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Is there evidence for sunspot forcing of climate at multi-year and decadal periods?

John Moore,[1] Aslak Grinsted,[1,2] and Svetlana Jevrejeva[3]

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[1] It has been proposed that solar cycle irradiance variations may affect the whole planet's climate via the stratosphere, the Quasi-Biennial Oscillation (QBO) and Arctic Oscillation (AO). We test this hypothesis by examining causal links between time series of sunspot number and indices of QBO, AO and ENSO activity. We use various methods: wavelet coherence, average mutual information, and mean phase coherence to study the phase dynamics of weakly interacting oscillating systems. All methods clearly show a cause and effect link between Southern Oscillation Index (SOI) and AO, but no link between AO and QBO or solar cycle over 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, and most likely reflects other natural cycles of the climate system such as the 14-year cycle, or a harmonic combination of multi-year cycles.
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1. Introduction

[2] There is considerable dispute as to the strength of the sun-climate link. Many proxy climatic time series exhibit significant power in the 11–14 year band, that 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]. Decadal cycles are fairly ubiquitous across the planet, and are therefore persuasive of a global-scale climate mechanism [*Jevrejeva et al.*, 2004]. Various mechanisms have been proposed to amplify the rather weak (0.1%) changes in solar energy output over an 11–12 year solar cycle to a level sufficient to produce changes in weather and climate. Several of these amplifying factors rely on the higher variability of solar energy at UV wavelengths to induce changes in stratospheric ozone and temperature, which can then propagate down to the troposphere [e.g., *Baldwin and Dunkerton*, 2005; *Labitzke*, 2005].

[3] 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]. The QBO (quasi-biennial oscillation) is a quasi-periodic oscillation of the equatorial zonal wind between easterlies and westerlies in the tropical stratosphere with a mean period of 28 months. Almost all plausible sun-climate links rely on modification of the polar stratosphere, usually with some mediation role being played by the QBO. *Labitzke* [2005] summarize the possible influence of solar cycle on QBO. *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 only on data available from 1948 and hence are not very statistically significant. *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, but there must be doubt to its statistical robustness as the data span less than two whole solar cycles. While it is clear that stratospheric anomalies can penetrate downwards to the troposphere, it is a rather atypical phenomena [*Baldwin and Dunkerton*, 1999, 2001], and in general the troposphere drives the stratosphere. *Mayr et al.* [2006] discuss a model simulation of the solar cycle and the QBO, and present evidence of a weak link, but their modeled solar cycle is fixed in period and amplitude. However, it is clear 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.

[4] In this paper we examine the plausibility of the argument that solar cycles are significant factors in climate on multi-year and decadal timescales. Causality relationships are analyzed using wavelet coherence methods. 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

[1]Arctic Centre, University of Lapland, Rovaniemi, Finland.
[2]Also at Department of Geophysics, University of Oulu, Oulu, Finland.
[3]Proudman Oceanographic Laboratory, Liverpool, UK.

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precede a reaction in the second. We firstly examine the link between the QBO and the AO to verify if there is a coherent relationship between these indices. Secondly we examine if there is a causal relationship between sunspot numbers and AO. Thirdly we test the mechanism that the solar cycle drives global climate via the polar regions by testing whether the arctic leads tropical climate in the solar cycle band.

2. Methods and Data

[5] We use monthly time series of the AO [*Thompson and Wallace*, 1998] and the QBO from http://www.cdc.noaa.gov/Correlation/qbo.data. ENSO time series comes from monthly SOI [*Ropelewski and Jones*, 1987], and the monthly Niño 3.4 SST index [*Smith and Reynolds*, 2004], defined as the monthly SST averaged over the eastern half of the tropical Pacific (5°S–5°N, 120°–170°W). We use the monthly International Sunspot numbers as the measure of the solar cycle (SC) available from 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. We removed the mean monthly values (the annual cycle) from all series, and as the time series are all of different lengths, we restrict analyses to the common period of 1900–2000.

[6] The methods we use in this paper rely on applying the Continuous Wavelet Transform (CWT) to time series. Two useful wavelets are the Morlet, defined as

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0\eta} e^{-\frac{1}{2}\eta^2}, \tag{1}$$

and the Paul [*Torrence and Compo*, 1998]:

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

where ω_0 is dimensionless frequency and η is dimensionless time, and m is the order, taken as 4 here. The idea behind the CWT is to apply the wavelet as a band pass filter to the time series. The wavelet is stretched in time, t, by varying its scale (s), so that $\eta = s \cdot t$, and normalizing it to have unit energy. The Morlet wavelet (with $\omega_0 = 6$) provides a good balance between time and frequency localization and is a good choice for feature extraction so will be used in the wavelet coherence analysis. For broad band pass filtering applications, we use the Paul as this is much less localized in frequency space. 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.

$$W_n^X(s) = \sqrt{\frac{\delta t}{s}} \sum_{n'=1}^{N} x_{n'} \psi_0 \left[(n' - n) \frac{\delta t}{s} \right]. \tag{3}$$

The complex argument of $W_n^X(s)$ can be interpreted as the phases of $X\{\phi_1 \ldots, \phi_n\}$,

[7] Following *Grinsted et al.* [2004] we define the wavelet coherence of two time series X and $Y\{y_1, \ldots y_n\}$ as

$$R_n^2(s) = \frac{\left|S\left(s^{-1} W_n^{XY}(s)\right)\right|^2}{S\left(s^{-1}\left|W_n^X(s)\right|^2\right) \cdot S\left(s^{-1}\left|W_n^Y(s)\right|^2\right)}, \tag{4}$$

where S is a smoothing operator which is a Gaussian along the time axis and boxcar along the wavelet scale axis, and designed to fit the wavelet decorrelation length [*Grinsted et al.*, 2004]. Notice that the definition of wavelet coherence closely resembles that of a traditional correlation coefficient, and it is useful to think of it as a localized correlation coefficient in time frequency space. We apply significance testing using Monte Carlo methods using a red noise model based on the autocorrelation functions of the two time series [*Grinsted et al.*, 2004].

[8] The other methods we consider are non-linear interactions between the two time series that may be chaotic. Both these methods rely on the phase expression of the time series derived from (3) with the Paul wavelet (2) of the desired Fourier wavelength, $\lambda = 4\pi s/(2m + 1)$ [*Torrence and Compo*, 1998]. The broadband Paul wavelet allows signals that are relatively aperiodic to be included in the analysis, and it also makes the results we show very robust over a large range of λ. We utilize the average mutual information, $I(X, Y)$, between the two series, [e.g., *Papoulis*, 1984, chap. 15]. In our case we are interested in causative relations, so it is appropriate to measure the $I(X, Y)$, between their respective phases ϕ, and θ.

$$I(X, Y) = \frac{1}{\log_2 B} \sum_{y \in Y} \sum_{x \in X} p(\phi, \theta) \log_2 \frac{p(\phi, \theta)}{f(\phi) g(\theta)} \tag{5}$$

where p is the joint probability distribution function of X and Y, and f and g are the marginal probability distribution functions of X and Y respectively, I is normalized by B, the number of histogram bins used to construct f and g.

[9] Another measure of coherence between the two time series is the angle strength of the phase angle difference between the series, also known as the mean phase coherence, ρ [*Mokhov and Smirnov*, 2006]:

$$\rho = \frac{1}{N} \sqrt{\sum_{t=1}^{N} \cos^2(\phi_t - \theta_t) + \sum_{t=1}^{N} \sin^2(\phi_t - \theta_t)} \tag{6}$$

We can search for the optimum relative phase delay between the two series by lagging one time series relative to the other by a phase lag, Δ, in both (5) and (6).

3. Results

3.1. QBO-AO Relationship: Wavelet Coherence

[10] Figure 1 shows the wavelet coherence between the two time series. While both QBO and AO exhibit considerable power at biannual periods, there is no consistent phase relationship between the two series as clearly shown by the random orientations of the arrows in Figure 1. There is no evidence that supports the hypothesis that the strength of any relationship varies with the solar cycle, as even periods of significant coherence at biannual periods separated by a decade do not show any consistent phase relationship, e.g. the phase angle in 1960 was almost 180° different from that in 1970. There is also no evidence of any significant coherence in the solar cycle 11-year band.

3.2. Sunspot Numbers: Phase Coherence

[11] Having failed to establish any significant relationship between QBO and AO, we now assess if any other

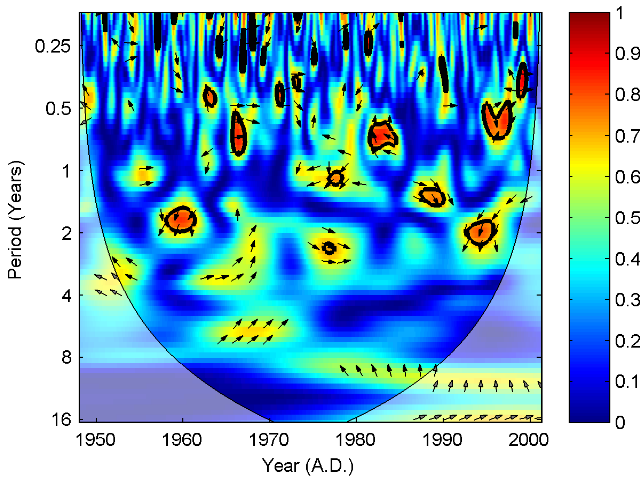

Figure 1. Squared wavelet coherence between AO and QBO. The 5% significance level against red noise is shown as a thick contour. The relative phase relationship is shown as arrows (with in-phase pointing right, anti-phase pointing left, and QBO leading AO by 90° pointing straight down).

links between solar cycle and AO, which may not be dependent on the QBO, can be found. For this analysis we use the I from (5) and ρ from (6). We firstly filter both time series with a Paul wavelet centred on 11 years. We also did the analysis with various other filters – the results are very insensitive and essentially the same as shown in Figure 2.

[12] To illustrate the results expected from successful application of the method we first examine the relationship between SOI and Niño 3.4 (Figure 2a). It is clear that there is the expected obvious relationship, even when the data are filtered with a 5 year centre frequency Paul wavelet. The peak in I and ρ is at 3 months with SOI leading Niño 3.4, as may be expected physically [*Clarke et al.*, 2000a, 2000b; *Jevrejeva et al.*, 2004]. Figure 2b shows that there is no peak in I when $\Delta > 0$ when sunspot number and AO are examined. The ρ has a pronounced minimum around $\Delta = 0$, where one may actually expect significant coherence if a simple physical relationship existed, but ρ does show a small peak at about Δ = 7 years. However the low significance of the peak may be judged by the much larger peak at $\Delta = -17$ years, which is clearly unphysical as AO does not drive sunspot numbers.

[13] To show that the method is capable of detecting a real relationship between two weakly interacting time series, we show the relationship between AO and Niño 3.4 (Figure 2c), where there is clear relationship in the 14 year band with a Δ = 3.5 years from tropics to Arctic. *Jevrejeva et al.* [2004] found a travel time of about 1 year for 13.9 period year waves to travel from tropics to polar regions due to transmission by slow moving ocean waves that are detectable in global sea surface temperature field. The longer delay found here is likely a result of the method, which in the case of weakly coupled oscillators close to synchrony, always displaces the peak to longer delays in lag space [*Cimponeriu et al.*, 2004].

[14] For completeness we also examined the sunspot - tropical climate relationship by examining its links with the SOI and Niño 3.4 indices (Figures 2d and 2e). Once again there is no peak in I and low values of ρ for all Δ up to 10 years.

4. Discussion

[15] It seems clear that there is no simple causative relationship between sunspot numbers (and hence solar insolation) and multi-year to decadal signals in the large circulation systems that largely define the planet's climate. The non-linear analysis we have done also seems to preclude even quite indirect linkages between solar insolation and the SOI or AO, as we would still expect to see evidence of sunspots cycles being ahead of AO even if that delay was quite variable in absolute months or years. More sophisticated analysis of phase interactions could be done [e.g., *Mokhov and Smirnov*, 2006], however such analyses are more suited to very low noise oscillators, or to where such basic information as the sign of the phase is undetermined. If the solar cycle has the large impacts widely claimed then its influence should be readily seen in simpler analyses. In contrast the 13.9 year cycle phasing is quite readily seen, despite

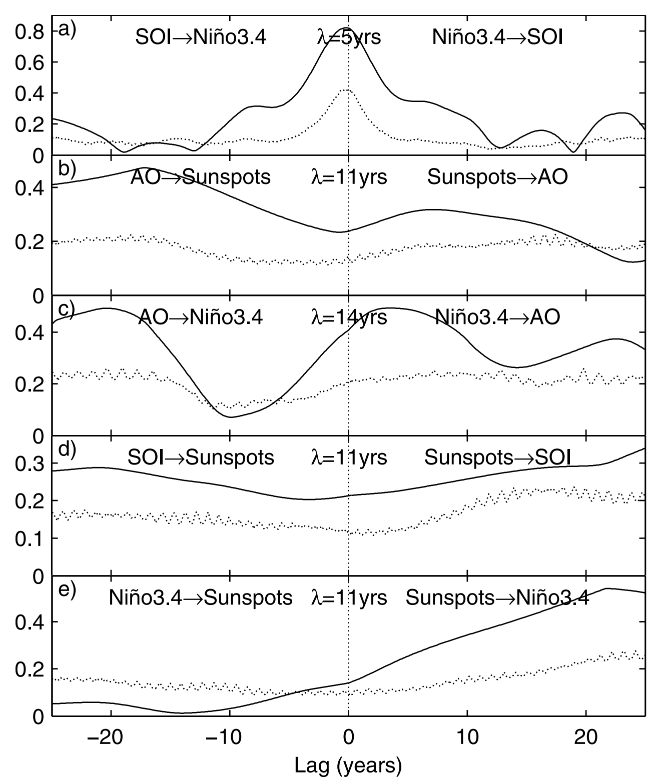

Figure 2. Relationships between time series that have been Paul wavelet filtered with centre frequency λ, expressed as average mutual information, (I), (dotted curves), and mean phase coherence, ρ, (solid line) as a function of the phase lag (Δ) between the series for (a) SOI and Niño3, (b) AO and SC, (c) AO and Niño3, (d) SOI and SC and (e) Niño3 and SC.

it contributing only about 5% of total variance to the SOI, Niño 3.4 and AO indices [*Jevrejeva et al.*, 2004]. Therefore we may confidently assert that the sunspot driving of the AO is certainly less than 5% of total variance; any signal probably accounts for less variance than the plausible limitations of noise in the long atmospheric circulation time series caused by varying spatial coverage, or temperatures being used as proxies for pressure fields.

[16] In time series spanning only 1 or 2 solar cycles it is simply not possible to find significant phase relationships, Figure 1 also illustrates this important point - with only 60 years of data there is only about 20 years of data in the decadal band which are not affected by the data boundaries. While the details of the influence of data boundaries are method-dependent, it is a common feature of the short series regularly used in solar-climate analyses that deriving any statistical significance, especially in realistic red-noise backgrounds, is very challenging.

[17] There is direct evidence from both linear wavelet coherence and from non-linear measures of interactions between time series, that it is the tropics that lead polar climate variability rather than vice-versa as has been proposed for a solar climate driver mechanism. Previous authors have reported numerous examples of 11-year cycles in many different proxy climate records, and often they were assigned to the sunspot cycle. But in the analyses that we have done we find no consistent phase relationship between sunspot numbers and variables such as sea ice extent or spring ice break-up in seas and ports, sea surface temperatures, sea level pressure, and various long meteorological records from cities in Europe. Many of the reports of 11-year cycles come from pure frequency domain analyses such as Fourier transforms, and many of them have dubious levels of significance – either being statistically untested, or only tested against white-noise rather than an appropriate red noise background. In several of these series there is some 11–14 year periodicity that may actually be the 13.9 year signal discussed by *Jevrejeva et al.* [2004] and which seems to be consistently present from the tropics to the polar regions in sea surface temperatures [*Jevrejeva et al.*, 2004], and in various proxy climate series from ice cores [e.g., *Fundel et al.*, 2006]. However, there are other plausible mechanisms for an 11-year cycle. A 5.2–5.7 year cycle is commonly observed in many climate records such as the AO [*Jevrejeva and Moore*, 2001], SSTs from several oceans [*Unal and Ghil*, 1995; *Moron et al.*, 1998], and central England temperatures [*Plaut et al.*, 1995]. A simple doubling of this period comes to 11 years, and such a doubling would be frequently seen, especially in simple Fourier analysis of the data. Natural auto-correlated red-noise in the climate would make this harmonic signal apparently more significant against white-noise background significance tests, thereby leading to claims for an 11 year signal rather than the 5.5 year signal.

5. Conclusion

[18] Numerous authors have considered the apparently self-evident hypothesis that since the sun is the fundamental driving force for the earth's climate, there should be clear links between the main climate patterns and the main index of solar variability. However, rigorous testing of causative links between sunspots and climate indices finds no links on time scales up to about 15 years. Solar driving of climate must be present at timescales relevant to glacial-interglacial cycles and most-likely at shorter scales as well, but solar and climate proxies that meet length and resolution criteria necessary to prove the hypothesis are yet to be adequately tested.

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References

Baldwin, M. P., and T. J. Dunkerton (1999), Propagation of the Arctic Oscillation from the stratosphere to the troposphere, *J. Geophys. Res.*, *104*, 30,937–30,946.

Baldwin, M. P., and T. J. Dunkerton (2001), Stratospheric harbingers of anomalous weather regimes, *Science*, *294*, 581–584.

Baldwin, M. P., and T. J. Dunkerton (2005), The solar cycle and stratosphere-troposphere dynamical coupling, *J. Atmos. Sol. Terr. Phys.*, *67*, 71–82.

Barnston, A. G., and R. E. Livezey (1989), A closer look at the effect of the 11-year solar cycle and the quasi-biennial oscillation on Northern Hemisphere 700 mb height and extratropical North American surface temperature, *J. Clim.*, *2*, 1295–1313, doi:10.1175/1520-0442(1989)002.

Cimponeriu, L. M., G. Rosenblum, and A. S. Pikovsky (2004), Estimation of delay in coupling from time series, *Phys. Rev. E*, *70*, 046213.

Clarke, A. J., J. Wang, and Van Gorder (2000a), A simple warm-pool displacement ENSO model, *J. Phys. Oceanogr.*, *30*, 1679–1691.

Clarke, A. J., J. Wang, and Van Gorder (2000b), Corrigendum: A simple warm-pool displacement ENSO model, *J. Phys. Oceanogr.*, *30*, 3271.

Fundel, F., H. Fischer, R. Weller, F. Traufetter, H. Oerter, and H. Miller (2006), Influence of large-scale teleconnection patterns on methane sulfonate ice core records in Dronning Maud Land, *J. Geophys. Res.*, *111*, D04103, doi:10.1029/2005JD005872.

Grinsted, A., J. C. Moore, and S. Jevrejeva (2004), Application of the cross wavelet transform and wavelet coherence to geophysical time series, *Nonlinear Processes Geophys.*, *11*, 561–566.

Hameed, S., and J. N. Lee (2005), A mechanism for sun-climate connection, *Geophys. Res. Lett.*, *32*, L23817, doi:10.1029/2005GL024393.

Jevrejeva, S., and J. C. Moore (2001), Singular spectrum analysis of Baltic Sea ice conditions and large-scale atmospheric patterns since 1708, *Geophys. Res. Lett.*, *28*, 4503–4506.

Jevrejeva, S., J. C. Moore, and A. Grinsted (2004), Oceanic and atmospheric transport of multi-year ENSO signatures to the polar regions, *Geophys. Res. Lett.*, *31*, L24210, doi:10.1029/2004GL020871.

Kodera, K., and Y. Kuroda (2002), Dynamical response to the solar cycle, *J. Geophys. Res.*, *107*(D24), 4749, doi:10.1029/2002JD002224.

Kuroda, Y., and K. Shibata (2005), Simulation of solar-cycle modulation of the Southern Annular Mode using a chemistry-climate model, *Geophys. Res. Lett.*, *33*, L05703, doi:10.1029/2005GL025095.

Labitzke, K. (2005), On the solar cycle-QBO relationship: A summary, *J. Atmos. Sol. Terr. Phys.*, *67*, 45–54.

Laut, P. (2003), Solar activity and terrestrial climate: An analysis of some purported correlations, *J. Atmos. Sol. Terr. Phys.*, *65*, 801–812.

Mayr, H. G., J. G. Mengel, C. L. Wolff, and H. S. Porter (2006), QBO as potential amplifier of solar cycle influence, *Geophys. Res. Lett.*, *33*, L05812, doi:10.1029/2005GL025650.

Mokhov, I. I., and D. A. Smirnov (2006), El Niño–Southern Oscillation drives North Atlantic Oscillation as revealed with nonlinear techniques from climatic indices, *Geophys. Res. Lett.*, *33*, L03708, doi:10.1029/2005GL024557.

Moron, V., R. Vautard, and M. Ghil (1998), Trends, interdecadal and interannual oscillations in global sea-surface temperatures, *Clim. Dyn.*, *14*, 545–569.

Papoulis, A. (1984), *Probability, Random Variables, and Stochastic Processes*, 2nd ed., McGraw-Hill, New York.

Plaut, G., M. Ghil, and R. Vautard (1995), Interannual and interdecadal variability in 335 years of central England temperatures, *Science*, *268*, 710–713.

Ropelewski, C. F., and P. D. Jones (1987), An extension of the Tahiti-Darwin Southern Oscillation Index, *Mon. Weather Rev.*, *115*, 2161–2165.

Smith, T. M., and R. W. Reynolds (2004), Improved extended reconstruction of SST (1854–1997), *J. Clim.*, *17*, 2466–2477.

Thompson, D. W. J., and J. M. Wallace (1998), The Arctic Oscillation signature in the winter geopotential height and temperature fields, *Geophys. Res. Lett.*, *25*, 1297–1300.

Torrence, C., and G. P. Compo (1998), A practical guide to wavelet analysis, *Bull. Am. Meteorol. Soc.*, *79*, 61–78.

Tsiropoula, G. (2003), Signatures of solar activity variability in meteorological parameters, *J. Atmos. Sol. Terr. Phys.*, *65*, 469–482.

Unal, Y. S., and M. Ghil (1995), Interannual an interdecadal oscillation patterns in sea level, *Clim. Dyn.*, *11*, 255–278.

A. Grinsted and J. Moore, Arctic Centre, University of Lapland, Box 122, FIN-96101 Rovaniemi, Finland. (ag@glaciology.net; john.moore@ulapland.fi)

S. Jevrejeva, Proudman Oceanographic Laboratory, Joseph Proudman Building, 6 Brownlow Street, Liverpool L3 5DA, UK. (sveta@pol.ac.uk)