ON TOTAL SOLAR IRRADIANCE VARIABILITY

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ABSTRACT

Recently compiled total solar irradiance dataset containing satellite based daily values during 20 years enables one to estimate temporal variability of the *solar constant* and its statistical relationship with Wolff numbers. The results are useful for energetic specification of the forces crucial for the global climate.

Key words: Solar irradiance, Wolff numbers, time series, anti-persistency.

1. INTRODUCTION

More than forty years ago Ernst Öpik (1958) wrote: ”From what is known of processes going on in the sun, the so-called *solar constant* certainly cannot be strictly constant; but the probable magnitudes and likely period-lengths of the variations cannot at present be determined”. Due to the efforts of international scientific community during the last decades a 20-year long daily irradiance record based on measurements from 5 satellites is compiled (Fröhlich and Lean 1998a). The dataset enables us to estimate short-range variability of the *solar constant*. The latter is the main parameter for climate studies.

2. DATA

A composite record of the Sun’s total irradiance compiled from measurements made by five independent space-based radiometers since 1978 and adjusted for drifts in the radiometric data by Fröhlich and Lean (1998a) is available on line. The composite record exhibits a prominent 11-year cycle with similar levels during 1986 and 1996, the two most recent minimum epochs of solar activity. Fröhlich and Lean (1998b) emphasize that no irradiance increase from 1986 to 1996 solar minima. Nor does the irradiance record support a recent upward irradiance trend inferred from solar cycle length. The dataset (labeled as INSL) contains daily irradiance values from 1978 to 2000.

Solar activity is traditionally characterized by means of Wolff numbers (e.g Eddy 1976). The Wolff sunspot number is defined as $R_w = k(10g + f)$, where f is the total number of spots (irrespective of size), g is the number of spot groups, and k is a normalizing factor to bring the counts of different observers, telescopes and sites into agreement.

Global temperatures have been monitored by satellite since 1979 with the Microwave Sounding Units (MSU) flying on the National Oceanic and Atmospheric Administration’s (NOAA) TIROS-N series of polar-orbiting weather satellites (Christy et al. 2000). Data of the thermal emissions of radiation by molecular oxygen at 4 frequencies near 60 GHz from nine separate satellites have been combined to provide a global record of temperature fluctuations in the lower troposphere (the lowest 5 miles of the atmosphere) have shown that the MSU calibrations have been very stable, with a precision of monthly satellite measurements of 0.02° Celsius for the global mean.

The global daily- and monthly-averaged temperature anomalies for the entire period of record (since January 1979) are available on line. Daily LTRP record, the average temperature anomaly for lower troposphere, during the time interval from January 1979 to September 2000 is used in the present study.

Data from Berger and Loutre (1991) are used to produce a comparison of insolation difference produced by changes in solar activity and in the earth’s orbital parameters. This dataset contains data on changes in the earth’s orbital parameters: eccentricity, longitude of perihelion, obliquity, precession, and the resulting variations in insolation during 5 million years.

3. VARIABILITY FOR ANNUAL ANOMALIES

Three datasets, R_w, INSL and LTRP are initially compared on the basis of variability for the annual mean anomalies (i.e for deviations from the corresponding sample means, 81 for Wolff numbers and 1366.2 for INSL). The LTRP dataset is originally presented by the anomalies. In order to get comparable scale $R_w/100$ is used instead of R_w for the Wolff numbers. These annual deviation values are shown in Figure 1. Scale on the y-axis is different for each dataset: $R_w/100$ for the Wolff

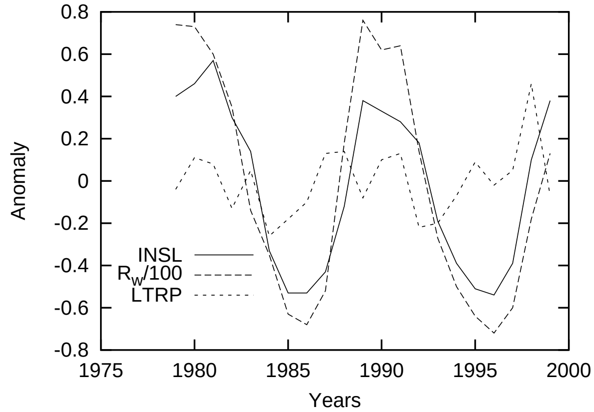

Figure 1. Annual mean anomalies for Wolff numbers (R_w-81)/100, total solar irradiance at the top of the atmosphere (INSL-1366.2) and mean tropospheric temperature.

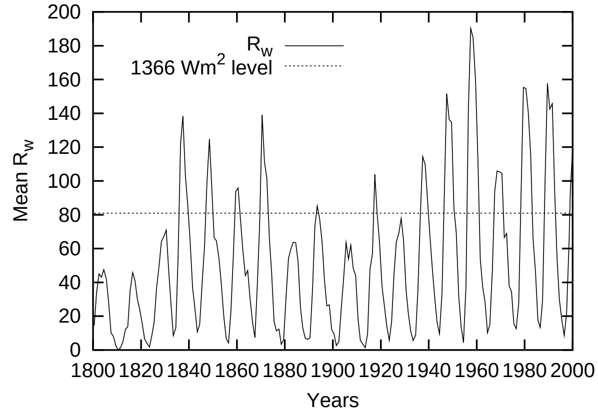

Figure 2. Annual mean R_w values and the statistical 1366 Wm^{-2} level

numbers; Wm^{-2} for the INSL and °C for the LTRP.

In average, the Wolff numbers and the total solar irradiance anomalies were changing in the same phase during the last 20 years. During the period of high solar activity the total solar flux density at the top of the atmosphere was higher and *vice versa*.

In the variability of the LTRP, another mechanism is dominating. Only about 15% of the total solar radiation is absorbed in the atmosphere (and about half of it in the stratosphere by ozone). About 30% is reflected back to space and roughly about 55% is absorbed by the earth surface. The troposphere is heated mainly by the underlying surface (convection). This means that annual cycle has a leading role in development of the average tropospheric temperature.

Denoting $\xi = INSL - 1366.2$ and $\eta = R_w/100$ a linear relationship between the annual mean values $\bar{\xi}$ and $\bar{\eta}$ can be produced

$$\bar{\xi} = A\bar{\eta} + B, \tag{1}$$

where A=0.67±0.01 and B=–0.56±0.005. Equation (1) explains 88% of the variance for the annual irradiance anomalies. Provided that the same relationship was holding already three centuries, the collected Wolff number record can be used for estimating longterm variability of the total solar irradiance at the top of the atmosphere. Annual mean R_w values for the last two centuries are shown in Figure 2. Also the statistical 1366 Wm^{-2} level produced by means of Eq. (1) is presented. The results enable one to suppose that the average difference in solar irradiance between high and low activity periods supports the global warming or cooling in the corresponding periods.

4. PERSISTENCY AND ANTI-PERSISTENCY

Let X_t be the value of interesting trajectory (R_w, INSL, LTRP) at the time t. It can be represented as

$$X_t = \sum_{i=0}^{\infty} x_{t-i}, \tag{2}$$

where $x_t = X_t - X_{t-1}$ are the corresponding increments. Estimating the variability of X_t is based on calculations of variance for the increment $(X_{t+\tau} - X_t)$ as a function of τ. Behavior of that is determined by statistical properties of the increments x_t. We need to study variance of the increment

$$X_{t+\tau} - X_t = x_{t+1} + \ldots + x_{t+\tau} \tag{3}$$

as a function of τ on the basis of some sample, $t = 0, 1, \ldots, T$,

$$Var[X_{t+\tau} - X_t] = \frac{1}{T-\tau} \sum_{t=1}^{T-\tau} (x_{t+1} + \ldots + x_{t+\tau})^2$$
$$= \tau[C(0) + 2\sum_{i=1}^{\tau-1}(1 - i/\tau)C(i)], \tag{4}$$

where $C(i)$ is the auto covariance for the increments x_t at the lag i. The important term for showing a convergence is

$$U(\tau) = C(0) + 2\sum_{i=1}^{\tau-1}(1 - i/\tau)C(i). \tag{5}$$

For independent and identically distributed increments, the variance (4) is growing proportionally to τ (i.e $C(i) = 0$ for $i > 0$). The situation corresponds to (1-dimensional) random walk model. The latter is a good tool to show maintenance of a long-range balance by means of random increments, i.e the amount of zero-crossings by the trajectory increases together with τ.

Asymptotically, three different situations are important for describing long-range properties of the increments while T and τ increase.

$U \to const < \infty$ means that the variance is growing proportionally to τ. The situation is a bit more general than for the common random walk, because not each $C(i)$ has to be zero but only their sum converges to a $const < \infty$. The situation takes place for short-memory series where C(i) vanish sufficiently quickly.

$U \to \infty$ means that positive covariances are dominating in the sum of the $U(\tau)$ expression for all τ range so that X_t tends to increase in the future if it has had an increasing tendency in the past. The feature is called *persistency*. Physically, a persistent system is going to increase a deviation showing a positive feedback dominating in the system governing the series. Mathematically, this means that the variance (4) is growing faster than that for random walk, might be proportionally to τ^{2H}, with $0.5 < H < 1$ (e.g Mandelbrot 2002).

$U \to 0$ means that the variance (4) is asymptotically independent of τ. To achieve that, negative covariations are dominating in the $U(\tau)$ expression (5) over any finite τ range, producing $H < 0.5$. X_t has a tendency to decrease in future if it has had an increasing tendency in the past and *vice versa*. The feature is called *anti-persistency*. The anti-persistency expresses a tendency of the values of increments to compensate for each over to prevent for the trajectory from blowing up too fast. Such a system tends to eliminate deviations showing a negative feedback in aggregate. An anti-persistent time series visit, on average, the mean value more often than random walk. Mandelbrot and Wallis (1969) showed that the perfect compensation occurs in pure sine wave leading to $H \to 0$ rapidly if τ exceeds the wavelength.

Actually, the limit (if $\tau \to \infty$) may or may not exist, but nevertheless, growing rate of the sample variance enables us to get an H estimate, Thus, the value of H (less or more than 0.5) determines whether the large deviations in trajectory are less or more probable in comparison with random walk. Large deviations in solar irradiance are crucial for the earth's climate and the estimation of H becomes important.

5. ACTUAL H ESTIMATES IN DIFFERENT SCALES

Growing rate for the variance (4) can be estimated directly from any sampled ($i = 0, 1, \ldots, T$) trajectory.

$$D(\tau) = \frac{1}{T-\tau} \sum_{i=1}^{T-\tau} (X_{i+\tau} - X_i)^2 \qquad (6)$$

For scale invariant processes in some range $\tau_0 < \tau < \tau_1$

$$D(\tau) \propto \tau^{2H}, \qquad (7)$$

and a linear least squares fit between the logarithms for $D(\tau)$ and τ gives us the average H value for that range.

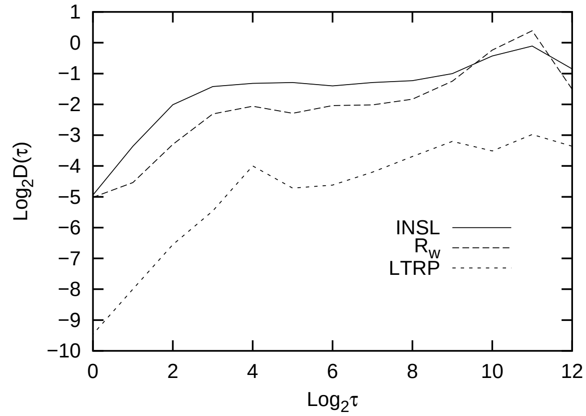

Figure 3. Estimated structure function $D(\tau)$ for three daily trajectories (τ in days).

Variability of the solar irradiance and Wolff numbers has strongly cyclic behavior. Such a behavior causes scale breaks toward $H \approx 0$ for some scale range. Thus, calculations over different scales are necessary for determining the ranges where $H > 0$. Next series for three time scales are used in order to demonstrate a long-range anti-persistence for the solar irradiance.

$D(\tau)$ values calculated for three daily series over the 20 year sample are shown in Figure 3. Figure shows an approximate scale invariance over a considerable range from 16 to 4096 days. Calculated H estimates are close for all three series (see Table 1.)

Figure 4 shows $D(\tau)$ values calculated for much longer scale range. Full line (R_w) shows the $D(\tau)$ for annual mean Wolff numbers calculated over 300 year period. $D(\tau)$ is approximately parallel to x-axis already for $\tau > 4$ (years). This is due to different actual length of the solar activity cycle. Registered maximum difference between the annual mean R_w values during the last three hundred years (Eddy 1976) does not exceed significantly the corresponding value for the last 20 years (from 0 to 190 and 10 to 160, respectively). confirming that the variance did not increase essentially during that interval. The situation is a presumption for stationarity. One can assume, that the variance may remain unchanged for longer scales, up to those where the changes in orbital parameters become influential. This variance then helps in determining variability of the irradiance (Eq. (1)).

The second $D(\tau)$ line is calculated using paleoclimatic insolation values dependent on changes in the earth's orbital parameters: eccentricity, longitude of perihelion, obliquity, and precession, (Berger and Loutre 1991). In-

Table 1. Estimates for H for three daily series

Data	scale range (days)	$H \pm \delta H$
Wolff numbers	16 – 4096	0.12±0.05
INSL	16 – 4096	0.06±0.02
LTRP	16 – 4096	0.12±0.02

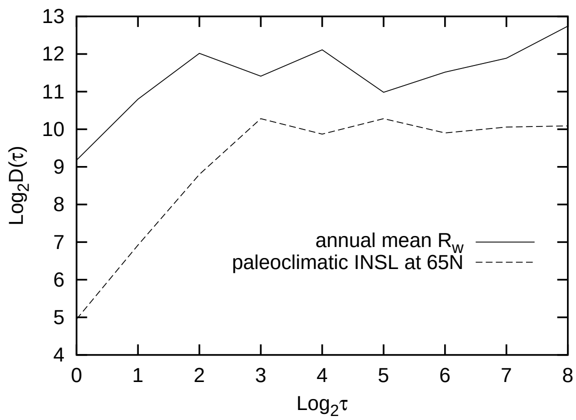

Figure 4. D(τ) values for two series. τ in years for R_w and 1000 years for INSL

solation values for mid-July at 65N for a time step 1000 years are used. Behavior of $D(\tau)$ explains that it will take about 8000 years to get a converged variance for the zonal irradiance. The slope is very flat and makes no sense in decadal scale, but certainly has an increasing influence together with the scale.

Earlier studies have shown that the hemispheric temperature fluctuations follow the scaling regime with H=0.4 (Lovejoy and Schertzer 1986) for a broad range from 5 to 40 000 years. The corresponding H value for the Greenland ice-core project proxy temperature fluctuations over the range from 400 to 40 000 years equals to 0.24 (Schmitt et al. 1995) Insolation series do not support so high H values.

6. CLIMATIC CONSEQUENCE

The new total solar irradiance dataset opened a way to study both its variability and statistical relationship to Wolff numbers on daily basis, and due to the latter relationship also the irradiance variability on the timescale up to 300 years. Combining eq (1) and Figure 2 one can assume that due to higher solar activity there was the annual mean irradiance during the second half of the 20th century about 0.16 W/m^2 higher than that for the first half. It is interesting to compare that value with some other forcing participating in the global warming debate. Estimates of the adjusted radiative forcing due to changes in the concentrations of the so-called *greenhouse gases* since pre-industrian times is 2.45 Wm^{-2} (IPCC 1996). If the increase was during 15 years its annual increment (0.16 Wm^{-2}) would be comparable to that solar activity caused surplus. Both quantities are working towards the same direction – warming. But still there is no indication about a permanent warming trend in the MSU dataset (Hurrell et al 2001). The MSU dataset is more reliable than any ground based one due to its well tested methodology and the global coverage (Christy et al.1995).

One physical cause of that may be an accumulation of anomalous solar energy in the oceans. Shortwave radiation absorbed under the thermocline may present a climate signal lasting several years (Webster and Stephens 1984). But the main reason seems to be statistical, i.e. the anti-persistent behavior of the increments of solar irradiance. The anti-persistency is evident in Figure 3. Standard deviation of the daily increments of total solar irradiance at the top of the atmosphere equals to 0.18 Wm^{-2}. Random character of the *solar constant* variability disturbs to some extent the influence of previously mentioned more stable forcings. But more powerful source of the anti-persistency for the global average temperature is the annual cycle of the solar irradiance due to eccentricity of the earth's orbit. Due to the periodicity, $H \to 0$, preventing large deviations for the trajectory (e.g Mandelbrot and Wallis 1969).

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