GEOPHYSICAL RESEARCH LETTERS, VOL. 21, NO. 24, PAGES 2733-2736, DECEMBER 1, 1994

Observations of the 5-day wave in the mesosphere and lower thermosphere

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Abstract. The 5-day planetary wave has been detected in the winds measured by the High Resolution Doppler Imager (HRDI) on the Upper Atmosphere Research Satellite (UARS) in the mesosphere and lower thermosphere (50-110 km). The appearances of the 5-day wave are transient, with a lifetime of 10-20 days in the two-year data set. The structures of selected 5-day wave events are in generally good agreement with the (1,1) Rossby normal mode for both zonal and meridional components. A climatology of the 5-day wave is presented for an altitude of 95 km and latitudes mainly between 40°S and 40°N.

Introduction

The 5-day wave is generally referred to as a westward traveling global oscillation with zonal wavenumber one and a period of 4-6 days. Evidence of the wave has been reported in a wide range of altitudes from the Earth surface to the lower thermosphere. Madden and Julian (1972) found a 0.5-2 mb oscillation with a period of 4.9 days and zonal wavenumber one in sea-level pressure data. Satellite observations of temperature (Rodgers, 1976), pressure (Hirota and Hirooka, 1984), and geopotential height (Venne, 1989) demonstrated the global existence of a ~5.5-day wave in the stratosphere. According to the satellite observations, the horizontal structure of the wave is similar to that of the first Rossby normal mode of wavenumber one, namely the (1,1) mode. The wave amplitude grows exponentially with height while the phase is slightly tilted. A disturbance with a period of ~6 days was also discovered in a D-region ionosonde parameter by Fraser and Thorpe (1976), who suggested possible penetration of the planetary wave to altitudes above the stratosphere. Rosenlof and Thomas (1990) were able to infer a 5-day oscillation from SME satellite ozone data at altitudes between 50 and 80 km. Radar measurements at a few sites (Massebeuf et al., 1981; Manson et al., 1982; Hirota et al., 1983; and Vincent, 1984) revealed a 5-day wind oscillation with an amplitude of 30 ms^{-1} in the upper mesosphere. However, an observation of the 5-day wave above the mesosphere has previously not been made.

Theoretically, Geisler and Dickinson (1976) studied the response of a 5-day disturbance for a solstice condition in the stratosphere and mesosphere. They reported significant latitudinal asymmetry in the wave amplitude with a larger value in the summer hemisphere. They also concluded that the asymmetry would be enhanced more in the upper mesosphere than in the stratosphere due to strong stratospheric jets. Salby (1981) systematically studied the response of several normal modes for both equinox and solstice conditions in a similar altitude range, and found that the period of the (1,1) mode varies between 4.4 and 5.7 days. According to his calculations, the wave structure is symmetric about the equator at equinox and asymmetric at solstice as suggested by Geisler and Dickinson (1976). However, the excitation mechanism of the 5-day wave is unclear at present. It has been conjectured that fluctuations and stochastic forcing in the atmosphere may give rise to transient existence of this wave. It may also be quickly enhanced under certain circumstances by coupling to barotropic and baroclinic instabilities. However, the understanding of the generation and development of the 5-day wave is far from complete.

In this letter, we report on evidence of the 5-day wave in the mesospheric and lower thermospheric winds measured by the High Resolution Doppler Imager (HRDI) on the Upper Atmosphere Research Satellite (UARS). A least squares method is employed for the spectral analysis of the space-time series from HRDI to obtain wave amplitudes and phases. The structures of selected 5-day wave events are compared to the (1,1) normal mode for both zonal and meridional components. We also present the climatology of the 5-day wave at 95 km for latitudes mainly between 40°S and 40°N.

Data and Wave Spectrum

The data analyzed here are the winds measured by UARS/HRDI in the mesosphere and lower thermosphere (50-110 km). UARS was launched on September 12, 1991, into a 585-km-high circular orbit with an inclination of 57°. About 15 orbits are completed in one solar day and the precession rate is about 5° per day in longitude. HRDI is a triple-etalon Fabry-Perot interferometer which observes wind fields in the mesosphere and lower thermosphere by resolving the Doppler shift of rotational lines in the O_2 atmospheric emission band ($b^1\Sigma_g^+ - X^3\Sigma_g^-$) (Hays, 1982). During the daytime this emission has a broad maximum allowing measurements over a large altitude range. At night the emission is restricted to a ~5-km wide layer near 95 km, yielding HRDI nighttime winds at essentially a single altitude. The vertical resolution of the wind profiles is 2.5 km. Further discussion of the instrument can be found in Hays et al. (1993) and Abreu et al. (1989).

The data was transformed to a grid of 5° in latitude and 2.5 km in altitude. The usual HRDI sampling scheme is to observe the mesosphere and lower thermosphere on alternate days except for campaign periods when it is viewed every day. This sampling rate is sufficient for the study of the 5-day wave, while campaign periods yield an even better signal-to-noise ratio. Figure 1 shows the wave spectra of the HRDI zonal winds at 95 km and at latitudes of 30°S, 20°S, 10°S, and 0° for the

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Paper number 94GL02660
0094-8534/94/94GL-02660$03.00

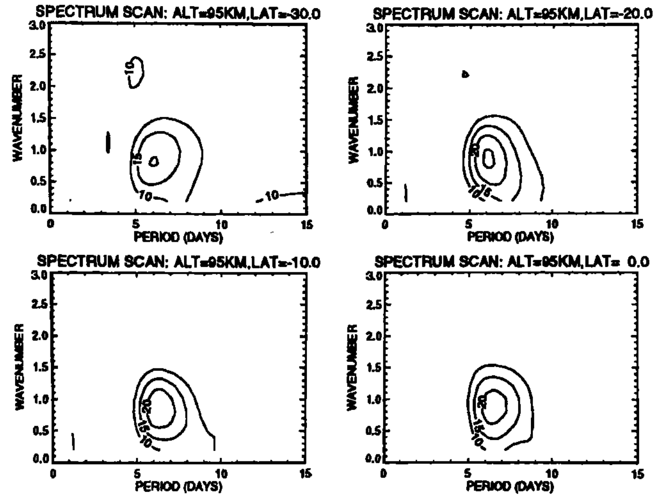

Figure 1. The wave spectra at latitudes of 30°S, 20°S, 10°S and 0°, as a function of period and wavenumber for only westward propagating components. Contoured are the zonal amplitudes based on the data at 95 km during November 1-12, 1992. Both daytime and nighttime data are used for the analysis.

period of Nov. 1-12, 1992. The amplitudes are given as a function of period and wavenumber, and are calculated using both day and night data. The noise level of the spectra is about 5 ms^{-1}, and the 5-day wave is not aliased by other waves within the Nyquist limit of the HRDI sampling rate. The most significant amplitude response appears near the period of ~6 ±1.5 days at zonal wavenumber one for all the four latitudes. The observed period is consistent with the radar measurements in the same region (Massebeuf et al., 1981; Manson et al., 1982), which also suggested a longer period (5.5-6 days) for the 5-day wave. This 5-day wave signal is extracted in the following analyses by using a band-pass filter which has a central frequency of 0.18 day^{-1} and a width of 0.1 day^{-1}.

Results

Figure 2 presents the HRDI climatology of the 5-day wave at 95 km from May 1992 to June 1994 for the zonal component. The noise level varies from 5 ms^{-1} in the tropical region to 10 ms^{-1} in the middle and high latitudes because of different sampling rates. Wave events are transient at this altitude with a typical duration of 10-20 days. Significant events occurred around May 3, August 22, September 28 and November 5 in 1992, September 4 and November 5 in 1993, and April 10, May 10 and May 25 in 1994. It is evident that the latitudinal structure of the wave amplitudes varies with season between latitudes of 20°, showing a slightly larger value in the summer hemisphere. This variation is indicated by a series of wave events between August and December 1992 and between February and May 1994. The observed asymmetry is qualitatively consistent with the model predictions (Geisler and Dickinson, 1976; Salby, 1981) and other satellite observations (Rodgers, 1976), which show a larger amplitude response in the summer hemisphere. It is worthwhile to point out that the 5-day wave in the upper mesosphere does not display any large amplitudes near the solstices in the two-year data. Whether the wave appears at very high latitudes for these periods is not clear since HRDI did not have a good coverage above latitudes of about 40°.

Comparisons between observed horizontal structures and the (1,1) Rossby normal mode are shown in Figs. 3 and 4 for two large 5-day wave events at 95 km. The amplitudes and phases of zonal and meridional components, on November 8, 1992, and April 8, 1994, are in generally good agreement with the structures of the normal mode. According to theory, the normal mode has a larger amplitude response in the zonal component than in the meridional component, and the zonal amplitude at the equator exhibits the largest value. Therefore, the existence of the normal mode is strongly supported by the observed amplitude ratio and the phase difference between the zonal and meridional components. Some asymmetry may exist in the amplitudes for the two events. For the event on November 8, 1992, the two nodes in the zonal component appear to be shifted to slightly lower latitudes than the predicted values of 41°S and 41°N, and there is the suggestion of some asymmetry in the latitude variation with larger amplitudes in the southern hemisphere. Corresponding large phase shifts are observed at the nodes as expected from the normal mode theory. The observed meridional amplitudes [Fig. 3(c)] also show an asymmetric structure. The node in the meridional winds, however, is not very clear because the amplitudes are generally small and are close to the noise level. A large phase shift is clearly seen near the equator [Fig. 3(d)]. For the event on April 8, 1994 [Figs. 4(a-d)], the structures are more symmetric than those in the previous example. Again, as a manifestation of the (1,1) normal mode, the variations in amplitude and phase are self-consistent in both zonal and meridional components.

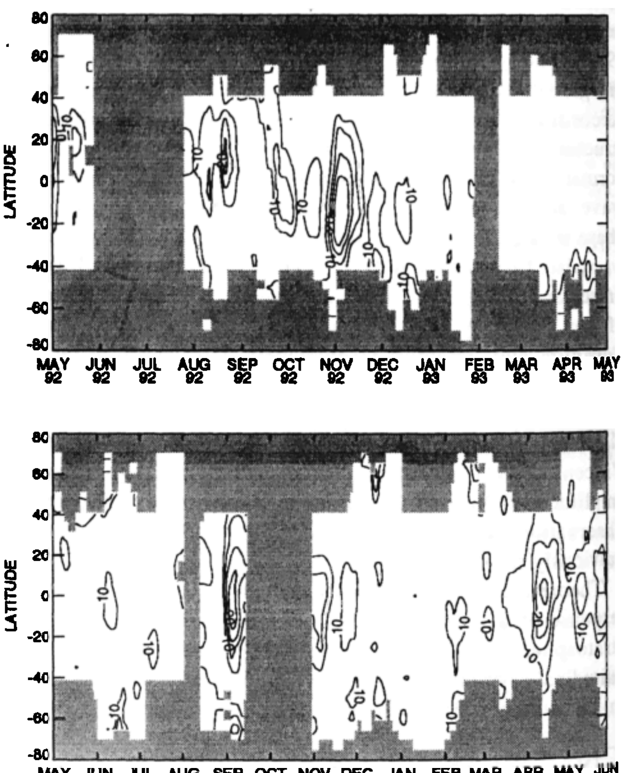

Figure 2. Climatology of the 5-day wave at 95 km for some periods between 1992 and 1994. Amplitudes are the zonal component, contoured from 10 ms^{-1} at an interval of 5 ms^{-1}. The shaded areas indicate the regions which are not well sampled by HRDI. The noise level is generally below 10 ms^{-1} for most of the covered regions.

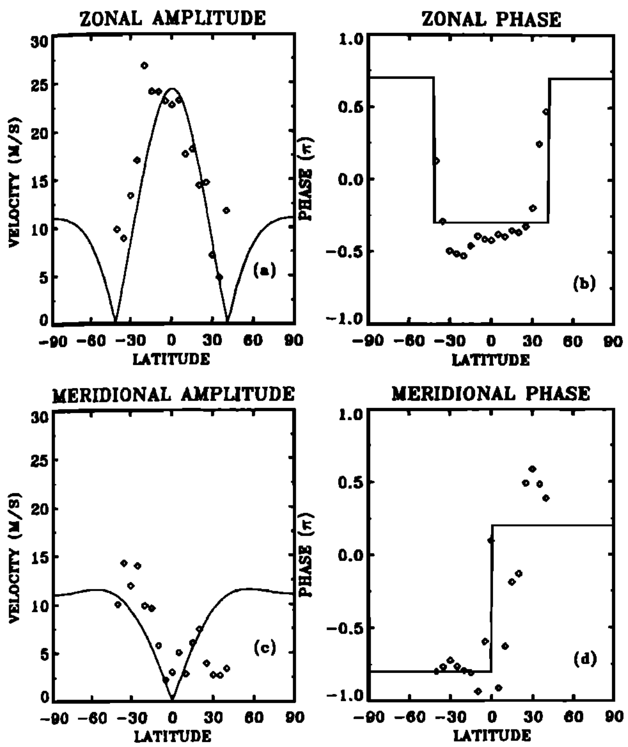

Figure 3. The horizontal structures of the 5-day wave for (a) zonal amplitude, (b) zonal phase, (c) meridional amplitude, and (d) meridional phase at 95 km on November 8, 1992. Symbols are the HRDI observations and solid lines are the classical (1,1) normal mode functions and phases for the wind fields.

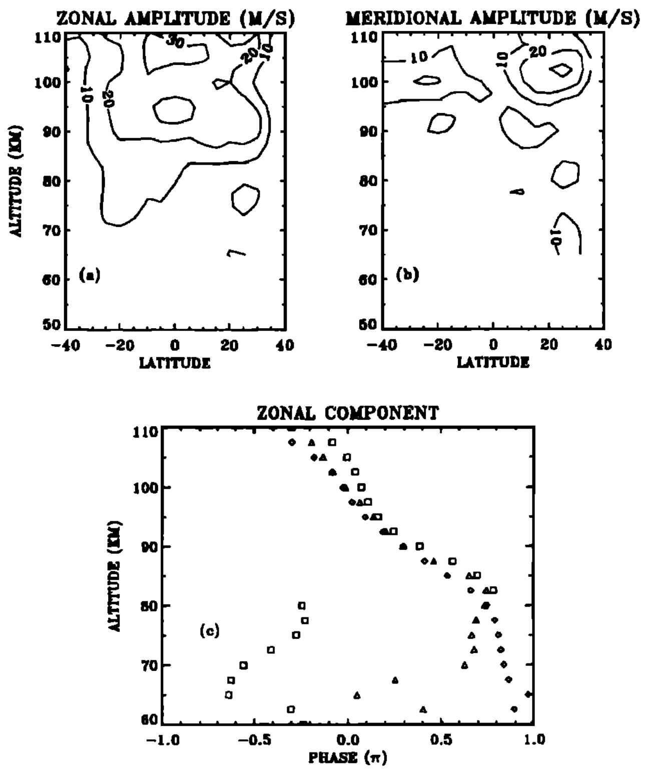

Figure 5. The 5-day wave amplitudes as a function of latitude and altitude for (a) zonal and (b) meridional components; and (c) the zonal phases as a function of altitude on November 8, 1992. Amplitude contours start from 10 ms^{-1} at an interval of 10 ms^{-1}. Phases are plotted at three latitudes, denoted by squares (20°N), triangles (0°), and diamonds (20°S).

Large 5-day wave amplitudes in wind fields appear mostly at altitudes above 80 km, as shown in Figs. 5(a) and 6(a). The 5-day oscillation on April 8, 1994, shows a more extended range in altitudes from 55 to 110 km than that on November 8, 1992, which ranges from 85 to 110 km. The horizontal structures of the wave amplitudes are basically symmetric about the equator at all altitudes for the zonal component. Asymmetry is more evident in the meridional component in the vicinity of 100 km, showing a larger amplitude in the southern hemisphere on April 8, 1994 (Fig. 6b), and in the northern hemisphere on November 8, 1992 (Fig. 5b).

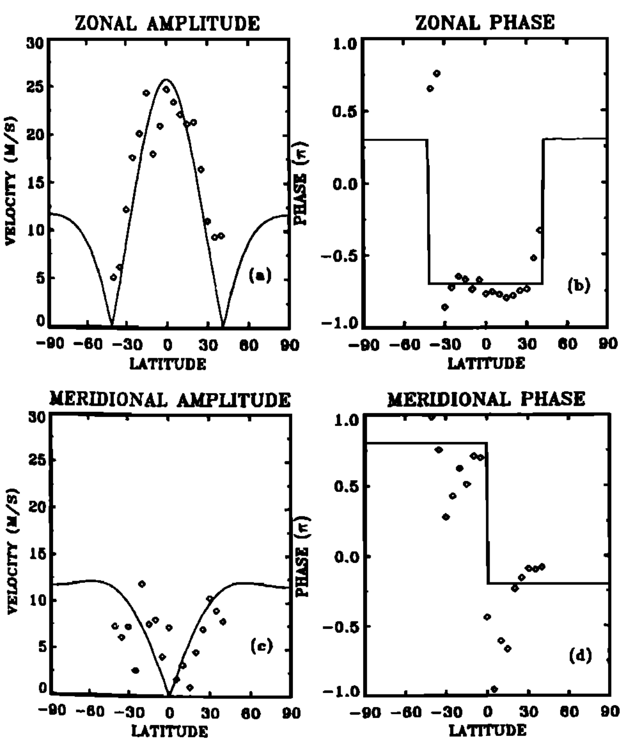

Figure 4. As in Fig. 3 but for April 8, 1994.

Tilted phase lines are apparent for all wave events, exhibiting a downward progression in time and a vertical wavelength of 60-80 km (Figs. 5c and 6c). According to the simulations (Salby, 1981), the tilting is basically a result of the asymmetry in background atmospheric conditions. However, the modeled atmosphere can be considered as a realistic one only below ~80 km since the mean zonal winds in the lower thermosphere were not included. This may explain the tilted phases observed on April 8, which is near the equinox. The phases below 75 km in Fig. 5(c) and below 80 km in Fig. 6(c) become more scattered than those at higher altitudes simply because the wave amplitudes diminish at the lower altitudes.

Summary and Discussion

The appearances of the 5-day wave in the upper mesosphere and lower thermosphere are transient with a typical lifetime of 10-20 days based on the UARS/HRDI wind observations. The wave events are well covered by the satellite at middle and lower latitudes at most times. The latitudinal variations of the observed wave amplitudes and phases is consistent with the

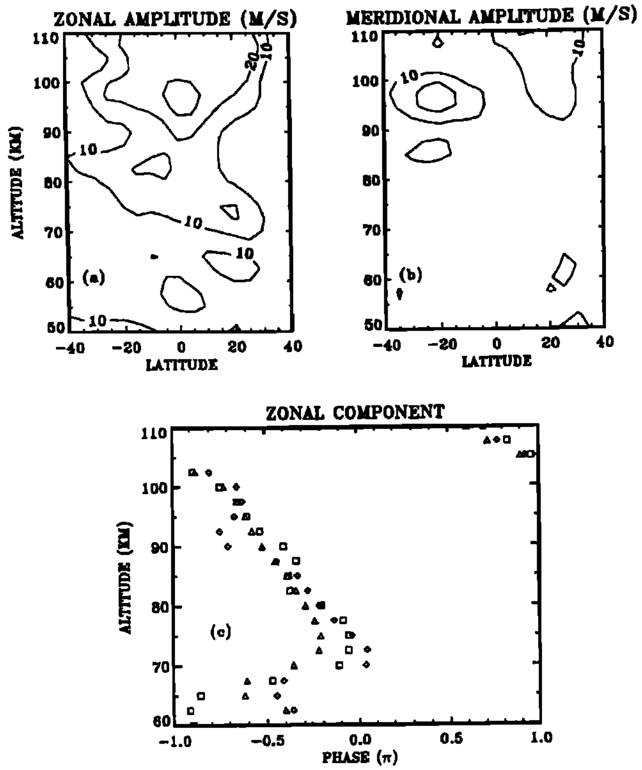

Figure 6. As in Fig. 5 but April 8, 1994.

structure of the (1,1) Rossby normal mode. The peak amplitude in the zonal component usually ranges between 15 and 30 ms^{-1}. There is some asymmetry in the zonal amplitudes near the mesopause, with the peak value usually appearing in the summer hemisphere, which is in agreement with the general tendency predicted by Geisler and Dickinson (1976) and Salby (1981). However, this represents a rather small distortion of the (1,1) normal mode structures. Our preliminary analysis shows that the meridional winds may be more sensitive to the seasonal differences than the zonal winds.

A complete understanding of the observed structures in this study requires further theoretical investigations in which realistic conditions must be incorporated into a model of the upper mesosphere and lower thermosphere. The lower thermospheric jets (Fleming et al., 1990) could significantly modify the wave structures and period in that region. The oversimplified background atmosphere in the model calculations (Geisler and Dickinson, 1976; Salby, 1981) may lead to very asymmetric structures in the upper mesosphere and lower thermosphere.

Acknowledgments. This work was sponsored by NASA under Contract No. NAS 5-27751 to the University of Michigan. The authors also wish to thank the HRDI science team for their support.

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(Received July 20, 1994; accepted September 13, 1994.)