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INTERNAL HYDRAULIC ADJUSTMENT ON A DISCONTINUOUS ESCARPMENT SLOPE

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1. INTRODUCTION

The mechanics of stratified slope flows remains an important area of study from both an academic and practical stand point. Efforts in understanding the varying aspects of these flows have long included modeling as well as field and laboratory experiments. The work presented here focuses on atmospheric field experiments carried out between July and October 2006, near Wagerup, Western Australia. The broad motivation of the experimental campaign was the study of atmospheric mixing and dispersion mechanisms in the area. The following results will focus on data collected using a scanning coherent Doppler lidar system deployed during the measurement campaign. One result of the study, detection of the presence of a possible internal hydraulic adjustment, will be presented.

1.1 Background

Interest in aspects of katabatic flow into a stratified environment has existed for some time. Katabatic flows occur when surface cooling on a slope causes a buoyancy deficit between the fluid near the slope and the ambient fluid. Radiative cooling of mountain slopes causes such flows in the atmosphere. Manins (1978) described a model for a katabatic flow in the presence of ambient stratification. Manins presented a criteria for supercritical flow that suggests that slope angles of $\alpha > 0.1^0$ favor supercritical katabatic flows. Supercritical katabatic flows, sometimes referred to as “shooting flows”, are flows in which small disturbance are unable to propagate upstream. These flows may become subcritical by passing through a hydraulic jump. The turbulence associated with a hydraulic jump is of interest in this study for its role in mixing and dispersion. Simulations of hydraulic jumps in katabatic flows were carried out by Yu (2006) using a Regional Atmospheric Modeling System (RAMS). Yu had success in qualitatively capturing hydraulic jump phenomena on a slope using the simulation.

As slopes in nature are usually quite complex, several studies have sought to explore the effects of topographic irregularities with respect to katabatic slope flow. Monti (2002) suggested that supercritical katabatic flows that originate on steep slopes may experience a hydraulic jump at a slope discontinuity where the steeper slope meets a lower altitude slope of shallow angle. A schematic of such a flow situation is displayed in Figure 1. This idea was tested in the laboratory using three connected slopes of 0, 10 and 35 degrees with respect to the horizontal (Fernando 2006). The experimenters found that the flow remained supercritical through the slope discontinuity between 35 and 10 degrees. A hydraulic jump was found to occur at the slope discontinuity between 10 and 0 degrees, after which the flow on the lowest slope was found to be subcritical. Large eddy simulations (LES) were also used to study the effects of slope discontinuity on a katabatic flow (Smith 2005). A rapid increase in flow depth was found at the discontinuity along with a marked increase in the height of the velocity maximum when comparing the shallower slope to the steeper slope.

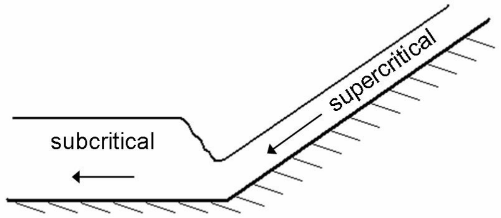

Figure 1. Schematic of hydraulic jump at a slope discontinuity.

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A scanning coherent Doppler lidar is utilized as the main measurement tool in the current study. Similar systems have been successfully utilized in the past to observe hydraulic jump-like features (Neiman 1988, Drobinski 2001, Shun 2003, Weismann 2004). One important virtue of a remote sensing system such as a coherent Doppler lidar with regard to such studies lies in the fact these systems allow for a wide spatial measurement domain. Internal hydraulic adjustments in the atmosphere are typically on large scales, both vertically and horizontally, making comprehensive in-situ measurements difficult to obtain.

1.2 Theory

Internal hydraulic jumps can be described, in the most simple case, by a two layer system. Consider a dense fluid layer of density ρ1 and of thickness h flowing along the bottom surface beneath a much deeper, less dense, fluid layer of density ρ2. If the fluid of density ρ1 has a flow velocity U parallel to the bottom surface then, an internal Froude number can be defined as eq. 1.

$$Fr = \frac{U}{(g'h)^{\frac{1}{2}}} \quad ; \; g' = g(\rho 1 - \rho 2)/\rho 1 \qquad (1)$$

The flow is considered supercritical for Fr > 1 and subcritical for Fr < 1 (Turner 1973). The notion of supercriticality is important in that a supercritical flow will ultimately become subcritical by way of hydraulic jump. The location of this hydraulic jump will thus be subject to a degree of turbulence as the flow adjusts from one state to the next.

Manins (1976) utilizes an alternative formulation of the Froude number for a flow intruding into a stratified fluid at its equilibrium buoyancy level.

$$Fr = \frac{c}{Nh} \quad (2)$$

Here c is the velocity of the intruding flow, h is the thickness of the intruding flow and N is the buoyancy frequency of the ambient fluid.

An alternative criteria for supercriticality specifically for katabatic flows is also given by Manins (1978).

$$CRi < 1 \text{ for supercritical flow} \quad (3)$$

Here Ri is the Richardson number and C is a coefficient that depends on scaling parameters as well as the slope. Manins suggests that all slopes with angles of inclination, with respect to the horizontal, of greater 0.1^0 favor supercritical flow.

2. EXPERIMENT

Field experiments took place from July 7, 2006 through October 12, 2006 near Wagerup, Western Australia. Measurements took place approximately 25km inland and 100km south of Perth, Western Australia near the Darling Scarp. The Darling Scarp is an escarpment that runs roughly north to south near the western coast of Australia. The escarpment rises to a height of approximately 300m near Wagerup.

Monitoring sites were dispersed through out the area in order to obtain a spatially varying data set. A scanning coherent Doppler lidar (Lockheed Martin Coherent Technologies) was deployed at the lidar site west of the escarpment. This lidar was operated by Arizona State University. Various meteorological stations were located at sites distributed in the area. These meteorological sites monitored wind speed and direction as well as air temperature at various heights above ground. The Escarpment and Bancell East meteorological stations were operated by Ecowise while the Bancell West station was operated by Compliance Monitoring. A flux tower was deployed at the Boundary road site which included a Gill HS Ultrasonic anemometer. Also located at the Boundary road site were a Remtech PA0 acoustic sounder, a Vaisala CL31 ceilometer, and a Proton Transfer Reaction Mass Spectrometer (PTRMS). The ceilometer and acoustic sounder were operated by the Western Australian Department of Environment and Conservation (DEC) while the remaining devices at the Boundary road site were operated by Commonwealth Scientific and Industrial Research Organization (CSIRO). Co-located at the Yarloop site was a DEC operated PTRMS and Ecotech operated Air Quality Monitoring Station (AQMS). Daily Radiosonde launches were carried out at 7:00am each morning in Wagerup by Alcoa. Unless otherwise noted, all monitoring equipment operated on a continuous 24 hour basis with temporary breaks for maintenance.

The scanning coherent Doppler lidar used in the experiment utilizes a 10cm diameter pulsed infrared laser beam. The 2mJ laser pulse has a wavelength of 2µm and is repeatedly pulsed at 500Hz. Aerosols in the atmosphere scatter the outgoing laser pulse producing a backscattered signal that is recorded by the lidar. Based on time of travel, Doppler shift compared to outgoing signal, and return signal strength, the device is able to measure radial velocity and a type of relative aerosol concentration at regular intervals along the laser beam path. In this experiment, data was averaged over 100 pulsed beams yielding 5Hz data at 88m intervals along the radial direction of the laser beam. Due to the dependence of the returned signal on ambient aerosol present in the measurement space, the maximum range of the device varies with ambient conditions. During this experiment a range of 5 to 6km horizontal was typical. Scans were preformed to obtain a time varying volumetric data set of the boundary layer near Wagerup. A combination of Range Height Indicator (RHI) and Plan Position Indicator (PPI) scans were used in repeating patterns that could be tailored to the specific data needs of the operators. RHI scans yield a plane of data perpendicular to the horizontal by scanning at a fixed azimuth angle and varying the elevation angle. PPI scans yield a cone shaped data surface with the cone's axis normal to the horizontal. These scans are preformed by holding the elevation angle constant while varying the azimuth angle.

3. RESULTS

The morning of August 27, 2006 was characterized by strong low level stable stratification with weaker stability aloft. The buoyancy frequency N, obtained from the 7:00am sounding was found to be approximately $0.029s^{-1}$. Synoptic flow was weak and from the southeast. An easterly flow near the escarpment slope was apparent in lidar PPI velocity data. Velocity plots of Lidar RHI scans taken into the direction of the flow revealed what appeared to be a hydraulic jump in the down slope flow. Figure 2 shows a representative plot taken at approximately 8:30 am local time. The figure shows a lidar RHI plotted on a terrain relief of the escarpment. The red colors in the lidar RHI plot represent positive velocities moving away from the lidar, while the blue represents velocities toward the lidar. The approximate location of the lidar unit is displayed near the left edge of the figure and scale is noted. The figure clearly displays a slope flow following the steeper slope of the escarpment, labeled here as A. The average slope of the escarpment here is 4.6 degrees. Quasi stagnant flow occupies the layer above the slope flow and is made apparent by the green patch on the RHI (labeled B). Upon passing through the slope discontinuity, the flow layer thickens and decelerates (labeled C). The lower slope here is approximately 0.7 degrees. The velocity maximum is no longer in contact with the slope after the discontinuity and a region of stagnant flow now occupies the lowest layer.

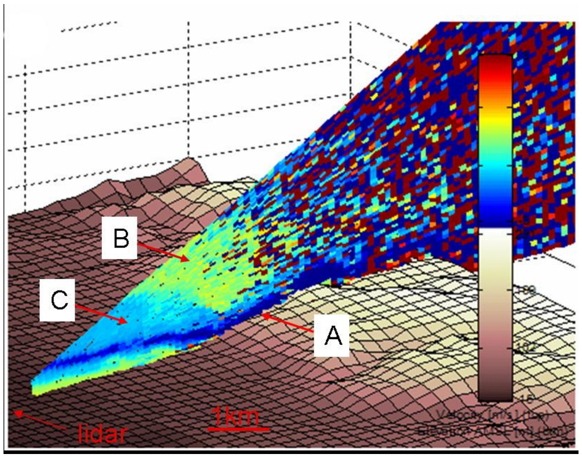

Figure 2. RHI lidar velocity plot displaying effect of discontinuity on slope flow.

Lidar data collected at 8:02 am on August 27, 2006 was coupled with sounding data in order to estimate the internal Froude number for the flow on either side of the slope discontinuity. The slope flow appeared to be a "shooting flow" when examined in lidar plots. This was confirmed with a supercritical Froude number of Fr = 1.27 found for the slope flow 4007m east of the lidar. The Froude number for the shallow slope was found to be Fr = 0.21 with the flow now subcritical.

4. DISCUSSION

Coherent Doppler lidar has been utilized to identify what appears to be an internal hydraulic jump at a slope discontinuity. A qualitative assessment of lidar velocity coupled with Froude number calculations strengthens this claim. A good qualitative correlation was found between the location of the onset of the flow layer thickening and the discontinuity between the steeper and shallower slopes of the escarpment. The flow pattern captured by lidar RHI velocity plots shares several features in common with those described in the literature (Shun 2003, Weismann 2004). These features include a "shooting flow" with overlying weak to stagnant winds followed by an abrupt thickening of the flow. In each case the Doppler lidar was able to capture these flow features that would be difficult to ascertain using in-situ measurement techniques.

The complexities of actual slope topography and atmospheric flow patterns can make comparison to simulations and laboratory experiments difficult. Results presenter here suggest that an internal hydraulic adjustment took place when a supercritical slope flow experienced a slope discontinuity from a steeper slope of approximately 4.6 degrees to a shallower slope of approximately 0.7 degrees. The shallower slope should favor supercritical flow according to Manins (1978) as the slope in this case is greater than the critical slope of $\alpha = 0.1^0$. Observation show that flow on the shallower slope though is indeed subcritical. One possible explanation may be the presence of a strong surface level inversion ($d\theta/dz = 0.2^0/m$) in the first 30m above the ground creating a pool of cold over the shallow slope. Interactions between a cold pool and a slope flow near a hydraulic jump were also noted by Yu (2006). This pool of cold air could prevent the slope flow from penetrating to ground level on the shallower slope, creating an effective horizontal floor. In this case the flow could become subcritical according to Manins' theory.

Previous studies have also shown that a supercritical flow passing through a slope discontinuity may remain supercritical even though the flow layer may thicken to a degree (Smith 2005, Fernando 2006). The experiments performed by Fernando show the flow remaining supercritical after passing through the discontinuity between two slopes that favor supercritical flow. In addition, the experiment shows that the flow transitions to subcritical upon passing through a slope discontinuity onto a purely horizontal plane. This observation is consistent with Manins' (1978) theory and perhaps lends to the idea of an effective horizontal floor contributing to the hydraulic jump-like flow pattern seen in the current study. Future work will be required to assess the plausibility of this explanation.

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