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FINAL REPORT OF THE GRANT:

VERTICAL TRANSPORT AND MIXING IN COMPLEX TERRAIN AIRSHEDS

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Harindra Joseph Fernando
James Anderson
Don Boyer
Neil Berman

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Abstract:

Stable stratification associated with nocturnal thermal circulation in areas of complex terrain leads to interesting and important phenomena that govern local meteorology and contaminant dispersion. Given that most urban areas are in complex topography, understanding and prediction of such phenomena are of immediate practical importance. This project dealt with theoretical, laboratory, numerical and field experimental studies aimed at understanding stratified flow and turbulence phenomena in urban areas, with particular emphasis on flow, turbulence and contaminant transport and diffusion in such flows. A myriad of new results were obtained and some of these results were used to improve the predictive capabilities of the models.

1. Introduction:

World population is expanding at a rate of ~ 1.5% annually, and has a strong tendency to pool in ever larger and more complex urban settings in search of an enhanced quality of life. The population tends to settle along transportation corridors along waterways, which are typically associated with complex terrain (defined as areas replete with mountains, valleys and escarpments). Uneven topography not only causes perturbations to the background large (synoptic) scale (~ 1000km) atmospheric flows, but also induces local flows within urban air basins (airsheds) known as *thermal circulation*; a combination of synoptic flow, thermal circulation and other local flows determines the local micrometeorology. The thermal circulation, which is driven by local diurnal solar heating and cooling of the topography, is broadly classified into two classes -- slope and valley flows, the former occurring on side slopes and the latter blowing along the valley. Up-slope (anabatic) and up-valley circulations occur during the day and down-slope (katabatic) and down-valley winds develop at night. These flows are exemplified in Figure 1 on a topographic map of the Salt Lake Valley, where an extensive measurement program -- Vertical Transport and Mixing eXperiment (VTMX) -- was conducted in October 2000 (Doran et al. 2002). VTMX concerned nocturnal thermal circulation under negligible (or weak) synoptic influence. Also of interest were the transition periods where winds shift their direction. In the evening, the winds switch from up slope/valley winds to down slope/valley winds (evening transition) and the opposite occurs during the morning transition. At night, the air layer near the sloping ground becomes heavier and drains down as down-slope (DS) or katabatic flows. A part of this flow accumulates ("pool") in the valley bottom as a stably stratified layer (which acts as a "smog trap," given that vertical turbulent diffusion is inhibited by stable stratification), whereas the rest drains along the valley slope forming down-valley winds (DV). This circulation pattern reverses during the day, forming up-slope (US) and up-valley (UV) winds. Figure 1 also shows the suite of instruments deployed by various groups during the VTMX Program, and the PIs set us their experimental gear at the location shown as the ASU site, located on a slope in the east valley. In addition, laboratory experiments and theoretical analyses were also conducted to elicit physical processes active in the thermally driven flows, the results of which are summarized in this report.

The contribution of the ASU group to the VTMX program, therefore, consists of (i) idealized laboratory studies on cold pool formation and destruction, (ii) theoretical modeling of slope flows and morning/evening transition, (iii) participation in the VTMX field campaign, and (iv) analysis of data from the Phoenix Air Flow EXperiments (PAFEX), focusing on nocturnal and transition periods. The laboratory experiments were conducted using a two-dimensional basin and a uniform slope; slope flows as well as transition periods were realized by subjecting the ground surface to a sinusoidal heating/cooling cycle. During the VTMX field program, our group deployed a host of equipment at the Mount Olivet Cemetery (ACS Site), and collected vertical profiles and point measurements of aerosols, mean flow and turbulence. The theoretical work was done in association with Professor J.C.R. Hunt of the University College, London. The numerical work was conducted using the MM-5 Meso-scale Meteorological model.

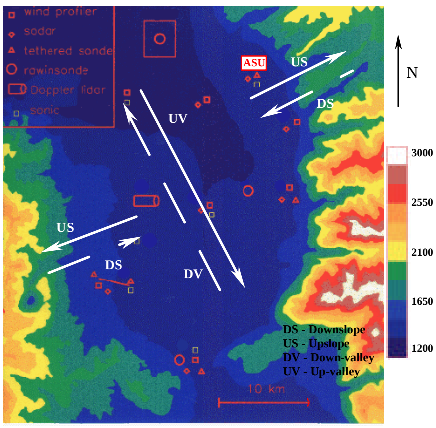

Figure 1: The thermal circulation in the complex terrain of Salt Lake Valley, Utah, where the VTMX campaign was conducted. The shading indicates the topography (in m).

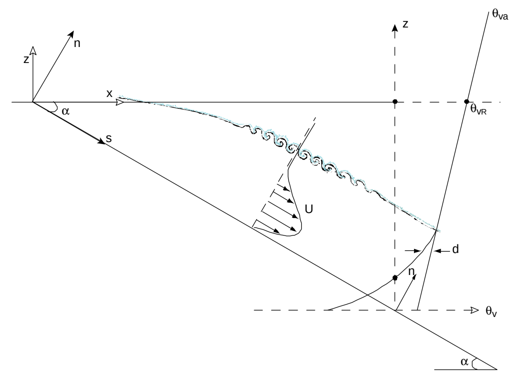

Figure 2: A schematic of a down-slope flow along a simple slope.

2. A Summary of the Results

It was shown theoretically that, upon heating with a constant heat flux, an up-slope flow develops with time and achieves a quasi-steady state wherein the characteristic velocity scale can be written as U = C (slope**0.33)(w*), where w* is the convective velocity. The constant C was evaluated using VTMX data and laboratory experiments as C = 3 - 5. The disturbances introduced during the start up of the up-slope flow propagate into adjacent plains at the long-wave speed, thus creating unsteady wave fronts. Since long waves propagate faster than the ensuing up-slope flow, the flow adjustments at the ends of the incline do not influence the establishment of the main up-slope flow. In the VTMX, aerosols are advected by the up slope flow from their source in the city toward the measurement site, thus recording high PM_{10} concentrations from mid-morning until early afternoon. In the mid-afternoon, PM_{10} decreases significantly, possibly due to the arrival of ground-level northwesterly lake breeze, which removes aerosols from near the ground.

The evening transition was theoretically modeled by cooling the slope in such a way that the entire surface-layer temperature drops linearly with time. By considering the effects of such cooling on Lagrangian motion of fluid parcels at different heights, it was shown that the wind shift from up-slope to down-slope is associated with the formation of a front (called a *transition front*). An overturning event with intense vertical mixing, which propagates down-slope, follows this front formation. Because the existing flow aloft has substantial momentum, however, the up-slope flow therein continues for some time after sunset. Eventually, there is transition of the entire up-slope flow to down-slope flow at all levels. Laboratory experiments with uniform slope confirmed the main features of this novel transition mechanism.

During VTMX, wind speeds during the morning (and evening) transition were small and highly variable. Sonic anemometers located at 4.5 m and 13.9 m indicated that the transition occurs at both levels simultaneously, while showing substantial vertical mixing. A local peak in PM_{10} was associated with the evening transition. This increase is due to the return of aerosols previously moved into the Wasatch Range by the up-slope flows. Analysis of PAFEX data show that the evening transition time in a function of the slope, with larger slopes showing an early transition (in the Phoenix area, this difference in transition time can be as high as three hours).

Laboratory results provided insights on plausible pooling mechanisms and the development of nocturnal stratification in air basins. Accumulation of katabatic flows in a valley bottom develops a strong stratification, but with time a continuous stream of dense air that slivers into the stratified layer weakens the stratification. This creates a basin-scale circulation as well as local flow modifications, the presence of which was corroborated by basin-scale flow patterns inferred from VTMX aerosol measurements.

Kelvin-Helmholtz (K-H) instabilities were found to develop at the edges of katabatic flows as well as surrounding the flow intrusions in the cold pool. The resulting turbulence was very weak in laboratory experiments, perhaps due to the low Reynolds numbers employed. The VTMX data, however, clearly showed the presence of sustained turbulence, vis-à-vis intermittent turbulence that is typical of a flat terrain nocturnal boundary layer. This continuous turbulence, perhaps produced and sustained by local shear, appears to contribute to weaker nocturnal stratifications observed in complex terrain. The turbulent intensity, however, underwent cyclic variations, out of phase with the gradient Richardson number *Ri*, which could be linked to the "Global Intermittency" of the nocturnal boundary layer. In this case, an increase of stratification (or *Ri*) shuts off turbulence and reduces vertical momentum transport, which, in turn, increases the shear, turbulence and momentum transport; the latter weakens the shear, increases stability and suppresses turbulence. These events recur over the night.

Theoretical analyses showed the possibility of another type of katabatic flow oscillations, which is essentially an along-slope internal wave-sloshing phenomenon. These oscillations were clearly evident from our own measurements as well as from those taken at a slope site on Oquirrh Mountains, with the predicted and observed frequencies of oscillations agreeing closely. These oscillations can enhance vertical shear, and hence may lead to the modulation of turbulence with a time scale on the order of several tens of minutes.

Because most basins are hemmed by non-uniform slopes, an analysis was performed on katabatic flows over a discontinuous slope. The results show that on higher elevation (steeper > 0.1) slopes the principal momentum balance occurs between buoyancy and shear stress gradients; the longer the slope and the steeper the gradient, the greater the depth and velocity of the current. The flow on the upper (higher-elevation) slope is generally supercritical; laboratory experiments show that its adjustment to the low-elevation (gentle) slope occurs *via* a hydraulic jump, if the downstream flow is subcritical. If the flow on the lower slope is supercritical, which was the case in VTMX, the flow adjustment at the slope discontinuity is rather smooth. In the supercritical regime, the katabatic flows are unaffected by the presence of down-wind perturbations such as topographic features in the bottom of the valley. Katabatic winds develop on the higher-elevation slopes overrun those of lower elevations, thus producing (cold) fronts, which can be called a "slope breeze" in analogy with its agnate "sea breeze".

Since the nocturnal ground level (< 10 m) flow was consistently down slope, the measurements taken therein could be used to obtain information on stably stratified atmospheric shear flows. The flow resembles a low level jet, with considerable shear and stratification. The variation of density stratification and shear over the night allowed the measurement of averaged flux Richardson number (mixing efficiency) R_f as a function of the mean gradient Richardson number Ri, an important relationship used for closure in geophysical prognostic models. The R_f - Ri relationship is roughly insensitive to the averaging time, when 30 - 900 s averaging periods are employed. The results are in broad agreement with the laboratory water tunnel measurements conducted using an inhomogeneous stratified shear flow (a mixing layer), wherein R_f increases to a maximum of ~ 0.4 at Ri ~ 1 and then decreases. Commonly used closure assumptions were not corroborated by the field and laboratory measurements, particularly at $Ri > 1$. The diffusivities of momentum and heat were evaluated as a function of Ri, and found to be well above their molecular diffusive values. A striking behavior was noted when the diffusivities are scaled with the shear length-scale and the *rms* vertical velocity fluctuation.

Katabatic flow advects air along the surface toward the west past the VTMX measurement site, whence intermittent peaks of PM_{10} are observed. Hypotheses were 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 test site. These hypotheses are yet to be tested.

Unlike in evening transition, a delayed <u>morning</u> transition, by as much as ½ - 1 hr, was observed at the lower sonic (4.9 m level). This phenomenon is caused by the generation of up-slope flows at lower elevations prior to that of the measurement location; this flow streams over the weakening katabatic current at the measurement location. The PM_{10} concentration begins to increase prior to the morning transition, which was attributed to aerosols being advected into the Wasatch mountain range by return westerly flows aloft at night.

Based on laboratory experiments, novel mechanisms were identified for the cold-pool destruction in air basins. The break up appears to be realized by the combined influence of along-slope flow, horizontal intrusions emanating from the slope flows and entrainment of these intrusions into the growing bottom convective boundary layer. A dimensionless parameter was derived that help delineate the dominant mechanism for a given set of background conditions. VTMX field data could be interpreted in light of these laboratory observations.

The ASU group also participated in the SUNRISE-2001 experiment conducted by the DOE in June 2001, with the focus of studying ozone distribution in the nocturnal and morning-transitional planetary boundary layer (PBL) of the Phoenix valley. The ground level ozone as well as mean meteorological variables and turbulence were measured over the entire period, and vertical profiling (using a tethered balloon) was made during the morning transition period. Approximately half of the observational days showed the usual diurnal cycle of high ozone during the day and low ozone at night with nitrogen oxides (NOx) showing an out-of-phase relationship with ozone. The rest of the days were signified by an anomalous increase of ozone in the late evening (~ 2200 LST), concomitant with a sudden drop of temperature, an enhancement of wind speed and Reynolds stresses, a positive heat flux and a change of wind direction. NO_x measurements indicated simultaneous arrival of an “aged” air mass, which was corroborated by the predictions of the MM-5 meso-scale numerical model. In all, the results indicated the recirculation of high ozone laden air masses, produced in the city and transported by upslope flow to the mountainous suburbs during the day and return back to the city at night *via* down-slope winds (mountain breeze). The vertical profiling of ozone and flow variables during the morning transition points to a myriad of transport, mixing and chemical processes that determine the fate of ozone near the ground. How well such processes are incorporated and resolved in predictive ozone models is key to the accuracy of their predictions.

The analysis of data taken during the first Phoenix Air Flow EXperiment (PAFEX-1) were continued to obtain further information on VTMX processes. The purpose of PAFEX-1 conducted during winter 1998 was to study the interactions of thermally driven flows of different scales and origin to gain an understanding of the transport and dispersion of contaminants during transition periods and at night. The Phoenix airshed is characterized by a large nearly flat plain to the west and mountains to the north and east. Local thermally driven winds concomitant with the absence of significant synoptic pressure gradients dominate typical winter conditions in the Phoenix valley. Measurements were made using a tethered balloon, sonic anemometer, balloon-based aerosol sampler, radiation sensors, cup anemometers, thermistors and humidity sensors in conjunction with data collected from 44 meteorological stations located throughout the valley. The general flow patterns were diurnal, but the details of the flows varied substantially. The measurements were consistent with the notion that the evening transition is associated with the formation of a stagnant front, followed by intense mixing and the movement of the front to establish down-slope winds. Flows originating from different slopes led to the arrival of fronts at various measurement locations at different times. These flows have different length and time scales, and intrude into the valley and interact with each other, often causing multi-layered vertical structure. The intrusions respond to the evolving stratification and cause striking variability of these layers, for example, periodic wind and temperature disturbances corresponding to the arrival of new intrusive fronts. Simultaneous analysis of Phoenix air pollution data collected by the Arizona Department of Environmental Quality showed that the morning transition has a direct bearing on the pollution episodes in the Phoenix airshed.

The analysis of Phoenix airshed data was extended to include some surface observations taken prior to and after the PAFEX-1 campaign. The results showed how the spatial distribution of near surface temperature, dew point, and winds in the evening transition period for weak synoptic winds is affected by the variation of slope and land cover in the wide desert-city valley of Phoenix. The evening transition was found to have three main features: unsteady-local stagnation and overturning events within 10 m of the surface; continued weak upslope flows persisting 3 to 5 hours after sunset with the sidewalls of the valley preventing Coriolis-induced turning of the winds; and the transition to downslope gravity currents (2 - 3 m/sec) on the lower slopes after the down-slope flow emanating from higher (steeper) slopes. When these currents are moderately strong they modify the pattern of local radiative cooling determined by land use and relief variations, for example, carrying cooler desert air into the outlying suburban urban fringe zones. The evening transition processes were found to affect major stations used for climate assessment in the Phoenix area.

The theoretical component of the research program also consisted of the analysis of down-slope and up-slope flows as well as evening transition periods using simplified terrain configurations (i.e. uniform simple slope). By employing assumptions on the flow structure and using parameterizations for pertinent processes an expression for the layer-averaged katabatic flow velocity was derived. Using energy arguments to calculate the growth rate of the katabatic-layer thickness, a new expression for the flow depth was obtained. Extensive comparisons between theoretical results and field observations were made, allowing cross-fertilization between theoretical developments, eduction of flow physics and interpretation of field data. Unsteady effects pertinent to katabatic flows were considered, following Fleagle's approach, and it was shown theoretically and using observations that the down-slope flow pulsates with a period inversely proportional to the background stratification and the slope angle. In concurrence with the theoretical analysis, the down-slope flow in two VTMX field sites was found to pulsate with a longer period on a gentle slope (70 to 130 minutes) and a shorter period on a steeper slope (20 to 50 minutes).

The work conducted on the morning transition was mainly laboratory experimental, wherein a V-shaped basin was used to study the morning inversion break up phenomenon. The working fluid (water) contained in the tank was initially stably stratified (thermally) with a pronounced inversion layer. Bottom heating with a specified heat flux was initiated and dye visualization, temperature and velocity measurements (Particle Tracking Velocimetry) were used to monitor the flow field. It was found that, at larger values of the parameter B = (N**2)(H**3)/q (buoyancy frequency N, inversion depth H, buoyancy flux q), cold pools are destroyed by the combined influence of along-slope flow, horizontal intrusions emanating from the slope flows and entrainment of these intrusions into the growing bottom convective boundary layer. This scenario is different from the previously held view of cold pool destruction by Whiteman (1982, 1990). Field data taken during the VTMX field campaign were interpreted in light of laboratory observations.

Turbulence generated under nighttime stably stratified conditions is patchy and intermittent in time, yet it plays an important role in VTMX processes. In order to gain an understanding on how such turbulence patches interact with background shear, a laboratory study was conducted by generating an isolated turbulent patch within the sheared interface between two counter-flowing fluid layers of different densities. This flow configuration permitted investigations of stratified shear flows with $Ri > 1$, where Ri is the gradient Richardson number. The turbulent patch was generated within the interface by an oscillating grid. The measurements in the presence and absence of shear under otherwise identical forcing and stratification conditions showed that the background shear significantly increases the patch size when Ri approaches 1. This observation is consistent with the theoretical results that turbulence within a patch can interact with mean shear and enhance turbulence production when $Ri = Rc$, where $Rc = O(1)$ is a critical Richardson number, and that below $Ri \sim 1$ shear across the patch boundaries can enhance local mixing. Both of these mechanisms can increase the size of a sheared turbulent patch beyond its mean shear-free counterpart. The opposite is observed at $Ri > Rc$, where gravitational collapse compounded with deformation by background shear causes a decrease of the patch size. The results suggest that strong Ri dependence should be accounted for in modeling VTMX processes under nighttime conditions.

The numerical component of research consisted of the application of the mesoscale meteorological model MM-5 to the Salt Lake basin to map the flow and turbulence structure as well to implement a new semi-empirical turbulence parameterization derived using the VTMX data (Monti et al. 2002). Eddy diffusivities were parameterized using two approaches: the dimensional eddy diffusivities as a function of Ri (Modification 1) and those normalized using the variances of vertical velocity and vertical wind shear as a function of Ri (Modification 2). In the new parameterization scheme the heat diffusivity is computed independently as a function of Ri, unlike other customary PBL schemes such as the Blackadar and the MRF schemes that set heat diffusivity equal to or a fixed fraction of the momentum diffusivity. Both new parameterization schemes showed a better agreement with observations than conventional schemes, in particular, for the near -surface temperature predictions.

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