Eleven-Year Solar Cycle Signals throughout the Lower Atmosphere

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Abstract.

A robust and statistically significant atmospheric signal, which represents the influence of solar radiation changes on our climate, is found in global data (1958-2003). Using a nonlinear, non-stationary time series analysis, called Empirical Mode Decomposition (EMD), it is shown that atmospheric temperatures and geopotential heights are composed of five global oscillations and a trend. The fourth mode is synchronized with the 11-year solar flux almost everywhere in the lower atmosphere. Statistical tests show that this signal is real, indicating that there is enhanced warming in the troposphere during times of increased solar radiation.

1. Introduction

In order to isolate anthropogenic effects on our climate, such as warming by greenhouse gases, we must also understand the natural variability of our atmosphere. Here we will show that the low-frequency variability of the region directly related to the surface climate, the troposphere, can be described in terms of five oscillations and a trend. The fourth mode in this analysis has an average period of 11 years and indicates enhanced thermal warming during times of maximum solar radiation. We use the longest global dataset available (NCEP/NCAR reanalysis from 1958 to 2003), which now spans four solar cycles. Over each 11-year solar cycle the total energy output of the Sun varies by about 0.1% and its ultraviolet radiation fluctuates by 6-8%, with higher irradiance values during solar maxima than during solar minima (*Willson and Hudson* [1988]; *Lean and et al.* [1997]; *Haigh* [2002]). Since 1795 it has been speculated that these variations influence our climate (*Hershel* [1801]). Accumulated observational (*Frederick* [1977]; *Labitzke* [1982]; *Crowley and Kim* [1996]; *Labitzke and van Loon* [1996]; *McCormack and Hood* [1996]; *van Loon and Labitzke* [1998]; *Haigh* [2002]; *Labitzke et al.* [2002]; *Gleisner and Thejll* [2003]) and modeling (*Wetherald and Manabe* [1975]; *Baldwin and Dunkerton* [1989]; *Hamilton* [1990]; *Kodera* [1993]; *Rind and Overpeck* [1993]; *Balachandran and Rind* [1995]; *Naito and Hirota* [1997]; *Haigh* [1999]; *Shindell* [1999]; *Soukharev* [1999]; *Tett et al.* [1999]; *Salby and Callaghan* [2000]; *Soukharev and Hood* [2001]; *Kuroda and Kodera* [2002]) studies point to the existence of a ten-to-twelve year oscillation associated with changes in the solar radiation. The statistical significance, amount of influence and spatial distribution of prior solar signals observed in the atmosphere are a point of contention because the atmospheric signals are small in amplitude and vary slowly over a relatively long period of time, making the signal difficult to accurately detect. In particular, it is not always clear how to determine the degrees of freedom for the calculation of significance. Previously (*Coughlin and Tung* [2003]), we pointed out that the interval between independent points in our analysis should be about five years for the purpose of determining the number of degrees of freedom for the solar cycle signal. Given the amplitudes of the detected signals, 45 years of data produces sufficient degrees of freedom to establish statistical significance. However, if the data record is shorter or sorted with respect to other atmospheric phenomena, the correlations would have to be higher in order to prove statistical significance. Since volcanic aerosols can warm or cool the atmosphere, it is also a concern that volcanic eruptions can contaminate the solar cycle signal (*Graf et al.* [1993]; *Haigh* [1999]; *Lee and Smith* [2003]). Of particular concern are the eruptions of El Chichon in 1982 and Pinatubo in 1991 during the previous two solar maxima. In the troposphere, volcanic effects cool the atmosphere (*Robock and Mao* [1995]). Despite the fact that these two major eruptions have occurred during solar max conditions, our results still show that the atmosphere is warmer during times of maximum solar radiation.

Tropospheric temperatures have previously been compared to solar variability in a number of ways. *Crowley and Kim* [1996] used the length of the solar cycles as well as solar activity to show that the annual mean temperatures in the Northern Hemisphere were correlated to solar variability. Labitzke used zonally averaged annual temperatures to show that there is a positive correlation with the 10.7 cm solar flux over all latitudes (*Labitzke et al.* [2002]). *van Loon and Shea* [1999, 2000] used three-year running seasonal means and showed that although the temperature is positively correlated with the solar flux, its effect seems to change with the seasons and the latitudes considered. The spatial structure of the correlations, however, are sensitive to the averaging period. With increased analysis it becomes obvious that it is not just seasonality and spatial distributions of the solar signal itself but mainly contamination of this small signal by other large signals in the atmosphere that causes difficulty in analyzing and substantiating the solar signal. *Gleisner and Thejll* [2003] used a multiple regression on annual mean temperatures to disentangle the atmospheric signals. Their multiple regression includes not only the solar cycle, but also ENSO, a trend and volcanic signals. *Haigh* [2002] includes these as well as other signals in her multiple regressions, like the quasi-biennial oscillation of the equatorial winds, and she recovers a different structure of solar influence. Since the solar cycle response is dependent on the choice of other signals used in multiple regression analysis, it is important to find a more objective way to disentangle the atmospheric signals. Therefore we think the determination of the spatial and temporal structures of the atmospheric response to the solar cycle involves more than correlating filtered atmospheric data with a solar cycle index. It should involve first establishing the structure of the atmospheric modes using objective means without reference to the solar cycle. Then we can ask whether an atmospheric mode is correlated with the solar cycle. So, now we are faced with the issue of not just finding a signal which has a decadal period but finding an intrinsically robust signal which is not only correlated with the solar flux but is also a statistically viable atmospheric signal itself.

2. Procedure

Using EMD, we are able to take into account other atmospheric signals without having to guess what they are before the analysis. This method separates each time series into its intrinsic oscillations without linear constraints. In this way, the major modes are accounted for and each atmospheric signal is less contaminated by the others. Our analysis also allows us to describe the statistical confidence of our results. We use monthly mean geopotential heights and temperatures (*Kalnay and Coauthors* [1996]) from 1000 hPa to 10 hPa, and from January, 1958 to December, 2003. At each height the total temperature and geopotential height is subdivided into area-weighted overlapping latitudinal strips of 20°, with 10° strips near the equator. The time series of each of these strips is decomposed into locally orthogonal modes using the Empirical Mode Decomposition (EMD) method (*Huang* [1998]). As an example, figures 1 and 2 shows the decomposition of a strip in the geopotential height decomposition and a strip in the temperature decomposition. These are temporal modes of the total geopotential height at 700 hPa averaged from 10°N to 30°N and of the total temperature at 600 hPa averaged from 70°N to 90°N. The results for all 17 levels of the NCEP/NCAR reanalysis show similar decompositions consisting of only five modes, each with a variable amplitude and period, and a trend. Figure 3 shows the decomposition of the average geopotential height in the Northern Hemisphere (from 20°N to 90°N) at 500 hPa. It too contains these same five modes and a trend. The fact that the decompositions are so similar indicates the robustness of these signals. The modes, defined by the EMD method, are called Intrinsic Mode Functions (IMFs). The first IMF is the annual cycle, with an average period of 12 months. The second mode has an average period of 28 months and is associated with the QBO phenomenon in the stratosphere. The third mode is positively correlated with the Multivariate ENSO index in the tropics, and anti-correlated near the surface between 40 °N and 60 °N. The fourth mode has an average period of 11 years. It is highly correlated with the 10.7 cm solar flux. In the first two examples (figures 1 and 2), the correlation coefficient is 0.72 and the change in amplitude between solar maxima and solar minima is about 5 meters at 700 hPa and 0.6°C at 600 hPa. We refrain from commenting on the fifth mode found since the data record contains only two periods of this oscillation. The trend here indicates warming in the troposphere in recent decades. A similar result at 30 hPa, in the lower stratosphere has been shown in *Coughlin and Tung* [2003], except that the secular trend in the stratosphere indicates cooling. These trends are consistent with the anticipated effect of increasing greenhouse gases.

To determine the statistical significance of these "intrinsic" modes we compare the power in each mode to the power in multiple decompositions of red noise spectra using a Monte-Carlo type method. Five hundred time series are randomly generated with the same auto-correlation as each real time series. Details of this technique are described in *Coughlin and Tung* [2003]. The noise spectrum for the data in figure 1 is shown in figure 4 with the average power of the atmospheric modes 2, 3 and 4 marked with stars. Since the power in each of the atmospheric modes is well above the noise level, this figure indicates that they contain significant signals. Similar results are found at the other tropospheric heights and latitudes, indicating that these IMFs are statistically significant signals. To demonstrate that the 11-year mode is not dependent on the previous modes in the decomposition, or the result of period-doubling, we remove a Fourier representation of the QBO signal from the data and then reapply the EMD. The 11-year signal remains, indicating that it is robust.

Once the modes are shown to be robust and significant, correlations can be calculated between the modes and related phenomena to determine their physical significance. Correlations between the 11-year temperature mode and the 10.7 cm solar flux are calculated for the decomposition of each latitudinal strip from 1000 hPa to 150 hPa and the correlation values are shown in figures 6. Figure 5 shows the correlations between the solar flux and the fourth mode of geopotential height.

3. Results

The solar flux is positively correlated with the fourth modes in temperature and geopotential height almost everywhere, with the exception of two decompositions at 600 hPa in the south polar temperature region and for one decomposition at the midlatitude surface (see figures 5 and 6). Low correlations are found in the South Hemisphere poleward of 40°S, where the data quality is known to be poor. There is also a narrow strip at 50°N with low temperature correlations. These correlations, however, do not indicate a reversal of the relationship or a change in amplitude. A closer inspection of the time series in these areas of low correlations reveals that the signal is not regular enough to produce a statistical connection. Only with more time can the relationship between the signal and the solar flux be established in these areas. However, in many places the correlations are large enough to demonstrate a high statistical relationship (correlations above 0.58 are statistically significant at the 95% level) and the overwhelming picture is that of a positive correlation between this mode and the solar flux (even in those regions with lower correlations) throughout the troposphere.

Previously, we showed that the 11-year solar cycle is statistically correlated with dynamical variables in the stratosphere (*Remsberg et al.* [2002]; *Coughlin and Tung* [2003]). Here we demonstrate (in figures 5, 6 and 7) that the fourth atmospheric mode is correlated with the 11-year solar cycle at all 17 levels (from 1000 hPa up to 10 hPa). Figure 7 shows the vertical structure of the fourth mode compactly. Not only is the mode vertically coherent throughout the stratosphere and troposphere but also it is synchronous with the solar flux shown in the horizontal strip at the top of figure 7. In this figure, the amplitudes of the fourth mode of the average Northern Hemisphere geopotential heights are scaled by the square root of the pressure (or analogously the density). The signals increase with height from about five meters in the troposphere to more than 70 meters in the stratosphere. On a finer scale, the amplitude and timing of the fourth mode is not so consistent or robust. However, when averaged over the extratropics, the results are robust. This is consistent with the composite differences, between solar maxima and minima, of the annual mean geopotential height found by *Labitzke et al.* [2002]. They found peak-to-peak differences of five meters at the surface increasing up to 100 meters at 10 hPa. Compared to their results, however, our correlation coefficients in the troposphere are higher (see figure 6), statistically significant and the timing and amplitudes remain consistent and barotropic throughout the lower atmosphere.

4. Conclusion

Through this EMD representation, we are able to see the natural variations in the atmosphere. This method is both compact and complete. We are able to completely describe the changes in the lower atmosphere with only five modes and a trend. Each of these modes are empirically determined and not artificially constrained to have fixed amplitudes or frequencies. The fourth mode is shown to be robustly present and coherent throughout the troposphere. We further show that this mode is positively correlated with the solar cycle from 10 hPa down to the surface of the earth over most of the globe. The statistical significance of this signal is firmly established. We conclude that the atmosphere warms during the solar maximum almost everywhere over the globe. It should be pointed out that changes in the correlation values with latitude do not imply similar amplitude changes with latitude. However, the fact that the correlation with the solar flux is positive everywhere over the globe does imply that, on average, the temperatures increase during solar maxima at all latitudes. This makes the phenomenon difficult to explain with dynamical mechanisms involving overturning meridional circulations in the troposphere.

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References

Balachandran, N., and D. Rind, Modeling the effects of uv variability and the qbo on the troposphere-stratosphere system. part i: The middle atmosphere, *J. Clim.*, *8*, 2058–2079, 1995.

Baldwin, M. P., and T. J. Dunkerton, Observations and statistical simulations of a proposed solar cycle/ qbo/ weather relationship, *Geophys. Res. Lett.*, *16*, 863–866, 1989.

Coughlin, K. T., and K. K. Tung, 11-year solar cycle in the stratosphere extracted by the empirical mode decomposition method, *Advances in Space Research*, in press., 2003.

Crowley, T., and K.-Y. Kim, Comparison of proxy records of climate change and solar forcing, *Geophys. Res. Lett.*, 1996.

Frederick, J., Chemical response of the middle atmosphere to changes in the ultraviolet solar flux, *Planet. Space Sci.*, *25*, 1–4, 1977.

Gleisner, H., and P. Thejll, Patterns of tropospheric response to solar variability, *Geophys. Res. Lett.*, 2003.

Graf, H.-F., I. Kirchner, A. Robock, and I. Schult, Pinatubo eruption winter climate effects: model versus observations, *Clim. Dyn.*, *9*, 81–93, 1993.

Haigh, J., A gcm study of climate change in response to the 11-year solar cycle, *Quarterly Journal of the Royal Meteorological Society*, 1999.

Haigh, J., The effects of solar variability on the earth's climate, *PHILOS T ROY SOC A*, *361*(1802), 95–111, 2002.

Haigh, J. D., The effects of solar variability on the earth's climate, *Phil. Trans.*, to be submitted., 2003.

Hamilton, K., A look at the recently proposed solar-qbo-weather relationship, *J. Climate*, *3*, 497–503, 1990.

Hershel, W., Observations tending to investigate the nature of the sun, in order to find the causes or symptoms of its variable emission of light and heat; with remarks on the use that may possibly be drawn from solar observations, *Phil. Trans. Roy. Soc. London*, *91*, 265–318, 1801.

Huang, N. E., et al., The empirical mode decomposition and the hilbert spectrum for nonlinear and non-stationary time series analysis, *Proc. R. Soc. Lond. A*, *454*, 903–995, 1998.

Kalnay, E., and Coauthors, The ncep/ncar reanalysis 40-year project, *Bull. Amer. Meteor. Soc.*, *77*, 437 – 471, 1996.

Kodera, K., Quasi-decadal modulation of the influence of the equatorial quasi-biennial oscillation on the north polar stratospheric temperatures, *J. Geophys. Res.*, 1993.

Kuroda, Y., and K. Kodera, Effect of solar activity on the polar-night jet oscillation in the northern and southern hemisphere winter, *J. Meteor. Soc. Japan*, *80*(4B), 973–984, 2002.

Labitzke, K., On the interannual variability of the middle stratosphere during northern winter, *J. Met. Soc. Japan*, *60*, 124–139, 1982.

Labitzke, K., and H. van Loon, Astep working group 5 report, *Tech. rep.*, 1996.

Labitzke, K., J. Austin, N. Butchart, J. Knight, M. Takahashi, M. Nakamoto, T. Nagashima, J. Haigh, and V. Williams, The global signal of the 11-year solar cycle in the stratosphere: observations and models, *J. Atmos. Solar-Terrest. Phys.*, *64*, 203–210, 2002.

Labitzke et al., K., The global signal of the 11-year solar cycle in the stratosphere: observations and models, *J. Atmos. Sol-Terr. Phys.*, *64*, 203–210, 2002.

Lean, J., and et al., Detection and parameterization of variations in solar mid- and near-ultraviolet radiation (200-400 nm), *J. Geophys. Res.*, *102*, 29,939–29,956, 1997.

Lee, H., and A. Smith, Simulation of the combined effects of solar cycle, quasi-biennial oscillation, and volcanic forcing on stratospheric ozone changes in recent decades, *J. Geophys. Res.*, *108*(D2), 4049, 2003.

McCormack, J., and L. Hood, Apparent solar cycle variations of upper stratospheric ozone and temperature: Latitude and seasonal dependences, *J. Geophys. Res. - Atmos.*, 1996.

Naito, Y., and I. Hirota, Interannual variability of the northern winter stratospheric circulation related to the qbo and the solar cycle, *J. Meteor. Soc. Japan*, *75*(4), 925–937, 1997.

Remsberg, E. E., P. P. Bhatt, and L. E. Deaver, Seasonal and longer-term variations in middle-atmosphere temperature from haloe and uars, *J. Geophys. Res. Atmos.*, *107*(D19), in press, 2002.

Rind, D., and J. Overpeck, Hypothesized causes of decade-to-century-scale climate variability; climte model results, *Quat. Sci. Rev.*, 1993.

Robock, A., and J. Mao, The volcanic signal in surface temperature observations, *J. Climate*, *8*, 1086–1103, 1995.

Salby, M., and P. Callaghan, Connection between the solar cycle and the qbo: The missing link, *J. Clim.*, *13*, 2652–2662, 2000.

Shindell, D., et al., Solar cycle variability, ozone and the stratospheric circulation over northern europe, *Science*, *284*, 305–308, 1999.

Soukharev, B. E., On the solar/qbo effect on the interannual variability of total ozone and the stratospheric circulation over northern europe, *J. Atmos. Sol. Terr. Phys.*, *61*, 1093–1109, 1999.

Soukharev, B. E., and L. L. Hood, Possible solar modulation of the equatorial quasi-biennial oscillation: Additional statistical evidence, *J. Geophys. Res.*, *106*(D14), 14,855–14,868, 2001.

Tett, S., P. Stott, M. Allen, W. Ingram, and J. Mitchell, Causes of twentieth century temperature change near the earth's surface, *Nature*, *399*, 369–372, 1999.

van Loon, H., and K. Labitzke, The global range of the stratospheric decadal wave. part i: its association with the sunspot cycle in summer and in the annual mean, and with the troposphere., *J. Climate*, *11*, 1529–1537, 1998.

van Loon, H., and D. Shea, A probable signal of the 11-year solar cycle in the troposphere of the northern hemisphere, *Geophys. Res. Lett.*, *26*(18), 2893–2896, 1999.

van Loon, H., and D. Shea, The global 11-year solar signal in july-august, *Geophys. Res. Lett.*, *27*(18), 2965–2968, 2000.

Wetherald, R., and S. Manabe, The effects of changing the solar constant of a general circulation model, *J. Atmos. Sci.*, *32*, 2044–2059, 1975.

Willson, R. C., and H. S. Hudson, Solar luminosity variations in solar cycle-21, *Nature*, *332*(6167), 810–812, 1988.

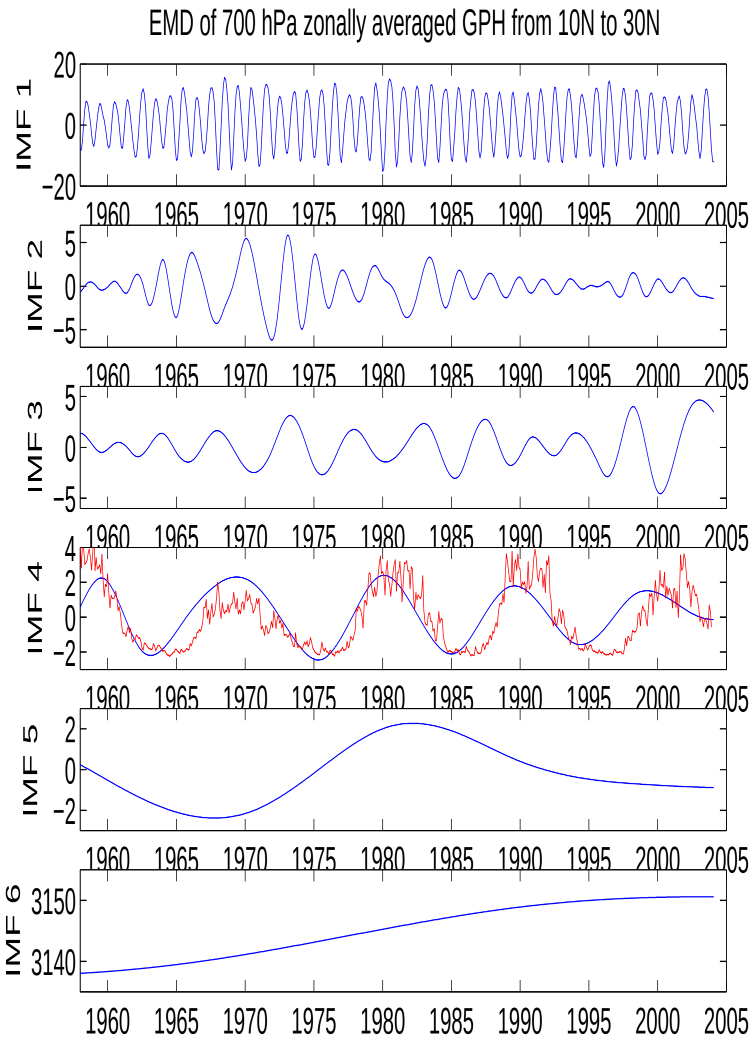

Figure 1. NCEP/NCAR reanalysis geopotential height for the period of January 1958 to December 2003 at 700 hPa from 10°N to 30°N are zonally and spatially averaged. The total height (in meters) is decomposed into five modes and a trend. The correlation between the fourth mode and the 10.7 cm solar flux is 0.72.

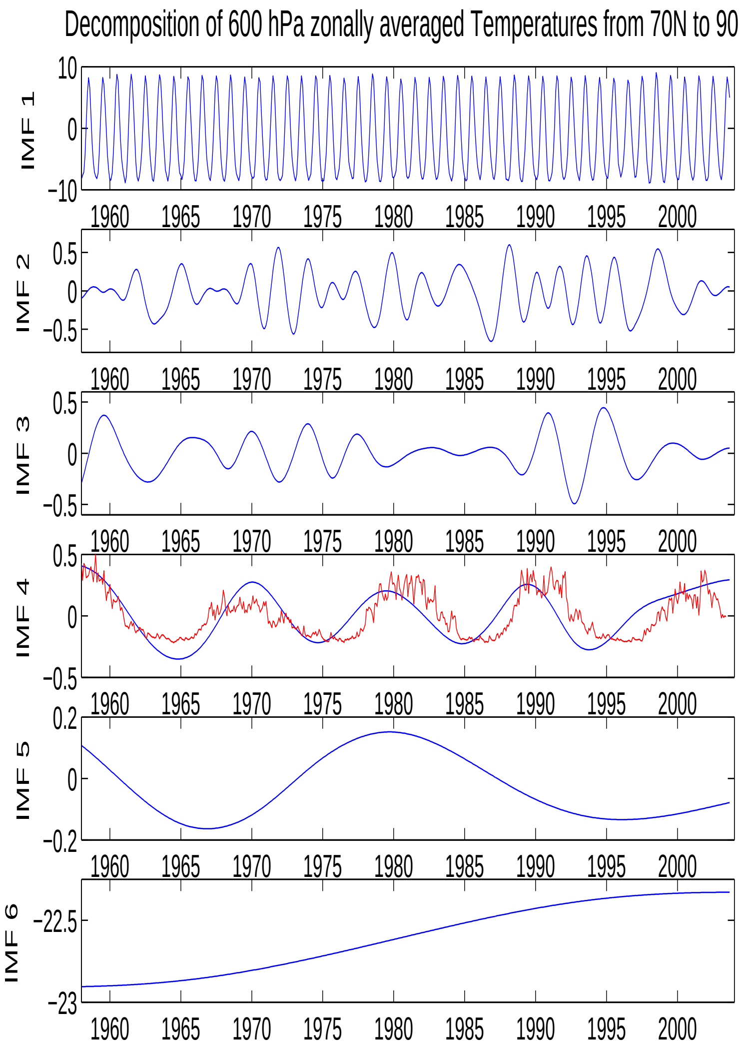

Figure 2. NCEP/NCAR reanalysis temperatures at 600 hPa from 70°N to 90°N are zonally and spatially averaged. The total temperature is decomposed into five modes and a trend. The correlation between the fourth mode and the 10.7 cm solar flux is 0.72.

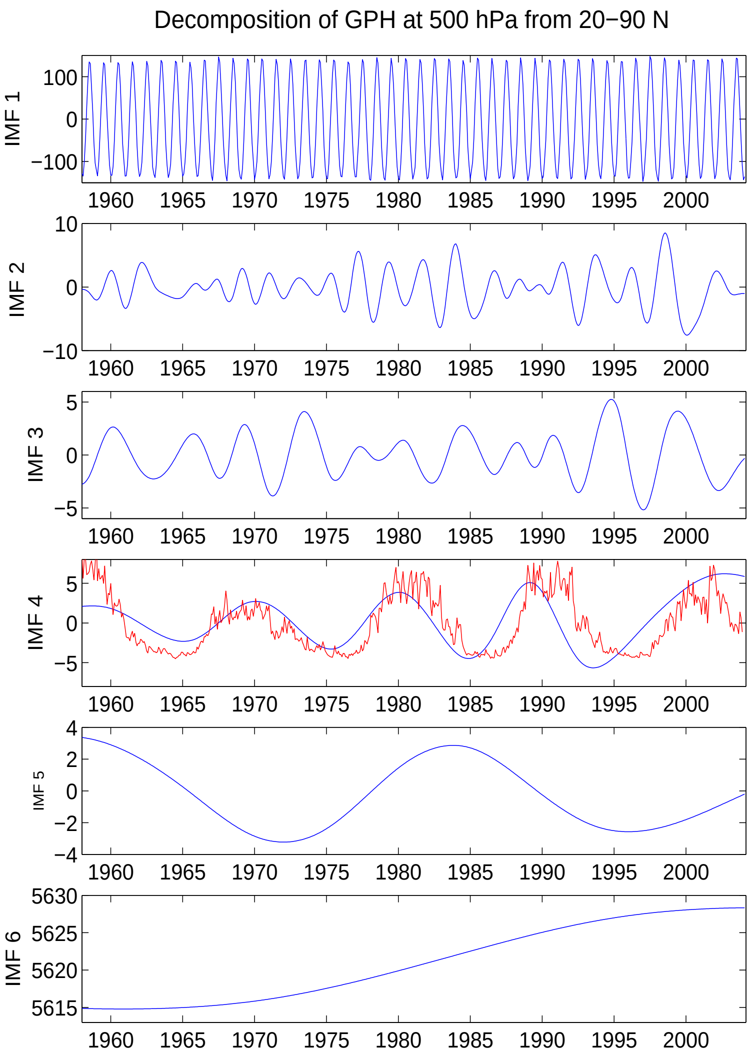

Figure 3. NCEP/NCAR reanalysis geopotential height for the period of January 1958 to February 2004 at 500 hPa from 20°N to 90°N are zonally and spatially averaged. The total height (in meters) is decomposed into five modes and a trend. The correlation between the fourth mode and the solar flux is 0.62.

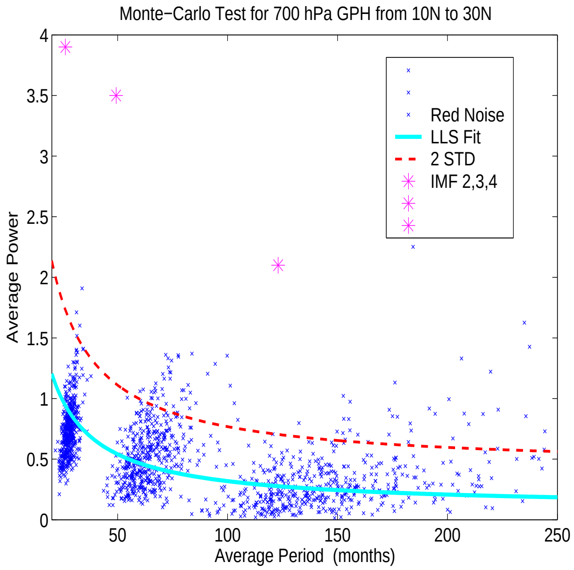

Figure 4. A Monte-Carlo type test of significance. 700 hPa climatology is added to 500 autocorrelated time series to generate a Monte-Carlo test. The red noise is calibrated using the difference between the first mode and the climatology (*Coughlin and Tung* [2003]) and the autocorrelation of the noise is the same as the autocorrelation of the 700 hPa geopotential height anomalies, 0.54. These time series are decomposed using the EMD method and the average power in modes 2, 3 and 4 of each of the decompositions is plotted in this figure. The solid blue line represents the linear least squares fit of these points and the red line is two standard deviations from the best-fit line. The average power of IMFs 2, 3 and 4 of the 700 hPa geopotential heights are plotted as stars and clearly lie above the random noise level.

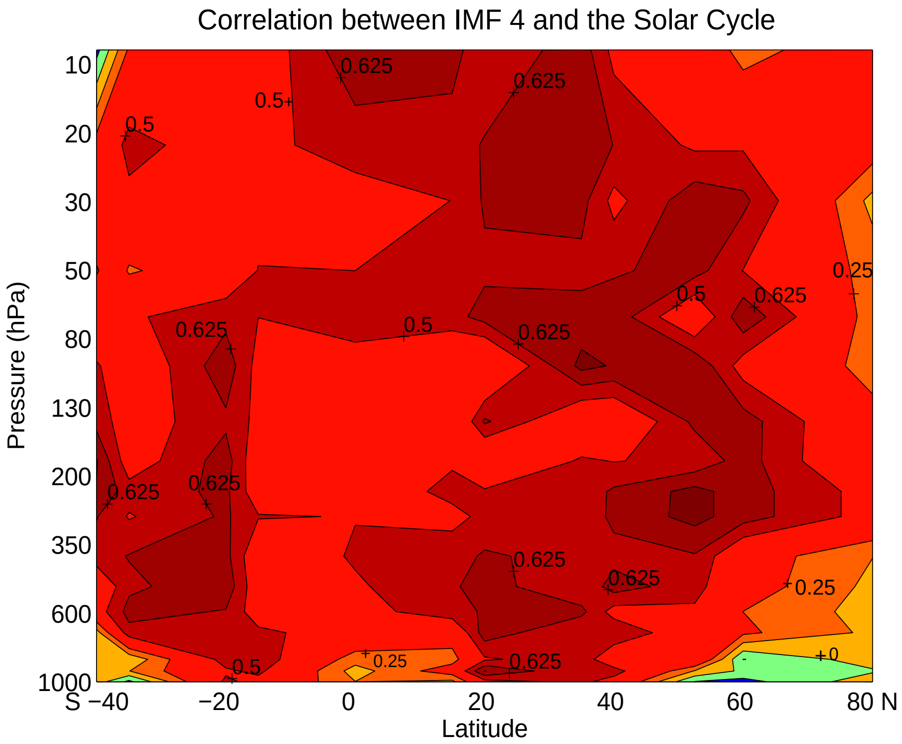

Figure 5. Correlation coefficients between the fourth mode of geopotential height and the Solar Flux. The coefficients are plotted at the pressure altitude and mean latitude of each decomposition.

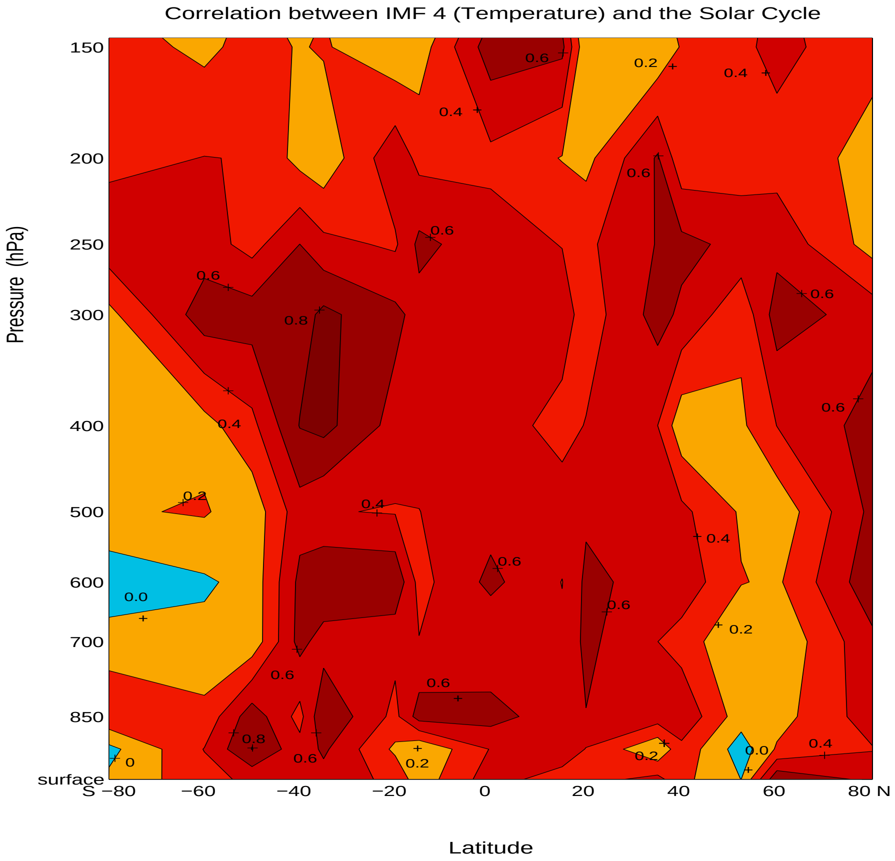

Figure 6. A map of correlation coefficients between the fourth mode of latitudinal strips of temperature and the Solar Flux. The coefficients are plotted at the pressure altitude and mean latitude of each decomposition. Contours indicate correlations chages of 0.2.

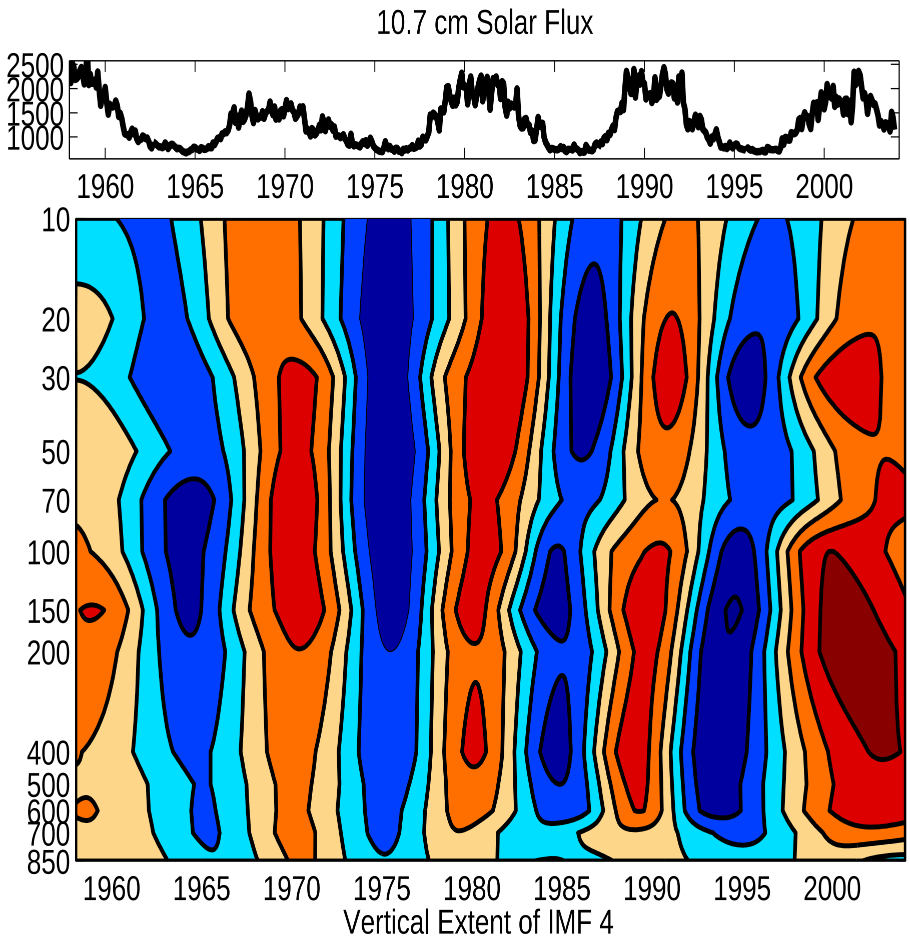

Figure 7. The fourth IMF of the spatially average Northern Hemisphere from 10 mb down to 850 mb. The colors indicated the strength of the signal over time where red values are positive and blue values are negative. The thin bar above the the contour plot shows the solar flux over time. Notice that the sunspots correlate well with the fourth IMF throughout the troposphere and lower stratosphere.