willson, 1984; Willson *et al.*, 1981; Eddy *et al.*, 1982). Precise estimates of insolation for short time periods must therefore include both orbital modulation and intrinsic variations in total solar irradiance. [Hereafter we shall use the term "total solar irradiance" $S(t)$, as distinct from "solar constant" S_0, to allow explicitly for intrinsic solar variability.]

2. Orbital effects

The daily value of insolation W_τ at the top of the atmosphere at latitude ϕ may be expressed (e.g., Kondratyev, 1969) as

$$W_\tau(\phi) = \frac{\tau}{\pi\rho^2} S(t)(\omega_0 \sin\phi \cdot \sin\delta + \sin\omega_0 \cos\phi \cos\delta) = S(t) \cdot F(\phi, \delta, \rho), \quad (1)$$

where

τ = mean solar day (86 400 s.),
ρ = sun–earth distance in astronomical units,
$S(t)$ = total solar irradiance,
δ = solar declination,
ω_0 = solar hour angle at sunset, given by

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$$\cos^{-1}(-\tan\phi\tan\delta), \quad |\tan\phi\tan\delta| \leq 1,$$
$$0, \quad |\tan\phi\tan\delta| > 1.$$

Since $S(t)$ appears in Eq. (1) as an explicit function of time one must know its instantaneous value. As explained in the next section we shall use here a modeled, mean daily value of $S(t)$ to correspond to calculated, mean daily values of ρ and δ.

The parameters ρ and δ in the orbital perturbation function F can be computed as a function of time from known analytical functions. Day-to-day excursions in these two quantities will be dominated by strong seasonal periodicities that result from the eccentricity e of the earth's orbit and the inclination i of its axis of rotation. They are also modulated at lower frequencies by small changes in e, i, and the longitude of perihelion that result from lunar and planetary perturbations on the earth and its orbit.

The climatic impacts of orbital forcing of W_τ on scales of thousands of years, known as the "Milankovitch effect," are commonly cited (e.g., Milankovitch, 1939; Hays *et al.*, 1976). It is also of interest, however, to examine the nature and magnitude of orbital effects on patterns of insolation on the shorter time scales of 1 to 100 years. In this domain one can identify the secular trends of the longer, Milankovitch cycles as well as the distinct signatures of higher frequency modulations that result from lunar and planetary gravitational perturbations. As noted by Borisenkov *et al.* (1983), the amplitude of these high-frequency, orbital variations is comparable to that of the century-scale trends of the long-period Milankovitch modulation. They found that the greatest short-period effect of orbital perturbations was expected at high latitudes in midsummer, where a lunar, 18.6-year modulation is imposed on W_τ with an amplitude of about 0.1%. We note that in this extreme case, the orbital modulation of insolation is equivalent to that brought about by solar activity. Borisenkov *et al.* noted that orbitally induced periods of about 2.7, 4.0, 5.9 and 11.9 years should also be apparent at all latitudes and seasons, though of considerably smaller amplitude; the first three they identified as multiples of the sidereal periods of revolution of Venus and Mars; the last is the sidereal period of Jupiter.

In this paper we calculate the net daily insolation at selected points of the earth's orbit for the period 1874–1981, combining the short- and long-term effects of orbital perturbations with intrinsic changes in $S(t)$ modeled from records of solar activity. Instantaneous values of the orbital parameters ρ and δ were computed using algorithms developed at the Institute of Theoretical Astronomy, USSR (Glebova, 1975). In calculating $F(t)$ in Eq. (1) ρ and δ were taken as constant during the ±12 hours before and after the instant of equinox or solstice ($\delta = 0$ or $|\delta|$ maximum) to give a mean daily value. In an earlier study (Borisenkov *et al.*, 1983) these algorithms were employed to calculate insolation changes for the period 1801–2100, assuming a constant S_0. Here we are limited to the 108-year period from 1874 to 1981 for which historical data allow reconstructions of daily values $S(t)$.

3. Intrinsic changes in $S(t)$

High precision, continuous measurements of the solar constant from orbital platforms have established that $S(t)$ is continually modulated at levels of up to about 10^{-3} by the presence of sunspots and faculae on the disk of the sun (e.g., Willson *et al.*, 1981; Willson, 1984). The effect of sunspots is to block upwelling radiation, and thus to deplete temporarily the undisturbed value of S_0; bright faculae on the face of the sun will enhance $S(t)$. The fractions of the apparent solar disk covered by sunspots and faculae vary from day to day as a result of solar rotation and the growth and decay of these ephemeral features of the sun. At any instant the net effect of solar activity on $S(t)$ as it is sensed at the earth is the result of these two opposing factors, weighted by the projected areas of sunspots and faculae and their respective contrasts, relative to the undisturbed disk.

The dominant and more easily recognized signal in daily records of $S(t)$ obtained from space is that of sunspot blocking (e.g., Willson *et al.*, 1981; Hudson and Willson, 1981; Hoyt and Eddy, 1982). But it is as yet unknown, and indeed controversial, whether opposing effects of sunspot blocking and facular brightening are kept in exact balance on time scales of months or less, or whether the blocked energy is stored for a longer time as thermal energy within the sun (see, for example, Chapman, 1980; Hudson and Willson, 1981; Spruit, 1982; Oster *et al.*, 1982; Foukal *et al.*, 1983; Hoyt *et al.*, 1983; Eddy, 1984; Chapman *et al.*, 1984). In either case there will be a day-to-day, relative modulation of $S(t)$. For storage times of ten years or more, the 11-year modulation will be maximized; for shorter storage times the solar cycle modulation will be diminished. For the sample-day calculations in this paper the difference is immaterial since we deal with daily values of the irradiance $S(t)$ with no assumption about storage. In calculating annual means later in the paper we assume a long storage time, following Hoyt and Eddy (1982) and consistent with the theory developed by Spruit (1982) and Foukal *et al.* (1983) for the dissipation of blocked energy in the solar convective zone.

Let S_0 represent the total irradiance of a quiet, or featureless sun. The variation in $S(t)$ resulting from effects of solar activity will be given by

$$\Delta S = S(t) - S_0 = \sum_i (-a_i u_i - b_i p_i) + \sum_j c_j f_j, \quad (2)$$

where u_i and p_i are areas of individual sunspot umbrae and penumbrae, respectively, expressed as fractions of the projected disk of the sun, a_i and b_i are their respective contrasts, f_j and c_j are the projected areas and contrasts of individual faculae, and the summations include all features on the visible disk of the sun.

In reality the contrasts a, b and c vary from spot to spot and from facula to facula, although accurate values for individual features are in most cases unavailable. For our purposes here we may safely approximate them with averaged, observed values of sunspot and facular contrast, with the former corrected for solar limb darkening. Then

$$\Delta S = \sum_i (-au_i - bp_i) \cdot F_\theta + cf, \qquad (3)$$

where

$$f = \sum_j f_j$$

now represents the total area covered with faculae and F_θ is the photospheric limb-darkening function (Allen, 1973),

$$F_\theta = \frac{I_\lambda(\theta)}{I_\lambda(0)} = 0.36 + 0.84\cos\theta - 0.20\cos^2\theta, \qquad (4)$$

where θ is angular distance from the central point of the solar disk.

If, following Hoyt and Eddy (1982), we take as mean contrast values of sunspot umbrae, penumbrae and faculae 0.75, 0.25, and 0.03, we obtain as a working model

$$\Delta S = +0.03f - \sum_{i=1}^{N} (0.36 + 0.84\cos\theta - 0.20\cos^2\theta)(0.75u_i + 0.25p_i). \qquad (5)$$

If the model parameters are accurate to ±5% the reconstructed solar irradiance will be accurate to better than ±0.04%.

Hoyt and Eddy (1982, 1983) found this analytical representation a good fit to daily observations of $S(t)$ made on the U.S. Solar Maximum Mission Spacecraft when used with daily, published values of sunspot areas. Uncertainties in sunspot areas gave rise to uncertainties in the modeled values of $S(t)$ of about ±0.006% on an average day in the comparison period, with 5% of the days having errors greater than ±.05% (Hoyt *et al.*, 1983). Uncertainties in facular parameters exceed those in sunspots, but the former are a less sensitive parameter in fitting the spaceborne measurements of $S(t)$. Hoyt and Eddy (1982, 1983) then applied historical values of daily sunspot and facular areas from the Royal Greenwich Observatory and the U.S. NOAA Environmental Research Laboratory in Eq. (5) to reconstruct modeled changes in $S(t)$ due to solar activity for each day in the period 1874–1981. Other models of effects of solar activity on $S(t)$ (Oster *et al.*, 1982; Schatten *et al.*, 1982) give more emphasis to the possible effects of facular emission; in terms of daily excursions of $S(t)$, however, the models differ only slightly. In using the Hoyt and Eddy model we generate upper limits to the possible effects of solar activity on $S(t)$.

In Table 1 we show as an illustration the solar irradiance variations induced by solar activity at ten-year spacings on four sampled days: the spring (VE) and autumnal (AE) equinoxes and the summer (SS) and winter (WS) solstices. Tabulated values are percent deviations in $S(t)$ for each of the four days. Departures range from a maximum depletion of −0.128% from the long-term mean on the summer solstice of 1885 to a maximum enhancement, induced by faculae, of +0.0013% on 23 September 1975.

The persistent pattern of larger, negative departures that characterize entries in the table between 1885 and 1935 reflect the fact that in this era mid-decade years fall near the maximum phase of the 11-year sunspot cycle, when we expect increased depletion by sunspot blocking. The years 1965 and 1975, by contrast, fall near minima of the solar cycle, and thus the departures here are smaller and more positive.

4. Combined orbital and solar activity effects

In what follows we combine the effects of orbital perturbations on insolation $F(t)$ calculated for the four equinox and solstice days with corresponding calendar-day values of $S(t)$ from the historical reconstructions of Hoyt and Eddy (1982). Significant day-to-day changes in sunspot and facular activity make the latter a rapidly varying quantity, as is evident in modern, precision measurements of $S(t)$ from spacecraft (Willson, 1984; Willson *et al.*, 1981). For climatological studies it is more meaningful to consider time-averaged insolation at these sampled dates; for this reason in combining $S(t)$ and $F(t)$ we have used 11-day averages of each, centered on days of VE, AE, SS and WS, as distinct from Table 1 where single-day values were given. The averaging process diminishes sampling effects in $S(t)$; more importantly, it represents a reasonable response time for the terrestrial atmosphere.

TABLE 1. Percent deviation $\Delta S(t)$ on sampled days.

Year	VE	AE	SS	WS
1875	−0.0169	0.0000	−0.0307	−0.0104
1885	0.0038	−0.0050	−0.1284	−0.0058
1895	−0.0827	−0.0166	−0.0337	−0.0620
1905	−0.0158	0.0031	−0.0036	−0.0361
1915	0.0004	−0.0479	−0.0973	−0.0004
1925	0.0006	−0.047	−0.0015	−0.1121
1935	−0.0014	−0.0406	−0.0151	−0.0237
1945	−0.0059	−0.0274	−0.0181	−0.0088
1955	0.0009	−0.0015	−0.0063	−0.0382
1965	0.003	−0.0005	0.0014	−0.0008
1975	0.0009	0.0013	0.0005	0.0009

Figure 1 displays annually sampled values of the combined insolation change ΔW_τ averaged over 11 days at the spring equinox for selected latitudes of the Northern Hemisphere. The scale is again percent departure from the mean for each latitude for the period 1874–1981. The extensions of the data beyond 1981, shown in each figure as a dashed curve, exclude effects of solar activity. As such they reveal the isolated form of the wholly predictable orbital perturbation component and illustrate the relative magnitudes of the quite disparate effects that are combined in earlier portions of each diagram.

At each latitude we note the monotonic increase in springtime insolation that is a feature of the long-term Milankovitch effect in the Northern Hemisphere (Borisenkov *et al.*, 1983)—the expected result of the secular precession of the equinoxes. The amplitude of this secular orbital trend, about 0.1% century^{-1}, is comparable to that of typical, short-term depletions in W_τ that are induced by solar activity; in terms of climatic impact the long-term orbital effect, being more persistent, is probably the more important term. Major depletions due to solar activity that are sampled in Fig. 1 tend to mark years of maxima of the 11-year solar activity cycle; this expected pattern is here modified, however, by short-period orbital trends and by the sometimes exaggerated effects of sampling in $S(t)$. In the dashed extensions to the year 2000 we see the cyclic nature of the high-frequency orbital forcing, which in this case is marked by a period of about four years and a full amplitude of about 0.05%.

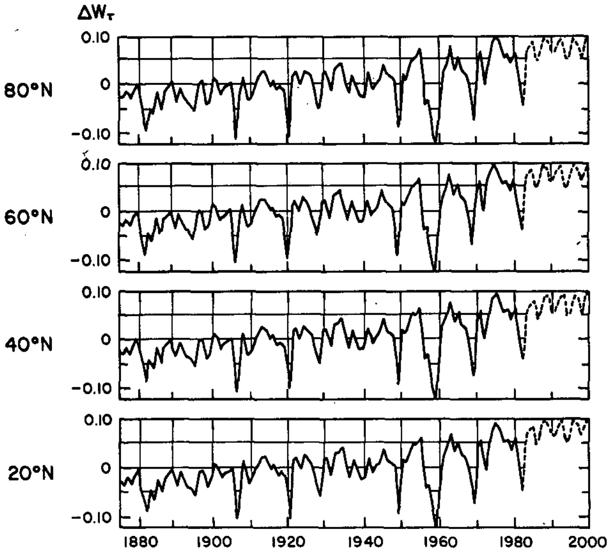

FIG. 1. Combined variation in insolation ΔW_τ for an 11-day period centered on the spring equinox for four northern latitudes. The scale is percent departure from the mean for each latitude for the period 1874–1981, the span of the combined data. Dashed extension of each record beyond 1981 includes effects of orbital perturbations only.

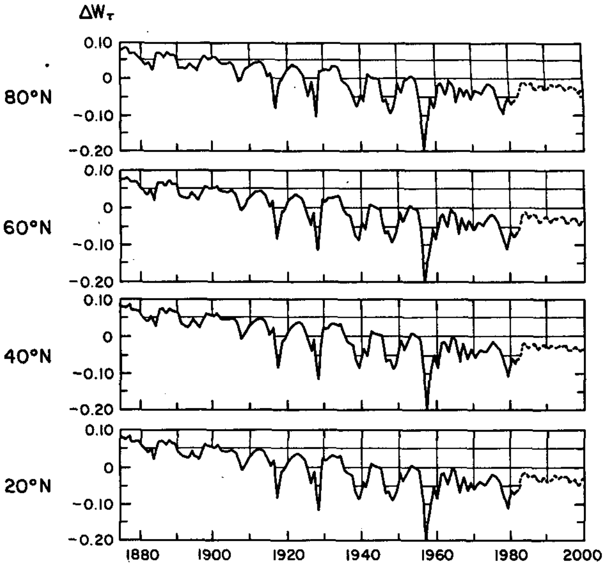

FIG. 2. As in Fig. 1 but for autumn equinox.

Similar illustrations of the annually sampled behavior of insolation are shown for the same latitudes in Figs. 2–4 for 11-day periods centered on the autumn equinox and the summer and winter solstices. In each case, as in Fig. 1, the short extrapolations beyond 1981 include only orbital effects, and the reference level from which all departures are reckoned is the 1874–1981 mean of ΔW_τ for the latitude in question.

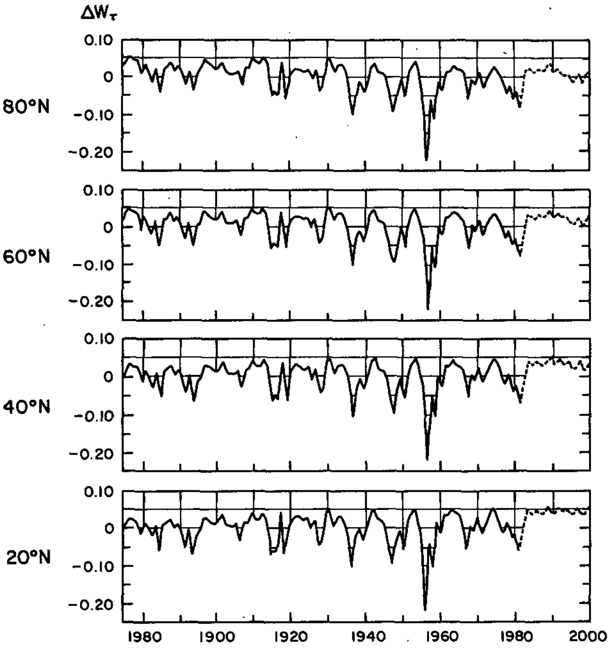

FIG. 3. As in Fig. 1 but for summer solstice.

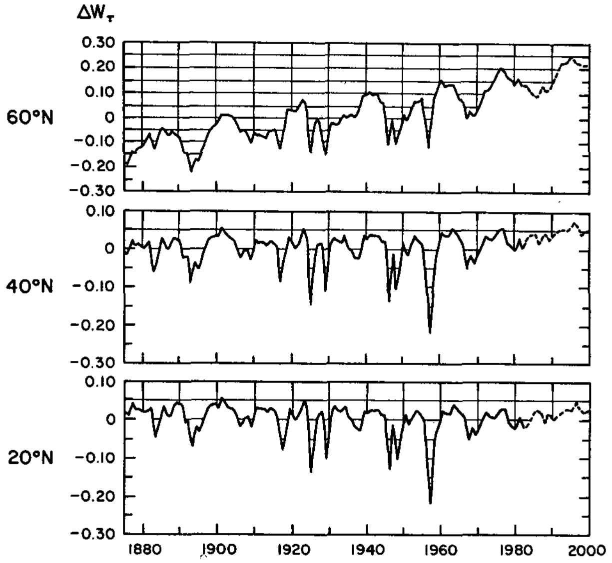

FIG. 4. As in Fig. 1 but for winter solstice.

For the autumn equinox (Fig. 2) sampled depletions due to solar activity appear against a consistent, orbitally induced decrease in W_τ of about 0.1%/century and a quasi-periodic orbital modulation that is less regular and of smaller amplitude than at the spring equinox. For days of summer solstice (Fig. 3) the secular, orbitally induced trend is suppressed and varies systematically with latitude, decreasing at about 0.04%/century at 80°N, remaining essentially flat at 60°N, and increasing at about 0.02% and 0.03%/century at 40 and 20°N, respectively. The deep depression of about 0.2% in 1957 in Fig. 3 results from the fact that late June of that year was one of the most heavily spotted periods in the century. The daily sunspot number R_Z for 21 June 1957 was 265. The annual sunspot number for 1957, at the peak of solar cycle number 19, was the highest yet recorded (190.2); since sunspot number and sunspot area are closely related, the Hoyt and Eddy (1982) reconstruction of $S(t)$ for 1957 is depressed in annual average by almost 0.12%.

In Fig. 4, for days of winter solstice, the character of ΔW_τ is markedly different at the highest of our four latitudes for which there is direct insolation on this day. At 60°N orbital effects dominate on all time scales: here an 18.6-year period lunar-induced nutation term is clearly distinguished against a secularly increasing background in W_τ of about 0.25% century^{-1} that is caused by long-period (Milankovitch) perturbations. As in Fig. 3, our 11-day sample at winter solstice in 1957 falls during another unusually spotted period at the maximum of solar cycle number 19. The annual-averaged sunspot number for 1957 was 190.2—the highest on record; for the 11 days about winter solstice it was 295. Yet at 60°N this extreme daily depletion only matches the scale of coincident and more persistent orbital effects. The dominance of orbital and especially nutation effects on midwinter insolation at a latitude so close to the Arctic Circle is easily understood as a consequence of low sun angle and spherical geometry. The effect falls rapidly with decreasing latitude; at 40°N the winter solstice background trend has diminished by a factor of 9 and at 20°N it has disappeared.

Spectral power densities calculated for the summer solstice data from Fig. 3 confirm that the dominant component of insolation modulation at midlatitudes is that of 10.6-year period, impressed on $S(t)$ by the solar activity cycle. Figure 5 shows a maximum entropy power spectrum for summer solstice days at latitude 40°N; corresponding power spectra for other latitudes at summer solstice were entirely similar, as one might expect. Unresolved in the major peak at 10.6-year period is a weaker component corresponding to a gravitational perturbation induced by the 11.8-year sidereal period of revolution of the planet Jupiter. Smaller and less significant features in Fig. 5 at periods of 5.3, 4 and about 2 years correspond, as noted earlier, to the fundamental and higher harmonics of the sidereal periods of revolution of Mars and Venus and blends of these.

5. Annual mean values

Combined departures in insolation can be expressed as annual mean values at any latitude by first calculating ΔW_τ for each day, as was done for sampled days in the section preceding, and then taking the mean over the year in the form

$$\bar{W}(\phi) = \overline{S(t)\cdot F(\phi, \delta, \rho)}. \qquad (6)$$

Here F expresses the mean daily insolation as in Eq. (1) but calculated for a constant $S(t)$, and ρ and δ are explicit functions of time. The mean of the product of the two functions may also be written as

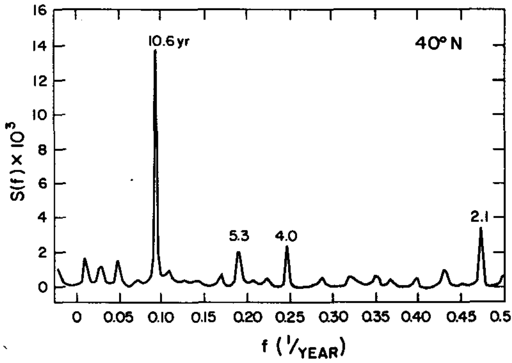

FIG. 5. Relative spectral power density (estimate by maximum entropy analysis) of combined insolation variation ΔW_τ at latitude 40°N for the period 1874–1981, for the period of summer solstice (as in Fig. 3).

$$\bar{W}(\phi) = \bar{S}(t)\cdot\bar{F}(\phi, \delta, \rho) + \overline{S'(t)\cdot F'(\phi, \delta, \rho)},$$

where the second term represents the difference between the mean of the product and the (operationally simpler) product of the means of the two functions. The difference, we found, would be very small, were it not for a result of the asymmetric form of the solar activity cycle (steeper rise and slower fall). Because of this effect, products of the mean calculated by the simpler formula

$$\bar{W}(\phi) = \bar{S}(t)\cdot\overline{F(\phi, \delta, \rho)}$$

introduce an erroneous phase delay of 1–2 years in the effect of solar activity. In all that follows, we use only the more exact mean of the product, as given in Eq. (6).

A practical difficulty that need not be elaborated here ensues from the necessity of combining orbital parameters calculated for a nonintegral-day tropical year with solar activity data computed for a conventional leap-year calendar.

As noted earlier, in deriving an annually averaged $S(t)$ from daily modeled values we implicitly assume a long storage time (greater than ten years) for blocked solar energy, following Hoyt and Eddy (1982). Were faculae to play a major role in re-emitting blocked radiation the storage time would be decreased; thus the results given here as annual average express an *upper limit* to possible solar activity modulation of W_τ.

In succeeding illustrations we show mean annual values of ΔW_τ for four northern latitudes throughout the 108-year interval of our study, first (Fig. 6) as an orbital perturbation alone and then (Fig. 7) combined with $S(t)$ variations as the mean of the product [Eq. (6)].

In Fig. 6 the secular Milankovitch trends that were divergent in sign at the nodal and solstice points at each latitude are now organized by annual weighting as consistent secular trends: decreasing at polar latitudes (−0.046 and −0.011%/century at 80 and 60°N) and more slowly increasing at 40 and 20°N. These trends, differing as a function of latitude in both magnitude and sign, are the result of spherical geometry and the current secular decrease in angle of inclination i. The 18.6-year lunar nutation term is evident in all cases in Fig. 6, although dropping in magnitude from polar to middle latitudes from a maximum, full amplitude of about 0.017% at 80°N. Between 60 and 40°N the lunar effect changes phase by 180° for the same reasons that the secular, background trend changes sign there. At lower latitudes, where the secular trend is diminished, the amalgamated pattern of gravitational perturbations of other planets is resolvable as a quasi-periodic signal of lesser amplitude.

In combined mean annual values (Fig. 7) the dominance of solar activity is evident at all latitudes; the depth of recurrent, 10.6-year depletions mirrors the generally increasing envelope of sunspot cycles in this period, reaching its greatest effect in solar cycle number 19 in the late 1950s. The imprint of lunar nutation, so evident in Fig. 6, is here almost wholly masked by the competing effect of the nearly commensurable sunspot cycle. At 80°N and to a lesser degree at lower latitudes the obvious effect of the lunar term is to distort the more regular waveform of the purely solar signal. The secular orbital trend is a major factor at 80°N where its amplitude equals that induced by solar activity. At 60°N the secular trend is still visible, although at lower latitudes it is overwhelmed by solar activity modulation. Figure 8 displays relative spectral power density (calculated by maximum entropy analysis) for the data for 80°N in Fig. 7. In addition to the obvious downward trend (due to combined orbital effects and the secular increase in solar activity) one finds a 10.5-year solar activity peak and another identifiable feature at about 18.2 years that is the result of an out-of-phase blending of the lunar 18.6-year period and the second multiple of the 10.5-year solar period.

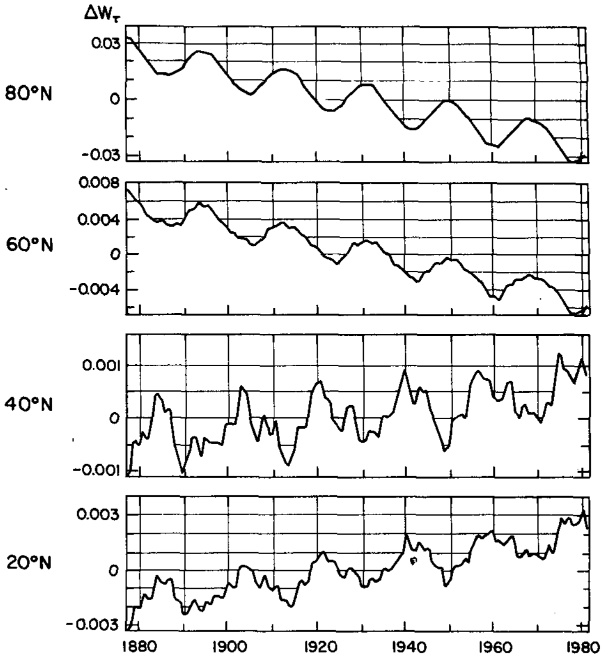

FIG. 6. Annual mean variation in insolation ΔW_τ due to orbital perturbations only for four latitudes in the Northern Hemisphere for the period 1874–1981. Scale in each case is percent departure from the mean for the full period shown.

6. Summary and conclusions

We have combined calculated effects of orbital perturbations with modeled solar activity modulation to examine patterns of terrestrial insolation as a function of latitude over a 108-year period of recent

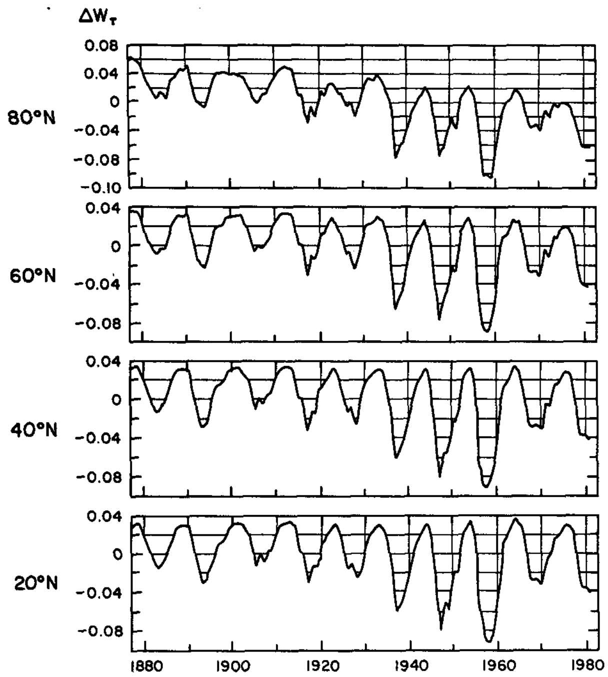

FIG. 7. As in Fig. 6 but due to combined orbital perturbations and modeled solar activity effects for four latitudes in the Northern Hemisphere.

history. In this paper we have considered the combined influence at times of the equinoxes and solstices, and as annual averages; the resultant patterns of *seasonally* averaged insolation will be treated in a second paper.

Orbital perturbations, in the absence of solar activity, introduce long-term monotonic trends that vary systematically in amplitude and sign with latitude. These are greatest near the poles, where at latitude 80°N the effect has been to drive zonal insolation downward by about 0.05% during the last century. In middle and low northern latitudes the orbitally induced trend is positive but about 100 times smaller. An 18.6-year gravitational perturbation of the moon, acting through nutation, adds a high-frequency modulation that in midwinter at high northern latitudes is about equal in magnitude to that of the secular, Milankovitch trend; the same effect has a full amplitude of almost 0.02% in annual average at 80°N. Gravitational influences of Jupiter and the inner planets appear as higher frequency signals of much smaller amplitude.

The addition of modeled sunspot blocking introduces a modulation at the 10.6-year period of the 20th century sunspot cycle, depleting global insolation in years of maximum sunspot number with a maximum amplitude of about 0.1%. At middle and low latitudes solar activity is easily the dominant, nonseasonal perturber of insolation. At higher latitudes of 60° and above, the net effect on annual mean insolation is a combination of three competing influences: solar cycle modulation, a generally downward secular orbital drift, and the superposed 18.6-year nutational forcing. At 80°N downward orbital drift and solar modulation are about equal in magnitude.

These external influences are distinctly minor perturbers of daily patterns of insolation when compared to the much larger seasonal cyclic forcing in δ and ρ or to the impact of common daily variations in cloud cover or sky transparency. On the scale of decades or centuries, however, they bear examination as the only predictable perturbers of insolation that are known in this time frame. As global climate models increase in sophistication and sensitivity these subtle insolation effects may represent practical inputs in the sense that a small but persistent trend in insolation at polar latitudes, for example, must alter global circulation in a systematic way. The 10.6-year forcing of insolation by sunspot blocking, although limited in annual average to a maximum of about 0.1% in amplitude, is far and away the most energetic effect yet known of solar activity on the lower atmosphere, exceeding by a factor of 20 the energy involved in known variations in solar ultraviolet irradiance, and by many orders of magnitude the energetic variability in solar particles and fields. Significant evidence has been reported for an 11-year cycle in regional surface temperatures in North America that fits the phase, amplitude and geographical enhancement expected of a solar activity modulation of $S(t)$ (Currie, 1981a; Hanson and Cotton, 1983; Eddy *et al.*, 1982). The

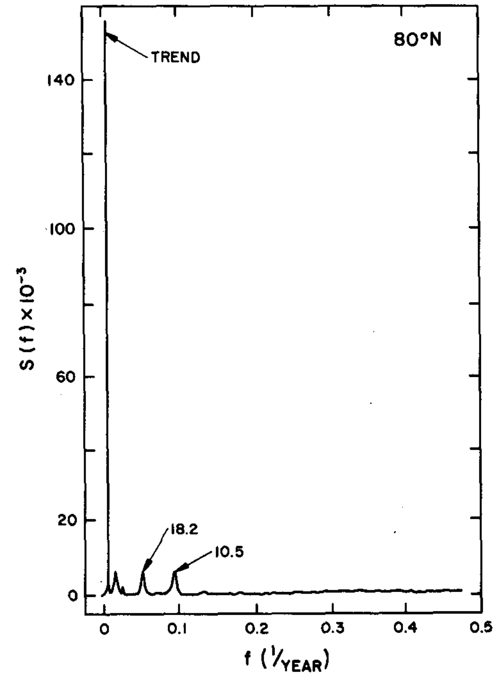

FIG. 8. Relative spectral power density (estimate by maximum analysis) of yearly means of combined insolation variation ΔW_T at latitude 80°N.

subtle 18.6-year forcing of high-latitude insolation by lunar-induced nutation is another factor that may warrant investigation as a possible mechanism for reported cyclic variations in regional North American drought enhancement at the same period (Currie, 1981b; Bell, 1981; Stockton *et al.*, 1983). In general, the combined effects of orbital perturbations and solar activity vary in sign and phase and amplitude with both latitude and time of year; this complex pattern of variation clearly must be considered in possible climatic interpretations of these subtle insolation effects.

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