A mechanism for sun-climate connection

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Received 13 August 2005; revised 7 October 2005; accepted 2 November 2005; published 10 December 2005.

[1] Mechanisms by which small changes in the sun's energy output during the solar cycle can cause changes in weather and climate have been a puzzle and the subject of intense research in recent decades. Here we report that differences in surface circulation conditions during solar maximum and minimum periods are caused by differences in the frequencies with which circulation perturbations in the stratosphere reach the surface. A much greater fraction of stratospheric perturbations penetrate to the surface during solar maximum conditions than during minimum conditions. This difference is more striking when the zonal wind direction in the tropics is from the west: no stratospheric signals reach the surface when equatorial 50 hPa winds are from the west under solar minimum conditions, and over 50 percent reach the surface under solar maximum conditions. It has been previously shown that stratospheric circulation perturbations reaching the surface change weather patterns by imposing atmospheric pressure anomalies characteristic of the Arctic oscillation.

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

1. Introduction

[2] It has been known empirically for more than a hundred years that changes in the solar cycle apparently produce corresponding changes in weather and climate on the earth's surface [*Lamb*, 1972; *Burroughs*, 1992]. The link between the solar cycle and climate has been a puzzle because the solar energy output changes by only about 0.1 percent during a typical solar cycle [*Lean and Rind*, 2001], a change that is too small to produce significant changes in surface conditions based on energy considerations. A possible clue is that changes in the output of solar ultraviolet (UV) radiation are significantly greater, up to 0.4% during a typical solar cycle [*Lean*, 2000]. Furthermore, the percent change in the UV radiation is greater at shorter wavelengths. Since the solar UV radiation is the main agent for producing ozone in the stratosphere we expect significant changes in ozone with the solar cycle. Such changes have been verified in observations [*Hood*, 1997] and also in modeling studies [*Lee and Smith*, 2003]. Systematic changes in the distribution of ozone result in changes in the temperature and pressure distributions in the stratosphere. It is now recognized that we expect different thermal and dynamical signatures in the stratosphere between solar maximum and minimum conditions [*Labitzke*, 2001; *Hood*, 2004] and these are modulated by the quasi-biennial oscillation of the zonal equatorial winds [*Labitzke*, 2003]. Several studies have demonstrated that solar cycle induced perturbations are large in the upper stratosphere and gradually descend to the lower stratosphere [*Kodera and Kuroda*, 2002; *Gray et al.*, 2004]. *Baldwin and Dunkerton* [1999, 2001] used the northern annular modes to demonstrate that some perturbations in the stratosphere can reach the surface. The northern annular mode (NAM) is the first empirical orthogonal function of geopotential height at each level and thus represents a principal mode of stratospheric circulation. These authors showed that positive and negative anomalies in the stratospheric NAM are generated often, and on occasions propagate to the surface maintaining the same sign. In the stratosphere annular mode values are a measure of the strength of the polar vortex, while the near surface annular mode is called the Arctic Oscillation.

[3] We have used the method of Baldwin and Dunkerton to investigate downward propagation in solar maximum and minimum conditions. Results show a clear difference: Many more stratospheric perturbations reach the surface in solar maximum conditions than in minimum conditions. Furthermore, no stratospheric signals reach the surface in minimum conditions when the quasi-biennial wind direction in the tropical lower stratosphere is from the west.

2. Method

[4] We use monthly NCEP geopotential height data for 1948–2004 for this analysis. Data for the extended winter from October to April was used to define the annular mode independently at each of the 17 pressure altitudes from the surface to 10 mb. At each pressure altitude the annular mode is the first empirical orthogonal function (EOF) of the geopotential height anomalies from 20°N to 90°N. Monthly values of the annular mode, spanning the 57-year data record, are calculated at each pressure level by projecting monthly geopotential height anomalies onto the leading EOF patterns. The method of calculation is as described by *Baldwin and Dunkerton* [2001].

3. Results

[5] We measure solar activity in each winter by the number of sunspots observed during the winter. Figure 1 shows the northern annular mode in the stratosphere-troposphere system for the five winters during 1948–2004 in which solar activity was the maximum. The panels in Figure 1 are arranged such that the winter of the maximum activity is at the top and the winter of fifth strongest activity is at the bottom. Only values greater than one standard deviation are shown at each level. Positive values of the NAM are shown in blue and negative values in red. The W and E on top of each panel give the direction of the QBO wind for each month at 50 mb. Thus we see in the top panel

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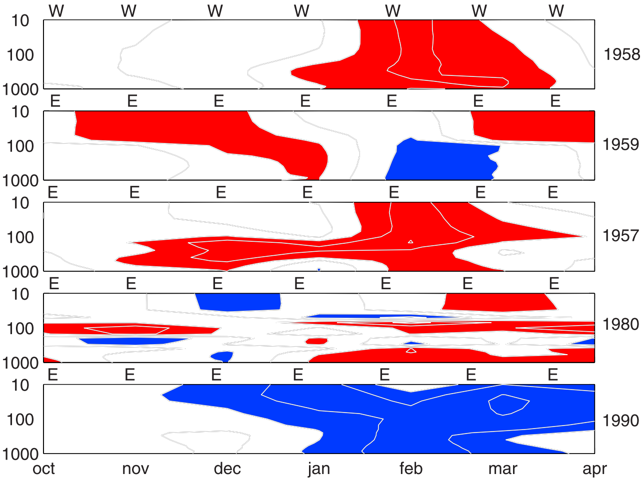

Figure 1. Time-height development of the northern annular mode during the five winters which had the strongest solar activity during 1948–2004. Values greater than one standard deviation are shown in color, and contour interval is one standard deviation. Equatorial zonal wind direction at 50 mb is shown for each month above each panel. Red represents negative values (a warm, disturbed polar vortex) and blue positive values (strong and cold polar vortex).

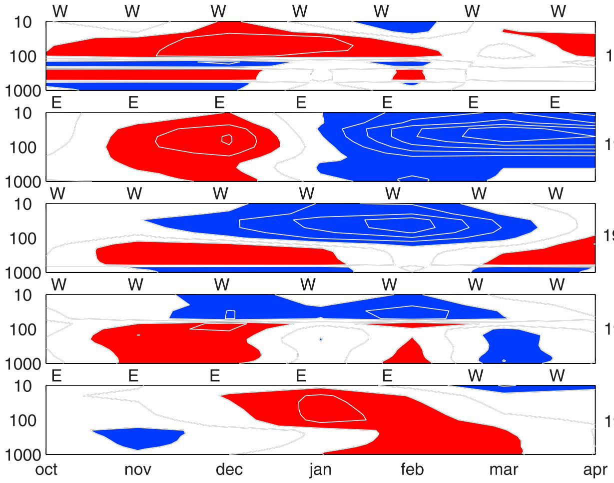

Figure 2. Time-height development of the northern annular mode during the five winters which had the weakest solar activity during 1948–2004. Values greater than one standard deviation are shown in color, and contour interval is one standard deviation. Equatorial zonal wind direction at 50 mb is shown for each month above each panel. Red represents negative values (a warm, disturbed polar vortex) and blue positive values (strong and cold polar vortex).

for the winter of 1957–58 that a negative signal develops at the upper level during February and March and reaches the surface. Figure 1 shows that during the five strongest solar maximum winters perturbations emerging in the stratosphere reach the surface in four of the winters. 1979–1980 is the exception because the signal breaks up and does not reach the surface. Of the four signals that reach the surface three are negative events and only one (1989–1990) is a positive event. During negative events the polar vortex is weak and warm, while it is strong and cold in positive events [*Baldwin and Dunkerton*, 2001].

[6] Figure 2 shows the northern annular mode during the five winters in which solar activity was the lowest during 1948–2004. The panel at the top for 1953–1954 was the winter with the weakest solar activity. Figure 2 shows that signals emerging from the stratosphere do not reach the surface in four of the winters, the exception being 1996–1997 when two signals emerge and propagate to the surface. We note that the wind direction is from the east during this winter.

[7] We expanded our database by considering the 15 winters with the highest sunspot numbers as representatives of maximum solar activity, and the 15 winters with the lowest sunspot numbers as representing solar minimum conditions. We again find that a significantly greater fraction of the stratospheric events reach the surface under solar maximum conditions than in minimum conditions. The comparison is made in Table 1. Results for two threshold values for defining the perturbations are given: 1.0 and 1.5 times the standard deviation of the northern annular mode. The second line in Table 1 lists the number of signals that occurred at 10mb level. Thus, for example, the amplitude of the annular mode exceeded one standard deviation 35 times during solar maximum conditions. The third row gives the number of times that the signal reached the surface. The fourth row gives the ratio of the signal detection at the surface to its occurrence at the 10 mb level. We notice a significant difference between solar maximum and minimum conditions. A signal generated in the stratosphere is much more likely to reach the surface under solar maximum conditions than in the minimum conditions. We have tested the statistical significance of these results in two different ways. Comparing the number of signals reaching 1000 mb (line 3, Table 1) using a t-test, we can reject the null hypothesis that the numbers for maximum and minimum conditions are the same at >99 percent confidence level. If we compare the ratios in line 4 using the standard normal distribution we can again reject the null hypothesis that the ratios are the same for solar maximum and minimum conditions at >99 percent confidence level.

[8] The last two rows in Table 1 give the ratio classified according to the prevailing zonal wind direction in the tropical lower stratosphere, and we notice that no signals reach the surface in the solar minimum conditions when the wind direction is from the west, while over 50% of the signals reach the surface under solar maximum conditions.

[9] The results in Table 1 are based on considering 15 winters of maximum sunspot numbers and 15 winters with minimum sunspot numbers during 1948–2004. Con-

Table 1. Statistics of perturbations in the stratosphere at 10 mb that reach the surface under Solar Maximum and Minimum conditions during 1948–2004

	Maxima		Minima	
Signal strength	1.0σ	1.5σ	1.0σ	1.5σ
10 mb	35	22	39	26
1000 mb	16	11	5	3
Ratio	0.46	0.50	0.13	0.12
ratio for west QBO	0.53	0.64	0.0	0.0
ratio for east QBO	0.39	0.36	0.31	0.27

sidering 16, 17, 18 or 19 winters of maximum and minimum sunspot numbers did not produce significant changes in the ratios in the last three rows of Table 1. Replacing the sunspot numbers by monthly solar irradiance (290–295 nm) presented by *Lean* [2000] to identify winters of high and low solar activity also did not change the ratios significantly.

4. Discussion

[10] The results obtained above may be understood in the context of findings by *Gray et al.* [2004] who studied the influence of the solar cycle and the quasi-biennial oscillation on the winter polar vortex in ECMWF Reanalysis data for 1957–2001. They examined composites of averaged zonal winds in the stratosphere for four categories: solar minimum conditions/easterly winds, solar minimum conditions/westerly winds, solar maximum conditions/easterly winds and solar maximum conditions/westerly winds. They find that the polar vortex in the stratosphere is more disturbed in years in which the wind is from the East than in years when it is from the West, in conformation with the Holton-Tan effect. However, they find an important difference in West years between solar minimum and maximum conditions. In the solar minimum/westerly winds composite the vortex is anomalously strong throughout the whole winter and an easterly anomaly in the winds does not appear until April. In the solar maximum/westerly winds composite, on the other hand, an easterly anomaly develops in February and moves poleward and downward by March indicating midwinter warming events in solar maximum/westerly years. Their results are consistent with previous work by Labitzke and coworkers who noted as early as 1982 that major midwinter stratospheric warmings do not occur during the QBO westerly phase except near solar maxima [*Labitzke*, 1982]. Together with our results, they suggest that the stable vortex in winters when solar activity is low and winds are from the west present conditions in which propagation of stratospheric signals to the surface is unlikely.

5. Conclusion

[11] This paper presents quantitative evidence for an increased rate of penetration of northern hemisphere winter circulation anomalies from the stratosphere to the troposphere under solar maximum conditions as opposed to solar minimum conditions. The difference occurs primarily during the QBO westerly phase. Previous work has shown that the occurrence of major midwinter stratospheric warmings also depends on both the QBO phase and the solar cycle. The leading candidate mechanism for effecting this dependence is solar ultraviolet variations, which influence ozone concentrations, radiative heating, and zonal circulation in the tropical upper stratosphere. In the QBO westerly phase, major midwinter warmings occur at an increased rate under solar maximum conditions as opposed to solar minimum conditions. Our results show that the circulation anomalies caused by these stratospheric warmings propagate down to the surface much more frequently under solar maximum conditions than under solar minimum conditions. This suggests that solar perturbation of the stratosphere by ultraviolet radiation variations followed by downward propagation of resulting circulation anomalies to the surface is the principal sun-climate mechanism.

[12] **Acknowledgments.** This work was supported by NASA's Living with a Star program. We thank Marvin Geller and Judith Lean for their comments on the manuscript and B. Naujokat for the equatorial 50 mb wind data. We would also like to acknowledge an anonymous reviewer whose summary of the paper we adapted as the "Conclusion" given above.

References

Baldwin, M. P., and T. J. Dunkerton (1999), Downward propagation of the Arctic oscillation from the stratosphere to the troposphere, *J. Geophys. Res.*, *104*, 30,937–30,946.
Baldwin, M. P., and T. J. Dunkerton (2001), Stratospheric harbingers of anomalous weather regimes, *Science*, *294*, 581–584.
Burroughs, W. J. (1992), *Weather Cycles, Real or Imaginary?*, 203 pp., Cambridge Univ. Press, New York.
Gray, L. J., S. A. Crooks, C. Pascoe, and S. Sparrow (2004), Solar and QBO influences on the timing of stratospheric sudden warmings, *J. Atmos. Sci.*, *61*, 2777–2796.
Hood, L. L. (1997), The solar cycle variation of total ozone: Dynamical forcing in the lower stratosphere, *J. Geophys. Res.*, *102*, 1355–1370.
Hood, L. L. (2004), Effects of solar UV variability on the stratosphere, in *Solar Variability and its Effects on Climate*, *Geophys. Monogr. Ser.*, vol. 141, edited by J. Pap et al., pp. 283–304, AGU, Washington, D. C.
Kodera, K., and Y. Kuroda (2002), Dynamical response to the solar cycle, *J. Geophys. Res.*, *107*(D24), 4749, doi:10.1029/2002JD002224.
Labitzke, K. (1982), On the interannual variability of the middle stratosphere during northern winters, *J. Meteorol. Soc. Jpn.*, *60*, 124–139.
Labitzke, K. (2001), The global signal of the 11-year solar cycle in the stratosphere: Differences between the solar maxima and minima, *Meteorol. Z.*, *10*, 901–908.
Labitzke, K. (2003), The global signal of the 11-year sunspot cycle in the atmosphere: When do we need the QBO?, *Meteorol. Z.*, *12*, 209–216.
Lamb, H. H. (1972), *Climate: Present, Past and Future*, vol. 1, pp. 440–464, Methuen, New York.
Lean, J. (2000), Evolution of the Sun's spectral irradiance since the Maunder Minimum, *Geophys. Res. Lett.*, *27*, 2425–2429.
Lean, J., and D. Rind (2001), Earth's response to a variable sun, *Science*, *292*, 234–236.
Lee, H., and A. K. Smith (2003), 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, doi:10.1029/2001JD001503.

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