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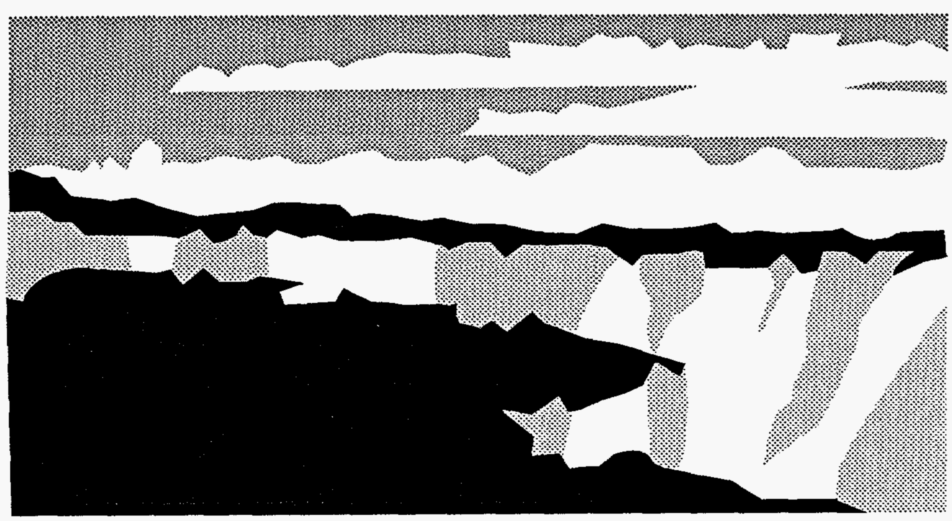

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ASSESSING THE INTERACTION OF MOUNTAIN WAVES AND KATABATIC FLOWS USING A MESOSCALE MODEL

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1. INTRODUCTION

This paper has two main purposes. The first is to evaluate the interaction of two common complex terrain meteorological phenomena, katabatic flow and mountain waves. Although occasionally investigated together (i.e. Barr and Orgill, 1989), generally, the large body of literature regarding them has treated each individually. The second purpose is to show the reader the utility of extracting high time resolution data sets of 1) standard meteorological variables and, 2) seldom used, components of the model equations. Using such time series, significant variability is found in the evolving, clear sky, nocturnal boundary layer, when meteorological variability is generally considered to be at its lowest point diurnally.

Our approach is to use results from three, 3-d, realistic topography simulations produced by the Regional Atmospheric Modeling System (RAMS, see Pielke et al., 1992 for a description.). RAMS is a primitive equation mesoscale model formulated in σ coordinates. The model is set up with five nested grids that focus on Eldorado Canyon, which is embedded in the Front Range slope of Colorado. On the finest grid $\Delta x = \Delta y = 400$ m and $\Delta z = 20$ m for the lowest 400 m above ground level (AGL). For greater detail on the model set up see Poulos (1996). The three simulations were, 1) a realistic simulation, 2) the same as 1) but without radiative forcing (referred to as mountain wave only or MWO) and, 3) the same as 1) but without boundary nudging and no initial winds (referred to as katabatic flow only or KFO). The case night is 3-4 Sep 1993 from the Atmospheric Studies in Complex Terrain (ASCOT) 1993 field program near Rocky Flats, Colorado. Both mountain waves and katabatic flows were occurring on this night.

2. RESULTS

To demonstrate the non-linear interaction of katabatic flow and mountain waves a point deep within lower Eldorado Canyon was chosen. This location is approximately 1.5 km west of the canyon mouth where two tributaries of South Boulder Creek converge and local relief is approxi-

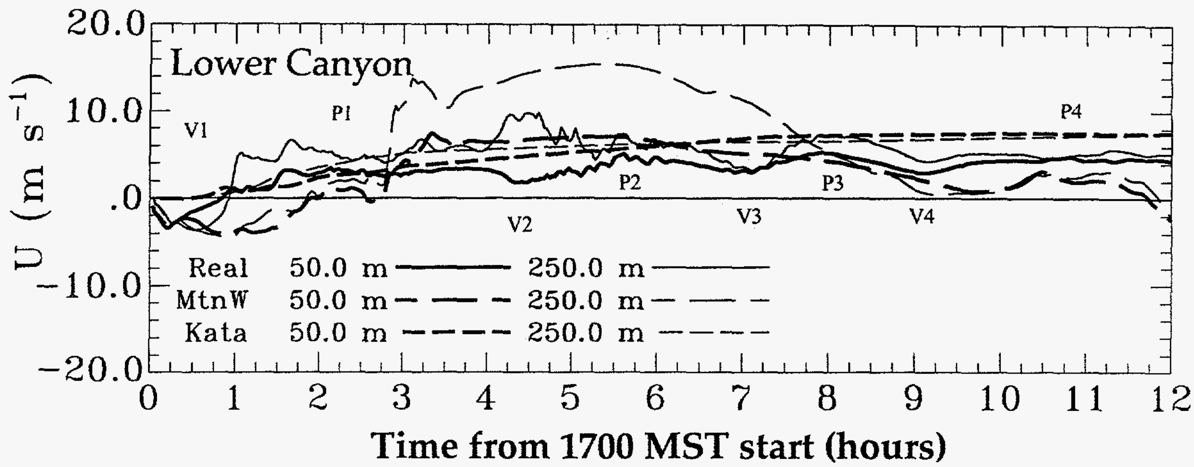

Figure 1. Two-minute resolution, u component winds versus time for lower Eldorado Canyon. Results are shown for the realistic (solid lines), mountain wave only

mately 400 m, so that it is somewhat sheltered from flow over the Continental Divide ~35 km to the west. Comparisons of the realistic simulation with observational data taken by ASCOT towers, sodars, wind profilers and standard meteorological maps, indicated a credible result, which gives confidence in the following analysis.

The u component, or along canyon, flow at 50 m and 250 m AGL for the lower canyon and each of the three simulations, is shown in Figure 1. The flow in the realistic simulation is more variable than either KFO or MWO, including some short time scale (5 -10 minute) variations while mountain wave breaking is occurring aloft. The u component in the KFO simulation steadily grows over time, eventually reaching a near steady state, at both plotted levels. The uniformity of the katabatic flow with height, rather than the typical jet structure, is explained in Poulos (1996). Low level MWO flow is similar to its upper level flow prior to 3 hours and after the 8 hour point, as this level is generally sheltered from the mountain wave. Between these two times, strong flow aloft is caused by the relatively long wavelength of the mountain wave and increased upstream flow. Flow at 50 m AGL from 3.5-8.0 hours is weaker than that at 250 m AGL due to surface friction. In Figure 1 for the realistic simulation, mountain wave influence is generally small due to the protective effect of developing thermal stratification and the shortening of mountain wave wavelength over time. This relatively quiescent condition is conducive to radiative cooling, and therefore the realistic simulation winds are most similar to KFO. A notable 1-3 m s^{-1} undulation in u speed at 50 m AGL of the realistic simulation, explained below, is indicated by ‘P’ for peaks and ‘V’ for valleys.

The combination of mountain wave and katabatic forcings creates, in Figure 2c, a more variable state than exists in with either forcing individually (panels a and b). This alone shows that the interaction dynamics are non-linear. The pressure gradient forcing in Figure 2c, for instance, is consistently large and positive after hour 1, whereas the MWO simulation is comparably large during only the 4-8 hour period. Also, from 4-8 hours the MWO tendencies have a smooth behavior and flow increases in this region, but with cooling added, as in the realistic simulation, the behavior is variable. Overall, similar to KFO, a force balance is struck between positive pressure gradient, and negative advective and turbulence tendencies. Another interesting aspect of Figure

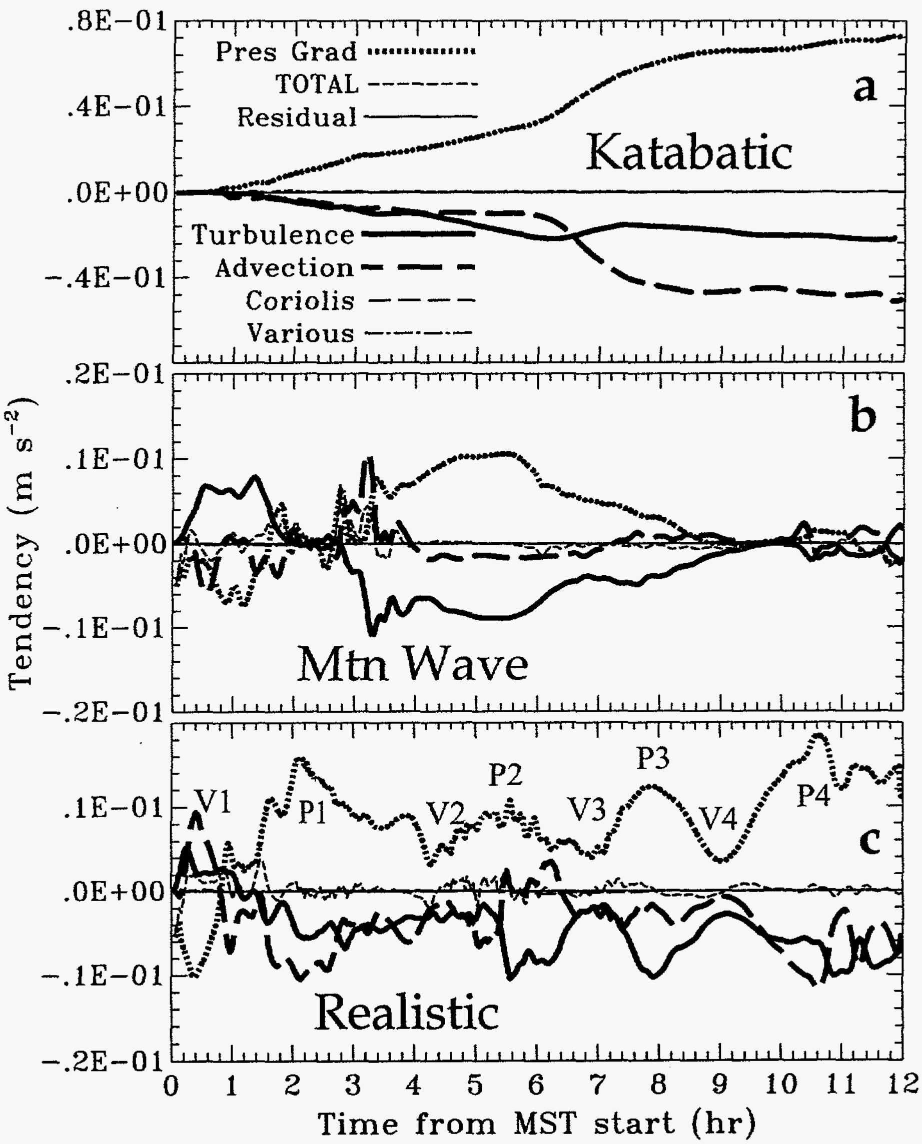

Figure 2. Terms of the conservation of u momentum equation as calculated by RAMS for the 3-4 Sep 1993 case night for the a) katabatic flow only, b) mountain wave only, and c) realistic simulations. 12 hours of data is presented in an 8 minute running average of 2 minute data for the lower Eldorado Canyon at 50 m AGL.

2c is the routine occurrence of peaks and valleys in the pressure gradient force that correspond with the peaks and valleys labeled on Figure 1. As in the MWO simulation, near surface horizontal pressure gradients are induced by the overlying mountain wave in the realistic simulation, though modified by radiative cooling. At P1, for example, not only has cooler, denser air, begun to accumulate and create a positive horizontal pressure gradient, but also the topographically induced gravity wave, which undergoes an upward motion at this horizontal location, locally increases the near surface pressure. As a consequence, the combined effect leads to a local-in-time maximum in horizontal pressure gradient to which low-level winds (see Figure 1) respond by increasing slightly. Each of the labeled peaks and valleys can be explained in similar fashion as various wave phases evolve above this horizontal position. This evolution is reflected as 1-3 m s^{-1} fluctuations in katabatic wind speed (Figure 1). Thus, dynamic pressure forcing, turbulent interaction and other effects from an overlying mountain wave can drastically influence the otherwise slowly varying pressure gradient forcing in katabatic flow (Figure 2a), inducing significant variability.

3. SUMMARY AND CONCLUSIONS

We find that mountain waves and katabatic flows can interact in a number of interesting ways to create a highly variable and evolving nocturnal atmosphere. In addition to those changes attributable to direct turbulent effects (e.g. deepening and weakening or scouring of katabatic flow), the most interesting effect is that due to dynamic pressure forcing by the mountain wave. If, say, the downward wave phase overlies the katabatic flow, local surface pressure will be reduced. Since katabatic flow is generated by cooling-induced horizontal pressure gradients the result is weakened katabatic flow - in this case by up to 3 m s^{-1}. This mechanism sheds light on how an overlying gravity wave can impart forcing on surface flow through changes to atmospheric column pressure, when interaction otherwise seems unlikely. Furthermore, the overlying gravity wave phase depends on the continually evolving atmospheric stratification and upstream flow. The combination of these effects is one likely explanation as to why katabatic flows are generally quite variable in complex terrain, despite the stable thermal stratification they reside within.

Finally, these conclusions were solidly aided by the use of high resolution time series of meteorological data and, more importantly, the actual model forcings. The authors suggest that the availability of forcing information is a significant, but frequently overlooked, benefit in the use of numerical models and encourage the use of this data as a fundamental analysis method.

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