Vertical Wind Variability Observed by VHF Radar in the Lee of the Colorado Rockies

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ABSTRACT

During March 1981 the Sunset and Platteville VHF clear-air radars located in Colorado to the east of the continental divide observed vertical winds continuously over a three-week period. The vertical winds at these locations contain fluctuations with periods from a few minutes to several hours and with magnitudes ranging up to a few meters per second. The Sunset radar, which is located in the foothills, observed systematically larger vertical velocities than the vertical velocities observed by the Platteville radar, which is located on the plains, some 60 km to the east. Although periods of enhanced vertical wind activity were observed to occur at the same time at both sites, attempts to correlate vertical wind structures over the two sites in detail were generally not successful.

The magnitude of vertical velocity fluctuations seen by both radars show large day-to-day variations with "active" periods alternating with "quiet" periods. An examination of upper level maps reveals that the occurrence of active and quiet periods are linked to the large-scale wind field. During the March experiment the magnitude of the vertical velocity variance was well correlated with the 500 mb zonal (west) wind.

1. Introduction

Vertical velocity plays an important role in the dynamics of atmospheric circulation systems on all scales. However, until very recently there has been no direct means to continuously measure vertical velocities. As a result our present knowledge of the role of vertical velocity in weather systems has been derived indirectly from kinematic analysis of large-scale synoptic wind fields. These analyses provide insight into the broad-scale features of vertical velocity on the synoptic scale but give us no information about the variability of vertical velocity at any particular location. The local vertical velocities can be expected to contain contributions from convection, gravity waves (including stationary lee waves) and turbulence, in addition to the much smaller synoptic-scale vertical wind.

Doppler radars sensitive enough to obtain useful echoes from clear-air refractive structure have provided new information on winds, waves, turbulence and atmospheric stability over the past several years (Gage and Balsley, 1978; Röttger *et al.*, 1978; Green *et al.*, 1979; Balsley and Gage, 1980; James, 1980). As part of this effort, several groups have reported limited observations of vertical winds in the troposphere and lower stratosphere (Woodman and Guillén, 1974; Balsley *et al.*, 1977; Röttger *et al.*, 1978; Fukao *et al.*, 1978; Green *et al.*, 1978; Peterson and Balsley, 1979; Gage *et al.*, 1981). These vertical wind observations have often shown oscillations with periods from about 5–30 min with amplitudes ranging from 0.1–1 m s^{-1}, which are apparently associated with propagating internal gravity waves. In addition to these oscillations, fairly steady vertical winds of up to 1 m s^{-1} have occasionally been observed to persist for several hours. These steady vertical winds are most likely due to non-propagating gravity waves such as lee waves. More recently, Ecklund *et al.* (1981a) presented over 30 days of nearly continuous observations of vertical winds up to 20 km obtained using the MST radar at Poker Flat, Alaska. Generally, fluctuations were found to be controlled by propagating planetary-scale waves that modulate the large-scale wind field. The strongest vertical winds were almost always associated with the enhanced wind and wind shear found in conjunction with intense baroclinc zones.

In this paper we present the results from a vertical wind experiment conducted in Colorado during March 1981. In the experiment two VHF clear-air radars separated by 63 km were operated continuously over a three-week period in order to obtain vertical winds up to an altitude of ~20 km with temporal resolution of a few minutes. There were two major motivations for conducting this experiment. First, since one site was located in the mountain foothills while the other site was located on the plains, we wanted to determine what effects local topography had on vertical wind fields. Second, we wanted to determine whether observed vertical wind structure could be correlated over the 63 km horizontal dis-

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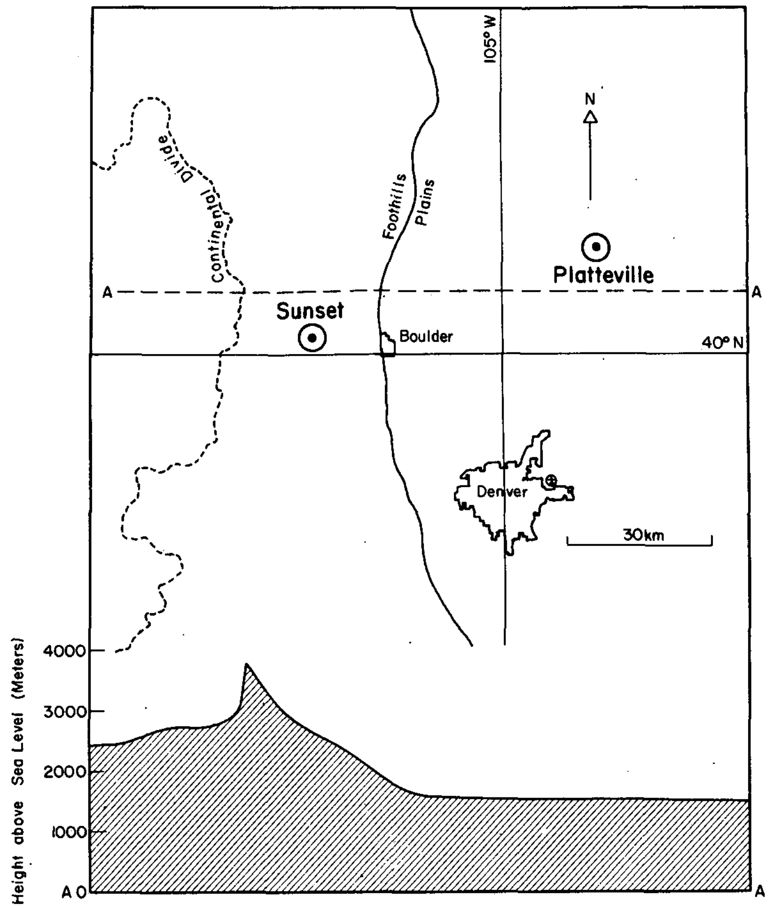

FIG. 1. Map of the experimental area.

tance between the two sites. Although attempts to correlate vertical wind structures over the two sites in detail were generally not successful, "active" periods of enhanced vertical velocity fluctuations were observed to occur at the same time at both sites. These "active" periods were found to correlate well with enhanced 500 mb zonal (west) wind.

2. The radar experiment

The relative locations of the two radar systems used in this experiment are indicated on the map in Fig. 1. Note that the site alignment is approximately east–west, i.e., in line with the prevailing wind pattern. An outline of the profile of the ground surface height on the east-west line between the two sites appears at the bottom of Fig. 1. The location of both sites relative to the continental divide and the beginning of the plains region is evident. Sunset is located in the foothills close to the divide, while Platteville is situated on the plains, but only 40 km from the edge of the foothills. The line-of-site distance between the two radars is ~63 km.

The Platteville (50 MHz) and Sunset (40 MHz) radars are pulsed, VHF Doppler systems operating at peak transmitted powers of 15 and 50 kW, respectively, with antennas comprised of phased arrays of dipole elements. A photograph of the Platteville array is shown in Fig. 2 to demonstrate the simplicity of this type of antenna. Detailed descriptions of the Sunset and Platteville radars can be found in Green *et al.* (1979) and Ecklund *et al.* (1979).

For the present experiment both systems operated almost exclusively with vertically directed beams, the exception being that Sunset performed a three-position scan every 12 h to measure the horizontal wind field as well. This procedure did not cause an appreciable deterioration of the vertical data and afforded a much more local picture of the horizontal wind profile than that which could be obtained from the twice-daily balloon soundings at Denver.

Data from both systems were processed in similar ways to afford the best comparison. The time resolution in the present data set has been standardized by appropriate computer averaging. The Sunset radar used a vertical resolution of 1 km and the Platteville radar used a vertical resolution of 2.3 km. To facilitate comparison, both radars were sampled at altitude in-

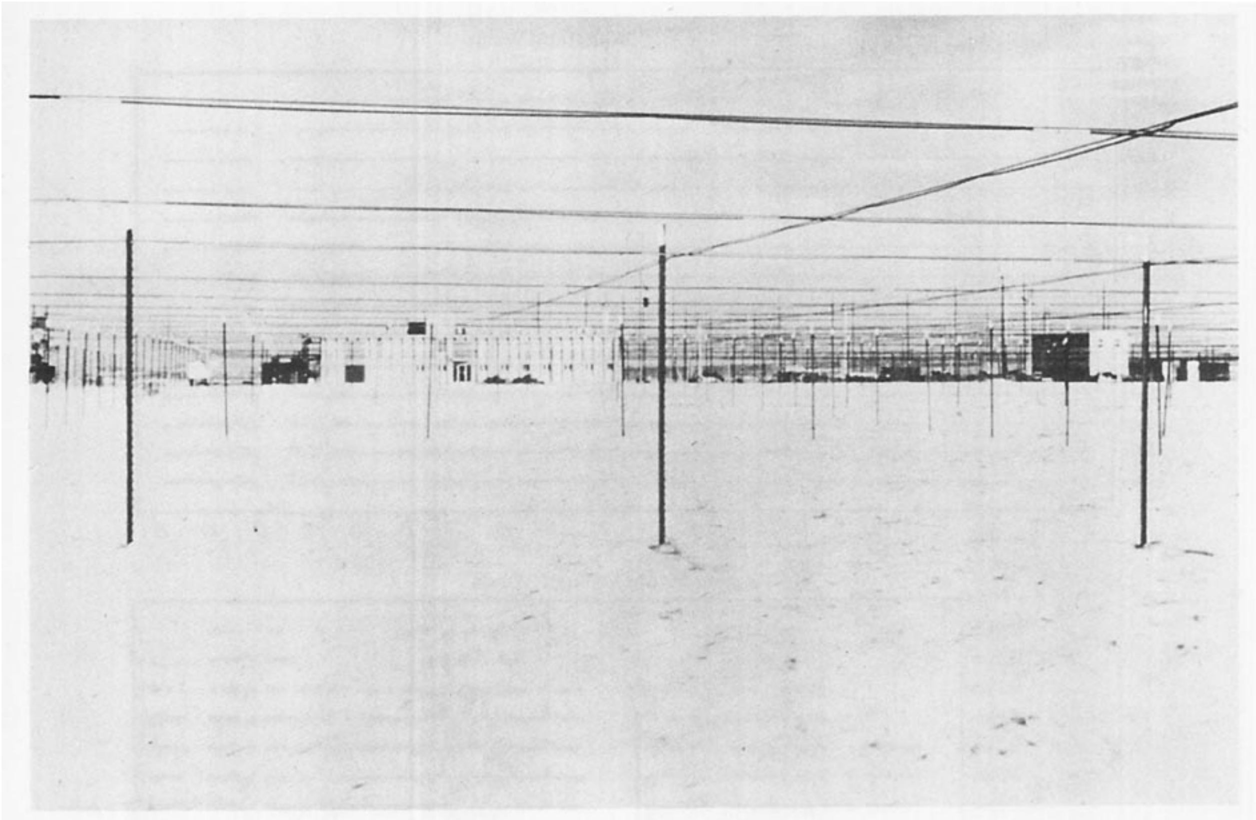

FIG. 2. Photograph of the Platteville antenna array.

tervals of 1.2 km. Thus the Sunset radar data were slightly undersampled and the Platteville data were oversampled by a factor of about 2.

3. The observed variability of the vertical wind

A composite picture of the vertical wind field over both Sunset and Platteville for the complete experimental period is shown in Fig. 3. Both data sets consist of 15 min averaged data and are plotted on the same time axis with the same vertical velocity scale to facilitate comparison. The vertical range of the data base extends from below 5 km to above 20 km (MSL). The upper limit is controlled primarily by the radar system sensitivity; more sensitive VHF radars (i.e., bigger antenna areas or higher average transmitter power) would extend this upper limit [see Green *et al.* (1979) and Balsley and Gage (1980) for details]. Obvious blank spots in the data arise from system outages; less obvious data dropouts occur occasionally on the Sunset data when the wind magnitude exceeds the nominal 2.0 m s^{-1} limit used in this figure.

There are a number of obvious similarities in the two data sets as well as a number of clear dissimilarities. These are treated in the following paragraphs.

Perhaps the most obvious similarity in the Sunset and Platteville results is the coincident pattern of active periods and quiet periods in the vertical winds over both locations. Here we define active periods as those times with enhanced vertical wind activity centered very roughly, for example, at 16, 19–20, 22–23 and 26–27 March. Similarly, quiet periods are typified by times with minimal vertical wind activity centered, for example, on 17–18, 21, 24–25 and 28 March. As shown in the next section, the overall activity in the vertical wind appears to correlate well with the magnitude of the westerly component of the tropospheric wind field. This suggests that the vertical wind structure arises at least in part from orographically generated gravity waves, since the sharp profile of the continental divide lies to the west of both sites (cf. Fig. 1). Moreover, if orography is the controlling factor, the activity would be expected to be considerably stronger at Sunset than that at Platteville, as observed. Since most of the vertical wind structures shown in Fig. 3 extend over several kilometers, the different vertical resolution at Sunset (1 km) and Platteville (2.3 km) cannot explain the stronger activity observed at Sunset. The point to be made here is that the activity occurs essentially simultaneously at both sites.

Attempts to correlate concurrent details in the vertical wind pattern at Sunset and Platteville meet with only marginal success. Possible evidence of a coherent feature over the two sites occurs in the forenoon of

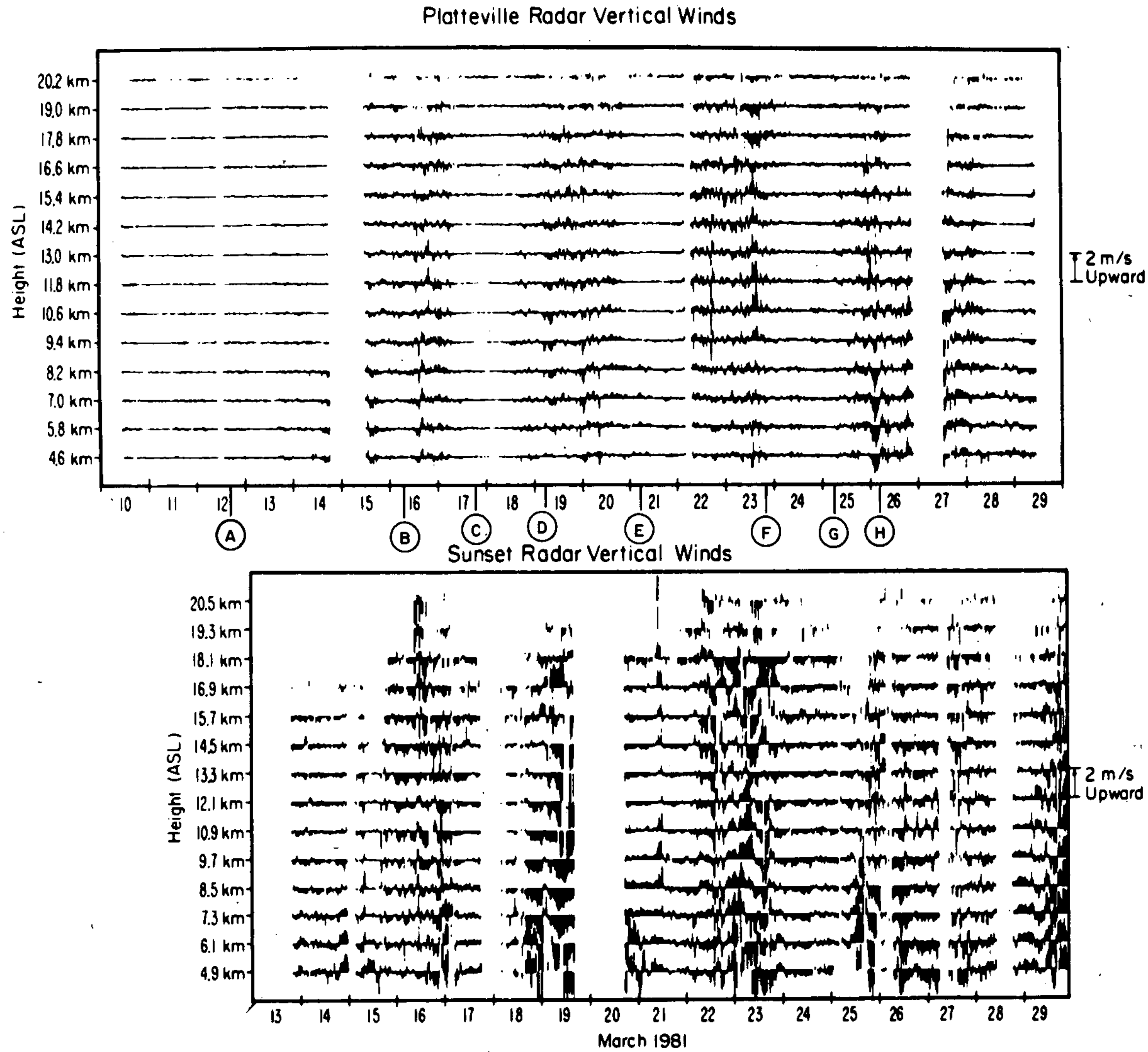

FIG. 3. Fifteen-minute-averaged vertical velocities over Platteville and Sunset, Colorado, for the complete experimental period.

19 March, where the downward flow pattern between 7 and 14.2 km at Platteville corresponds to the (stronger) downward flow over Sunset below 15.7 km. The vertical flow reverses at higher heights (16.6 km at Platteville; 16.9 km at Sunset). However, evidence for comparable structures over the two sites is generally not convincing. This may be due to the fact that the gravity waves (including lee waves) typically have spatial scales smaller than the 63 km spacing between the radars. Comparison may also be complicated by the fact that the two stations do not necessarily lie along the direction of the mean wind.

A more detailed plot of one active day (23 March 1981) over Sunset and Platteville appears in Fig. 4. The time resolution for this plot is 5 min. Here the vertical scales have been adjusted to reproduce wind velocities up to 5 m s^{-1}. (Note that the "periodic" structures at 0400 and 1700 MST on the Sunset data are due to vertical data dropouts when the antenna was scanned to obtain oblique wind information.)

Some general correlation between the gross vertical motion at the two sites can be seen in this record. For example, the period of enhanced flow between 1300 and 1700 above about 8 km appears on both records; the sense of the general vertical flow, however, is reversed (Sunset flow is downward below the 13.3 km level while Platteville is upward below the 16.6 km level; the reversed situation is seen above these levels). This reversed picture is also seen at the ~15–16 km level on both systems between 0000 and 0200. A possible explanation for the reversed vertical winds at the two sites during this period is that each radar was observing a different phase of a large-amplitude mountain lee wave. The horizontal wavelength of the proposed lee wave cannot be determined because the radars are too far apart to eliminate spatial ambiguities. Future experiments should use three or more stations (if possible) with closer spacing along the east–west line.

4. Day-to-day variability of vertical wind and the large-scale wind field

As discussed above, the most striking feature of the vertical wind structure seen by the Platteville and Sunset radars is the large overall day-to-day variation in the magnitude of the vertical velocity fluctuations with "active" periods alternating with "quiet" periods. In order to gain some perspective on the relationship between day-to-day variations in the magnitude of vertical velocity fluctuations and synoptic-scale weather features we have examined the upper-level synoptic maps. Selected synoptic maps for the 500 mb level are reproduced in Fig. 5. These maps are keyed to the synoptic times A–H indicated on the graph of vertical winds in Fig. 3. Map A shows the large-scale wind field at 1700 MST 12 March 1981. At this time the winds over the western United States were very weak. This synoptic situation persisted for several days and coincided with the lack of activity in the vertical winds at the beginning of the observing period 10–14 March 1981. The first active period occurred on 15–16 March, and at this time map B (0500 MST 16 March) shows that the large-scale gradient in the height field has increased considerably and a ridge has built over the mountain states. Map C (1700 MST 17 March 1981) shows a much more complex synoptic pattern. At this time low pressure has developed to the east of Colorado and the zonal wind over eastern Colorado is very weak. This corresponds to a quiet period in the vertical wind activity. The next active period is shown on the synoptic map D for 0500 MST 19 March. At this time the gradient in the height field is quite strong. This situation is also revealed on the map by the strong winds observed at Denver. The remaining two cycles of active and quiet periods shown in Fig. 3 also show strong zonal flow during active periods with an upper level low typically located to the east with weak zonal flow over Colorado during quiet periods.

In the preceeding section we have shown an association between periods of enhanced/suppressed activity in vertical winds with strong/weak zonal flow. To further examine this relationship throughout the observing period, we have compared the variance of the vertical wind observed by the Platteville radar (the radar vertical wind variance was obtained over 4 h periods bracketing the rawinsonde synoptic observing times) with the 500 mb zonal wind component observed by the Denver rawinsonde. This comparison is shown in Fig. 6. For convenience, we have

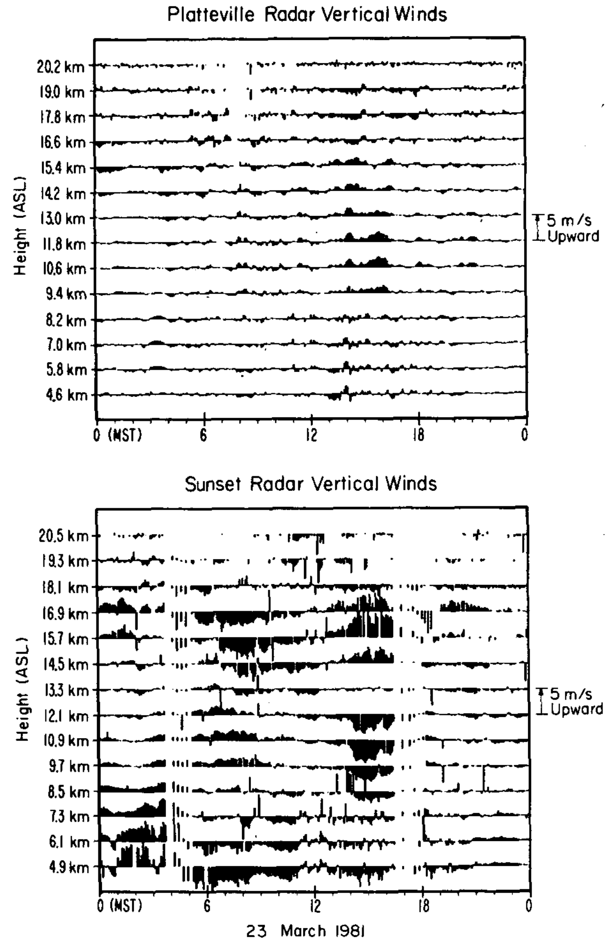

FIG. 4. Five-minute-averaged vertical velocities over Platteville and Sunset for the active period 23 March 1981.

divided the radar data into three height ranges. Each of the height ranges is an average of two radar heights. A comparison between the vertical wind variance at the three separate height ranges and the 500 mb zonal wind shows a very good correlation. The best correlation appears to occur near the tropopause level. Since the vertical wind variance at Platteville and Sunset appears to be highly correlated (cf. Fig. 3) it is reasonable to expect that the result shown in Fig. 6 for Platteville would also have been obtained by using Sunset data. The Platteville data were used in this example only because they were available for a longer period of time.

5. Concluding remarks

In this paper we have presented the vertical winds observed by the Platteville and Sunset radars during a three-week observing period in March 1981. Our analysis shows that during this period the overall day-to-day variability of vertical wind activity is affected primarily by synoptic-scale weather patterns in general and by the magnitude of the zonal wind in par-

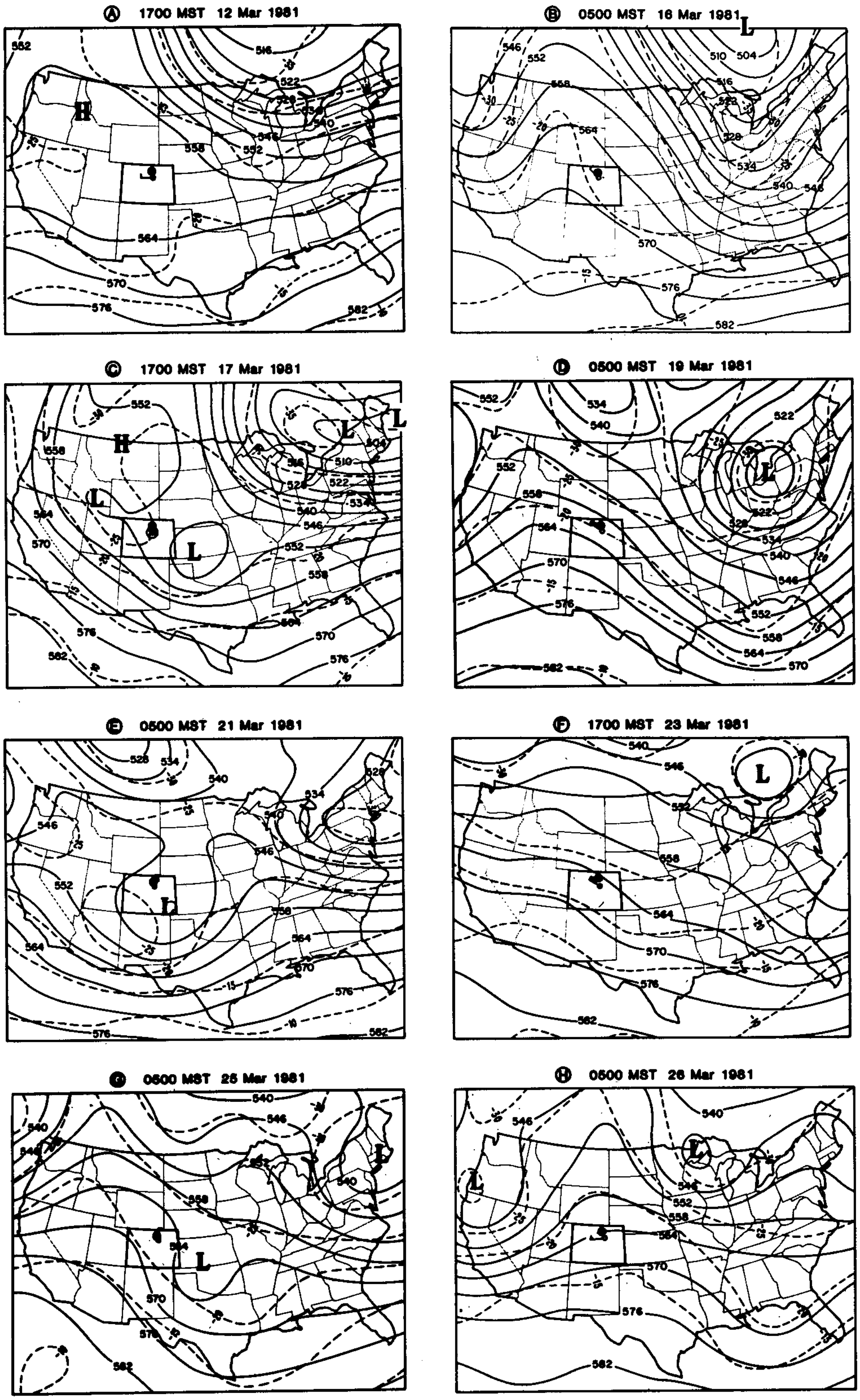

FIG. 5. 500 mb synoptic maps for the observing period of Fig. 3. The circled letters (A)–(H) at the top of each map correspond to the times denoted by the circled letters in Fig. 3.

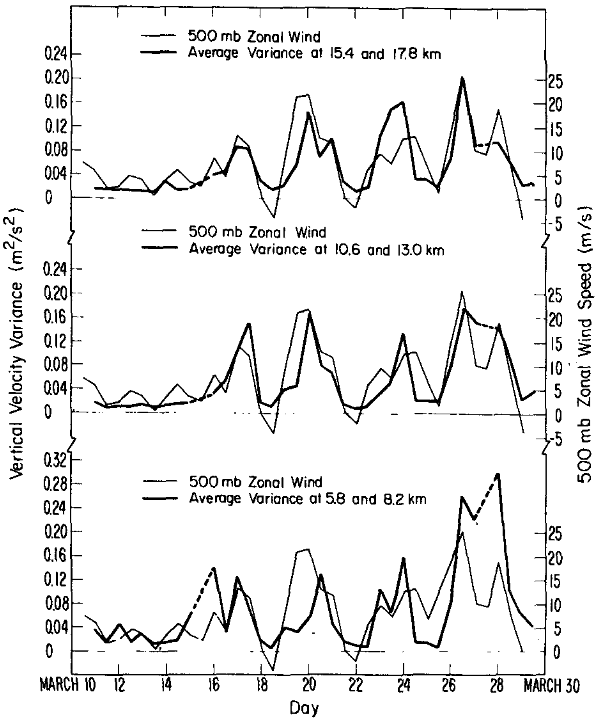

FIG. 6. A comparison of vertical velocity variance at three heights with the 500 mb zonal wind speed.

ticular. Although not discussed in this report, at times during the observation period vertical winds appeared to be also affected by convective activity as evidenced by the presence of cumulus clouds (Ecklund *et al.*, 1981b).

The day-to-day variability of vertical wind activity observed at Platteville can be compared to observations of vertical wind activity at Poker Flat, Alaska, reported by Ecklund *et al.* (1981a). Although the magnitude of the vertical wind activity in both Alaska and Colorado alternates between quiet and active periods in response to the large-scale wind field, there are important differences in the way this variation takes place. At Poker Flat the variation in vertical wind activity is correlated generally with wind speed and wind shear and not directly with wind direction. At Platteville, on the other hand, we find a very good correlation between the magnitude of vertical wind activity and the magnitude of the zonal wind (i.e., there appears to be a direction dependence). The difference in behavior at the two locations may be ascribed to differences in orography, since at Poker Flat rough terrain is fairly uniformly distributed in all directions while in Colorado there is a pronounced east-west asymmetry in roughness. In Colorado wind from the west flows over the continental divide whereas wind from other directions comes primarily over the plains. It remains to be determined to what extent vertical wind activity varies over regions of smooth terrain.

The fairly steady vertical winds ranging up to several meters per second and lasting for several hours observed in this experiment are probably due to mountain lee waves. However, because of the difficulty in correlating concurrent details of vertical wind patterns at the two radars, it has not been possible to estimate the relative importance of stationary gravity waves (lee waves) and propagating gravity waves in generating the observed vertical wind variability. Multiple radars with horizontal spacing considerably less than the 63 km spacing used in this experiment should allow this question to be resolved in future experiments.

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