Analysis of Ducted Motions in the Stable Nocturnal Boundary Layer During CASES-99

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Abstract

Data obtained with multiple instruments at the Main Site of the Cooperative Atmosphere-Surface Exchange Study (CASES-99) are employed to examine the character and variability of wave motions occurring in the stable nocturnal boundary layer during the night of 14 October 1999. The predominant motions are surprisingly similar in character throughout the night, exhibiting largely westward propagation, horizontal wavelengths of ~ 1 to 10 km, phase speeds slightly greater than the mean wind in the direction of propagation, and highly-coherent vertical motions with no apparent phase progression with altitude. Additionally, vertical and horizontal velocities are in approximate quadrature and the largest amplitudes occur at elevated altitudes of maximum stratification. We interpret these motions as ducted gravity waves that propagate along maxima of stratification and mean wind and that are evanescent above, and occasionally below, the altitudes at which they are ducted. Modal structures for ducted waves are computed for mean wind and stratification profiles for three specific cases and are seen to provide a plausible explanation of the observed motions.

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1. Introduction

An extensive suite of instruments was employed in southeast Kansas during October 1999 for studies of the structure of, and the dynamics occurring within, the stable nocturnal boundary layer (NBL). This Cooperative Atmosphere-Surface Exchange Study (CASES-99) was motivated by a recognition that the dynamics accounting for boundary layer structure and transport under stable conditions are poorly understood and poorly parameterized at present in large-scale models. The CASES-99 field program merged ground-based and in situ measurement capabilities, through a series of intensive observing periods (IOPs), to provide sensitivity to a range of dynamical processes expected to influence NBL structure and morphology. An overview of the CASES-99 field program, including scientific goals and initial observations, is provided by Poulos et al. [2002]. Data analysis and modeling activities are now being pursued to quantify our understanding of a variety of NBL dynamical processes identified in the CASES-99 data, among them Kelvin-Helmholtz (KH) shear instability beneath the nocturnal jet [Blumen et al., 2001; Newsom and Banta, 2002], episodic turbulence in the surface layer [Coulter and Doran, 2002; Sun et al., 2002], drainage flows or gravity currents [Soler et al., 2002; Sun et al., 2002], and NBL forcing due to airflow over three-dimensional (3D) terrain [Balsley et al., 2002a]. Our purpose in this paper is to examine the character of very different motions that are prevalent on a number of occasions during CASES-99, which appear to play a more passive role in NBL morphology, but which nevertheless may be an important component of NBL variability. These are ducted, or external, gravity waves whose propagation and character depend on the details of the wind and thermal structure within the NBL. Wave motions observed under stable boundary layer conditions have been studied previously by Einaudi [1989] and Rees et al. [2000], but we believe this is the first systematic analysis of ducted motions under such conditions. Our analysis was made possible by the comprehensive suite of instrumentation employed for the CASES-99 field program.

Wave ducting (and evanescence) occurs on a wide range of scales in the atmosphere. We will use the term "ducting" to refer to a motion that is trapped at the Earth's surface and evanescent above or that is trapped at one or more interface(s) or layer(s) of finite depth and is evanescent above and below. The Earth's surface provides a ducting interface for waves of very large scales, for example Lamb waves and planetary-scale normal modes. Variable thermal structure enables ducting at levels of enhanced stratification for acoustic-gravity wave motions having phase speeds of several hundred ms^{-1}. At scales more relevant to this paper, gravity waves having smaller phase speeds can be ducted either at the Earth's surface, at levels of enhanced stratification, at local wind maxima in the direction of wave propagation, or at levels exhibiting combinations of these effects.

Trapped lee waves are an example of ducting at the Earth's surface and have been addressed by many authors [Gossard and Hooke, 1975; Gill, 1982]. Such ducted motions have structure dependent on both wind and stability profiles and have been implicated in a variety of processes, among them organization of convection and modulation of turbulence [Finnigan and Einaudi, 1981; Finnigan et al., 1984; Stobie et al., 1987; Monserrat and Thorpe, 1996]. Ducted motions have likely also contributed to the high-frequency, coherent variability observed under stable boundary layer conditions, though distinctions between ducted and vertically-propagating motions have typically not been made [Einaudi, 1989; Rees et al., 2000].

Ducting at stratification maxima has been considered in oceanic and atmospheric contexts since the work of Eckart [1961]. This work identified a phenomenon now known as Eckart's resonances in the presence of more than a single ducting level (termed "kissing" modes by Jones [1970]), in which adjacent modes exchange character as wavenumber increases or decreases. Evidence for such resonances was subsequently found in observations and model results [Katz and Briscoe, 1979; Peters, 1983], while Liu et al. [1980; 1982] and Liu and Benney [1981] examined energy exchanges between ducting levels and the effects of nonlinear wave trains on adjacent ducts. More recently, Chimonas and Hines [1986] analyzed the role of wind maxima in creating ducts, while Fritts and Yuan [1989] examined the nature of "dual" ducting by both stratification and wind maxima. These latter studies are particularly relevant to ducting in the NBL during CASES-99 because of the complex thermal and wind profiles occurring under stable boundary-layer conditions. Essentially, multiple ducting levels offer a potential for more complex flow evolutions and energy exchanges between ducting levels than are possible for simpler profiles with only a single ducting level.

Our purposes in this paper are 1) to examine the persistent wave structures present in a number of data sets collected during IOP 6 on the night of 14 October 1999 of the CASES-99 field program, 2) to demonstrate that these motions are consistent with ducted wave structure, and 3) to evaluate their possible significance in NBL evolution and structure. We begin in Section 2 with a discussion of the instrumentation used for this study. The evolution of the mean state within which wave and turbulence motions occur is described in Section 3. Section 4 examines the evidence for ducted motions in the CASES-99 data and the theoretical basis for this interpretation. We explore in Section 5 possible links between ducted motions and observed NBL turbulence. Section 6 provides a summary of these observations, their comparison with theory, and our conclusions.

2. Instrumentation

Instrumentation employed for the CASES-99 field program has been described at length in earlier papers. Here, we will summarize only the operational parameters for the instruments employed in our study and refer readers to earlier papers for more detailed descriptions of specific instruments.

a. King Air

The Wyoming King Air was made available for CASES-99 measurements as a part of the field support extended by the Atmospheric Technology Division of the National Center for Atmospheric Research (NCAR). It was employed in IOP 6 for primarily horizontal flight tracks extending from ~ 160 to 1300 m above ground level (AGL). Flight tracks were along an east-west path, centered ~ 1 km south of the 60-m tower at the CASES-99 Main Site, and ~ 25 km in length (see Figure 1). Data employed in our analysis includes horizontal and vertical winds, temperature, and turbulence (*i.e.* high-frequency fluctuations of velocity and temperature). For our purposes here, the King Air data were averaged to 1 (u' and T') and 25 Hz (v' and w') to display both wave and turbulence structures. Additional discussion of King Air instrumentation is provided at http://www-das.uwyo.edu/research.html.

b. Tethered Lifting System

The Tethered Lifting System (TLS) of the University of Colorado was deployed ~ 500 m WSW of the 60-m tower at the CASES-99 Main Site (see Figure 1). Under light surface wind conditions, the TLS was deployed beneath a blimp. This was the case during IOP 6 where the TLS was employed to perform two complete profiles from the surface to $\sim$ 870 m AGL and three partial profiles above $\sim$ 450 m AGL. Each profile was performed at an ascent or descent rate of $\sim$ 0.4 ms^{-1}. The initial ascent occurred from 0210 to 0252 UT and the final descent occurred from 0545 to 0612 UTC. For two intervals, from $\sim$ 0306 to 0400 UT and from $\sim$ 0415 to 0520 UT, the TLS performed measurements at approximately constant altitudes of 680 and 470 m AGL, respectively. The TLS payload package for this flight contained fast-response cold- and hot-wire probes for temperature and wind speed measurements. A solid state temperature sensor and a Pitot tube for calibrating, respectively, the cold- and hot-wire probes were also included in the package, in addition to "housekeeping" instruments (tilt sensors, pressure sensor, and magnetometer for wind direction determination). All of the above data were archived onboard the payload using a high-speed digital storage device. Accurate measurements of the turbulence quantities C_T^2 and ϵ (the turbulence temperature structure parameter and the energy dissipation rate) were provided by the fine-wire instruments in addition to accurate mean wind (speed and direction) and temperature information. For additional details about the TLS capabilities, the reader is referred to Balsley et al. [2002b].

Energy dissipation rate, ϵ, was determined using a thin (fast-response) hot-wire sensor in combination with a calibrated Pitot tube. Both instruments were suspended in one of five possible packages from the TLS tether [Balsley et al., 2002c]. Determination of ϵ consisted of spectrally matching the high-frequency fluctuations obtained from the hot-wire sensor with the low-frequency fluctuations from the Pitot tube. Because of the different frequency responses of the two instruments, matching was performed over the frequency range where both instruments had reasonable responses. The resulting 1-s calibrated spectra were then best fit to a -5/3 turbulence spectral slope allowing for a possible noise floor. A value of ϵ for each spectrum was determined using the spectral density at 1 Hz. The temperature turbulence structure parameter, C_T^2, was determined in a similar manner, but using a thin cold-wire sensor in combination with a calibrated (slow-response) solid-state temperature sensor.

c. GLASS radiosondes

A GPS Loran Atmospheric Sounding System (GLASS) radiosonde capability was provided at the CASES-99 Main Site by ATD at NCAR. The radiosondes provided hourly profiles of wind, temperature, and relative humidity at 1-s intervals, or $\sim$ 5-m altitude intervals, though wind data were often sparse or suspect at low altitudes during rapid horizontal acceleration, typically because of insufficient GPS satellite acquisition. These systems were employed primarily to define the evolution of the mean flow throughout the IOP.

d. Raman lidar

The Raman lidar provided by the University of Iowa was deployed adjacent to the TLS $\sim$ 500 m WSW of the 60-m tower at the CASES-99 Main Site (see Figure 1). The lidar measured absolute humidity from $\sim$ 50 to 800 m AGL with altitude and time resolution of 1.5 m and 5.35 seconds. Data collected during IOP 6 were used to define the evolution of the mean absolute humidity profile and absolute humidity fluctuations for correlative studies with other data sets. Vertical scans provided additional information on the direction and wavelength of the gravity waves. Additional details about the Raman lidar can be found in Eichinger et al. [1999].

e. High-resolution Doppler lidar

The high-resolution Doppler lidar (HRDL) was specifically designed by the Environmental Technology Laboratory (ETL) for atmospheric boundary layer research. It was deployed $\sim$ 1.4 km SSE of the 60-m tower at the CASES-99 Main Site (see Figure 1). HRDL achieves a minimum range resolution of 30 m, a measurement accuracy of ~ 0.1 ms^{-1} for diffuse aerosol backscatter, and has several operational modes. A vertical scan, or range-height indicator (RHI), can be used to define the vertical and horizontal structure of boundary layer motions. Alternatively, a velocity-azimuth display (VAD) can provide definition of the larger-scale horizontal wind field. In our study of the ducted wave dynamics occurring during IOP 6, the RHI was employed. Additional discussion of the HRDL is provided by Newsom and Banta [2002].

f. 60-m tower anemometers hot-wire probes

Winds were detected on the 60-m tower at the CASES-99 Main Site at twelve altitudes. Eight of these employed sonic anemometers recording winds at 20 Hz; an additional four levels employed pro-vane anemometers recording winds at 1 Hz. Temperatures were measured with hot-wire probes. Those data used in this study were obtained with the anemometers and the temperature probe at the 55-m position. Further information on the tower instrumentation is provided by Sun et al. [2002].

g. Microbarographs

The Atmospheric Turbulence and Diffusion Division (ATDD) of NOAA's Air Resources Laboratory operated six differential microbarographs in an array illustrated with the filled circles on the site map in Figure 1. The microbarographs are described in Nappo et al. [1991].

The differential microbarographs measure the pressure difference $\delta p(t)$, between the static atmospheric pressure, $p_a(t)$, and the pressure in a thermally insulated closed reference chamber, p_c,

$$\delta p(t) = p_a(t) - p_c. \tag{1}$$

The microbarograph has a range of 250 Pa, and over the course of a day and especially during frontal passages the change in atmospheric pressure can exceed this value and cause the microbarograph to saturate. To prevent instrument saturation, the reference chamber pressure is periodically set to atmospheric pressure by opening the solenoid valve. During CASES-99, the reference pressure was set to the ambient atmospheric pressure every 15 minutes. To construct a continuous string of differential pressure, the 15 min segments are concatenated. Data sampling was at 10 Hz, and from these values 10-s averages were formed and stored in the data logger. The inner array (ST 1, ST 4, and ST 5) was connected to a single data logger which controlled the valve opening, calculated averages, and stored the data for each of the three stations. The outer array stations (ST 7, ST 8, and ST 9) each had their own data loggers. Data were collected continuously from 3 to 31 October 1999.

3. Mean State Evolution

The mean structure of the NBL evolved throughout IOP 6 in a manner typical of a decaying convective boundary layer under light wind, clear sky conditions. The major influences under such conditions are radiative cooling, flow accelerations accompanying large-scale ageostrophy, and small-scale dynamics, transport, and mixing accompanying the temporal evolution of the NBL. Early temperature profiles (at $\sim$ 0200 to 0400 UT, or 2000 to 2200 LST) exhibit a weakly stratified layer extending from $\sim$ 100 to 600 m AGL, with strong inversions below and above. Successive profiles show the layer above $\sim$ 100 m to become increasingly stratified with time, with the inversions below and above expanding in altitude and variable, though weakening, with time. The upper inversion also descends from ~ 650 m to ~ 500 m by 0600 UT and thereafter. Successive humidity profiles exhibit a parallel evolution of the humidity gradient capping the residual layer. The evolving relative humidity, virtual potential temperature, and stratification (N^2) profiles are displayed using available balloon and TLS data between $\sim$ 0200 and 0800 UT in Figure 2a to c. Note, in particular, that there remain two significant local maxima in N^2 throughout the evolution of the NBL, one near the surface and a second descending from ~ 650 m to ~ 500 m throughout the observation period. These maxima will be seen below to have significant implications for ducting behavior in the NBL.

Profiles of zonal and meridional wind obtained approximately each hour are shown in Figure 2d. At early times winds achieve a weak amplitude maximum of ~ 8 to 10 ms^{-1} between ~ 50 and 300 m AGL, with amplitude increasing in time and decreasing slowly with altitude (to $\sim 5\ \mathrm{ms}^{-1}$) at the upper inversion and more quickly as altitude increases further. The wind direction at early times is nearly uniform across the residual boundary layer from $\sim 45^o$ and slightly more southward at greater altitudes. Throughout IOP 6, the wind becomes initially more westward across the NBL, increases to $\sim 10\ \mathrm{ms}^{-1}$ from ~ 100 to 200 m AGL, decreases slightly below ~ 70 m, and maintains a significant (and nearly constant) shear below the broad jet maximum. Beyond $\sim$ 0600 UT, the mean wind increases to $\sim 12\ \mathrm{ms}^{-1}$ between ~ 100 and 200 m altitude and continues an anticyclonic rotation, achieving flow towards the NW by about 0800 UT, suggestive of a large-scale, quasi-inertial oscillation over the depth of the boundary layer.

Richardson number profiles were derived from temperature, humidity, and wind profiles throughout this portion of IOP 6. These are not displayed, as there was no obvious connection between small Richardson numbers and apparent instability structures at spatial scales resolved by CASES instrumentation. This does not imply, however, that instabilities and turbulence were not present (as they surely were) on smaller scales or for short intervals of time. Evidence of the turbulence that was present during IOP 6 will be examined in Section 5.

4. Ducted Motions

a. Observations and General Characteristics

We turn now to an analysis of the data suggestive of ducted motions within the NBL during IOP 6. These data are available from a broad range of instrumentation because of the comprehensive measurements of the CASES-99 IOPs. However, several data sets were not employed in this study, notably the wind profilers and the sodars, because of their lack of sensitivity at the required scales or altitudes.

a.1. King Air data

Data obtained during the first King Air flight in support of IOP 6 spanned $\sim$ 0400 to 0800 UT and are displayed in two time intervals in Figures 3 and 4. The three panels in each figure show T' with w' (a), u' with w' (b), and u' with v' (c), with (u', v', w') to the east, north, and vertical, independent of flight direction or mean wind orientation. Flight track times and directions are displayed to the left of each track and approximate altitudes (in decameters AGL) are displayed to the right. The means for each variable on each flight segment have been removed for convenience.

A number of features of the motion fields can immediately be inferred. First, there are wave-like motions present much of the time, primarily below 1 km AGL, having apparent wavelengths ranging from less than 1 km to greater than 10 km, though true wavelengths will be smaller (larger) than measured if the direction of wave propagation is parallel (anti-parallel) to the flight track and smaller than measured if there is a component of wave propagation normal to the flight track. Second, vertical motions are typically comparable to or larger than horizontal motions, zonal and meridional motions may be correlated or anti-correlated, and vertical motions are typically in approximate quadrature with both components of horizontal motion. The quadrature relations between horizontal and vertical velocities imply small or zero vertical momentum fluxes, $\overline{u'w'}$ or $\overline{v'w'}$, no vertical propagation, and a likelihood that these motions are trapped or ducted within the NBL. Third, vertical velocities and perturbation temperatures, T', are in approximate quadrature, as required for approximately adiabatic motions, with w' maxima westward of T' minima, implying a westward component of phase progression for virtually all motions. Together, these data suggest ducted motions of several km wavelengths propagating generally westward, with some directional variations depending on specific sources and the local NBL structure.

Exceptions to these general observations include typically small-scale motions having apparent wavelengths of 1 km or less, seen at the east ends of the flight tracks from

0415 to 0435 UT, the center of the flight track from 0513 to 0518 UT, and the east end of the flight tracks from 0625 to 0629 UT. These motions typically have the opposite correlation between w' and T', suggesting propagation against the mean westward flow, but perhaps not propagation eastward. While the geographic localization of most of these motions and their w' and T' correlations suggest a possible stationary lee wave response to slight terrain east of the CASES-99 Main Site, these small-scale motions are not our focus here. It is also possible that these motions are KH shear instability occurring at levels of enhanced shear, but it is difficult to make this assessment without additional quantification of the local environment.

a.2. Raman lidar and HRDL

Other CASES-99 instrumentation obtained data providing additional insights into the character of the motions discussed above. The Raman lidar and HRDL provided vertical profiles of humidity and velocity, enabling an evaluation of the vertical structure of these motions. The Raman lidar yielded estimates of mixing ratio, thus perturbation humidity by subtraction of the mean humidity at each altitude, which is a tracer of vertical motions in the presence of a well-defined mean vertical gradient of humidity.

Small humidity and velocity perturbations are related through

$$\frac{\partial q'}{\partial t} + \overline{\mathbf{u}} \cdot \nabla q' + \mathbf{u}' \cdot \nabla \overline{q} = 0, \tag{2}$$

where overbars denote local means (which may have horizontal and vertical gradients) and primes denote perturbations about the means. For well-defined $\overline{q}_z(z)$ and small $\overline{q}_x$ and $\overline{q}_y$ (where subscripts denote derivatives), Eq. (2) provides a direct relationship between w' and q' when the properties of the perturbation fields are known sufficiently well. Where $\overline{q}_z(z)$ is small, however, as occurs across much of the NBL and above the upper inversion layer, Eq. (2) is ill-conditioned and w' estimates based on q' are subject to large uncertainties.

When $\overline{q}_z(z)$ is well defined, a wave motion of the form

$$\phi'(x, y, z, t) = \phi_0 e^{i(kx+ly+mz-\omega t)}, \tag{3}$$

with wavenumber $\mathbf{k} = (k, l, m)$, intrinsic frequency $\omega_i = k_h c_i$, $k_h = \sqrt{k^2 + l^2}$, and c_i the intrinsic phase speed in the direction of propagation given by $\mathbf{k}_h/|k_h|$, with $\mathbf{k_h} = (k, l)$, yields an expression for w' given by

$$w' = i(\omega - k_x\overline{u} - k_y\overline{v})q'/\overline{q}_z(z) = i\omega_i q'/\overline{q}_z(z). \tag{4}$$

To explore the implications of these data for wave character, we display q' fields from 0300 to 0900 UT during IOP 6 in Figure 5a. A crude estimate of w' from q' at heights near the maximum humidity gradient (see Figure 5b) is shown in Figure 6a-c. For this estimate, we assume that $k_x = k_y = 0$, or alternatively that $\overline{u} = \overline{v} = 0$, $\omega = \omega_i$, and $w' = -(\partial q'/\partial t)/\overline{q}_z = i\omega q'/\overline{q}_z$ in Eq. (4). This amounts to an overestimate of w' by the ratio ω/ω_i. Given that the mean horizontal wind $\overline{u}_h$ at ~ 500 m is $\sim 1/2$ the maximum at lower altitudes and that $c_h > \overline{u}_h$, this ratio is likely ~ 2 to 3 at most. Direct measurements of vertical motions were obtained with HRDL during the interval from 0617 to 0647 UT. These data at altitudes from ~ 270 to 500 m AGL are displayed in Figure 6d. Comparison of the w' magnitudes in Figure 6c and d seems to support the above arguments.

Examination of both lidar data sets suggests that large vertical motions 1) were confined to altitudes below ~ 1.5 km AGL, 2) were highly coherent vertically, with little or no evidence of phase variations of q' or w' with altitude, and 3) had peak amplitudes of ~ 0.3 ms^{-1} or larger, consistent with King Air measurements. We also note that the HRDL data suggest significant vertical velocities extending over a larger altitude range than inferred from the q' data. This is because q' is maximum where $\overline{q}_z(z)$ is large, and this appears to be a more restricted altitude range than the occurrence of large w'. The lidar data suggest several intervals of particularly strong and coherent wave motions, and these will be examined further below. Examination of Figure 6c and d reveals that the vertical velocities at the two sites are in approximate antiphase up to ~ 0630 UT.

a.3. TLS, 60-m tower, and microbarograph data

Several other data sets corroborate the apparent ducted wave structure described above. TLS horizontal wind and temperature data obtained during the constant-altitude segment from ~ 0415 to 0520 UT (see Figure 7) exhibit ~ 4 to 5-min oscillations with in-phase temperature and (westward positive) horizontal wind perturbations, consistent with King Air inferences (both T' and u' were in quadrature with w'). These perturbations cannot be the result of vertical advection, $u' \approx iw'\overline{u}_z/\omega_i$, because the mean wind is essentially unsheared at this altitude and time. TLS T' (at $\sim$ 460 m) are also seen to be in approximate quadrature with Raman lidar vertical velocities (at 500 m) from $\sim$ 0500 to 0520 UT (compare Figs. 6a and 7), with w' maxima leading T' minima, confirming the lack of phase variation with altitude seen in the lidar data above.

Anemometers and hot-wire probes on the 60-m tower also exhibit $\sim$ 4- to 5-min oscillations, together with higher-frequency oscillations that are not as apparent at higher altitudes. The 55-m perturbation winds and temperature are displayed in the same manner as the King Air data, with w' and T', u' and w', and u' and v' shown together in Figures 8 to 10, respectively. Much of the higher-frequency activity appears primarily in the u', w', and T' fields, is likely Doppler shifted to higher frequencies (relative to the atmospheric reference frame), ducted, propagating westward, and more confined in altitude and thus not as evident in TLS and lidar data at higher altitudes. These multiple motions complicate identification of the relative phases between the velocity and temperature perturbations more in the tower data than at greater altitudes. Other motions may be signatures of flow instabilities and turbulence at smaller scales due to the strong shears below $\sim$ 100 m (see Section 5 below).

Velocities measured on the tower, while somewhat correlated with data collected at higher altitudes, are ambiguous in their implications for wave structure and propagation direction. One reason for this is the much higher wind shears at tower altitudes than at higher altitudes, and the greater potential for horizontal velocity perturbations to be imposed by vertical advection of vertical wind shears. With a zonal mean wind shear of $\overline{u}_z \sim 0.1$ s^{-1}, a mean temperature gradient of $\overline{T}_z \sim$0.03 Km^{-1}, and $T' \sim 0.05$ K (implying vertical displacements of $\sim$ 1 to 2 m), $w' \sim 0.05$ ms^{-1} implies $u' \sim 0.1$ to 0.2 ms^{-1}. These velocity fluctuations are comparable to observed u' and v' fluctuations, though vertical advection is only able to account for large u' and v' fluctuations proportional to the mean shears in these directions. Such perturbations likely contribute to less well defined phase relations between horizontal and vertical velocities in the tower winds than are observed at greater altitudes.

Finally, some of the motions discussed above are apparent in the microbarograph data at various locations around the CASES-99 Main Site. Data obtained at 5 m on the 60-m tower and six surrounding towers (see Figure 1) for the interval from 0430 to

0730 UT are displayed in Figure 11b. A Morlet wavelet analysis of the data from station 1 subjected to a 1- to 30-min bandpass is shown in Figure 11b. These data reveal a dominance of fluctuations with $\sim$ 4 to 5-min periods, as noted above, with both smaller-amplitude fluctuations at shorter periods and more sporadic responses at longer periods. These results are confirmed by a cross S-transform [Stockwell and Lowe, 2001] analysis designed to identify responses that are coherent across two spatially displaced sensors (see Figure 12). These results suggest a typical coherent wave packet duration of $\sim$ 3 to 6 cycles, consistent with the various time series and spatial data discussed above.

Both these analyses identify $\sim$ six discrete events, three of which will be examined more closely below. We note, however, that there is not a complete correlation between events that are significant in the microbarograph data and those that are more apparent at higher altitudes. One example is the motions detected in the King Air and Raman lidar data prior to 0500 UT (particularly w' and q'), but which contribute little in terms of surface pressure or tower velocity and temperature fluctuations. Other examples are the motions observed from $\sim$ 0520 to 0550, 0610 to 0640, and 0710 to 0730 UT with significant surface pressure signatures for which there are corresponding fluctuations in the King Air, TLS, and lidar data. Below, we discuss three case studies for which a) King Air, TLS, lidar, and/or tower data exhibit significant wave-like motions and b) microbarograph data permit estimates of wave propagation direction and phase speed.

b. Case Studies

b.1. Case 1: 0400 to 0500 UT

As noted above, the dominant motions during this interval at upper levels have periods of $\sim$ 4 to 5 min, $w' \sim 0.5$ ms^{-1}, w' maxima westward of T' minima (*i.e.* westward propagation), u' and w' in apparent quadrature with u' leading w', and generally small u' and smaller v'. The stratification during this interval exhibits an extended maximum from $\sim$ 450 to 700 m, and the q' measurements and w' inferences with the Raman lidar indicate that vertical motions are highly coherent across this altitude range (see Figures 5a and 6a). We also note from Figure 3 that u' is much smaller than w' at these altitudes, but that u' is larger and in approximate quadrature with w' at lower and higher altitudes.

Velocity perturbations obtained with the King Air indicate u' and v' most often in antiphase, but with u' typically larger, indicating a largely westward wave propagation (given the w' and T' correlations discussed above). Likewise, u' most often leads w', except within the layer of higher stratification, where this correlation is less apparent or inverted. These correlations have been confirmed by S-transform cospectra and quadrature spectra of u' and v', but these plots provide little additional insight beyond that obtained from the data shown in Figures 3 and 4 and are not shown.

Data from the TLS (see Figure 7) exhibit a clear correlation between T' and wind speed (or westward velocity) within the layer of higher stratification ($\sim$ 470 m) which appears to contradict the more general correlations implied by the King Air data, but which agrees with King Air data for the flight segments from 0423 to 0435 UT within this same layer. TLS temperatures are in approximate quadrature with Raman lidar vertical velocities at greater altitudes, confirming the vertical coherence of the wave motions described above.

Data from the anemometers and hot-wire probe at 55 m on the 60-m tower are displayed in Figures 8 to 10. The upper panels in these figures exhibit the same $\sim$ 4 to 5-min periods observed by the King Air, TLS, and Raman lidar during the interval 0400 to 0500 UT, with apparent quadrature phase relationships between w' and both T' and u'. Additional motions are seen at higher frequencies (periods of $\sim$ 1 to 2 min) for which there is also some evidence at higher altitudes. The dominant signatures of these higher-frequency motions appear in the u', v', and T' fields, suggesting that they propagate preferentially toward the west and are Doppler shifted to observed frequencies significantly higher than intrinsic frequencies. Phase relationships and wave structures appear somewhat more complex in the tower data, however. There are likely several reasons for this. One noted above is the presence of a strong vertical shear of the mean zonal wind which, in the presence of vertical advection, contributes to perturbation zonal velocities and an imposed quadrature phase relationship expressed by Eq. (2). A second possible explanation for some of the enhanced activity and complexity of the motion field at higher frequencies is the potential for shear instabilities at smaller scales of motion within the strong mean wind shear beneath the low-level jet (see Section 5).

Because of the caveats expressed above about the tower wind and temperature data, we consider the King Air, TLS, and Raman lidar data to be more representative of the larger-scale motions within the NBL during this interval. In this case, the horizontal wavelengths apparent in the King Air data provide reasonably accurate estimates of the true wavelengths after accounting for the horizontal phase speed of the wave relative to the horizontal motion of the King Air. Given that the waves are propagating largely westward, they must have a speed greater than the maximum westward mean wind, or $c_x > 10$ ms^{-1} to the west. This westward phase progression will decrease (increase) the apparent wavelengths by a fraction of $\sim |c_x/U_{KA}|$ for eastward (westward) flights, where $U_{KA} \sim 80$ ms^{-1} is the speed of the King Air. In either case, apparent wavelengths are $\sim$ 1 to 3 km, and we will focus on these horizontal scales in our evaluation of possible wave structures below. Estimated phase speeds, assuming the dominant periods apply to all observed horizontal wavelengths, vary from $\sim$ 4 to 12 ms^{-1}. These are clearly appropriate only for the larger wavelengths, since there is no evidence of critical-level behavior in the strong shears at the lower altitudes. Interestingly, the surface pressure perturbations during this interval are significantly smaller than those for later periods, even though w' and its temporal variations at greater altitudes are as large or larger during this interval.

The wave structures and correlations among variables described here are suggestive of the character of ducted motions discussed above. A more detailed analysis of this behavior for the specific cases considered here is provided in Section 4c below.

b.2. Case 2: 0500 to 0600 UT

Motions observed with the King Air and other instrumentation during this interval differ in important respects from those discussed immediately above. While pressure fluctuations at longer periods are comparable to Case 1, there is now much more power at $\sim$ 5 min periods. The characteristic horizontal scales are likewise significantly larger, now $\sim$ 3 to 8 km, and King Air horizontal velocity perturbations are smaller and vary from being correlated to apparently uncorrelated. Correlations between u' and w' continue to suggest a more nearly quadrature than in-phase or antiphase relationship (see the flight tracks from 0505 to 0509 and 0530 to 0534 UT in Figure 3b), again suggesting no momentum flux and no vertical propagation. S-transform cospectra and quadrature spectra of the perturbation velocities (not shown) reinforce these conclusions.

T' and w' correlations continue to imply westward propagation (see the flight track from 0513 to 0518 UT in Figure 3a), but because most flight altitudes are above the upper maximum in stratification during this interval, T' tends to be small. TLS data continue to show an in-phase relation between T' and westward velocity (consistent with quadrature between u' and w'), while vertical motions implied by q' likewise suggest high vertical coherence and no apparent vertical phase progression (also consistent with TLS and King Air inferences). Phase speeds for these motions (inferred from observed wavelengths, propagation directions, and periods) are $\sim$ 10 to 25 ms^{-1}, typically faster than mean winds in the direction of propagation, and consistent with a ducted wave interpretation of these motions. Tower velocity and temperature perturbations also exhibit a dominance of $\sim$ 4 to 5-min periods, especially in the meridional component which cannot be attributed to vertical advection. Tower velocities likewise differ in their phase relationships relative to those observed in the King Air and TLS data. Hence tower measurements continue to suggest additional motions at lower altitudes than those imposed by ducted motions at greater altitudes. The higher-frequency motions in the tower data, in particular, are suggestive of small horizontal wavelength (and small phase speed) motions that are more confined at the lowest altitudes.

The larger pressure fluctuations at $\sim$ 5 min periods during this interval suggest that the wave motions observed at upper levels may extend with larger amplitude to lower altitudes than those motions discussed in Case 1 above. An understanding of these differences will be sought in terms of the differing modal structures in Section 4c.

b.3. Case 3: 0600 to 0700 UT

Motions during this interval are more similar to those of Case 1 than Case 2 above. As in Case 1, the dominant motions at upper levels of the NBL have periods of $\sim$ 5 min, $w' \sim 0.5\ \mathrm{ms}^{-1}$, westward propagation ($w'$ maxima westward of T' minima), and u' and w' in apparent quadrature with u' (generally) leading w'. In this case, both positive and negative correlations between u' and v' are observed, with largely positive correlations prior to $\sim$ 0630 UT and largely negative correlations thereafter, suggesting propagation preferentially towards the NW (SW) at the earlier (later) times. As in Cases 1 and 2 above, S-transform cospectra and quadrature spectra of u' with v' and u' with w' support these conclusions, but offer little additional insight and are not shown.

Apparent wavelengths are $\sim$ 1 to 7 km, implying, with the preferred directions of propagation, real wavelengths smaller by $\sim$ 30%. As in Case 1, u' is comparable to or smaller than w' along the King Air flight tracks. The stratification profile is much like the earlier cases, and the q' measurements of the Raman lidar again indicate that w' is highly coherent and there is little or no phase variation across the altitude range of high stratification (and large $d\overline{q}/dz$). As noted above, HRDL data available during the interval 0617 to 0647 UT (see Figure 6d) reveal both coherent vertical motions supporting inferences from the Raman lidar and a tendency for vertical velocities to decrease away from the upper stratification maximum. Examination of Figure 6c and d reveals that the vertical velocities at the two sites are in approximate antiphase up to $\sim$ 0630 UT. Given a separation of the two lidars by $\sim$ 1.5 km, this suggests a wavelength (assuming propagation toward the NW) of $\sim$ 3 km or less, in agreement with the estimates based on King Air data above.

A more quantitative view of the along-track scales of the wave motions measured by King Air instrumentation is provided by the S-transform of the various perturbation fields. Those obtained for w' and T' are shown for the flight segment from 0614 to 0619 UT in Figure 13. In both data sets, motions are observed west of the CASES-99 Main Site (and east to a lesser extent) having wavelengths of $\sim$ 1.7, 3.5, and 7 km. The approximately integral relationship between these motions suggests a possible nonlinear coupling of wave energy, as examined by Liu et al. [1980, 1982] and Liu and Benney [1981], but further exploration of such a linkage is beyond the scope of this paper. Such an analysis is useful in quantifying the scales of motion present in the King Air data, but it does not facilitate an intercomparison of spatial and temporal data because it is not obvious how to relate events having discrete multiple signatures in frequency or wavenumber.

Tower velocity and temperature perturbations again exhibited primarily $\sim$ 4 to 5-min periods, but also $\sim$ 1 to 2-min periods more similar to Case 1 than Case 2. Surface pressure perturbations during this interval are larger than those in Case 1, despite smaller wave perturbations in general, and may imply lower ducted motions than were typical during Case 1. However, u' and v' fluctuations measured on the tower do not exhibit correlations that agree well with those observed at greater altitudes. As above, this may be due to the more complex factors influencing horizontal velocity perturbations in the presence of strong mean wind shears and vertical advection.

c. Theory

Many characteristics of the motions described above are suggestive of wave structures that are ducted within the NBL, *i.e.* that have evanescent character above the upper layer of enhanced stratification and possibly within the NBL itself. The characteristics most suggestive of ducting include 1) the vertical coherence and lack of vertical phase progression of the motions and 2) the apparent quadrature between horizontal and vertical velocities indicating small or zero momentum fluxes (per unit mass), $\overline{u'w'}$ and $\overline{v'w'}$. Wave periods near the local buoyancy period and horizontal wavelengths of a few km or less are also suggestive of wave ducting, but wave periods are an ambiguous indication when wave phase speeds are comparable to mean winds.

The vertical structure of gravity waves is described by the Taylor-Goldstein equation [Gossard and Hooke, 1975; Gill, 1982]

$$\frac{d^2w'}{dz^2} + m^2 w' = 0, \tag{5}$$

where

$$m^2 = \frac{N^2}{c_i^2} + \frac{\overline{u}_{zz}}{c_i} - k_h^2 - \frac{1}{4H^2}, \tag{6}$$

$\overline{u}_{zz}$ is the second derivative with height of the mean wind in the direction of wave propagation, H is the scale height, and other quantities are as defined above. Typically, the first three terms on right side of Eq. (6) are the largest and largely control modal structures in a variable environment. The last term in Eq. (6) is negligible for motions having large m^2, but is important near turning levels where $m^2 \sim 0$. Ducted motions may have one or more local (positive) maxima of m^2 occurring between regions of either negative m^2 or a reflecting surface, *i.e.* the ground.

The vertical structure of ducted motions representative of the cases discussed above is determined by solving Eq. (5) for eigenvalues c_i (or $c_h = c_i + \overline{u}(z)$) for specified profiles of N^2 and $\overline{u}(z)$ and specific k_h, and subject to appropriate boundary conditions [Chimonas and Nappo, 1987; Nappo, 2002]. In our cases, these boundary conditions include a rigid lower boundary below the low-level nocturnal jet and an upper boundary condition specifying an exponential decay with height that matches that expected from Eq. (6).

The resulting motions represent eigennmodes of the system that would be resonant under sustained forcing with these specific wave characteristics. In the absence of such forcing, however, they represent free solutions of the system. Assuming the latter, solutions are obtained by setting $w' = 0$ and $dw'/dz = 1$ at the lower boundary, integrating the solution from the lower to the upper boundary, and iterating the initial guess for c_i until the solution matches the required decaying wave structure where the upper boundary condition is imposed. The resulting vertical profiles of perturbation vertical velocity w' are the eigenmodes corresponding to the eigenvalues c_i for each set of mean profiles and k_h.

We perform calculations of the modal structures for three sets of profiles corresponding as closely as possible to the three cases discussed above. These are the profiles at 1) 0401, 2) 0544, and 3) 0600 UT. The raw data and the spline fits to each of the N^2 and wind profiles in the direction of inferred wave propagation are shown in Figure 14.

Exploration of the full range of parameters available to modes that exhibit ducted behavior is challenging. We nevertheless try here to illustrate the character of ducted waves for a range of plausible phase speeds and horizontal wavelengths. For this purpose, we assume propagation directions imposed by the correlations among King Air horizontal velocity fluctuations, *i.e.* toward the W, SW, and NW for Cases 1, 2, and 3 discussed above. The vertical profiles of vertical wavenumber squared, $m^2 = N^2/c_i^2 + \overline{u}_{zz}/c_i - k_h^2 - 1/4H^2$, for wavelengths from 1 to 3 km and horizontal phase speed judged most likely for each case are shown in Figure 15a to c. In each case, the greatest structure is exhibited by the motions with the smallest horizontal wavelength and phase speed for which the curvature term plays the greatest role. The vertical structure of the mode 0 response in u' and w' for a horizontal wavelength of 1 km is shown for each case in Figure 16.

Additionally, we show in Figure 17 the dispersion curves for modes zero to three for each case for a range of shorter horizontal wavelengths. These curves exhibit clear indications of Eckart's resonances arising from the multiple ducting structures within the NBL. Such ducting behavior suggests an explanation for the complex wave structures exhibited in several of the data sets considered above. In particular, the changing slopes of the dispersion curves with wavenumber indicate a transition from a dominant response at one ducting level to another as well as a change in the group velocity of the corresponding wave motion. As noted by Fritts and Yuan [1989], portions of the dispersion curves with intrinsic frequency decreasing with increasing k_h correspond to a dominant response at the thermal duct and increasing intrinsic frequency with increasing k_h correspond to a dominant response at the Doppler duct. A more complete analysis of these features is anticipated elsewhere.

Inspection of the m^2 profiles in Figure 15 reveals that, for the phase speeds and propagation directions selected, ducting occurs largely as a result of the elevated inversion at 0400 UT and more in response to the combination of thermal and Doppler ducts at later times. The profiles of m^2 at 0400 and 0544 UT, in particular, illustrate clearly the role of curvature of the mean wind in contributing to negative m^2 and localized vertical structure. In all cases, the modal structures suggest motions that have highly coherent vertical velocities in the vertical, with vertical extents that are sensitive to environmental structure, phase speed, and horizontal wavelength. Note also the phase reversal of the horizontal velocity that accompanies each w' maximum and which is characteristic of such ducted motions.

For the profiles at 0400 UT, for which m^2 exhibits a pronounced minimum near the core of the low-level jet, the mode 0 response is broad and centered near the upper inversion. In particular, the modal structure appears to account for the extended coherence of w' and the observed dominance of w' over u' in King Air data at $\sim$ 450 to 700 m. There is also a very small response of mode 0 at a wavelength of 1 km below 200 m, suggesting that the motions observed with tower instrumentation may occur at larger k_h for which the lower Doppler duct may be dominant. The rapid changes in modal character with k_h seen in the dispersion curves in Figure 17 suggest the largest distinctions between thermal and Doppler ducting responses in Case 1.

Ducted wave structure during Case 2 (for the mean profiles at 0544 UT) exhibits a broader response in altitude because the maxima and minima of m^2 are less pronounced, particularly for the larger horizontal wavelengths for which m^2 is $\sim$ zero over an extended altitude range (see Figure 15b). We also see from the dispersion curve for mode 0 in Figure 17b that the 1 km wavelength is near an Eckart's resonance and thus has a response distributed across both thermal and Doppler ducts. The occurrence of ducting over a greater depth of the NBL during this time, and in particular the extension of significant u'

and w' to much lower altitudes, likely also accounts for the better correlation of elevated velocity fluctuations with surface pressure fluctuations noted in Case 2 above. Wave periods for the phase speeds, horizontal wavelengths, and propagation directions most representative of Case 2 vary from $\sim$ 140 to 300 s and are consistent with the periods observed in the TLS and surface pressure data.

The smaller horizontal wavelengths occurring during Case 3 (Figure 15c) imply more localized responses in the vertical, with the slope of the dispersion curve for mode 0 suggesting primarily Doppler ducting character. Wave periods for the assumed phase speed and horizontal wavelengths in this case are $\sim$ 120 to 180 s and are more likely to be reflected in the tower and surface pressure data because of the larger amplitudes near the ground than in Case 1. As in Case 1, however, mode 0 responses near the ground appear to be much smaller than for Case 2.

The picture that emerges from this analysis is one of a variety of possible ducted wave responses to the mean wind and stability profiles at any one time, depending on horizontal wavelength, direction of propagation, and horizontal phase speed of the wave motion. The vertical structure of such motions is especially sensitive to phase speed and horizontal wavelength, as these largely determine, for given profiles of N^2 and mean wind, over what altitudes m^2 is positive and at which ducting level the maximum response occurs. Indeed, ducted motions may easily occur simultaneously at each of the m^2 maxima, thus contributing to a potential for apparently different velocity correlations near the upper and lower ducts, as seen in the analysis above. What is central to our argument here is that the wave structure within each duct (or for each mode) exhibits the correlations observed by the King Air, the lidars, and the TLS during IOP 6 of CASES-99. Thus, while no single wave motion is likely to account for all of the observed wave structures, a superposition of such ducted motions seems to pose a very plausible explanation for the statistics and character of our IOP 6 wave observations in general.

5. Implications for Turbulence and Mixing

We noted in the discussion of King Air data above that there were occurrences of enhanced small-scale structure during several of the flight segments. These occurred primarily during flights prior to 0542 UT shown in Figure 3. Small-scale structure was also observed with the TLS both during ascents and descents and in measurements at a constant altitude. We assume that these small-scale structures are signatures of turbulence, and we assess here their possible association with the ducted wave motions analyzed above.

Inspection of Figure 3, where turbulence is indicated by fine structure in the w' and v' fields, reveals that turbulence occurs with significant magnitude either nearly continuously, as in the flight segments after 0522 UT, or in very localized patches, as seen at the east ends of the flight segments prior to 0419 UT. In several cases, turbulence appears to be associated with other wave-like activity occurring at very small spatial scales, as in the flight segments prior to 0419 UT and from 0513 to 0518 UT. Only in the flight segment from 0530 to 0534 UT is there any suggestion that turbulence intensity might be correlated with the larger-scale wave activity discussed above.

A more sensitive measure of the presence of turbulence, particularly at low intensities, is the TLS instrumentation. Figures 18 and 19 show estimates of ϵ and C_T^2 derived from the anemometer and hot-wire probe on the TLS for both the interval from 0415 to 0520 UT at $\sim$ 470 m altitude and the ascent and descent (left and right panels in Figure 19) occurring from 0527 to 0612 UT. The first thing to note here is the very low turbulence intensities observed at all altitudes and times. The small turbulence intensities and the near-uniform magnitude of ϵ during the interval at constant altitude suggest a decaying phase of turbulence rather than an active source modulated by significant wave activity. More likely, variations in ϵ are a signature of vertical advection in the presence of weak vertical gradients of ϵ, as the late stages of turbulence decay following shear instability exhibit considerable horizontal homogeneity [Werne and Fritts, 1999]. Variations in C_T^2 with time are larger, but given the weak variations in ϵ, the variations of C_T^2 are more likely indicative of varying temperature gradients on small vertical scales that are advected vertically.

Vertical profiles of ϵ and C_T^2 reinforce the above interpretation since, except for the very small values of ϵ between 700 and 800 m, C_T^2 appears to exhibit somewhat greater variability with altitude. Sharper vertical gradients of C_T^2 than of ϵ will necessarily contribute larger temporal variations in the presence of vertical advection. The small-scale variability in the vertical profiles of ϵ and C_T^2 also provides evidence that the observed turbulence and its spatial and temporal variability are not directly attributable to the ducted wave motions. These wave structures have small vertical gradients and much larger vertical extents than the spatial variations observed in the ϵ and C_T^2 profiles. As such, it appears much more likely that variations in these quantities are due largely or entirely to vertical advection of turbulence that arose due to shear instability of the NBL at small vertical scales and had a localized vertical extent. Such a view is also easier to reconcile with the general agreement between the larger-scale features of the ϵ and C_T^2 profiles observed above $\sim$ 500 m during the ascent and descent displayed in Figure 19, since we expect turbulence generated by shear instability to be localized vertically but extended horizontally [Werne and Fritts, 1999].

6. Summary and Conclusions

We have described a series of wave motions occurring in the stable nocturnal boundary layer during IOP 6 of the CASES-99 field program performed in southeast Kansas in October 1999. IOP 6 occurred during the night of 14 October and measured NBL motions under light wind, clear sky conditions. The mean state on this night was characterized by a low-level jet having a maximum wind speed of $\sim$ 8 to 12 ms^{-1} at altitudes of $\sim$ 50 to 300 m, a clockwise rotation of the jet with an apparent inertial period, a strongly stratified shear flow beneath the jet, a weakly-stratified residual convective boundary extending to $\sim$ 500 to 650 m AGL, and a strongly-stratified inversion above that descended throughout the night.

The predominant motions observed during IOP 6 were similar in character throughout the night, exhibiting largely westward propagation, horizontal wavelengths of $\sim$ 1 to 10 km, phase speeds greater than the mean wind in the direction of propagation, and observed periods of typically 4 to 5 min, but with some periods as long as 10 to 20 min and as short as 1 to 2 min. Wave vertical velocities were as large as 0.5 ms^{-1}, tended to be highly coherent in the vertical, and exhibited no apparent phase progression with altitude. Vertical and horizontal velocities were in approximate quadrature and the largest amplitudes occurred at altitudes of maximum stratification. Wave amplitudes varied with time and exhibited $\sim$ six maxima throughout the interval from 0400 to 0800 UT at periods near 5 min. Measurements of wave activity throughout the NBL were correlated somewhat with surface pressure and low-altitude wind measurements. However, the correlations were not as strong as we had initially expected, due both to the dependence of vertical wave structure on horizontal wavelength and to the confinement of wave activity at altitudes above the ground. The observed wave motions were interpreted as ducted gravity waves that propagate horizontally along maxima of the stratification and mean wind, and that are evanescent above, and possibly below and/or between, the ducting level(s).

To support our interpretation of the observed wave motions, modal structures for ducted waves were computed for mean wind and stratification profiles for three specific cases. The resulting wave structures were found to have u' and w' in quadrature, with the vertical extent of the motions dependent on horizontal wavelength, direction of propagation, phase speed, and the mean stratification and wind profiles. While no single ducted wave response can explain the observed wave structures at all altitudes, superpositions of such motions offer a likely explanation of the observed waves. The apparent presence of Eckart's resonances in the ducted wave structures, and the apparent integral relationships among wave scales in some of the frequency and wavenumber data, suggest possible interactions among components of the motion field and a potential for energy transports, both spatially and spectrally.

Turbulence observed during IOP 6 was judged to not be in response to the observed ducted wave motions, but rather to likely arise from small-scale instabilities localized in the vertical, with observed temporal variations due to vertical advection of vertical gradients of turbulence quantities. The observed ducted motions therefore contribute significantly to NBL fluctuating velocities, but very little or not at all to vertical mixing and transport processes.

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References

Balsley, B. B., R. G. Frehlich, Y. Meillier, and M. L. Jensen, 2002c: Preliminary CASES-99 Measurements of Steep Vertical Gradients in Temperature and Turbulence Structure Using a Tethered Lifting System, Bound. Layer Meteor., **xx,** submitted.

Balsley, B. B., D. C. Fritts, R. G. Freligh, M. Jones, S. L. Vadas, and R. Coulter, 2002a: Up-gully flow in the Great Plains region: A mechanism for perturbing the nighttime lower atmosphere?, Geophys. Res. Lett., **20** (19), 10.1029/2002GL015435.

Balsley, B. B., M. L. Jensen, R. G. Frehlich, Y. Meillier, and A. Muschinski, 2002b: On Layered Temperatures and Stratified Turbulence Characteristics in the Nighttime Stable Boundary Layer during CASES-99: A Case Study Using the TLS, Bound. Layer Meteor., **xx**, submitted.

Blumen, W., R. Banta, S. P. Burns, D. C. Fritts, R. Newsom, G. S. Poulos, and J. Sun, 2001: Turbulence statistics of a Kelvin-Helmholtz billow event observed in the nighttime boundary layer during the CASES-99 field program, Dyn. Atmos. Oceans, **34**, 189-204.

Chimonas, G., and C. O. Hines, 1986: Doppler ducting of atmospheric gravity waves, J. Geophys. Res., **91**, 1219-1230.

Chimonas, G., and C. J. Nappo, 1987: A thunderstorm bow wave, J. Atmos. Sci., **44**, 533-541.

Coulter, R. L. and J. C. Doran, 2002: Spatial and temporal occurrence of intermittent turbulence during CASES-99, Bound. Layer Meteor., **105**, 329-349.

Eckart, C., 1961: Internal waves in the ocean, Phys. Fluids, **4**, 791-799.

Eichinger, W. E., D. I. Cooper, P. R. Forman, J. Griegos, M. A. Osborn, D. Richter, L. L. Tellier, and R. Thornton, 1999: The development of Raman water-vapor and elastic aerosol lidars for the Central Equatorial Pacific Experiment, Atmos. Oceanic Tech., **16**, 1753-1766.

Einaudi, F., 1989: A climatology of gravity waves and other coherent disturbances at the Boulder Atmospheric Observatory during March-April 1984, J. Atmos. Sci., **46**, 303-329.

Finnigan, J. J., and F. Einaudi, 1981: The interaction between an internal gravity wave and the planetary boundary layer, Part II: Effect of the wave on the turbulent structure, Q. J. Roy. Met. Soc., **107**, 807-832.

Finnigan, J. J., F. Einaudi, and D. Fua, 1984: The interaction between an internal gravity wave and turbulence in the stably-stratified nocturnal boundary layer, J. Atmos. Sci., **41**, 2409–2436.

Fritts, D. C., and L. Yuan, 1989: An analysis of gravity wave ducting in the atmosphere: Eckart's resonances in thermal and Doppler ducts, J. Geophys. Res., **94**, 18,455–18,466.

Gill, A. E., 1982: Atmosphere-Ocean Dynamics, Academic Press, New York.

Gossard, E. E., and W. H. Hooke, 1975: Waves in the Atmosphere, Elsevier, Amsterdam.

Jones, W. L., 1970: A theory for quasi-periodic oscillations observed in the ionosphere, J. Atmos. Terres. Phys., **32**, 1555-1566.

Katz, E. J., and M. G. Briscoe, 1979: Vertical coherence of the internal wave field from towed sensors, J. Phys. Ocean., **9**, 518-530.

Liu, A. K., and D. J. Benney, 1981: The evolution of nonlinear wave trains in stratified shear flows, Stud. Appl. Math., **64**, 247-269.

Liu, A. K., T. Kubota, and D. R. S. Ko, 1980: Resonant transfer of energy between nonlinear waves in neighboring pycnoclines, Stud. Appl. Math., **63**, 25-45.

Liu, A. K., N. R. Pereira, and D. R. S. Ko, 1982: Weakly interacting internal solitary waves in neighboring pycnoclines, J. Fluid Mech., **122**, 187-194.

Monserrat, S., and A. J. Thorpe, 1996: Use of ducting theory in an observed case of gravity waves, J. Atmos. Sci., **53**, 1724-1736.

Nappo, C. J., 2002: An Introduction to Atmospheric Gravity Waves, Academic Press.

Nappo, C. J., T. L. Crawford, R. M. Eckman, and D. L. Auble, 1991: A high-precision sensitive electronic microbarograph network. Proc. 7th AMS Symp. on Meteorol. Obs. and Instrum., New Orleans, J179-J181.

Newsom, R. and R. M. Banta, 2002: Shear-instability gravity waves in the stable nocturnal boundary layer as observed by Doppler lidar during CASES-99, J. Atmos. Sci., in press.

Peters, H., 1983: The kinematics of a stochastic field of internal waves modified by a mean shear current, Deep Sea Res., **30**, 119-148.

Poulos, G. S., W. Blumen, D. C. Fritts, J. K. Lundquist, J. Sun, S. P. Burns, C. Nappo, R. Banta, R. Newsom, J. Cuxart, E. Terradellas, B. B. Balsley, and M. Jensen, 2001: CASES-99: A comprehensive investigation of the stable nocturnal boundary layer, Bull. Amer. Meteor. Soc., in press.

Rees, J. M., J. C. W. Denholm-Price, J. C. King, and P. S. Anderson, 2000: A climatological study of internal gravity waves in the boundary layer overlying the Brunt Ice Shelf, Antarctica, J. Atmos. Sci., **57**, 511-526.

Soler, M. R., C. Infante, P. Buenestado and L. Mahrt, 2002: Observations of nocturnal drainage flow in a shallow gully, Bound. Layer Meteor., **105**, 253-273.

Stobie, J. G., F. Einaudi and L. W. Uccellini, 1983: A case study of gravity waves - convective storms interactions: 9 May 1997, J. Atmos. Sci., **40**, 2804-2830.

Stockwell, R. G., and R. P. Lowe, 2001: Airglow imaging of gravity waves 1. Results from a small network of OH nightglow scanning imagers, J.Geophys. Res., **106**, 17,185-17,203.

Sun, J., D. H. Lenschow, S. P. Burns, R. Banta, R. Newsom, R. Coulter, S. Frasier, T. Ince, C. Nappo, B. Balsley, M. Jensen, D. Miller, B. Skelly, J. Cuxart, W. Blumen, X. Lee and X.-Z. Hu, 2002: Intermittent turbulence associated with a density current passage in the stable boundary layer, Bound. Layer Meteor., **105**, 199-219.

Werne, J. A., and D. C. Fritts, 1999: Stratified shear turbulence: Evolution and statistics, Geophys. Res. Lett., **26**, 439-442.

Figure Captions

Figure 1. Schematic of the instrument placement at the CASES-99 Main Site. Shown are the locations of the Main Tower (CMS), the Raman (RL) and HRDL lidars, the blimp/kite TLS, the microbarographs (ST #1 - 6), and the range of distances south of the CMS of the E-W King Air flight tracks (N-S arrow).

Figure 2. Relative humidity (a), virtual potential temperature (b), stratification (c), and zonal (solid) and meridional (dashed) wind (d) profiles for each balloon and TLS profile from 0200 to 0800 UT during IOP 6. Beginning times are shown for each profile, soundings at 2:10 and 5:44 were obtained with the TLS, and other sounding were obtained by radiosonde. The radiosondes take $\sim$ 2.7 min to go from the surface to 800 m. The tethered soundings extended over $\sim$ 30 min. The first tethered sounding which began at 2:10 UT was from the surface up and the second tethered sounding at 5:44 was from upper altitudes to the surface. Winds have been smoothed over 20 m and successive profiles have been offset by 100% relative humidity, 20 K, 2×10^{-3} s^{-2}, and 20 ms^{-1}, respectively.

Figure 3. The three panels display T' (dashed line) with w' (a), u' (dashed line) with w' (b), and u' (dashed line) with v' (c) for King Air flight tracks from 0407 to 0542 UT during IOP 6. The u' and T' data are shown at 1 Hz, v' and w' data are shown at 25 Hz, and mean values have been removed from each variable for each track for convenience, mean altitudes for each track are shown at the right, scales and offsets are 1 K for T', 1 ms^{-1} for w', and 2 ms^{-1} for u' and v', and $x = 0$ corresponds to the longitude of the 60-m tower.

Figure 4. As in Figure 3 for flight tracks from 0608 to 0735 UT.

Figure 5. Time-height displays of q' (a) and $\overline{q}$ (b) obtained with the Raman lidar from 0300 to 0900 UT at altitudes from 200 to 800 m. Range and time resolution for the raw data were 1.5 m and 5 s, and the data presented here were filtered with a 2- to 10-min bandpass.

Figure 6. Vertical velocities inferred from the humidity variations measured by the Raman lidar at altitudes of (a) 500 m from 0500 to 0600 UT, (b), 500 m from 0600 to 0700 UT, and (c), and 475 m from 0700 to 0800 UT and (d) measured by HRDL during the interval 0617 to 0647 UT between 270 and 500 m AGL. Note the coherent vertical motions and

decrease in magnitude at lower altitudes in (d).

Figure 7. TLS horizontal wind (lower) and temperature (upper) data obtained during the constant-altitude segment at $\sim$ 470 m from $\sim$ 0415 to 0520 UT. The temperature has been displaced 6 K toward negative values for convenience.

Figure 8. Perturbation temperature (solid, left axis) and vertical wind (dashed, right axis) obtained at 55-m altitude on the 60-m tower at the CASES Main Site from 0400 to 0800 UT on 14 October 1999 during IOP 6. Data have been band passsed from 2 to 10 min. Note the dominance of $\sim$ 4 to 5 min oscillations, with higher-frequency oscillations increasing at later times.

Figure 9. As in Figure 8 for zonal (solid, left axis) and vertical (dashed, right axis) winds.

Figure 10. As in Figure 8 for zonal (solid, left axis) and meridional (dashed, right axis) winds.

Figure 11. Microbarograph data obtained at 5 m on the main tower and six surrounding towers during IOP 6 (a) and band-passed from 1 to 30 min and analyzed for dominant periods using Morlet wavelets (b) from 0430 to 0730 UT during IOP 6.

Figure 12. As in Figure 11b, but employing a cross S-transform using microbarograph data from stations 1 and 2. The cross S-transform provides a measure of the coherence of motions between two stations.

Figure 13. S-transforms of w' (top) and T' (bottom) for the flight segment from 0614 to 0619 UT. In both cases, the data suggest an approximate integral relationship between motions having $\sim$ 1.7, 3.5, and 7 km wavelengths.

Figure 14. Wind profiles (left panel) and N^2 (right panel) used for eigenmode calculations for Cases 1 to 3. The three profiles in each panel are for the balloon ascents at 0401 (left) and 0600 UT (right) and the TLS descent beginning at 0544 UT (center), with zero indicated by a vertical line in each case. Dashed and solid lines denote the measured profiles and the fitted profiles employed in the eigenmode calculation, respectively. Wave propagation directions for the three cases were assumed to be toward the W, SW, and NW, respectively.

Figure 15. Profiles of $m^2 = N^2/c_i^2 + \overline{u}_{zz}/c_i - k_h^2 - 1/4H^2$ based on N^2 and wind profiles for Case 1 (a), Case 2 (b), and Case 3 (c). Profiles for Case 1 assume propagation to the W, horizontal wavelengths of 1, 2, and 3 km, and corresponding horizontal phase

speeds of 10.2, 13.0, and 15.8 ms^{-1}. Profiles for Case 2 assume propagation to the SW, horizontal wavelengths of 1, 2, and 3 km, and corresponding horizontal phase speeds of 7.3, 8.9, and 10.3 ms^{-1}. Profiles for Case 3 assume propagation to the NW, horizontal wavelengths of 1, and 1.6 km, and corresponding horizontal phase speeds of 8.7 and 9.3 ms^{-1}.

Figure 16. Normalized modal structures for u' and w' (assuming u' in the direction of wave propagation) for a wavelength of 1 km and the directions of propagation assumed in Figure 15 for the mean profiles at 0400 (a), 0544 (b), and 0600 UT (c).

Figure 17. Dispersion curves for modes 0 to 3 in Figure 16 for Case 1 (a), Case 2 (b), and Case 3 (c). A 1 km wavelength corresponds to $k_h = 0.00628$ in each case. Note the locations where adjacent modes approach closely, especially for Cases 1 and 2. These are the Eckart's resonances discussed in the text.

Figure 18. Time series of ϵ (bottom) and C_T^2 (top) for the interval from 0415 to 0520 UT at a 470-m altitude. Note that ϵ varies by only a factor of ~ 2 or so, while C_T^2 varies by as much as a decade on time scales ranging from ~ 1 to 10 min. Units for ϵ and C_T^2 are $m^3 s^{-3}$ and $K^2 m^{-2/3}$, respectively.

Figure 19. Vertical profiles of $\log \epsilon$ (left) and $\log C_T^2$ (right, and offset to the right by two decades) for the TLS ascent from 0527 to 0544 UT (left panel) and the descent from 0544 to 0612 UT (right panel). Units are as in Figure 18.