Influence of Solar Activity Cycles on Earth's Climate

Task 4 – Quantification of global climate modulations

WP 403 – Stratosphere

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1 Introduction

We focus in what follows on deriving the solar signal in stratospheric temperatures and zonal winds. To this end we apply a multiple regression technique to zonal mean data from the NCEP/NCAR reanalysis data set. Because our work, as previous studies, suggests that the solar influence on the lower atmosphere depends on dynamical coupling between different atmospheric layers we also consider some tropospheric signals, where these are linked, and consider how solar forcing influences the atmospheric polar modes of variability. We conclude by presenting a summary of the current understanding of how stratospheric ozone responds to changes in solar activity.

2 Regression technique

Most of the analysis described below has been carried out using a multiple regression technique.[1] This may be represented by:

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{u}$$

where:

- **y** is a rank-*n* vector containing a time series of the data to be analysed;
- **X** is an *n*x*m* matrix containing time series of *m* factors (indices) which are supposed to influence the data;
- $\boldsymbol{\beta}$ is a rank-*m* vector containing the amplitudes of the indices, these are what we wish to estimate and
- **u** is the (unobserved) noise term representing all sources of observational error, un-modelled variability, internal noise etc. The variance and autocorrelation of the noise are estimated from the residual ($\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}}$, where $\hat{\boldsymbol{\beta}}$ is an estimate of $\boldsymbol{\beta}$); a red noise function (here assumed to be of order 1) is fitted to the residual then the values of $\hat{\boldsymbol{\beta}}$ and the noise parameters are iterated until the noise model fits within a pre-specified threshold. This method minimises the possibility of noise being interpreted as a signal and also produces, using a Student's t-test, measures of the confidence intervals of the resultant $\boldsymbol{\beta}$ values taking into account any covariance between the indices.

The indices used in **X** include representations of some or all of the following features:

- a constant, or individual constants for each month to represent the annual cycle;
- a linear trend representing long term climate change;
- a chlorine index (an edited version of the Level of Effective Chlorine in the Stratosphere from the European Environment Agency at http://dataservice.eea.eu.int/dataservice/viewdata/viewpvt.asp?id=9, courtesy of Ingo Wohltmann & Markus Rex, AWI-Potsdam) representing ozone depletion - assumed to be the main cause of stratospheric temperature change in the Antarctic polar vortex. This index is only used for the SAM data analysis, in place of the linear trend;
- solar activity – this has been represented using three alternative indices: (a) 10.7cm solar radio flux from the National Geophysical Data Center, USA at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/); (b) cosmic rays counted at Climax Colorado, also from NGDC at http://www.ngdc.noaa.gov/stp/SOLAR /ftpcosmicrays.html and (c) total solar irradiance based on the PMOD composite since 1979 and a reconstruction based on sunspot data prior to that (Natlie Krivova, Max Planck Institute for Solar System Research, Katlenberg-Lindau, personal

[1] Code provided by Myles Allen, University of Oxford, UK.

communication). For most of this report the results using the 10.7cm index are presented but some alternatives are presented in the Appendix.

- the QBO - zonal wind at 40hPa over Singapore (Barbara Naujokat, Free University of Berlin, personal communication);
- ENSO - the "cold tongue" index from the University of Washington at Seattle at http://tao.atmos.washington.edu/data_sets/cti/) and
- volcanic aerosol – global average stratospheric aerosol loading as constructed by Sato et al (1993); a background level is assumed since 1996.

The indices are shown graphically in Figure 1; values are scaled so that the maximum range of each is unity over the time period of the data, 1958-2001, (except in the case of the linear trend where the change over one decade is specified). This allows direct inter-comparison of the magnitudes of the derived $\boldsymbol{\beta}$ components, as presented in the results below.

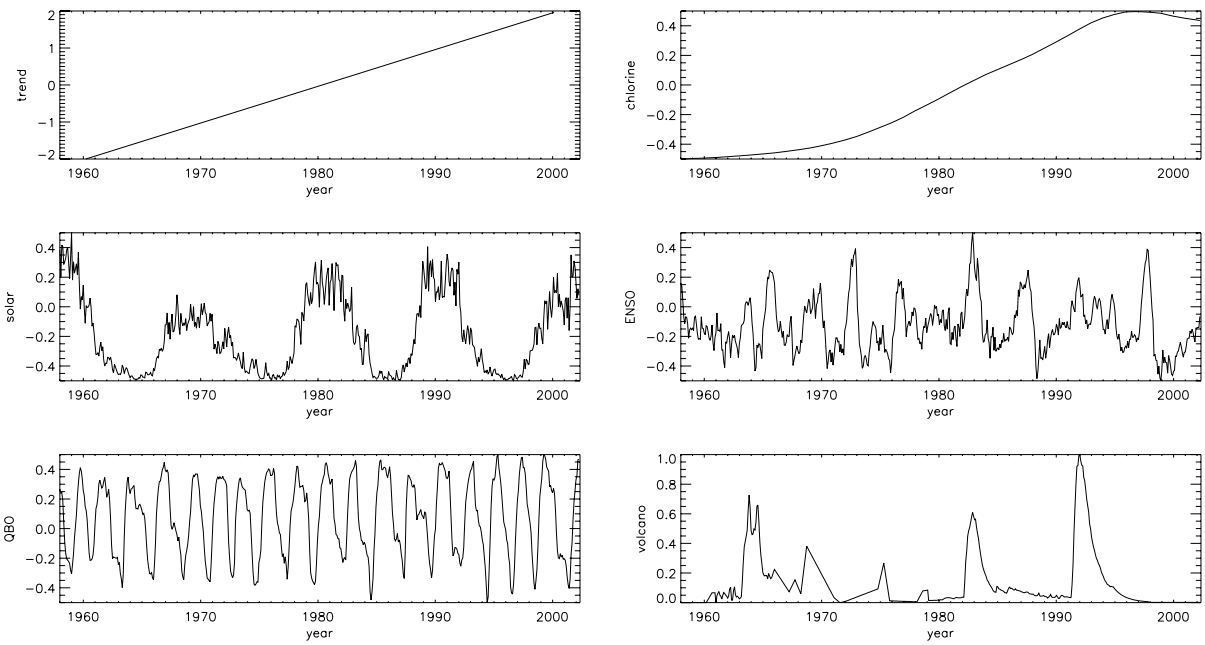


Figure 1 Time series of the indices used in the regression analysis, identified by the labels on the vertical axes.

3 Temperature

Van Loon and Labitzke (1994), reviewing their work up to that date, concluded that a 10-12 year oscillation, in phase with solar activity, occurs over much of the Northern Hemisphere in both the stratosphere and troposphere. They found highest correlations in the summer stratosphere south of about 45ºN, associated with a corresponding periodicity in the temperature of the middle and upper troposphere in the tropics and sub-tropics and deduced that the oscillation is associated with variations in the tropical and sub-tropical circulation. In all their work, however, they used a single linear regression and thus were not been able to estimate the effects of different factors simultaneously influencing the temperature field.. This could lead to misattribution of non-solar effects to the sun or, alternatively, to missing solar effects where these interact with the other influences. Most of their studies were also confined to discussions of correlation coefficients and so did not consider the magnitude of the implied solar signals.

By adopting the multiple regression approach described in Section 2 the responses to all forcing indices supposed to influence temperature are derived simultaneously. Here we assess the solar contribution, along with the other factors outlined above, to variations in zonal mean temperature in the troposphere and lower stratosphere using the National Centers for Environmental Prediction – National Center for Atmospheric Research (NCEP/NCAR) Reanalysis dataset (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html). We use data only since 1979 as it is well documented (see e.g. Randel and Gaffen, 2000; Haigh 2003) that before that date the lack of satellite data makes unreliable the values in the stratosphere. The annual mean results are shown in Figure 2. There is a clear long-term cooling trend in stratospheric low to mid-latitudes; the characteristic signal of the QBO is displayed in the equatorial stratosphere; ENSO shows a warming of the tropical troposphere a cooling above and a significant warming in the northern polar stratosphere while there is a strong response to the injection of volcanic aerosol – warming the stratosphere and cooling the troposphere. The solar signal shows a statistically significant warming in vertical bands in the mid-latitude troposphere in both hemispheres (discussed previously by Haigh 2003) and a bipolar structure in the lower stratosphere with preferential warming in the sub-tropics (previously noted in ERA-40 data by Crooks and Gray, 2005).

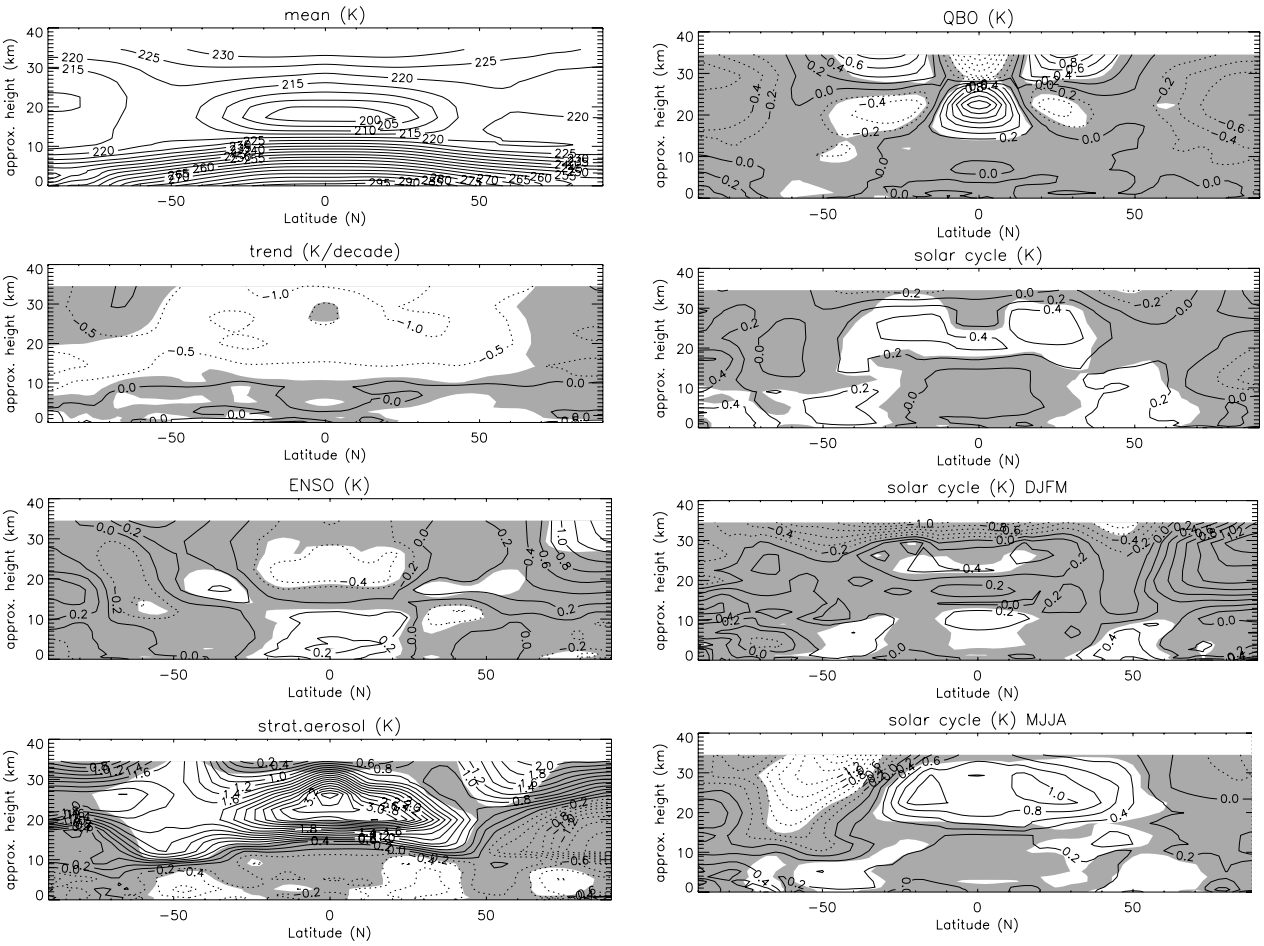


Figure 2 Signals in zonal mean temperature derived from NCEP/NCAR Reanalysis data 1979-2002. The component is identified in the title of each panel. The first six panels relate to the annual mean; the last two are the solar components derived from separate analyses of the DJFM and MJJA seasons. The contour interval is 5K for mean, 0.5 K decade^{-1} for trend, 0.2K all others. Shaded regions are not significant at the 5% level.

The last two panels in Figure 2 show the solar signals derived in separate regression analyses for the solstice seasons, December-March and May-August. Both show the same gross features seen in the annual mean results (warming bands in the mid-latitude troposphere, bipolar warming in the low to mid-latitude lower stratosphere) although the stratospheric response in much larger in MJJA. The suggestion of a cooling in the mid-to high latitude middle stratosphere has also been seen in SSU/MSU satellite data (Keckhut et al, 2004). The patterns of response to higher solar activity in both the troposphere and stratosphere suggest that dynamical, as well as direct radiative, factors are taking effect.

4 Zonal wind

Associated with the temperature response to solar variability are changes in the zonal winds. These have also been analysed with data from the NCEP/NCAR Reanalysis and some of the results are shown in Figure 3. The annual mean signal shows the characteristic inverted horseshoe shape negative (easterly) anomaly in low latitudes, first identified as a solar signal in the modelling study of Haigh (1996), representing a weakening of the tropospheric jets. The seasonal data show very similar effects (though with somewhat different magnitudes) in the two winter hemispheres and the two summer hemispheres throughout the stratosphere and troposphere. In winter the sub-tropical jets are weaker when the sun is more active while in summer mid-latitude jets move polewards. In the stratosphere the summer easterly winds weaken poleward of 50º while the winter westerly polar jet moves equatorward.

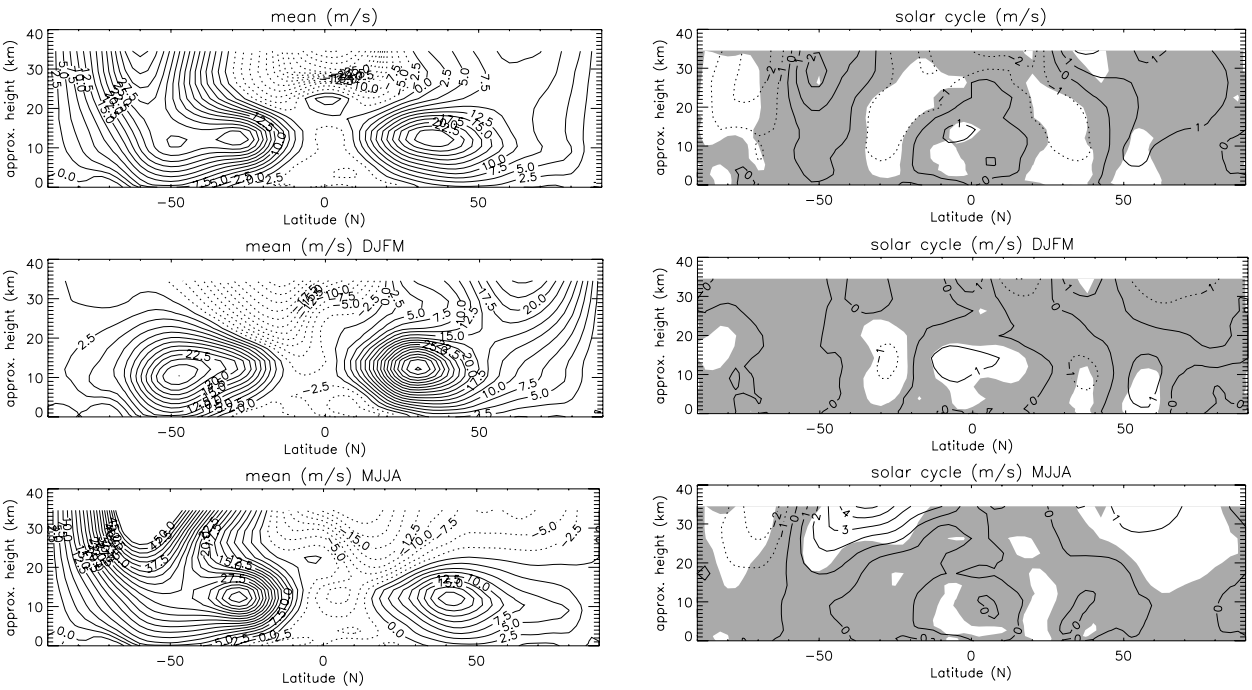


Figure 3 Signals in zonal mean zonal wind derived from NCEP/NCAR Reanalysis data 1979-2002. The top, middle and bottom rows contain analyses for the annual mean, DJFM and MJJA seasons respectively. The left hand column shows the mean values and the right the solar signal. The contour interval is 2.5 m s^{-1} for mean, 1 m s^{-1} for solar cycle. Shaded regions are not significant at the 5% level.

The changes in the zonal wind structure imply a redirection of vertically-propagating waves, which could then further impact the zonal winds if they are dissipated in different regions, as

first proposed by Kodera (1995). To date numerical models of the global circulation of the middle atmosphere have had only limited success in reproducing the apparent solar signals and it will only be when a fuller understanding of these types of feedback effects is achieved that a more complete picture will emerge of solar effects on the middle and lower atmosphere.

5 Polar modes of variability

As outlined in WP104 the atmosphere exhibits a number of characteristic modes of variability, that are important in determining the local climate in various regions, and it has been suggested that the impact of solar variability, as well as other climate forcing factors, may be to affect the frequency of occupation of certain phases of these modes. Studies of the polar annular modes have suggested that in both Northern (Hartley et al., 1998, Baldwin and Dunkerton, 1999, 2001) and Southern (Thompson et al., 2005) high latitudes variations in the strength of the stratospheric polar vortex often precede similarly signed anomalies in the troposphere. Not all events follow this pattern (Black and McDaniel, 2004), and a chain of causality explaining the mechanisms involved has yet to be established, but the evidence suggests one route whereby any factor (and here, of course, we are specifically interested in solar variability) influencing stratospheric circulations might have an impact on surface climate.

Some authors (e.g. Kuroda & Kodera 1998; Castanheira & Graf 2003) have found evidence of modulation of the NAO by the state of the stratosphere and some (e.g. Kodera 2002; Boberg & Lundstedt 2002; Thejll et al 2003) of a solar signal in the polar modes. All of these studies, however, like Labitzke, have used single linear regression and often confined their discussions to correlation coefficients and so have not considered the magnitude of the implied solar signals in the context of other potential forcing factors.

Here we present a multiple regression analysis of factors potentially influencing the northern and southern annular modes, including the factors outlined in Section 2. We investigate levels from the surface to the middle stratosphere and we also conduct a similar analysis of the North Atlantic Oscillation (NAO) in surface pressure, which some authors see as a particular aspect of the NAM but which may alternatively give a more local picture representing synoptic scale variability in the position of the North Atlantic storm track.

The annular mode data used in this study (Mark Baldwin, Northwest Research Associates, USA, personal communication) are based on, at each pressure level, the first empirical orthogonal function (EOF) of 90-day low-pass filtered anomalies, poleward of 20º latitude in each hemisphere, of geopotential heights from the NCEP/NCAR reanalysis. Daily values of the annular mode from 1 January 1958 to 31 December 2001 are obtained by projection of the daily geopotential data onto the EOFs. For further details see Baldwin and Dunkerton (2001) regarding the NAM and Thompson et al. (2005) the SAM. We use monthly averages of the daily values, as we are more interested in the climatological response than in daily development, and we focus on three pressure levels: 1000hPa, 250hPa and 30hPa representing behaviour at the surface, the tropopause and the stratosphere respectively. In the stratosphere we restrict our analysis to data since 1979 because the NCEP reanalysis of the stratosphere is less reliable before this, as mentioned above. At other levels we retain all 44 years of data to provide statistical rigour.

The NAO data used are based on the monthly mean difference in sea level pressure between Gibraltar and South West Iceland as calculated by the University of East Anglia, UK, see http://www.cru.uea.ac.uk/~timo/projpages/nao_update.htm.

No indices representing inter-month variability (annual cycle etc.) are included in the regression analysis as the data are essentially de-seasonalised by the procedure of taking anomalies, as described above. The regression coefficients (β values) for the five varying indices are presented in Table 1. Values assessed to be statistically significant at the 80% confidence level and above are shown in bold type with levels indicated by different colours (see the caption to Table 1).

Table 1 Regression coefficients for the five standard indices. The data covers the period 1958-2001, except for the 30hPa level for which only values since 1979 are used. Colours indicate the statistical significance levels of the values, derived using a Student's t-test, as follows: 99%, 95%, 90%, 80%, <80%.

	pressure (hPa)	**Trend**	**Cl**	**ENSO**	**Vol**	**Sol**	**QBO**
NAO		0.02		-0.09	**0.89**	**0.63**	0.24
NAM	**30**	0.07		-0.22	0.40	0.17	0.22
	250	0.02		**-0.49**	**0.46**	-0.02	0.05
	1000	**0.13**		**-0.53**	**0.53**	0.09	0.20
NAM	**30**	0.05		-0.38	0.67	0.24	0.73
(DJFM)	**250**	0.06		**-1.38**	0.53	0.64	0.39
	1000	**0.23**		-0.82	**1.08**	**0.81**	0.64
SAM	**30**		**0.71**	-0.30	**-0.71**	-0.27	0.31
	250		**0.61**	-0.26	**-0.65**	-0.09	-0.14
	1000		**1.01**	**-0.82**	**-0.65**	-0.04	0.13

Looking first at the results for the NAO we find no significant trend over the period 1958-2001, nor any substantial influence of ENSO. There is a small response to the QBO showing positive NAO anomaly during the QBO-W, but this is not statistically significant. The responses shown to the solar and volcanic forcings, however, are clearly significant at the 95% level; with a positive NAO anomaly shown in response to both higher solar activity and the presence of stratospheric aerosol. While other authors have indicated a link between NAO and solar variability we believe this is the first time that its magnitude has been estimated within a statistically robust framework, taking into account other potential influences.

The volcanic signal is also seen at 1000hPa in the NAM, although somewhat weaker, but the solar signal has disappeared. If, however, the analysis is carried out using only winter months (average of December to March) there is again a large solar signal (the reduced significance level occurs as a result of the factor 12 decrease in the number of degrees of freedom). A strong ENSO signal is seen in NAM, in both all-month and winter analyses, with a positive ENSO phase being associated with a weaker Arctic circulation, as previously noted by Labitzke and van Loon (1999). No statistically significant solar or QBO signals are found in the stratosphere.

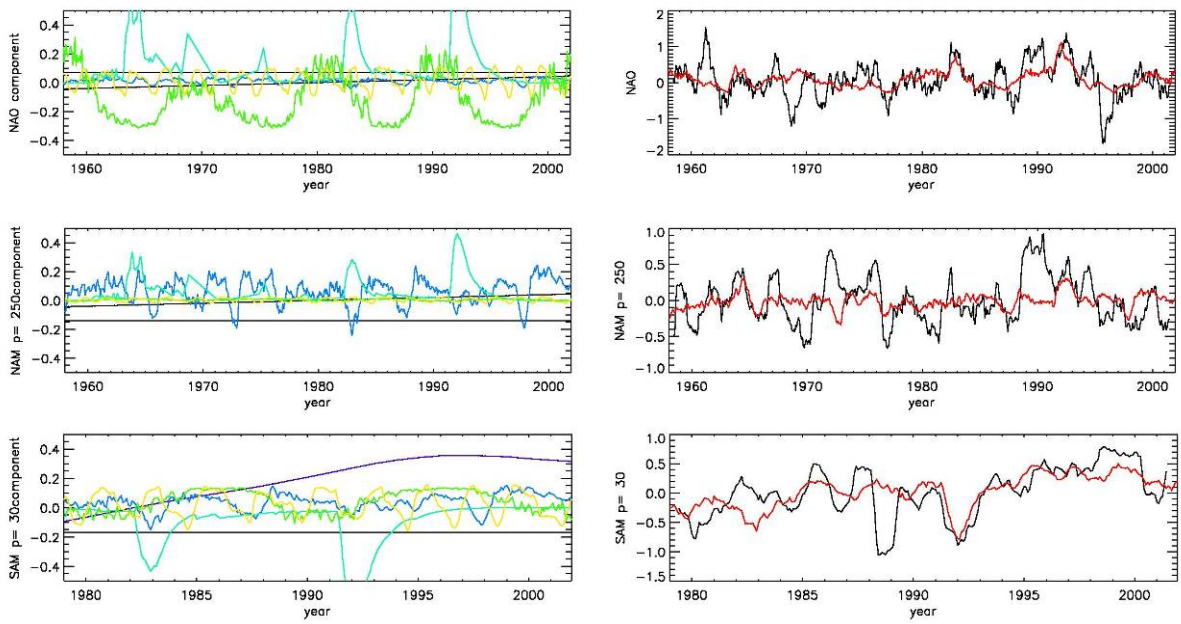


Figure 4 Results of the regression analysis of: Top: NAO; Middle: NAM at 250hPa; Bottom: SAM at 30hPa. The left-hand column shows the time series of the individual components deduced to be contributing to the data. The solar signal is in green, other components as follows: constant (black), linear trend (for NAO and NAM, black), chlorine (for SAM, purple), ENSO (blue), volcanic aerosol (cyan), QBO (yellow). The right-hand column shows the original time series of data in black and the reconstruction from the regression components (without noise component) in red, both smoothed by a 12-month running mean.

SAM shows a strong correlation with stratospheric chlorine at all levels, indicating a cooling and strengthening of the Antarctic tropospheric polar vortex and confirming the results of Thompson and Solomon (2002). It is also found to be associated with the negative phase of ENSO. No significant response is found to either the Sun or the QBO but a large signal is found of volcanic aerosol of opposite sign to that found in NAM.

6 A new index

Labitzke and van Loon (1999, LvL) found that the quasi-biennial oscillation modulates the solar signal. By grouping the data according to the phase of the QBO they showed that when it is easterly (QBO-E) the Arctic lower stratosphere is colder when the sun is more active, implying a stronger polar vortex and more positive NAM, but that the opposite holds during QBO-W. More recently Labitzke (2004) has extended this work and shown that introduction of the QBO also aids analysis of northern hemisphere summers, because of changes in global scale Brewer-Dobson circulation, and furthermore that the Antarctic polar vortex is influenced by the solar cycle, modulated by the QBO, in much the same way as the Arctic. This suggests that during QBO-E the SAM is also stronger when the sun is at maximum activity.

Apart from a solar signal in the NAO the responses, shown in Table 1, of the polar modes to solar variability and the QBO appear weak. However, perhaps this is due to the compensating effects described by LvL. To test this out in a statistically robust framework, which avoids the necessity of having to pre-sort data, we define a new regression index

composed of the product of the original solar and QBO indices, as shown in Figure 5. Because the original indices were scaled to lie equally about zero their product represents a modulation such that a combination of high solar activity and QBO-W, or low solar activity and QBO-E, has positive values while solar max/QBO-E, or solar min/QBO-W, has negative.

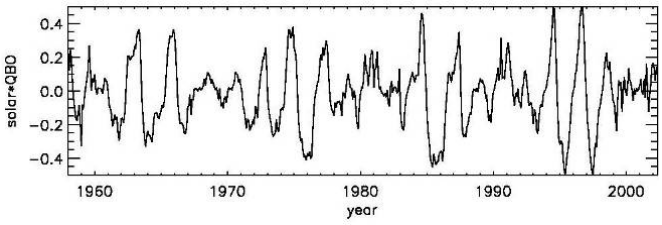


Figure 5 Composite index; this is the product of the independent solar and QBO indices shown in Figure 1, scaled to lie within unit range

This index has been used in the regression analysis in place of the individual solar and QBO indices. An example of its application is shown in Figure 6 which presents, in the right-hand panel, the amplitude of this index for the zonal mean temperature data in DJFM. The left-hand panel shows the individual solar cycle and QBO signals from the original DJFM analysis for comparison.

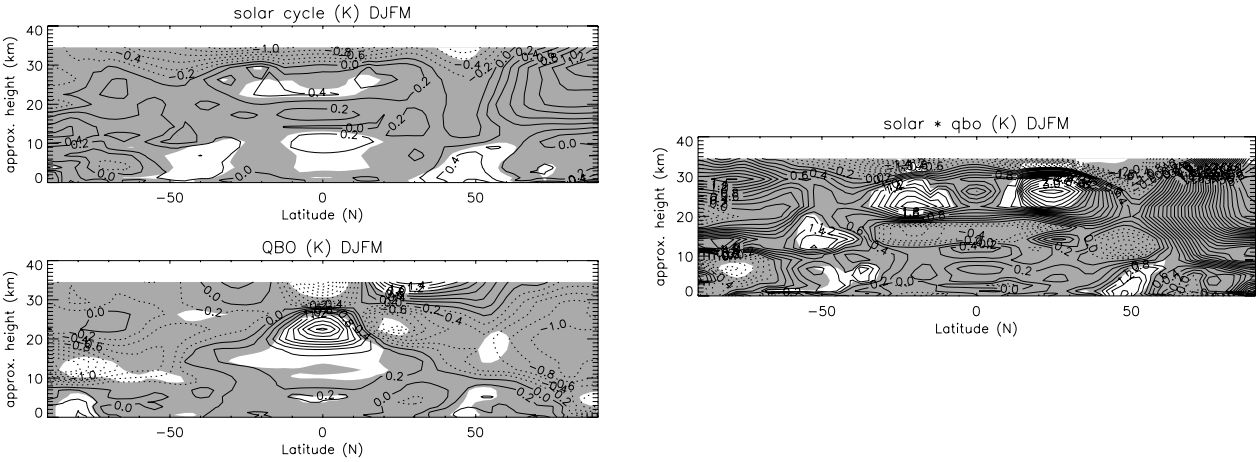


Figure 6 Signal in DJFM zonal mean temperature;left hand side shows results of regression using individual solar and QBO indices (as Figure 2); right handside shows signal from compound index when this is used in the regression in place of the two original ones.

The regions of significance are still fairly restricted, although with the large internal variability and only 23 data points this is understandable, but it is clear that the signals are much larger than the responses derived for the solar cycle and QBO individually. In the winter polar stratosphere there is a substantial (exceeding 6K) positive response, i.e. the pole is warmer during solar min/QBOE and solar max/QBOW and colder during solar min/QBOW and solar max/QBOE, consistent with the LvL criterion. Signals exceed 2K in the sub-tropical lower stratosphere and 1.5K in the mid-latitude troposphere. This provides

significant new evidence that in order to understand solar influences on the lower atmosphere it is necessary to consider dynamical coupling between the stratosphere and troposphere.

Table 2 As Table 1 for values derived using the compound solar*QBO index in place of the solar and QBO indices independently

	pressure (hPa)	Trend	Cl	ENSO	Vol	Sol*QBO
NAO		0.03		-0.13	**0.85**	0.11
NAM	**30**	0.05		-0.25	0.40	-0.14
	250	0.02		**-0.47**	**0.45**	-0.16
	1000	**0.13**		**-0.52**	**0.50**	-0.27
NAM	**30**	0.02		-0.47	0.73	-0.13
(DJFM)	**250**	0.07		**-1.39**	0.38	**-0.91**
	1000	**0.24**		-0.85	0.96	**-1.16**
SAM	**30**		**0.78**	-0.27	**-0.76**	**-0.53**
	250		**0.61**	-0.17	**-0.71**	**-0.57**
	1000		**1.01**	**-0.71**	**-0.75**	**-0.89**

The derived regression coefficients for the annular modes derived using the composite index are presented in Table 2. The first thing to note is that the values for the trend/chlorine, ENSO and volcanic signals are very similar to those in Table 1: this provides evidence of the independence of the indices and the robustness of these signals. The right-hand column of Table 2 shows all negative values (except for the NAO) consistent with the Labitzke criterion stated above. The signals in NAM (except at 30hPa) and in SAM are larger in magnitude than the individual solar and QBO signals in Table 1 and generally statistically more robust. This is particularly true of SAM for which a strong signal emerges at all levels where very little was shown for the individual indices.

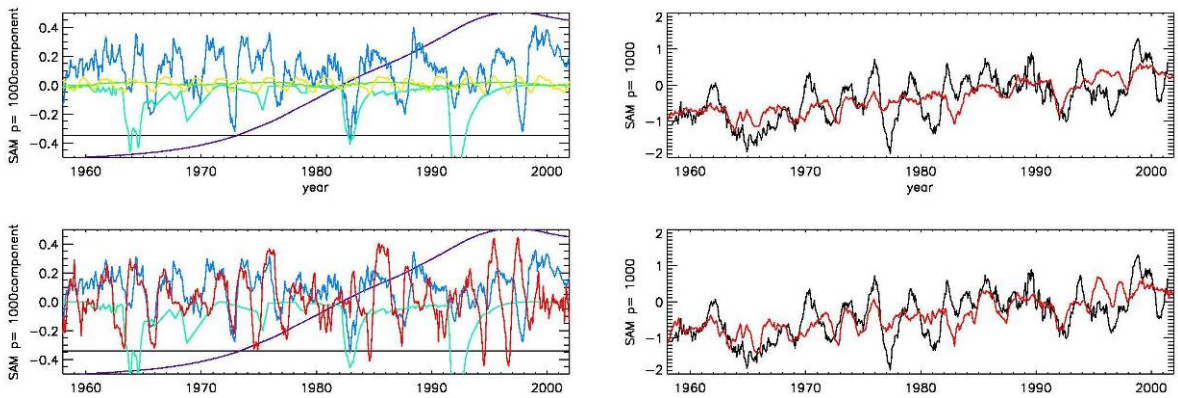


Figure 7 Results of the regression analysis of SAM at 1000hPa. The left-hand column shows the time series of the individual components deduced to be contributing to the data. The top row presents the results using the original indices (colours as in Figure 4 with the solar signal is in green); the lower row shows the results using the compound (Solar x QBO) in place of the solar and QBO indices individually. with the compound index in red and other indices unchanged. The right-hand column shows the original time series of data in black and the reconstruction from the regression components (without noise component) in red, both smoothed by a 12-month running mean.

As an example the time series of the derived components of SAM at 1000hPa, and of the original and reconstructed data, are presented in Figure 7. The amplitude of the composite component is clear in the lower left-hand panel of this Figure and the right-hand panels show that the reconstructed time series is able to reproduce more of the variance in the original data than could be achieved with the original components.

7 Stratospheric ozone

Global satellite remote sensing records of ozone column amounts now exceed 25 years in length. Figure 8 (b) shows the time series of TOMS/SBUV ozone column data averaged over the 35ºS to 35ºN region from 1979 to 2003 inclusive. Eyeball comparison with the solar UV proxy portrayed in Figure 8(c) suggest a solar cycle signal but extraction of its magnitude has been complicated by the volcanic eruptions of El Chichon (April 1982) and Pinatubo (June 1991) which occurred near the ends of the 1980 and 1990 solar maxima. This is because volcanic aerosol provides the conditions for the destruction of ozone by anthropogenic chlorine compounds. Furthermore, ozone column amounts are dominated by the contribution from the lower stratosphere which is where the greatest concentration of volcanic aerosol resides. The passage of the most recent solar maximum without a coincidental major volcanic eruption has, however, provided additional evidence of a statistically significant solar cycle variation of nearly 3% (peak-to-peak), about 9 Dobson Units, in the tropics. This is confirmed by independent analysis of ground-based ozone column data (1964-2005) by Fioletov (2006).

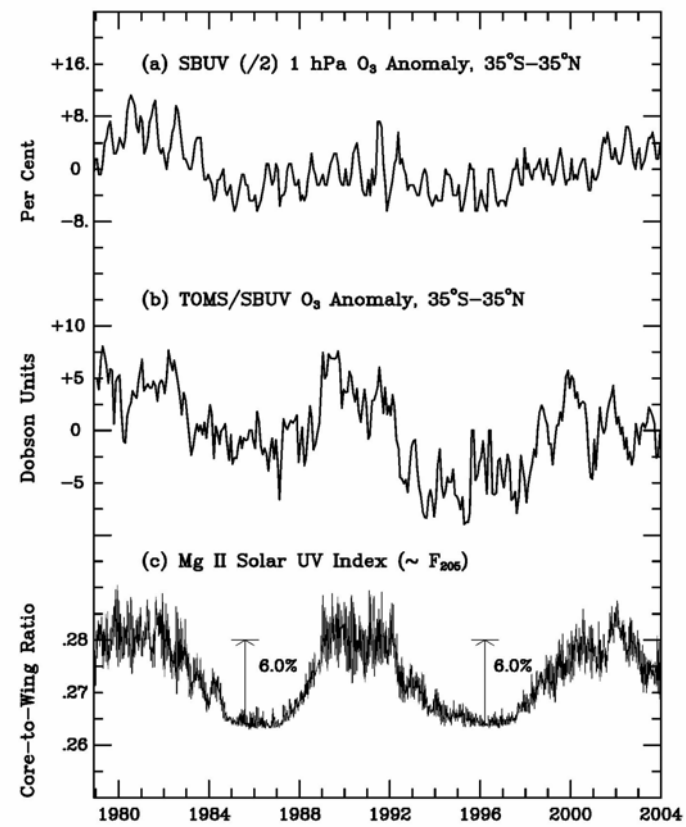


Figure 8 (a) Low latitude (area-weighted) ozone at 1 hPa from SBUV(/2) data; (b) Low latitude (area-weighted), deseasonalised ozone columns from TOMS/SBUV data; (c) Daily MgII 280nm core-to-wing ratio (as proxy for solar UV radiation). From the review by Hood (2004).

Volcanic aerosol is less likely to have an effect in the upper stratosphere and Figure 8(a), showing low latitude ozone concentrations near the stratopause, again suggests a solar cycle influence. Here, however, the problem is one of inter-calibration of the satellite instruments used at different times during the record. Figure 9 shows the solar signals derived in ozone profiles from two different satellite data sets. The overall structure is similar with largest increases (from solar min to solar max) in the upper stratosphere, very small (or possibly negative) responses in the tropical middle stratosphere and increases into the lower stratosphere. However, at any given point there can be sizeable differences between the results of the two analyses so the response of ozone profiles to solar variability remains very uncertain. No model results published to date have been able to reproduce the apparent minimum in the tropical middle stratosphere so, if it is real, it appears that there is a significant gap in our understanding. It has been suggested by Lee and Smith (2003), however, that this minimum may be an artifact introduced into the regression analysis by inappropriate handling of the QBO and volcanic signals. A solution to this problem will come only with acquisition of well-calibrated ozone data well past the next solar minimum.

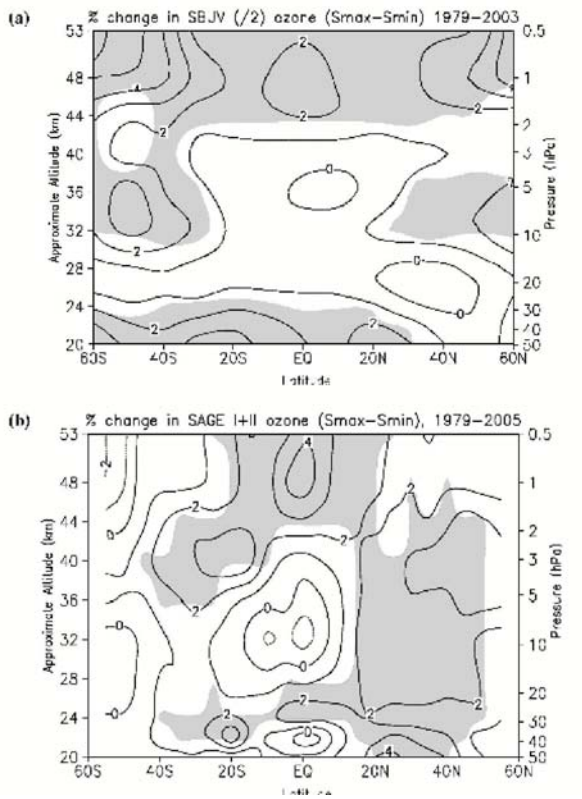


Figure 9 Annual mean solar regression coefficient of ozone concentration as a function of latitude and height using (a) SBUV/SBUV(2) data and (b) SAGE I/II data. The values are percent change in ozone for a 100 unit change in solar 10.7 cm radio flux. Shaded regions are statistically significant at the 5% confidence level. (Lon Hood, personal communication)

8 Summary

Our studies of the NCEP/NCAR Reanalysis dataset show signals in response to the solar cycle in zonal mean temperatures and winds throughout the troposphere and stratosphere and

in all seasons. The clearest patterns to emerge are warming of around 0.5K (in solar max relative to solar min) in the low to mid-latitude lower stratosphere with largest values in the sub-tropics and northern hemisphere summer and vertical bands of warming, of a few 1/10ths K, in the mid-latitude troposphere. The winter polar stratospheric jet moves equatorward while the summer stratospheric easterlies weaken; in the troposphere the winter sub-tropical jets weaken and the mid-latitude jets move poleward. There is a clear solar influence detected in the NAO, consistent with the strengthening of the winter westerlies near 50ºN, but no statistically significant signals of solar forcing are found in either the NAM or SAM.

Based on Labitzke and van Loon's findings concerning the combined influence of solar activity and the phase of the QBO on polar meteorology we have defined a new regression index, the product of the solar and QBO indices. When this is used is used in place of the two factors individually then several other features appear. Firstly, as expected, a strong signal in winter polar stratospheric temperatures, as identified by Labitzke and van Loon but we are now able to place these findings within a statistically robust framework and to assess the magnitudes of the effects in the presence of influences by other factors such as volcanic eruptions and ENSO. We also find that the magnitudes of the temperature signals in the tropical lower stratosphere and mid-latitude troposphere are considerable larger than derived using the solar and QBO indices separately.

A strong influence of the composite index is found throughout the atmosphere in the SAM which showed very little solar or QBO signals in the original analysis. The signal in winter NAM is also increased. Perhaps surprisingly our results for the polar modes show more significance in the troposphere than the stratosphere, but this may be due to the necessity of using a shorter time series at higher altitudes because of the unreliability of the reanalysis datasets in the stratosphere before the inclusion of satellite data.

The NAO behaves differently to the NAM (and SAM) in that the signal found for the combined solar*QBO index is in a different sense to that found in the other modes and also of smaller magnitude than that found for the single solar influence in the original analysis. We tentatively conclude that solar variability influences NAM and SAM through its impact in the polar stratosphere, modulated by the QBO, whereas the solar influence on the NAO is the result of a different process. Our previous work (Haigh 1999, Larkin et al 2000, Haigh et al 2005) suggests this may involve changes in the tropospheric Hadley circulation and storm tracks resulting from solar heating of the tropical lower stratosphere but the mechanisms whereby all these processes take place remain to be elucidated.

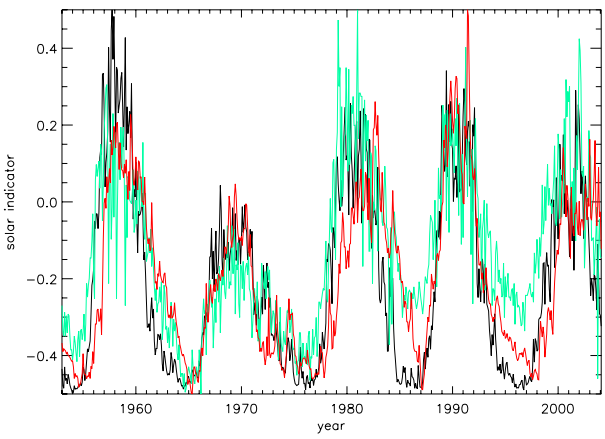
A signal in low latitude ozone column of about 3% peak-to-peak over the solar cycle is becoming better established as the lengths of the data series extend. However, substantial uncertainties still remain in the response of ozone vertical profiles to solar variability with reservations concerning both observational data analyses and model simulations.

[A paper (Haigh and Roscoe, 2006) has been written which describes the definition of the "composite solar-QBO index" and its application to analysis of the polar modes of variability and which includes acknowledgment of the ESA funding for this work.]

Appendix – use of alternative solar activity measures

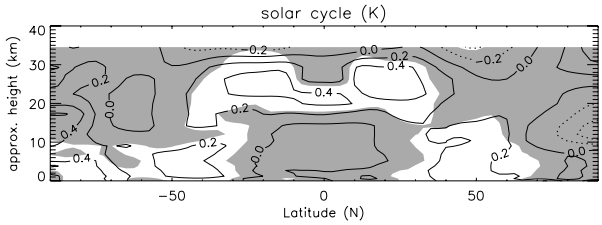
The results discussed in Sections 3 to 6 above are based on regressions using the 10.7cm radio flux to represent solar activity. This was chosen as it has a robust long-term record and provides a good proxy for solar ultraviolet emission but it is interesting to assess to what

extent the results are dependent of the choice of solar indicator. The results of using the two alternative measures (outlined in Section 2) are now presented for the case of the NCEP Reanalysis zonal mean temperatures (as discussed in Section 3). Figure A1 shows, in its left-hand panel, the time series of the three solar indices. All clearly display the 11-year cycle but there are differences in timing and magnitude: radio flux is greatest at the peak of solar cycle 19, whereas TSI and inverted GCR peak during cycles 21 and 22 respectively. The TSI shows an upward trend determined as part of the Krivova and Solanki reconstruction which remains to be confirmed. The GCR index tends to lag behind the others, especially near solar minima.

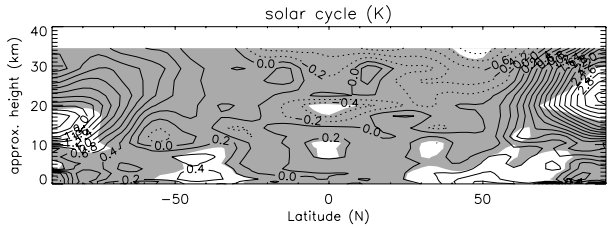


Black: 10.7cm radio flux; green: total solar irradiance; red: cosmic ray count (inverted). Note that for the temperature regressions (right) only data since 1979 were used.

10.7cm:



TSI:



GCRs:

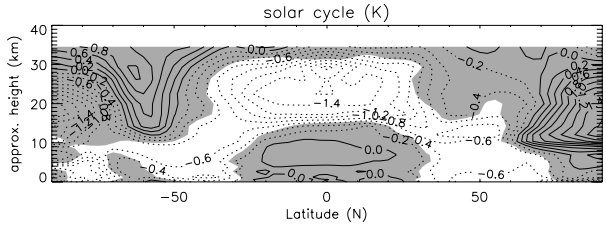


Figure A1 Left: Time series, monthly 1953-2004, of the three solar activity indices, see Section 2 for details. Right: component deduced as due to solar variability when the regression is carried out using the alternative indices.

The right-hand panel of Figure A1 shows the solar cycle signal deduced when each of the three solar indices is implemented. All other indices are the same. The top panel (using radio flux) is identical to that shown for the annual mean in Figure 2 but is repeated here to allow easy comparison. All 3 results show the bands of warming in the mid-latitude troposphere during higher solar activity (NB negative for GCRs because these are greater as solar minimum). Otherwise, the signal from the TSI index is much weaker throughout the domain and showing little statistical significance, except possibly in the polar lower stratosphere. The GCR signal has a very similar structure to that derived using the radio flux although possibly with somewhat larger amplitude. This result is interesting but whether it is robust for other meteorological indices remains to be tested.

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