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Highly-Resolved LES of the Stable Boundary Layer over Terrain

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P7.4 HIGHLY-RESOLVED LES OF THE STABLE BOUNDARY LAYER OVER TERRAIN

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1. INTRODUCTION

One of the most important scenarios for atmospheric modelers is the stable boundary layer (SBL). Airborne material released near the ground will likely be trapped near the ground in high concentrations due to the reduced dispersion in the SBL. Hence the SBL is often the worst case scenario for studies of health impacts from routine or accidental release of toxic materials to the atmosphere.

Unfortunately the SBL is very challenging to understand and model correctly. There is also a limited number of field studies with which to verify models, although recent studies (such as CASES-99) are promising. It is difficult for traditional Reynolds-averaged models of turbulence to capture the weak, spatially- and temporally-varying fluctuations that contribute to dispersion the SBL. Large-eddy simulation (LES) has become a promising approach to study the SBL because much of the dynamical structure is explicitly resolved and allowed to develop according to the full equations of motion (see, e.g., Cederwall and Street, 1999). The presence of topography further complicates the simulation of SBL flows. The drainage flows that develop as the surface cools must be resolved, along with their interaction with other drainage flows of varying scales and the main forcing (synoptic scale) flow.

In this study, we have used LES techniques to simulate flows in complex terrain during the development of the SBL at night. We have begun to evaluate the effects of resolution on the simulations, though this effort is continuing at the time of this writing. Simulations are conducted for the area around Salt Lake City, where several field activities are planned for the future. The study will be extended to the small scale terrain associated with the CASES-99 experiment, and comparisons made with observations.

2. MODELING APPROACH

The LES model used in this study is an extension of a finite element model used to simulate heavy-gas dispersion (Chan, 1994; Gresho and Chan, 1990). The model integrates the time-dependent, incompressible Navier-Stokes equations and uses boundary-fitted meshes combined with an ability to mark specified cells as 'solid' (i.e., useful for detailed resolution of flow domains which include buildings). The modeling framework has been improved using an object-oriented approach with message passing, as discussed in Stevens and Bretherton (1996) and Stevens, et al. (2000a, 2000b). We have performed planetary boundary layer simulations with this framework with up to 40 million gridpoints. At this stage of the project, we are using a simple eddy viscosity model to account for subgrid scale turbulence, although we are involved in a simultaneous effort to develop and test more sophisticated subgrid scale models (see Katopodes, et al., 2000, this proceedings).

3. ONGOING PLAN

In this paper, we report on the initial stage of our effort to utilize these tools to simulate stable boundary layers over terrain. The results presented below represent the first stage of the project and are medium resolution simulations using approximately a quarter of a million gridpoints. At the time of writing, results for five million gridpoint runs are just becoming available. Our plan is to compare higher

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resolution results with lower resolutions in order to discover the requirements for accurate simulation of intermittent, drainage flows for intermediate-scale domains (i.e., 2 to 20 kilometers). After testing the methods on the Salt Lake City domain, we plan to simulate the CASES-99 Gully experiment.

4. TERRAIN

We have chosen a region of complex terrain north and east of Salt Lake City. Several large experimental campaigns are scheduled to gather data in and around the city in the coming year. A topographical contour map is shown in Figure 1. The vertical domain spans approximately 2800 meters from the valley floor to the top of the domain. The maximum rise of the topography off the valley floor is approximately 900 meters. In these runs, we are using 100 meter horizontal grid spacing and a stretched grid vertically with a minimum grid spacing near the topography of 2 meters.

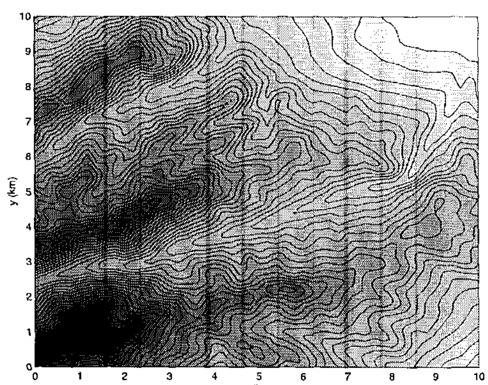

Figure 1. Topography of simulation volume. North is on the bottom of the graphic. Salt Lake City is located near the upper right.

5. THE SIMULATIONS

The simulations were integrated forward in time for approximately 1 hour of simulated time with no surface cooling. After 1 hour, cooling was applied to the ground surface [-20 W/m^2] for another 5 hours. The results displayed below are for approximately 4 hours into the simulation.

The computational grid and a cross-cut are shown in Figure 2. We use a neutral inflow boundary condition on the side of domain that is near the bottom of Figure 2, and a convective outflow condition for the side near the top of the graphic. The lateral sides and bottom are simple walls and the upper boundary uses a free-slip condition. The cross-cut crosses several valley areas of the topography. The position of the cross-cut is the same as that shown in Figures 4 and 5.

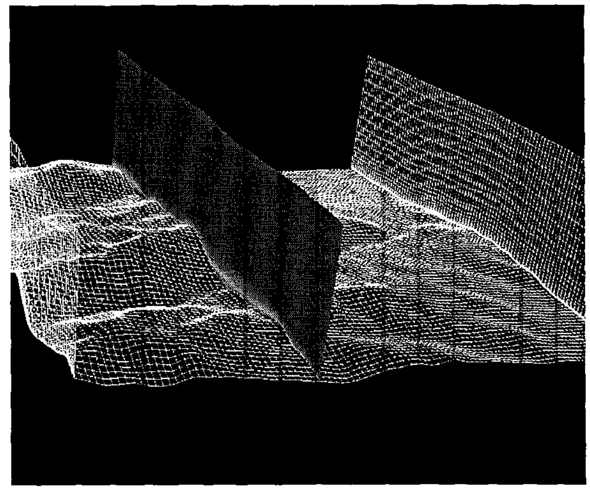

Figure 2. Grid and cross-cut location; the north edge is at the bottom.

Air flows down through the valleys as can be seen in Figure 3. In this Figure, isosurfaces of perturbation temperature [-1.3 degrees] are shown shaded by wind speed. This figure shows how stronger cooling is present in the valleys.

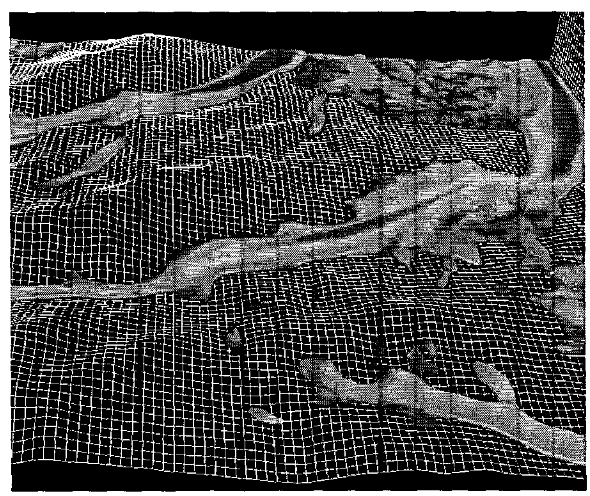

Figure 3. Isosurfaces of perturbation temperature [-1.3 degrees] shaded by wind speed.

The effects of topography on channeling the flow are evident in the local wind speed maxima in the valley regions in Figure 4. The temperature minima are also located in the valleys (see Figure 5). However, it is not clear that the wind speed maxima are directly related to the temperature minima via drainage flow effects. We suspect that finer resolution is needed to capture this, and are still investigating the interplay between the topographical forcing and stratification effects in these areas.

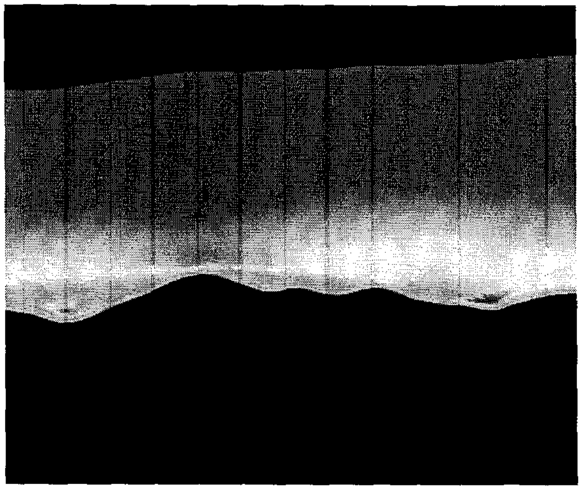

Figure 4. Cross-cut showing contours of windspeed. The valley local maximum on the left has a magnitude of 2.8 m/s and the maximum on the right has a value of 3.5 m/s. For reference, the windspeeds at the top of the domain are about 5 m/s.

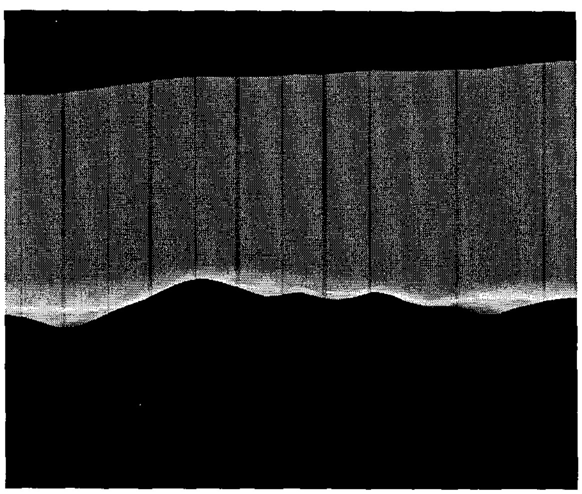

Figure 5. Cross-cut showing perturbation temperature where colder air is designated by darker shading. Minimum on the left is –1.8 degrees and the minimum on the right is -1.9 degrees.

6. DISCUSSION

Our preliminary runs show collection of colder air in valleys and air flow which moves down the valleys. We are still investigating the roles of topographic forcing and stratification in these flows. Even some of the smaller-scale gullies appear to collect colder air. We suspect that the ability of simulations to capture the flows in the smaller scale gullies will be highly dependent on resolution.

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7. REFERENCES

Cederwall, R.T., and Street, R.L., 1999: Turbulence modification in the evolving stable boundary layer: a large-eddy simulation. *13th Symposium of Boundary Layers and Turbulence*, AMS, Dallas, TX, 223-226.

Chan, S.T., 1994: FEM3C – An improved three-dimensional heavy-gas dispersion model: User's Manual. Report UCRL-MA-116567 Rev. 1, LLNL, Livermore, CA.

Gresho, P.M., and Chan, S.T., 1990: On the theory of semi-implicit projection methods for viscous incompressible flow and its implementation via a finite element method that also introduces a nearly consistent mass matrix. Part 2: implemetation. *Intl. J. Num. Meth. Fluids*, **11**, 621-659.

Katopodes, F.V., Street, R.L. and Ferziger, J.H., 2000 Subfilter-scale scalar transport for large-eddy simulation. This proceedings.

Stevens, D.E., and C.S. Bretherton, 1996: A forward-in-time advection scheme and adaptive multilevel flow solver for nearly incompressible atmospheric flow. *J. Comp. Physics*, **129**, 284-295.

Stevens, D.E., J.B. Bell, A.S. Almgren, V.E. Beckner, and C.A. Rendleman, 2000a: Small-scale processes and entrainment in a stratocumulus marine boundary layer. *J. Atmos. Sci.*, **57**, 567-581.

Stevens, D.E, A.S. Almgren, and J.B. Bell, 2000b: Adaptive simulations of trade cumulus convection. *Mon. Wea. Rev.*, in press.