Slope Flow Measurements During Vertical Transport And Mixing (VTMX) Field Experiment, Salt Lake City, 2000

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Abstract

During the month of October 2000, a major field campaign dealing with urban flow and pollution dispersion took place in Salt Lake City, Utah. Named "Vertical Transport and Mixing" (VTMX) experiment, this project was funded by the US Department of Energy's Environmental Meteorology Program (EMP). The aim of VTMX was to investigate vertical transport and mixing in stable atmospheric boundary layer (ABL) of complex terrain, with emphases on weak or intermittent turbulence that occur under stable conditions, morning/evening transitions around urban basins or valleys, formation and evolution of inversions and the motion of pollutants within stable layers trapped in valleys. The overall research program is expected to contribute significantly to the knowledge of complex-terrain flow processes and will lead to better prediction of urban air quality.

The Environmental Fluid Dynamics (EFD) Program at ASU is one of the several groups participated in this experiment. EFD's research program was focused on thermally induced circulation, for example, slope and valley wind systems, pooling of cold air in basins and breakup of cold pools during which the trapped air is dispersed vertically. In addition to field measurements, laboratory, theoretical and numerical simulations are being conducted to better understand flow, mixing and transport in complex terrain. This paper contains some slope flow measurements taken during the VTMX program by the ASU/EFD group.

1. Introduction

VTMX is a research program supported by the U.S. Department of Energy under the auspices of the Environmental Meteorology Program (EMP) of the Office of Biological and Environmental Research (http://www.pnl.gov/vtmx; http://vtmx.eas.asu.edu/vtmx). It is aimed at investigating vertical transport and mixing processes in the atmospheric boundary layer (ABL) in complex terrain, with research attention focused on strong stably stratified conditions that lead to weak or intermittent turbulence as well as on morning/evening transitions. VTMX is centered primarily around urban basins or valleys and will investigate phenomena such as the formation and evolution of inversions and the motion of pollutants in layers trapped in valleys. The first field campaign for VTMX was conducted in the Salt Lake Valley over the month of October 2000. Figure 1 shows the EFD experimental site.

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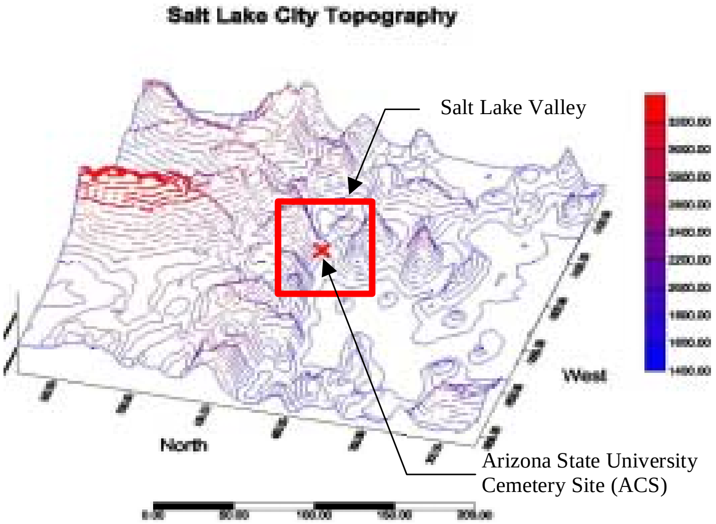

Figure 1. The VTMX experimental site.

Equipment employed by the EFD group consisted of sonic and cup anemometers, thermistors, radiometers, tether sondes, two different devices for measuring PM10 particulate - TEOM and Dustrack as well as particle streaker for determining the chemical composition of the air. The instruments were located in a local cemetery, with coordinates: North 40.75315; West 111.84864; and Elevation 1410 m. Two sonic anemometers were mounted at 4.5 m and 13.8 m and the radiometers were mounted 3.2 m above the ground surface. The sonic anemometers were operated with a frequency of 10 Hz. Two thermistors, placed at 1.8 m and 6.9 m, two cup-anemometers, mounted at 2 m and 7.3 m, and the radiometers collected averaged data every 5 minutes.

The weather during the VTMX Intense Observational Period (IOPs) was characteristic of the season with clear skies, generally weak winds and dry air. The air temperature, humidity, wind direction and turbulent fluxes showed a normal diurnal cycle associated with maximum heating during the day and rapid cooling at night. A well-mixed convective boundary layer was typical of the daytime, while a stable, nocturnal boundary layer fluctuated between 8 and 12°C in the morning, rising to over 20 - 25°C in the afternoon.

2. Analysis and results

2.1 Anabatic (up-slope) flow

Hunt et al. (2001^5) derived a theoretical model for up-slope winds in complex terrain on a heated simple slope. By considering the momentum and temperature equations in a coordinate system with axes parallel and normal to the slope, assuming that the anabatic flow consists of three different sublayers consisting of a surface layer, denoted by [*S*], a middle layer [*M*] and an inversion layer [*I*], and taking into account that each sublayer also can have layers of different dynamics [e.g. S consists of a surface layer [S_S] and a convective layer [S_C], demarcated by the Monin-Obukhov length scale $L_* = (u_*/w_*)^3 h$], a detailed analysis was carried out.

Assuming self-similar profiles of mean velocity in [M], determined by a balance between inertia and shear stress gradients, and considering entrainment of external fluid into [I] determined by buoyancy, inertia and shear stresses, the layer-averaged up-slope flow velocity U_M in [M] for sufficiently small slope angles β was shown to be

$$U_M = \lambda_u \beta^{1/3} w_* , \qquad (1)$$

where $\lambda_u \sim \ln(L_*/z_0)/\kappa$ is a factor that depends on the size of the Monin-Obukhov scale relative to the roughness height z_0 of the slope surface and determines the depth of the logarithmic layer.

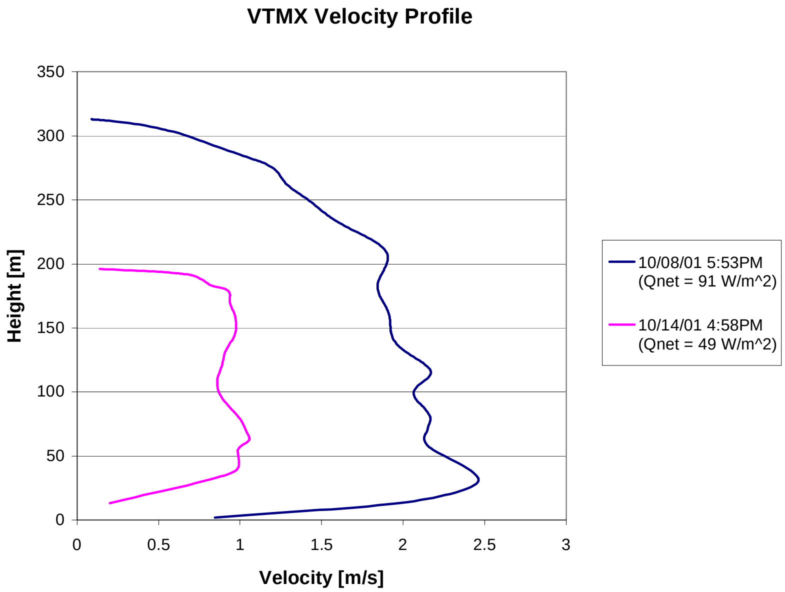

Figure 2. VTMX velocity profiles.

Figure 2 shows some anabatic velocity profiles measured during the VTMX campaign. In order to evaluate the constant λ_u in equation 1, the layer velocity U_M can be plotted against the quantity $w_* \beta^{1/3}$ [right hand side of Eqn (1)] for low synoptic flow conditions. The daily averages are then calculated by using all daytime data throughout the VTMX field experiment (Figure 3). The constant λ_u is then found to be 4.15 ± 0.44. Note that the data taken from the vertical profiles agree reasonably well with the data taken from the sonic anemometer. Also shown in Figure 3 are the laboratory results of Chan (2001[1]).

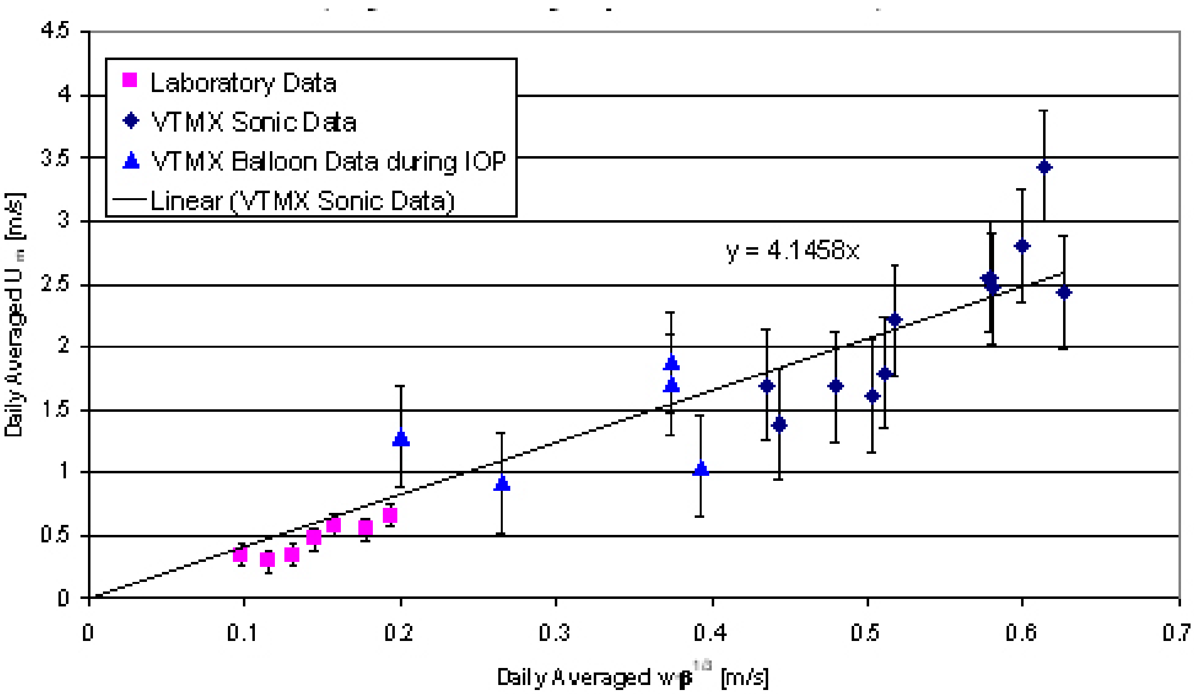

Figure 3. A comparison of the measured and calculated anabatic flow velocities. For VTMX, the days included are Oct 1 – 5, 7, 11, 14 – 17, 2000 where the intense operational periods were in effect.

2.2 Katabatic (down-slope) flow

Numerous studies have been carried out to investigate slope flows. In the approach of Manins & Sawford (1979[6]), full two-dimensional unsteady equations for momentum and potential temperature were integrated in the direction normal to the slope over a large depth H to obtain layer-averaged equations, for which solutions were obtained using closure assumptions. The layer averaging reduces the complexity of equations and yields representative along-slope velocity (U), buoyancy (Δ), length scale (h) of the flow and the net inflow velocity $(-w_H)$ into the current, as defined by

$$
\begin{aligned}
&Uh = \int_0^H u\,dn && U^2 h = \int_0^H u^2\,dn\,; \\
&U\Delta h = \int_0^H u g'\,dn\,; && S_1 \Delta h^2 = 2\int_0^H g' n\,dn\,; \qquad (2) \\
&S_2 \Delta h = \int_0^H g'\,dn && \int_0^H w\,dn = w_H.H - S_3 w_H h\,.
\end{aligned}
$$

Here (u, w) are the along-slope (s) and normal (n) velocities, $g' = (\theta_a - \theta)g/\theta_r$ the reduced gravity, g the gravity, θ the potential temperature, θ_a the ambient potential temperature and θ_r a reference temperature. This procedure, however, introduced new unknowns, the “shape” factors S_1, S_2 and S_3, and the “surface” shear stress $-\overline{(u'w')}_0$ or the drag coefficient C_D [defined as $-\overline{(u'w')}_0 = C_D U^2 = u_*^2$, where u_* is the friction velocity] which is needed to be parameterized in modeling. The relevant forcing parameter is the “surface” buoyancy flux $B = g[(R_H - R_0) - Q]/\rho_r C_p \theta_r$, where C_p is the specific heat at constant pressure, ρ_r the reference density, $R_H - R_0$ is the radiation divergence over the height H (which is zero for laboratory experiments) and Q is the “surface” heat flux. Hitherto, S_1, S_2 and S_3 have been estimated either using rudimentary field observations (Manins & Sawford 1979[6]; Horst & Doran 1986[4]) or laboratory observations of gravity currents on simple slopes (Ellison & Turner 1959[2]).

In our work, the profile factors were evaluated by analyzing velocity and temperature profiles taken during VTMX campaign. Figure 4 show the variation of the profile factors S_1 and S_2 with respect to Richardson bulk number, $Ri = h\Delta \cos\alpha / U^2$, where, α is the slope angle. Slope angle on our site was 4°. We were unable to evaluate profile factor S_3 because there was no measurements of vertical velocity profiles (w), which are necessary for calculating profile factor S_3

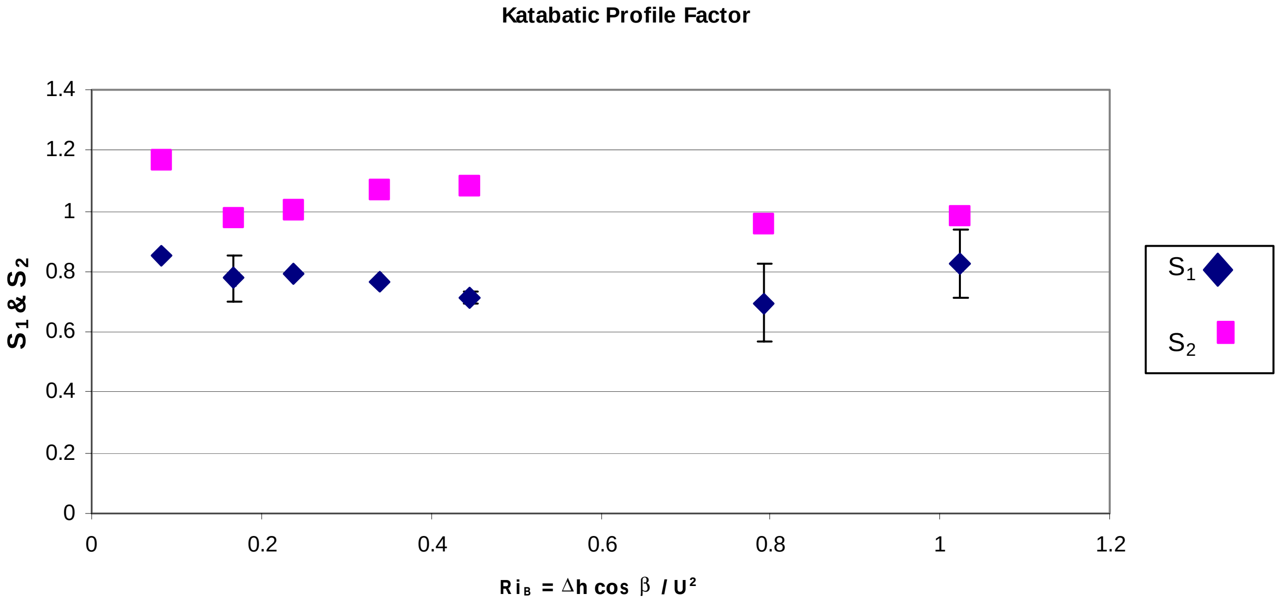

Figure 4. Katabatic profile factors calculated using VTMX field data

3. Conclusions

Some results pertinent to slope flows in complex terrain obtained during the VTMX field campaign were presented in this paper. The experimental data confirmed the result for anabatic flow $U_m = \lambda_u w_* \beta^{1/3}$ for the convective period, in the absence of synoptic flow. For daily averaged VTMX data, λ_u was found to be approximately 4.2 which is somewhat higher than λ_u = 3.3 obtained using the laboratory data reported by Chan 2001[1].

For katabatic flows, profile factors S_1 and S_2 were measured as a function of the flux Rayleigh number. Both S_1 and S_2 converge to a constant value, 0.8 and 1, respectively. Profile factor S_2 is in agreement with the laboratory results (Fernando 2000[3]), but S_1 is somewhat lower than $S_1 = 1$ obtained using laboratory data (Fernando 2000[3]).

Acknowledgements:

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