Vertical Transport and Mixing in the Salt-Lake Basin

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1. INTRODUCTION

A month-long meteorological field campaign VTMX (Vertical Transport and MiXing), sponsored by the Department of Energy's Environmental Meteorology Program, was conducted during October 2000 in the Salt Lake Valley to perform complex investigation of vertical transport and mixing in the atmospheric boundary layer (ABL) [1]. Approximately 100 people from 9 research laboratories and two universities, including ASU, performed extensive meteorological measurements at twelve different locations in the vicinity of the Salt Lake City (SLC). The main goal of the experiment was to improve our understanding on meteorological processes characteristic of complex terrain surrounding urban basin and valleys. Such an improved understanding is necessary to develop and benchmark numerical models that are used to predict transport of air pollutants in these regions.

Our VTMX-based research program paid particular attention to 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. The evolution of nocturnal boundary layer as well as evening and morning transitions that occur before and after the nocturnal cooling period play an important role in micrometeorology and contaminant dispersion in complex terrain airsheds. The heating and cooling of near-slope air lead to up-and down-slope winds that are central to the understanding of circulation patterns in complex terrain basins, such as those found in sun-belt cities of the southwestern US. In the late afternoon, the ground cooling causes dense air layers to develop near the ground, which become unstable on slopes and drain downslope to pool in basins. As stable stratification develops in basins due to such pooling, slope flows intrude into the stratified layer at their equilibrium density level. Since the strength and density of flows originating at different slopes and valleys have different densities, directions, speeds and the structure of these flows in air basins tend to be complex, and thus form a skewed stratified shear flow, with changing wind speeds and directions with changing altitude. These layers can be well distinguished from the diversity of aerosols trapped in these layers, the origin of which can be traced to far and near field sources.

In this paper we describe our measurement program conducted during the VTMX field campaign performed in SLC, Utah during October 2000. A large amount of detailed data was collected on temperature, wind and aerosol concentration at a field site located at the west slope of the valley.

The days of the three-week duration of our measurements could be separated into four different periods of weather conditions, allowing generalization of measurement conditions. The collected data are correlated with additional information available from over twenty meteorological surrounding stations. Typical characteristics of the valley wind circulation corresponding to the above weather categories were identified and were investigated. Our attention is primarily focused on the effects of the periodic evening/morning transitions, pollutant transport and distribution in the airshed and vertical mass transfer due to turbulent mixing.

2. ASU SITE DESCRIPTION

The ASU field study was conducted during 1 - 18 October 2000 period. The ASU site (ACS) was located in the northeast part of the Salt Lake Basin about 1410m above the mean sea level (MSL), on a field adjacent to the Mt. Olivet Cemetery. The site is bordered by the Oquirrh Mountains (and Salt Lake City) to the west and Wasatch Mountains to the east. The downtown metropolitan area is located about 10km away, in the northeastern part of the Salt Lake Valley. The two mountain ranges from the east and the west confine the valley, creating ideal conditions for studying up- and down-slope convection. Thermally driven mountain and lake circulations develop during periods of weak synoptic forcing. The higher terrain surrounding SLC (up to 2300m above MSL) contributes to the formation of stable nocturnal cold pools each night with downslope and canyon flows affecting the site. The ASU site (ACS) was located at the east slope with gentle inclination of about 0.07, only 10km to the first high mountain peaks. In the direct vicinity of the site there are three canyons, firmly modifying the wind pattern. The City Creek Canyon at the north side of the city influences wind patterns from the north. Red Butte Canyon sits to the northeast side of the site with its mouth ending near the site. The wind direction observed at the site usually indicates flow from or to this canyon. To the east, the massive Emigration Canyon modifies wind patterns in the southern region of the site. Our measurements were made in a grassy open area, about 200m away from trees and small buildings to avoid interference of obstacle wakes. Estimates show that the urban heat island associated with SLC and the lake breeze of the Great Salt Lake do not affect the nocturnal winds at ACS.

The meteorological instruments used by the ASU group consisted of a 14m mast equipped with two 3-cup anemometers (Met One Instruments, Inc., starting speed $0.5ms^{-1}$, accuracy ±1.5%), mounted at 2.0m and 7.3m above the ground level; two thermistors placed at 1.8m and 6.9m (accuracy ±0.1K); two spectral pyranometers (Eplley Lab, Inc) at 3.0m, one upward facing for incoming radiation and one downward facing for outgoing ground radiation (sensitivity $4 \cdot 10^{-6}$ V/Wm^2, response time 2s). A Data Logger (OM-220 Omega Tech) provided computation and storage of 5 mts-averaged air temperature, wind speed and radiation. Two ultrasonic fast-response anemometers-thermometers (Applied Technologies, Inc. & Metek GmbH) placed at 4.5m and 13.86m were used to measure the velocity components (U positive along W-E direction, V positive along S-N direction and vertical component W positive when directed upward; resolution and accuracy: $0.01ms^{-1}$and $\pm 0.05ms^{-1}$), the wind direction (measured clockwise, N taken as 0°) and the air temperature T (resolution and accuracy: 0.01°C and ±0.05°C) at 10Hz repetition rate. DustTrack (model 8520 TSI) and TEOM located at 2.5m, about 10m from the mast were used for aerosol measurements. The above instruments were run continuously during the entire 18-day period delivering main collection of the data (about 40Mbytes/day).

In order to analyze the vertical structure of the lower atmosphere, two tethered balloons (Atmospheric Research Inc. TSB-9, 9m^3 balloon) carrying 4 tethersondes (TMT-5A-SP, Vaisala), DustTrack and “home-made” streaker were used to measure the air temperature, relative humidity, pressure, wind speed and direction, and aerosol concentration. The resolution and accuracy of tethersonde measurements are as follows: temperature (0.01°C, ±3%), humidity (0.01%, ±3%), pressure (0.01mb, ±1mb), wind speed (0.1ms^{-1}, ±0.5ms^{-1}), and wind direction (0.1°, ±10%). The tethered balloon measurements were performed during periods of intense observation (IOP) predefined for all research groups. During the VTMX campaign 12 IOPs were defined, each starting about one hour before sunset and ended the next morning about two hours after sunrise. ASU participated in five of them: IOP1 (10/2-3), IOP2 (10/6-7), IOP5 (10/14-15), IOP6 (10/16-17) and IOP7 (10/17-18).

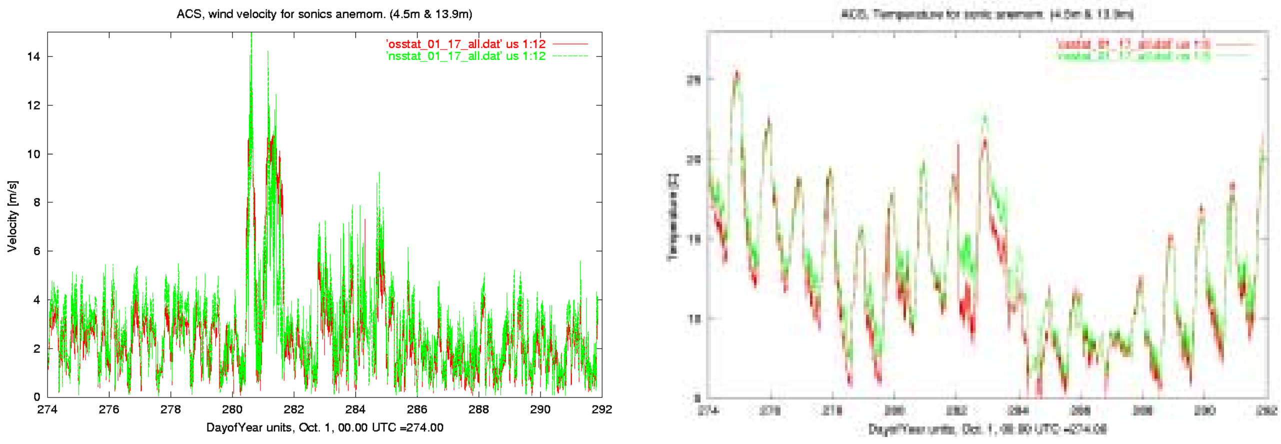
Weather conditions varied during the VTMX campaign, *viz.* low wind (5m/s), sunny and dry period (10/1-6); transition period with gusts up to 25m/s (10/6-8); partly cloudy with some precipitation and relatively strong winds of 15m/s (10/8-13); and stable with clear sky and low winds but relatively cold period (10/13-18). These four different weather conditions allowed us to capture the effects of morning and evening transition at low synoptic winds as well as dominant modulations due to traversing fronts.

3. OBSERVATIONS

In this section we provide a brief description of some of the observed wind, temperature and turbulence features found during our VTMX campaign. These provide typical conditions observed during transition periods with weak synoptic forcing and mostly clear skies. They also provide background information for detailed on-going investigations that will be described in future reports. More detailed analyses of data are still in their early stages, so we provide only examples of features that were observed. The full set of collected data is available in public domain for those who are interested [3].

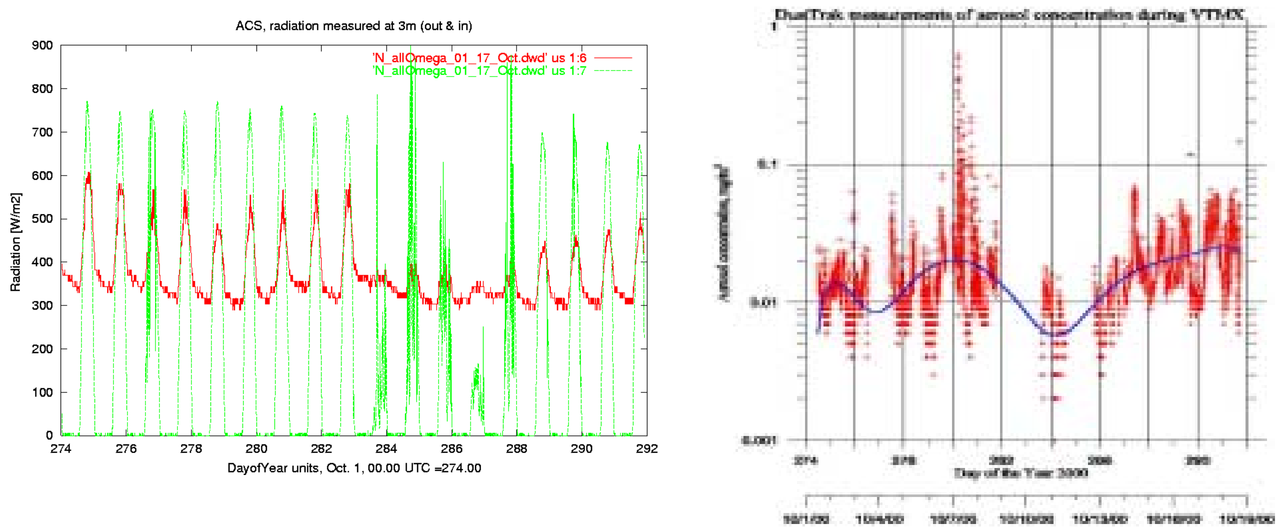
Figure 1 shows two time series of sonic velocity and temperature collected for the entire observational period. The data are collected at two altitudes (4.5m and 13.9m) at the meteorological tower and are averaged over a 5 min period. Here one may identify all of the aforementioned periods: initially calm winds, strong eruption of winds between 280.5 and 281.8 Julian day, short intermittent periods, medium winds with low temperatures for the fourth period and periods with stable conditions characterized by low nocturnal winds and temperatures. Very similar data were obtained for both cup anemometers and thermistors located at the 2m and 7m altitudes of the tower.

The incoming and outgoing radiation measured by two pyrometers at 3m show typical fluctuation of energy flux following sunrise and sunset sequence. Strong effects of solar radiation, up to 800 W/m^2 during sunny days, and relatively steady nocturnal outgoing radiation (around 350W/m^2) characterize the radiation time series (Fig. 2a). Strong pulsations of incoming radiation during cloudy days (285-287 Julian day) were also observed, eliciting typical amplification effects due to secondary light reflections from clouds.



a b

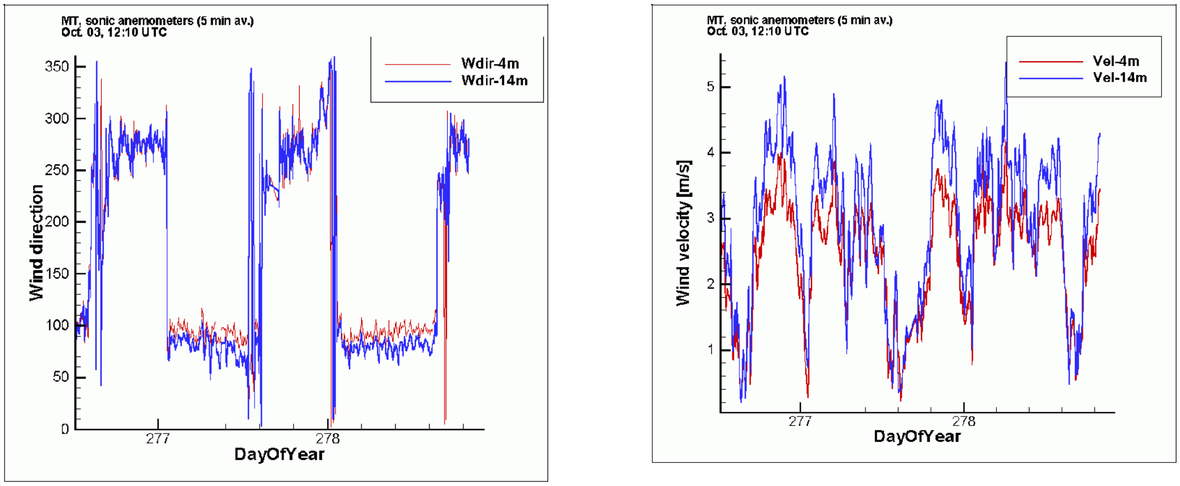
Fig. 1. *Wind velocity (a) and air temperature (b) measured at two altitudes (4.5m & 13.9m) at the meteorological tower, 5 mts averages.*



a b

Fig. 2. *(a) Solar (short wave) and outgoing (long wave) radiation recorded at the meteorological tower for the entire period of the experiment. During this period the sunrise and sunset time changed from 13:24/01:09 UTC for Oct. 1 to 13:43/0:42 UTC for Oct. 18; (b) Aerosol concentration recorded by DustTrack for the entire period of the experiment.*

Airflow patterns over uneven surfaces usually differ from those of synoptic winds of higher altitudes, in part due to buoyancy forces inducing up- or down-slope flow of air. The sun's radiation penetrating into the valley during morning hours causes the growth of a surface convective layer of air. Due to the inclination of the surface, the tangential component of buoyant forces causes almost instantaneous onset of the up-slope (anabatic) motion of the warm air (and down-slope motion during nights). Regular variations of wind direction, with sharpest changes just after sunset, and about 1 hour after sunrise are shown in Fig. 3a. The horizontal velocity decreases almost to zero when transition commences (Fig. 3b). The vertical velocity component appears to follow strictly a kinematic relation, being positive for the uphill flow and changing sign during nocturnal downhill flow. Concentration of measured aerosols (Fig. 2b) follows these variations, increasing during the day (wind from the polluted city) and decreasing during nights (due to up-slope air).



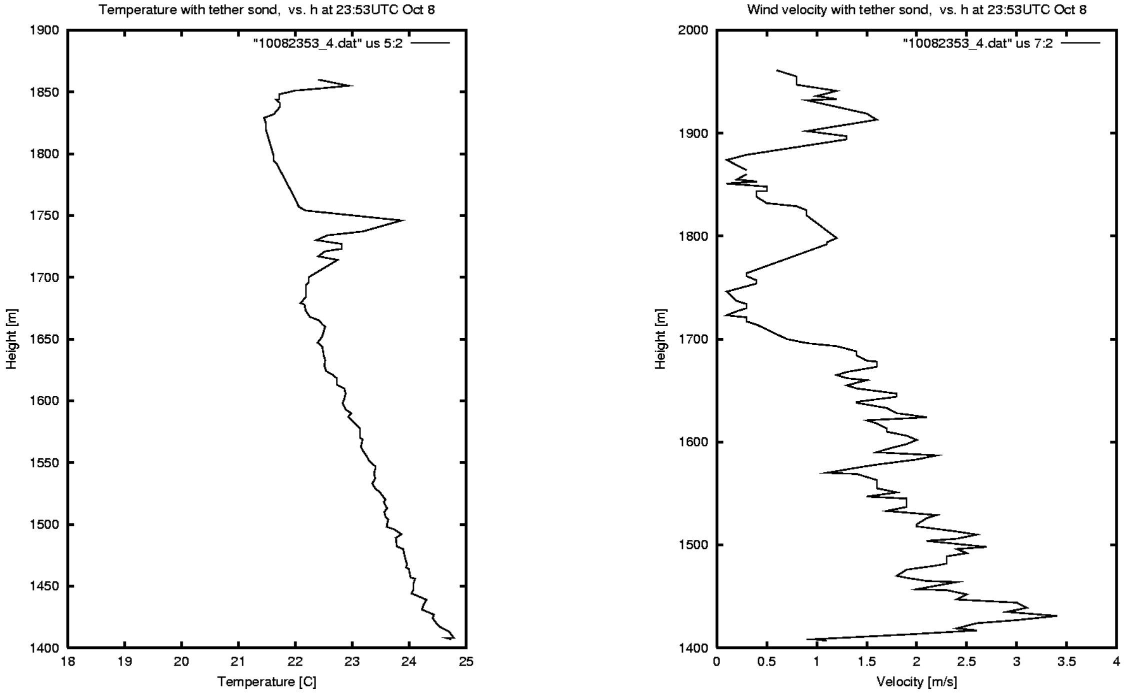
a

b

Fig. 3. *The variation of wind direction (a) and velocity (b) during anabatic - katabatic flow transitions. Transition takes place almost exactly during sunset (0.04 Julian day) and sunrise (0.55 Julian day).*

The atmospheric boundary layer is typically turbulent, which was apparent in all measurements. The mean wind speed, air temperature and humidity varies following the diurnal cycle. The fluctuations of the amplitude of these quantities depend on several factors. Large eddies and billowing with scale over 100m appear as low frequency oscillations with typical period of 20-50 mts. Small-scale turbulence, especially in the mixing regions of the surface layer, characterizes a time scale of several seconds. Typical diurnal temperature fluctuations recorded with a sonic anemometer (10Hz sampling rate) show relatively high amplitude during the daytime, a sudden decrease during the evening transition, and relatively low levels at night. When the surface thermal boundary layer starts to grow, large amplitude daytime fluctuations appear again. A similar characteristic is evident for all velocity components. Temperature profiles indicate that the air layer is strongly stably stratified by katabatic flow; it inhibits turbulent mixing, allowing sustained large velocity shears between different layers during nights.

The presence of layers of different densities and velocities, stacked one above the other, is particularly striking in the urban air basin where katabatic flows from slopes of different orientation can intrude into the basin. These layers flow one layer above the other in different directions at their neutral density levels [2]. Fig. 4 demonstrates such multi-layered structure recorded by a tethersonde at ACS. It can be seen that close to the surface the temperature profile exhibits a negative lapse rate ($-0.01^{o}C/m$) characteristic for the unstable daytime atmosphere. Close to the surface the anabatic wind (Fig. 4b) shows a maximum at about 30m above the ground. At a higher altitude, two relatively sharp jumps in the temperature curve can be found (Fig. 4a). It appears that at approximately 1750m and 1880m there are two layers of air where the temperature is about $1^{o}C$ higher than above and below. The relatively thin layer of warm air at 1750m is transported in the down-slope direction, whereas at lower and higher elevations up-slope anabatic flow still prevails. This type of layering was observed during the evening transition as well as during nocturnal experiments.



(a) (b)

Fig. 4. *Typical temperature (a) and velocity profile (b) measured just before evening transition: Oct 8, 23:53 UTC; flow layers at 1750 m and 1880 m*

4. SUMMARY

The collected data clearly illustrated an up-slope (anabatic) flow during the day (100-500m thick) and down-slope (katabatic) flow at night, both having magnitudes approximately 4m/s. The thickness of the katabatic flow decreased with increasing synoptic winds, and observed winds vary from 15 to 50m in altitude. The wind speeds during the morning and evening transitions were small and highly variable. Sonic anemometers located at 4.5m and 13.86m indicated that the evening transition of most of the days occurs at both levels simultaneously. A delayed morning transition, as much as ½-1 hr, however, was observed at the lower sonic. Measurements suggest that the up-slope flow generated at a lower elevation above the weakening katabatic flow at the measurement location is responsible for this phenomenon. 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 different 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 the other.

REFERENCES

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