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Investigations of Internal Gravity Waves Using Three Vertically Directed Closely Spaced Wind Profilers

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A network of three wind profilers spaced about 5 km apart was operated in southern France during the Alpine Experiment (ALPEX) program. The wind profilers measured vertical motions, and the experiment was designed to study traveling internal waves by comparing the vertical velocity fluctuations observed at each station. The measured phase velocities, together with the observed periods, were used to deduce the horizontal wavelength of the waves. Only a relatively few cases of monochromatic waves could be identified using this array. Most of the waves that were detected had phase velocities opposite to the prevailing wind and had the speeds required to cause trapping as the intrinsic frequency was Doppler shifted upward to the Brunt-Väisälä frequency.

1. INTRODUCTION

During the past 2 decades, internal gravity waves have become widely recognized as important contributors to the dynamics of mesoscale atmospheric motions [Gossard and Hooke, 1975; Einaudi *et al.*, 1979]. Many of their properties have been deduced from studies utilizing ground-based pressure sensors [Keliher, 1975; Gedzelman and Rilling, 1978; Gedzelman, 1983]. A few studies have attempted to relate wave activity observed by remote probes with wave activity observed on the ground by sensitive microbarographs [Ottersten *et al.*, 1973; Hooke and Hardy, 1975; Einaudi *et al.*, 1987].

With the advent of wind profiling Doppler radars [Gage and Balsley, 1978], a new tool is available to study in more detail internal waves in the troposphere and lower stratosphere. The first continuous observations of vertical velocities using wind profiler technology began in 1979 when the first phase of the Poker Flat MST mesosphere, stratosphere, troposphere radar, located near Poker Flat, Alaska, became operational [Balsley *et al.*, 1980]. An analysis of the first vertical velocity data from Poker Flat [Ecklund *et al.*, 1981] showed ubiquitous internal wave activity. The outstanding feature of the multiheight time series of vertical velocities was the clear alternation between periods of "quiet" and "active" wave activity every few days. During the active periods all altitudes observed showed the increased wave activity simultaneously. Ecklund *et al.* [1981] were able to relate the active periods to the occurrence of strong wind and wind shear associated with baroclinic zones. A recent study of the spectrum of vertical motions [Ecklund *et al.*, 1986] observed by various wind profilers under light wind conditions supports the idea of a nearly universal spectrum of internal gravity waves in the free atmosphere analogous to the Garrett-Munk spectrum of internal waves in the ocean [VanZandt, 1982].

A few cases of monochromatic wave activity were isolated during the early months of operation at Poker Flat. Perhaps the best example of a monochromatic wave event was the case of October 12, 1979 [Gage *et al.*, 1981], when a nearly sinusoidal wavelike oscillation was observed in vertical velocity. This wave event, reproduced in Figure 1, persisted for several hours and was evident in several adjacent range gates spanning about 4 km in altitude. The oscillation in vertical velocity had an amplitude of about 1.5 m/s and a period of 18 min.

The wave event of October 12, 1979, is fairly typical of coherent wave events observed in vertical velocity data. In particular, individual events show little evidence of vertical phase progression, suggesting that they may be trapped waves. However, when data are available only from a single station, further study of the dynamics of such waves is quite limited. A network of at least three stations is needed to unambiguously determine the horizontal wavelength and phase velocity of internal gravity waves.

2. OBSERVED WAVE ACTIVITY DURING THE ALPEX INTERNAL WAVE EXPERIMENT

In the spring of 1982 a cooperative United States-France clear air radar experiment was carried out on the southern coast of France during the Alpine Experiment (ALPEX). Three relatively small vertically directed 50-MHz wind profilers were set up with spacings of about 5-6 km. Figure 2 shows the location and configuration of the radars, while Table I gives the system parameters. The three radars were operated concurrently for a period of about 6 weeks, with 1-min temporal resolution and 750-m height resolution. Doppler spectra of the return signals were computed at each site and tape recorded for later analysis. A time series of vertical velocities at each sampled range gate was created for each station by computing the first moment of the Doppler spectra. A more complete description of the experiment together with an examination of temporal and spectral characteristics of the vertical velocity fluctuations has been presented by Ecklund *et al.* [1985].

Examples from the ALPEX data set displayed in Figure 3 show the highly variable nature of the vertical velocity fluctuations. This variability was directly related to the background wind conditions. For example, during April 30,

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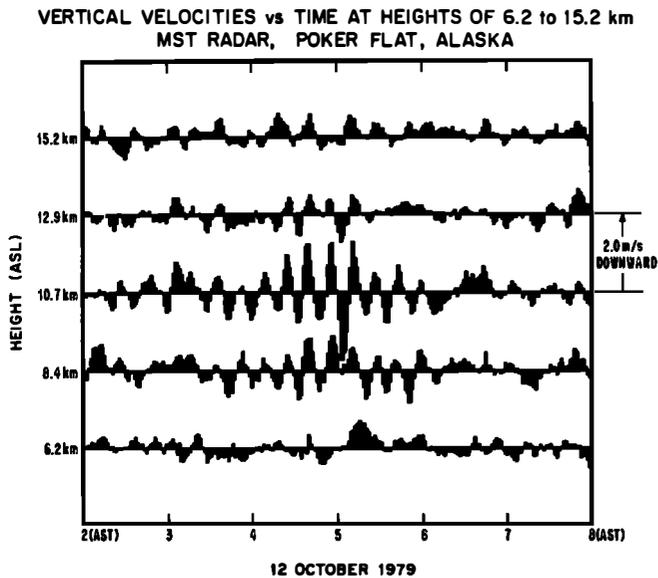


Fig. 1. Vertical velocities observed from 6.2 to 15.2 km for 6 hours on October 12, 1979, by the Poker Flat MST radar [after Gage *et al.*, 1981].

an active period of strong (30–40 m/s) southward mistral winds, the vertical velocities often reached 2 m/s, with dominant periods of several hours. However, during quiet periods of weak horizontal winds (less than 5–10 m/s) such as occurred on May 14 the vertical velocities were less than 10–20 cm/s, sometimes with noticeable oscillations near the Brunt-Väisälä period (around 10 min). For most days, like May 10, for example, vertical wind velocities were between these extremes, with horizontal winds around 10–20 m/s and vertical velocity fluctuations which were broadband and variable. There were also a very few instances of monochromatic wave events, such as on May 25. These events generally occurred with rather low (<10 m/s) background horizontal winds.

3. DETECTION OF SPECIFIC WAVE EVENTS

Our goal in this experiment was to investigate the characteristics of gravity waves as they propagated across the network of three wind profilers. Horizontal characteristics of propagating gravity waves (e.g., wavelength, phase speed, and propagation direction) can be determined by measuring the phase differences in the vertical velocity fluctuations between all station pairs, provided that the wavelengths are resolved by the network dimensions. Two separate methods were used in our analyses to determine the phase differences, that is, cross-correlation analysis and coherency (cross-spectral) analysis.

Cross-Correlation Analysis

The entire data set from the profiler network was first visually searched for large-amplitude, nearly monochromatic vertical velocity fluctuations. A cross-correlation function was computed for each of these wave events in order to obtain the time delay between each station pair. As an example, the cross-correlation functions for a 100-min interval on May 25 are shown in Figure 4. For this particular period the correlation is extremely good. The wave has a period of about 25 min. By using the local maximum closest

to zero time lag in each function the wave can be shown to have a horizontal wavelength of about 15 km and a phase velocity of approximately 10 m/s from an azimuth of about 350°.

Table 2 shows the wave parameters derived from cross-correlation analyses for other times of obvious wave activity. Also given are the mean wind magnitude and direction at the altitude of the wave, as determined by sounding balloons launched at 6-hour intervals by the French Meteorological Service at Nimes (compare Figure 2). Except for May 22 the other events listed in Table 2 were not nearly as sinusoidal as on May 25, but occasionally a wavelike oscillation would last long enough to allow computation of the correlation function. The wave periods ranged from 15 to 60 min, and the computed horizontal wavelengths were between 7 and 20 km. Two wave directions are given for May 22, since the time lag between two of the radars was about half a wave period, and thus it could not be determined which station was leading the other. Such spatial aliasing is, of course, a possibility for any of the other waves, although only the unaliased wave solutions are shown. Amplitudes of the oscillations varied between about 0.25 and 1.0 m/s.

Coherency Analysis

The cross-correlation analysis works well when the two time series being compared contain large-amplitude monochromatic waves. On the other hand, when multiple waves are present or when the wave is weak and embedded in noise, other techniques must be applied to derive wave parameters. Since there were very few strong wave events observed during the ALPEX observation period, we decided to use a coherency spectrum analysis to search for weaker waves that may be in the data. Because the coherency spectrum can be thought of as a cross correlation that is a function of frequency, it should be better able to separate coherent signals from the more broadband uncorrelated velocity fluctuations.

The coherence function used here is defined as the square root of the magnitude-squared coherence function (see, for example, Bendat and Piersol [1971] and Julian [1975]). Coherence functions were calculated from cross spectra of vertical velocities for each of the three possible pairs of stations for the entire 6-week observing period. Typically, cross spectra were computed for data sets of 256 one-min velocity points to which a Hanning window had been applied [Saunders and Hamrick, 1982]. To reduce the variance and the bias of the calculated coherence functions, the cross spectra were averaged in time over periods from 6 to 24 hours and in height over six range gates between 3.1 and 6.9 km altitude. The data sets were overlapped 50% in time. Because the windowing function had been applied to the data, the cross spectra from these sets were essentially independent [Harris, 1978].

Wave parameters (horizontal wavelength, phase speed, and direction) were calculated from the phases of each cross-spectral point within a band of frequencies in which the coherence for each station pair was above the 99% confidence level. Additionally, the wave analysis was often extended to adjacent frequency points whose phases were consistent with those in the high coherence band, even if not all the coherences at those points quite reached the 99% confidence level. The limiting coherence at confidence level p is given by

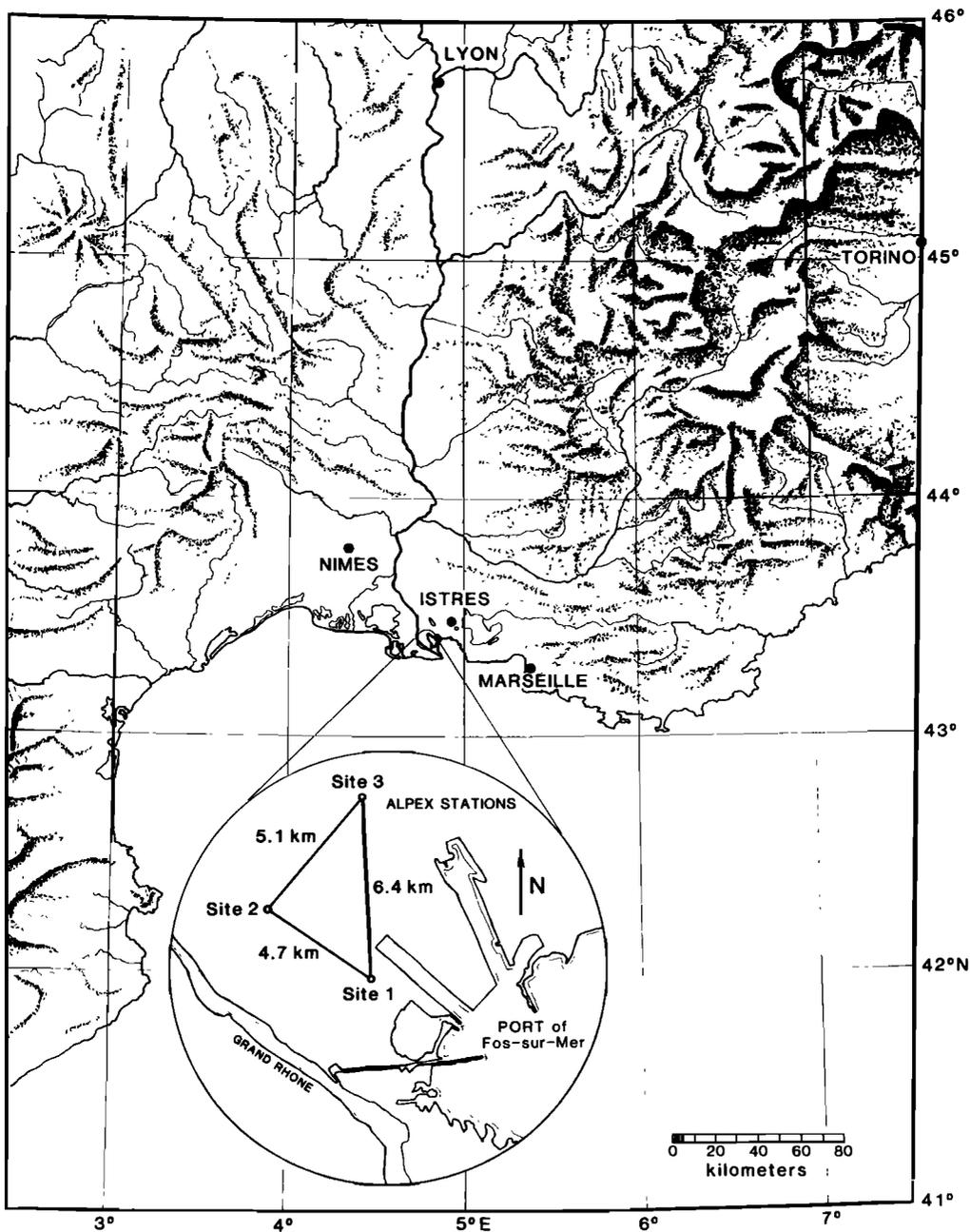


Fig. 2. Plan view of the three-station ALPEX radar experiment in southern France. Inset shows details of site locations.

$$[1 - (1 - p)^{1/(n-1)}]^{1/2} \quad (1)$$

where n is the number of independent cross spectra averaged together [Julian, 1975].

As an example, the coherence spectra for May 14 appear in Figure 5. The coherences were calculated over a 25-hour data set and represent the average of 66 cross spectra. The long-dashed line indicates the 99% confidence level. The

TABLE I. System Parameters for the ALPEX Radar Experiment

Site	Frequency, MHz	Antenna Dimensions, m ²	Average Transmitted Power, W	Pulse Width, μs	Height Resolution, m	Time Resolution, min
1	49.640	(70 × 100)	~200	5	750	~1
2	49.920	(70 × 100)	~200	5	750	~1
3	48.850	(70 × 50)	~200	5	750	~1

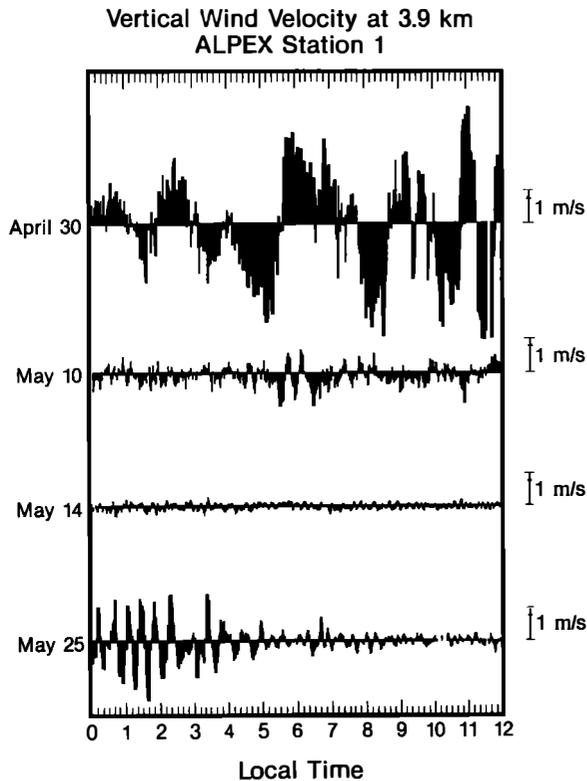


Fig. 3. Examples of the vertical velocity at 3.9 km from site 1 for 12-hour periods on four different days.

short-dashed line below that represents the bias for zero coherence, that is, the expected value of the calculated coherence for signals with a true coherence of zero [Carter *et al.*, 1973]. Note that the coherences for all three station pairs are significant between about 3×10^{-4} and 6×10^{-4} Hz (about 30- and 60-min periods) and that the coherence between sites 1 and 2 is much higher at low frequencies than the coherences involving site 3.

Figure 6 shows the phases corresponding to the coherences in Figure 5. Wave parameters were calculated from the phases at frequencies within the high coherence band. For reference, the dashed curve in Figure 6 represents the phase that would occur for waves propagating at 12 m/s from an azimuth of 230° for all periods between about 15 min and 2 hours. The observed phases follow this general curve even at wave frequencies where the coherences did not reach the 99% confidence level. Note that the deduced wave propagation was not simply due to wind advection of velocity fluctuations, since the winds during this period were light and variable up to about 7 km altitude and were from an azimuth of 300° near 10 km.

Out of the entire ALPEX data set, seven wave events were detected by the coherency analysis technique. Table 3 lists these events along with their derived wave parameters and the horizontal winds at the wave altitude (measured 60 km away at Nimes). The wave periods of the seven events ranged from 20 to 90 min, and the deduced horizontal wavelengths were between 10 and 40 km. Amplitudes of the waves can be estimated by integrating the spectral power within the frequency band of high coherence. The value of the coherence indicates what fraction of that power is due to the coherent wave. Calculated amplitudes ranged from 3 to 10 cm/s.

A comparison can be made between the cross-correlation results shown in Table 2 and the coherence results in Table 3 for three common days: April 25, May 2, and May 10. The wave direction derived from cross correlations of short periods of sinusoidal oscillations agree well with those determined from the coherence analysis over a longer time period.

Table 3 shows that the background winds during the wave events detected by the coherency analysis were generally moderate, averaging about 10–20 m/s in the 3- to 7-km observational height range. Both very active and very quiet days tended to have poor coherences between radar sites. The lack of coherence on very active days such as April 30, shown in Figure 3, is consistent with the impression that the strong vertical fluctuations were due to lee wave structures. Such structures would have no consistent phase relationship from site to site for significant periods. With the exception of

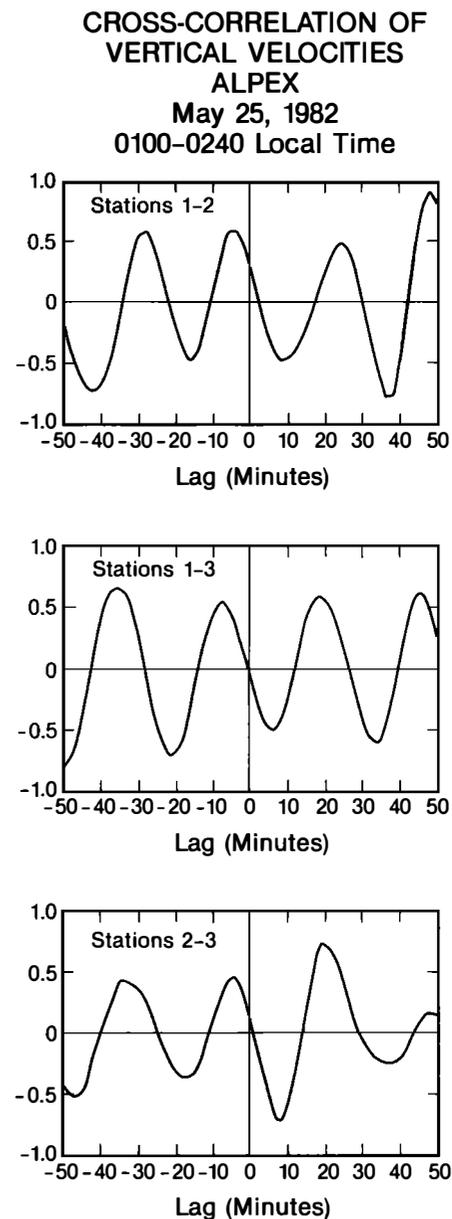


Fig. 4. Cross-correlation functions computed between the three pairs of radar sites at 3.1 km for 0100–0240 LT on May 25, 1982. Positive values of lag time indicate that the first station leads the second station of the pair.

TABLE 2. Waves Derived From Cross-Correlation Analysis

	Time	Height, km	Wave Period, min	Horizontal Wavelength, km	Horizontal Phase Speed, ms ⁻¹	Wave Direction	Wind Direction	Wind Speed, m/s
April 25	0600–0800	4.5	30	10	5.6	200°	0–20°	10–15
May 2	1400–1600	4–5	60	15	4.2	170°	300°	15–20
May 9	1500–1700	4	40	12	5.0	330°	240°	15–20
May 10	2200–0200	4–5	40	20	8.3	320°	~270°	5–10
May 11	1700–1820	4	20	15	12.5	90°	200°–240°	5–10
	1800–1900	7–8	20	18	15.0	110°	200°–240°	5–10
May 22	0100–0200	4	15	7	7.8	270°	300°–340°	5–10
						or 80°		
May 25	0100–0240	3.4	25	15	10.0	350°	340°	10

May 14, the correlation was also poor on very quiet days, that is, days with low horizontal winds and low-amplitude vertical velocity fluctuations. Although fluctuations near the Brunt-Väisälä period could be discerned in the time series on these quiet days, the coherent wave periods, if there were any at all, tended to be around 30–60 min. This lack of coherence between radar sites for oscillations near the Brunt-Väisälä period suggests that their correlation distance was less than about 5 km.

4. ANALYSIS OF WAVE EVENTS

From the cross correlation and coherency analyses of the profiler network data we have been able to derive the horizontal propagation characteristics of several wave events, as summarized in Tables 2 and 3. Furthermore, since we also have measurements of the horizontal wind from the Nimes balloon, we can derive additional parameters relating to the vertical propagation of the waves.

As discussed, for example, by *Bretherton* [1969], vertically propagating internal gravity waves conserve their observed frequency and phase speed relative to the ground, as well as their horizontal wavelength. However, both vertical wavelength and intrinsic frequency change as the wave propagates through a height-varying background wind.

The intrinsic frequency of an internal wave ω , that is, the frequency of the wave in the frame of reference moving with the wind, is related to the observed frequency ω_0 ($=2\pi/T_0$) by

$$\omega = \omega_0 - \vec{u} \cdot \vec{k} \quad (2)$$

where \vec{u} is the mean flow velocity and \vec{k} is the wave number vector of the wave ($|\vec{k}| = 2\pi/\lambda$). Within the bounds of the WKB approximation, that is, assuming that the characteristics of the atmosphere change very slowly with respect to the wavelength and wave period, the vertical wavelength λ_z can be approximated from

$$\lambda_z^2 = \lambda_H^2 [\omega^2 / (\omega_{BV}^2 - \omega^2)] \quad (3)$$

where λ_H is the horizontal wavelength, and the Brunt-Väisälä (B-V) frequency is given by $\omega_{BV}^2 = (g/\theta)(\partial\theta/\partial z)$. g being gravitational acceleration and θ the potential temperature. It is also assumed in (3) that the intrinsic wave period $T = 2\pi/\omega$ is much less than the inertial period (17.5 hours at the ALPEx profiler network latitude).

According to (2), the intrinsic wave frequency is equal to the observed frequency Doppler shifted by the component of the wind in the direction of wave propagation. The sign of

this component determines whether the intrinsic frequency is Doppler shifted to a higher or lower frequency compared to the observed frequency. Figure 7 displays the wave propagation direction and the background wind direction at the wave altitude for each of the seven wave events detected by the coherence analysis (Table 3). The striking point to notice is that in most cases the waves were propagating essentially into the mean wind. Exceptions occur on May 10 and May 14, when the waves were propagating perpendicular to the background wind. During the May 10 event, however, the wind just above the observed wave also had a strong component opposite the wave direction.

The effect of the background wind profile upon the intrinsic period of each wave event in Table 3 is shown in Figure 8. The intrinsic period as a function of height was calculated from (2) using the radar-observed frequency ω_0 , horizontal wavelength, and propagation direction (all assumed to remain constant with height), along with the height-dependent horizontal winds measured at Nimes. The observed range of coherent wave periods is shown at the bottom of each graph, and a typical Brunt-Väisälä period of 10 min is also indicated by the vertical dashed line. The actual B-V period as calculated from the Nimes rawinsonde observations typically varied with height between values of about 8 and 12 min.

It can be seen in Figure 8 that for every wave event except one (May 14), the intrinsic wave period was Doppler shifted toward higher frequencies and at some height in the upper troposphere reached or came very close to the Brunt-Väisälä period. From (3) it can be seen that as the intrinsic wave frequency approaches the B-V frequency, the vertical wavelength λ_z approaches infinity. Further vertical wave propagation is impossible at that point, and the wave is reflected. Thus 6 of the 7 waves detected by the coherence analysis were most likely trapped in the troposphere. The only exception occurred on May 14, when the wind and wave propagation were at right angles at all heights and no Doppler shifting took place.

Of the wave events analyzed by the cross-correlation technique (Table 2), three (April 25, May 2, and May 10) occurred during periods of trapped waves already shown in Figure 8. In addition, analysis of the wind profiles during the two events of May 11 shows that the intrinsic frequencies of those waves were also Doppler shifted to the B-V frequency, thus trapping them in the lower troposphere. Therefore excluding the ambiguous case of May 22, only two of the

VERTICAL VELOCITY COHERENCES

ALPEX Wind Profilers
1982 May 14, 0400 LT to May 15, 0536 LT
Heights 3.1–6.9 km

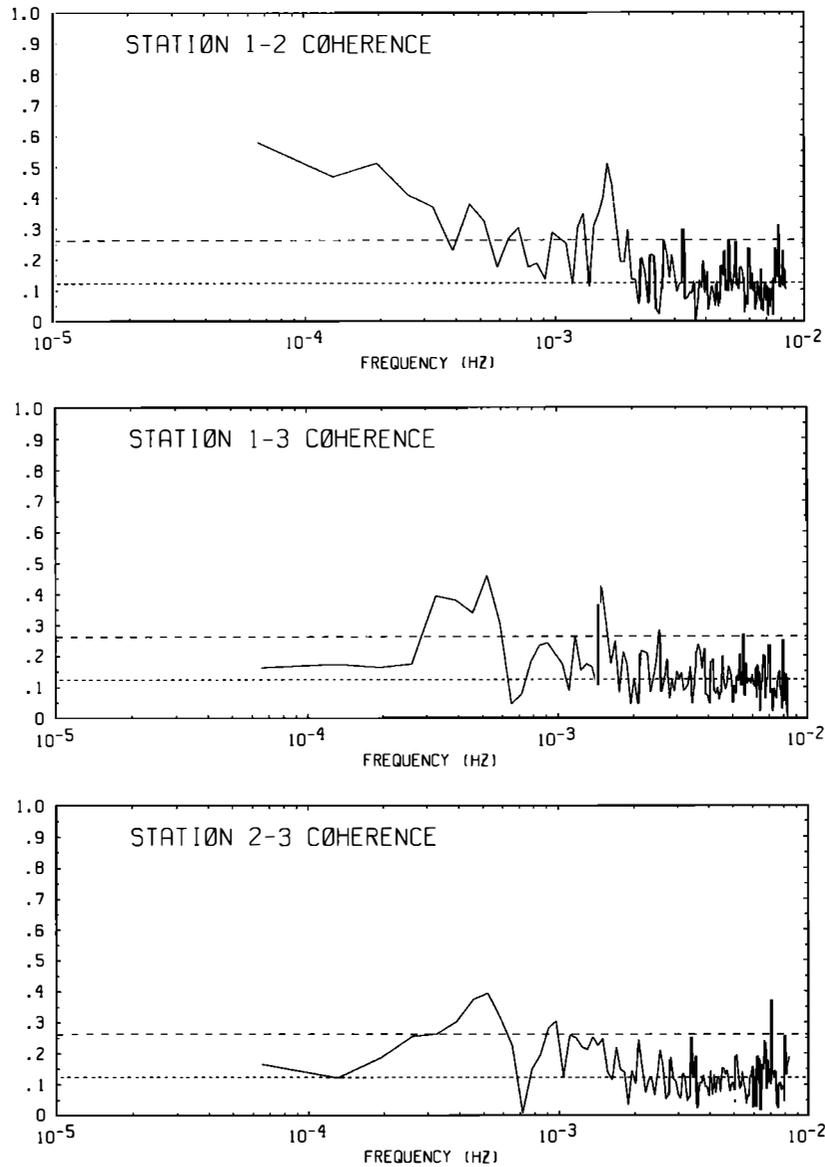


Fig. 5. Coherence spectra for May 14, 1982. The spectra were averaged over 25 hours and six height ranges between 3.1 and 6.9 km. The long-dashed line is the 99% confidence level. The short-dashed line is the bias of the estimate for zero coherence.

events listed in Table 2 (May 9 and May 25) appear not to have been trapped waves.

For those wave events listed in Table 3, the coherence of the vertical velocity fluctuations between different heights was also calculated. The amplitude of the coherence fell off rapidly with increasing height separation and typically lost significance beyond three range gates (2.25-km separation). For the first six wave events in Table 3 the phase differences between heights were very noisy but were consistent with the zero-phase progression with height that would be expected for trapped waves. Of course, as a trapped wave approaches its reflection point and the vertical wavelength begins to approach infinity, the conditions for the WKB approximation are no longer valid, and the detailed behavior

of the wave in this region becomes more complicated. For the nontrapped wave event (May 14), vertical phase differences also had large variance but seemed to indicate a vertical wavelength of around 5–10 km, which is roughly what would be expected for a non-Doppler shifted wave with a 45-min period and a 30-km horizontal wavelength.

5. LONG-TERM COHERENCE BETWEEN STATIONS

Although the coherence analysis discussed above was applied to specific wave events with high coherence in a rather narrow frequency band, the same analysis can be applied to the entire data set over a wide range of frequencies to determine the overall coherence of vertical velocity fluctuations between

VERTICAL VELOCITY PHASES

ALPEx Wind Profilers
1982 May 14, 0400 LT to May 15, 0536 LT
Heights 3.1–6.9 km

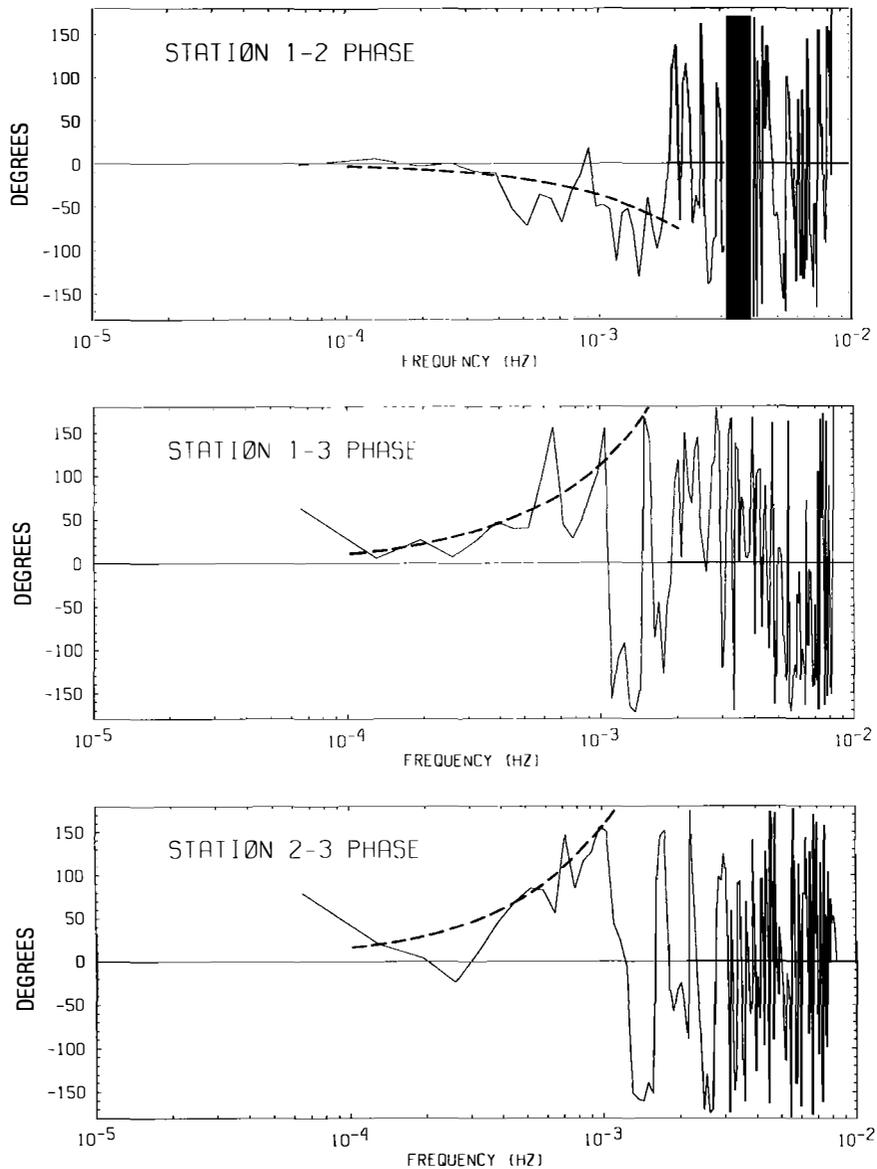


Fig. 6. Phase spectra for May 14, 1982. The phases are the phases of the cross spectra used to derive the coherences in Figure 4. The dashed curves are the phases for waves propagating at 12 m/s from an azimuth of 230°.

stations about 5 km apart. Figure 9 displays the average coherence between stations 1 and 2 for the period April 25–June 1, 1982. This plot was created by averaging two different sets of coherence calculations. The first set, covering periods from 2 min to 4 hours, was made up of coherences based on cross spectra of 256 one-minute points averaged over an approximately 25-hour period and over six range gates from 3.1 to 6.9 km altitude. Twenty of these daily coherences were then averaged together. This last averaging step reduces the variance of the coherence function but does not alter the bias, which depends upon the number of cross spectra that make up the individual daily coherences. The second set was done in a similar manner but was based upon cross spectra of 128 twelve-min data points and covered periods between 24 min and 25 hours. Both averaged coherence functions were then

smoothed in frequency, and the calculated coherences were corrected by the bias term [Carter *et al.*, 1973], which can be expressed as a function of the calculated coherence for a given number of degrees of freedom.

The corrected, smoothed coherence, plotted in Figure 9, should give a good indication of the true mean coherence between the two stations, 4.7 km apart, for vertical velocity fluctuations with periods between 2 min and 25 hours for the monthlong data set. The plot shows that the coherence increases toward lower frequencies. This result is to be expected, since the longer period waves should, in general, have longer wavelengths and be more coherent than shorter period waves over the same distance. The maximum coherence at 10^{-5} Hz (25-hour period) is roughly 0.6. Therefore if we presume that the vertical velocity field observed at each of the two sites

TABLE 3. Waves Derived From Cross-Spectral Analysis

	Time	Height, km	Wave Period, min	Horizontal Wavelength, km	Horizontal Phase Speed, ms ⁻¹	Wave Direction	Wind Direction	Wind Speed, m/s
April 25	0000-0630	3-6	40-80	10-15	3-4	220°-270°	0°-45°	10-15
	0800-1430	3-6	20-25	10-15	8-10	200°-230°	0°-45°	10-15
April 27	0000-1100	3-6	30-60	10-15	4-6	~270°	30°-60°	10-20
May 2	1400-2400	3-7	30-90	10-15	3-6	~130°	~310°	15-20
May 3	0000-0900	3-7	25-40	8-12	5	~140°	270°-300°	10
May 10	0000-2400	3-6	35-45	~15	5-7	~330°	240°-270°	10-20
May 14-15	0400-0400	3-6	30-60	20-40	10-20	~200°	variable	<5

consists of a common, coherent velocity component plus an uncorrelated "noise" component, then approximately 60% of the variance (or spectral power) at that frequency is due to the coherent component [Carter *et al.*, 1973].

6. DISCUSSION

In this paper we have presented an analysis of nearly monochromatic internal gravity waves detected during approximately six weeks of multiheight vertical velocity observations obtained by a triangular configuration of spaced wind profilers. Wave activity evident in the vertical velocities during this period was typically incoherent. This feature was consistent with the results of previous studies. Only occasionally was it possible to extract monochromatic waves from the vertical velocity records. This result is perhaps not

too surprising in the light of the results of the trimoored internal wave experiment (IWEX) in which moored current sensors were used at varying depths and horizontal spacings to investigate the coherence of ocean internal waves [Briscoe, 1975]. The IWEX results confirm the view that a large part of the internal wave field in the ocean is composed of a random superposition of weakly nonlinear internal waves. Recent atmospheric studies suggest that the same is true in the atmosphere [Ecklund *et al.*, 1986], and this study reinforces this view.

There are, nevertheless, times when essentially monochromatic waves can be detected above the "noise" of the background random internal wave field. Nearly monochromatic waves, for example, have been extensively studied on the basis of their pressure signatures recorded by arrays of sensitive microbarographs. Pressure fluctuations observed in this way have also been identified with radar-observed

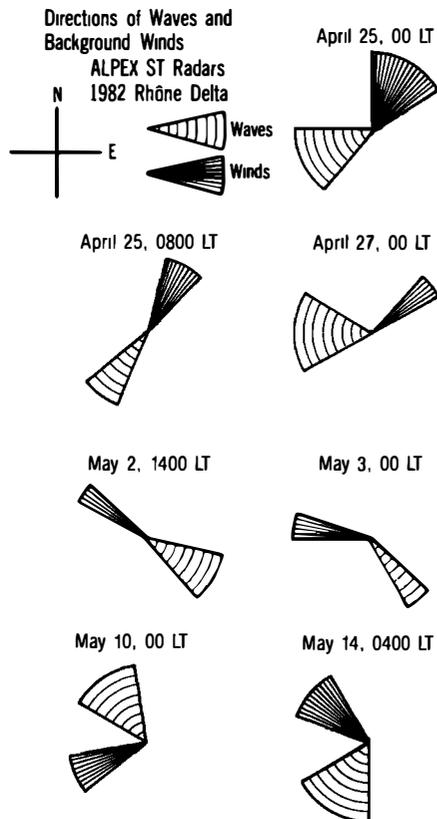


Fig. 7. Directions of waves observed by radar and winds measured by rawinsonde for the events detected by coherence analysis, listed in Table 3. Sectors indicate the directions from which waves and winds were coming averaged over 6-24 hours and over an approximately 3- to 6-km height range.

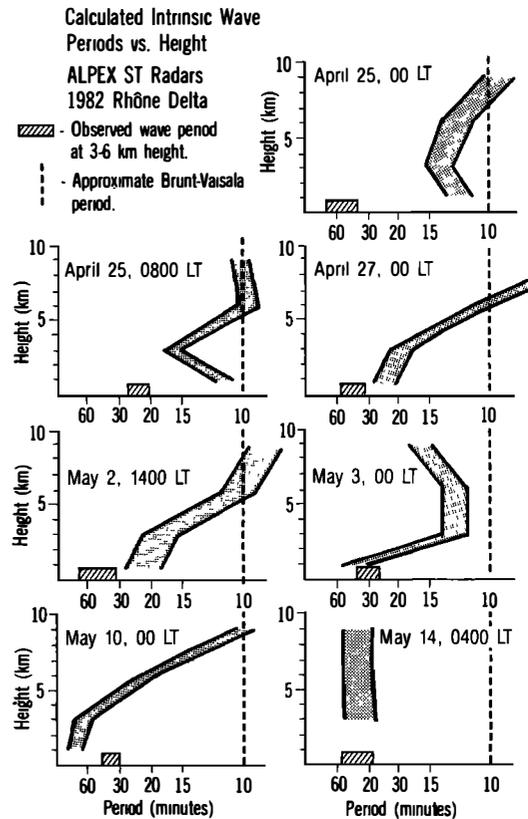


Fig. 8. Intrinsic wave periods for the same events as in Figure 7. The hatched bar along the abscissa indicates the wave period observed by the radar. A typical tropospheric Brunt-Väisälä period of 10 min is indicated by the vertical dashed line.

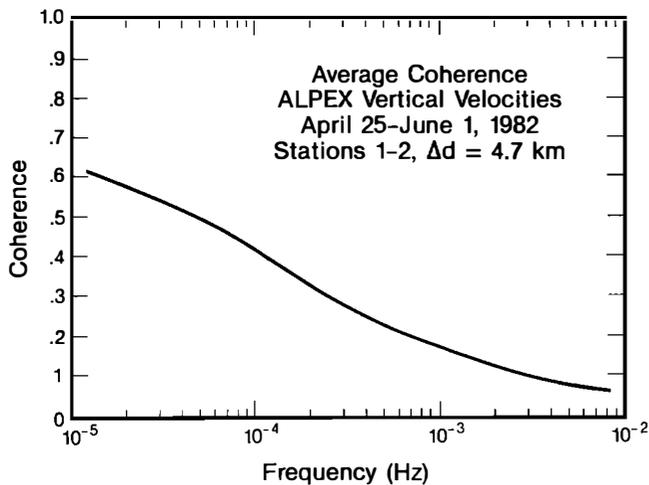


Fig. 9. Average coherence between station 1 and station 2 between April 25 and June 1, 1982.

wavelike structures in the boundary layer and free troposphere [Gossard *et al.*, 1970; Hooke and Hardy, 1975]. Many of the observed monochromatic waves evident in surface microbarograph records can be related to shear instability in tropospheric winds [Keliher, 1975; Gedzelman and Rilling, 1978; Greene and Hooke, 1979]. When shear instability leads to wave generation, the horizontal wave phase velocity is generally in the direction of the wind and of magnitude closely related to tropospheric wind speeds [Greene and Hooke, 1979]. Of the monochromatic waves revealed by this study only a single case (May 25, see Table 2) is likely to have been caused by this process.

Another class of waves commonly seen in single station vertical velocity data is that of internal waves excited at the Brunt-Väisälä period. While these waves represent a preferred scale of oscillation in the atmosphere, their horizontal wavelengths are typically only a few kilometers and consequently they cannot be detected by the ALPEX array.

In the vast majority of cases examined in this study the observed waves were propagating approximately against the prevailing wind. For these waves the intrinsic frequency is Doppler shifted toward higher frequencies. In most cases this shift is sufficient to cause the waves to be trapped. These trapped modes show little phase progression with height and evidently remain coherent over long time periods, thus enhancing their detectability in the cross-spectral analysis. We tentatively conclude that trapped modes are a common feature of "moderate period" (≈ 60 min) monochromatic wave events seen in vertical velocities observed by wind profilers.

In this study, two different analysis techniques were used, both of which have their advantages for different types of wave events. The cross-correlation analysis works well on relatively large-amplitude waves that can have durations as short as a few wave periods. The coherency technique has been shown to be valuable for detecting and analyzing waves that otherwise are too weak to be visible above the random background velocity fluctuations or the sometimes stronger oscillations near the Brunt-Väisälä frequency. The disadvantage of the coherency analysis is that in order to reduce the bias and variance of the coherence function the cross spectra must be averaged over many data sets. Although the exact duration of the wave events detected by the coherency

technique cannot be determined precisely, it is presumed that in most cases they must have lasted for several hours in order to produce the observed significant coherences.

The above characteristics of the coherency analysis technique may partially explain why the majority of wave events observed by that method were trapped waves. Out of the presumably wide spectrum of weak waves that passes over a given station, trapped waves may dominate, since they should remain in the troposphere longer and propagate farther than nontrapped waves.

No specific sources could be identified with any of the observed wave events. Most of the waves were propagating from the direction of the Mediterranean Sea and so probably had no topographic origin. Examination of meteorological charts for Europe also showed no obvious atmospheric features that might have created these waves.

The wave observations described in this paper show the usefulness of wind-profiling Doppler radars for studying gravity waves in the lower atmosphere. There are several factors, however, which limit the number of waves that can be detected and which need to be considered in the design of similar future experiments.

The first factor is horizontal spacing. With radar separations of roughly 5 km, waves with horizontal wavelengths less than about 10 km will be aliased in these analyses. On the other hand, 5-km spacing may not be large enough to accurately determine wave parameters for wavelengths of the order of 100 km or more. Additional stations at other spacings are needed to increase the range of observable wavelengths. The wind profiler demonstration network being deployed in the central United States will have 30 profilers with separations of the order of 400 km [Chadwick, 1988].

The fact that only vertical observations were made also limited the waves that could be detected. Gravity wave particle motion is purely vertical at the Brunt-Väisälä period and becomes nearly horizontal as the intrinsic period approaches the inertial period. At 2-hour periods, non-Doppler shifted waves have vertical amplitudes that are one-tenth the horizontal amplitudes. Thus longer period waves are increasingly difficult to observe with vertically directed radars. A system with oblique as well as vertical radar beams could extend the range of detectable waves to longer periods. In addition, horizontal wind measurements by the profiler would avoid the need to use wind observations from distant rawinsonde sites.

Local orography is another factor affecting radar observations of gravity waves. On high wind days, when large-amplitude lee waves were present, no coherent waves could be detected by the ALPEX profiler network. Even on moderately active days, the enhanced vertical velocity fluctuations generated over nearby rough terrain may interfere with the detection of gravity waves. Mountainous terrain may also affect the propagation of the waves, making interpretation of observations more difficult. The Flatland wind profiler [Green *et al.*, 1988] was built on the plains of central Illinois in order to avoid the contaminating effects of local orography. Locating future profiler networks in similar regions of flat terrain would significantly improve their wave detection capabilities.

The antenna beam width may also need to be considered when doing wave studies using vertically directed radars. There were several occasions during the ALPEX experiment when the coherence between sites 1 and 2 was very good, but

the poor coherences with site 3 prevented the determination of horizontal wave parameters. It can be seen from Table 1 that the site 3 antenna area was one half that of the others and so had a wider beam width. In addition, it was necessary to operate that radar at a frequency that was 1 MHz away from the design frequency of the coaxial collinear antennas. The effect of this mismatch was to significantly increase the level of the first side lobe. This effectively wider beam may have been more sensitive to specular reflections from off-vertical, tilted layers, which would tend to destroy the coherence of the resulting radial velocities. Thus it may be that narrow beams (at least as narrow as the $\approx 3^\circ$ beams at sites 1 and 2) are necessary for short-period wave vertical observations.

7. CONCLUSIONS

An analysis of vertical velocity data from three closely spaced wind profilers located in southern France during ALPEX revealed a few cases of monochromatic waves that possessed sufficient horizontal coherence to derive wave horizontal phase velocity and other wave parameters. We conclude from the analysis that monochromatic wave activity is a relatively rare occurrence and that most of the time a wide spectrum of waves influences the vertical velocities in an incoherent fashion. Of the few instances of monochromatic wave activity that were detected by the analysis, the majority of cases appear to involve trapped modes with coherent wave trains that may have traveled considerable distances against the prevailing wind.

This experiment has shown that networks of wind profilers, with their continuous, high-resolution wind measurements, can be valuable tools for the study of internal gravity waves. The information derived from such systems can be significantly expanded in the future by using networks located in flat terrain with multiple spacings between sites and with horizontal as well as vertical wind measurements. By using a variety of analysis techniques, such as the cross-correlation and coherence methods used here, large-amplitude, short duration waves as well as weaker, underlying waves can be detected and studied.

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REFERENCES

- Balsley, B. B., W. L. Ecklund, D. A. Carter, and P. E. Johnston, The MST radar at Poker Flat, Alaska, *Radio Sci.*, *15*, 213–113, 1980.
- Bendat, J. S., and A. G. Piersol, *Random Data: Analysis and Measurement Procedures*, John Wiley, New York, 1971.
- Bretherton, F. P., Waves and turbulence in stably stratified fluids, *Radio Sci.*, *4*, 1279–1287, 1969.
- Briscoe, M. G., Preliminary results from the trimoored internal wave experiment (IWEX), *J. Geophys. Res.*, *80*, 3872–3884, 1975.
- Carter, G. C., C. H. Knapp, and A. H. Nuttall, Estimation of the magnitude-squared coherence function via overlapped fast Fourier transform processing, *IEEE Trans. Audio Electroacoust.*, *AU-21*, 337–344, 1973.
- Chadwick, R. B., The wind profiler demonstration network, in *Extended Abstracts, Symposium on Lower Tropospheric Profiling: Needs and Technologies*, pp. 109–110, American Meteorological Society, Boulder, Colo., 1988.
- Ecklund, W. L., K. S. Gage, and A. C. Riddle, Gravity wave activity in vertical winds observed by the Poker Flat MST radar, *Geophys. Res. Lett.*, *8*, 285–288, 1981.
- Ecklund, W. L., B. B. Balsley, D. A. Carter, A. C. Riddle, M. Crochet, and R. Garello, Observations of vertical motions in the troposphere and lower stratosphere using three closely spaced ST radars, *Radio Sci.*, *20*, 1196–1206, 1985.
- Ecklund, W. L., K. S. Gage, G. D. Nastrom, and B. B. Balsley, A preliminary climatology of the spectrum of vertical velocity observed by clear-air Doppler radar, *J. Clim. Appl. Meteorol.*, *25*, 885–892, 1986.
- Einaudi, F., D. P. Lalas, and G. E. Perona, The role of gravity waves in tropospheric processes, *Pure Appl. Geophys.*, *117*, 627–663, 1979.
- Einaudi, F., W. L. Clark, D. Fua, J. L. Green, and T. E. VanZandt, Gravity waves and convection in Colorado during July 1983, *J. Atmos. Sci.*, *44*, 1534–1553, 1987.
- Gage, K. S., and B. B. Balsley, Doppler radar probing of the clear atmosphere, *Bull. Am. Meteorol. Soc.*, *58*, 1074–1093, 1978.
- Gage, K. S., D. A. Carter, and W. L. Ecklund, The effect of gravity waves on specular echoes observed by the Poker Flat MST radar, *Geophys. Res. Lett.*, *8*, 599–602, 1981.
- Gedzelman, S. D., Short-period atmospheric gravity waves: A study of their statistical properties and source mechanisms, *Mon. Weather Rev.*, *111*, 1293–1299, 1983.
- Gedzelman, S. D., and R. A. Rilling, Short-period atmospheric gravity waves: A study of their dynamic and synoptic features, *Mon. Weather Rev.*, *106*, 196–210, 1978.
- Gossard, E. E., and W. H. Hooke, *Waves in the Atmosphere*, 456 pp., Elsevier Science, New York, 1975.
- Gossard, E. E., J. H. Richter, and D. Atlas, Internal waves in the atmosphere from high-resolution radar measurements, *J. Geophys. Res.*, *75*, 3523–3536, 1970.
- Green, J. L., K. S. Gage, T. E. VanZandt, W. L. Clark, J. M. Warnock, and G. D. Nastrom, Observations of vertical velocity over Illinois by the Flatland radar, *Geophys. Res. Lett.*, *15*, 269–272, 1988.
- Greene, G. E., and W. H. Hooke, Scales of gravity waves generated by instability in tropospheric shear flows, *J. Geophys. Res.*, *84*, 6362–6364, 1979.
- Harris, F. J., On the use of windows for harmonic analysis with the discrete Fourier transform, *Proc. IEEE*, *66*, 51, 1978.
- Hooke, W. H., and K. R. Hardy, Further study of the atmospheric gravity waves over the eastern seaboard on 18 March 1969, *J. Atmos. Meteorol.*, *14*, 31–38, 1975.
- Julian, P. R., Comments on the determination of significance levels of the coherence statistic, *J. Atmos. Sci.*, *32*, 836, 1975.
- Keliher, T. E., The occurrence of microbarograph-detected gravity waves compared with the existence of dynamically unstable winds shear layers, *J. Geophys. Res.*, *80*, 2967–2976, 1975.
- Ottersten, H., K. R. Hardy, and C. G. Little, Radar and sodar probing of waves and turbulence in statically stable clear-air layers, *Boundary Layer Meteorol.*, *4*, 47–89, 1973.
- Saunders, K. D., and F. C. Hamrick, A note on cross spectrum and coherence calculations, *J. Geophys. Res.*, *87*, 9699–9703, 1982.
- VanZandt, T. E., A universal spectrum of buoyancy waves in the atmosphere, *Geophys. Res. Lett.*, *9*, 575–578, 1982.
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