LIDAR OBSERVATIONS OF FINE-SCALE GRAVITY WAVES IN THE NOCTURNAL BOUNDARY LAYER ABOVE AN ORCHARD CANOPY

Shane D. Mayor[1], Elizabeth R. Jachens[2], Tyson N. Randall[3]

[1]*Department of Physics, California State University Chico, sdmayor@csuchico.edu*
[2]*Department of Civil Engineering, California State University Chico, ejachens@mail.csuchico.edu*
[3]*Department of Geosciences, California State University Chico, trandall4@mail.csuchico.edu*

ABSTRACT

Fifty-two episodes of micrometeorological gravity wave activity were identified in data collected with the Raman-shifted Eye-safe Aerosol Lidar (REAL) near Dixon, California, during a nearly continuous 3-month period of observation. The internal waves, with wavelengths ranging from 40 m to 100 m, appear in horizontal cross-sectional elastic backscatter images of the atmospheric roughness sublayer between 10 m and 30 m AGL. All of the episodes occur at night when the atmosphere tends toward stability. Time-series data from in situ sensors mounted to a tower that intersected the lidar scans at 1.6 km range reveal oscillations in all three wind velocity components and in some cases the temperature and relative humidity traces. We hypothesize that the lidar can reveal these waves because of the existence of vertical gradients of aerosol backscatter and the oscillating vertical component of air motion in the wave train that displace the backscatter gradients vertically.

1. INTRODUCTION

The atmospheric boundary layer (ABL) is that part of the troposphere that is directly influenced by the presence of the earth's surface, and responds to surface forcings with a timescale of about an hour or less [1]. During the daytime and over land, the ABL is usually hundreds of meters to a kilometer or more in depth and is characterized by large eddies that mix heat, moisture, trace gases, pollutants, and momentum very effectively in both the horizontal and vertical dimensions. At night, radiant energy from the sun is no longer available to warm the surface and drive convective thermals. As a result, the nocturnal ABL tends towards static stability supporting stratification, vertical wind shear, gravity wave activity, and intermittent turbulence confined to shallow layers. This complex nocturnal flow regime presents significant observational and modeling challenges. In this paper, we report on new atmospheric lidar observations of what appear to be fine-scale waves within 20 m of the top of an orchard canopy.

Observations in the form of time-series and limited amounts of spatial sampling from previous studies have revealed wave-like oscillations at night in this shallow region above forest canopies [2 - 8]. However, we could find no papers on lidar observations of canopy waves. This may be due to the difficulty of observing the waves in the very shallow layer immediately above tree tops. Herein we report on our preliminary investigations of what appear to be "canopy waves" observed with the Raman-shifted Eye-safe Aerosol Lidar (REAL) [9] during the 2007 Canopy Horizontal Array Turbulence Study (CHATS) [10]. The REAL is a ground-based elastic backscatter lidar operating at a wavelength of 1.54 microns.

2. EXPERIMENTAL SETUP

CHATS took place in Dixon, California, from mid-March through early-June of 2007. The main part of the experiment was a horizontal array of sonic anemometers located approximately 100 m south of a 30 m tall vertical instrumented tower in a walnut orchard. The REAL was located 1.61 km directly north of the tower (see Fig. 1) and scanned at a sufficiently low elevation angle as to intersect the vertical tower at about 18 – 20 m AGL (see Fig. 2). "Wide scans" covered 60-degrees of azimuth and "narrow scans" 10-degrees of azimuth. The update rate for scan images depended on the azimuthal range and scan rate and ranged between 10 s and 40 s per scan.

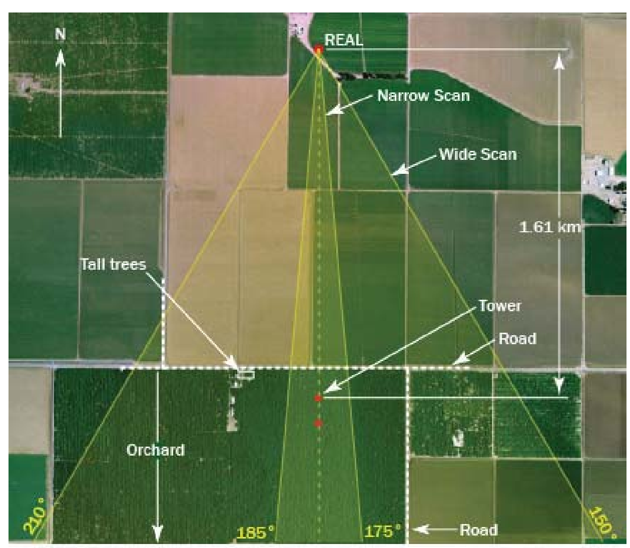

Figure 1. Plan view of the experimental area for the 2007 CHATS. The REAL was located 1.61 km directly north of the 30-m tall NCAR ISFF tower.

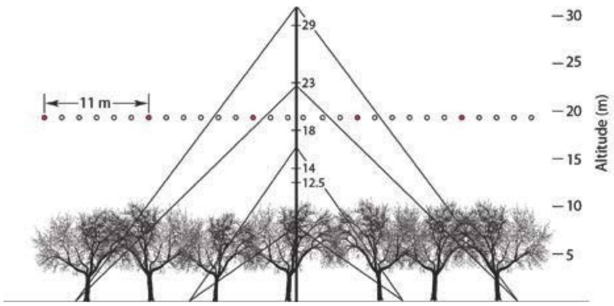

Figure 2. Side view of NCAR ISFF tower at CHATS and the approximate altitude, size, and spacing of laser pulses from the REAL (horizontal row of circles.) when looking north (or south). The circles filled in red show the east-west spacing of the laser pulses (11 m) at the range of the tower based on a 10 Hz pulse rate and 4 degrees per second azimuthal scan rate.

3. HYPOTHESIS

The first question that we wish to address is "Why is the REAL capable of detecting canopy waves?" We hypothesize that during the evening and night, as the earth's surface cools and the atmospheric surface layer tends toward stability, the lower atmosphere becomes stratified with layers that are horizontally homogeneous in terms of temperature, relative humidity, and aerosol However, the variation in these properties may change significantly with height. (See Fig. 3.) These aerosol "strata" may then be displaced vertically as internal gravity waves form. (Fig. 4.) The horizontally scanning lidar beam may then penetrate and reveal the waves as shown in Fig. 5.

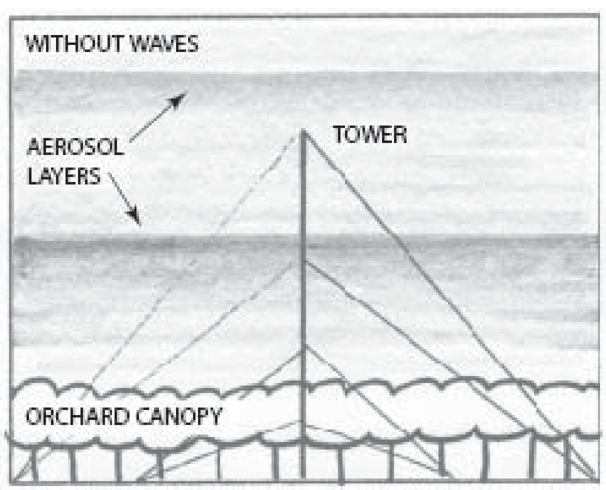

Figure 3: Sketch of a vertical cross-section of the lower atmosphere (from the surface to about 40 m AGL) that may occur at night during quiescent conditions. Stable stratification and weak flow result in the formation of vertical gradients of aerosol backscatter that are horizontally invariant.

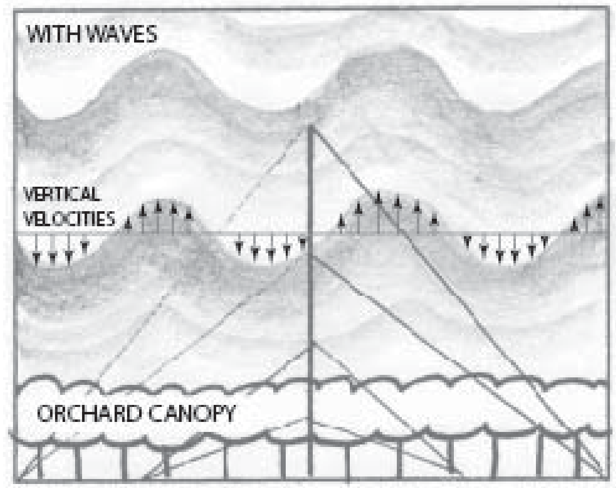

Figure 4: Sketch of a vertical cross-section of the lower atmosphere showing how the vertical wind component *w* caused by internal gravity waves (as observed in the bottom traces in Fig. 6 and all levels in Fig. 7) can vertically displace the horizontal aerosol strata shown in Fig. 3 and enable the elastic backscatter lidar to observe the wave structure in a near-horizontal plane as shown in Fig. 5. The horizontal line above is the approx. altitude of the horizontal lidar scans in Fig. 5.

4. OBSERVATIONS

Time-lapse animations of more than 1800 hours of high-pass filtered REAL images from the entire CHATS data set were created. The animations of nearly-horizontal scans were carefully examined for the presence of fine-scale wave packets. A wave packet is distinct from other flow features observed in the lidar images in that the linear bands of enhanced backscatter intensity tend to be oriented perpendicular to the wind direction and the direction in which they propagate. Furthermore, they appear to have a high degree of spatial and temporal coherence compared to plumes and wind parallel streaks sometimes observed during periods of turbulent flow. For a wave packet to be included in this study, it must have passed through the tower (located 1.6 km directly south of the lidar) and have a lifetime longer than one minute. Our subjective judgments of the coherence of the wave packets were based on the clear identification of crests and troughs and movement together as a group. Fifty-two wave episodes met the criteria. All cases had one thing in common: none of the wave packets were present during daylight hours. All cases existed between 5:00 and 14:00 UTC, which corresponds to 20 PST to 6 PST. During data collection, the average time of sunset was at 19:44 PST and sunrise at 6:09 PST. On the next page we present just one of the 52 cases.

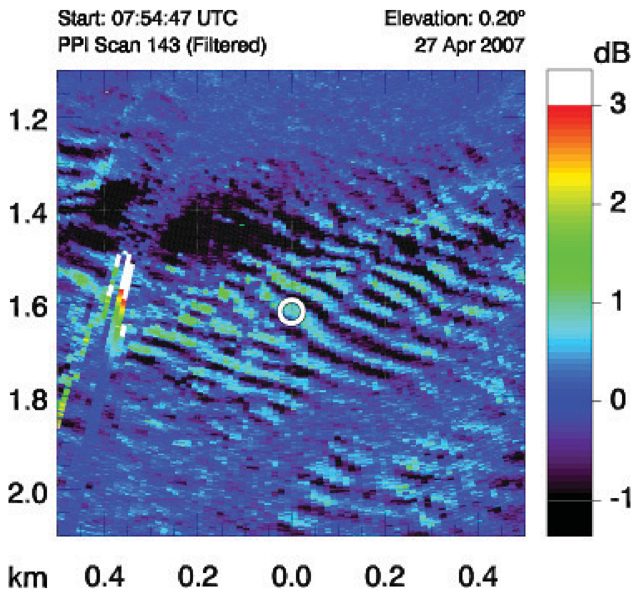

Figure 5: 1 km^2 section of a single, nearly-horizontal, lidar scan through gravity waves on 27 April 2007 at 7:54 UTC. The white circle at the center is the location of the tower. The bright marks on the left side are the result of a grove of trees that stood higher than the orchard trees. Color represents backscatter intensity. The canopy wave wavelength above is about 70 m.

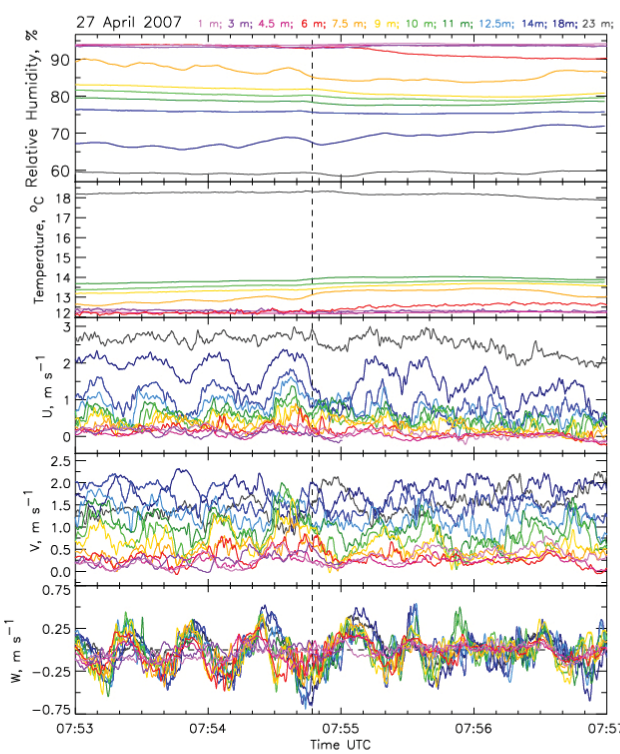

Figure 6. Four minutes of relative humidity, temperature, and three wind components (u, v, and w) from 12 altitudes on the tower for 27 April 2007 between 7:53 and 7:57 UTC. The wave period is approx. 30 s. The vertical dashed line is placed at the time corresponding to the image in Fig. 5.

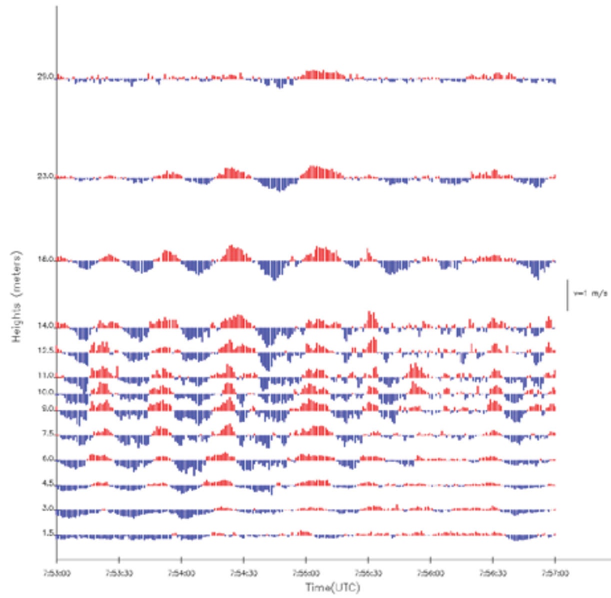

Figure 7: Vertical velocity w from tower-mounted sonic anemometers as a function of time and height for 27 April 2007 between 7:53 and 7:57 UTC. Upward air motion is colored red and downward air motion is blue. The plot suggests the waves have a strong vertical coherence and do not tilt appreciably within this span of altitudes.

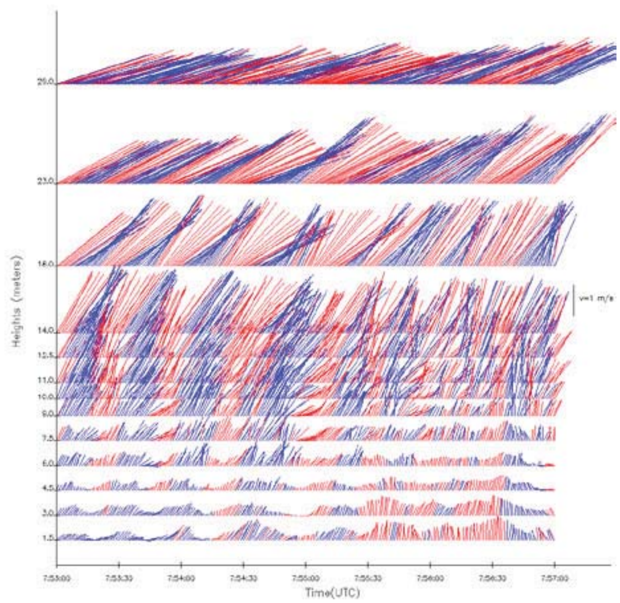

Figure 8: Horizontal wind vectors (resulting from u and v components) from tower-mounted sonic anemometers as a function of time and height for 27 April 2007 between 7:53 and 7:57 UTC. The vectors are colored according to the direction of w as in Fig. 7. The plot reveals oscillations in speed and direction as well as vertical shear in the mean speed and direction.

5. DISCUSSION

The lidar can provide the wavelength of the waves. When the lidar scan "frame rate" is fast enough it can also provide a direct measurement of the wave phase speed. However, for the wide scans the frame rate is a little too slow. In that case however, the phase speed can be computed by taking the wavelength and dividing by the period of the oscillations as obtained from in situ measurements. For the 27 April 2007 case presented, the lidar data reveal a wavelength of about 70 m and the tower data reveal a period of about 30 s resulting in a wave phase speed of about 2.3 m s^{-1}. This is approximately the same speed as the wind speed at the 18 and 23 m altitudes. Additional cases in the CHATS data set were observed with narrow scans and faster frame rates thereby enabling direct measurement of the phase speed.

6. CONCLUSIONS

The horizontally scanning eye-safe elastic backscatter lidar can identify and confirm the presence of fine-scale gravity waves over forest canopies. The lidar images contain quantitative spatial information such as wavelength that is not available from in situ time-series data. Key requirements for such lidar measurements is eye-safety, horizontal scanning, high spatial resolution images and sensitivity to small changes in aerosol backscatter. Radial high-pass median filtering is used to clarify the presence of the waves in the images. We note the spacing of backscatter data points in the radial direction of the REAL data is 1.5 m. This enables the instrument to resolve these wave structures that occur on scales of tens of meters.

ACKNOWLEDGMENTS

This work was supported by NSF AGS 0924407.

REFERENCES

1. Stull, R. B. An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, Dordrecht, The Netherlands, 1988.

2. Cava, D., U. Giostra, M. Siqueira, and G. Katul, 2004: Organised Motion and Radiative Perturbations in the Nocturnal Canopy Sublayer Above an Even-Aged Pine Forest, *Boundary-Layer Meteorol.*, **112**, 129-157.

3. Van Gorsel, E., I. N. Harman, J. J. Finnigan, and R. Leuning, 2011: Decoupling of Air Flow Above and in Plant Canopies and Gravity Waves Affect Micrometeorological Estimates of Net Scalar Exchange, *Agr. Forest Meteorol.*, **151**, 927-933.

4. Lee, X., 1997: Gravity Waves in a Forest: A Linear Analysis, *J. Atmos. Sci.*, **54**, 2574-2585.

5. Lee, X., 1997: Gravity Waves in a Forest: A Linear Analysis, *J. Atmos. Sci.*, **54**, 2574-2585.

6. Fitzjarrald, D. R. and K. E. Moore, 1990: Mechanisms of Nocturnal Exchange between the Rain Forest and the Atmosphere, *J. Geophys. Res.*, **95(D10)**, 16,839-16,850.

7. Lee, X., and A. G. Barr, 1998: Climatology of GravityWaves in a Forest, *Q. J. Roy. Meteorol. Soc.*, **124**, 1403-1419.

8. Bergström, H. and U. Högström, 1989: Turbulent exchange above a Pine Forest. 2. Organized Structures, *Boundary-Layer Meteorol.*, **49**, 231-263.

9. Mayor, S. D., S. M. Spuler, B. M. Morley, and E. Loew, 2012: Polarization lidar at 1.54-microns and observations of plumes from aerosol generators, *Opt. Eng.*, **46**, DOI: 10.1117/12.781902.

10. Patton E. G., et al., 2011: The Canopy Horizontal Array Turbulence Study (CHATS), *Bull. Amer., Meteor. Soc.*, **92**, 593-611.