Flow and Aerosol Measurements During VTMX and Their Interpretation Using Simple Models

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Nocturnal atmospheric boundary layer data taken during the Vertical Transport and Mixing eXperiment (VTMX), conducted in the Salt Lake City air basin during October 2000, was used to study the nature of nocturnal circulation in a complex terrain airshed. A 14 m tower instrumented with sonic and cup anemometers, thermistors, radiometers as well as two tethered balloons carrying meteorological sondes and aerosol samplers were used for measurements. The measurement location was an approximately uniform eastern slope of the valley with E-W slope angle 4^o, covered with grass and small shrubs away from large obstacles. The emphasis was on periods of clear skies and low synoptic winds so that the local thermal circulation dominates the basin circulation. Since the slope flows are primarily driven by diurnal thermal forcing, micrometeorological variables such as temperature, wind velocities and sensible heat and momentum fluxes showed nearly periodic behavior for the days studied. The *rms* temperature fluctuations (5 mts averaged), however, remained nearly constant over the entire diurnal cycle, contributed by thermal convection during the day and internal wave activity at night, except when there is significant low frequency internal wave activity.

The data clearly illustrated an up-slope (anabatic) flow during the day (100-500 m thick) and down-slope (katabatic) flow at night, both having magnitudes ~ 4 m s^{-1}. The thickness of the katabatic flow decreased with the increase of the speed of headwinds aloft, and was found to vary from 15 to 100 m.

The wind speeds during morning and evening transitions were small and highly variable. Sonic anemometers located at 4.5 m and 13.86 m indicated that the evening transition occurs at both levels simultaneously. A delayed morning transition as much as ½-1 hr, however, was observed at the lower sonic. Observations suggest that this phenomenon is caused by the generation of up-slope flows at lower elevations prior to that of the measurement location; these up-slope flows stream over the weakening katabatic current at the measurement location.

Layers of different density and wind speed/direction characterized the vertical structure of the flow. These layers may have formed due to different air masses of disparate densities originating at slopes of different orientation surrounding the air basin. The suppression of turbulence by the stable stratification reduces shear stresses between these layers, thus allowing them to slide one above another. This intensifies shear across the layers, and hence generates turbulence whence the averaged local gradient Richardson number ($\overline{Ri_g}$) drops below a critical value (~1). The fluctuations of ($\overline{Ri_g}$) were pronounced, often crossing the threshold of turbulence production, thereby maintaining (at least weak) turbulence in the katabatic layer. The level of turbulence also modulated concurrent with the ($\overline{Ri_g}$) variation. Two types of fluctuations were observed, high frequency oscillations with period several tens of seconds and low frequency oscillations (period ~30 mts) corresponding to internal wave oscillations along the slope. Turbulence of the sloping boundary layer considered here appears to be different from its flat-terrain counterpart where highly intermittent turbulent patches are sporadically generated and decay rapidly (Mahrt 1998).

The variation of density stratification and shear over the night allowed the measurement of averaged flux Richardson number (mixing efficiency) $\overline{Ri_f}$ as a function of the mean gradient Richardson number $\overline{Ri_g}$, an important relationship used in geophysical closure models. It was found that $\overline{Ri_f}$ - $\overline{Ri_g}$ relationship is insensitive to the averaging time, when 30-900 s averaging periods were employed. The results were in broad agreement with the laboratory water tunnel measurements of Strang & Fernando (2001 a,b) conducted using an inhomogeneous stratified shear flow (a mixing layer), wherein $\overline{Ri_f}$ increases to a maximum of ~0.4 at $\overline{Ri_g}$ ~1 and then decreases. The diffusivities of momentum and heat were also evaluated as a function of $\overline{Ri_g}$, and found to be well above their molecular diffusive values (Figure 1). A striking behavior was noted when the diffusivities are scaled with the shear length-scale and the *rms* vertical velocity fluctuation.

In addition to meteorological measurements, ground level and vertical measurements of aerosols and other pertinent meteorological parameters were made at our VTMX test site. Analyses of aerosol samples taken using TEOM and Dustrack instruments revealed that temporal variations of aerosol concentration are profoundly affected by both thermal forcing and synoptic scale flows. For predominantly thermally driven flows at the ground level (i.e., negligible synoptic scale winds), the diurnal variations of PM_{10} concentration were well evident. For these flows the daytime flow initially consists of up-slope flows which advect aerosols from their source in the city toward the measurement site, thus giving high values of PM_{10} concentration from mid-morning until early afternoon (Figure 2). In the mid-afternoon, the PM_{10} concentration decreases significantly, possibly due to the arrival of a ground-level northwesterly lake breeze, which removes pollutants from near the ground. A local peak in the PM_{10} concentration was associated with the evening transition. This is possibly due to the return of aerosols, previously moved into the Wasatch Range by the upslope flows, during the evening transition.

During the nighttime, a katabatic flow advects air along the surface toward the west and thus past the ACS site. One aspect of this katabatic flow is that intermittent peaks of the PM_{10} concentration are observed. Hypotheses are advanced that these may owe to (i) unsteady down-canyon flows or (ii) eddies generated by a northwesterly flow past the basin scale topography upwind of the ACS test site.

The PM_{10} concentration begins to increase prior to the morning transition. This owes to aerosols being advected into the Wasatch mountain range by return westerly flows during the nighttime. The vertical distribution of aerosols is sensitive to the thermal forcing, which exerts the driving influence on thermal circulation within the Salt Lake Valley.

As stated earlier, during the nighttime a multi-layer flow structure was observed. Along the surface the flow is an easterly drainage current with a westerly return flow immediately above and then elevated easterly winds further aloft. Within the first few hours after the evening transition westerly return flows are associated with enhanced PM_{10} concentrations while easterly currents led to reduced concentrations. Owing to the fact that aerosols are advected by the return flow in the nighttime and eventually are introduced into the down-slope flow, this circulation led to increased PM_{10} concentrations at the ACS site in the early morning.

References:

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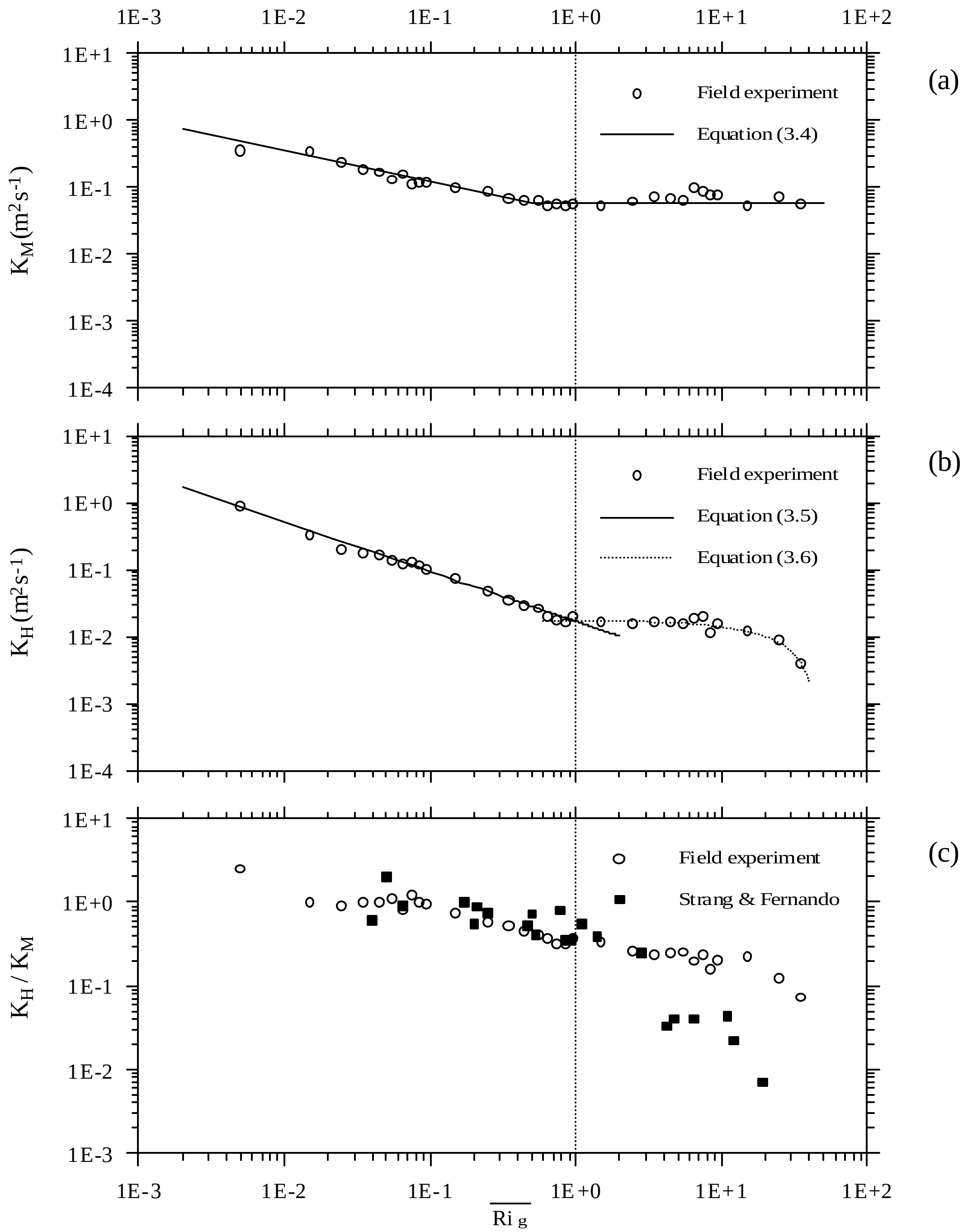

Figure 1. (a) Dimensional form of the eddy diffusivity for momentum as a function of $\overline{Ri_g}$. (b) dimensional form of the eddy diffusivity for heat as a function of $\overline{Ri_g}$. The solid and dashed lines indicate empirical fits delineated by Monti et al. (2001); equation numbers used in their paper are indicated. (c) ratio of the eddy diffusivities K_H/K_M as a function of $\overline{Ri_g}$. The full squares indicate the ratio obtained by Strang and Fernando (2001a). Field data are based on a data set taken from 1900-0700 LST during 1-5 October. Averages over 60 s were used.

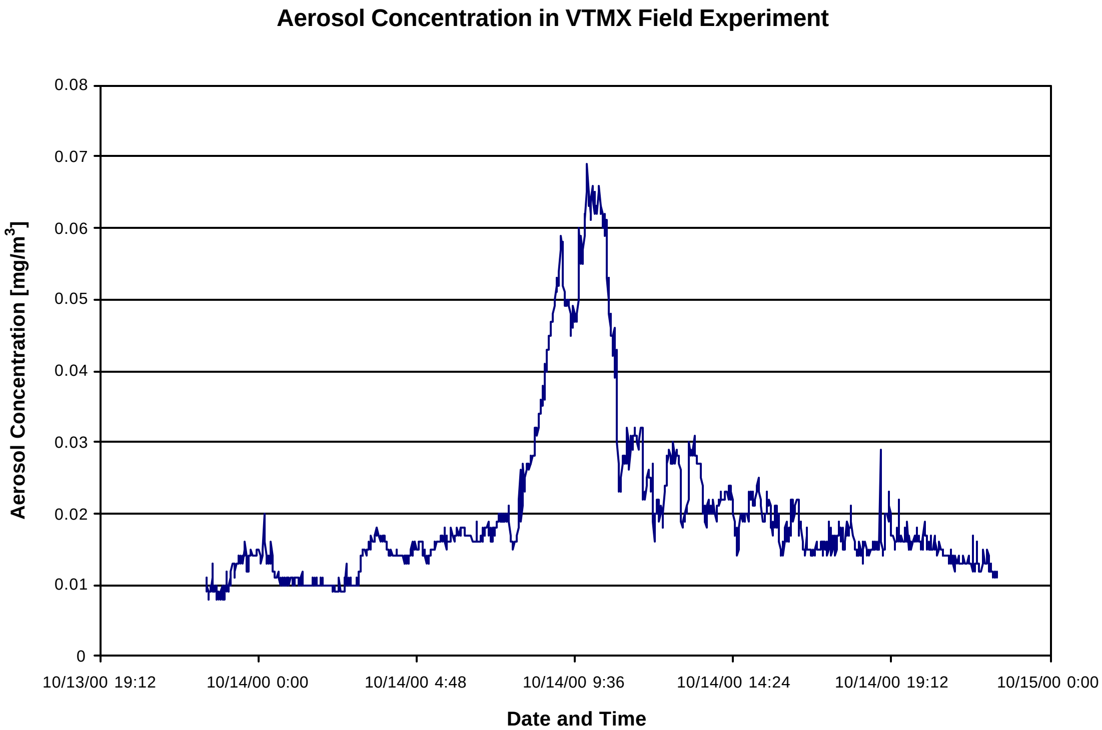

Figure 2. The aerosol concentration measured on Sunday, 10/14/00. A Dustrak instrument was used for the measurements. Note the increased particle concentration in the morning, perhaps due to early morning Sunday traffic which trails away into the morning. The upslope flow carries aerosols to the site.