SEMIDIURNAL SOLAR TIDES IN THE MOUNTAIN ATMOSPHERE

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Semidiurnal Solar Tides in the Mountain Atmosphere

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1. Introduction:

In this paper, harmonic analysis is applied to hour-average wind profiles obtained from pulsed Doppler radars at three sites on the west side of the Rocky Mountains. The analysis identifies a previously unreported coherent semidiurnal wind system that is present at all three sites. The wind system characteristics suggest that it is a semidiurnal solar tide.

2. Data Analysis

Clear air, pulsed Doppler, radar wind profilers (Neff, 1990) were developed for meteorological applications in the late 1980s. Data sets from these instruments are now becoming available for mountainous areas, and the analyses to be reported in this paper come from 915 MHz wind profilers at the sites shown in Figure 1 and listed in Table 1.

Available horizontal wind data during the period of record at each of the sites were averaged vectorially for each hour of the day at each range gate (i.e., altitude) to produce a time-height cross section of hourly vector winds for a mean day, as illustrated for Page, Arizona, in Figure 2 and for Temple Bar, Arizona, in Figure 3. An intriguing feature of the wind fields at all three sites is the apparent semidiurnal wind oscillation at heights above the wintertime atmospheric boundary layer.

To investigate the semidiurnal wind oscillations further, the wind data were broken into u (eastward directed) and v (northward directed) components and harmonic analyses were performed for each range gate. The results are shown in Figures 4 and 5. Figure 4 shows that the amplitudes of the semidiurnal components generally increase with height. Except in the near-surface boundary layer, the diurnal (not shown) and semidiurnal components are of roughly equal amplitudes, attaining speeds near 1 m/s at 4 km. Figure 5 provides phase information on the semidiurnal harmonic components (indicated by the subscript 2), expressed in terms of the times at which the u2 and v2 components reach a maximum. The semidiurnal components reach a maximum twice per day at times separated by 12 hours. The phases of the semidiurnal components above the boundary layer are generally consistent between the sites, with the u2 component maxima occurring between 1 and 4:30 am (and 1-4:30 pm) and the v2 maxima occurring at around noon (and at midnight).

3. Results and Discussion

The most interesting result from the harmonic analysis is the significant semidiurnal oscillation seen at all three sites. This oscillation has about the same amplitude as the diurnal oscillation and has a phase that is consistent among the sites and with elevation. Hodograms of the sum of the mean and semidiurnal components at Page and Temple Bar are presented in Figure 6 to illustrate the twice-daily clockwise turning of the semidiurnal winds at selected heights. The semidiurnal winds have an amplitude of 1.5 m/s at altitudes where the mean winds have amplitudes of about 6 m/s. They are thus seen to be a significant feature of the
Figure 2. Time-height cross section of mean hourly horizontal winds at Page, Arizona. A vector pointing up represents a wind blowing from south to north, a vector pointing to the right blows from west to east, etc. The dashed line indicates the surface.

Figure 3. Same as Figure 2 for Temple Bar.

Figure 4. Amplitudes as a function of height.

Figure 5. Times of the wind maxima for the $u$ and $v$ semidiurnal harmonic components.

overall mean daily wind system above the Rocky Mountains. The physical origin of this wind system is of interest, as its characteristics differ so significantly from the diurnal wind systems that are a feature of most complex terrain areas. We have considered and rejected several hypotheses regarding the origin of these semidiurnal winds, settling on the hypothesis that the winds are semidiurnal solar tides. The semidiurnal solar tide (Chapman and Lindzen, 1970) is produced by solar heating in the stratosphere by ozone absorption (Butler and Small, 1963). Heating by water vapor absorption also plays a lesser, though significant, role (Siebert, 1961). The heating occurs above the terminators where the solar radiation path lengths are longest. Since the terminators sweep around the earth twice per day this produces two cycles of heating (and winds) per day. Large semidiurnal tidal wind oscillations are produced by the upward propagation of this heating into the mesosphere and lower thermosphere (Greenhow and Neufeld, 1961). The semidiurnal solar tides are also responsible for semidiurnal surface pressure oscillations, whose general variation with latitude $\theta$ and longitude $\phi$ have been described by Haurwitz (1956), using the formula

$$S_2(p) = 1.16 \cos^3 \theta \sin(2t'+2\phi + 158^\circ) \text{ mb}$$ (2)
Figure 6. Hodograms of the sum of the mean daily wind \((u_0,v_0)\) and the mean hourly semidiurnal components \((u_2,v_2)\) at different indicated heights (m MSL) above (a) Page, Arizona, and at ~200-m height intervals beginning at 637 m at (b) Temple Bar, Arizona. The 24 points making up each hodogram represent the hours of the day and each point defines the tip of a wind vector which originates at the coordinate origin \((0,0)\). This vector rotates clockwise twice per day around each of the hodograms.

where \(S_2(p)\) represents the semidiurnal surface pressure component and \(t'\) is Universal Time measured in degrees from lower transit (midnight), with one hour corresponding to 15°. The form of this equation illustrates the essential wave nature of the oscillation with two complete waves around the earth and with highest amplitudes at the equator. Since the tide follows the apparent path of the sun, the times of maximum pressure are 0944 and 2144 local mean solar time (LMST) at all longitudes.

Long time series observations of surface pressure (U.S. Weather Bureau, 1943) are available for the U.S., and Spar (1952) has used these data to produce more detailed maps of semidiurnal surface pressure oscillations that show significant perturbations in the Rocky Mountains.

4. Equations of Motion

The hypothesis that the observed semidiurnal winds are semidiurnal solar tides can be evaluated by comparing the wind system characteristics with those of the semidiurnal solar tide, where the tidal characteristics are determined by substituting Haurwitz’s formula (2) for the semidiurnal pressure perturbation into the equations of motion for the atmosphere on a rotating earth, ignoring friction

\[
\begin{align*}
\frac{\partial u}{\partial t} & = \frac{1}{
\rho R_E \cos \theta \mathbf{P}} \frac{\partial p}{\partial \phi} - 2 \Omega v \sin \theta \\
\frac{\partial v}{\partial t} & = \frac{1}{
\rho R_E \cos \theta \mathbf{P}} \frac{\partial p}{\partial \theta},
\end{align*}
\]

In this formula, \(u\) and \(v\) are velocities, \(t\) is time, \(\Omega\) is the angular velocity of the Earth, \(\rho\) is air density, \(R_E\) is the Earth's radius, and \(p\) is the semidiurnal pressure oscillation, assumed independent of height.

The solutions (Chapman and Lindzen, 1970) at Page’s latitude are \(u_2 = 0.31 \sin (2t + 338°)\) and \(v_2 = 0.30 \sin (2t + 68°)\) m/s, and are considered valid just above the planetary boundary layer, where the effect of friction becomes negligible. These solutions require the maximum \(u_2 (v_2)\) component to occur at 0344 and 1544 (0044 and 1244) LMST. The tidal wind components are 90° out of phase and the vector wind rotates clockwise with time. The amplitudes, times, and sense of rotation are in general agreement with the radar profiler data.

5. Conclusions

Harmonic analysis of Doppler radar wind profiler data west of the Rocky Mountains has identified a coherent semidiurnal wind system above the wintertime boundary layer at multiple sites in the region. The unusual characteristics of this mountain wind system (its semidiurnal frequency, amplitude, phase, and direction of
rotation) suggest that it is a semidiurnal solar tide. Such tides have not been previously documented in the mountain atmosphere or in the troposphere generally but, because semidiurnal signatures are well known in surface barometric traces, and large amplitude semidiurnal tides are known in the upper atmosphere, they are not unexpected.

Our interpretation of these winds as tidal wind systems is supported by a solution of the momentum equations for frictionless flow on a rotating earth in which a simplified fit to global semidiurnal surface pressure observations is used to drive the equations. The resulting solution generally matches the observed winds in frequency, amplitude, phase, and direction of rotation. The phase of the observed winds varies somewhat from site to site and in the vertical at individual sites, producing some discrepancies between the observations and model. This is probably due to statistical uncertainty in the observations resulting from the short period of record, and the falloff in the number of observations with height. The model also lacks detail on phase and amplitude variations of the semidiurnal surface pressure fields in the Rocky Mountain cordillera.

Our future research on this semidiurnal cordilleran wind system will focus on obtaining sufficient data to resolve further the vertical structure, seasonal variation, and spatial variations of the wind system. Of particular interest is the role of the Rocky Mountains and other cordilleras in modifying the global tides. It remains to be seen whether semidiurnal cordilleran circulations will be of sufficient magnitude to be observed across major arcuate-shaped east-west-oriented mountain massifs such as the Alps. There, wind systems may develop in response to pressure gradients (Frei and Davies, 1993) that form across the Alps due to differences in the amplitudes and phases of semidiurnal and diurnal pressure oscillations on the north and south sides of the mountain barrier.

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