A MECHANISM INVOLVING SOLAR ULTRAVIOLET VARIATIONS FOR MODULATING THE INTERANNUAL CLIMATOLOGY OF THE MIDDLE ATMOSPHERE

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ABSTRACT

In years of low solar activity, free traveling wave modes in the upper stratosphere are dominated by atmospheric normal modes such as the 16-day wave. However, within a 4-year interval centered on the 1980-81 solar maximum, cross-spectral analyses of zonal mean satellite temperature data versus the solar UV flux demonstrate significant power near 27 and 13 days, providing indirect evidence that short-term UV variations were capable of exciting traveling planetary-scale waves in the upper stratosphere. Previous theoretical and observational work has indicated that interference between traveling waves and stationary waves forced from below (and the resulting oscillating latitudinal heat transports) plays a likely role in the initiation of stratospheric warmings. We therefore hypothesize that the initiation of a major stratospheric warming in the upper stratosphere and lower mesosphere may depend to some extent on the amplitude of longer-period 27-day traveling waves in the upper stratosphere. This would represent a new mechanism for solar UV effects on stratospheric climatology that may be relevant to the interpretation of some recent long-term correlative results.

INTRODUCTION

Labitzke [1982] originally noted a tendency for the occurrence of major mid-winter warmings in the northern hemisphere to depend on (a) the phase of the equatorial quasi-biennial oscillation (QBO) at 50 mbar and (b) the 11-year solar activity cycle. Labitzke and van Loon [1989] have reported a resulting correlation between January-February average north polar temperature at 30 mbar during QBO west winters (i.e. when 50 mbar equatorial winds are westerly) and the solar 10.7 cm flux. The latter authors also found that QBO west years with major mid-winter warmings have occurred only during periods of relatively high solar activity (F10.7 > 160 units) since the mid-1950's when QBO records were begun. Although Baldwin and Dunkerton [1989] and others have argued that the statistical significance of these correlations may not be as high as calculated by Labitzke and van Loon (1989), the preference of major warming years for times of high 10.7 cm flux during the QBO west phase seems clear from their work. In addition, van Loon and Labitzke (1990) have more recently found a consistent pattern of correlation between 30 mbar temperature (or geopotential height) and the 10.7 cm flux for separate 2-month epochs in their 31-year data set without sorting according to QBO phase.

One aspect of solar activity changes that may influence thermal and dynamical processes in the middle atmosphere is solar ultraviolet variability through its effects on ozone concentration and radiative heating. The solar flux variation near 200 nm is important for producing changes in molecular oxygen photodissociation (hence, ozone production) and is therefore most relevant for the middle atmosphere. According to available satellite measurements [e.g., Rottman, 1988], the solar flux variation at 205 nm (usually chosen as a reference wavelength) consists of a long-term solar cycle variation of order 5 to 7% on which is superposed short-term (mainly 27-day) variations associated with the rotation of active regions on the solar disc. Near solar maximum, the amplitude of the short-term variations exceeds five per cent and is comparable to the solar cycle variation amplitude. Near solar minimum, the amplitude of the short-term variations is typically near one per cent.

Most previous models for effects of solar UV variations on stratospheric dynamics have considered only the solar cycle variation of UV spectral irradiance. In these models, solar cycle changes in ozone (and resulting latitudinal changes in radiative heating) modify the stratospheric zonal wind field. Changes in the zonal wind field then alter the transmissivity of the stratosphere to upwardly propagating planetary waves [Hines, 1974; Springer, 1983]. Numerical studies have indicated that solar cycle UV effects on planetary wave propagation are significant in the upper stratosphere but become negligible below 10 mbar for plausible solar cycle changes in UV flux [Callis et al., 1985]. In this paper, we suggest that the fluctuating component of solar UV variations (occurring mainly on the 27-day time scale) may also have significant perturbing effects on stratospheric dynamics that may be relevant to the long-term statistical results of Labitzke and van Loon. In particular, on the basis of a cross-spectral analysis of zonal mean ozone and temperature measurements versus the solar 205 nm flux near the 1980 solar maximum, it is suggested that short-term solar UV variations may be capable of exciting or modulating traveling planetary-scale waves in the upper stratosphere. These waves may then increase the probability of occurrence of major stratospheric mid-winter warmings at high northern latitudes under solar maximum conditions.

OBSERVATIONAL BACKGROUND

Previous work on the stratospheric photochemical and radiative heating effects of short-term solar UV variations has shown that the ozone response at low latitudes maximizes near 3 mbar (about 40 km altitude) and amounts to about 0.5% for each 1% change in the solar flux at wavelengths near 200 nm [Hood and Cantrell, 1988; Keating et al., 1987; and references therein]. Variations in the solar 205 nm flux are as large as 6-7% on the 27-day time scale near solar maximum so that peak-to-peak ozone mixing ratio changes of as much as 3% near 3 mbar are observed. The corresponding ozone column changes are in all cases much less than 1%. Zonal mean temperature perturbations at low latitudes in the upper stratosphere derived from satellite radiances have been found to be weakly correlated ($R \simeq 0.3$) with solar ultraviolet variations (Keating et al., 1987; Hood and Cantrell, 1988). The temperature response maximizes near the stratopause and amounts to about 0.06% ($\sim$ 0.16 K) for a 1% change in the solar flux near 200 nm. Actual temperature changes are as large as 1 K on the solar rotation time scale. The mean temperature phase lags are large, ranging from about 6 days near 1 mbar to about 13 days near 10 mbar. Hood and Douglass [1988] have shown that the observationally derived coupled ozone and temperature responses to short-term solar ultraviolet variations are consistent with the odd oxygen continuity equation using currently accepted photochemistry.

Earlier comparisons of theoretical models with observationally derived ozone and temperature responses to solar ultraviolet variations have suggested that a dynamical component of the stratospheric response may be necessary [Hood, 1987; Brasseur et al., 1987]. In particular, the measured temperature phase lags (e.g., 6-9 days at 2 mbar) are larger by a factor of about 2 than expected if radiative heating changes alone are responsible. Ebel et al [1988] have applied a global three-dimensional numerical circulation model to show theoretically that dynamical effects in the middle and lower stratosphere may be produced by weak perturbations at stratopause heights.

Further evidence of the existence of a dynamical component of the upper stratospheric response is obtained by considering the latitude dependence of the ozone and temperature fluctuations and their relation to solar ultraviolet variations. Figure 1 shows an example of 1.5 mbar ozone and temperature deviations for a 7-month interval compared to the Nimbus 7 solar backscattered ultraviolet (SBUV) solar 205 nm flux. This interval was chosen because it was characterized by relatively strong and regular 27-day solar ultraviolet variations. All time series were detrended to remove periods greater than about 35 days. At low latitudes, the behavior is generally consistent with the ozone and temperature response measurements summarized above. For instance, between 20°S and 20°N, ozone maxima tend to occur approximately in phase with solar ultraviolet maxima. Temperature variations (dashed lines) also show an approximate 27-day periodicity but occur at substantial lags following the UV flux maxima, as expected from the temperature response measurements. However, at approximately 30° to 40° latitude in the winter hemisphere, both the ozone and temperature variations begin to change phase and, by 60°N, are nearly 180° out of phase with corresponding fluctuations at low latitudes.

As shown, for example, by Chandra (1985; 1986), out-of-phase temperature oscillations between low and higher latitudes are a common characteristic of the winter hemisphere upper stratosphere even in the absence of solar ultraviolet variations. They are also a common property of temperature changes in the middle and lower stratosphere, including those associated with mid-winter warmings (Fritz and Soules, 1970; van Loon et al., 1975). These oscillations are typically driven by the interaction of stationary upward propagating planetary waves with free traveling Rossby wave modes under the influence of tropospheric forcing (see below and the reviews by Madden [1979] and by Salby [1984a,b]). However, the phase relationships between ozone, temperature, and solar ultraviolet variations evident in Figure 1 suggest also a possible role of solar UV variations during this time period under solar maximum conditions.

Figure 2 summarizes results of a Box-Jenkins cross spectral analysis of the 4 available years of 2 mbar SAMS temperature data averaged between 20°S and 20°N versus the SBUV solar 205 nm flux (F205). This analysis is a desirable supplement to earlier cross correlation results for the same data [e.g., Hood and Cantrell, 1988] which did not rigorously determine the statistical significance of the reported correlations. As shown in the top panel, the F205 autospectrum (solid line) contains a large maximum near 27 days and a secondary maximum near 13 days. The 13-day periodicity is not a simple harmonic of the 27-day period but represents an actual forcing component arising when active regions tend to cluster in opposite hemispheres on the solar disk [Donnelly et al., 1986]. The 27-day period arises when active regions tend to cluster in a single hemisphere. The averaged SAMS temperature autospectrum (dashed line) exhibits a broad maximum centered on approximately 27 days and a secondary maximum at a period near 16 days (frequency 0.062 days^{-1}). The latter period corresponds to the second symmetric (1,3) free Rossby wave mode that is prominently observed in the upper stratosphere [Hirooka and Hirota, 1985]. The largest maximum at $\sim$ 25 - 29 days period appears to be a possible result of solar ultraviolet forcing during this 4-year interval. A visual inspection of Figure 1 confirms the tendency for temperature maxima to occur at $\sim$ 25-30 day intervals within the 7-month time section shown. The second panel shows the coherency square statistic with two maxima exceeding 95% confidence at periods of 24-28 days and at $\sim$ 12.5 days. The derived phase lag (lower panel) is large as expected from the correlative results of Hood and Cantrell [1988]. At a period of 25 days where the coherency square reaches a maximum, the phase lag is 8 ± 2 days. Similar applications to other SAMS pressure levels yield coherency maxima that are positive at 95% confidence between 1 and 3 mbar. The phase lags for the $\sim$ 27-day maximum increase with decreasing altitude in agreement with the correlative results of Hood and Cantrell [1988].

Given that statistical evidence exists for a relation between solar ultraviolet variations on the solar rotation time scale and temperature variations in the low-latitude upper stratosphere, it is next of interest to see whether the low-latitude temperature variations are related to those at higher latitudes. Figure 3 shows results of a cross-spectral analysis of the low-latitude average temperature variations versus those averaged for latitudes of 40°N to 60°N for the October to March epoch of the 4 available years of SAMS data. The autospectra in the top panel show maxima near periods of 25 days and 16 days; these maxima are largest for the higher-latitude data as expected from the increased amplitudes of winter temperature fluctuations at higher latitudes (e.g., Figure 1). The coherency square statistic plotted in the center panel of Figure 3 shows two broad maxima at periods of 23-27 days and $\sim$ 13.5 days that are positive at 95% confidence; in contrast, the 16-day period has no significant coherency maximum between the chosen latitude bands during this 4-year time period. The phase plotted in the lower panel is centered on 180° for both the $\sim$ 25-day and the $\sim$ 13-day periods, confirming the qualitative interpretation of Figure 1 given above. Since the coherency square between low and higher latitude temperature fluctuations is significantly positive preferentially near 27 and 13 days (Figure 3), and since the low-latitude fluctuations are significantly coherent with F205 (Figure 2), it may be inferred that solar ultraviolet variations are either forcing or modulating latitudinal temperature oscillations in the upper stratosphere during the time interval of this study. Similar applications to other pressure levels between 1 and 3 mbar yield qualitatively similar results.

INTERPRETATION AND PHYSICAL MECHANISMS

One way of interpreting the occurrence of out-of-phase latitudinal temperature oscillations is in terms of corresponding oscillations in the zonal mean wind field at middle latitudes. As indicated qualitatively in Figure 4 (see also Figure 6.7 of Andrews et al. [1987]), a decrease in the zonal wind velocity ($d\overline{u}/\ dt < 0$) induces a poleward meridional circulation, due mainly to coriolis torques (an easterly flow is deflected northward in the northern hemisphere). By mass conservation, the poleward flow results in upwelling at low latitudes and downwelling at higher latitudes in the stratosphere. The reverse occurs in the mesosphere. The downwelling heats the stratosphere at higher latitudes while the upwelling results in a simultaneous adiabatic cooling at low latitudes. Opposite temperature tendencies are induced in the mesosphere, as is observed [Labitzke, 1972]. The cross spectral results of Figures 2 and 3 could be understood if short-term solar UV variations either force or modulate variations of the mean zonal wind velocity at middle latitudes at periods near 27 and 13 days.

Changes in the zonal wind at middle latitudes can be produced by wave-mean flow interactions if there are corresponding variations in the convergence of the planetary wave (Eliassen-Palm) flux ($\nabla \cdot \mathbf{F} < 0$; see Figure 4). This follows from the zonal momentum equation in the transformed Eulerian mean system (see Andrews et al. [1987]; p. 129). Any initial convergence of **F** produces a deceleration of the zonal wind and is followed by a secondary induced meridional circulation.

Salby (1984a,b) (see also Salby and Garcia (1987)) has reviewed evidence that interference between stationary and traveling planetary wave components can produce a modulation of the EP flux and resulting latitudinal temperature vacillations. A qualitative picture of the wave interference process for modulating the EP flux can be seen in Figure 10 of Salby [1984b] or in Figure 3 of Salby and Garcia [1987]. The phase surfaces of the stationary wave tilt with height while simple traveling waves are nearly barotropic. Interference between these waves therefore results in a modulation of the EP flux components in height and in time. At a given height, the EP flux appears as a sequence of pulsations and the divergence of the EP flux is oscillatory with frequency σ.

Given the cross-spectral results of Figures 2 and 3 combined with the current theory of stratospheric latitudinal temperature vacillations, one is led to hypothesize that solar UV variations may either force or modulate traveling waves with a period near 27 days in the upper stratosphere. Solar ultraviolet variations may be capable of forcing or modulating wave disturbances in the upper stratosphere via their effects on ozone concentration and radiative heating. These waves could then interfere with the time-averaged stationary wave at these levels to produce dynamical oscillations in step with solar UV variations. If so, then this would represent an initial mechanism for dynamical effects of short-term solar UV variability in the middle atmosphere.

IMPLICATIONS FOR THE SOLAR CYCLE TIME SCALE

Madden (1975; 1983) and others have discussed the likely role of interference between free traveling planetary wave modes and forced stationary waves (and the resulting oscillating latitudinal heat transports) in initiating stratospheric warmings. Also, Hirooka and Hirota (1985) have shown that higher-degree (longer-period) atmospheric normal modes are often amplified simultaneously, especially before the occurrence of sudden warmings. It may therefore be suggested that transient wave disturbances in the upper stratosphere driven by short-term solar UV variations may be capable of affecting the initiation of stratospheric warmings. Of course, the primary energy that is involved in generating warmings originates in the troposphere through the forcing of stationary and transient waves that propagate upward through the winter westerlies and interact with the zonal flow (e.g., Andrews et al., 1987). However, it may be hypothesized that the initiation of a major warming in the upper stratosphere and lower mesosphere may depend at least in part on the amplitude of "27-day" waves so that more major warmings are produced near solar maximum than near solar minimum.

The QBO, on the other hand, also is capable of modulating warmings such that major warmings occur in the east phase but not in the west phase in the absence of any solar UV variations. This is at least partly due to the weaker (more easily reversed) polar night jet at 500 mbar during the east phase QBO as compared to the west phase QBO (Holton and Tan, 1980; 1982). It is possible that years of the east phase QBO are sufficiently prone to the occurrence of major warmings that the smaller upper stratospheric effects of solar UV variations have a small or negligible influence. However, the initiation of major warmings during years of the west phase QBO may be more sensitive to the amplitude of the 27-day wave in the upper stratosphere, thus yielding the stratospheric temperature correlation with the solar cycle reported by Labitzke and van Loon. Quantitative tests of this hypothesis will require detailed analysis of atmospheric planetary wave statistics in addition to the zonal mean ozone and temperature fields considered in this paper.

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REFERENCES

Andrews, D. G., J. R. Holton, C. B. Leovy, 1987: *Middle Atmosphere Dynamics*, 489 pp., Academic Press, New York.

Baldwin, M. P., and T. J. Dunkerton, 1989: Observations and statistical simulations of a proposed solar cycle/QBO/weather relationship, *Geophys. Res. Lett., 16*, 863-867.

Brasseur, G., A. de Rudder, G. M. Keating, and M. C. Pitts, 1987: Response of middle atmosphere to short-term solar ultraviolet variations: 2. Theory, *J. Geophys. Res., 92*, 903-914.

Callis, L. B., J. C. Alpert, and M. A. Geller, 1985: An assessment of thermal, wind, and planetary wave changes in the middle and lower atmosphere due to 11-year UV flux variations, *J. Geophys. Res., 90*, 2273-2282.

Chandra, S., 1985: Solar-induced oscillations in the stratosphere: A myth or reality?, *J. Geophys. Res., 90*, 2331-2339.

Chandra, S., 1986: The solar and dynamically induced oscillations in the stratosphere, *J. Geophys. Res., 91*, 2719-2734.

Donnelly, R. F., D. E. Stevens, J. Barrett, and K. Pfendt, 1987: Short-term temporal variations of Nimbus 7 measurements of the solar UV spectral irradiance, *NOAA Tech. Memo. ERL ARL-154*, Air Resour. Lab., Silver Spring, M.

Ebel, A., M. Dameris, and H. J. Jakobs, 1988: Modelling of the dynamical response of the middle atmosphere to weak external forcing: Influence of stationary and transient waves, *Ann. Geophys., 6*, 501-512.

Fritz, S., and S. D. Soules, 1970: Large-scale temperature changes in the stratosphere observed from Nimbus III, *J. Atmos. Sci., 27*, 1091-1097.

Hines, C. O., A possible mechanism for the production of sun-weather correlations, *J. Atmos. Sci., 31*, 589-591, 1974.

Hirooka, T. and I. Hirota, 1985: Normal mode Rossby waves observed in the upper stratosphere. Part II: Second antisymmetric and symmetric modes of zonal wavenumbers 1 and 2, *J. Atmos. Sci., 42*, 536-548.

Holton, J. R., and H.-C. Tan, 1980: The influence of the equatorial quasi-biennial oscillation on the global circulation at 50 mb, *J. Atmos. Sci., 37*, 2200-2208.

Holton, J. R., and H.-C. Tan, 1982: The quasi-biennial oscillation in the northern hemisphere lower stratosphere, *J. Met. Soc. Japan, 60*, 140-148.

Hood, L. L., 1987: Solar ultraviolet radiation induced variations in the stratosphere and mesosphere, *J. Geophys. Res., 92*, 876-888.

Hood, L. L., and S. Cantrell, 1988: Stratospheric ozone and temperature responses to short-term solar ultraviolet variations: Reproducibility of low-latitude response measurements, *Ann. Geophys., 6*, 525-530.

Hood, L. L., and A. R. Douglass, 1988: Stratospheric responses to solar ultraviolet variations: Comparisons with photochemical models, *J. Geophys. Res., 93*, 3905-3911.

Keating G. M., G. P. Brasseur, J. Y. Nicholson III, and A. De Rudder, 1985: Detection of the response of ozone in the middle atmosphere to short-term solar ultraviolet variations, *Geophys. Res. Lett., 12*, 449-452.

Keating G. M., J. Y. Nicholson III, D. F. Young, G. Brasseur, and A. De Rudder, 1987: Response of middle atmosphere to short-term solar ultraviolet variations: 1. Observations, *J. Geophys. Res., 92*, 889-902.

Labitzke, K., The interaction between stratosphere and mesosphere in winter, *J. Atmos. Sci., 29*, 1395-1399, 1972.

Labitzke, K., On the interannual variability of the middle stratosphere during the northern winters, *J. Meteor. Soc. Japan, 60*, 124-138, 1982.

Labitzke, K., and H. van Loon, Association between the 11-year solar cycle, the QBO, and the atmosphere. Part III: Aspects of the association, *J. Climate, 2*, 554-565, 1989.

Madden, R. A., Oscillations in the winter stratosphere: Part 2. The role of horizontal eddy heat transport and the interaction of transient and stationary planetary waves, *Mon. Wea. Rev., 103*, 717-729, 1975.

Madden, R. A., The effect of the interference of traveling and stationary waves on time variations of the large-scale circulation, *J. Atmos. Sci., 40*, 1110-1125, 1983.

Nathan, T. R., 1989: On the role of ozone in the stability of Rossby normal modes, *J. Atmos. Sci., 46*, 2094-2100.

Rottman, G., *Adv. Space Res., 8*, 53-60, 1988.

Salby, M., 1984a: Survey of planetary-scale traveling waves: The state of theory and observations, *Rev. Geophys. Space Phys., 22*, 209-236.

Salby, M., 1984b: Transient disturbances in the stratosphere: Implications for theory and observing systems, *J. Atmos. Terr. Phys., 46*, 1009-1047.

Salby, M., and R. Garcia, 1987: Vacillations induced by interference of stationary and traveling planetary waves, *J. Atmos. Sci., 44*, 2679-2711.

Springer, B. D., Solar variability and quasi-stationary planetary wave behavior, in *Weather and Climate Responses to Solar Variations*, edited by B. M. McCormac, Colorado As-

sociated University Press, Boulder, p. 381-394, 1983.
van Loon, H. and Labitzke, K., 1990: Association between the 11-year solar cycle and the atmosphere. Part IV: The stratosphere, not grouped by the phase of the QBO, *J. Climate*, *3*, in press.
van Loon, H., R. A. Madden, and R. L. Jenne, 1975: Oscillations in the winter stratosphere: Part 1. Description, *Mon. Wea. Rev.*, *103*, 154-162.

Figure 1

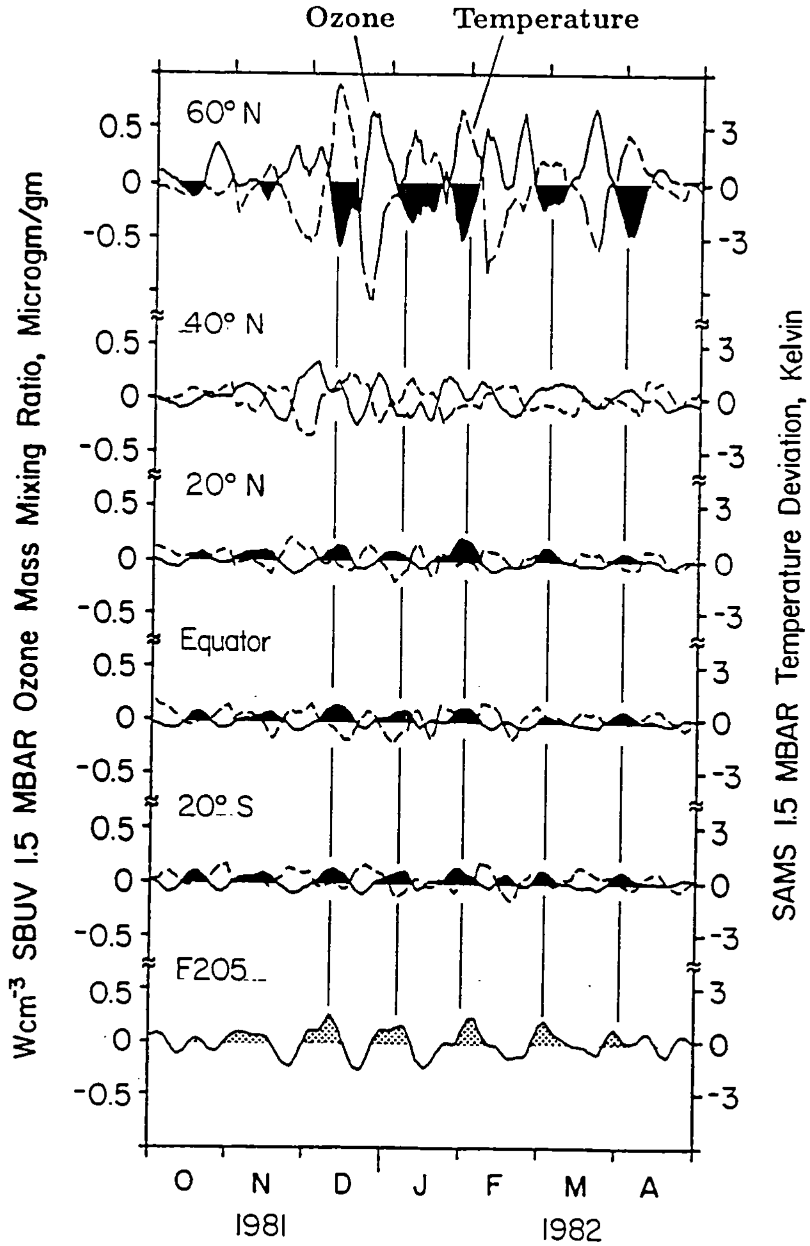
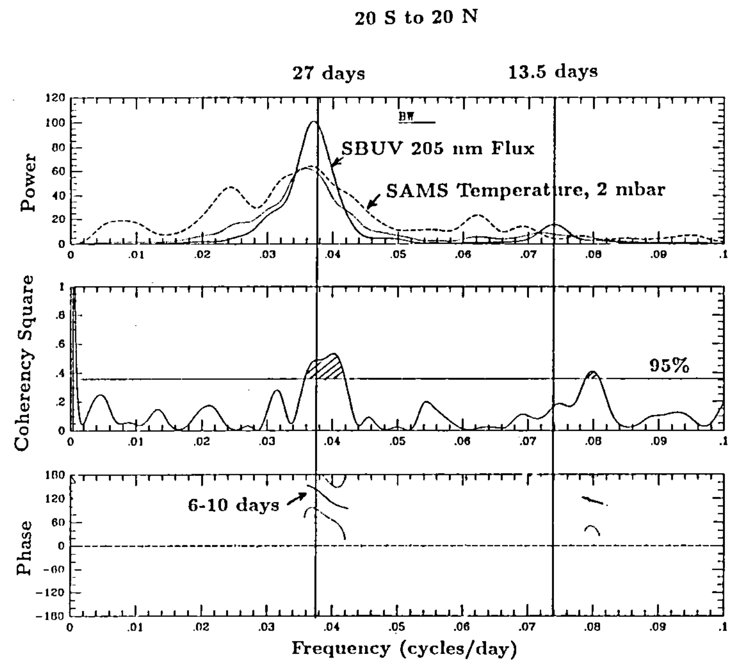


Figure 2



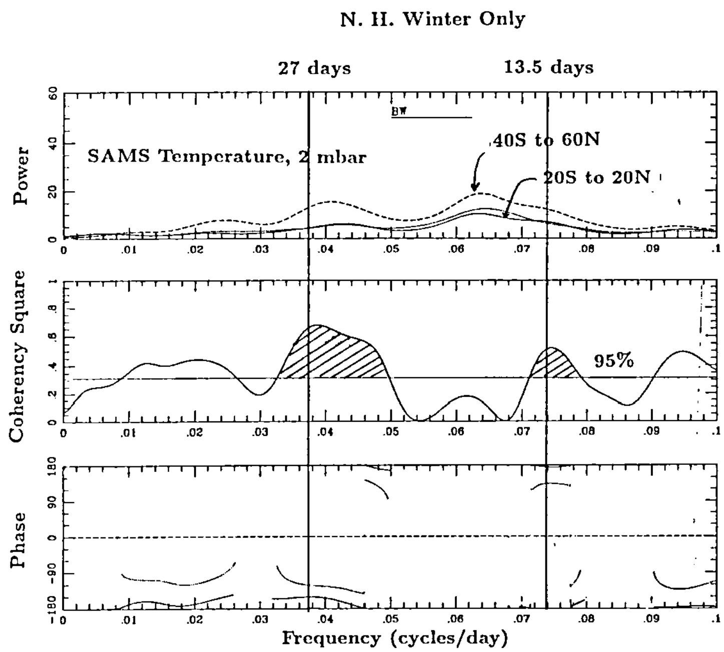


Figure 3

Figure 4