NOCTURNAL FLOW ON A WESTERN COLORADO SLOPE*

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INTRODUCTION

The Department of Energy sponsored Atmospheric Studies in Complex Terrain (ASCOT) program has conducted a research program designed to increase our knowledge and understanding of terrain-dominated flows with specific emphasis on nocturnal flows within mountain valleys. ASCOT has sponsored both field studies and numerical modeling efforts to improve our understanding of the wind, temperature and turbulence structure of nocturnal drainage flows. One of the most recent ASCOT sponsored field studies involves a study within the Mesa Creek Basin in western Colorado to investigate the seasonal frequency of occurrence of drainage flows along the sloped surfaces and within the basin, and to evaluate the effect of the ambient meteorology on their development.

The Mesa Creek Basin, situated on the north slope of the Grand Mesa, encompasses a roughly 10 x 20 km area that is approximately 30 km east of Grand Junction. The observational segment of the study was undertaken jointly by the Lawrence Livermore National Laboratory and the NOAA Wave Propagation Laboratory, and involved the operation of a network of eight meteorological towers and a monostatic sodar within the Mesa Creek study area over a period of one year that extended from December 1988 through November 1989. These measurements were augmented by tethered observations to define the vertical wind and temperature structure during a few nights. The preliminary results of the field study will be reported in King, Gudiksen, and Russell (1990). The modeling portion of the study is being undertaken by Lawrence Livermore Laboratory using a three-dimensional prognostic boundary layer model to gain further insight into the dynamics of the seasonal variations and the effect of cloud cover on the development of the drainage flows. It is the purpose of this paper to present preliminary results from a numerical simulation done as part of this study.

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THE MODEL

The model used for the simulations reported here solves the 3-dimensional, nonhydrostatic, Boussinesq equations of motion shown below.

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\Theta_0 \frac{\partial x}{\partial z} + f(v - v_g) + \frac{\partial}{\partial x}(K_H \frac{\partial u}{\partial z}) + \frac{\partial}{\partial y}(K_H \frac{\partial u}{\partial y}) + \frac{\partial}{\partial z}(K_V \frac{\partial u}{\partial z})$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\Theta_0 \frac{\partial y}{\partial z} - f(u - u_g) + \frac{\partial}{\partial x}(K_H \frac{\partial v}{\partial x}) + \frac{\partial}{\partial y}(K_H \frac{\partial v}{\partial y}) + \frac{\partial}{\partial z}(K_V \frac{\partial v}{\partial z})$$

$$\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\Theta_0 \frac{\partial z}{\partial z} + (\frac{\partial \theta}{\partial z} - g) + \frac{\partial}{\partial x}(K_H \frac{\partial w}{\partial x}) + \frac{\partial}{\partial y}(K_H \frac{\partial w}{\partial y}) + \frac{\partial}{\partial z}(K_V \frac{\partial w}{\partial z})$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

$$\frac{\partial \theta}{\partial t} + u \frac{\partial \theta}{\partial x} + v \frac{\partial \theta}{\partial y} + w \frac{\partial \theta}{\partial z} = \frac{\partial}{\partial x}(K_H \frac{\partial \theta}{\partial x}) + \frac{\partial}{\partial y}(K_H \frac{\partial \theta}{\partial y}) + \frac{\partial}{\partial z}(K_V \frac{\partial \theta}{\partial z})$$

where the usual meteorological notation has been used with u, v, w are the x, y, z components of the velocity respectively; θ is the deviation potential temperature, and θ is the deviation Exner function. The constants f, g, u_g , and v_g are the Coriolis parameter, the gravitational acceleration, and the x and y components of the large scale geostrophic wind, respectively. The equations have been linearized about a motionless hydrostatic basic state defined by:

$$\Theta(x, y, z, t) = \Theta_0 + \theta(x, y, z, t)$$

$$\Pi(x, y, z, t) = \Pi_0(z) + \pi(x, y, z, t)$$

$$\text{where } \frac{\partial \Pi_0}{\partial z} = \frac{g}{\Theta_0} \text{ and } \frac{\partial \pi}{\partial z} = g \frac{\theta}{\Theta_0^2}$$

with $\theta'(z)$ a horizontally averaged potential temperature.

To close the system of equations, we must define the turbulent diffusivities, K_H and K_V . For the simulations reported herein, the horizontal eddy diffusivity has been taken to be constant with a value of $100 \text{ m}^2/\text{s}$, while the vertical diffusivity, K_V , was modeled using a parameterization developed by McNider and Pielke (1981).

The spatial discretization of the equations is accomplished via the finite element method using tri-linear basis functions for the velocity components and the temperature and piecewise constant basis functions for the pressure. For efficiency, mass lumping and 1 point quadrature were employed. The time integration scheme is a variant of the forward Euler scheme. The forward backward scheme of Sun (1980) is used on the buoyancy term, and the advection terms are stabilized via the implementation of the balancing tensor diffusivity. (The model is described in detail in Leone and Lee, 1989.)

Figure 1. The topography within the computational domain, contours every 200 m. Also shown are the locations of 6 of the observational towers.

THE SITE

The topographic features of the Mesa Creek drainage basin resolved within the modeled terrain and the locations of six of the meteorological towers are shown in Fig. 1. The study area is bounded on the south and west sides by the Grand Mesa, a ridge on the east side and the Plateau Valley toward the north. The terrain varies in height from 3200 m on the Grand Mesa to about 1500 m within the basin. The slope generated flows drain into the basin where they merge with those generated within the Plateau valley whose drainage area is largely situated east of the study area. The flows within the Plateau Valley subsequently drain westward into the Colorado River drainage area.

THE SIMULATION

The horizontal domain used for the simulations reported here is the area shown in Fig. 1 and encompassed a distance of 14 km in the cross basin direction and 22.5 km in the down basin direction. The top of the domain was taken to be at 4500 meters above mean sea level giving a vertical domain size of 1489 meters above the highest point and 2976 meters above the lowest point. The domain was divided into

twenty-eight (28) 500 m long elements in the cross basin direction, thirty (30) 750 m long elements in the down basin direction, and sixteen (16) elements in the vertical direction which were 7.5 m high at the ground and increased in size toward the top of the domain.

The simulation reported here was for a simple undisturbed nocturnal flow development. The large scale geostrophic wind was assumed to be zero as was the initial velocity field. The initial potential temperature field was slightly stable, with a vertical gradient of 1 K/km, and horizontally uniform. The driving force was a surface heat flux of -40 Wm^{-2} applied uniformly on the domain for a period of two hours. The velocity boundary conditions were the no-slip condition on the surface and at the top of the domain the velocity was set equal to the large scale geostrophic wind (zero in this case). The lateral boundary conditions were:

$$f_n = -\pi + K_H \frac{\partial u_n}{\partial x_n} = 0.0 ;$$

$$f_n = K_\eta \frac{\partial u_n}{\partial x_n} = 0.0; \quad f_\tau = K_\eta \frac{\partial u_\tau}{\partial x_n} = 0.0 ;$$

$$\frac{\partial \theta}{\partial x_n} = 0.0 \text{ where } n \rightarrow \text{normal and } \tau_i \rightarrow \text{the } i\text{th tangent to the boundary.}$$

THE RESULTS

The results presented here will be for a simulated time of 2 hours. While the details of the flow were not at steady state, the main features were well established and steady. Also, it was felt that continuing the simulation with a constant surface heat flux as a forcing would be unrealistic. Figure 2 is a snapshot of the flow at 7.5 meters above ground level (AGL) after two hours of cooling. Three distinct drainage regions can be seen; one originating on the southeast rim of the basin, a second coming from the center of the mesa, and the third flowing off the west wall of the basin. These merge into a single down basin flow through the center of the basin.

Figure 3 presents a series of cross-basin vertical cross sections of the northerly velocity component. Figure 3a, located on the upper slope (arrow 1 in Fig. 2), shows a significant down-basin flow across 3/4's of the basin with two distinct centers representing the northeast corner flow and the central flow. The maximum down-basin speed is 2.9 m/s within the central flow. Fig. 3b, half way down the basin (arrow 2 in Fig. 2), shows a continuation of this pattern. However, the central flow is now clearly dominant with the maximum speed increasing to 3.4 m/s. Figure 3c, just before the entrance to the Plateau River Valley (arrow 3 in Fig. 2), shows a single strong core flow with a maximum speed of 5.1 m/s. The flow is seen to be vertically confined to a shallow layer. Figure 3d, within the Plateau River Valley (arrow 4 in Fig. 2), shows a significantly altered pattern. Here the maximum speed in the northerly direction is only 2.5 m/s and the height of the jet core has elevated significantly. We believe that this anomaly is a numerical artifact of two weaknesses in the simulation. The first is the lack of significant terrain within the model domain north of the Plateau River Valley, and the second is the inability of the model to reproduce the flow down the Plateau River Valley due to upstream influences. Each of these contribute to the lack of turning of the local flows into and down the Plateau River Basin. We believe however, that these effects are very local and do not significantly perturb the solution on the basin slopes.

Figure 2. The horizontal wind field after 2 hours of cooling at 7.5 m AGL. Terrain contours every 400 m are provided for reference. The numbered arrows on the left side of the figure indicate the positions of the vertical cross sections presented in Fig. 3.

As a further aid in understanding the structure of the flow and the representativeness of the observation sites, we examined the flow in more detail at the six tower locations marked on Fig. 1. Sites 1, 2, and 3 represent an across basin section, while sites 4, 5, and 6 depict a down basin section. The vertical profiles of down slope winds across the basin are plotted in Fig. 4. Site 1 which is in the southeast rim flow and site 2 which is in the central flow are seen to be very similar in both speed and vertical structure. Site 3 which is between the central flow and the west wall flow is significantly weaker and shallower. These results seem to indicate that the difference is caused by the character of the upwind terrain. Site 3 is down wind of a relatively flat region that does not appear to drain as readily as the more sloped regions upwind of the other two sites. In contrast, the vertical temperature change profiles shown in Fig. 5 for the same site show a more uniform change with the eastern site having cooled the most, the western site cooling the least, and the central site midway between.

The down basin variation of the vertical profiles of downslope winds is presented in Fig. 6 using sites 4 on the mesa top, 5 about half way down the basin, and 6 near the entrance to the Plateau River Valley. The flow on the mesa top is weak and relatively shallow. The flow at site 5 is seen to be deeper than on the mesa top, but only very slightly stronger. The slow speed is a function of the site's position just to the west of the core of the flow which has a maximum speed of 3.4 m/s. This

Figure 3. Vertical cross sections of the northerly component of the wind at the 4 locations marked in Fig. 2. The contour interval 0.5 m/s. a) is along the slope (arrow 1 in Fig. 2) b) is in the middle of the basin (arrow 2 in Fig. 2) c) in near the entrance to the Plateau River Valley (arrow 3 in Fig. 2) d) is in the Plateau River Valley.

Figure 4. Vertical profiles of downslope velocity after two hours of cooling at the sites marked as 1, 2, and 3 in Fig. 1.

Figure 5. Vertical profiles of the total temperature change over two hours at the sites marked as 1, 2, and 3 in Fig. 1.

Figure 6. Vertical profiles of downslope velocity after two hours of cooling at the sites marked as 4, 5, and 6 in Fig. 1.

suggests that the tower data may underestimate the speed of the drainage flow at mid-basin. The flow at site 6 is significantly faster than at the other two sites but the flow depth is approximately the same as at site 5 indicating that the drainage flow depth is not strictly a function of mass flux but also a strong function of thermal structure which is shown in Fig. 7. As expected, the maximum cooling has taken place at site 6 at the foot of the basin and the least has taken place at site 4 on the mesa top. The depth of the cooling reaches a maximum at approximately site 5 and is constant down to the foot of the basin.

Figure 7. Vertical profiles of the total temperature change over two hours at the sites marked as 4, 5, and 8 in Fig. 1.

DISCUSSION

While a comprehensive comparison with data is not yet possible, we surveyed some preliminary observations to gain insight into the performance of the model. Because the night for which data were available had a non-zero geostrophic wind rather than the assumed calm conditions, the comparison must be treated as indicative rather than absolute. The results of the comparison demonstrated that the model is qualitatively correct except within the Plateau River Valley. Further, there are indications that the model results may be correct in some details. For example, the observations show that site 3 had the weakest drainage flow of the cross basin sites with an observed difference from the flow at site 3 of approximately 0.9 m/s. This is remarkably similar to the model result of a difference of 1.0 m/s. Also, the downslope wind speed at site 2 was observed to be 3.2 m/s which is very similar to the 2.6 m/s wind produced by the model. However, not all comparisons were as favorable. The model did not produce a significant difference between sites 1 and 2 while the observations showed that site 3 was 2 m/s stronger than at site 2. The model seems to overpredict the depth of the drainage flow by a factor of 2 or more. While the available data were not sufficient to determine if the model was correct in predicting that site 5 would be located east of the drainage flow maximum, the observation that the flow at site 1 was stronger than at site 4 could imply that the model was correct. In order to determine exactly how much of the agreement is serendipitous, we will have to wait until the full data set is available.

As the data become available, we plan to make in depth comparisons with the model results with the two-fold objective of improving the modeling capabilities and increasing our understanding of the phenomena lurking behind the relatively sparse data. We believe that a cooperative exchange between modeling and observational efforts will yield the maximum benefit for the study of terrain driven flows.

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