1. Introduction

The comment by Browning et al. (2000) is built upon three primary assertions. 1) The accuracy of wind profiler vertical velocity measurements, in general, is not well established but is not better than 0.2–0.8 m s\(^{-1}\); 2) the data processing procedures used by Ralph et al. (1993a) were inappropriate; and 3) the magnitude of vertical motions associated with mesoscale gravity waves is \(O(0.1 \text{ m s}^{-1})\). These assertions led them to suggest that the magnitude of the wave vertical motions, in general, is too small to have been observable using a wind profiler, and thus the results of Ralph et al. (1993a) must be incorrect. This would then provide a justification for important contradictions between conclusions of their recently published theoretical paper (Browning and Kreiss 1997) and the observations presented in Ralph et al. (1993a), which included observations of a gravity wave in surface pressure data that was consistent in phase and amplitude with profiler-observed vertical velocities and vertical structure. The conclusions in Browning and Kreiss (1997) that contradict those in Ralph et al. (1993a) include a statement in their abstract that wind profilers cannot measure such waves, an assertion that “in the absence of topography, mesoscale motions with vertical velocities \(O(1 \text{ m s}^{-1})\) can exist only in the presence of heating,” and a claim that previous gravity wave studies that depended upon surface pressure time series in cases that included deep convection were flawed because latent heating in a convective line would produce an indistinguishably similar signal at the surface.

This reply will address each of the three core assertions, focusing in detail on the first two, and pointing out that even if their third key assertion is correct, it does not mean that gravity waves of greater amplitude do not occur. First, a detailed review of issues affecting profiler vertical velocity measurement accuracy will be provided, including an explanation of why the estimated minimum accuracy given in Browning et al. (2000) is incorrect, and why the experience they quote with the National Profiler Network (NPN) is not representative. Second, the approaches that were used to reduce random and geophysical noise in the profiler data will be described in more detail than originally provided in Ralph et al. (1993a), where it was assumed that readers would understand or look up basic data processing concepts. Third, a summary is given of the internal consistency checks that were performed by Ralph et al. (1993a) to assess the reliability of the gravity wave interpretations. These consistency checks were emphasized by Ralph et al. (1993a) specifically because there existed no absolute verification of the accuracy of a key measurement, the profiler vertical velocities. These cross-checks included use of surface mesonet data from which the wave propagation and surface perturbation characteristics were determined; 7 soundings in 12 h that were used to assess the ducting criteria of Lindzen and Tung (1976); and comparisons of the vertical structure, phase, and amplitude relationships that were observed versus those expected for a ducted wave. Finally, some comments will be made concerning the inconsistencies that arise concerning an alternate hypothesis that the observed vertical velocities were instead manifestations of convective vertical motions.

This reply concludes that the original interpretations in Ralph et al. (1993a) were robust, partly because the data processing substantially reduced noise in the data, which led to improved accuracy (probably near 10 cm s\(^{-1}\)) that allowed the relatively strong (50 cm s\(^{-1}\)) gravity wave signal to emerge. Waves of similar amplitude were described by Pecnick and Young (1984) using satellite cloud-top temperatures and by DeMaria et al. (1989) using the kinematic method based on closely spaced rawinsondes. In short, their comments missed the fact that a particular realization of a mesoscale gravity wave can exceed the average amplitude of 0.1 m s\(^{-1}\) that they assumed, and that their review of vertical velocity measurement accuracy is incomplete and overestimates the measurement errors.
2. On the accuracy of wind profiler vertical air motion measurements

The accuracy of vertical air motion measurements by wind profilers has been considered in several studies; however, independent measurements are not readily available for verification because the velocities are relatively small. Because Browning et al. (2000) provide an adequate review of the problem, and a thorough review of the subject of profiler vertical velocity uncertainty has not been published, this comprehensive section will illustrate the key issues, provide some examples, and show how these examples indicate that the accuracy is closer to 5–10 cm s\(^{-1}\) rather than 20–80 cm s\(^{-1}\) as suggested by Browning et al. (2000). Along with recent advances in radar technology and understanding, the absence of a current review paper on the accuracy of wind profiler vertical velocity measurement capabilities and limitations, and the relevance of such a review to this comment and reply, should lead to the creation of a formal review paper in the near future.

a. Some sampling limitations and physical processes affecting the accuracy of the measurements

The simultaneous presence of echoes from the air itself (Bragg scattering and specular reflection) and from hydrometeors (Rayleigh scattering) in the Doppler power spectrum can bias the measured velocity toward the fall velocity. In fact, the vertical velocity measured can, at times, be the reflectivity-weighted hydrometeor fall velocity instead of the vertical air motion (Fig. 1). The shorter the wavelength of the radar, and the heavier the precipitation, the more likely it is that the velocity measured will be the reflectivity-weighted fall velocity rather than the air motion (e.g., Röttger and Larsen 1990; Ralph 1995).

Spatial and temporal variability within the atmosphere on the scale of the sampling implies that the mean Doppler shift is an average of motions on smaller scales than represented by the pulse volume and sample time of the radar. Greater variability of motions on these scales leads to a broadening of the spectral width and to reduced accuracy of the vertical velocity measurement (e.g., Gage 1990; Ferrat and Crochet 1994).

Longer averaging in the radar signal processing improves accuracy by increasing the signal to noise ratio. Mismatch between the sample volume and scattering layers can result in errors due to the finite range volume effect (Fukao et al. 1988).

If the vertical beam is not perfectly vertical, then the radial velocity can include contributions from the horizontal wind (Huaman and Balsley 1996). However, this is a problem mainly when studying very small long-term average vertical velocities. It is normally thought of as producing a bias, and it is very unlikely to produce sinusoidal variations over time that could be mistaken as a gravity wave.

It has been suggested from theory that tilted scattering layers can cause errors in very high frequency (VHF) radar vertical velocity estimates due to tilting of the vertical beam by refraction (e.g., Larsen and Röttger 1991; Palmer et al. 1991). However, McAfee et al. (1994) recently showed that the vertical velocity observed by a 404-MHz radar, which is at a wavelength that does not exhibit aspect sensitivity (Röttger and Larsen 1990), matched very closely that of a collocated 50-MHz radar in an environment highly perturbed by mountain waves (Fig. 2). Thus, McAfee et al. (1994) concluded that “both systems are measuring true vertical velocities,” and that “the lack of difference in the two measurements implies, at least in this case, VHF biases . . . were not present.” They also concluded in their case that “The lack of a bias between the two sets of velocities suggests that the pointing errors are very small.”

b. A rare direct comparison between wind profiler and airborne measurements

Caccia et al. (1997a) compared independent vertical motion measurements by profiler, aircraft, and balloons. The comparison used data from within a train of strong trapped lee waves with vertical motions of up to 5 m
Long-term studies of variance have also been performed, but in those studies the measured variance is a combination of variance due to true atmospheric motions and variance due to measurement errors. Thus, the most reliable estimate of measurement error should be found in data for which true atmospheric variance is at a minimum. Results from several earlier studies are reviewed in the context of this concept.

The influence of variance in the atmospheric vertical motions on the total variance is illustrated clearly by Caccia et al. (1997b), which shows a close correlation between vertical velocity standard deviations and the height of nearby mountains upstream of the radar, which is used as a proxy for the strength of vertical motions induced by mountain waves (Fig. 3). [Recall that it has been well established that vertical air motions have larger variance near mountains than over flat terrain, e.g., Nastrom and Fritts (1992).] In Caccia et al. (1997b), the standard deviations range from 5 cm s\(^{-1}\) in flat terrain to 1 m s\(^{-1}\) near the highest mountains, such as the Colorado Rockies.

Another relevant study is McAfee et al. (1995), which also illustrates the impact of temporal averaging and data editing in data gathered at the eastern edge of the Colorado Rocky Mountains. The standard deviations calculated from 6 weeks of data gathered near the Rocky Mountains decreased from about 50 cm s\(^{-1}\) when unedited 1-min samples were not averaged and outliers were not removed, to about 25 cm s\(^{-1}\) when outliers were removed, and to 3 cm s\(^{-1}\) when the edited vertical velocities were first averaged over 24 h before the standard deviations were calculated. The estimate of 25 cm s\(^{-1}\) standard deviation is close to the estimate from Strauch et al. (1987) of 20 cm s\(^{-1}\) based on measurements from a five-beam radar in the same area. However, in both of these cases the variance includes variance from true atmospheric motions. In the case of McAfee et al. (1995), the time series contain true atmospheric vertical motions, which are expected to be rather large near the mountains. Strauch et al. (1987) used opposing oblique (off-vertical) radar beams to provide measurements of the vertical velocity for comparison with the value determined from a single vertically pointing beam. The standard deviation of the differences was 20 cm s\(^{-1}\), but part of this arises from true variations between the vertical motions at the positions of the different sample volumes and true temporal variations over the

\[ \text{Velocity (m s}^{-1} \text{)} \]

\[ \text{Hour of day 325, 1991} \]

\[ \text{Velocity (m s}^{-1} \text{)} \]

\[ \text{Hour of day 300, 1991} \]

**Fig. 2.** Direct comparison of vertical air motions observed in the (a) stratosphere and (b) troposphere by collocated UHF and VHF wind profiling radars at Platteville, Colorado, near the Rocky Mountains (from McAfee et al. 1994). The large velocities represent mountain waves, and the similarity between the measurements at the two wavelengths led McAfee et al. (1994) to conclude that “both systems are measuring true vertical velocities,” and that “the lack of difference in the two measurements implies, at least in this case, VHF biases (that have been suggested could arise at VHF due to aspect sensitivity) were not present.” They also concluded in their case that “The lack of a bias between the two sets of velocities suggests that the pointing errors are very small.”

The three methods showed agreement to within \( \pm 0.5 \) m s\(^{-1}\), which is the accuracy of their airborne measurements. Thus, this unique comparison cannot lend insight into the accuracy of the wind profiler data, except to suggest that the uncertainty is \( \pm 0.5 \) m s\(^{-1}\). It should be noted that the number of samples (six) is very small and that some of the difference is likely due to the average horizontal distance of 4 km between the measurements in an environment containing large horizontal gradients of vertical motion.

c. **Using variance in long time series to estimate uncertainty arising from measurement errors**

A standard method for determining instrument noise and bias is to make many measurements of a parameter that has a constant known value. The variance is a measure of the noise in the measurement, and the difference between the average of the samples and the known value is the bias. In the case of wind profiler vertical velocity measurements this ideal approach cannot be used. Instead, studies must depend on data gathered in the real atmosphere and thus include an unknown amount of variance due to true atmospheric motions.

Although the variance due to true atmospheric vertical motions relative to instrument error is unknown, the fact that the long-term (months to years) average vertical motion over flat terrain should be zero has allowed the detection of a bias in the measurements. Nastrom and VanZandt (1994) found that the monthly mean values measured by the Flatland VHF radar in Illinois range from about –3 to –7 cm s\(^{-1}\). They conclude that the bias arises due to the negative correlation between vertical motion and perturbations to static stability induced by gravity waves with upward energy propagation. Their data suggest that in the midtroposphere, about 60% of the gravity wave energy is in waves with upward energy propagation. Because VHF radar backscatter is sensitive to static stability, long-term averages are thus biased toward negative velocities.

Long-term studies of variance have also been performed, but in those studies the measured variance is a combination of variance due to true atmospheric motions and variance due to measurement errors. Thus, the most reliable estimate of measurement error should be found in data for which true atmospheric variance is at a minimum. Results from several earlier studies are reviewed in the context of this concept.

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roughly 5 min between sample times at the different beam positions. Thus, the variance introduced by measurement error alone in these studies must be less than 20–25 cm s$^{-2}$.

Additional studies include Gage (1990), which showed results from Kansas where the rms vertical velocity was about 10 cm s$^{-1}$ using frequent sampling in a quiescent period. Nastrom et al. (1990) used a full year of data from Illinois to determine that the monthly means of the standard deviation of the vertical velocity sampled every 2.5 min over 3-h periods were 15–20 cm s$^{-1}$ under all conditions but, under clear-sky conditions, were as low as 10–12 cm s$^{-1}$ for several months (Fig. 4).

As noted above, the best estimate of measurement errors should be found under conditions when the atmospheric contribution to the variance is minimized. The smallest published values include 5 cm s$^{-1}$ (Caccia et al. 1997b) and 10 cm s$^{-1}$ (Nastrom et al. 1990; Gage 1990) over flat terrain, as well as 20 cm s$^{-1}$ (Strauch et al. 1987) and 25 cm s$^{-1}$ (McAfee et al. 1995) near the Rocky Mountains where variance due to true atmospheric vertical motions are high. It should be noted that even these relatively small values of 5 and 10 cm s$^{-1}$ still include an unknown amount of true atmospheric variance and thus are not just due to measurement error. These results indicate that such radars can have accuracies of at least 10 cm s$^{-1}$, and probably better than 5 cm s$^{-1}$, even at high time resolutions (<10 min).

d. Indirect evidence based on experience from mesoscale meteorological studies

Some studies have used profiler vertical velocity data to explore the structure and behavior of mesoscale phenomena. Confidence is gained in the observed structure through comparison with ancillary measurements, with theory, and with numerical simulations. These studies lend insight into the accuracy because agreement would not be possible if the data were too inaccurate.

One of the earliest findings was that measured vertical velocities had the greatest amplitude and variability when a profiler was located downstream of mountains and were thus affected by mountain waves. Initially, studies documented this enhanced variability at various places around the world (Ecklund et al. 1982; Balsley and Carter 1989; Sato 1990). Ralph et al. (1992) then showed that the timing and vertical structure of the vertical velocity perturbations observed by a profiler were consistent with theoretical expectations based on well-established mountain wave theory that allowed distinction between vertically propagating and trapped mountain waves. This consistency was illustrated further by Prichard et al. (1995) and by Worthington and Thomas (1996). Worthington and Thomas (1996) showed that the profiler-observed vertical motions decreased to less than 10 cm s$^{-1}$ on average above a mean state critical level through which theory predicts upward propagating gravity wave energy originating from below cannot pen-
etrate. Most recently, Ralph et al. (1997) showed remarkable agreement between the observed vertical structure of a trapped lee wave and that predicted by a numerical model in a study of mountain wave nonstationarity (Fig. 5).

Profiler vertical velocities have also been used in studies of fronts. The vertical air motions associated with a strong and precipitating warm front were shown by Crochet et al. (1990) to have a structure characteristic of direct vertical circulations known to occur with such fronts. In their study the maximum vertical air motions within the frontal zone were found to be 30–40 cm s\(^{-1}\), which is nearly identical to the values found in an earlier study by Heymsfield (1979) that used two scanning Doppler radars. In Ralph et al. (1993b) the data revealed a train of vertically trapped gravity waves triggered by a cold front. The observed waves extended up to 3.5–4.0 km had horizontal spacing of 8.2 km between major downdrafts, and the vertical velocity amplitude was at least 3 m s\(^{-1}\). A numerical simulation of this case (Jin et al. 1996), which was initialized using the observed complicated stratification and vertical wind shear, also produced a train of waves. The simulated waves were almost identical to those observed. They extended up to 3.5–4.0-km altitude, had a horizontal spacing of 7.1 km between major downdrafts, and the vertical velocity amplitude was at least 3.6 m s\(^{-1}\).

The successful diagnosis of mesoscale structures associated with mountain waves and fronts through the use of profiler vertical velocity measurements in these many and varied studies indicates that the technique is accurate enough to describe these phenomena, which had amplitudes of 0.4–4.0 m s\(^{-1}\). It should also be noted that these later observations contradict the generalization in Browning and Kreiss (1997) that “in the absence of topography, mesoscale motions with vertical velocities \(O(1 \text{ m s}^{-1})\) can exist only in the presence of heating...”. For another well-established example of this one need only to consider trapped lee waves. Several studies (e.g., Foldvik 1962; Vergeiner and Lilly 1970; Cruette 1976; Ralph et al. 1997) have documented vertical motions of up to at least 7 m s\(^{-1}\) and horizontal wavelengths of 10–25 km, a horizontal scale that is well within the mesoscale as defined by Orlanski (1975).

e. Application of error estimation theory for wind profiler sampling strategies

Another approach to assessing accuracy is based on the theoretical sampling error estimation technique of Ferrat and Crochet (1994). This approach indicates that the vertical velocity estimation error for a radar with the characteristics of that used in Ralph et al. (1993a) was 12 ± 6 cm s\(^{-1}\), depending on whether a narrow or a broad spectral width is assumed. [Relevant radar parameters in Ralph et al. (1993a) were spectral resolution = 0.20 m s\(^{-1}\); number of spectral averages = 3; and signal to noise ratio at the appropriate altitudes were generally greater than 0 dB.]

f. Summary of accuracy issues

Although the assessment of profiler vertical velocity accuracy is made difficult by the absence of verification
data, and not all profilers provide data of equal accuracy, a host of observational and theoretical studies provide insight into what this accuracy might be. Direct comparisons between collocated radars (McAfee et al. 1995) or between opposing beams of the same radar (Strauch et al. 1987) yield standard deviations of 20–25 cm s$^{-1}$ for short timescale measurements, but these comparisons were made in a region characterized by large natural background vertical velocity variance due to mountain waves (Caccia et al. 1997b). [In Strauch et al. (1987) this standard deviation is increased by inclusion of spatial and temporal variances due to the use of several off-zenith beams run sequentially rather than a single dedicated vertical beam, such as was used in Ralph et al. (1993a).] When a similar comparison was made over flat terrain, the differences between vertical motions measured in nearly the same sample volume by different beams results in an estimated uncertainty of 10 cm s$^{-1}$ (W. Clark 1998, personal communication).

In most of these cases, the Doppler power spectra were not carefully edited, a step that reduced background noise in Ralph et al. (1993a) simply by removing obvious outliers and by reducing contamination of the first-moment calculation due to precipitation echoes in the Doppler power spectrum. While it is impossible to provide an absolute value for the accuracy of the vertical velocity measurements used in Ralph et al. (1993a), it is reasonable to conclude that it is 10 cm s$^{-1}$ or better, based on estimation error characteristics, on the careful editing of the Doppler power spectra, and on experience from other statistical and dynamical studies that used such data.

3. Limitations of the review of accuracy presented by Browning et al. (2000)

The summary of profiler vertical velocity accuracy by Browning et al. (2000) does not provide an adequate review. For example, they refer to Wuertz et al. (1988) as evidence that vertical velocity errors in precipitation are at least 0.4–0.8 m s$^{-1}$, but these values are based on the maximum range of velocity differences between four different ways used to measure fall speeds using 1-h averages of different configurations of a five-beam profiler. This required assuming spatial and temporal homogeneity on scales 5–10 times larger than those required for the single vertical beam technique used in Ralph et al. (1993a) and in most other profiler vertical velocity studies. This fact, along with the nonstatistical nature of the comparison, suggest that this approach to estimating clear-air vertical velocity measurement uncertainty is inappropriate.

Browning et al. (2000) also depend largely on experience from the NPN’s 404-MHz radars that have relatively large noise in their vertical velocity data, as illustrated by a comparison with a collocated 50-MHz profiler presented by McAfee et al. (1995). This comparison (Fig. 6) showed that the standard deviation of the 404-MHz measurements was 2–4 times that of the 50-MHz profiler data over a 6-week period, where the highest time resolution data (i.e., 1–6 min) were used. Additionally, their examples are based on data that have not been carefully edited at the level of the Doppler power spectrum, as is done in research where more subtle signals are the subject of study. Part of this difference lies in the fact that the 404-MHz radar network was implemented primarily as an operational observing system rather than as a system of research radars.

It is possible to use the results of McAfee et al. (1995) to estimate the minimum uncertainty of the vertical velocity measurement of the 404-MHz Platteville, Colorado, wind profiler. Because both radars were sampling very similar volumes in space, it should be expected that the variance in the time series that is the result of true atmospheric motions should be approximately equal for both radars. This implies that the difference between the variances in the two systems arises only from noise and differences between sources of backscatter (i.e., hydrometeor fall velocities dominate more at UHF than at VHF). However, even at stratospheric altitudes where hydrometeors are not present, the difference between the variances is large. Thus, the comparison of McAfee et al. (1995), which is shown here in Fig. 6, indicates that the measurement noise in the 404-MHz radar vertical velocities is at least 0.4 m s$^{-1}$. Thus, the subjective
opinion proffered by Browning et al. (2000), that 0.5 m s\(^{-1}\) amplitude waves are not evident in the 404-MHz profiler network, is consistent with the fact that these radars are too inaccurate to see such waves. Thus, their cursory impressions cannot be used to support the conclusion in Browning et al. (2000) that waves of 0.5 m s\(^{-1}\) amplitude, such as documented by Ralph et al. (1993a), are not observable by wind profilers.

In addition, after simple removal of outliers based on spectral moment data, and avoiding periods of precipitation, McAfee et al. (1995) showed that the variance in the 404-MHz data was reduced to almost match that of the 50-MHz data. This strongly suggests that even simple removal of outliers could give the NPN profiler data an improved possibility to see these waves; however, there still is no method to retrieve the vertical air motions in the presence of precipitation from the NPN data, such as has been often employed in numerous studies using other radars (e.g., Wakasugi et al. 1986; Gossard 1988; Gossard et al. 1990; Rogers et al. 1991; Ralph et al. 1993a; May and Rajopadhyaya 1996). Thus, the NPN spectral moment data would remain unable to reveal the waves in the context of the much larger fall velocities (2–10 m s\(^{-1}\)) that the NPN radars observe in precipitation.

4. Reducing noise in the data

Noise can enter measurements through random errors, systematic errors, geophysical phenomena that interfere with the signal of interest, etc. One of the most effective ways to reduce noise in wind profiler data is to manually examine and edit the Doppler power spectra where several sources of random and geophysical noise can be readily apparent, as in the example from May and Rajopadhyaya (1996) shown in Fig. 1. [See Gage (1990); Gossard (1990) and Ralph et al. (1995) for descriptions of the wind profiler measurement technique and the Doppler power spectrum.] Although this step is time-consuming, it takes advantage of human pattern recognition abilities and thus was used by Ralph et al. (1993a). Ultimately Ralph et al. (1993a) employed a wide range of well-established data processing techniques (point-by-point removal of obviously spurious data, physics-based removal of geophysical noise, and spectral filtering) to extract a subtle signal from the measurements. These techniques were described concisely in the original text and are expanded upon here.

1) Obviously spurious data points, such as those likely due to aircraft and radio interference, were removed by editing the Doppler power spectra.

2) Contributions to the Doppler power spectrum by Rayleigh scattering from hydrometeors were edited out of the spectra, and then the first moment of the spectrum (i.e., the radial velocity) was recomputed. This was done because the Doppler power spectrum observed by a VHF wind profiler can contain signals from both the clear air (through Bragg scattering from turbulence and specular reflection from thin stable layers) and from hydrometeors (through Rayleigh scattering). Bragg and Rayleigh scattering leave distinctive signatures in the Doppler power spectrum because one represents the vertical air motion and the other the reflectivity-weighted fall velocity of the hydrometeors (Fig. 1). This can be used to separate the two signals, as was the case in the data of Ralph et al. (1993a), and as is widely used to measure drop-size distributions (e.g., Wakasugi et al. 1986; Gossard 1988; Gossard et al. 1990; Rogers et al. 1991; May and Rajopadhyaya 1996). As pointed out in reviews of radar meteorology by Battan (1973) and Jameson and Johnson (1990), this knowledge improves on other techniques where vertical air motions have to be inferred or assumed in order to calculate drop-size distributions. Removal of the Rayleigh scattering part of the spectrum in Ralph et al. (1993a) not only eliminated those velocities that represented precipitation fall velocities instead of air motion, but it also reduced biases in measured vertical air motion that arise when the spectrum includes both components. This approach yielded the best estimates of vertical air motion. It should also be noted that under precipitating conditions, such as shown in Fig. 1, the distinct separation between the clear-air and precipitation echoes in the Doppler power spectrum in rain implies that the accuracy of the vertical air motion measurements in rain (after removal of signals from Rayleigh scattering) should be comparable to that found in the absence of rain.

3) Because convective updrafts and downdrafts represent another form of geophysical noise with respect to the search for the weaker mesoscale gravity wave motions, these strong vertical motions were removed by editing the time series of vertical velocity measurements. This editing represented a form of filter based on the assumption that a scale separation exists between the relatively weak gravity wave vertical motions and the convective vertical motions. A threshold of 2 m s\(^{-1}\) was used as a criterion to separate the wave and convective motions. This value was based on the fact that vertical air motions within deep convective storms (such as those that crossed the profiler) can greatly exceed this threshold, while mesoscale gravity wave motions should not be that strong. Because there were very few measurements of air motions greater than 2 m s\(^{-1}\), and those exhibited little temporal continuity, the resulting data gaps were filled by interpolation in time (recall that measurements were made every 1–3 min and the wave period was 90 min). Removal of these isolated sharp spikes in the time series helped suppress leakage of this high-frequency energy into lower frequencies during Fourier time series analysis.
4. The last step in isolating the gravity wave signal from noise consisted of Fourier spectral analysis and application of a bandpass filter.

5. Consistency checks on the mesoscale gravity wave interpretations

Ralph et al. (1993a) used not only wind profiler vertical velocity data but also additional data from a major field program. This allowed the results of the profiler analysis, including those aspects for which Browning et al. (2000) have expressed doubts, to be tested for internal consistency and for consistency with theoretical expectations. The key facts are as follows:

- A mesoscale network of eight surface barographs over a 50 km × 50 km domain allowed measurement of the horizontal phase velocity of a disturbance found in surface pressure that had the same dominant 90-min periodicity as was found in the profiler vertical velocities.
- The availability of seven radiosonde ascents during 12 h of the period of interest allowed a determination that the ducting criteria of Lindzen and Tung (1976) were met. However, the presence of some wave energy just above the critical level (Ralph et al. 1993a; Ralph 1997) indicates that the duct was leaky. [Browning et al. (2000) wonder why the wave was not present earlier and later than it was. This leakiness, along with the simple fact that the duct did not extend to infinity in the horizontal or in time, limited the spatial and temporal extent of the wave. In addition, the layer of weak stability that helps form the wave duct is also susceptible to convective motions, and thus it is not surprising that the wave and convection are found in proximity to one another.]
- Ducted gravity wave theory provided a method to predict the horizontal phase speed based on the characteristics of the wave duct, and the impedance relation allowed surface data to predict the phase speed as well using completely independent data. Both of these methods, each based not on the dynamics of convection but rather on gravity wave dynamics, predicted the same horizontal phase speed that was observed using cross-correlation methods applied to the surface pressure data independent of theory.
- The phase relationship between the profiler-observed vertical structure and the surface wind and pressure fit the structure of a ducted gravity wave.
- The amplitude of the vertical motions were shown to be consistent with the observed surface pressure perturbation amplitude.
- The vertical structure observed in Ralph et al. (1993a), and interpreted as a mesoscale ducted gravity wave, matches very closely the vertical structure predicted for such a wave by linear theory in a similar event studied by Monserrat and Thorpe (1996), as is shown in Ralph (1997).

These facts show strong internal consistency using independent measurements and consistency with the theory for ducted mesoscale gravity waves. In contrast, the supposition by Browning and Kreiss (1997) that the surface pressure perturbations are primarily a consequence of latent heating and cooling due to deep convection would predict that the vertical structure should include large vertical motions in the vicinity of the near-neutral layer where potential instability would be realized. However, the observations indicate that a node (zero vertical velocity) is located at this near-neutral, or conditionally unstable, layer, as is expected for a ducted gravity wave based on Lindzen and Tung (1976). Their supposition also includes a prediction that the surface pressure perturbation is a result of the convection. However, Ralph et al. (1993a) demonstrated that no clear correlation existed between precipitation, which is tied to the convection, and surface pressure perturbations. In short, because the vertical structure of a ducted gravity wave is fundamentally different from that of convection, measurements of the vertical structure provide a means to distinguish between them.

6. Summary

Although direct verification of high time resolution VHF profiler vertical velocities is nearly impossible, the summary provided in section 2 provides evidence that the accuracy of such measurements is at least 10 cm s⁻¹, and probably better than 5 cm s⁻¹, even in rain. It was also shown that the data processing performed by Ralph et al. (1993a) reduced well-established sources of random and geophysical noise in the data through careful editing of the Doppler power spectrum and through Fourier spectral analysis.

It is difficult to fathom how all of the internal and theoretical consistencies, both structural and quantitative, presented in Ralph et al. (1993a) and summarized above could hold and yet the analysis be invalid due to unknown uncertainty in the profiler vertical velocity measurement technique and supposedly improper data editing. It is precisely the consistency between the independent datasets, and theory that makes the interpretations of ducted wave structure most reliable.

Finally, in contrast to several assertions in Browning and Kreiss (1997) and in the comments by Browning et al. (2000), the evidence presented here strongly supports the view that mesoscale gravity waves can be detected in surface data in the presence of deep convection and that such waves can be distinguished clearly from the convection through careful analysis of VHF wind profiler vertical velocity data.

REFERENCES


