Evidence from Wavelet Lag Coherence for Negligible Solar Forcing of Climate at Multi-year and Decadal Periods.

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Abstract. We examine possible links between solar cycle irradiance variations the large atmospheric circulation systems that affect whole planet's climate. In particular we examine the putative mechanism of solar forcing mediated by changes in induced stratospheric conditions over the polar regions. We test this hypothesis by examining causal links between time series of solar irradiance based on both amplitude and length of the 11-year solar sunspot cycle and indices of Arctic Oscillation AO and ENSO activity. We use a wavelet lag coherence method based on wavelet filtering to examine the significance and magnitude of the phase coherence of the pairs of series in lag-period space. Hence we study the non-linear phase dynamics of weakly interacting oscillating systems. The method clearly shows no link between AO or SOI with solar irradiance at all scales from biannual to decadal. We conclude that the 11-year cycle sometimes seen in climate proxy records is unlikely to be driven by solar forcing.

1 Introduction

Decadal cycles are fairly ubiquitous across the planet, and are therefore persuasive of a global-scale climate mechanism (Jevrejeva, Moore and Grinsted, 2004; Moron, Vautard and Ghil 1998; Dijkstra and Ghil 2005). Several authors have been tempted to ascribe to solar sunspot cycles, however, detailed statistical analysis of many of these correlations shows them to be spurious or statistically insignificant (Laut,2003; Tsiropoula 2003). The 11-12 year solar sunspot cycle produces rather weak (0.1%) changes in solar energy output, and this is unlikely to directly to be sufficient to produce changes in weather and climate. Amplification factors have been proposed due to the higher variability of solar energy at UV wavelengths which may induce changes in stratospheric ozone and temperature, which can then propagate down to the troposphere (e.g. Baldwin and Dunkerton 2005; Labitzke 2005).

The main features of the planet's climate are the ENSO and the polar annular modes. The strength of the polar stratospheric vortex determines the index of annular mode, which are called the Arctic Oscillation, (AO) and the Antarctic Annular Mode (AAM) (Thompson and Wallace 1998). Almost all plausible sun-climate links rely on modification of the polar stratosphere. Though Hedfors, Aldahan, Kulan, Possnert, Karlsson, and Vintersved (2006) in common with many others discuss the link between cloud formation and cosmic ray intensity – when sunspot numbers are low, more cosmic rays reach lower altitudes and the atmosphere becomes cloudier. Laut (2003) showed how problematic these studies were, and it is further shown in the later study where the authors point out that there is a large lag between ^{7}Be (a proxy for cloudiness) and the solar cycle of up to 1.5 years, and the dataset extends over only 1 solar cycle. Physically we may expect cloud condensation nuclei to be active for very short times, and so there should be phase delays very close to zero.

Kuroda and Shibata, (2005) modeled the impact of solar cycle on the AAM using a coupled chemistry-climate model in two 21-year long model runs with constantly repeating Sea Surface Temperature (SST). They found that increased ultra-violet radiation led to a more persistent signal from the AAM in the Antarctic stratosphere than during low UV model runs due to formation of an ozone anomaly (amounting to 2-3%). Furthermore they show that it is UV rather than cosmic rays that produce the difference in their model.

Barnston and Livezey (1989), and later Hameed and Lee (2005) showed that stratospheric perturbations are more likely to penetrate to the troposphere during solar cycle maximum than minima, and that the effect is also dependent on the direction of the zonal wind direction in the tropics. However these analyses rely on only data available from 1948 and hence are statistically rather insignificant. Kodera and Kuroda (2002) interpreted re-analyses data from 1979 to 1998 and proposed a mechanism for the dynamical and radiative forcing of the stratosphere by the solar cycle, while the analysis is provocative, there must be doubt to its statistical robustness as less than two whole solar cycles are included in the data set. While it is clear that stratospheric anomalies can penetrate downwards to the troposphere, it is a rather atypical phenomenon (Baldwin and Dunkerton 1999; 2001), and in general the troposphere drives the stratosphere. However, it is clear that from both observational and modeling studies that the stratosphere can provide an efficient and fast transport mechanism for linking tropical and polar climate (Baldwin and Dunkerton 2005; Jevrejeva et al. 2004), thus the stratosphere provides a bridge between the annular modes and ENSO phenomena, and so we may expect it be one factor that it is especially sensitive to the solar cycle.

Moore, Grinsted and Jevrejeva (2006) found that sunspot number is not significant factors in climate on multi-year and decadal timescales. They analysed causality relationships using wavelet coherence methods, which are developed further in this paper, and a new method of representing phase relationships is introduced. Wavelet coherence is useful as relative phase relationships between two time series across a wide spectrum of temporal scales are produced. If the variable represented by one of the time series is really the causal agent of the variability in the second time series, then a change in the first must always precede a reaction in the second. We will discuss not the sunspot numbers here but the solar radiation received at the Earth's surface, which has only been measured globally since the satellite era, but which is extended backwards in time in two distinctly different ways: based on the length of the sunspot cycle, and on the intensity of the sunspot cycle.

2 Methods and data

We use monthly time series of the AO (Thompson and Wallace 1998.), spanning 1899-2001. ENSO time series comes from monthly SOI (Ropelewski and Jones 1987) spanning 1865-2005. Moore et al. (2006) used the monthly International Sunspot numbers as the measure of the solar cycle (http://sidc.oma.be/DATA/monthssn.dat) As accurate measurements of total and surface solar irradiance variations have been made for only 2-3 decades, reconstructions based on sunspot number are needed prior to 1978. There are several different available, but here we use two that have been recently compared with climate statistics by Solanki and Krivova (2003) back to 1700; before 1978 these are reconstructions following Fligge and Solanki (2000). A secular increase in the total solar irradiance of about 2 Wm^{-2} since the Maunder minimum is assumed, TSI_A follows the solar cycle amplitude evolution, and TSI_L follows solar cycle length evolution. We removed the mean monthly values (the annual cycle) from all series.

The method we use determines the non-linear interactions between the two time series that may be chaotic. We extract the phase expression of the time series derived from the Continuous Wavelet Transform (CWT) of a time series (e.g. Grinsted, Moore and Jevrejeva 2004; Torrence and Compo 1998). The idea behind the CWT is to apply the wavelet as a band pass filter to the time series. As we desire a broad band pass filter, we use the Paul as this is not very localized in frequency space, and allows signals that are relatively aperiodic to be included in the analysis:

$$\psi_0(\eta) = \frac{2^m i^m !}{\sqrt{\pi(2m)!}}(1 - i\eta)^{-(m+1)} \tag{1}$$

where ω_0 is dimensionless frequency and η is dimensionless time, and m is the order, taken as 4 here. The centre frequency of the Paul wavelet, λ, is an important parameter in the analysis and is given by

$$\lambda = (2m+1)/(4\pi s)). \tag{2}$$

The wavelet is stretched in time by varying its scale (s), so that $\eta = s \cdot t$, and normalizing it to have unit energy. The CWT of a time series X, $\{x_n, n=1,\ldots,N\}$ with uniform time steps δt, is defined as the convolution of x_n with the scaled and normalized wavelet.

$$W_X(s,t)\Big|_{t=n} = \sqrt{\tfrac{\delta t}{s}} \sum_{n'=1.}^{N} x_{n'} \psi_0\left[(n'-n)\tfrac{\delta t}{s}\right]. \tag{3}$$

The complex argument of $W_X(s,t)$ can be interpreted as the phases of $X\{\varphi_1 \ldots, \varphi_N\}$ at the scale s. We utilize the angle strength of the phase angle difference between two series (X and Y), also known as the mean phase coherence, $\rho(X,Y)$ (Mokhov and Smirnov 2006). We are interested in causative relations, so it is appropriate to measure ρ between the phases φ_x, φ_y of the two time series.

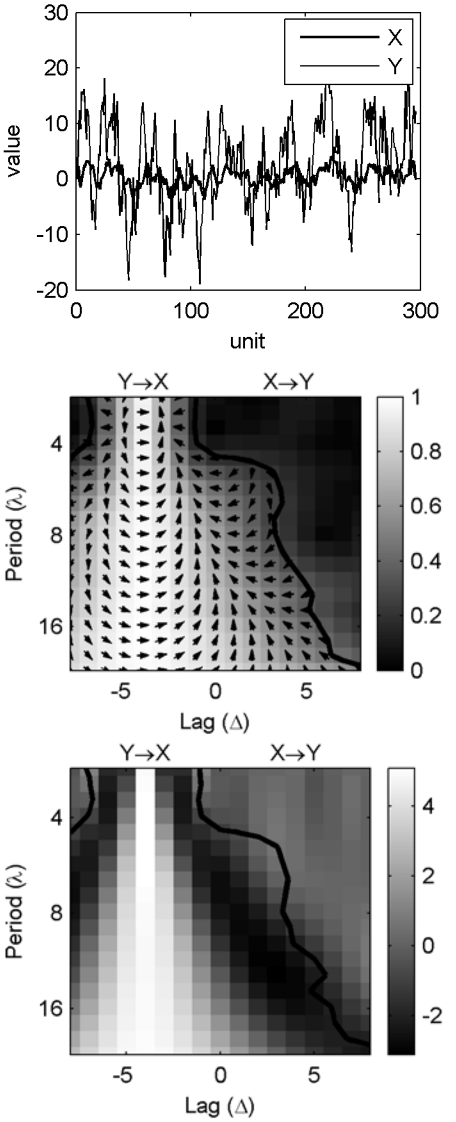

Fig. 1. Top: scatter plot of x and y data and the linear best fit the data: Y = 1.9X + 0.61, which fails to capture any important linkage between the two noisy series. Middle: the wavelet lag coherence plot showing values of mean phase coherence (ρ) and its 95% confidence interval by the solid black contour. Note the arrows points to the right at a lag of -4 indicating that is when X and Y are in phase at all λ. Bottom: the sensitivity, m, in the equation Y = mX for the same data. Note that the value of m =5 at a lag of -4 for all λ. The confidence interval shown is that for ρ, as this is where the values of m have true predictive value.

We vary the relative phase delay between the two series by lagging φ_y relative to φ_x by a phase lag, Δ:

$$\rho(\Delta) = \frac{1}{N}\sqrt{\sum_{n=1}^{N-\Delta}\cos^2(\phi_{x,n} - \phi_{y,n+\Delta}) + \sum_{n=1}^{N-\Delta}\sin^2(\phi_{x,n} - \phi_{y,n+\Delta})} \qquad (4)$$

Significance testing of ρ is done by Monte Carlo methods against 1000 realizations of a red noise background (Grinsted et al., 2004), and the results can be visualized in a two-dimensional plot of ρ in λ-Δ space analogous to the wavelet frequency-time space plot. As a further refinement in the utility of such a plot we find it useful to contour the strength of linear regression of the wavelet filtered time series as a function of λ and Δ, so that the color scale bar corresponds to the value of *m* in the equation of $W_Y(\lambda,t+\Delta) = m\, W_X(\lambda,t)$. The phase relationship over the range multi-year to decadal periods was examined by filtering both time series with a Paul wavelet with λ between the Nyquist frequency and 40 years with six λ per octave of scale.

To illustrate the method, we show an example (Figure 1) using series where the *X* is red noise with a first order regressive coefficient of 0.8, mean of zero and unit variance, and series *Y* and equal to 5*X* plus white noise (zero mean, unit variance). *X* is then lagged by 4 time units relative to the *Y*, so that it in our sense it *Y* leads and hence is causative of *X.* Simple regression analysis yields a linear best fit the data: Y = 1.9X + 0.61, which fails to capture any important linkage between the two noisy series. However, applying the phase coherence test immediately yields a region of significant coherence, and at a lag of -4 units an in-phase relationship at all filtering periods exists. Finally the bottom panel in Figure 1 shows the magnitude of the lagged regression fit, with an obvious peak value of 5 over all filtering periods at a lag of -4 units.

3. Results

We now use the lag-coherence method to investigate phase relationships between solar irradiance and the atmospheric circulation indices represented by the Arctic Oscillation (AO) and Southern Oscillation Index (SOI). Figure 2 shows the sensitivity of the AO to TSI_L and TSI_A. It is clear that there is little of the λ-Δ plot where the phase coherence, ρ is significant, except for the long period TSI_L plot, essentially due to trends in the AO and the irradiance data.

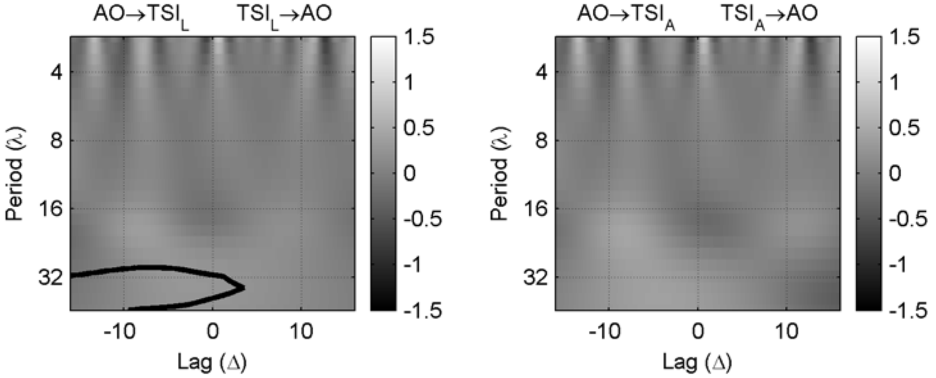

Fig. 2. The sensitivity of the monthly Arctic Oscillation index on total solar irradiance based on length (Left panel) and amplitude (Right) of solar cycle. The 95% confidence level of ρ is shown as a thick black contour.

However, the majority of the significant area is in the negative Δ part of the plot, implying that TSI_L would be driving solar cycle – which is physically meaningless. The sensitivity values, especially in the small regions of significant ρ at positive Δ in both panels of Figure 2 are almost absent at period longer than 2 years.

In comparison the TSI links with the SOI (Figure 3) show no indication of causality – neither physically meaningful values of lag, nor relationships on any scale with irradiance.

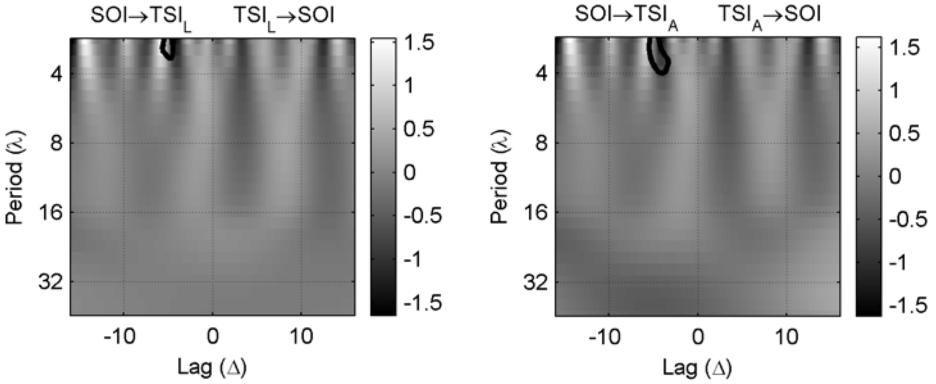

Fig. 4. The sensitivity of the monthly Southern Oscillation Index on total solar irradiance based on length (Left panel) and amplitude (Right) of solar cycle. The 95% confidence level of ρ is shown as a thick black contour.

4. Discussion and conclusions

The analysis presented shows clearly that there is no significant causality between solar irradiance and large-scale circulation atmospheric patterns. Thus we extend the analysis of Moore et al. (2006) who showed that simple sunspot numbers had no causal relations with the circulation indices at multi-year to decadal periods. This must cast doubt on the postulated solar UV polar forcing mechanism of climate variability. We have not tested other possible means of solar variability, such as due to solar modulation of cloud intensity via variations in the Earth's magnetic field and cosmic ray fluxes (Hedfors et al., 2006). While such mechanisms may lead to 11-year periodicities in some climatic indices, the importance of statistically testing their significance against appropriate noise backgrounds is often unappreciated. Of equal importance when causality is alleged, the relative phase of the time series much be tested to verify that hypothesized physical causality is consistent with actual phasing of the time series.

We have shown that a new method of wavelet filtered regression and phase relationship analysis can be used to extract information on lagged responses at specific periods between time series. We show how the significance of the phase relationship can be tested and produce a new type of period-lag plots that shows the regression coefficient between the two time series over a wide range of relative phase lags and frequencies. Thus the specific analysis of a few Paul wavelet periods carried out by Moore et al., (2006) can be extended over the entire range of statistically meaningful periods.

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