Agricultural and Forest Meteorology 244–245 (2017) 136–150

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Observations of microscale internal gravity waves in very stable atmospheric boundary layers over an orchard canopy

Shane D. Mayor*

California State University, Chico, Chico, CA 95928, USA

A R T I C L E I N F O

Keywords:
Gravity waves
Internal waves
Wave breaking
Shear flow instabilities
Stable boundary layers
Turbulence
Canopy
Lidar
Aerosol

A B S T R A C T

Fifty-three episodes of internal gravity waves, with horizontal wavelengths ranging from 30 to 100 m, were identified in time-lapse animations of numerically filtered elastic backscatter lidar images collected during the Canopy Horizontal Array Turbulence Study (CHATS). The waves existed in and above a 10 m tall walnut orchard and are also present in time-series data of meteorological variables such as wind and temperature as measured by in situ sensors at multiple heights on a 30 m tower centrally located in the lidar scan area and inside the (1.6 km)^2 orchard. All of the episodes occurred at night in the presence of temperature inversions and light winds. Wave periods from time-series analysis of the in situ data range from 20 to 100 s. Sequences of lidar images reveal that the waves propagate in the direction of and at phase speeds less than that of the mean wind. The in situ data indicate the presence of a wind shear maximum and an inflection point at the top of the canopy. Gradient Richardson numbers near that altitude range between 0 and 0.20 indicating hydrodynamic instability. Range versus height lidar images from one case show the wave structures tilting downstream with altitude. In some cases, horizontal scans reveal that the gradient of aerosol backscatter tends to be larger on the upwind side of the crests. The environment and observations are consistent with the prevailing theory that the waves are the result of inflection point instability and the lidar data suggest that in 42% of the episodes the waves may have begun, or be on the verge of, breaking.

1. Introduction

Temperature inversions routinely form during the night over land when the surface of the earth cools faster than the air above it. Such environments are statically stable arrangements of the lowest levels of the atmosphere that resist the production of turbulence and support vertical oscillations known as internal gravity waves (Fernando and Weil, 2010; Sutherland, 2010; Nappo, 2012; Mahrt, 2014). Herein, observations of organized groups of relatively *clean*[1] internal gravity waves in the very stable, nocturnal atmospheric boundary layer over a (1.6 km)^2 walnut orchard block in the Central Valley of California are presented. The dataset is unique because of the simultaneous availability of wind velocity and air temperature measurements from mast-mounted fast-response in situ sensors in the form of time-series at multiple altitudes and 2D images of relative aerosol backscatter from a ground-based scanning elastic lidar system. The use of both types of data begin to reveal the 3D structure and motion of waves in the atmospheric roughness sublayer. The waves are significant because continued amplification will eventually result in unstable vertical arrangements of the air that lead to *breaking* and episodes of turbulence that are responsible for vertical fluxes of heat, momentum, and trace gases (Fitzjarrald and Moore, 1990; Sun and Coauthors, 2015).

Waves over forest canopies are commonly referred to as *canopy waves* because they result from the shear-induced inflection point instability (Kundu et al., 2016) that the canopy induces on the mean horizontal flow. Prior studies of canopy waves include those by Paw U et al. (1992); Raupach et al. (1996), Lee et al. (1996), Lee (1997), Lee et al. (1997), Lee and Barr (1998), Pulido and Chimonas (2001), Hu et al. (2002), Finnigan et al. (2009), Gavrilov et al. (2011), and Belcher et al. (2012). Very recent work includes Arnqvist et al. (2016) and Bailey and Stoll (2016). The waves described herein likely correspond to the waves shown in panels a and b of Fig. 14 in Finnigan et al. (2009). That is, most of them appear to have an approximately sinusoidal shape in the direction of the mean flow such as shown in Fig. 14a in Finnigan et al. (2009) and about 42% of the cases exhibit asymmetry that is a characteristic of Kelvin-Helmholtz billows such as shown in Fig. 14b in Finnigan et al. (2009). These phases of wave development occur prior to the more developed turbulence that makes it difficult to

* Corresponding author at: California State University, Chico, 400 West First Street, Chico, CA 95928, USA.
E-mail address: sdmayor@csuchico.edu.

[1] Clean refers to waves with a number of cycles of approximately constant amplitude and period.

http://dx.doi.org/10.1016/j.agrformet.2017.05.014
Received 2 December 2016; Received in revised form 8 April 2017; Accepted 18 May 2017

recognize the turbulent coherent structures that occur after the waves break as shown in Figs. 14c and 14d in Finnigan et al. (2009). However, there is one important difference: the waves herein exist in stably stratified environments whereas the work described by Finnigan et al. (2009) is focused on neutral conditions. An excellent summary of instabilities in stratified shear flows can be found in Lawrence et al. (2013). Papers treating the details of internal wave mechanics include Carpenter et al. (2012). Reviews of coherent eddy structure over plant canopies can be found in Shaw et al. (2013) and Patton and Finnigan (2013).

This paper is organized as follows. Section 2 describes the lidar system that provided the 2D cross-sectional images of the waves. Section 3 presents the experimental design. Section 4 explains why the lidar is capable of observing the waves. Section 5 describes the data analysis methods. Section 6 describes four episodes in depth. Section 7 describes the mean environmental conditions and wave characteristics of all 53 episodes. Section 8 presents the conclusions. The primary goals of the paper are to (1) document the experimental methods used to observe the waves (in particular, use of elastic backscatter aerosol lidar) and (2) describe the physical characteristics of the observed waves. It is hoped that the former will facilitate improved observations of canopy waves in future field experiments and the latter will aid the understanding of the transition of flows to turbulence in stably stratified forest environments.

2. REAL

The Raman-shifted Eye-safe Aerosol Lidar (REAL) (Mayor and Spuler, 2004; Spuler and Mayor, 2005; Mayor et al., 2007) is a ground-based, scanning elastic backscatter lidar. It does not have the ability to sense the wind-induced frequency shift of the backscattered laser radiation as Doppler lidars do. The strength of the REAL is in its ability to provide high-resolution images of elastic backscatter intensity. This is accomplished by using short and energetic laser pulses, sensitive analog direct detection, and 40-cm diameter receiving optics. Operation at the infrared wavelength of 1.54-μm results in an invisible beam and strong pulse energy while remaining eye-safe. Specifications of the lidar system as configured for the experiment reported herein are listed in Table 1 of Mayor et al. (2012).

The REAL operates at 10 Hz pulse repetition frequency and each laser pulse is sufficiently energetic that useful backscatter intensity signal can be detected to several kilometers range from individual pulses. No averaging of the backscatter from multiple pulses is necessary as is the case with micropulse lidars (Spinhirne, 1993; Mayor et al., 2016). The data acquisition system samples the backscatter at 100-million samples per second (MSPS) resulting in one data point every 1.5 m in range. The REAL data, like all scanning radar and lidar data, are collected in a spherical coordinate system with coordinates of elevation, azimuth, and range. As a result, the density of data points that makes up a scan decrease with range. The REAL, like many lidars, uses a beam steering unit (BSU, also known as a *scanner*) to collect either nearly-horizontal or vertical atmospheric cross-sections referred to as *scans*. The nearly-horizontal scans are known as *plan position indicator* or PPI scans and the vertical scans are known as *range height indicator* or RHI scans. The transmitted laser pulses are approximately 7 cm diameter as they exit the scanner and increase to about 0.5 m diameter at 1.61 km range.

3. Experimental design

Deployment of the REAL was an appendix to the Canopy Horizontal Array Turbulence Study (CHATS) (Patton and Coauthors, 2011; Dupont and Patton, 2012a,b). The deployment was a pilot study aimed at determining whether the lidar could detect *turbulent* coherent structures—not waves and billows in strongly stably stratified conditions as described herein. The main focus of CHATS was the operation of height-

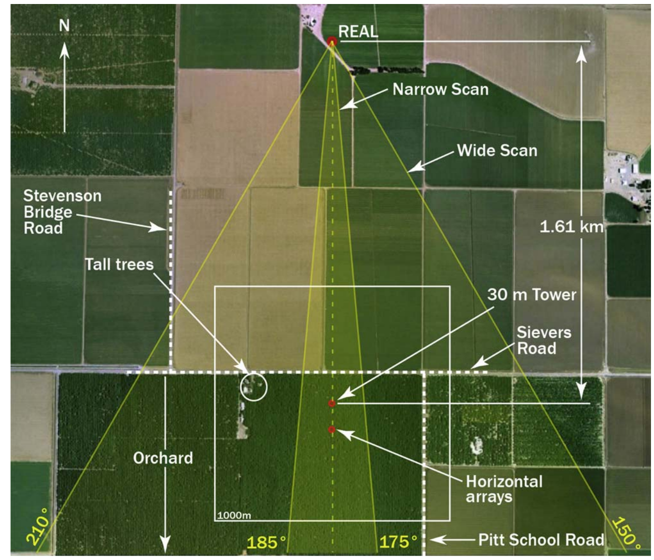

Fig. 1. Plan view of the experimental area for the 2007 CHATS experiment. The REAL was located 1.61 km directly north of the 30-m-tall NCAR ISFF tower. The analysis of waves was limited to the 1 km^2 square centered on the tower (outlined in white). Wide and narrow PPI sector scan regions from the REAL are shaded in yellow. The orchard was south of Sievers Road which is indicated by a horizontal dashed white line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

adjustable horizontal arrays of sonic anemometers deployed in the orchard. In addition, a 30-m tall instrumented tower (the Integrated Surface Flux Facility, ISFF) was deployed nearby in the orchard to provide vertical profiles of meteorological variables. The REAL was located 1.61 km north of the 30-m tall tower (see Fig. 1). From this distance, the lowest elevation angle for a PPI scan that could observe the atmosphere over the orchard was about 0.2° above horizontal. However, the REAL platform was precisely positioned in the east-west direction so that the RHI scans would fall between a pair of rows of trees adjacent to the ISFF. In this way, RHI scans could sample the atmosphere below the canopy top when the narrow region between the rows of trees was clear of foliage.

The 10 Hz laser pulse rate of the REAL is not adjustable, but the angular speed at which the scanner moves its mirrors is fully adjustable. For CHATS, and subsequent experiments, experience shows that it works best to scan at 4° s^{-1} in order to observe areas spanning several square kilometers and complete the sector scans[2] within 30 s. This scan rate provides sufficient temporal coherence of turbulent aerosol features in time-lapse animations of PPI scans to estimate wind vectors objectively (Mayor et al., 2012). It is also convenient, if not intentional, that the spacing between the radial arrays at 1.61 km range is about 10 m—and a good match for Cartesian grids with the same grid spacing which is necessary for application of motion estimation algorithms. However, identification of the wave episodes was based on visual inspection of filtered backscatter data rendered to images at 1.5 m range increments. The high range resolution of the REAL, and images rendered in the native polar coordinate system, improves one's ability to identify these very fine scale waves.

Determining the true elevation angle of the lidar beam is important in order to link the aerosol features in the lidar images with the in situ data from the closest corresponding altitude on the tower. The location of the tower in the PPI images can be easily determined by the occasional hard target reflections that it causes. The hard target reflections from the tower, however, are intermittent in time-lapse animations of

[2] A 60° sector scan with useful data from 500 m to 3 km range covers 4.6 square kilometers.