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Newly Found Evidence of Sun–Climate Relationships

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Newly Found Evidence of Sun–Climate Relationships

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PREFACE

Global surface temperatures slowly fluctuate from decade to decade. Are these variations simply chaotic ? Many books and scientific articles on climate change link global warming closely to man's ever-expanding activities and its policy implications. However there is an element in global climate change that has not been well addressed in on-going climate change research programs: the evidence relating current and past changes in solar total irradiances to the thermal budget of the Earth and its significance. This overlook may stem from difficulties associated with gathering interdisciplinary evidence --- from the sciences of solar physics and climatology. For this reason, the recent findings on Sun-climate relationships were presented as a part of a Sun-Climate seminar held at Goddard in March, 1993, and disseminated as this Technical Memorandum for peer review. (HHK)

ABSTRACT

Solar radiation cycles drive climatic changes interannually and intercyclically. Evidence of the Sun-Climate link was first detected by comparing satellite measured variations in solar total irradiance with the global and zonal surface-air-temperature (SAT). Surprisingly the annual SAT responds to the solar total irradiance variations with a correlation coefficient as high as 0.78. As yearly solar irradiance variations from 1978 to 1990 were overlain on the "SAT box grid" (Hansen, et al., 1987), geographic patterns of Sun-climate correlation emerge which display a meridional component apparently driven by "the conditions of cloud coverage" and "the effectiveness of heat transport processes of the oceans".

The last one hundred years history of global SAT also match a solar irradiance model based on solar proxy data. A correlation coefficient of 0.82 was derived with appropriate parameterization of temperature response in long-term trends. Also, it has been observed that the derived correlation coefficient can typically peak when a built-in phase lag of 32-40 months is instituted in temperature response.

CONTENTS

1) INTRODUCTION

Based on all the accepted reconstruction of the climate history in the past, the global temperature has fluctuated over a considerable range. Prior to modern times, none of the large fluctuations could have been anthropogenic, for only in recent time has *homo sapians* become the dominant environmental factor for change to the Earth. There are several causes for past natural climate fluctuations, but the most prominent one agreed upon by the science community has been attributed to the variations in the solar irradiance.

The Sun is thought to have a thick ionized gaseous envelope. Even though strong gravity effectively confines its energy within the radiation interior, the interior oscillations can surface through the outer convective layer creating visible turbulent activity in the form of sunspot and faculae cycles against the backdrop of its status-quo luminescent photospheric surface at a black body temperature of 5762K. Contrary to the Sun, the Earth is a celestial body which has already undergone considerable cooling since primordial time. There is little, or no self-generated radiation from the earth. Its mantle, already hardened except for occasional volcanic eruptions, receives about 10^{23} joules of solar energy every year. Thus the earth's climatic processes are totally driven by the radiation received from the Sun, with other factors, such as major volcano eruptions, CO_2 concentration, etc. acting as modifying parameters.

Having accepted the existence of the radiative transfer between the Sun and Earth, an interesting question emerges: To what extent is the Earth's climate influenced by the forcing of solar irradiance variations ?

The sensitivity of Earth's temperature to the external forcing such as solar irradiance variations can be expressed as

$$\Delta T(K) = k * \Delta S \ (W/m^2) \qquad (1)$$

where the ΔT denotes the temperature change in response to the solar irradiance variance, ΔS. The proof of the connection between ΔS and ΔT can be established if the sensitivity term, k, can be determined after a correlation between the two separate variables is proven.

Even though the Earth is the receptor of the Sun's radiation, the system maintains an overall energy balance. This can be written as a non-dimensional energy balance,

$$R_{(bal)} = S(1-\rho) - 4\sigma T^4 = 0 \qquad (2)$$

where ρ denotes the planetary albedo, and σ is the Stefen-Boltzman constant. The temperature being referred is the black body temperature at the top of Earth's black body sphere. A more practical surface energy balance can be expressed as (Kim, 1992b)

$$R_{(bal\text{-}sfc)} = F(1-\rho)-(\varepsilon\ \sigma T^4 + Hs + LE + Others) = 0 \qquad (3)$$

where the F denotes downwelling solar flux at the ground level and has a quantitative relation of $F = S/4$. The ρ now refers to ground reflectivity, the ε is surface emissivity, the T is surface temperature, the H_S is convective heat flux, the LE is latent energy, and the "Others" include components of the heat balance---such as heat transfer by the ocean currents, melting of ice as well as the conversion of solar energy in photosynthesis. $R_{(bal)}$ is an equilibrium status and any perturbation brought on by any external forcing such as solar forcing or albedo change will create a temperature response to restore the equilibrium. This extent of forcing can be determined by differentiating in respect to F and T

$$dR(F,T)=\{dR_{(bal)}(F,T)/dT\}dT + \{dR_{(bal)}(F,T)/dF\}dF \qquad (4)$$

$$dF = -4\sigma T^3\ dT \qquad (5)$$

The derivative, $-4\sigma T^3$, is referred as "blackbody negative feedback parameter" (Dickinson, 1982). And alternatively the sensitivity parameter is defined as

$$dT = (1/-4\sigma T^3)\ dF \qquad (6)$$

The proof of the Sun-climate relationships can be established if observed slopes, *k*, fit within the context of ~$(1/-4\sigma T^3)$. Unfortunately, the *k* cannot be derived in a straight forward manner. For, solar irradiance measurements available are not long enough in time to form the empirical relationship spanning last 110 years of recorded temperature history. However, on the other hand, we do have detailed knowledge of several parameters that enable us to build both approximate numerical solar and climate models aided by the relatively short 13 year measurements. Faced with this impasse, an indirect procedure was found: to establish, first, the relationships between solar irradiances based on the observational measurements taken by ERB 10C and SAT records. After bilateral relationships were established the logic transitive property of the relationships were evoked to correlate the solar activity with the SAT data.

2) EVALUATION OF SOLAR IRRADIANCE VARIATIONS

The Sun's influence on the Earth's climate has been known since its rhythmic fluctuations of long-term Milankovitch cycles were theorized in conjunction with the occurrence of the ice-age (Milankovitch, 1941; Budyko, 1969; and Hays *et al.*, 1976). Eddy in 1977 summed up that both the changes in the envelope of solar activity and the changes in climate result from long-term fluctuations of about 1% in the solar constant. Then he commented that individual ups and downs of the 11-year cycle, or of shorter-term solar variability, are almost wholly unrelated to the sun-climate problem. Shortly thereafter, Hoyt (1979) wrote that the history of sunspot structure measured by taking the ratio of the area of the umbra to that of the penumbra is remarkably similar to the temperature record of the Northern Hemisphere. He related sunspot structure to solar luminosity and subsequently to the Earth's climate. Later, Gilliland (1982) included solar luminosity variations as one of the contributing factors equivalent to aerosols, CO_2 and volcanic activity in the formation of climate. His postulation is based on observed solar radius variations along a long-term time scale. More recently there have been a number of papers which began to link the recorded history of global temperature anomalies to the Sun's inner instability (Reid, 1987 & 1991; Wu et.al., 1990). Particularly, Reid (1987, 1991) put forth a Sun-climate theory relating the envelope of the 11-year cycle of solar activity known as the Gleissberg cycle (Gleissberg, 1965 and 1966) to variations in sea-surface-temperature (SST). Though the significance of his correlative study results has been questioned by others (Kelly *et al.*,1990), Reid has introduced a plausible mechanism for assessing the influence of solar forcing on the global climate. His argument was followed by the Friis-Christensen *et al.*'s report (1991) which showed the Sun-climate relation to be better correlated with the varying length of the sunspot cycle rather than sunspot number. In support of the theory, a correlation coefficient of 0.95 was found in a time series analysis which encompassed the last 120 years of SAT history for the northern hemisphere, a period which includes the last 11 sunspot cycles. A weak point in the work would appear to be the conclusion is not based on direct instrumental measurements of the Sun's total output energy which should be related to the global SAT record. This weakness, in general, was recognized by Hoffert *et al.* (1980, 1988). After comparing five years data from satellite measurements of solar variability taken by the Active Cavity Radiometer Irradiance Monitor (ACRIM) against the transient climate model of the world oceans, they concluded that additional decades worth of solar irradiance measurements would be required to prove such correlation.

On the other hand, the theory of 11-year solar activity cycles is well established; changes in solar luminosity are the result of enhanced magnetic field formation and ebbing of the field as the active regions move towards the equator until the magnetic polarity reversal (Babcock, 1961; Harvey, 1992). Much shorter period oscillations were identified with the rotation of 'g-modes oscillation' by Wolff (1983 and 1984) Varying features of coronal disturbance, faculae, and sunspots are not only useful in building an empirical model for the Sun's luminescent behavior but also in developing an insight into the formation of the theory of the Sun (Hoyt *et al.*, 1982; Foukal *et al.*, 1986 and 1989; Lean *et al.*, 1988; and 1991). The needed data is available now. In a recent article, Kim *et al.* (1992b) presented a set of quantitative evidence showing that solar irradiance variations of the past 13 years monitored by the Earth Radiation Budget (ERB) Channel 10 cavity radiometer is closely correlated to the annual mean of global and zonal SAT measured. Especially the annual mean SAT for the 23.6 ^{o}S - 44.4 ^{o}S latitude zone of the southern hemisphere duplicates closely the solar fluctuation of the last 13 years. In our approach, the last 13-year ERB record was, first, interpreted as an unambiguous evidence that the solar irradiances in an activity cycle display net positive gain rather than luminosity deficit implying that the added emissions from surrounding faculae actually exceed the portion of average photospheric luminance being blocked by the dark sunspots seen from the Earth. The enhanced emissions, S_e, during an activity cycle can be estimated as the residual of the total irradiance measurement, S, subtracted by the irradiance of the quiet Sun, S_o, and a blocking factor by sunspot dark region, P_s,

$$S_e = S - S_o - P_s \tag{7}$$

in which P_s is given by

$$P_s = -0.164 * A_s * \mu\,(3\mu + 2) \tag{8}$$

where A_s denotes the active region in millionths of the solar disc and μ is a phase angle formed to the center of the solar disc (Hudson *et al.*, 1982). In this paper, S_o was determined from a regression performed on the monthly ERB readings with the sunspot numbers in Eq.(9) and given as 1371.331 W/m^2 by setting the Wolf number is zero.

$$\Delta S = 0.007269 * \text{Wolf Nr} + 1371.331 \tag{9}$$

Variations recorded by sunspot number index are but one manifestation of the Sun's cyclic activity. In addition to the sunspot number index, the faculae record compiled by the Greenwich Royal Observatory since 1874 are also available. The one hundred year faculae record is direct and effective solar proxy data for restoring the solar irradiance history. There, however, is a shortcoming in Greenwich data set: It abruptly ceased in 1975 denying any opportunity to calibrate the solar history against the satellite irradiance measurements. To circumvent this problem, we have selected the data from Taipei Observatory to fill the gap. The Taipei observatory record since 1964 contains meticulous detail on the areal size of each active region and the groups' location with respect to the center of the solar disc. In Figure 1, the solar total irradiance based on the Taipei data is represented as a line and the monthly mean values of solar constants obtained from 4672 daily ERB measurements from the first datum of Nov 1978 till July 1991 are presented as diamonds. In Figure 2 the result of overlaying the Taipei active regions data and Greenwich faculae data for the 10 year period of Cycle 20 is shown. The information given in both data sets, in millionths of solar disc area, have been converted into solar irradiances using regression analysis resulting in Eq. (9). Even though the Taipei data have been successfully applied to link the Greenwich faculae data with ERB calibration, it is reminded here that the restored solar total irradiance variations based on proxy data remains to be an estimate. Errors in the solar indices exist and given set of proxy data tends to depict only one facet of the solar activity leaving other solar indices and parameters unaccounted. For instance, contradicting studies are available on the relative influence by faculae emission and sunspot to the solar luminosity: Daily subset studies by Chapman (1980) and Lawrence *et al.* (1985) show faculae emission to be about 50% of the sunspot blocking. However, Foukal *et al.* in 1988 reported that the relative faculae and sunspot contributions to Sun's total luminosity to be at the level of 0.4% over a cycle. Such large faculae indexing would appear to agree with observations of Ca-K plages (Vrsnak *et al.*, 1991), and Lyman-α Hydrogen line (Pap *et al.*, 1991), and 10.7-cm microwave flux measurements. In solving the energy discrepancy between sunspot count and enhanced solar luminosity, Gleissberg (1949) and Moreno-Insertis *et al.*(1988) suggested that the decay rate of individual sunspots and the length or time rate in which the sunspot cycle diminishes as important factors. In addition, detectable solar diameter variations, according to Sofia *et al.* (1979), Frohlich *et al.* (1984), and Endal *et al.* (1985), might have as much as a 0.01% influence on the solar luminosity. Recently Hoyt *et al.*, (1993) took into several empirical indices in the form of a network in simulating long-term solar irradiance history. When the method was extended back to the mid-1700s, the peak to peak luminosity fluctuation stacked up a lower limit of 0.23% variation including a projected long-term solar total irradiance increase at the rate of 3.4 W/m^2 in last 200 years.

Recognizing all the complications, we deem that the simplistic faculae model built here are sufficient for our purpose where intercyclic variations are primarily sought in relative terms. The upper trace shown in Figure 3 represents estimated variations of solar total irradiances from 1874 till present. The data base used in this plot consists of the monthly mean faculae area readings for 1874 - 1975 and modeled irradiances based on sunspot group tagging from the period of 1964 till present. The data do not account for any possible long-term solar irradiance trends.

3) GLOBAL SAT ANOMALIES

The lower trace of Figure 3 was taken from the monthly mean global SAT anomalies compiled by Goddard Institute of Space Studies (GISS) recently. Documented record of SAT from world-wide meteorological stations are available from the World Meteorological Organization since 1860. Different groups of investigators, (Hansen *et al.*, 1987; and Jones, 1988) are sorting out voluminous global temperature records into a more useful format. Especially the GISS's data catalog the world's temperature records in geographical patterns by dividing the global temperature scene into 80 equal "boxes". The dimensions of a box are about 2500 by 2500 km^2 and this convenient temperature changes of the 80 boxes can be grouped into eight latitudinal zones to give a meridional profile. In Fig. 4, the annual-mean SAT anomalies taken from Hansen *et al.* are plotted for four latitudinal zones in the southern hemisphere and given as sample profiles since the turn of the century.

4) CORRELATION BETWEEN THE RECENT ERB AND SAT DATA.

The solar total irradiance, (or solar constant) is one of the most simple and effective measures of solar effects provided such data will be the measurements made above the atmosphere. The first successful effort to collect solar total irradiance data began in 1978, when a cavity radiometer of the ERB on board the Nimbus-7 satellite began to measure the solar total irradiances from the top of the atmosphere (Hickey *et al.*, 1988). Remarkably, the Nimbus-7 satellite with its ERB sensors onboard is still in orbit continuing the informative flow into its 15th year of operation.

The significance of the ERB 10C data is twofold: First, the measurements are important as a calibrated input function to observe the thermal properties of the Earth where climate sensitivity is measured in terms of temperature change per quanta of solar energy imbibed. Secondly, the irradiances measured at the top of the atmosphere become a unique source to calibrate the solar luminosity during solar activity cycles. In 1981, another satellite-borne radiometer known as ACRIM on the Solar Maximum Missions (SMM) (Wilson, 1984) was launched and simultaneously monitored the Sun's total irradiance during the years of 1981-1989. Since agreement between the two contemporaneous satellite measurements has been satisfactory for the overlapping 8 years of ACRIM period, the focus of this investigation will be on the application of the longer ERB data set of the period from 1978 to the present.

Table 1 summarizes the yearly mean solar energy input to the climate system from November 16, 1978 to July 31, 1991. Listed in the Table are the interannual variability, its mean deviation, and the peak and minimum daily values for each year. Note that SAT

Table I Annual-mean solar irradiances from 1978-1991 monitored by the ERB Cavity Radiometer.

Period	Solar Irradiance Variations			
	Mean (W/m^2)	Mean Div.	Min (W/m^2)	Max (W/m^2)
Nov-Dec, 1978	1372.69	0.462	1371.32	1373.66
Jan-Dec, 1979	1373.36	0.519	1371.37	1374.88
Jan-Dec, 1980	1372.62	0.439	1370.83	1373.60
Jan-Dec, 1981	1371.97	0.482	1369.20	1373.04
Jan-Dec, 1982	1371.73	0.514	1369.85	1373.14
Jan-Dec, 1983	1371.69	0.259	1370.04	1372.43
Jan-Dec, 1984	1371.36	0.339	1368.57	1372.43
Jan-Dec, 1985	1371.48	0.136	1370.67	1372.11
Jan-Dec, 1986	1371.40	0.139	1370.88	1371.86
Jan-Dec, 1987	1371.55	0.244	1370.76	1372.80
Jan-Dec, 1988	1371.88	0.327	1369.46	1373.69
Jan-Dec, 1989	1372.24	0.513	1369.67	1373.69
Jan-Dec, 1990	1372.63	0.415	1370.26	1373.77
Jan-Dec, 1991	1372.77	0.574	1370.40	1374.07

anomalies are given in interannual terms instead of daily or monthly means to avoid the noises being compounded by the basic features of seasonal variability. A detail worthwhile to bring up at this juncture is the fact that the early ERB's radiometric readings would appear to be marred by a small error in the pointing knowledge of the telescope. For this reason, a revised algorithm has been introduced which corrects values for the period 1978-89 (Hoyt, *et al.*, 1992). However, according to Foukal *et al.* (1988), the solar irradiances of the ERB's values for the first two years may still include other uncertainties which have not been corrected in the revision by Hoyt *et al.* That may be the cause of the slight departure from the Taipei line trace in the first 20 months depicted in Figure 2. This difference between ERB team and the Foukal model puts the solar irradiance peak within the period from either late in the winter of 1980 to the spring of 1981. The ERB's interpretation closely following the model of Schatten (1988) places the solar irradiance maximum for cycle 21 as early as 1979. This controversy over interpretation of the early ERB data can have significant influence on a temperature-irradiance correlative study. Especially when SAT response to solar stimulus could have built in delays and is only being considered on an interannual basis, which reduces the precision of information for there are only 11 annual-mean data points to directly compare to SAT data.

In Figure 5, the global annual mean SAT for the 1978-1990 period, and SAT data for the southern hemispheric belt 23.6 $^{\mathrm{o}}$S - 44.4 $^{\mathrm{o}}$S taken from the shaded box area of Figure 4 are shown as two upper traces, 5a and 5b. The lower two traces, 5c and 5d, are for the annual mean solar irradiances measured by ERB, and modeled solar irradiances. All four traces exhibit a downward decline concurrent with the waning of the solar cycle 21 from 1980 to 1986 and this is followed by an upturn as the current cycle 22 begins in 1987 except for the local departures in global SAT profile. Note that the ERB measurements in 5c are closely duplicated by the SAT readings of the southern hemispheric zone given in 5b. This particular comparison results in a correlation coefficient of 0.786 while a correlation coefficient of 0.61 is obtained for the overall global temperature scene. Both sets exclude the controversial '78 and '79 data. Table II lists derived correlation coefficients for the ERB solar data and remaining zonal temperatures. In Figure 6, the regression of ERB measurements vs the southern hemispheric zonal and global SAT anomalies is presented. In this scatter plot, the SAT are referenced to the 1986 data point which was arbitrarily taken as the origin of the regression analysis. The linear regression of the data set yields

$$\Delta T_{yr}(K) = 0.17 * \Delta S_{yr}(W/m^2) + 0.04 \quad (10)$$

where the ΔT_{yr} denotes the temperature fluctuations in response to the interannual solar irradiance variations, ΔS_{yr}.

5) GEOGRAPHICAL PATTERNS OF SUN-CLIMATE CORRELATION.

The regional response to solar forcing is also interesting. In Figure 7, Hansen's "80 equal SAT box" grid is overlaid on the annual global mean cloud cover map of the Nimbus-7/ ERB for the period of April 1979 - March 1985 (Kyle, 1988). The numerical value within each box is the derived correlation coefficient between the yearly mean solar irradiance variances from 1978-1990 and the mean SAT of each grid box. Based on this coarse overlain map and the results of Table II, several leading mechanisms that influence the

Table II Derived Sun-SAT relationships For Global and and Eight Latitudinal Zones

Zone	Correlation Coefficient	Regression Coef. Slope	Constant
Global Mean	0.608	0.169	0.014
66 - 90 °N	0.432	0.419	0.056
46 - 66 °N	0.489	0.421	- 0.1
24 - 46 °N	0.548	0.249	-0.03
Equator-24 °N	0.267	0.099	0.08
Equator-24 °S	0.187	0.072	0.08
24 - 46 °S	0.786	0.179	0.0
46 - 66 °S	0.093	0.039	-0.02
66 - 90 °S	-0.149	-0.14	-0.24

regional SAT response can be listed: the cloud coverage, the heat transportation processes, and the levels of surface albedo primarily associated with land usages.

The climate in its purest form is driven by the absorbed solar energy. The imbibed solar energy directly heats the surface and the heated surface gives off its heat content largely radiatively and as sensible heat flux. However, this is not the case in many regions of the Earth where many days of cloud cover are found. The cloud optical thickness governs the

percentage of absorbed solar energy while the cloud base and top heights influence the outgoing longwave radiation (OLR). Available evidence indicates that it is easier to establish correlations of surface temperatures and the cloud cover given both total cloud and altitude (Reynolds, 1988). The relationship between absorbed sunlight and surface temperature is often ambivalent in such regions: The role of absorbed sunlight is largely consumed to foster evaporation. In any event, the derived zonal correlation coefficients in Table II are almost inversely related to six-year zonal means of cloud amount reported by Weare (1992). The impact of cloud cover can be observed in Figure 7 where the positive correlation coefficients greater then 0.5 are found mostly from those land areas where an annual global mean cloud cover is less than 20%; such as the Arabian Peninsula and the North African continent near the Red Sea and the Australian continent. One would expect that large arid land areas would respond to solar irradiance fluctuations provided the area's albedo remain unchanged during the observation. Any large scale anthropogenic alterations on the land will contribute to changes causing warming (or cooling) of the region. Categorically, bare soil, short cut grass, or urban structure tend to give off heat content in the form of sensible heat fluxes while forests, rivers or lakes dissipate the energy in the form of latent heat of evaporation. Other strong correlation areas in Figure 7 are found in the vicinity of the southern gyres of both the Pacific and Atlantic. In this regard, we will have to consider the effect of the heat transport processes due to the general circulation patterns of the ocean and the atmosphere. Over the global ocean, heat is transported by the major current systems, which can certainly mask the direct effect of the solar irradiances. The time scales of the global circulation gyres are different. Therefore, the correlation of the ocean region with the solar irradiance are also non-uniform. In order to demonstrate the short-term direct effect of the solar irradiance, one has to look for a region with relative sluggish circulation. The extratropical oceans which form a closed circulation gyre seem to meet this criteria better than other parts of the oceans: The tropical oceans in the Pacific Equatorial current and under current are strong, and interannual *El Nino* oscillations are also known to occur. The zonal region covering 44.4 ^{o}S - 64.2 ^{o}S coincides with the circum polar current. Large amounts of heat between the ocean and the atmosphere are exchanged there where the world's deep ocean water is also formed. In the case of both polar regions, the climate is usually made of one gigantic eddy circulation which takes in all the low latitude heat transports. Thus, any anomalous heat transport patterns from the lower latitude would be amplified and the effect of the direct solar forcing would have a secondary role as shown by the high variability in the bottom trace of Figure 4 zonal temperature anomaly profile.

With these considerations, one can accept that the SAT changes of the 23.6 ^{o}S - 44.4 ^{o}S zonal area closely reflect interannual variations of the solar irradiance during the last decade. Because the zone is predominantly made up of oceanic areas and small fractions of land areas that include the southern halves of Australia, South American and the African continents. This combination of the areal oceans constituting the centers of three large counter clockwise gyres, namely the South Atlantic Gyre, the South Indian Gyre, and the South Pacific Gyre and the arid landscapes, create the zonal temperature conditions which are susceptible to the annual solar insolation changes as demonstrated in Figures 5b and 5c.

6) SUN-CLIMATE RELATIONSHIPS SINCE 1874

Having established a positive correlation between the interannual solar variability and SAT, correlations between the Sun and Earth climate over a time scale of decades was sought. In our approach to restore the history of solar variations, Greenwich observatory's faculae record was chosen as preferred proxy data after several tryouts with other forms of solar proxies and indices in search of a solar data set which fits best with the SAT anomalies. In this aspect the entire Earth is considered as a radiometer of the Sun. At a glance, the two traces of the Fig. 3 do not appear to be correlated. This impression is due to the fact that the solar input function of monthly means display a strong 11-year component whereas the Earth's temperature is characterized by the presence of noise in all frequencies. A wavelet analysis was performed on both data by the use of a Morlet wavelet. The results of the wavelet module analysis were integrated with respect to time to give a power spectrum. The top profile shown in Fig. 8 pertains to the power spectrum derived from the monthly global SAT record. Solar cycle signatures are found in every 11.8 years. A small indentation at 18.1 and a peak at 5 year period have been identified as those belonging to the temperature changes caused by lunar nodal crossings and *El Nino* oscillations respectively. Of particular interest is the solar peak at 11.8 years, even though the peak is a relatively small and slightly longer than the average 10.8-year period found in the bottom profile. The presence of this component was already reported by Currie (1981a and 1981b). He was able to identify both 11-year solar cycle and 18.6-year lunar nodal signals from North American temperature records by applying high resolution signal processing called the maximum entropy method (MESA). The mean amplitude fluctuation caused by the solar cycles was reported as 0.1^{o}C with the temperature period lagging the solar cycle by 3.0 +/- 0.7 years. The spectral analysis, however, will not give the phase information, which is of critical importance in the climate study. We will discuss this aspect in next.

The correlation based on 11 years activity cycles can be further evaluated by matching in-phase responses of the SAT. For this purpose, both events, solar irradiance and SAT, were each treated as discrete time series of unequal intervals determined by the length of each solar activity cycle. The length of each solar cycle, in monthly terms, was determined by two different methods; first, by smoothing the sunspot number index with a 10-term polynomial fit and, secondly, by observing the flip of solar magnetic poles determined by the geomagnetic indices (Gonzales *et al.*, 1989). After locating a trough between consecutive cycles, the time integration of both irradiance and the respective temperature for each cycle was carried out. The resulting values are the mean intensities of the solar activities and corresponding SAT responses. The rationale for this method is, in part, found in past studies by Friis-Christensen and Lassen in 1991, who proposed the length of the solar cycle as an important parameter in Sun-climate relationships. Accepting this hypothesis, the intensity of the solar activities, together with the length of the cycle, are represented by the time integral of each cycle and analyzed. In Fig. 9, derived mean irradiances and temperature responses for last 10 cyclic events are plotted. The solar irradiances are represented by square dots and connecting lines and temperature responses with a built-in 32 months phase lag and without any lag are shown in triangular and circular dots and connecting lines respectively. A correlation coefficient of 0.57 was initially obtained for the sunspot minima data. Then the correlation coefficient improved to 0.61 as cyclic lengths determined by the geomagnetic indices were applied. Fig. 10 demonstrates correlation coefficients which peak at 0.69 as varying length of time lags are instituted for SAT response; a proof that climatic response to the solar irradiance impulses develop rather slowly in about 32 months.

A linear regression of the intercyclical data yields a temperature sensitivity of 1.62 K-m^2/W which is an order of magnitude larger than that has been observed from interannual data. The cause for the large discrepancy was traced back to the fact that even though the amplitudes of solar irradiance variations in intercyclic terms have been reduced by a factor of about 10 by averaging, the temperature during the period have shown an increase at the rate of 0.52 K per 1298 months. The presence of long-term trends in SAT history needs to be addressed.

The following causes are conceivable for the long-term temperature trends:

A) First, one may assume that there has been a gradual increase of internal longwave radiation flux during the period caused by CO_2 and / or aerosol concentration increase in the atmosphere. Such changes constitute internal forcings.

B) Alternatively, one can look for a gradual change in solar total irradiance during the last 110 years which had not been duly accounted in our solar model.

Table III Derived Mean Solar Irradiances and SAT For Last Ten Solar Activity Cycles 12 - 21.

Solar Cycles	Length (Mos)	Mean Irradiance		SAT Anomalies (^oC)
		Detrended (W/m^2)	With Trend (W/m^2)	
12	110	1371.604	1371.739	-0.551
13	143	1371.703	1372.060	-0.438
14	148	1371.675	1372.268	-0.466
15	124	1371.602	1372.433	-0.233
16	116	1371.726	1372.768	-0.197
17	124	1371.722	1372.969	-0.143
18	120	1371.731	1373.101	-0.141
19	137	1371.685	1373.348	-0.209
20	145	1371.743	1373.636	-0.323
21	112	1371.899	1373.99	-0.00

Setting aside the aspect of anthropogenic greenhouse effect theory for now, an argument is being made focusing on the aspect of a long-term solar flux change. The rationale for such argument can be found in the previous works of Gleissbery and Hoyt. For instance, Gleissberg back in 1965 reported the observation of auroral frequency numbers which relates closely to the solar activity cycle trends in the form of several solar activity cycles within an envelope with high and low undulations. According to such prediction, Cycle 20 in 1960s should signal the end of Gleissberg Cycle III and the rapid rise of Cycle 21 and 22 can be seen as the beginning of Gleissberg Cycle IV. More significantly, Hoyt *et al.*, (1993) recently reported that the combined solar irradiance model shows long-term trends of solar total irradiance increase at the rate of 3.4 W/m2 during the last 200 years since 1800 to present. Their model incorporates three solar indices: the length of solar cycle, decay rate of the solar cycle and the mean level of solar activity. In Fig. 11, the mean solar irradiances of the last ten cyclic events which incorporates a long-term trend of 2.2 W/m2 solar irradiance increase in 1298 months are plotted along with SAT responses. The correlation coefficient derived under these conditions peaks at 0.82 and a *k* parameter of 0.2 K-m^2/W is obtained.

$$\Delta T_{cyc}(K) = 0.2 * \Delta S_{cyc}(W/m^2) + 0.47 \qquad (11)$$

where the ΔT_{cyc} denotes the intercyclic temperature change in response to the intercyclic solar flux variance, ΔS_{cyc}. Table III summarizes mean irradiance values derived from detrended and with a built-in long-term increment, and corresponding SAT responses with and without built-in phase lag, for last 10 solar activity cycles.

7) DISCUSSION

The two derived slopes, *k*s, in Eqs. (10) and (11) are temperature sensitivity parameters in K-m^2/W. Due account must be taken in reference to the climate feedback of Eq.(5). The practical implication of a feedback parameter is that it not only defines temperature changes induced by an external forcing but also can be taken as the change in terms of outgoing longwave radiation as the system responds to the imposed forcing Table IV lists

Table IV Feedback Parameters Of Solar Forcing At a Range of Surface Temperatures.

Temperature (K)	$4\sigma T^3$ (W/m^2-K)
255	3.76
288	5.4
300	6.12

the levels of blackbody feedbacks for the imposed solar forcing of one degree change for a range of temperatures. Against such a setting, the k values are for the solar total irradiance measured at the top of atmosphere, ΔS. Hence in the feedback calculation, the ΔS needs to be converted into ΔF dividing by a factor of 4. Then the derived slopes of 0.17 and 0.2 translate to nominal blackbody feedbacks of about 1.47 and 1.25 W/m^2-K respectively. In climatology, such feedbacks are referred to climatic processes that can modify temperature changes. The important question is " how significant is the solar forcing in the total picture of global SAT change". In Table V, the derived solar feedbacks are compared against feedback parameters of several other climatic processes observed in the history of SAT anomalies. Scaling of the list was done as a nominal feedback parameter of 1.5 W/m^2-K for solar forcing is applied to the results of power spectrum analysis given in Fig.(6).

Next comes a crucial question of why the observed solar forcing is particularly effective in raising the surface temperature. The derived feedback parameter of about 1.5 W/m^2-K implies that less than 1.5 W/m^2 solar flux change is required to alter the surface temperature by one degree. This contradicts with the theoretical feedback parameter of

Table V Feedbacks of Various Climate Processes Contributing In the Formation of SAT Anomaly.

Forcing	Periodic Occurence	Feedback (W/m^2-K)
Solar forcing	Every 11 yrs	1.47
Unknown Trends (Probably of solar forcing)	In 28 - 50 yrs	1.47
Lunar Nodal	Every 18 .6 yrs	0.9
ENSO like Features	Every 5-7 yrs	2.5
Other Spurious Events	Every 3 yrs	1.9

6.14 W/m^2-K at 300 ^oK in Table IV. Such dichotomy is not too difficult to understand if one takes into the account of Earth's natural greenhouse effect. In this context, it should be pointed out to the fact that in reality the actual solar flux which reaches to the ground, especially at lower latitudinal zones during the daytime, is close to a 1000 W/m^2. The temperature response measured under these conditions will be responsible for the feedback parameter in the proximity of several W/m^2-K which is perfectly within the range of Table IV. And ensuing hypothesis is that this momentary SAT response attained at the height of solar illumination will not be dissipated into space but largely retained within the Earth's black body sphere. Relatively slow heat dissipation rate at the top of the black body sphere of 255 K is largely responsible. Thus the imposed solar forcing at the rate of 5 to 6 W/m^2-K at the surface will largely remain as excessive heat fluxes creating the conditions of magnifying the temperature response. Such proposition, if proven, should explain why the observed temperature responses are highly sensitive to external solar forcing.

8) CONCLUSIONS

In summary, our renewed argument on the Sun-climate connection is based on the observational fact that the ERB's Channel 10C data demonstrates the Sun's annual mean irradiance fluctuated about 2 W/m^2 in amplitude during the recent transition between solar activity cycles 21 and 22. This less than 0.15% solar fluctuation was thought to be too small to influence the Earth's climate. Our analysis indicates otherwise. Solar irradiance variations have been observed to trigger temperature responses with a correlation coefficient as high as 0.78. The power spectrum of the monthly temperature history demonstrates that the solar total irradiance variations can influence the SAT as much as other co-factors such as Lunar nodal crossing, *El Nino* like oscillations, and other transient events.

In addition the study proves that over the time period of recorded global temperature, there has been a gradual up-swing of temperature which peaks during the 1930s-1940s. Then a decadal decline causes a small trough in 1960s, and this period is followed by the recent upsurge to an unprecedented peak. This slowly drifting temperature excursions are about 90% correlated to the solar total irradiance variations of the period. The finding is largely based on modeling, albeit the modeling of solar irradiance history is still imperfect.

Then, the presence of up to 32 months phase lag in temperature response has been observed. In all probability, the phenomenon is associated with the climate's feedback mechanism which is known to be slow in developing, for example, the relatively weak coupling between the atmosphere and the ocean.

As a closing remark, it is emphasized here that the Earth' climate system is truly complex. Understanding this complex web of interactions among many elements of the climate poses a serious challenge to this particular blend of interdisciplinary science; solar physics and climatology. In this context, what is being presented here is newly found evidence of the role of the Sun in climate change. This is done so in spite of the facts that the present solar irradiance measurements from satellite are only marginal in length, solar proxy data available are fragmentary, and undoubtedly errors and uncertainties in the solar irradiance modeling based on proxy data and solar indices do exist. With this acknowledgment and looking ahead in a critical manner, we would like to close this article by stating that, if the present Sun-climate correlation continuously persists for next five year period to the end of Cycle 22, it would provide more definitive scientific data in resolving the question in regard to what extent solar irradiance and man's infusion of the man-made greenhouse gases in the atmosphere are responsible for global climate change.

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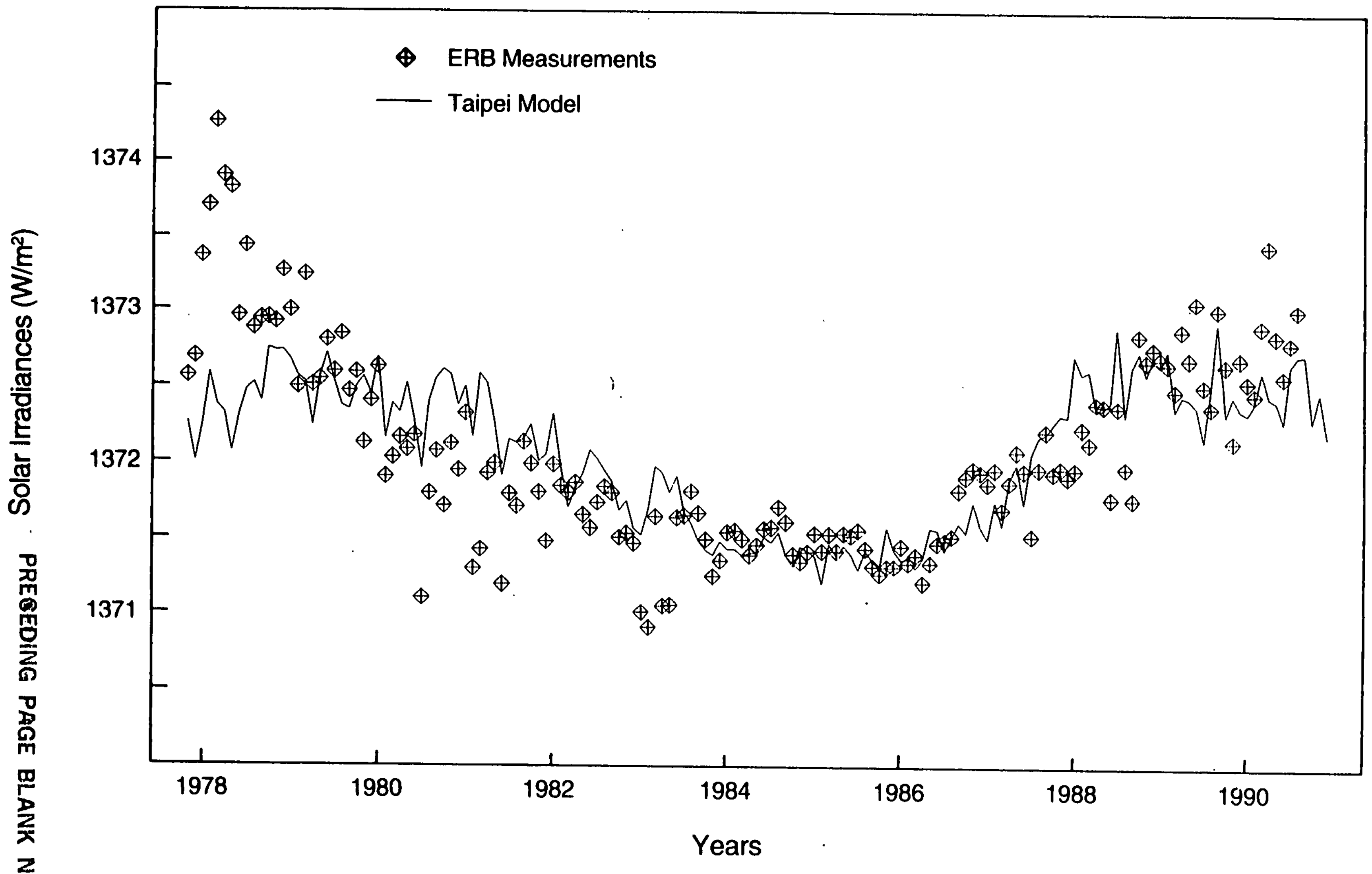


Figure 1. ERB's monthly mean solar total irradiances (in diamond dots) are overlain on the irradiance residuals derived from Taipei active region data.

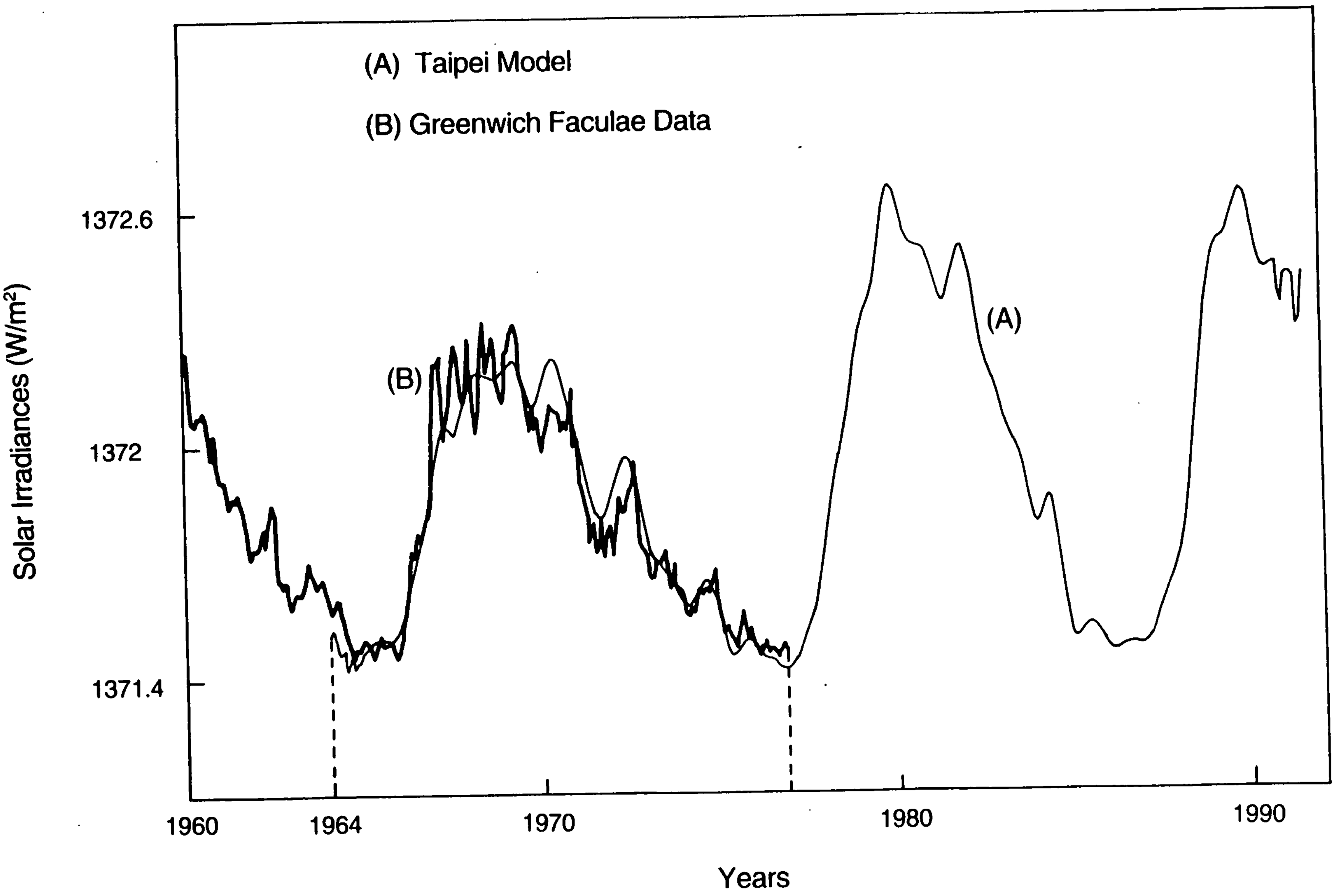


Figure 2. Greenwich faculae data and Taipei active regions data are cross calibrated by the 10-year overlapping period of Cycle 20.

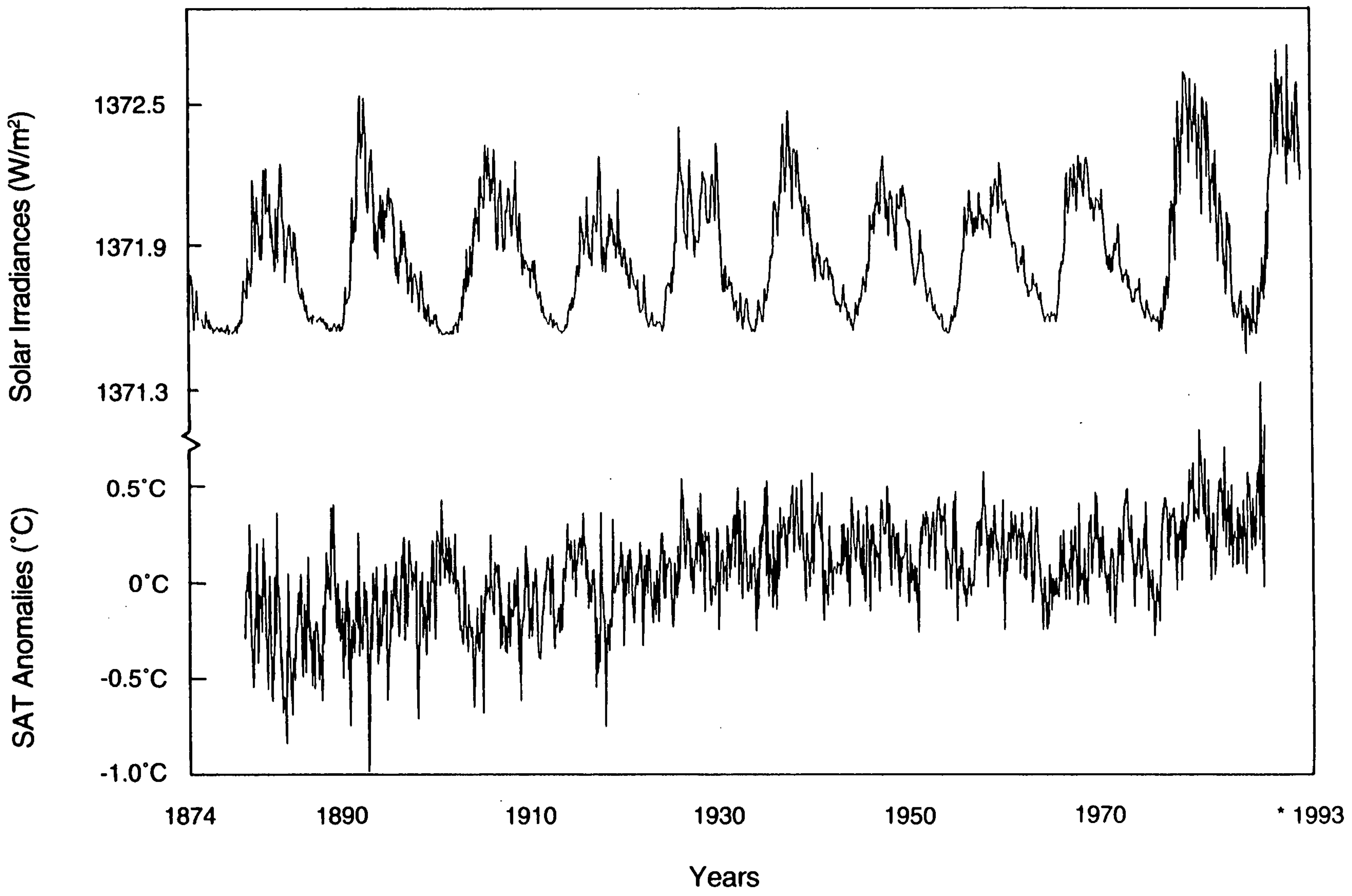


Figure 3. Estimated variations in the solar total irradiances from 1874 till present are shown in top trace, and the monthly mean global SAT anomalies are shown in the lower trace.

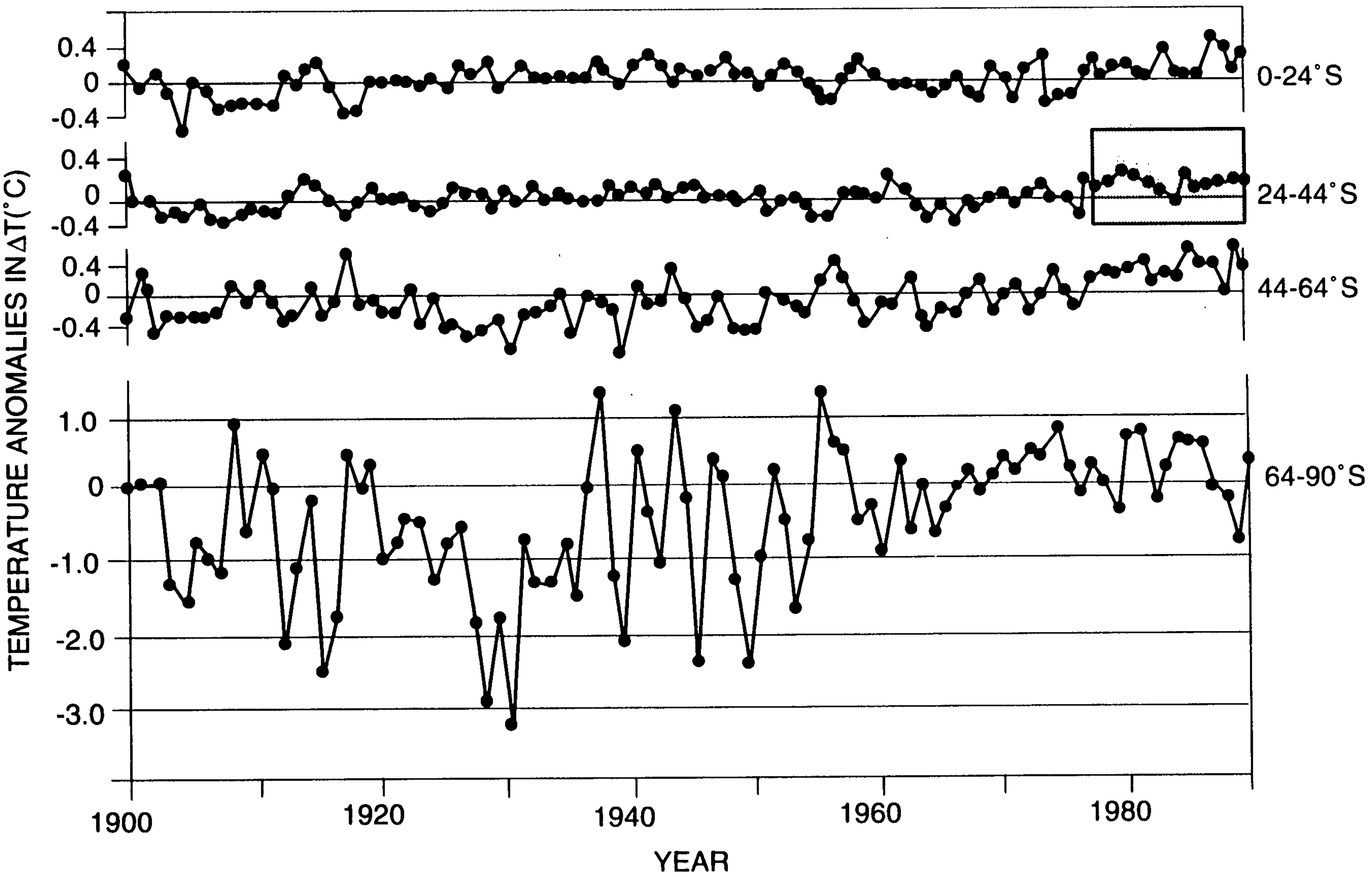


Figure 4. Temperature Anomalies of the southern hemisphere since 1900 (Hansen, *et al.*,1987) are shown in four latitudinal zones. The temperature profile within the shaded box pertains to the particular profile which seems to coincide with the ERB data.

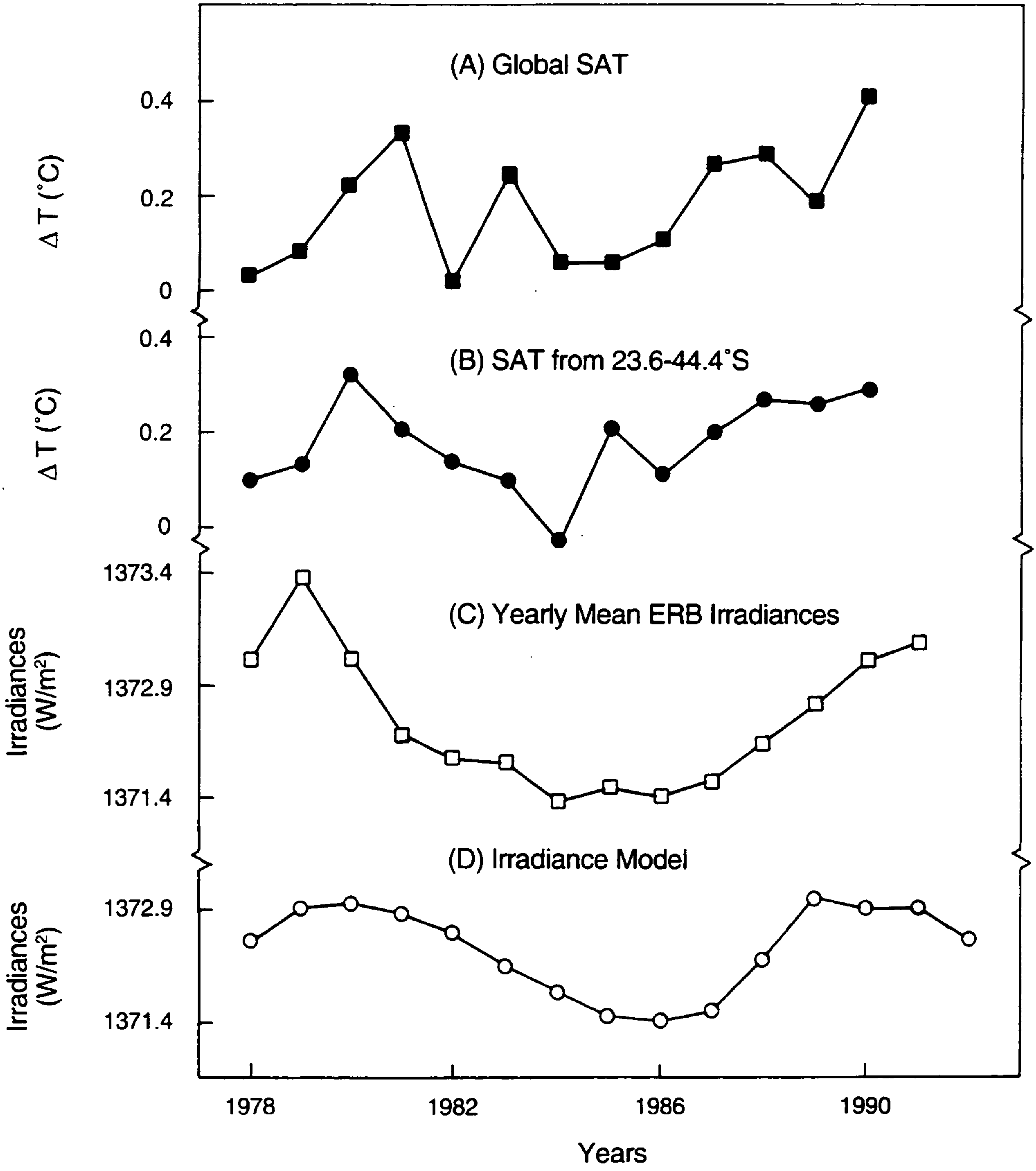


Figure 5 SAT variations observed in global yearly mean, zonal mean from 23.6 oS - 44.4 oS latitudes, solar total irradiance variations from ERB measurements, and from that of modeled are respectively given as traces 5a, 5b, 5c, and 5d.

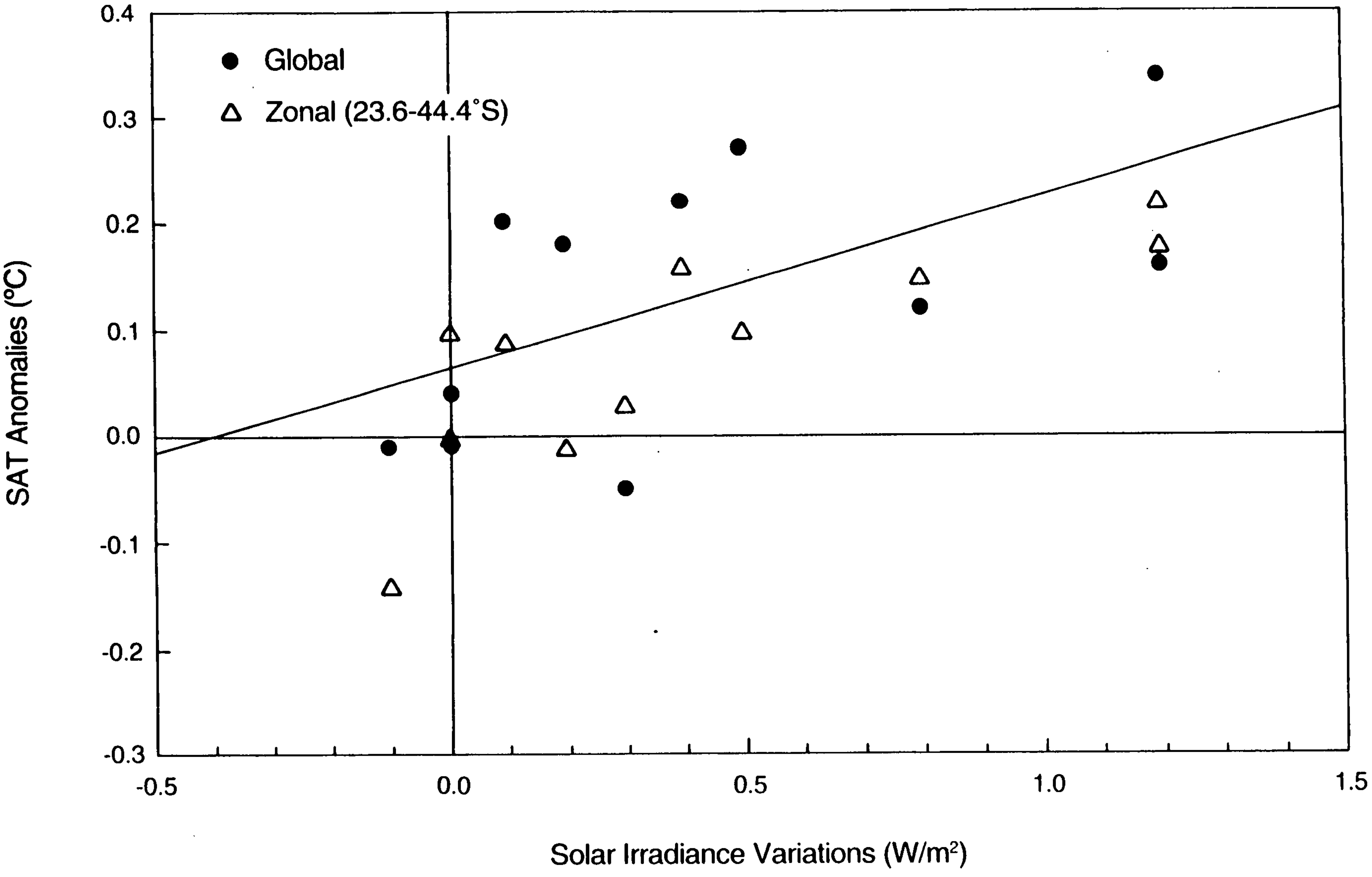


Figure 6 The scatter of 11 global and 11 zonal SATs are shown as the function of solar total irradiances. The regression line has a slope of 0.17°C per W/m^2 insolation change.

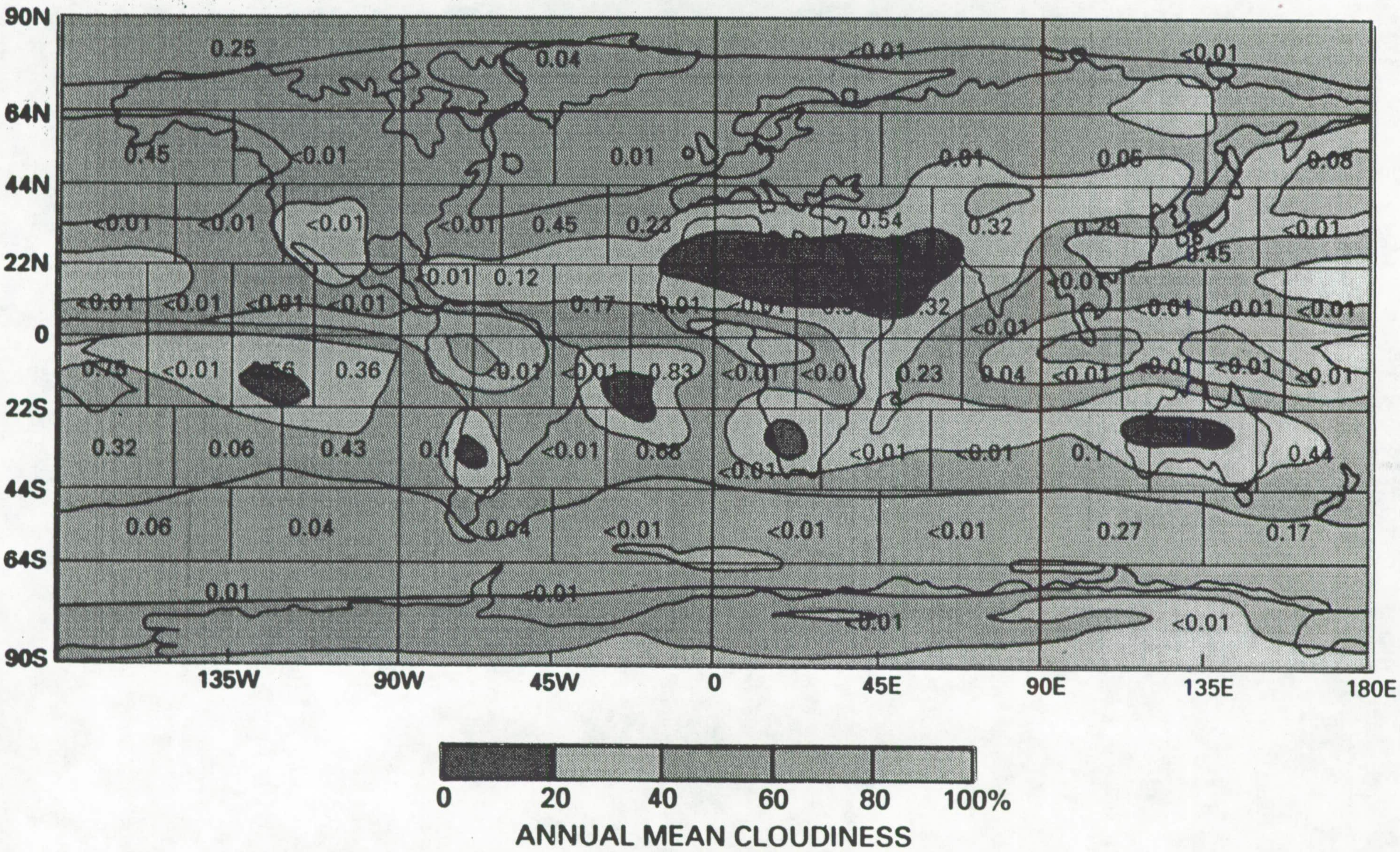


Figure 7. Correlation coefficients between the solar total irradiance and SAT are projected on the ERB cloud cover map in "80 equal-areal temperature box grid" given by Hansen *et al.*

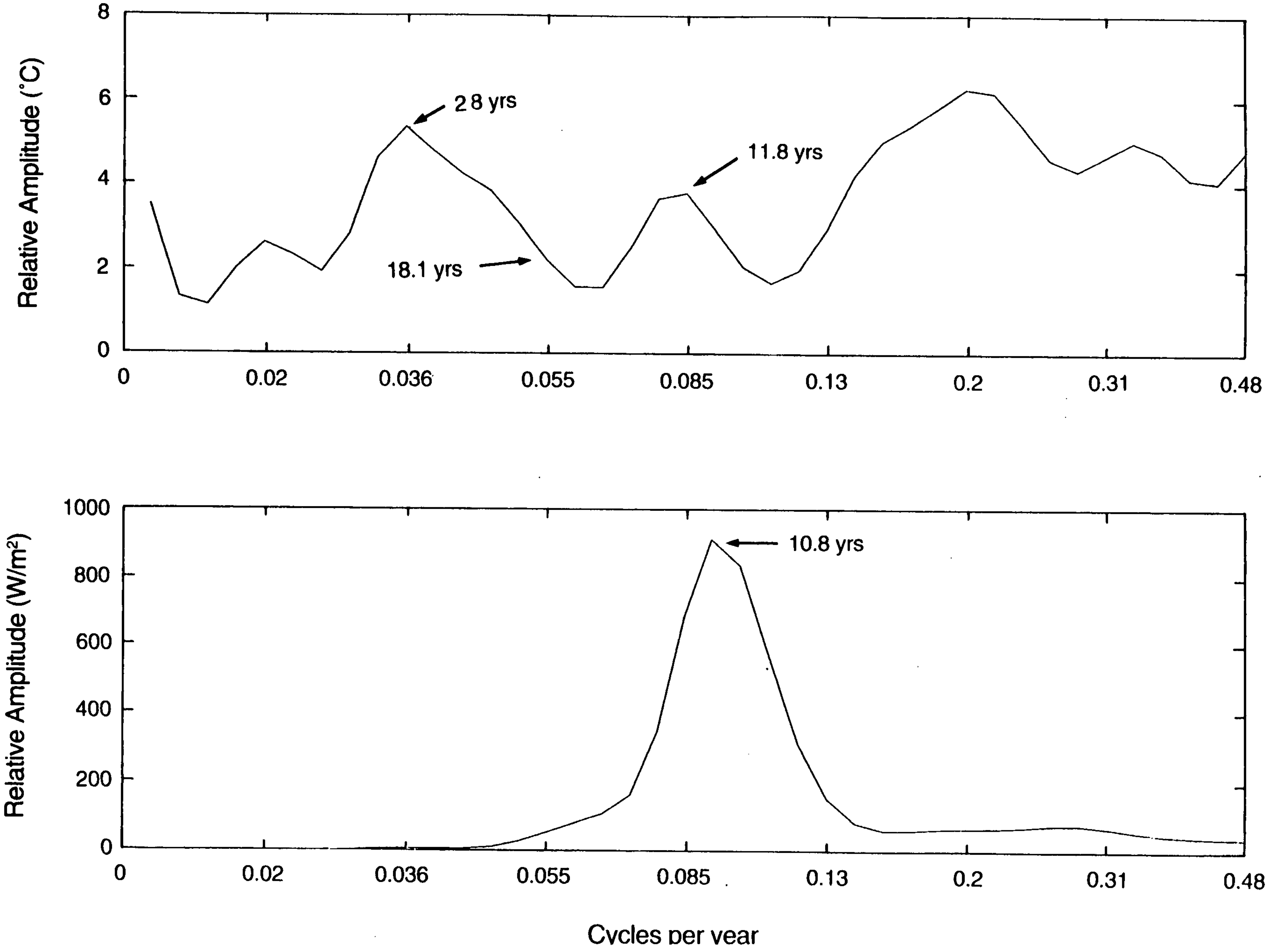


Figure 8. Power spectra derived from monthly mean SAT and solar total irradiances are shown as the top and bottom plot.

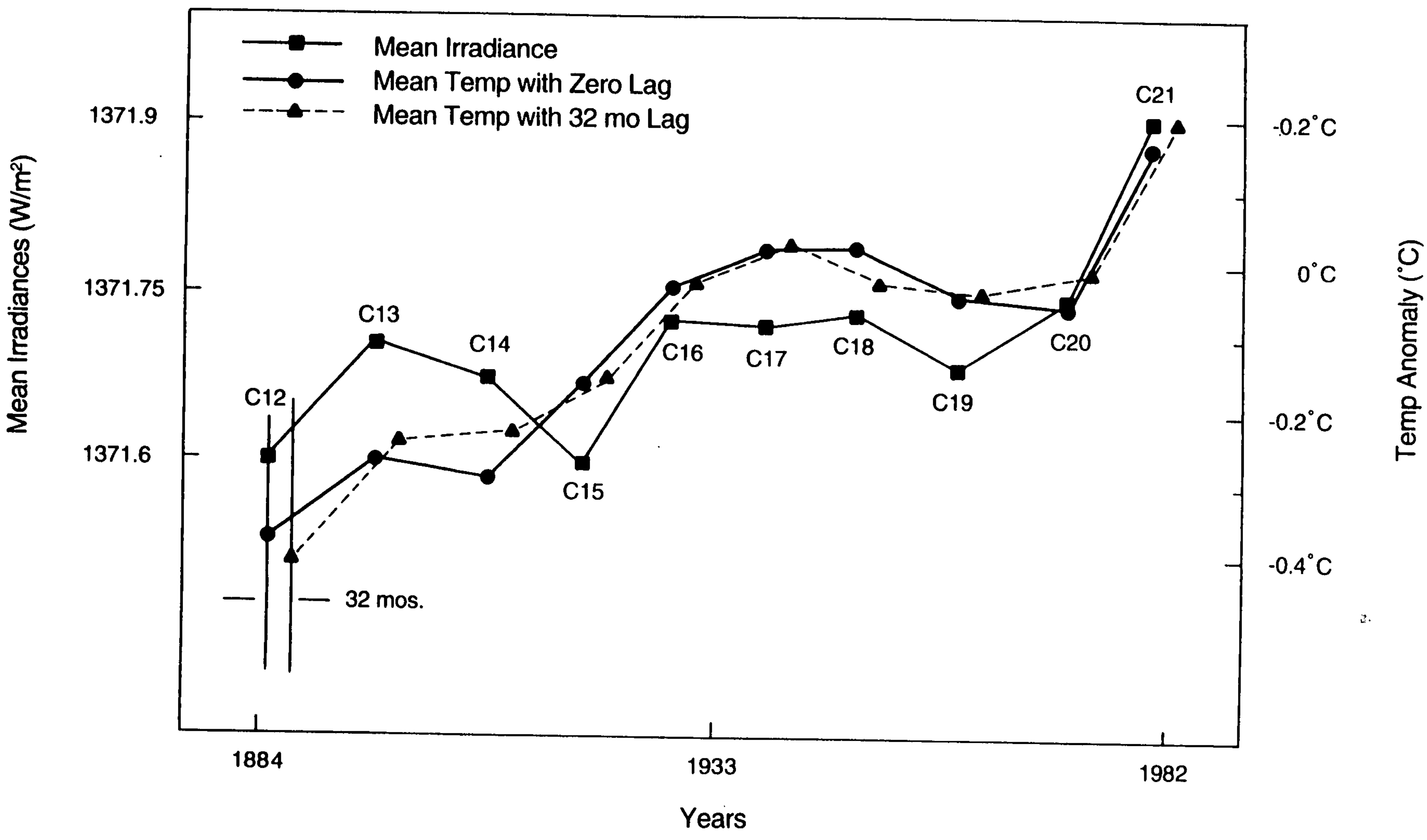


Figure 9 The last ten solar activity cycles are treated as an input function (shown in solid square and line) to SAT record by the time integration of the length and irradiances of each cycle. The SAT responses in broken line trace are for the responses with a 32 months time lag.

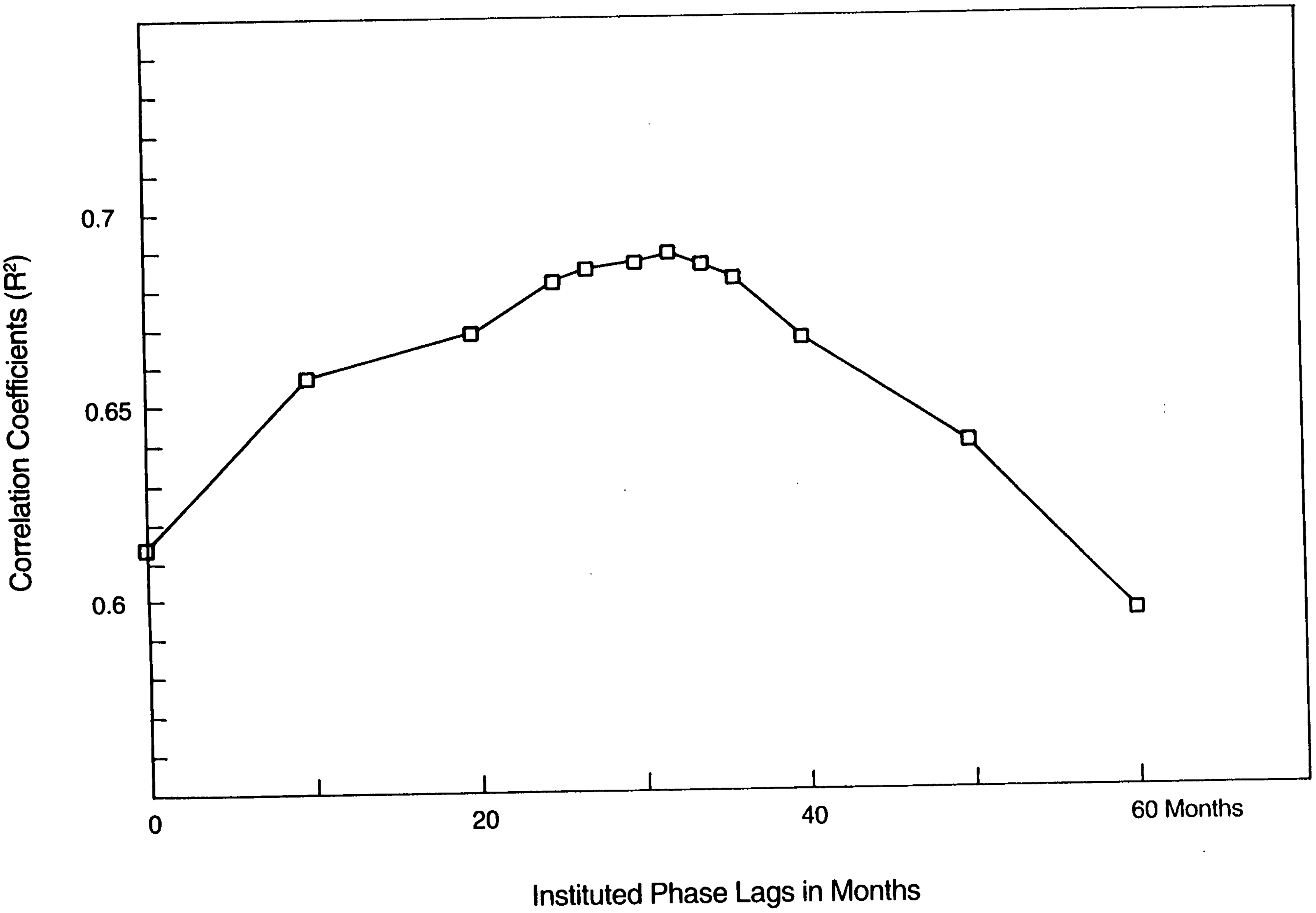
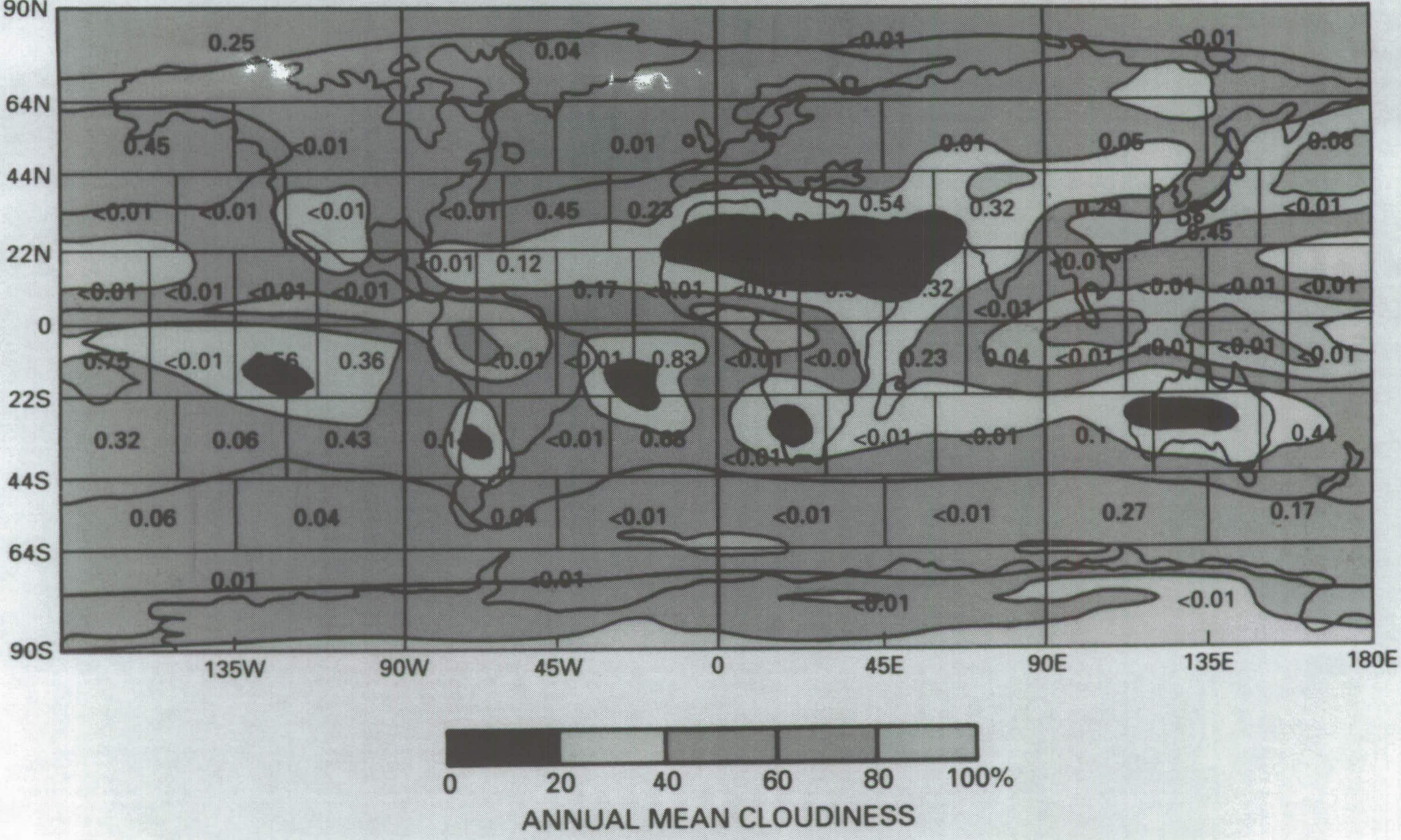


Figure 10. Derived correlation coefficients between the solar total irradiances and Earth's SAT anomalies are plotted as the function of built-in phase lags.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64N
44N
22N
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22S
44S
64S
90S
135W
90W
45W
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45E
90E
135E
180E
0.25
0.04
<0.01
<0.01
0.45
<0.01
0.01
0.01
0.05
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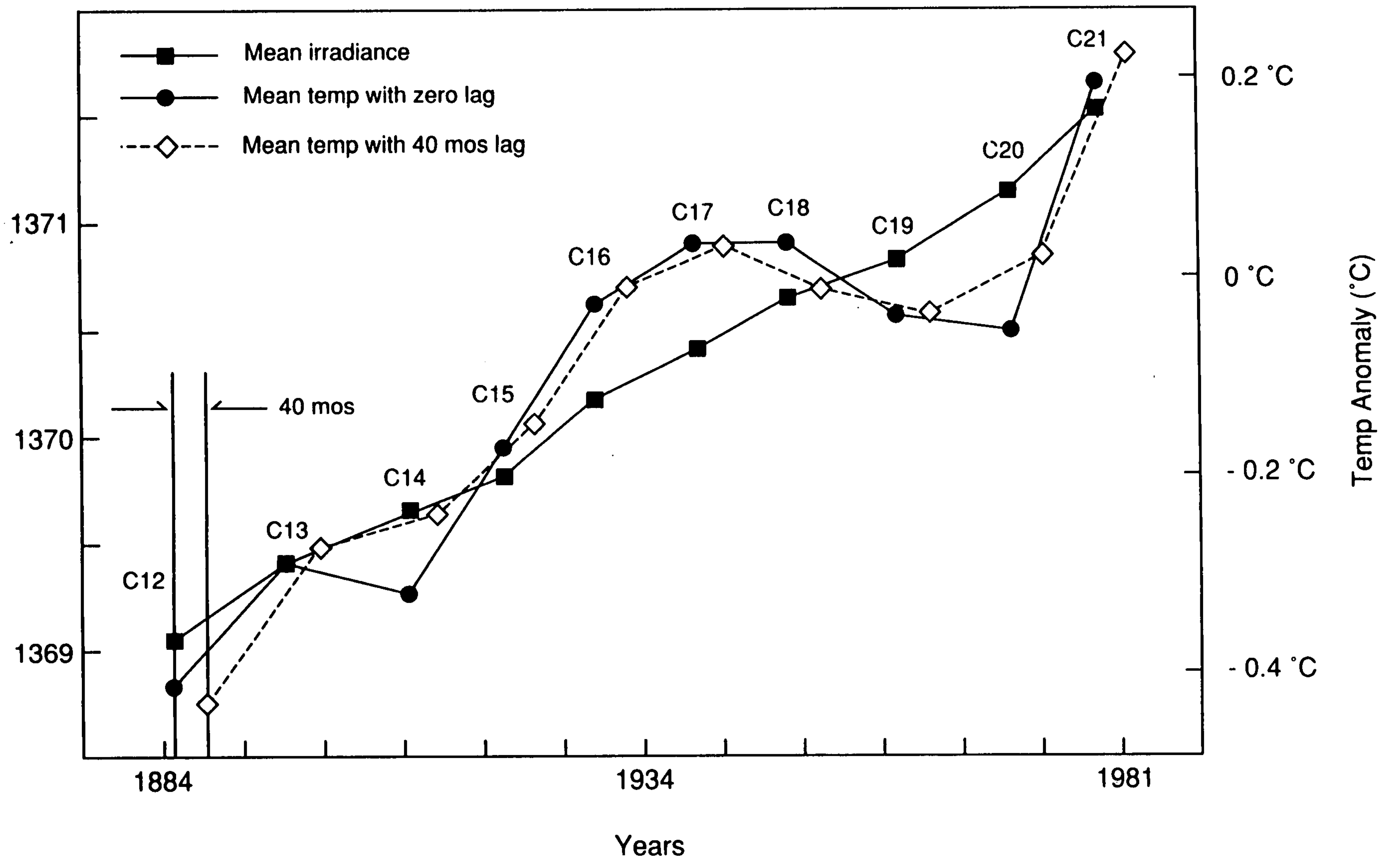

Figure 11. SAT responses are shown along with a solar model which incorporates long-term trends of 2.2 W/m^2 increase in 1298 months (See Fig. 9).

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13. ABSTRACT *(Maximum 200 words)*

Solar radiation cycles drive climatic changes intercyclically. These interdecadal changes were detected as variations in solar total irradiances over the time period of recorded global surface–air–temperature (SAT) and have been restored utilizing Earth Radiation Budget Channel 10C measurements (1978–1990), Greenwich Observatory faculae data (1874–1975), and Taipei Observatory Active Region data (1964–1991). Analysis of the two separate events was carried out by treating each as a discrete time series determined by the length of each solar cycle. The results show that the global SAT responded closely to the input of solar cyclical activities, S, with a quantitative relation of $T = 1.62 * S$ with a correlation coefficient of 0.61. This correlation coefficient peaks at 0.71 with a built–in time lag of 32 months in temperature response. Solar forcing in interannual time scale was also detected and the derived relationship of $T = 0.17 * S$ with a correlation coefficient of 0.66 has been observed. Our analysis shows derived climate sensitivities approximately fit the theoretical feedback slope, $4T^3$.

14. SUBJECT TERMS

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