Atmospheric Gravity Waves, Low-Level Jets, and Mountain Gap Flows Measured by ETL's Doppler Lidars during October 1999

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ABSTRACT

Doppler lidar technology has matured and been proven in enough cases that it is now capable of providing key contributions to the achievement the scientific objectives of major meteorological field programs. For example, two of ETL's Doppler lidars played key roles in two separate field campaigns during October 1999. One, the CASES-99 project, was a study of the nighttime stable boundary layer over the central Kansas prairie, whereas the other, the Mesoscale Alpine Programme (MAP), was a study of mountain gap flows north of the Brenner Pass in the Austrian Alps near Innsbruck. The lidars were both important during the field phase, because of their real-time ability to scan and assess the changing conditions as intensive operations were in progress. The visual nature of the real-time displays allowed an immediate picture of where (and when) interesting phenomena were occurring, and this information was crucial to directing aircraft and other movable instruments, such as the kitesonde, to the appropriate locations and at the appropriate times. In the analysis phase, the lidar images are critical to proper interpretation of the data from other instruments. This is especially true because the data were taken in repeated scans that can be animated, adding the aspect of time-dependent behavior as an even more powerful interpretation tool. Quantitative information is also available from the scan data, including the heights and depths of layers, the wavelengths and dimensions of flow phenomena, and the horizontal frequency of occurrence and spatial distribution of features of the flow. During CASES-99 impressive examples of gravity waves, turbulent eddies, and low-level jets were observed in images and animations. In MAP, mountain waves, turbulent eddies, hydraulic jumplike structures, and a spectacular fast-moving cold front are all part of the dataset. Examples of these atmospheric structures are presented in this paper.

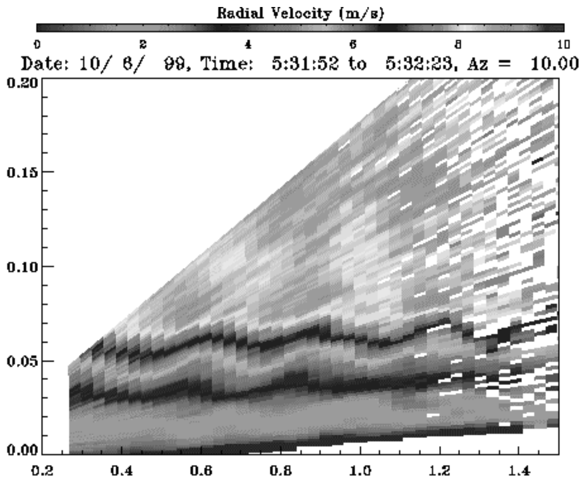
1. Introduction

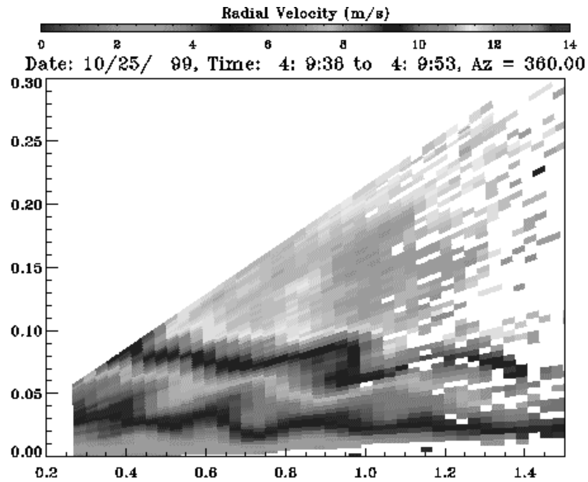
Doppler lidars deployed by the Atmospheric Lidar Division of NOAA's Environmental Technology Laboratory (ETL) were critical components of two separate field experiments during October 1999. One was the nocturnal stable-boundary-layer project at the Cooperative Atmosphere-Surface Exchange Study (CASES) site in south central Kansas, called CASES-99. In this study ETL's High-Resolution Doppler Lidar (HRDL) provided critical scan data revealing the structure and temporal behavior of gra-vity waves, turbulence, and low-level jets in the nighttime boundary layer. The other was the Meso-scale Alpine Programme (MAP), where ETL's bigger, higher-power lidar, $TEACO_2$, scanned from an Austrian Alpine valley to the north of Brenner Pass to reveal important aspects of the structure of the flow coming through the gap at Brenner Pass. In this paper we describe the experiments, show the key role of the lidar in achieving the program objectives, and present several dramatic examples of the kind of data available from the lidar.

2. CASES-99 Stable Boundary Layer

The broad objective of CASES-99 is to better understand turbulence and mixing processes in the nighttime stable boundary layer (SBL) and the physical processes that control them. The SBL is poorly understood and even more poorly represented in numerical models. Major reasons for this lack of knowledge are that flow-structure and turbulent-eddy sizes are small, turbulence occurs in intermittent or sporadic patches, and the flow occurs in layers which may be very thin (10 m or less), because of the lack of sustained vertical mixing. These make sampling by conventional techniques, as well as effective numerical modeling of these processes, very difficult.

Because of the very small-scale nature of the important phenomena to be studied, the philosophy of CASES-99 was to deploy a large number of instruments over a small area. The central study area was 3 km x 5 km, and over this region a 55-m tower densely instrumented in the vertical, several surface-flux and meteorology stations, profilers, sodars, an FM/CW radar, tethered balloons, and a sophisticated kite sonde were distributed.





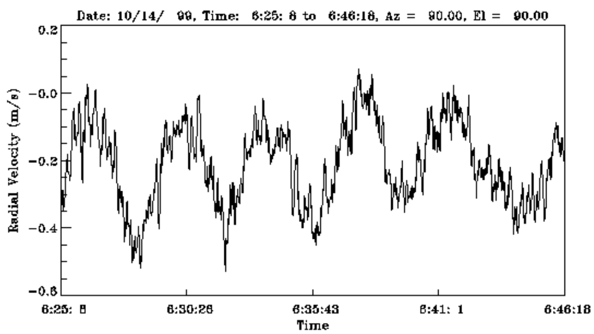


Fig. 1: Nocturnal SBL data obtained by HRDL during CASES-99. (Top left) Vertical-slice scan showing gravity-wave structure centered near 50 m AGL on 6 Oct 1999. Horizontal axis is distance from the lidar in km, and vertical axis, height above the lidar (km). Gray shade scale is in m s^{-1}; gray shades are repeated to show extent of wave structure. (Bottom left) Time series of vertical velocity from HRDL in vertical staring mode on 14 Oct 1999. Horizontal axis is time (UTC), and vertical axis is atmospheric vertical velocity in m s^{-1}. Note wave structure with period ~3.5 m s^{-1} and amplitude ~20 cm s^{-1}. (Above) Vertical-slice scan showing wavelike structures overturning into turbulence below 100 m AGL on 25 Oct 1999 at ~0409 UTC. Axes and gray shades are as in top left panel.

Instrumented aircraft were also an important part of the assemblage. This is a denser instrumentation than has been used previously to study the SBL. Although all of these kinds of instrument systems had been used in previous SBL investigations, what set this experiment apart from prior field investigations of the SBL was the use of HRDL.

HRDL performed several critical roles during CASES-99. The images allow for an easy and immediate interpretation of the dominant flow structures and their vertical and horizontal dimensions. The lidar covered vertical regions with nearly continuous measurements from the surface to several hundred meters AGL, including the region between those reliably covered by sodar and profiler (~50-150 m). Because of its real-time display, the lidar was able to provide guidance to other researchers (for example, for the aircraft and the kitesonde) in the field by calling attention to levels of strong meteorological activity of interest, thus contributing to the overall quality of the total dataset.

In the analysis phase currently in progress, the highly visual lidar scan data provide a context in space and time for the other measurements, an efficient means for perusing the data for periods of interest to analyze in detail, and confidence in the interpretation of the data.

The HRDL CASES-99 dataset includes dramatic examples of gravity-wave, turbulent-eddy, and LLJ structure and time evolution (see Fig. 1). Animation of the repeated vertical-slice scans taken during CASES provides an unprecedented view of the short-time (10-20 min) behavior of these phenomena, which significantly enhances the ability to unequivocally interpret not only the lidar data, but data from all the other instruments at the site. This kind of information has not previously been available to boundary-layer researchers.

3. Mesoscale Alpine Programme

MAP was a massive, multi-objective field intensive focused in the European Alps. ETL's big

Fig. 2: Three vertical-slice scans showing flow in the Wipp Valley, Austria, between Innsbruck and the Brenner Pass. Axes are as in Fig. 1 (top), and crosses represent a square 2-km grid superimposed on the scans. (Top) Scan toward Brenner Pass showing a dual wave structure in the velocity field coming over the pass and toward the lidar (i.e., flow is right to left). (Middle) Cold front at lower levels moving past the lidar and toward the pass (left to right motion represented by lighter gray shades) undercuts southerly flow (darker gray) coming over the pass. (Bottom) Stronger (darker gray) flow near the surface, coming over the pass (right to left), forms a thin layer near the pass that 'jumps' to a deeper layer as it proceeds toward the lidar.

Doppler lidar, $TEACO_2$, was sited in Austria's Wipp Valley ~15 km north of the Brenner Pass, the major notch in the east-west Alpine chain, primarily in support of the MAP objective on gap flows. Flows at or near the surface through mountain gaps can produce property damage and other hazards to human activity, yet they are generally very difficult to forecast or even diagnose from existing meteorological data and models. The goals of the MAP gap-flow study are to better understand the structure and mechanisms of gap flows and to determine what steps are necessary for improved forecasting of these events.

The Wipp valley was instrumented with a dense network of surface observing stations, a rawinsonde balloon during intensive operating periods (IOP's), sodars, tethered balloons, a wind profiler at Innsbruck, and research-aircraft flights in the valley. A key role for the lidar was once again to help direct the aircraft timing and flight levels as conditions evolved through an IOP. The lidar saw a variety of wave and turbulence phenomena flowing over the pass and through the gap, hydraulic jumplike structures, and during one period a spectacular fast-moving cold front, exhibiting density-current structure and penetrating southward through the valley. Examples of several such structures are shown in Fig. 2.

4. Summary

The potential of Doppler lidar to contribute significantly to major field studies of atmospheric processes is becoming more widely recognized. For example, the two lidars deployed during October 1999 played key roles in the experiments in which they participated. They were both important during the field phase, because of the real-time ability to scan and assess the changing conditions as intensive operations were in progress. The visual nature of the real-time displays allowed an immediate picture of where (and when) interesting phenomena were occurring, and this information was crucial to directing aircraft and other movable instruments, such as the kitesonde, to the appropriate locations and at the appropriate times.

During analysis, the lidar images are also critical to proper interpretation of the data from other instruments. This is especially true because the data were frequently taken in sequences of repeated scans that could be animated, adding the dimension of time-dependent behavior as an even more powerful interpretation tool. But the usefulness of the lidar data is not limited to the visual impact of the data. Quantitative information from the images includes vertical structure (such as heights and depths of layers), the wavelengths and dimensions of flow phenomena, and the horizontal frequency of occurrence and spatial distribution of features of the flow. Velocity values within the scans are well determined and allow an accurate assessment of maximum and minimum values, or mean values determined over any desired region of space or over any layer. The values are also of high enough accuracy to calculate fluctuation statistics such as variances (and standard deviations), integral scales, spectra, and others. Backscatter data are also available simultaneously with the velocities, and ways of integrating the analysis of aerosol data with the kinematic data have been developed and are being refined and extended.

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