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4.5B TROPOSPHERIC GRAVITY WAVES OBSERVED BY THREE CLOSELY SPACED ST RADARS

D. A. Carter*, B. B. Balsley*, W. L. Ecklund*,
M. Crochet**, A. C. Riddle***, and R. Garello***

*Aeronomy Laboratory, National Oceanic and Atmospheric Administration
Boulder, CO 80303

**L.S.E.E.T., "LaGiponne" Boulevard des Armaris
Toulon 83100, France

***CIRES, University of Colorado
Boulder, CO 80309

INTRODUCTION

In the spring of 1982 a cooperative U.S.-France clear-air radar experiment was carried out on the southern coast of France during the ALPEX (Alpine Experiment) program. Three relatively small vertically directed 50-MHz ST radars were set up with spacings of about 5-6 km. Figure 1 shows the location and configuration of the radars, while Table 1 gives the system parameters. The three radars were operated concurrently for a period of about 6 weeks with 1-minute temporal and 750-m height resolution. Doppler spectra were computed at each site and tape recorded for later analysis. An examination of the temporal and spectral characteristics of the vertical velocity fluctuations has been presented by BALSLEY et al. (1983). One of the principal purposes of the experiment was to examine the horizontal and vertical properties of gravity waves in the lower atmosphere. In this report we will describe the techniques used and the first results from this wave study.

Examples from the ALPEX data set displayed in Figure 2 show the highly variable nature of the vertical wind velocity fluctuations. This variability was directly related to the background wind conditions. For example, during April 30, an active period of strong (30-40 m/s) northerly Mistral winds, the vertical velocities often reached 2 m/s with dominant periods of several hours. On the other hand, during quiet periods of weak horizontal winds (less than 5-10 m/s) such as occurred on May 14, the vertical winds showed fluctuations of less than 10-20 cm/s, sometimes with noticeable oscillations near the Brunt-Vaisala period (around 10 minutes). Most days, like May 10, for example, were between these extremes, with horizontal winds around 10-20 m/s and vertical fluctuations which were broadband and variable. There were also a very few instances of monochromatic wave events, such as on May 25, which generally occurred with rather low (<10 m/s) background horizontal winds.

WAVE ANALYSIS

With vertical velocity observations from three locations, the horizontal characteristics (wavelength, phase velocity, and propagation direction) can be determined for waves of any frequency by measuring the phase of that frequency component at each station. Equivalently, phase differences between all station pairs can give the same information. Two methods were used in this anlaysis to determine those phase differences: cross-correlation functions and coherence spectra.

For nearly monochromatic wave events a cross-correlation function was computed, which gave a time delay between each station pair. As an example, the cross-correlation functions for a 100-minute interval on May 25 are shown in Figure 3. For this particular period, the correlation is extremely good. The

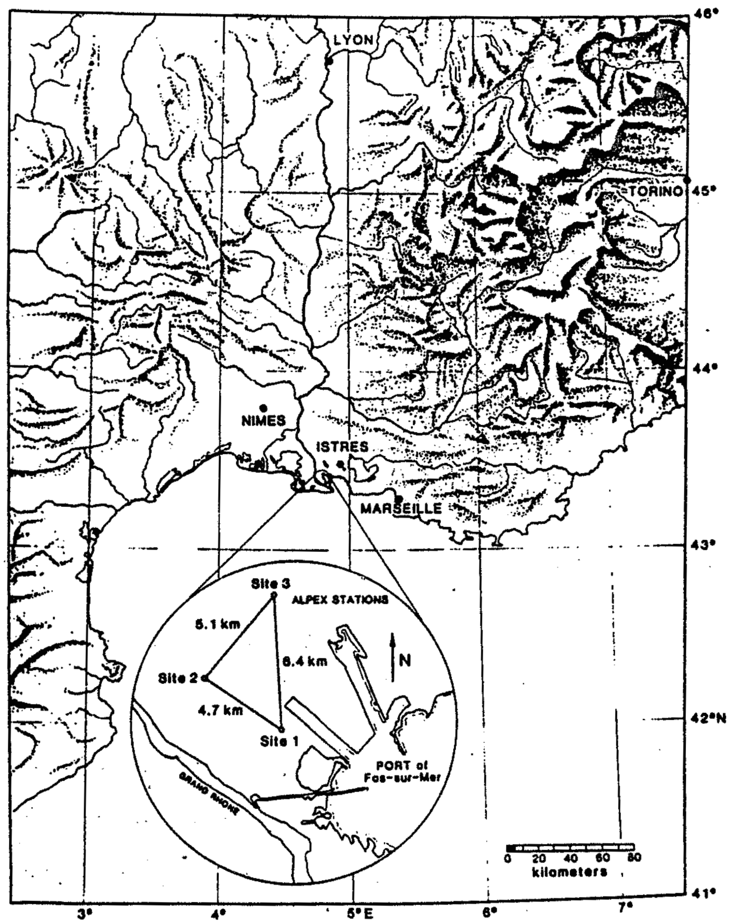

Figure 1. Plan view of the three-station ALPEX radar experiment. Inset shows details of site locations.

Table 1

SITE	FREQUENCY (MHz)	ANTENNA DIMENSIONS	AVERAGE TRANSMITTED POWER	PULSE WIDTH	HEIGHT RESOLUTION	TIME RESOLUTION
1	49.640	$(70 \times 100)m^2$	∿ 200 w	5 μs	750 m	∿ 1 min
2	49.920	(70 x 100)m	∿ 200 w	5 μs	750 m	∿ 1 min
3	48.850	(70 x 50)m	∿ 200 w	5 μs	750 m	∿ 1 min

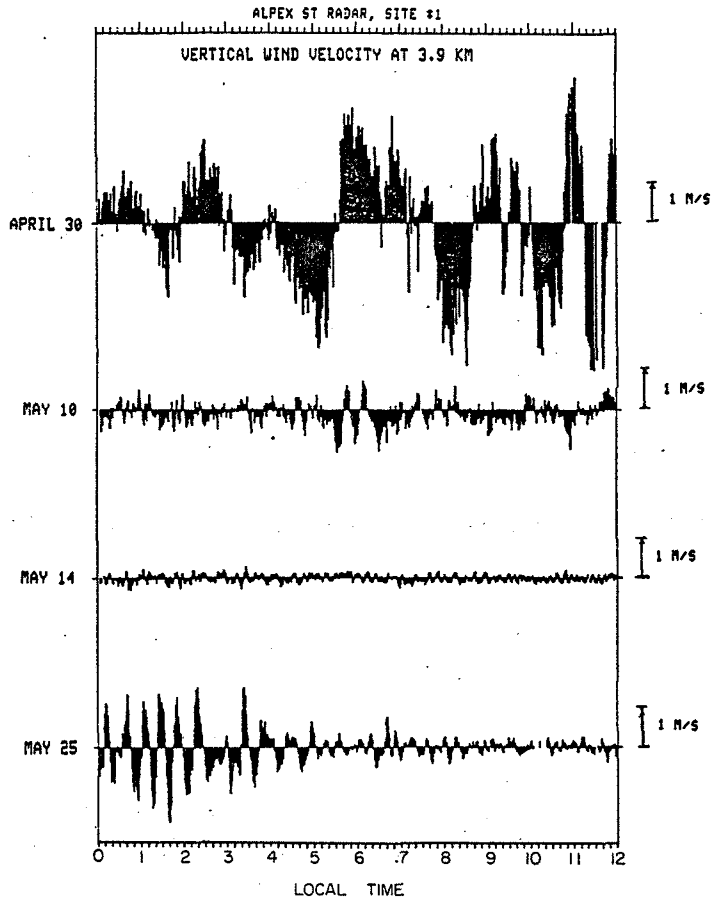

Figure 2. Examples of the vertical velocity at 3.9 km from Site 1 for 12-hour periods on four different days.

wave has a period of about 25 minutes. By using the local maximum that is closest to zero time lag in each function, the wave can be shown to have a horizontal wavelength of about 15 km and to be coming from an azimuth of about 350°.

Table 2 shows the wave parameters derived from cross-correlation analyses for other times of nearly monochromatic waves. Also given are the mean wind magnitude and direction at the altitude of the wave as determined by sounding balloons launched at six-hour intervals by the French Meteorological Service at Nimes (also shown in Figure 1). Except for May 22, the other events were not nearly as strongly sinusoidal as on May 25, but occasionally a wave-like oscillation would pop up long enough to compute a correlation function. The wave periods ranged from 15 to 60 minutes 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 possiblity for any of the other waves, but only the unaliased wave solutions are shown.

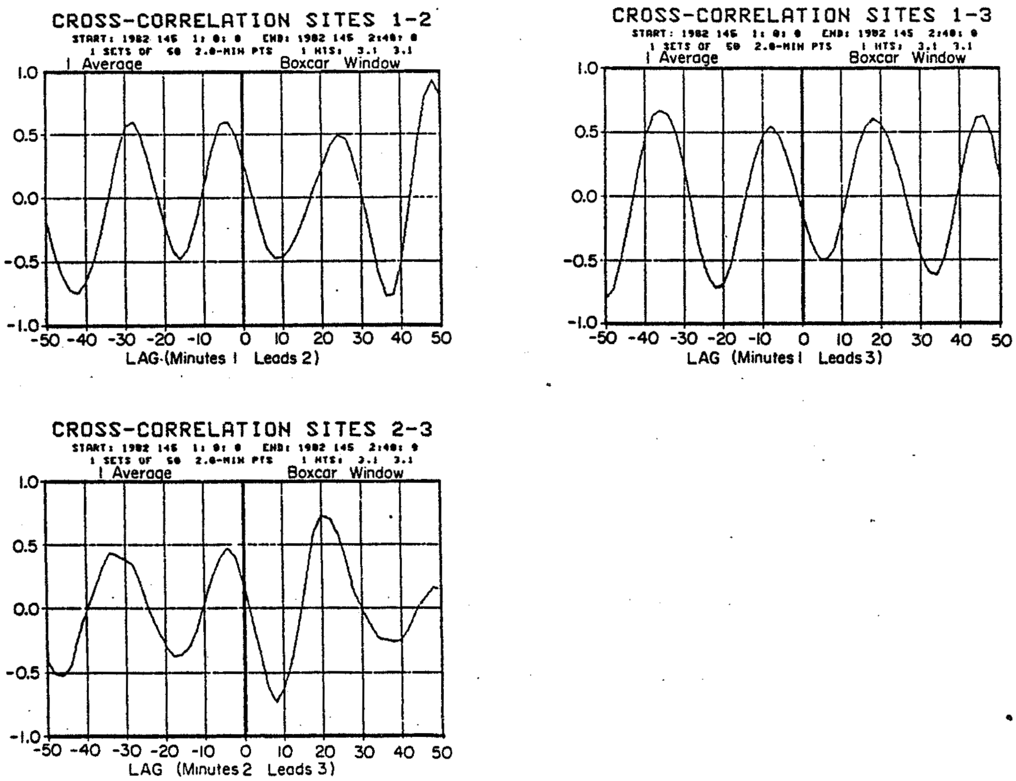

Figure 3. Cross-correlation functions computed between the three pairs of radar sites at 3.1 km for 0100-0240 local time on May 25, 1982.

Table 2. Waves derived from cross-correlation analysis.

Time		Height	Wave Period	Horizontal Wavelength	Wave Direction	Wind Direction	Wind Speed
April 25	0600-0800	4-5 km	30 min	10 km	200°	0-20°	10-15 m/s
May 2	1400-1600	4-5 km	60 min	15 km	170°	300°	15-20 m/s
May 9	1500-1700	4 km	40 min	12 km	330°	240°	15-20 m/s
May 10	2200-0200	4-5 km	40 min	20 km	320°	∿270°	5-10 m/s
May 11	1700-1820	4 km	20 min	15 km	90°	200°-240°	5-10 m/s
	1800-1900	7-8 km	20 min	18 km	110°	200°-240°	5-10 m/s
May 22	0100-0200	4 km	15 min	7 km	270° or 80°	300°-340°	5-10 m/s
May 25	0100-0240	3-4 km	25 min	15 km	350°	340°	10 m/s

The cross-correlation function works well on monochromatic waves, but for the rather broadband fluctuations that were usually observed, the cross correlation gives no information on the individual frequencies present. A spectral analysis was needed to find any waves hidden in the typical vertical velocity fluctuations. For any time series a Fourier transform could be computed to derive an amplitude and phase value for each Fourier component. But this computation produces phases for uncorrelated noise as well as waves and does not distinguish between the two. A coherence spectrum, however, can give an indication of how well correlated or coherent a particular frequency component is between two time series.

The coherence spectrum is essentially the normalized magnitude of the complex cross spectrum of two time series (see BENDAT and PIERSOL, 1966). To be meaningful, the complex cross spectrum must be averaged over several data sets. If the relative phase at a given frequency varies randomly between successive complex cross spectra, the normalized magnitude (the coherence) of the average will approach zero. On the other hand, if there is a coherent signal running through all the data sets, then the cross phase will be constant, the complex cross spectra will add in phase, and the coherence will approach a value of one.

In the search for waves, the coherence analysis was applied to the entire ALPEX data set. Typically, a cross spectrum was computed between each pair of stations using a data set of 256 1-minute velocity points to which a Hanning window had been applied (SAUNDERS and HAMRICK, 1982). The complex cross spectra were averaged in time over data sets which were overlapped 50% (with a Hanning window, these data sets are 83% independent (HARRIS, 1978)). Cross spectra from several tropospheric heights were also averaged together.

A coherence spectrum and a cross-phase spectrum (phase of the cross spectrum) was computed between each of the three station pairs. Only those frequency components whose coherence met or exceeded the 1% significance level were used to compute wave parameters. The 1% significance level (the coherence above which uncorrelated signals should reach only 1% of the time) is defined by

$$\sqrt{1 - (0.1)^{1/(n-1)}}$$

where n is the number of cross spectra averaged (JULIAN, 1975). The cross phases for bands of frequencies with significant coherences were then used to calculate the horizontal wave parameters.

The results of the coherence analysis were mixed. On very active, high wind days, such as April 30 shown in Figure 2, there were no significant coherences. This result is in agreement with the impression that the strong vertical fluctuations were due to lee wave structures which would have no consistent phase relationship between radars throughout a day. In general, the very quiet days also had poor coherences, although there were some significant exceptions (such as May 14 shown in Figure 2). Although fluctuations near the Brunt-Vaisala period could be discerned in the time series, the coherent wave periods, if there were any at all, tended to be around 30-60 minutes. This implies that the correlation distance of the Brunt-Vaisala oscillations was usually less than about 5 km. Most of the data sets that showed significant coherences were moderately active days with background winds around 10-20 m/s. Table 3 lists the results from those periods which met the coherence criterion.

Figure 4 shows an example of the coherence spectra for May 14. The dashed line represents the 1% significant level. Note that the coherences for all three station pairs are significant between 2×10^{-4} and 5×10^{-4} Hz (about 30 and 80 minute periods) and that the coherence between sites 1 and 2 is much higher at low frequencies than the coherences involving site 3.

Table 3. Waves derived from coherence spectral analysis.

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

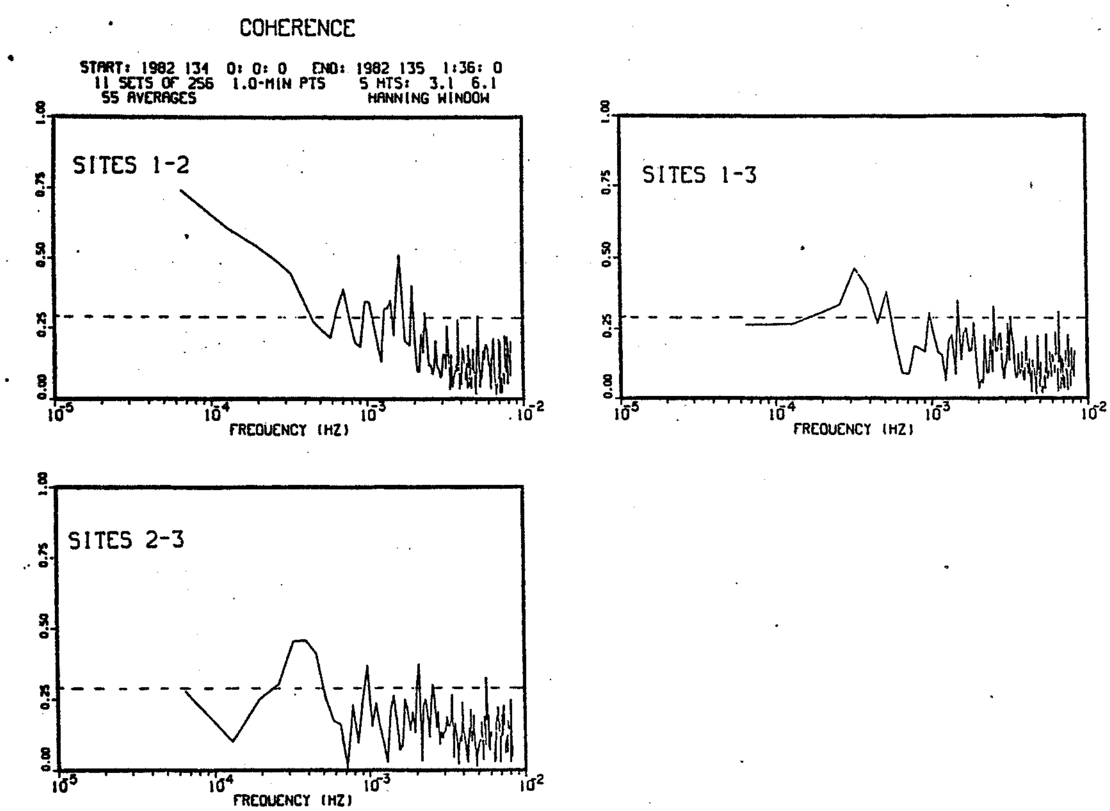

Figure 4. Coherence spectra for May 14, 1982. The spectra were averaged over 25 hours and 5 height ranges between 3 and 6 km. The dashed line is the 1 percent significance level.

Figure 5 gives the phases corresponding to the coherences in Figure 4. The dashed curve in Figure 5 represents the phase differences that would occur for waves propagating at 13 m/s from an azimuth of 230° for all periods between about 15 minutes and 2 hours. The observed phases follow this general curve even at wave frequencies where the coherences did not reach the 1% significance level. This was fairly common during other days also; the cross phases appeared to be able to give good wave determinations even with marginally good coherences.

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 directions derived from cross correlations of short periods of sinusoidal oscillations agree well with those determined from the coherence analysis over a longer time period.

It must be noted here that good coherences and consistent cross phases do not necessarily imply a wave. Turbulent structures that are "frozen" into the mean wind and are advected past the radars will produce a phase speed and a propagation direction equal to the horizontal wind speed and direction. For the May 14 data this is not the case, however, since the background wind was less than 5 m/s compared to a deduced wave speed of 10-15 m/s. Table 3 shows that most wave patterns derived from the coherence analysis actually had components in the opposite direction of the background wind at the same altitude.

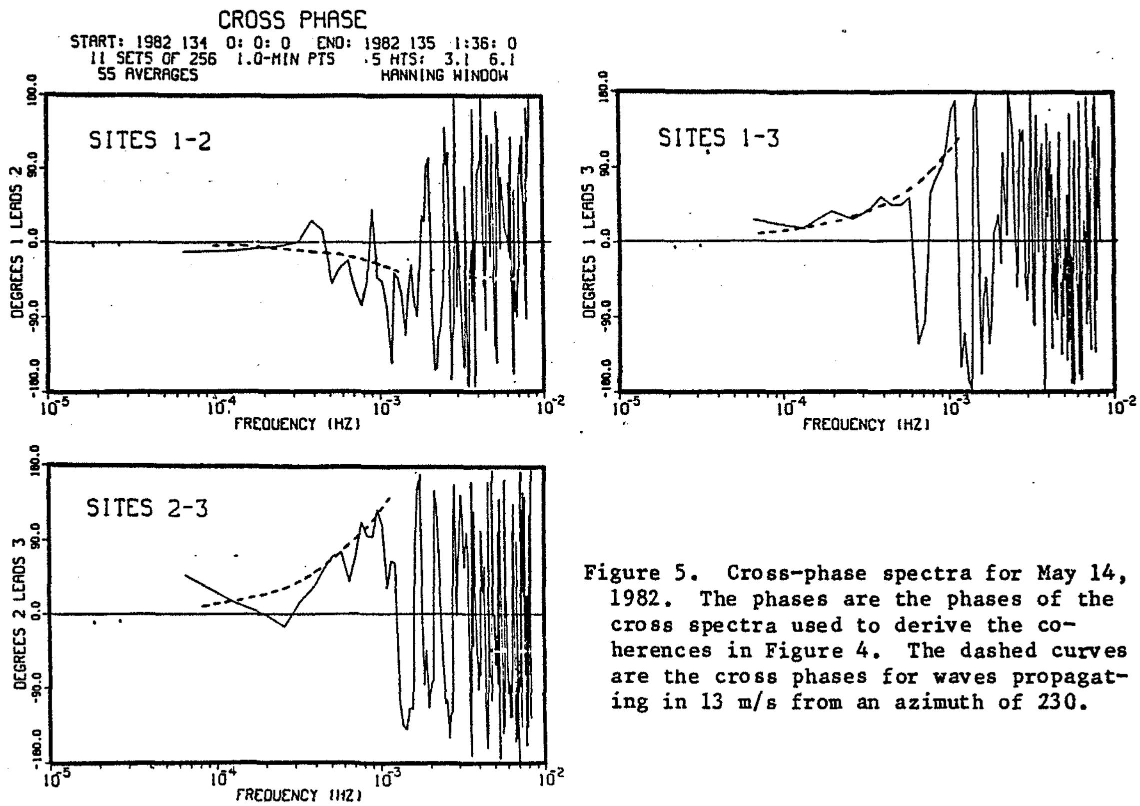

Figure 5. Cross-phase spectra for May 14, 1982. The phases are the phases of the cross spectra used to derive the coherences in Figure 4. The dashed curves are the cross phases for waves propagating in 13 m/s from an azimuth of 230.

The coherence spectral analysis was also used to examine the coherence and phase shifts between heights at each radar. The coherences were almost always very high for periods of 10-100 minutes over height separations of up to about 2 km. In nearly all cases, the phase differences between heights were essentially zero, which implies a very large vertical wavelength.

The theoretical relationship between the horizontal wavelength, λ_H, and vertical wavelength, λ_z, for an internal gravity wave is

$$\lambda_z^2 = \lambda_H^2 \cdot \frac{\omega^2}{N^2 - \omega^2}$$

where N is the Brunt-Vaisala frequency are ω, the intrinsic wave frequency is related to the observed frequency, ω_o, by

$$\omega = \omega_o - \vec{k} \cdot \vec{U}$$

where $\vec{k}$ ($|\vec{k}| = 2\pi/\lambda$) is the total wave vector and $\vec{U}$ is the mean wind. Both ω_o and λ_H remain constant through slow variations in U and N. In equation (1) ω is assumed to be much less than the inertial frequency, whose period is 17.5 hours at the ALPEX radar sites. From the above relations it can be seen that Brunt-Vaisala period waves should have infinite vertical wavelengths and longer period waves should have progressively shorter vertical wavelengths.

For a typical wave observed during the ALPEX experiment with λ_H = 15 km and period T = ($2\pi/\omega_o$) = 30 minutes, the vertical wavelength should be about 5 km for a Brunt-Vaisala period of about 10 minutes and no background wind. An opposing mean wind, however, would Doppler shift the intrinsic frequency toward higher frequencies and thus lengthen the vertical wavelength.

Table 4 presents horizontal and vertical wavelength data for May 2 that may show evidence for gravity-wave Doppler shifting. For each observed frequency listed, the measured horizontal wavelength was used to compute the wind component in the direction of wave propagation which would be needed to produce the observed vertical wavelength. The results show a consistent picture of an opposing wind component of about 11-13 m/s that is Doppler shifting the waves to longer vertical wavelengths. (Note that the last frequency listed in Table 4 (T = 32 minutes) has an anamolous measured λ_H of 15 km. If this λ_H was more in line with the others of 10-12 km, the computed wind component would also be about -12 m/s.) Based on Nimes balloon measurements, the background wind during May 2 was approximately 15 m/s from an azimuth of 310°, yielding a component in the wave direction of -13 to -15 m/s, very close to the computed value.

Actually, this good agreement is somewhat surprising since the equations upon which the computations were based are applicable to infinite plane waves propagating under slowly varying background conditions. The Brunt-Vaisala frequency, however, changes abruptly at the tropopause, whose height (8-12 km) is much smaller than the observed vertical wavelengths. The tropospheric waves did not appear to propagate beyond the tropopause boundary and may have been trapped in the troposphere.

DISCUSSION

The wave observations described above show the usefulness of ST radars for studying gravity waves in the lower atmosphere. There were several factors, however, which limited the number of waves that could be detected and which need to be considered in the design of similar future experiments.

Table 4. May 2, 1400-2400 local time.

Wave Period	Horizontal Wavelength	Vertical Wavelength	Computed U_k
85 min	11.2 km	11 km	-11 m/s
64 min	12.3 km	17 km	-13 m/s
51 min	10.2 km	35 km	-13 m/s
43 min	10.3 km	35 km	-12 m/s
37 min	10.4 km	62 km	-12 m/s
32 min	15.1 km	00 km	-17 m/s

U_k is the component of the mean wind in the direction of the horizontal wave vector $\vec{k}_H$.

The first factor is horizontal spacing. With radar separations of roughly 5 km, waves with horizontal wavelengths less than about 10 km could be aliased and appear to have longer wavelengths. Since most observed waves had measured wavelengths around 10-12 km, it is possible that some of these were aliased. Additional stations at other spacings would increase the range of observable wavelengths.

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-Vaisala period and becomes totally horizontal at the inertial period. At 2-hour periods, non-Doppler shifted waves have vertical motions that are one-tenth the horizontal motion. Thus longer period waves are increasingly difficult to observe with vertical radars. This is evidenced by the typical drop in coherences between the ALPEX radars above about 1-hour wave periods. A system with oblique as well as vertical radar beams could extend the range of detectable waves to longer periods.

For vertical radars, the antenna beam may be an important factor. 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 sidelobe. 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 $\sim 3°$ beams at sites 1 and 2) are necessary for short-period wave vertical observations.

SUMMARY

During the ALPEX experiment there were only a few instances of nearly monochromatic wave events upon which a cross correlation could be performed.

However, it appears that the coherence spectral analysis can detect waves that otherwise would have gone unnoticed. This method requires averaging over rather long time periods and/or several heights (over which the wave field must remain steady). Several periods of good coherences were observed, particularly on quiet or moderately active days. The waves derived from the coherence analysis appeared to have long vertical wavelengths. Most seemed to be propagating in a direction opposite to the background wind, which would Doppler shift gravity waves to longer vertical wavelengths. Perhaps on such relatively quiet days, where there are no obvious isolated sources for waves, the direction into the wind is a preferred direction for persisting waves. Further analysis of the waves observed during ALPEX is continuing. Future experiments with various radar configurations could significantly contribute to the understanding of gravity waves in the atmosphere.

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