The 11-Yr Solar Cycle in ERA-40 Data: An Update to 2008

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(Manuscript received 27 March 2009, in final form 3 November 2009)

ABSTRACT

Multiple linear regression is used to diagnose the signal of the 11-yr solar cycle in zonal-mean zonal wind and temperature in the 40-yr ECMWF Re-Analysis (ERA-40) dataset. The results of previous studies are extended to 2008 using data from ECMWF operational analyses. This analysis confirms that the solar signal found in previous studies is distinct from that of volcanic aerosol forcing resulting from the eruptions of El Chichón and Mount Pinatubo, but it highlights the potential for confusion of the solar signal and lower-stratospheric temperature trends. A correction to an error that is present in previous results of Crooks and Gray, stemming from the use of a single daily analysis field rather than monthly averaged data, is also presented.

1. Introduction

The magnitude and nature of the response of the climate system to the variations in solar irradiance associated with the 11-yr solar cycle remains uncertain. However, there is a mounting body of evidence indicating significant 11-yr “solar signals” in the climate system (Gray et al. 2005). The detection of solar signals in the stratosphere has largely been restricted to the analysis of data since ~1979 when satellite observations became routinely available. Despite this limitation, periodic signals in phase with the 11-yr solar cycle have been detected in reanalysis and observations of zonal-mean temperature and zonal wind (Haigh 2003; Crooks and Gray 2005; Haigh et al. 2005; Claud et al. 2008) and stratospheric ozone (Hood 1997; Steinbrecht et al. 2001; Soukharev and Hood 2006). If they are assumed to be caused by the solar cycle, these signals represent a relatively rapid linear adjustment of the climate system to variations in incoming solar radiation. Several authors have presented evidence for the detection of more complex nonlinear relationships between the 11-yr solar cycle and other leading “modes of variability” such as El Niño–Southern Oscillation (van Loon et al. 2007; White and Liu 2008) and the quasi-biennial oscillation (QBO; Labitzke 2005; Salby and Callaghan 2004). This present study is

concerned primarily with the characterization of the linear response in zonally averaged zonal wind and temperature.

The character of the solar signal detected in zonal-mean fields may be summarized as follows. The increased incoming radiation during solar maximum produces a localized, 1–2-K increase in temperature just below the equatorial stratopause, as shown in Fig. 1a (reproduced from Crooks and Gray 2005). The magnitude of this temperature anomaly is somewhat larger than would be expected from estimates based solely on total incoming solar radiation changes. This difference has been attributed to increased photochemical production of ozone under solar maximum conditions, which heats the atmosphere (Haigh 1994). This increase in ozone concentrations has been detected in satellite observations (e.g., Hood 1997; Soukharev and Hood 2006; Randel and Wu 2007). Gray et al. (2009) have shown that approximately 60% of the temperature signal may be associated with direct solar irradiance effects and 40% may be due to the indirect effect of ozone production. The increased meridional temperature gradients associated with the equatorial stratopause temperature anomaly induce a thermally balanced zonal wind flow in the upper-stratospheric/lower-mesospheric low latitudes. These features of the signal are fairly well understood, although there are several other aspects that remain less well explained.

In addition to the upper-stratospheric temperature and wind responses Crooks and Gray (2005) identified a separate statistically significant lower-stratospheric

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FIG. 1. The annually averaged solar signal in zonal-mean temperature: (a) 1979–2001 original Crooks and Gray (2005), (b) 1979–2001 correction to Crooks and Gray (2005), and (c) 1978–2008.

temperature signal at around $\pm 20^\circ\text{N}$, 20–30 km. This signal is more controversial. A similar structure is also evident in the solar signal in ozone observations, and Gray et al. (2009) have used the Stratospheric Aerosol and Gas Experiment (SAGE) ozone observations from Randel and Wu (2007) in a fixed dynamical heating model to successfully reproduce the lower-stratospheric temperature signal. On the other hand, analysis of the Stratospheric Sounding Unit dataset (Ramaswamy et al.

2001) suggests only a single deep maximum that extends from the upper stratosphere down to the lower stratosphere. Lee and Smith (2003) and Smith and Matthes (2008) have suggested that the two separate signals may in fact be due to “contamination” of the solar signal by the QBO, whereas McCormack (2003) and McCormack et al. (2007) advocate the existence of a direct solar influence on the QBO. In contrast to both of these points of view Austin et al. (2008) find that the presence of

a QBO in model simulations has little impact on the diagnosed solar signal.

A further complication in assessing the impact of the 11-yr solar cycle on the lower stratosphere comes from the influence of two major volcanic eruptions that occurred in 1982 (El Chichón) and 1991 (Mount Pinatubo). Each of these eruptions occurred near the end of a solar maximum period, which means there is a potential for the misattribution of the solar and volcanic signals. However, the most recent solar maximum of 2002 has passed without significant volcanic activity and presents the opportunity to reassess the solar signal with a reduced likelihood of contamination from volcanic aerosols.

In this paper we present an update to Crooks and Gray (2005) using the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) dataset extended to 2008 using the ECMWF operational analysis. We also present a correction to the results of Crooks and Gray (2005) stemming from an error in the data used in their analysis. We also demonstrate the potential for confusion of the solar signal and trend term, especially in the lower stratosphere.

The paper is divided into three sections. In section 2 we describe the regression model and data processing. In section 3 we present the correction to the analysis of Crooks and Gray (2005) for the period 1979–2001 and then extend their regression analysis to 1978–2008. Section 4 gives a summary of the results and conclusions.

2. Data processing and regression model

The solar signal is detected using a linear regression analysis of zonally averaged monthly-mean zonal wind and temperature fields from the ECMWF. The ERA-40 dataset (Uppala et al. 2005) spans the period from 1 September 1957 to 1 August 2002 but, because of the lack of stratospheric observations in the earlier period, only data from 1978 onward have been utilized. After August 2002 the ECMWF operational analysis fields are used. For the period of September 2002–February 2006 these were produced on 60 hybrid pressure model levels (L60), consistent with the ERA-40 dataset, after which the vertical resolution was increased to 91 hybrid pressure levels (L91)—see <http://www.ecmwf.int> for details on ECMWF vertical grids. For consistency the L91 data have been interpolated onto the L60 vertical grid in this study. The interpolation was performed on monthly and zonally averaged data by first determining the pressure coordinates associated with each vertical column in the latitude–height grid, using zonally/monthly averaged surface pressure. The field at each latitude was then interpolated onto the equivalent L60 pressure levels using

FIG. 2. Time evolution of (bottom to top) 10.7-cm solar flux, volcanic aerosol mixing ratio, NAO index, Niño-3 index, and QBO indices 1 and 2.

a cubic-spline interpolant. In this way, a relatively coherent time series for the period of 1979–2008 was achieved.

As in Crooks and Gray (2005), the following climate indices were included in the regression: the 10.7-cm solar flux, stratospheric aerosol optical depth, Niño-3 anomaly, North Atlantic Oscillation (NAO) index and two QBO indices. These indices have been extended to 2008 and are shown in Fig. 2. As described in Crooks and Gray, the QBO indices were defined as the first two principal components of the residuals in the equatorial lower-stratospheric winds from an initial regression using all of the other indices.

In addition to the climate indices shown in Fig. 1, a linear trend term and three step functions to account for the joining of data streams were included. The three step functions take into account the discontinuities in the data that stem from 1) joining of ERA-40 data streams in April 1986, as employed by Crooks and Gray, 2) the boundary between the end of ERA-40 and start of the operational data in September 2002, and 3) the switch from L60 to L91 in February 2006. The regression of Crooks and Gray (2005) included an additional 12 indices to account for any seasonality in the independent variables, but they have not been included here. The omission of these indices was found to have negligible impact on the diagnosed signals.

Two types of regression are performed. The first is a regression to obtain the “annual averaged” signal using all of the monthly data, deseasonalized by subtracting the mean of each month. The second, which calculates the “monthly” signal, is a regression using data separated by month (e.g., using only data from December).

A Durbin–Watson test (Durbin and Watson 1950) clearly indicates the presence of serial correlation in the residuals from the regression onto all months, with p values of less than 0.01 for all grid locations. To prevent the effects of serial correlation leading to overestimation of the significance values, the regression is performed with an autoregressive term. The results are found to be fairly insensitive to the order of the autoregressive model; in the results shown, a third-order model is used—primarily for consistency with Crooks and Gray (2005). As an additional check the regression analysis was also performed using annually averaged data. This additional analysis produced solar signals that were very similar to those obtained using monthly data. Durbin–Watson tests of the residuals from these regressions were not clear-cut, with p values varying from 0 to 1, with slightly more grid points having low p values. However, the diagnosed solar signal was found to be insensitive to the use of an autoregressive term, indicating that, while there is autocorrelation in the residuals from the regressions using monthly averaged data, they should not significantly affect the results. For the residuals from the regressions onto monthly separated data, the results of the Durbin–Watson test are very similar to those using annually averaged data, and the results of the regression are also found to be insensitive to the use of an autoregressive term. For simplicity, no autoregressive term has been used in the regressions using monthly separated data.

3. Results

a. 1979–2001 solar signal

The results of Crooks and Gray (2005) employed monthly-mean, zonally averaged fields. However, as a result of a misspecification of the data, the stratospheric components of the fields employed single analysis fields from the first day of every month instead of the monthly average. In this section we present the solar signal diagnosed using the corrected data for the same period as presented in Crooks and Gray (2005).

Figure 1b shows the annual-averaged solar signal in zonal-mean temperature for the period October 1979–July 2001 using the corrected monthly-mean dataset, which can be compared with the results of Crooks and Gray (2005) in Fig. 1a. The most striking difference is the increased smoothness and symmetry of the signal (particularly near the equatorial stratopause) when the correct monthly averaged data are used. The overall structure of the signal is otherwise very similar and of similar magnitude. There are, however, some differences in the detailed structure that are worth highlighting.

The first of these differences is the presence of a significant equatorially confined positive temperature signal in the equatorial stratosphere around 30–40 km in Fig. 1b. This signal is fairly sensitive to the specification of the QBO index, and despite the strength of the signal it cannot robustly be associated with the solar cycle. This is confirmed by the absence of the signal in Fig. 1c, which shows results from the extended dataset for the period of 1978–2008. Salby and Callaghan (2004) have proposed a nonlinear relationship between the phase speed of the QBO and the solar cycle, which may explain the sensitivity of the results in this region; however, such relationships are beyond the reach of linear regression and the scope of this paper.

The second difference between Figs. 1a and 1b is in the strength and extent of the signal in the lower stratosphere at low latitudes. Two positive temperature signals at $\pm 20^\circ\text{N}$ are evident in both Figs. 1a and 1b but are stronger and significant over a larger area in the latter. There is also a statistically significant third maximum in the temperature signal in the equatorial region just above the troposphere in Fig. 1b that is not evident in Fig. 1a. The final difference is that, while both have negative signals in the Northern Hemisphere extratropics at around 40–50 km, in the corrected analysis these signals are no longer statistically significant.

Figures 3a,b show the corresponding solar signals in zonally averaged zonal wind. Comparison of Figs. 3a and 3b reveal that the effects of using the corrected monthly averaged data as opposed to single analysis fields are small. Both signals feature two westerly maxima at upper levels at around 30°S and 35°N and latitudinally banded anomalies reaching into the troposphere. However, there is an asymmetry in the amplitude of the upper-level wind maxima, with the Southern Hemisphere maximum being stronger than that in the Northern Hemisphere. A second difference is the appearance of a significant equatorially and vertically confined westerly signal in the lower stratosphere (~ 20 km) in Fig. 3b, which is not present in Fig. 3a. This westerly signal is collocated with the equatorially confined vertical temperature dipole seen in Fig. 1b, but whether these signals are direct responses to solar forcing that can be cleanly separated from the QBO remains unclear.

b. 1978–2008 solar signal

The coincidence of two major volcanic eruptions (in 1982 and 1991) with the end of two of the solar maxima has led to speculation that the diagnosed solar signal (particularly that of temperature in the lower stratosphere) is in part attributable to volcanic aerosol forcing. Arguments against this include the fact that the volcanic index and solar cycle index are not highly correlated (the

FIG. 3. As in Fig. 1, but for zonal-mean zonal wind.

correlation coefficient is 0.1) and that a Fourier analysis of the indices (not shown) indicates that, while both the volcanic and solar indices (Fig. 2) contain spectral peaks in the decadal range, the spectral components are almost 90° out of phase. The implication of these two facts is that confusion of the signals would result in either a linear, but lagged, temperature response to the volcanic aerosol (and/or 11-yr solar cycle) or a strongly nonlinear response that leads to responses with significantly different

time signatures to those of the forcings. The 2002 solar maximum has passed without significant volcanic activity, and so by extending the analysis to cover this solar maximum we may separate more clearly the response to solar forcing from that of volcanic aerosol.

Figures 1c and 3c show the annual-mean solar temperature and zonal wind responses for the extended ECMWF dataset for January 1978–September 2008. Comparison of Figs. 1b and 1c and Figs. 3b and 3c

FIG. 4. (a) The fraction of the covariance of the 10.7-cm solar flux index and temperature at 23-km height at 24°S attributed to each index. (b) The fraction of the linear temperature trend at 23-km height at 24°S attributed to each index.

indicates that similar significant signals are detected in both the ERA-40 and extended datasets. The signals from the extended dataset are, however, weaker than those from ERA-40, although they remain statistically significant in roughly the same regions. This is particularly true for the low-latitude temperature signal in the lower stratosphere.

Because of this reduction in signal amplitude, Fig. 1c alone provides insufficient evidence that the solar and volcanic aerosol signals are cleanly separated; that is, the weakening in signal strength could be the result of an absence of any solar signal in the additional years of data. However, a more detailed examination of the data reveals that this is not the case. For example, taking a sample gridpoint in the subtropical lower stratosphere, the correlation between the solar-cycle index and temperature at 23 km, 24°S reduces by only 3% when the extra years are included in the correlation calculation. Such a small change in correlation certainly cannot explain the difference between the amplitude of the diagnosed lower-stratospheric temperature signal in Figs. 1b and 1c, and implies that the source of the correlation is not confined to the years around the major volcanic eruptions.

To examine the reason for the reduced amplitude signal, we can consider the amount of the covariance of the 10.7-cm solar flux index with the temperature that is explained by each of the regression indices and the residuals from the regression. This procedure can be

FIG. 5. The variation with data window length of the apparent trend associated with the solar signal in lower-stratospheric temperature.

understood by considering that the sum of the regression indices (weighted by their respective regression coefficients) and the residuals is equal to the original data. We can therefore view the correlation of the data with one index as being attributable to each individual element in that sum. Figure 4a shows the fraction of the covariance of the 10.7-cm solar flux and the temperature at 23 km, 24°S explained by each element in the regression. This particular location is chosen because it is close to the maximum of the solar signal in lower-stratospheric temperature, but the results are similar for the rest of the diagnosed lower-stratospheric solar signal. The black bars show the results for the 1979–2001 period and the gray bars show the results for the 1978–2008 period. What is immediately apparent is that, when compared with the 1979–2001 results, the 1978–2008 results show a reduction in the fraction of covariance attributed to the solar cycle, which is largely explained by increases in the fraction attributed to the trend term. While there is a small increase in the fraction of covariance in the volcanic index, this is small relative to the reduction in that explained by the solar cycle, indicating that the diagnosed solar signal is fairly insensitive to the volcanic eruptions.

Figure 4a demonstrates that the diagnosis of the solar signal is sensitive to the presence of trends in the data. To a large extent this sensitivity is attributable to the windowing of the data. In the 1979–2001 regression, the end points of the time series were chosen carefully to span approximately two solar cycles and whole periods of the QBO. For the 1978–2008 regression, the end points were chosen to span whole periods of the QBO. However, the window was constrained by the desire to (i) include as much as possible of the data from the extended period up to 2008 when the data were not

FIG. 6. The monthly solar signal in zonal-mean temperature (1978–2008).

affected by volcanic eruptions and (ii) not include data much earlier than 1979 when satellite coverage was limited. The start date of January 1978 was chosen as the best compromise because it allowed the data window to

span whole periods of the QBO. However, it meant that the window was several years too short to cover three whole periods of the solar cycle. Because of this, we see an increase (relative to the 1979–2001 window) of the

FIG. 7. As in Fig. 6, but for zonal-mean zonal wind.

correlation of the trend index with the 10.7-cm solar flux index by a factor of ~ 1.5 , which we suggest is the primary cause of the reduced amplitude of the 11-yr solar cycle signal in lower-stratospheric temperatures.

Given the sensitivity of the diagnosed solar signal in temperature to windowing of the data, it is also worth considering the sensitivity of the diagnosed trend to the solar cycle. Using the same data point for illustration,

Fig. 4b shows the fraction of the trend in the data; that is, the covariance of the trend term with the data that is attributed to each of the indices in the regression. What is immediately apparent is that, because of the large disparity in amplitude, the diagnosed trend is fairly insensitive to changes in the magnitude of the trend associated with the solar cycle, which is reassuring for those who are primarily interested in trend analyses. This might not be the case, however, if one were interested in shorter-term trends. Figure 5 shows the apparent temperature trend in the lower stratosphere induced by the solar cycle as a function of window length, based on the assumption that the regression coefficient for the 1978–2008 period at 23 km, 24°S is correct and that the start of the data window is January 1978. As might be expected for an approximately periodic signal, the magnitude of the apparent trend oscillates as the length of the window passes through whole periods of the signal, and the amplitude of these oscillations decays as the window length becomes larger. For the 1978–2008 window (31 yr) the apparent trend is relatively small, but for shorter periods of approximately a decade the effects of windowing may be much larger [$\sim 1 \text{ K} (10 \text{ yr})^{-1}$ in Fig. 5].

c. The annual cycle in the solar signal

The diagnosed solar signals presented thus far were obtained by regression onto all months of the dataset to produce an annual-mean signal. Since the data have been deseasonalized it is tempting to view the diagnosed signals as low-frequency (i.e., interannual) signals that are present throughout the year. However, it must be remembered that deseasonalizing the data only removes the annual cycle in the mean and not the annual cycle in variance. Since it can be expected that the variance will possess a strong seasonal cycle, particularly at high latitudes, the residuals from the regression model must suffer from a degree of seasonal heteroskedasticity, essentially meaning that some months have greater influence on the model fit than others. To get a clearer picture of the influence of the solar cycle throughout the year, the regression analysis was performed on individual months of the data—for example, on every December.

Figures 6 and 7 show the 11-yr solar signals in zonal-mean temperature and zonal wind for each individual month. The first thing that immediately stands out in Fig. 6 is that the upper-stratospheric equatorial temperature signal seen in Fig. 1 is present and of similar magnitude (although not always significant) throughout most of the year but is strongest around the time of the vernal equinox in March. This upper-level temperature signal is accompanied by westerly wind anomalies in

the subtropical upper stratosphere (Fig. 7) that oscillate with the season, moving poleward and downward during the winter in each hemisphere. In the Southern Hemisphere statistically significant westerly anomalies move gradually poleward and downward during May–August but do not extend poleward of $\sim 45^\circ\text{S}$. By contrast in the Northern Hemisphere over the winter period (November, December, and January) the signals are seen to propagate much farther poleward, although they are not statistically significant—probably because of the greater variability in the Northern Hemisphere. The double-peaked structure in zonal winds at upper levels in the annual-mean signal (Fig. 3) is made up of a maximum in each hemisphere that is present primarily during winter, as noted by Kodera and Kuroda (2002).

In the Northern Hemisphere, the poleward and downward progression of the subtropical zonal wind anomaly from November through to May is disrupted by a large, statistically significant easterly wind anomaly in February. This anomaly is associated with a large positive temperature anomaly, indicative of stratospheric sudden warmings. The progression of this anomaly with time and its relationship to the QBO has been studied in more detail by Lu et al. (2009) using daily data.

4. Summary and discussion

A linear regression analysis has been used to diagnose the signal of the 11-yr solar cycle in both the ERA-40 dataset (1979–2001) and an extended ECMWF dataset covering the period 1978–2008. The results presented here confirm the general picture described by Crooks and Gray (2005). By performing the regression analysis for the period 1978–2008 it has been demonstrated that it is unlikely that the diagnosed solar signal in lower-stratospheric temperature was strongly influenced by the eruptions of El Chichón and Mount Pinatubo. However, because of windowing effects and because the 11-year solar cycle is not perfectly periodic, it is found that the diagnosis of the solar signal is sensitive to the presence of trends in the data, and potentially vice versa. It is also found that results obtained by partitioning the data by month support the findings of Kodera and Kuroda (2002) and show a poleward, downward progression of the signal during the winter of each hemisphere.

Acknowledgments. This study was supported by the U.K. Natural Environment Research Council.

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