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Solar cycle signals in sea level pressure and sea surface temperature

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Abstract

We identify solar cycle signals in 155 years of global sea level pressure (SLP) and sea surface temperature (SST) data using a multiple linear regression approach. In SLP we find in the North Pacific a statistically significant weakening of the Aleutian Low and a northward shift of the Hawaiian High in response to higher solar activity, confirming the results of previous authors. We also find a weak but broad reduction in pressure across the equatorial Pacific. In SST we identify a weak El Niño-like pattern in the tropics, unlike the strong La Niña-like signal found recently by some other authors. We show that the latter have been influenced by the technique of compositing data from peak years of the sunspot cycle as these years have often coincided with the negative phase of the ENSO cycle. Furthermore, the date of peak annual sunspot number generally falls a year or more in advance of the broader maximum of the 11-year solar cycle so that analyses which incorporate data from all years represent more coherently the difference between periods of high and low solar activity on these timescales.

1 Introduction

Signals of the 11-year solar cycle in various meteorological fields of the lower atmosphere, and in sea surface temperatures, have been presented by a number of authors. There is a consensus that any warming due to increased solar activity is not uniform, either within the atmosphere or at the ocean surface, but the patterns and amplitudes of the derived responses in temperature, and other fields, are still the subject of some uncertainty. In sea level pressure (SLP) the Aleutian Low tends to be weaker when the Sun is more active and that the Hawaiian High moves northwards (Christoforou and Hameed, 1997). A large response is found in the Pacific in boreal winter: a positive anomaly in the Bay of Alaska, consistent with Christoforou and Hameed results, and also a reduction in SLP near the date line around 20–40° N with a positive anomaly south of the equator (van Loon et al., 2007) (subsequently vL07). This has been interpreted as a strengthening of the SE trade winds crossing the equator, driving increased ocean upwelling and cooler equatorial temperatures (van Loon and Meehl, 2008).

This is consistent with the vL07 analysis of sea surface temperatures (SSTs) which shows a strong La Niña (Cold Event, CE)-like signal when the Sun is more active. However, another SST analysis (White et al., 1997) shows a slightly warmer band of water across the tropical Pacific associated with peaks in a decadal signal (DSO) identified as in phase with solar activity. A modeling study suggests that coupling of changes in surface windstress to ocean circulation produces a Warm Event (WE) a few years after solar maximum (Meehl and Arblaster, 2009) (MA09). It also suggests that the White et al results might be interpreted as lagging solar maximum by 1–2 years so that the results are not inconsistent. A more recent SST analysis (White and Liu, 2008), however, shows a phase-locking of harmonics of the ENSO time series with the solar cycle resulting in a WE-like signal for about 3 years around the peak of the DSO (with CEs approximately 2 years either side of the peak, and stronger WEs peaking 3–4 years before and after it). Thus there is no clear picture of the SST response at solar maximum.

Any strong signal in SSTs would likely also be seen in near surface air temperature but a multiple regression analysis of 118 years data (Lean and Rind, 2008) shows very little solar signal in the tropics. It does, however, show bands of warming around mid-latitudes in both hemispheres, consistent with a response seen previously in 27 years of zonal mean tropospheric air temperatures (Haigh, 2003). In this paper we investigate further the solar signal in SLP and SSTs using a multiple regression technique.

2 Data and methodology

We present results of a multiple linear regression analysis of over 150 years of SLP and SST data. For sea level pressures we use the Hadley Centre HadSLP2 dataset acquired from http://www.hadobs.org. This is an upgraded version of the monthly historical mean sea level pressure dataset HadSLP1, based on a compilation of numerous terrestrial and marine data over the time period 1850–2004 (Allan and Ansell, 2006).

ACPD

9, 25839–25852, 2009

We analyse two different sets of data for sea surface temperatures: one from the Hadley Centre and another from NOAA. The Hadley Centre dataset (HadSST2), obtained from http://hadobs.metoffice.com/hadsst2/, is based on the recently created International Comprehensive Ocean Atmosphere Data Set (ICOADS) (Rayner et al., 2006). SST anomalies (relative to the mean values over 1961–1990) have been calculated over the globe between 1850 and 2004. The other SST dataset we use is the NOAA extended reconstructed sea surface temperature data set (ERSST.v2) for 1854–2007 from http://www.cdc.noaa.gov/cdc/data.noaa.ersst.html. The two SST datasets differ in their data sources, in analysis procedure and the corrections algorithm applied before 1940s. In terms of sources, the NOAA product uses only in situ measurements while Hadley centre data includes satellite-derived SST since early 1980s. The latter also includes additional in situ observations from the UK Meteorological Office archive which are not included in the former (Vecchi et al., 2007).

The independent time-varying indices we use in the multiple regression are a linear trend (to simulate long-term climate change), stratospheric aerosol optical depth (mainly representing the influence of explosive volcanic eruptions), solar variability and ENSO. We employ a code which estimates amplitudes of variability due to these climate factors using an autoregressive noise model. In this methodology, noise coefficients (that might be present due to several unobserved sources) are calculated simultaneously with the components of variability so that the residual is consistent with a red noise model of order one. By this process it is possible to minimize noise being interpreted as signal. We then use a Student's t-test to measure the level of confidence of variability for different indices.

Stratospheric aerosol optical depth data are from http://data.giss.nasa.gov/modelforce/strataer/tau_line.txt. It has been extended to 2005 with near zero values. To represent the time variance of ENSO we use the Niño 3.4 index obtained from www.cpc.noaa.gov/data/indices. For the solar influence we use monthly sunspot numbers available from ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/MONTHLY.

Thus we include solar variability on solar cycle timescales but do not include the effect of any underlying long-term variations in solar irradiance which are difficult to separate statistically from a climate change signal.

3 Results

The signal in SLP associated by the multiple regression analysis with solar cycle variability is presented in Fig. 1. It shows a region of positive anomaly, of up to 5 hPa, in the North Pacific with a smaller negative anomaly, magnitude around 0.5 hPa, in the equatorial Pacific. This pattern is robust to the inclusion or not of the ENSO index as an independent index in the regression analysis. It is consistent with the results of Christoforou and Hameed (1997) who showed that the Aleutian Low is weaker, and the Hawaiian High positioned further north, during periods of higher solar activity. It is also consistent with observational studies (Brönnimann et al., 2006; Haigh et al., 2005) and modeling studies (Haigh, 1996, 1999; Larkin et al., 2000; Matthes et al., 2006) which have indicated an expansion of the zonal mean Hadley cell, and poleward shift of the Ferrel cell, at solar maxima. It does not, however, reproduce the pattern found by vL07, using the HadSLP1 dataset, which placed a negative anomaly around 10–30° N in the mid-Pacific.

The solar cycle signal deduced in the NOAA SST data is presented in Fig. 2. No regions of high statistical significance are found but the pattern is essentially reproduced using the HadSST2 dataset and is robust to the inclusion or otherwise of an independent ENSO index. In the Eastern equatorial Pacific a tongue of warmer water is found, resembling a weak warm event. A stronger region of warming, of around 0.5K occurs at 40° latitude across the North Pacific, and more weakly in the South Pacific, with cooler regions equatorward in both hemispheres. The results in the North Pacific are qualitatively similar to those of vL07, although of much smaller magnitude, but in the tropics they do not indicate the strong CE-like cooling found in the eastern Pacific in that paper. The overall pattern is consistent with the analysis of (White et al., 1997)

ACPD
9, 25839–25852, 2009

and also the analyses of near surface air temperature by (Lean and Rind, 2008) and (Haigh, 2003).

4 Discussion

To explain the apparent discrepancy between the different results, we investigate the different methodologies employed. vL07 deduced the solar signal by taking a composite of the data corresponding to the years identified with the peaks of the 14 solar activity cycles within the data period, and then associating the anomaly relative to the climatology with the effects of the Sun. The pattern was robust to the removal of data from either 1989 or 1905, the only years identified as having a strong ENSO influence.

To investigate further any potential link between the apparent solar signal and ENSO Fig. 3a presents a scatter plot of the values of these two parameters. No obvious relationship exists, and this is confirmed by a separate regression analysis of the ENSO time series (not shown). This would suggest that a signal identified with solar variability in tropical sea surface temperatures would be unlikely to express a particular phase of ENSO. When, however, solar cycle maximum years are identified, as shown in Fig. 3b, nine of the fourteen have a value of ENSO index lower than the average, and four of these years (1893, 1917, 1989, 2000) are associated with particularly strong cold events. Only one solar maximum year is associated with a significant positive ENSO signal and this, 1905, is a weak solar cycle. As it is only the solar maximum years that are used by vL07 to characterize the solar signal it is clear that their result will resemble a Cold Event (La Niña) pattern. It then remains to be determined to what extent the derived signal can be assigned as due to the Sun rather than mainly due to natural ENSO variability.

It is not immediately obvious why Fig. 2 should show a weak WE-like response associated with higher sunspot numbers (SSNs) rather than the CE pattern of vL07, and as suggested by Fig. 3. One possibility is that the multiple regression technique treats the solar and ENSO signals as linearly independent whereas, as discussed by White

ACPD

9, 25839–25852, 2009

and Liu (2008) there is non-linear coupling between the two influences and that the latter cannot be cleanly separated from the former. However, this cannot be the whole story as the solar signal produced by the regression is essentially unaffected by the inclusion of an independent ENSO index and, furthermore, White and Liu (2008) show a WE pattern at the peak of the DSO with or without ENSO coupling. Rather, the answer appears to be related to the definition of peak solar activity.

Figure 4 shows the time series of monthly SSNs and of their annual means, it also identifies the years of highest annual SSN for each solar cycle, as used by vL07 to label solar peak years. It is apparent that peak years tend to occur very soon after the solar cycle becomes more active – this is true of all the stronger cycles – and at least a 1 year before a date that would represent the peak of a broader decadal variation. Thus an analysis based on solar peak years, such as the vL07 results, represents the solar signal at a particular phase of the solar cycle while Fig. 2, and the results of White et al. (1997), represent more broadly the difference between periods of higher and lower SSN. The work of White and Liu (2008) provides an indication as to why these may not give the same results as a WE signal near the peak of the DSO is typically preceded and followed, with a lead/lag of about 2 years, by a CE.

This difference in timing might also provide an explanation for other apparent discrepancies in solar signals. For example, in observational data van Loon et al. (2004) find a strengthening of the tropical Hadley cell when the Sun is more active while Kodera and Shibata (2006) find it weakened. Peak sunspot number composites are used in the former paper while correlations between meteorological data and the 10.7 cm solar activity index are used in the latter and thus, from the arguments presented above, they represent different aspects of solar cycle variability. Similarly in modeling studies: Meehl et al. (2008), with a transient model run analysed by peak SSN year, find a stronger Hadley circulation while Haigh (1996, 1999), using equilibrated solar maximum and minimum experiments, finds a weaker Hadley cell.

Our analysis provides some coherence to published results and may thus contribute to advance understanding of the associated physical process. One explanation for the solar response (Meehl and Arblaster, 2009) requires that changes in absorption of solar radiation at the ocean surface initiate the earlier CE response. The processes involved would be akin to those proposed to be acting on centennial to millennial timescales, in which overall global warming increases meridional gradients in tropical sea surface temperatures, surface winds and shallow meridional overturning of the ocean (Clement et al., 1996). Thus periods of higher insolation are statistically associated with an increased frequency of La Niña-like events (Mann et al., 2005). How the necessary changes in ocean circulation might become established within the timescale of the ascending portion of the solar cycle still needs to be established.

Given the small signals, and the availability of data covering only 14 solar cycles, it remains a possibility that apparent solar cycles in tropical SSTs are produced by random statistical fluctuations. The signal in SLP, however, appears more robust. Studies with atmosphere-only models have shown that a significant mid-latitude response in temperature, wind and surface pressure can be induced by solar changes in the stratosphere (Haigh, 1996, 1999). A more complete coupled atmosphere-ocean-chemistry model study presents a similar tropospheric response to stratospheric solar forcing and suggests that this is responsible for more than half of the solar signal found in the troposphere (Rind et al., 2008).

5 Summary

We identify solar cycle signals in the North Pacific in 155 years of sea level pressure and sea surface temperature data. In SLP we find in the North Pacific a weakening of the Aleutian Low and a northward shift of the Hawaiian High in response to higher solar activity, confirming the results of previous authors. We also find a broad reduction in pressure across the equatorial region but not the negative anomaly in the sub-tropics detected by vL07. Again, in SST we identify the warmer and cooler regions in the North Pacific found by vL07 but instead of the strong Cold Event-like signal in tropical SSTs we detect a weak WE-like pattern. We find that the peak years of the solar sunspot cycles have often coincided with the negative phase of ENSO so that analyses, such

ACPD
9, 25839–25852, 2009

as that of vL07, based on composites of sunspot peak years find a La Niña response. As the date of peak annual sunspot number generally falls a year or more in advance of the broader maximum of the 11-year solar cycle, analyses which incorporate data from all years represent more coherently the difference between periods of high and low solar activity on these timescales.

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ACPD

9, 25839–25852, 2009

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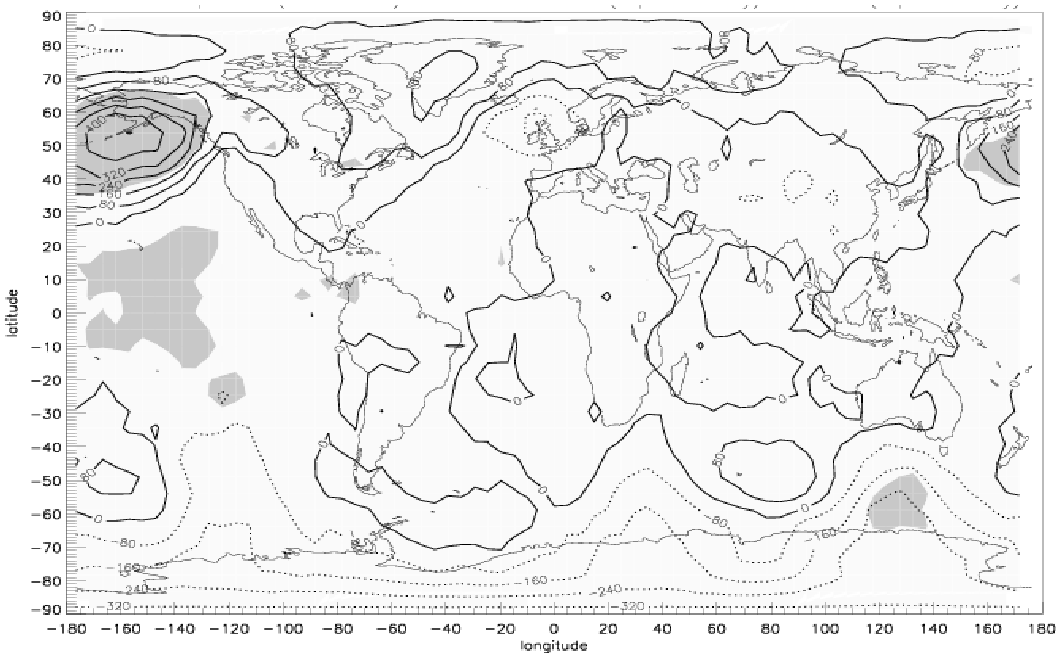

Fig. 1. The solar cycle signal in DJF sea level pressure (solar max – solar min, Pa). The solar activity index used in the multiple regression analysis is sunspot number. Other independent parameters are a linear trend and indices of stratospheric aerosol optical depth and ENSO. Shaded regions are significant at the 95% level.

ACPD
9, 25839–25852, 2009

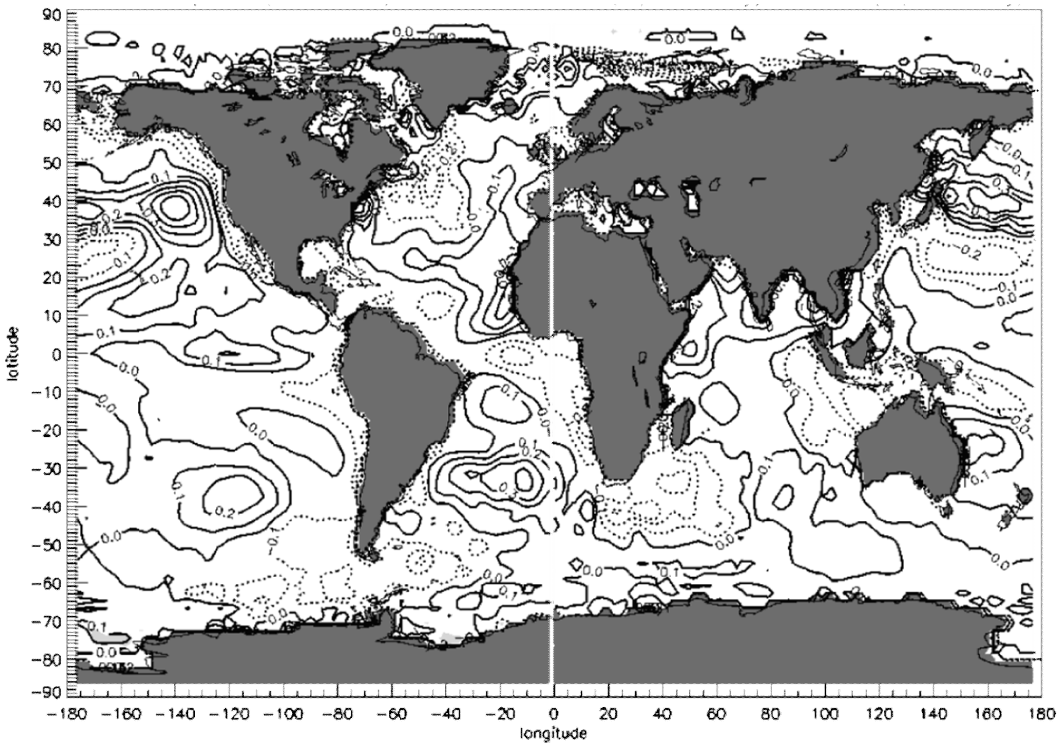

Fig. 2. The solar cycle signal in DJF sea surface temperature (solar max – solar min, K) using the NOAA dataset. The solar activity index used in the multiple regression analysis is sunspot number. Other independent parameters are a linear trend and indices of stratospheric aerosol optical depth and ENSO. Shaded regions (few and small) are significant at the 95% level.

ACPD
9, 25839–25852, 2009

Solar cycle signals in sea level pressure and sea surface temperature

I. Roy and J. D. Haigh

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀I | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

ACPD

9, 25839–25852, 2009

Solar cycle signals in sea level pressure and sea surface temperature

I. Roy and J. D. Haigh

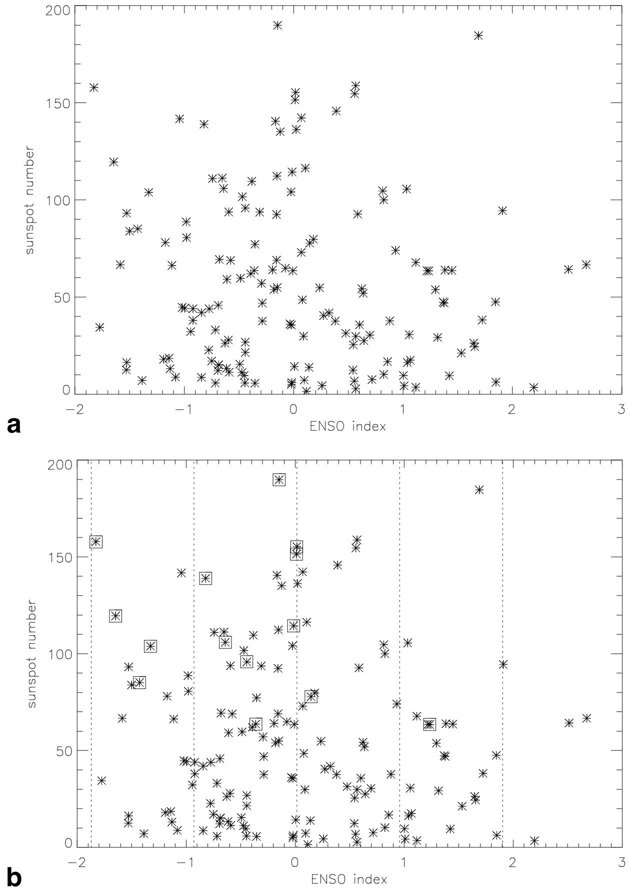

Fig. 3. (a) Scatter plot of ENSO index against sunspot number, DJF values from 1856 to 2007 inclusive. **(b)** As in **(a)** but years of solar cycle maximum are now identified with a box. Dashed vertical lines indicate the mean ENSO index and values at ±1 and 2 standard deviations from the mean.

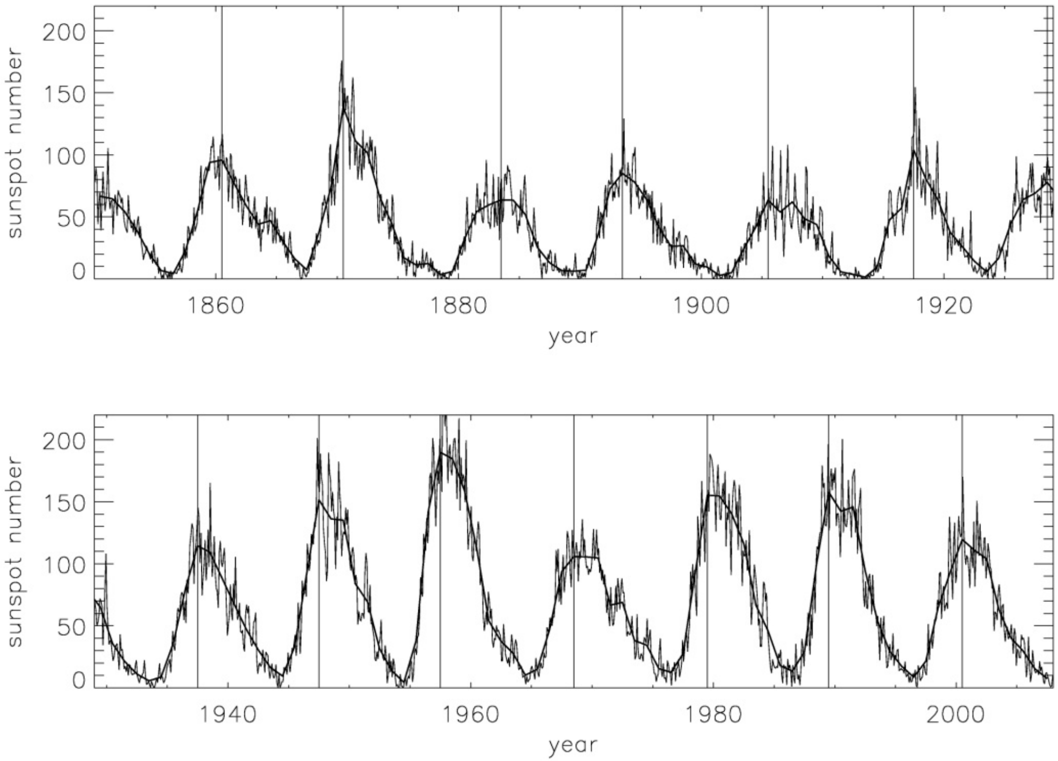

Fig. 4. Monthly mean sunspot number (thin curve) and the annual mean (thick curve). Vertical lines indicate the year of peak annual sunspot number for each solar cycle.

ACPD
9, 25839–25852, 2009