Climate sensitivity of the Earth to solar irradiance

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[1]   The mean surface temperature of the Earth depends on various climate factors with much attention directed toward possible anthropogenic causes. However, one must first determine the stronger effects such as El Niño/La Niña and volcanoes. A weaker effect, which must exist, is solar irradiance. We have determined the solar effect on the temperature from satellites measurements (available since 1979) of the solar irradiance and the temperature of the lower troposphere. We find the sensitivity to solar irradiance to be about twice that expected from a no-feedback Stefan-Boltzmann radiation balance model. This climate gain of a factor of two implies positive feedback. We also have determined a linear trend in the data. These results are robust under truncation from either end of the of the data record. These measurements of solar sensitivity are consistent with prior estimates from ocean temperatures on decadal scales and of paleo-reconstructed temperatures on centennial scales.   INDEX TERMS: 1620 Global Change: Climate dynamics (3309); 1650 Global Change: Solar variability; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620)

1.   Introduction

[2]   The importance of solar irradiance I and its influence on the climate of the Earth has been discussed by *Lean and Rind* [1998], *White et al.* [1997], *Baliunus and Soon* [1998], *Reid* [2000] and others. In particular, they recognized that the question of the sensitivity of the global-average surface temperature response of the Earth to changes in the Sun's irradiance was one of the key question in the study of climate variability. The status of this situation was declared by Lean and Rind who stated: "Present inability to quantify climate forcing by solar radiation, whether negligible or significant, is a source of uncertainty that impacts public policy making regarding global climate change."

[3]   The more general question of what factors are important in climatology is one of intense scientific interest. Much of this interest is directed toward anthropogenic effects. However, one must first understand and determine the changes in the climate which occur from natural processes such as volcanoes and El Niño/La Niña. Both these effects are shown to be present in satellite measurements of the lower troposphere global temperature T [*Christy et al.*, 2000] and have a magnitude $\Delta T \approx 0.5C$. *Christy and McNider* [1994] and *Michaels and Knappenberger* [2000]

have modelled these two effects and attempted to remove these signals from the data. The effect of changes in solar radiance I on T is smaller and can be estimated from simple radiative equilibrium models without feedback as $\Delta T/T \approx \Delta I/4I$. For a change $\Delta I \approx 1$ W/m^2 (comparable to estimates of the amplitude of the '11 year' sunspot period and the secular change in I since 1900) one estimates $\Delta T \approx 288(1/4 * 1365) \approx 0.05C$. Our measurements yield a value of about twice this. This value, however, is not negligible compared to some estimates of anthropogenic effects. The framework for a quantitative discussion is developed below.

2.   Climate Models

[4]   Models of the Earth's climate system generally assume that there is a forcing ΔF (volcano, solar, etc.) which causes a change ΔT in the mean temperature of the Earth's surface. In equilibrium the relation between these is

$$\Delta T = \lambda \Delta F \tag{1}$$

where λ is the climate sensitivity, and where ΔF is defined as an equivalent solar flux averaged over the earth and referred to the 'top of the atmosphere'. We report the determination of the value of λ for Solar forcing but do not determine it directly. We determine the irradiance constant k which we define as

$$\Delta T = k \Delta I \tag{2}$$

The relation between λ and k is found as follows. The forcing ΔF is obtained by averaging ΔI over the whole surface of the earth and allowing for a fraction (albedo a) of ΔI to be reflected away $\Delta F = \frac{1-a}{4}\Delta I$. The climate sensitivity λ is thus given by

$$\lambda = \frac{4}{1-a}k \tag{3}$$

3.   Data and Analysis

[5]   Since 1979 satellite measurements of I showing two and a half solar activity cycles are available [*Fröhlich and Lean*, 1998] as well as lower troposphere measurements of T anomalies [*Christy et al.*, 2000]. From these two data sets we determine k. *Christy and McNider* [1994] (CM) showed that there was a strong influence of the Pacific ocean ENSO effects (S) and by Volcanoes (V) in the T data. They modelled and removed these effects from the data. *Michaels*
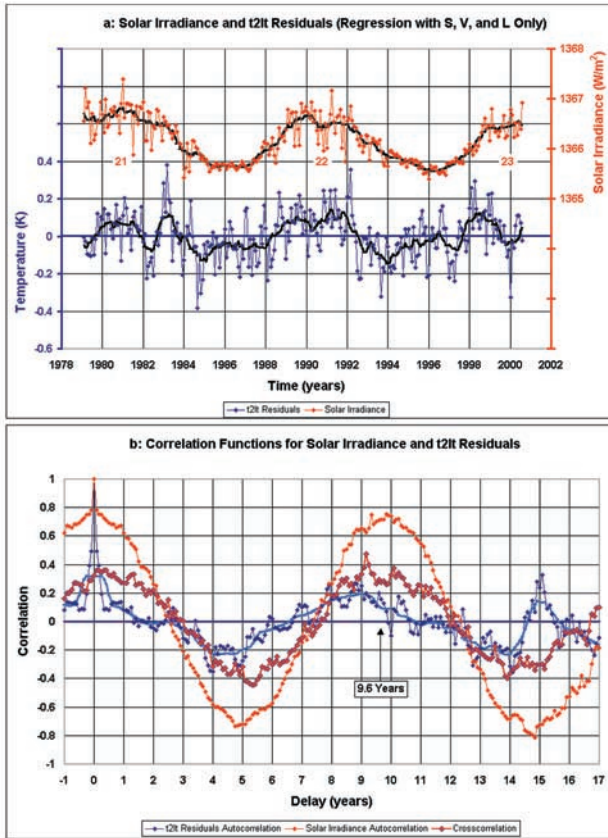
Figure 1. (a) *T* residual values after *S*, *V*, and *L* are removed and the Solar Irradiance values. (b) Correlation functions of *T* and *I* showing a period of about 9.5 years. In a separate calculation, best sinusoids were fit to both *T* and *I*. The corresponding amplitudes were 0.071 °K and 0.52 Wm^{-2} from which we compute *k* =0.14 *K/(W/m²)*.

and Knappenberger [2000] (MK) performed an update. They reported a trend line and suggested that a solar signal was also present. Our analysis goes beyond the work of CM and MK and determines both the solar signal and a new trend line.

[6] We determine the effect of the various geophysical phenomena by multiple regression analysis where a predictor *C* for *T* is assumed to be of the form

$$C = k_1 S + k_2 V + k_3 I + k_4 L + b \qquad (4)$$

We chose 4 predictor variables: El Niño, Volcano, Solar irradiance, and Linear.

1. *S*: The El Niño effects are modelled using the sea surface data SST from region 3.4 [*Garrett*, 2001]. A lag time of 6 months gives the highest correlation in agreement with CM and MK. We also use a template for *S* discovered by *Douglass et al.* [2002b] to predict future values of *T*.

2. *V*: The volcano effects are modelled with the AOD index used by MK. We find a lag of 3 months.

3. *I*: We used solar irradiance data of *Fröhlich and Lean* [1998]. Here the lag is ~3 months.

4. *L*: This is assumed. The origin is to be discussed.

[7] Figure 1a shows the Solar irradiance *I* where one clearly sees solar activity cycles 21 and 22 and part of 23.

Because the solar effect *I* is weaker by a factor of 10 than that of *S* and *V*, we first do a regression analysis on *T* with only *S*, *V*, and *L*. The residuals show a signal similar to the solar signal. The autocorrelation of *I* shown in Figure 1b shows a clear cosine behavior with a period of 9.6 years, corresponding to that of the sunspot cycle. The autocorrelation of the *T* residuals and the cross-correlation both show the same period.

[8] Figure 2 shows the results of the full regression analysis. The *T* data and the predictor *C* are shown in the top plot. The contribution of each predictor variable is shown below. *S* and *V* are plotted together with *S* translated by 6 months and *V* by 3 months. The *I* and *L* plots and the residuals are shown lower in the figure. It is particularly noted that no averaging was done before the regression analysis. The numerical results of the regression analysis and other associated quantities are shown in the table, Figure 3. The first row in the table gives the values of the coefficients and their standard error. The fraction of the total variance accounted for by the predictor variables is given by the coefficient R^2 which we determine to be 0.93.

[9] Because of the 'short' record (22 years), the question of robustness of the results arises. We tested robustness by truncation of the record by one year from the end and repeating the regression analysis. Figure 4a shows that the regression coefficients are essentially unchanged by 6 applications of this process (i.e., from 2000 to 1995). A
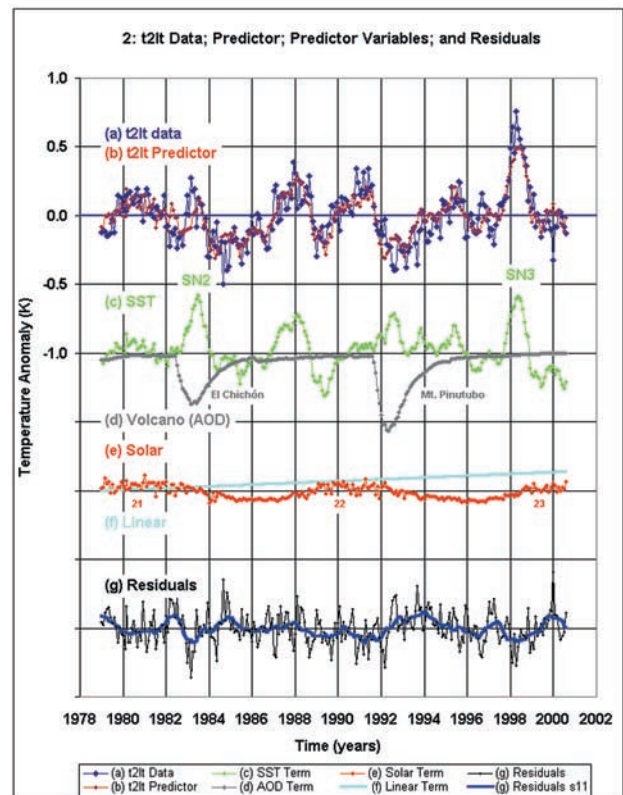

Figure 2. (a) Satellite temperature anomalies, *T* (t2lt) (b) *T* predictor *C* based upon the predictor variables which are: (c) SST 3.4 index *S* shifted by 6 months, (d) AOD index *V* shifted by 3 months. (e) Solar Irradiance *I*, and (f) Unknown linear effect *L*. (g) The Residuals.

Fig. 3 Table of Values
Regression Analysis of t2lt data T (1979 to Sept 2000)
Predictor C of t2lt is determined from 4 predictor variables:
SST (S); AOD (V); Solar Irradiance (I); and a constant (b).
All data used are monthly values with no averaging. The regression assumption is
$C = k_1 S + k_2 V + k_3 I + k_4 L + b$.
Analysis determines the 4 regression coefficients k_1, k_2, k_3, k_4 and b.

		t2lt	t2lt predictor	SST	AOD (Volcano)	Solar Irradiance	Linear term	Constant	Residuals
Symbol		T	C	S	V	I	L	b	r
	coefficient			k_1 (K/K)	k_2 (K/micron)	k_3 (Knf/watts)	$k_4*10000$ (mK/decade)	b (K)	
	value ±stand error		value =±0.12	0.145 ±0.008	-3.8 ±0.2	0.101 ±0.018	64.3 ±12.4	-0.013 ±0.017	
	signal/noise			327.7	361.0	31.4	27.0	0.8	
	truncated: (1994-2000 average) ± stat error			0.133 ±0.009	-3.6 ±0.2	0.112 ±0.006	64.8 ±10.7		
	truncated: (1979-1982 average) ± stat error			0.145 ±0.001	-3.8 ±0.1	0.107 ±0.004	62.2 ±3.6		
variance*1000		38.1	23.9	19.7	16.0	2.00	1.50	0.0	13.7

Multiple correlation coefficient, R^2. From the data above, $R^2 = 1$-var(r))/var(T) = 0.64. Inspection of the residuals in fig.1 shows mostly 'high frequency noise'. A better and more meaningful R^2 is obtained when an 11 month average on the residuals is performed from which one obtains var(r) *1000 = 2.68 and an R^2 = 0.93. One concludes from this that 93% of the variance of T has been removed by the 4 regression variables S, V, I, and L.

trend line (mK/decade)									
1. Expected result: T = C.		47.3	47.3	-14.2	17.0	-19.8	64.3	0.0	0.0
2. Unexpected result: C = S+V+I+L = 47.3.									

Figure 3. Table of values from the regression analysis.

second truncation analysis on the beginning of the record showed that 4 years could be removed without changing the coefficients. See Figure 3.

[10] *Santer et al.* [2001] and *Wigley and Santer* [2001] have questioned the validity of regression analysis on the satellite data because large El Niño events occurred at the same time as the two volcanoes which resulted in a correlation of the order of 0.4 to 0.5. They claim that such 'high' correlations indicate collinearity that can adversely affect any regression analysis such as reported here. This assertion is refuted by the truncation experiments where the coefficients were essentially unchanged by removing the Mt Pinatubo volcano in the first truncation and El Chichón in the second. In addition, *Belsley* [1991] has devised statistical tests to determine the presence of degrading or harmful collinearity among regression variables. *Douglass et al.* [2002a] have used these tests on this data to show that the regression coefficients used here have neither degrading nor harmful collinearity.

4. Discussion and Conclusions

4.1. Solar Sensitivity

[11] The sensitivity coefficient k for solar irradiance is the regression coefficient found above. The best value is the average of the 6 determinations from the first truncation analysis

$$k = 0.11 \pm 0.02 K/(W/m^2). \quad (5)$$

This is the first determination of this sensitivity parameter based upon a globally complete tropospheric temperature data set. This measurement is for decadal time scales. In addition to the study of the satellite temperature anomalies we have repeated the analysis using three other temperature anomalies data sets for the same time interval. We find the following results:

Radiosonde Temp [*Parker et al.*, 1997] $k = 0.13 \pm 0.02$
Surface Temp [*Jones et al.*, 2001] $k = 0.09 \pm 0.02$
Surface Temp [*Hansen and Lebedeff*, 1987] $k = 0.11 \pm 0.02$

[12] *White et al.* [1997] have studied upper ocean temperatures and report a solar regression coefficient of

$k = 0.10 \pm 0.02$ (delay = 0 ± 2 years) also on decadal time scales for the period 1955–1994. *Lean and Rind* [1998] have reconstructed the solar irradiance I from 1600 to the present. For the period 1610 to 1800 they found a correlation maximum of 0.86 at a delay of 0 years between I and a paleo-reconstructed T scale and report $\Delta T = (169 \pm 24) + (0.12 \pm 0.02)I$. We infer from their result a sensitivity coefficient $k = 0.12 \pm 0.02$ on centennial time scales. The close agreement of these various independent values with our value of 0.11 ± 0.02 suggests that the sensitivity k is the same for both decadal and centennial time scales and for both ocean and lower tropospheric temperatures.
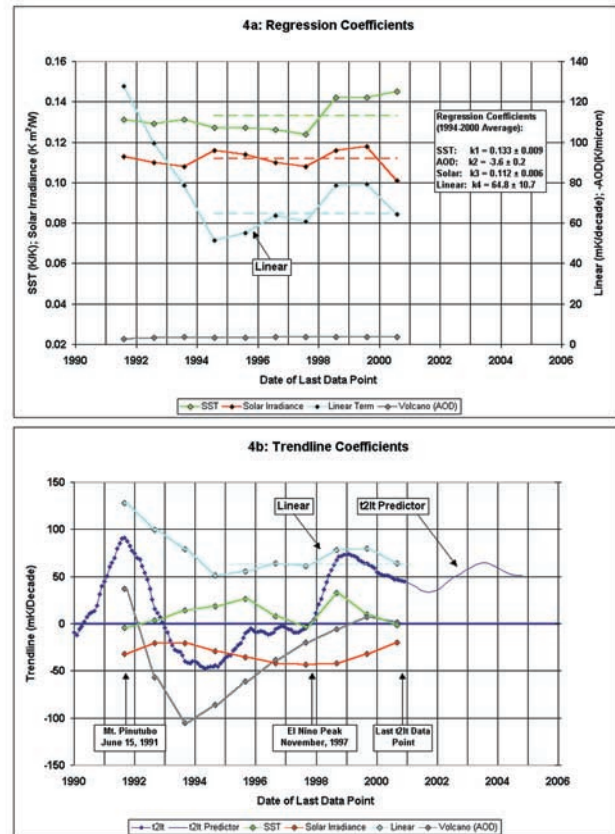

Figure 4. Values of regression coefficients as data is truncated. The trend lines for the regression variables was calculated for the truncations (4b). From the data one sees that the trend line of C equals the trend line of T, as it should. Also, the sums of the trend lines of the 4 regression variables add to that of C which is expected if the variables are statistically independent. This is additional confirmation that collinearity is not present. Using this result one can see in Figure 3b that the variation of the data trend line is due to the trend lines of S, V and I, but not L. At the time of this analysis (Oct 2000), the data trend lines of S and V are near 0 and hence the data trend line differs from L entirely because of the negative trend line of I of about −20 mK/decade. We also calculated future values of the data trend line (see comment in table) using the results of *Douglass et al.* [2001b].

[13] We now calculate λ using eq. 3 and an albedo of 0.30

$$\lambda = 0.63 \, K/\left(W/m^2\right). \qquad (6)$$

In climatology theory [*Hansen et al.*, 1984] λ depends on an intrinsic λ_0 and a gain g. The gain g arises from processes with feedback f.

$$\lambda = g\lambda_0; g = \frac{1}{1-f} \qquad (7a, b)$$

[14] *Rind and Lacis* [1993] estimate the no gain $\lambda_0 = 0.30$ $K/(W/m^2)$, which has been adopted by the Intergovernmental Panel on Climate Change [*Shine et al.*, 1995]. We calculate

$$g = (0.63/0.30) = 2.1; f = 0.52 \qquad (8a, b)$$

This value of f is consistent with that from positive water vapor feedback [*Lindzen*, 1994] and the delayed oscillator process proposed by *White et al.* [2002].

[15] Our measured value for the response time of a few months is at variance with tens of years estimated in some energy-balance models involving the mixed-layer of the ocean. For example, *Wigley and Raper* [1990] predict that the sunspot cycle signal would be attenuated to values of $0.02-0.03°K$ which is about 30% of what we observe. We suggest that this difference is due to their assumption of longer response times. If we assume that $\Delta T = k \, \Delta I$ is true for centennial time scales then we calculate a surface warming of $0.2°C$ over the last 100 years from the inferred increase in the solar irradiance of 1.5 W/m^2 [*Lean*, 2000]. This is a significant fraction (25–30%) of the estimated change of surface temperature estimated to be in the range 0.55 [*Parker et al.*, 1994] to $0.65°C$ [*Hansen et al.*, 1999].

4.2. Trend Line in the *T* Data

[16] Whether or not *T* shows an increasing trend is one of the questions currently of interest. This study accounts for three of the natural effects (*S*, *V*, and *I*) that obscure the observation of any underlying trend line. The data trend line for the satellite *T* data is computed and published every month [*Christy et al.*, 2000] and is often quoted as representing the linear trend of the data. This statistic at various dates is shown in Figure 4b and is seen not to be a reliable constant [*Christy et al.*, 2000]. This is because the effect of *V* is negative and that of *S* can be positive (El Niño) or negative (La Niña). We show that the solar influence is negative (During this time period there is an underlying decrease in the irradiance of the sun of -0.20 W m^{-2}/decade).

[17] We believe that the sought-for trend is the coefficient of the linear term from our regression analysis because it is unchanged under truncation. Its value is $+65 \pm 12$ mK/decade.

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Fig 1a: Solar Irradiance and t2lt Residuals (Regression with S, V, and L Only)
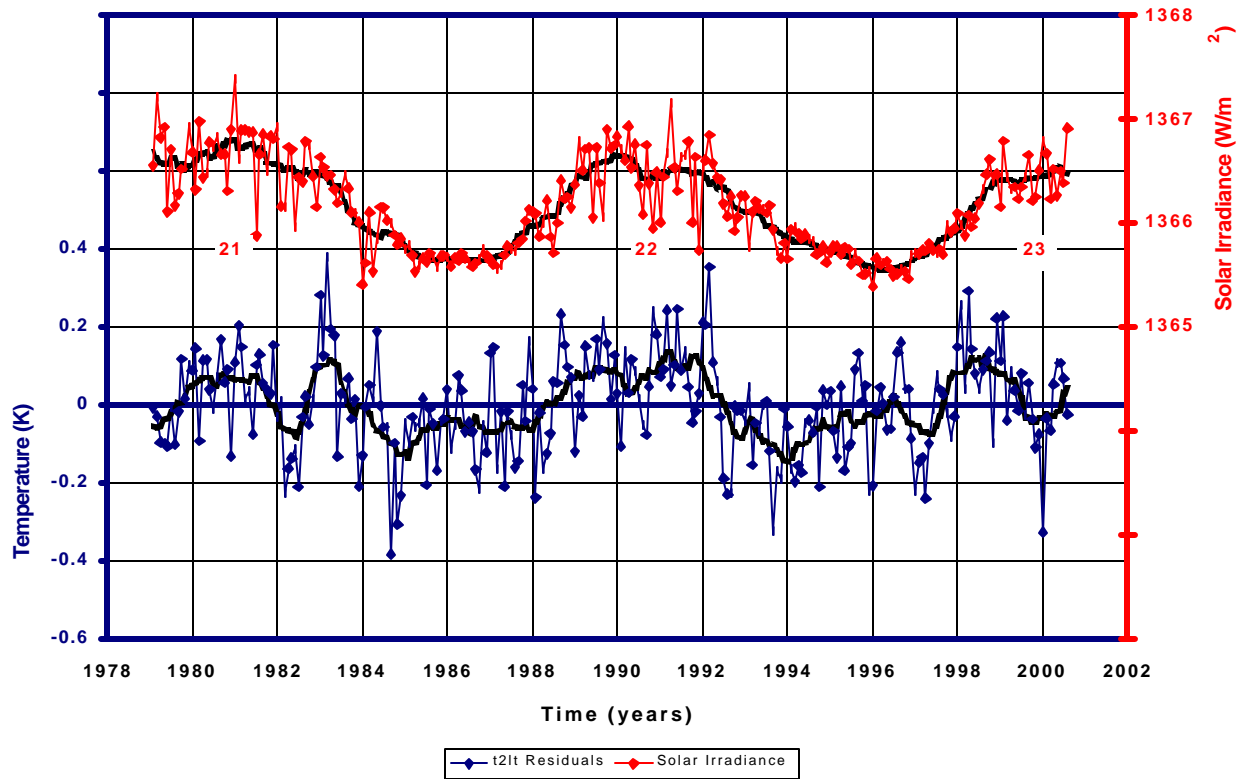
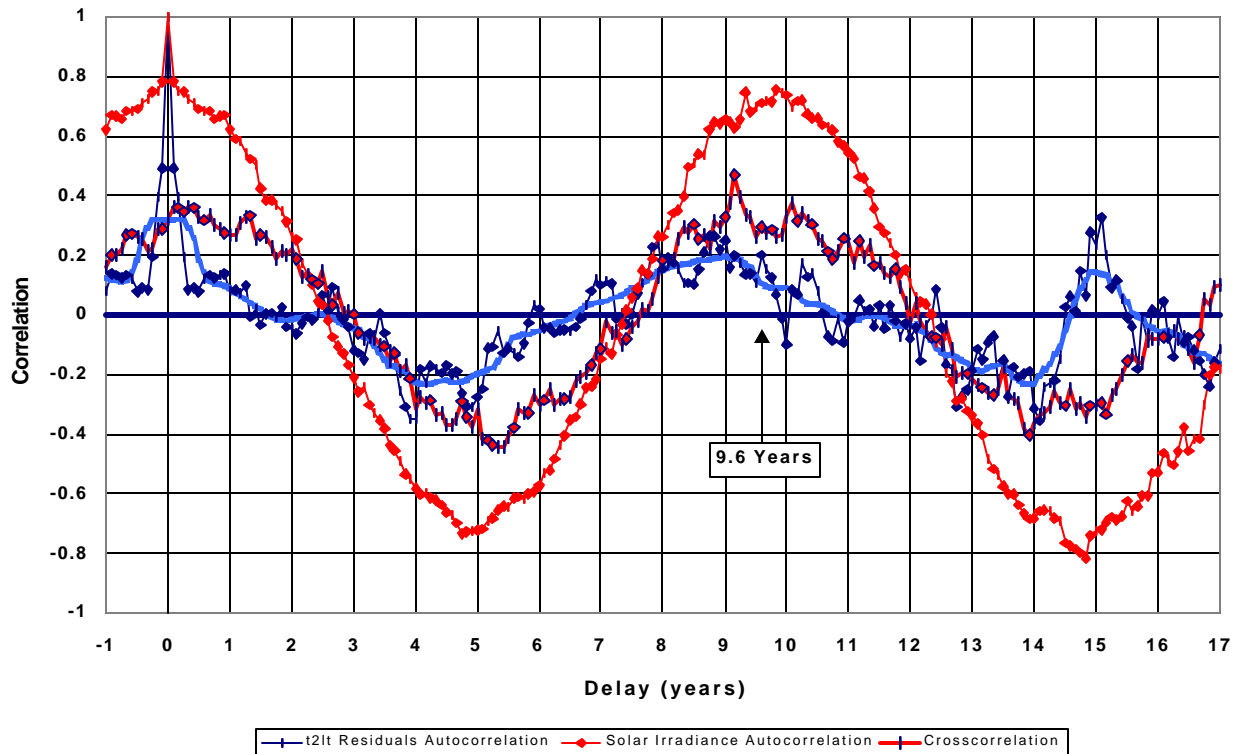**Fig 1b: Correlation Functions for Solar Irradiance and t2lt Residuals**

9.6 Years

Fig.2: t2lt Data; Predictor; Predictor Variables; and Residuals

Fig. 3 Table of Values

Regression Analysis of t2lt data T (1979 to Sept 2000)
Predictor C of t2lt is determined from 4 predictor variables:
   SST (S); AOD (V); Solar Irradiance (I); unknown linear (L); and a constant (b).
All data used are monthly values with no averaging. The regression assumption is
   $C = k_1 S + k_2 V + k_3 I + k_4 L + b.$
Analysis determines the 4 regression coefficients k_1, k_2, k_3, k_4, and b.

		t2lt	t2lt predictor	SST	AOD (Volcano)	Solar Irradiance	Linear term	Constant	Residuals
Symbol		T	C	S	V	I	L	b	r
Regression	**coefficient**			k_1 (K/K)	k_2 (K/micron)	k_3 (Km^2/watts)	k_4*10000 (mK/decade)	b (K)	
	value ±stand error		value =±0.12	0.145 ±0.008	-3.8 ±0.2	0.101 ±0.018	64.3 ±12.4	-0.013 ±0.017	
	signal/noise			327.7	361.0	31.4	27.0	0.8	
	truncated: (1994-2000 average) ± stat error			0.133 ±0.009	-3.6 ±0.2	0.112 ±0.006	64.8 ±10.7		
	truncated: (1979-1982 average) ± stat error			0.145 ±0.001	-3.8 ±0.1	0.107 ±0.004	62.2 ±3.6		
variance*1000		38.1	23.9	19.7	16.0	2.00	1.50	0.0	13.7

Multiple correlation coefficient, R^2. From the data above, $R^2 = 1 - var(\mathbf{r})/var(\mathbf{T}) = 0.64$. Inspection of the residuals
   in fig.1 shows mostly 'high frequency noise'. A better and more meaningful R^2 is obtained when an 11 month
   average on the residuals is performed from which one obtains var(**r**) *1000 = 2.68 and an $R^2 = 0.93$.
   One concludes from this that 93% of the variance of **T** has been removed by the 4 regression variables **S**, **V**, **I**, and **L**.

| **trend line (mK/decade)** **1. Expected result:**   **T = C.** **2. Unexpected result:**   **C = S+V+I+L = 47.3.** | | 47.3 | 47.3 | -14.2 | 17.0 | -19,8 | 64.3 | 0.0 | 0.0 |

Fig. 4a: Regression Coefficients

Regression Coefficients
(1994-2000 Average):

SST: k1 = 0.133 ± 0.009
AOD: k2 = -3.6 ± 0.2
Solar: k3 = 0.112 ± 0.006
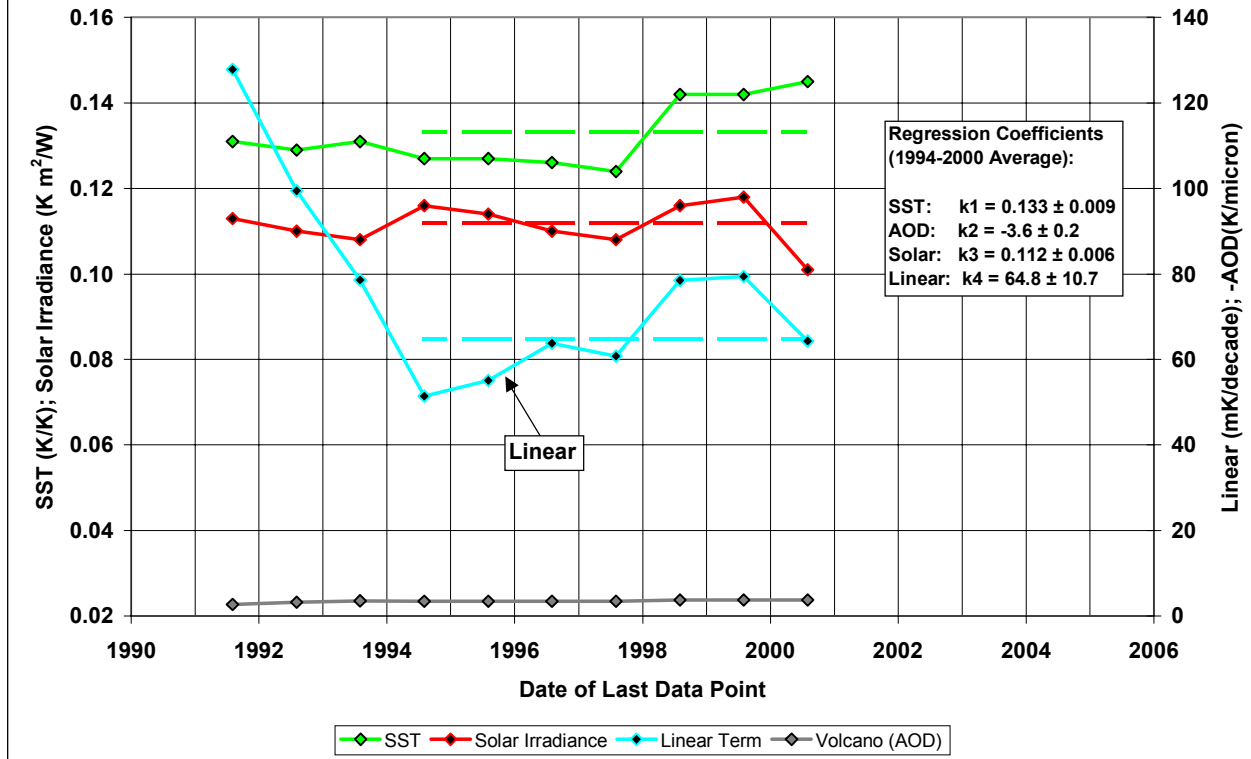Linear: k4 = 64.8 ± 10.7

Linear

SST — Solar Irradiance — Linear Term — Volcano (AOD)

Fig. 4b: Trendline Coefficients

Linear   t2lt Predictor

Mt. Pinutubo
June 15, 1991

El Nino Peak
November, 1997

Last t2lt
Data Point

t2lt — t2lt Predictor — SST — Solar Irradiance — Linear — Volcano (AOD)