4.5 EVENING TRANSITION IN INLAND AND COASTAL MOUNTAINOUS TERRAIN

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1. INTRODUCTION

Although the thermal circulation (slope/valley flows) in complex terrain has been well studied, especially the down-slope/valley flows, the dynamics of transitional flows between up and down slope flows (evening transition) and *vice versa* (morning transition) are still being delineated. During the VTMX Program (Doran et al. 2002) we have conducted theoretical (Hunt et al. 2003; Princevac et al. 2008), numerical (Lee et al. 2006) and laboratory (Princevac & Fernando 2008) studies on complex terrain flows, and proposed several morning and evening transition mechanisms. The latter occurs via the formation of a stagnation front during cooling of the ground, wherein overturning motions and strong turbulence are prevalent, whence turbulent entrainment of fine dust causes high particulate matter (PM) concentrations in the atmosphere (Fernando 2010). Verification of this prediction was the aim of an experiment conducted in the Phoenix area, TRANSFLEX-2006 (Transition Flow Experiment), which will be briefly described below. With respect to morning transition, three major mechanisms of cold pool (stagnant stable boundary layer in basins) destruction involving convective boundary layer growth and upslope flow formation were proposed by Whiteman (1990, 2000), and an additional mechanism embodying intrusion formation has been proposed by Princevac & Fernando (2008). While field and numerical experiments adumbrate this fourth mechanism, further direct verification of it is warranted. Transition from down to up slope flow over a simple slope is yet to be studied experimentally.

The complexity of slope/valley flows is increased by coastal effects, understanding of which is meager and on which only a few studies exist. The presence of an urban area in the valley increases the complexity still, on which there is no existing literature to our knowledge. Pressure gradients due to differential heating and cooling between the ocean, land and urban areas may cause a delay of evening transition as well as a rapid morning transition, allowing more pollution to build up during the evening rush hour. The thermal circulation in coastal cities is the topic of the Meteo-Diffusion experiment summarized below. This was conducted in the Biferno Valley of eastern Italy and was coordinated by the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA: Principal scientists - Giovanni Grandoni and Maria Cristina Mammarella) and Consorzio per lo Sviluppo Industriale della Valle del Biferno (COSIB).

2. TRANSFLEX-2006

2.1 *Site and Instruments*

The experiment was conducted between the 7th and 17th of January 2006 to capture and observe the evening transition as it moves down the mountain slopes of Phoenix from the eastern slopes to the central city area (Fig. 1). The valley represents the Salt River Basin (with river bed running east to west) that originates in approximately 2200 m tall mountains to the northeast. The quick drop from the mountains results in Phoenix having an elevation of approximately 320 m. As part of the Colorado Plateau, these mountains span the greater Phoenix area to the north and east. The smaller Sierra Estrella Mountains of the South Mountain Preserve encircles the valley to the south. Because of the preponderance of sloping terrain to the east and northeast, the smaller mountains are usually considered as unimportant for the local meteorology of the valley (but this was not found to be the case). Two special measurement sites — Mountain View High School (MVHS) (33°26’14” latitude, -111°43’59” longitude; slope ~ 0.3°; elevation 392 m) located in Mesa, Arizona and another in south Phoenix (PHX) (33°24’22” latitude, -112°08’40” longitude; slope ~ 0.1°; elevation 314 m) — were selected for evening transition observations, and were outfitted with a host of fast-response in situ as well as remote sensing instrumentation. Each instrumentation set included a sodar, a tethered balloon with two sondes, a PM analyzer and an instrumented 12 m flux tower (with three ultrasonic anemometers at 3.4 m, 7.6 m and 11.8 m AGL; a krypton hygrometer; a finewire thermocouple at 3.4 m; a net radiometer; an IR

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thermometer; a soil heat flux plate; and soil thermistors). Further information is given in Verhoeff (2006).

2.2 *Results*

Since the presence of multiple mountain ranges complicated the flow at PHX, only the results from MVHS are described here. Fig. 2 shows the (a) wind components, (b) temperature and (c) the wind direction measured at 11.8 m and/or 3.4 m. Note the change of wind direction at 17:49 LST at the 3.4 m level and 17:53 LST at the 11.8 m level. Associated with the wind shift is a flow stagnation (Fig. 2a), an increase in the temperature at 3.4 m, indicating the "paint stripper" effect and a decrease of temperature at the upper levels. This indicates the arrival of a trailing current. These observations are in good agreement with the theoretical predications of Hunt et al. (2003). The difference in the time of arrival at the two levels is an indication of the sloping nature of the front. The typical slope (nose) angle of the front is between 15-20°.

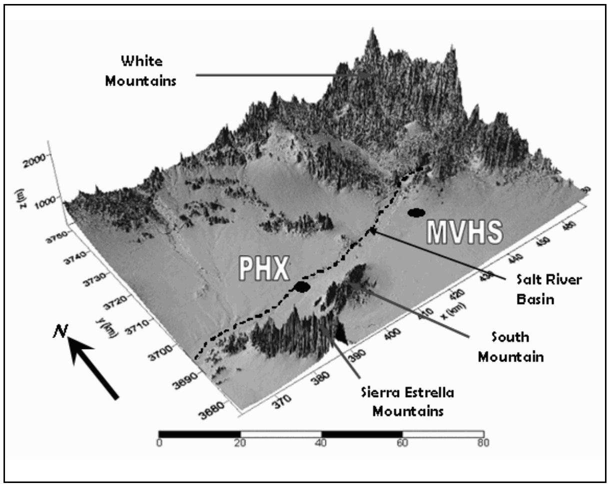

Figure 1*:* Three-dimensional representation of the Phoenix valley showing the two measurement sites. Axes are in UTM (Universal Transverse Mercator) coordinates, zone 12.

To illustrate small-scale processes occurring behind the transition front, the temperature and 10-s averaged heat flux are shown in Fig. 3. The example selected concerns the 7.6 m level, which is representative of other levels studied. As the front passes by the probe, it feels rising colder air $(\overline{T'w'} < 0)$ behind the front (indicated by A); also note the temperature, which begins to drop, is affected by the overturning of an eddy and cold air falling $(\overline{T'w'} > 0)$ (indicated by B). The turbulence so generated causes warmer air entrainment from aloft, signified by $(\overline{T'w'} < 0)$ at C, followed by rise of this warm air again (at D $(\overline{T'w'} > 0)$). Cooling continues, with trailing colder fluid now arriving at the probe and mixing with fluid above the gravity current, leading to a drop in temperature. Entrainment of warmer air from the top causes intermittent bursts of warm air to arrive into the gravity driven flow behind the front. Mixing and overturning thereafter causes flux oscillations (indicated by E), interspersed by intermittent injection of warmer air due to entrainment events $(\overline{T'w'} < 0)$ or falling of colder air $(\overline{T'w'} > 0)$ caused by convective instability.

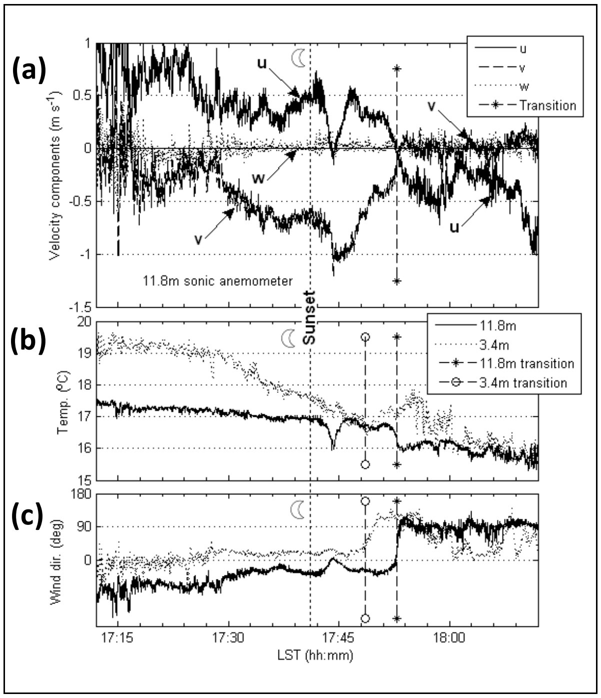

Figure 2*:* Raw data from 12 January 2006, MVHS showing time series plots of (a) velocity components at 11.8 m, (b) temperature at 11.8 and 3.4 m, and (c) wind direction at 11.8 and 3.4 m during the time of evening transition. Time of sunset is shown in the figure, which occurred at 17:41 LST.

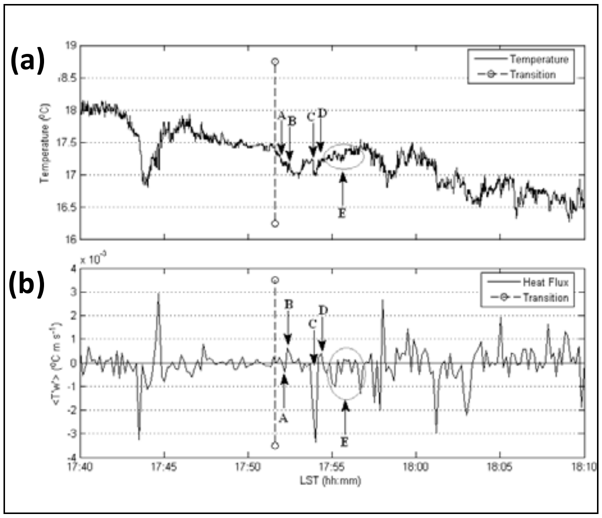

Figure 3*:* Thirty-minute time series comparing (a) temperature (raw data) and (b) heat flux (10-s average) at 7.6 m AGL. Shown is the first transition observed on 12 January 2006 at MVHS. An explanation of features A-E is given in the text.

3. METEO-DIFFUSION

3.1 *Site and Instruments*

High frequency (20 and 50 Hz) flow and sonic temperature measurements were obtained during an intense 10-day campaign (1 – 10 July 2009) using ultrasonic anemometers, which recorded the three components of velocity and virtual temperature. They were placed at three sites in the lower part of Biferno Valley (Fig. 4a; blue box). The measurement section is about 2 km wide (along the northwest - southeast direction) and its longitudinal extension is about 6 km from the Adriatic Sea, with a slope of ~ 0.5°; Fig. 4b shows an enlarged map of the experimental sites and Fig. 4c gives the relative positions of the four anemometers. This segment of the valley is characterized by industrial plants, built areas and vegetation, and the proximity of the study area to the ocean causes the thermal circulation to exhibit some interesting dynamics. Meteorology of the area was available from Aereonautica Militare weather station in Termoli city. When (roughly) estimating the ocean-land pressure gradients, $(\partial p/\partial x)_{OL}$, hourly data of air temperature from the Termoli station were used to obtain the marine air temperature T_S (Fig. 5). The campaign days were mainly dominated by high pressure and weak synoptic forcing.

3.2 *Phenomenological Description*

The marine and urban atmospheres juxtaposed along the Biferno valley (Fig. 6) trigger local thermal circulation patterns that are more complex than those have been reported previously. This is illustrated in the schematic of wind speed and direction time traces in Fig. 7. In the early morning, the effect of the urban heat island (UHI) at site B is negligible or absent while the negative pressure gradient $(\partial p/\partial x)_{OL}$, which is usually responsible for sea breeze, decelerates the already subsiding katabatic flow and leads to a sharp morning transition (indicated by *α* in Fig. 7).

In the early-mid afternoon, the UHI begins to amplify, which is signified by an increase of upslope winds. This is because of the strong along-valley temperature gradient that exists as a result of the land cover variation (Fig. 6) and the overall shoreward pressure gradient $(\partial p/\partial x)_{UHI} < 0$ in this locality due to the UHI. The combined effects of $(\partial p/\partial x)_{UHI} < 0$ and the ocean-land pressure gradient greatly influence the circulation in the afternoon and evening (after cooling starts; when $(\partial p/\partial x)_{OL} > 0$), leading to modification of the mechanism of evening transition. In fact, the evening transition is now driven by a composite effect of ground cooling (aiding transition), $(\partial p/\partial x)_{OL} > 0$ (aiding transition) and $(\partial p/\partial x)_{UHI} < 0$ (adverse). As such, the transition period in coastal areas is longer than what is typical for over inland.

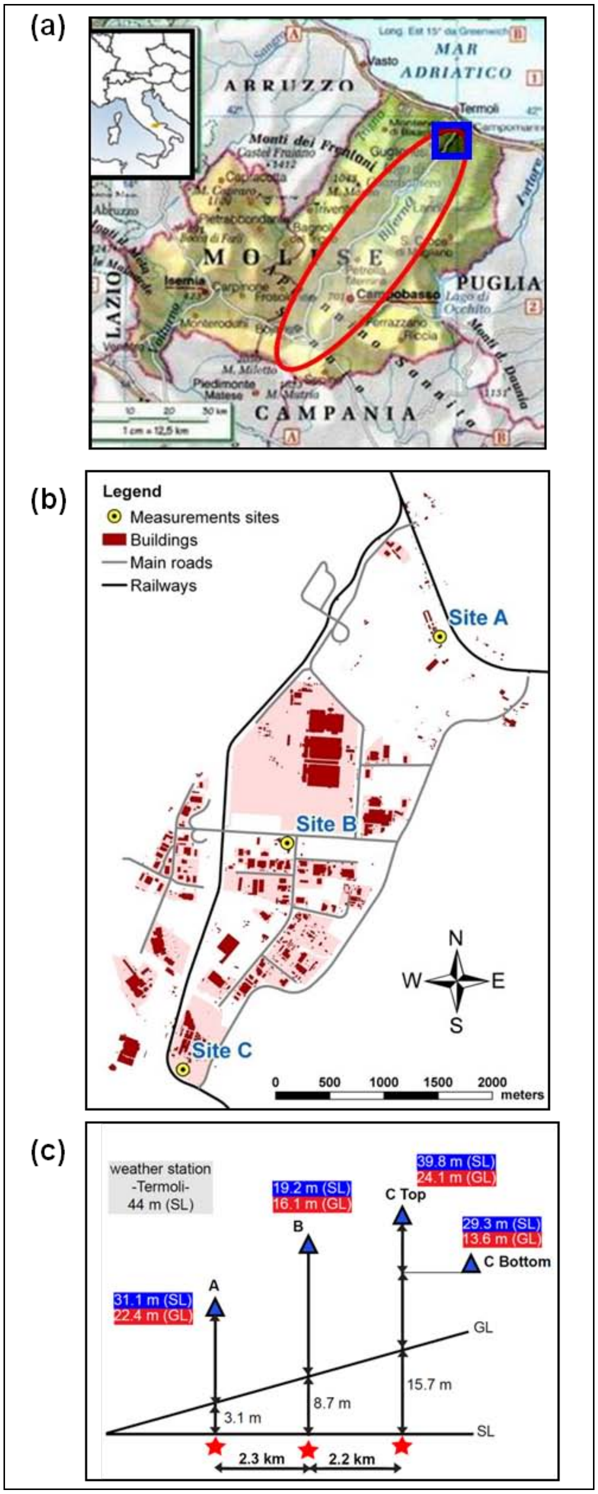

Figure 4: (a) Geography of the Biferno Valley region (marked in red). The area in the blue box represents the lower part of the valley considered in this study; (b) building footprints and measurement sites; (c) sea and ground level instrument elevation. Site C has two measurement levels.

3.3 *Results*

Fig. 8 summarizes main features of flow patterns in the Biferno Valley derived from the four sonic anemometer measurements taken during weak synoptic conditions and clear skies (Julian days (*Jdays*) 182-185). Time series of streamwise wind velocity (*U*), virtual temperature (*T*), wind direction (*WD*) and sensible heat flux (H_o) based on 20-min averages are plotted. Repeated diurnal patterns are evident. The analysis of *T* in Fig. 8b effectively highlights the existence of a horizontal temperature gradient along the valley mainly due to higher *T* at site B for most of the day (UHI). At the same time, *U* trends in Fig. 8a show expected deviations from a "pure" thermally-driven flow inland, as anticipated from above discussions (in Section 3.2).

During morning transition an abrupt drop of U to about 0.5 - 1 m/s was recorded simultaneously at all sites around 7:00 - 8:00 am, which is accompanied by the *WD* shifting from down to up valley. The rapidity of this wind shift was due to the ocean-land pressure gradient $\left(\partial p/\partial x\right)_{OL} < 0$, which increases after sunrise, leading to a rapid deceleration of katabatic flow and an initiation of anabatic flow (Fig. 8a). The initial northward alignment of flow during the transition period until 9:00 - 10:00 am confirms the presence of favorable forcing until mid morning (Fig. 8c). After that time, with heating of the ocean, the upslope flow becomes mainly driven by heating of the ground, as in Hunt et al. (2003). The *WD* aligns along the valley axis, and anabatic flow velocity is maintained at about 3 m/s at sites A and C, while it was about 4 - 4.5 m/s at site B.

This flow regime remains undisturbed until early to mid afternoon, when the ocean-land pressure gradient reverses sign $\left(\partial p/\partial x\right)_{OL} > 0$, leading to deceleration of anabatic flow (Fig. 8a). At the same time the UHI effect becomes pronounced as is highlighted in Fig. 9. This figure reports a virtual temperature differences between site B (urban-like) and the other two sites, and indicates a negative pressure gradient $\left(\partial p/\partial x\right)_{UHI} < 0$ that starts exacerbating in the early afternoon (signified by an isolated peak of *U* around 4:00 - 5:00 pm).

However, the effect of $\left(\partial p/\partial x\right)_{UHI}$ is soon moderated by the composite effect of (a) $\left(\partial p/\partial x\right)_{OL}$ that became larger around 5:00 - 6:00 pm and (b) ground cooling, as highlighted by very low values of H_o (Fig. 8d), and decreasing *T* (Fig. 8b) from 6:00 pm onward. This caused an unusually long period of evening transition, which is a resultant effect of ground cooling, UHI and land-ocean pressure gradient. As such, the evening transition for this case was characterized by (i) longer periods of stagnation flow (*U* < 1 m/s), (ii) simultaneous occurrence of flow stagnation at all three sites A, B and C, and (iii) low turbulence levels for the entire duration of stagnation.

Note that Fig. 8a shows a prolonged stagnation starting around 6:00 pm and persisting for 2 - 3 hours. The phenomenon was more striking at site A where *U* ~ 0.5 m/s. The initiation of a very slow katabatic flow can be identified by the reversing of *WD* that occurred around sunset (7:40 pm, UTC+1), while stagnation was still occurring. Note that no substantial differences between the sites A, B and C with regard to the time for stagnation and subsequent *WD* reversal.

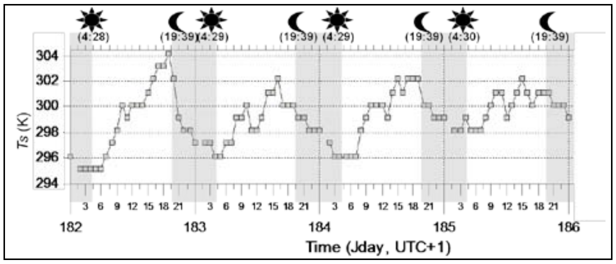

Figure 5: Time series of hourly temperature data recorded by the Aeronautica Militare weather station 16232. This was considered as representative of the marine air temperature.

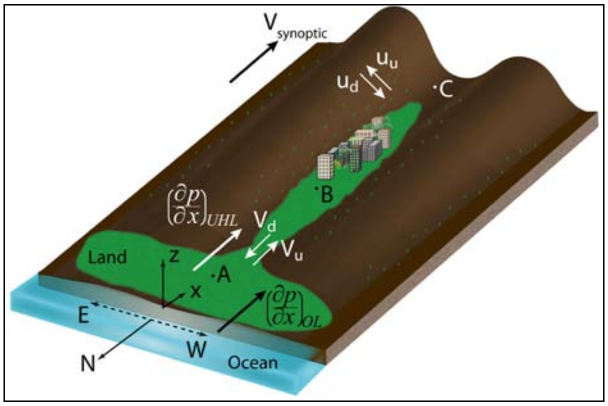

Figure 6: Schematic representation of a coastal valley with an urban site at some distance away from the coast

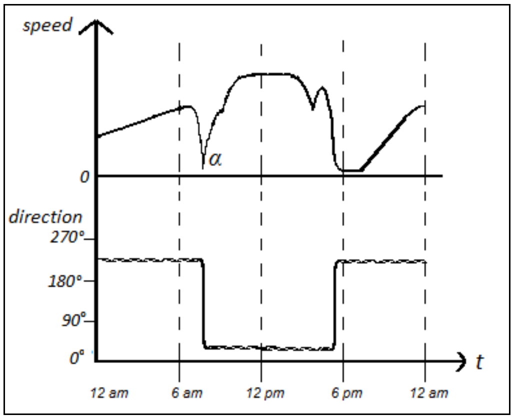

Figure 7: Schematic of the speed and direction time traces of thermal circulation affected by additional forcing mechanisms due to land cover inhomogeneities (ocean-land pressure gradient plus UHI effect)

This observation contrasts those made in non-coastal environments, such as that observed in TRANSFLEX, where evidence of a transition front propagating downslope/downvalley is observed (Section 2) and flow reversal at different locations occurs at different times (Brazel et al. 2005, Hunt et al. 2003, Monti et al. 2002).

Around 8:30 - 9:00 pm, the flow stagnation has been relaxed and the katabatic flow (U) develops gradually, and its full strength seems to occur at around 10:00 pm. This flow, however, never achieves a real steady state but rather progressively accelerates down valley to reach a maximum of about 3 m/s close to sunrise, maintaining it for about 2 - 3 hours in the early morning. The adverse $\left(\partial p/\partial x\right)_{UHI}$ that slowly decreases during the night, and the ocean-land pressure gradient $\left(\partial p/\partial x\right)_{OL}$ which returns to negative due to cooling of the ocean in the late night - early morning, may explain this trend, where nocturnal flow during most of the night is affected by adverse pressure gradients.

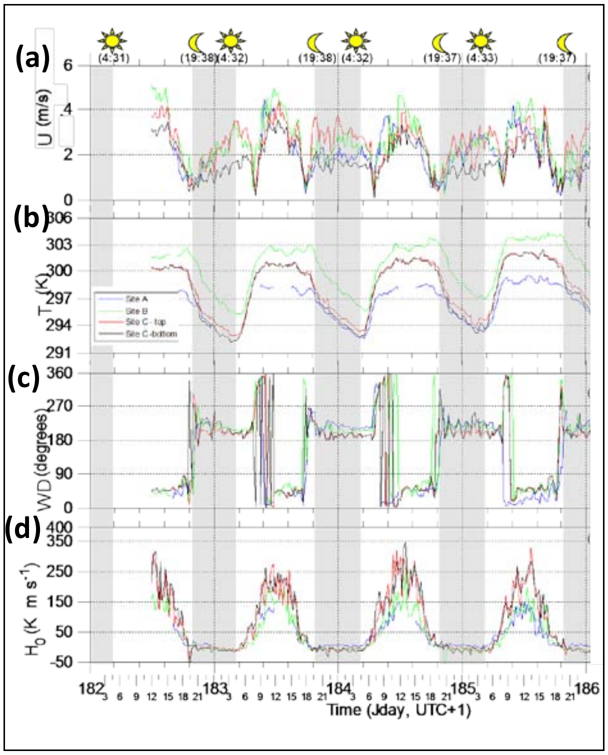

Figure 8: 20-min averaged (a) wind speed U (b) virtual temperature T (c) wind direction WD and (d) turbulent sensible heat flux H_0 from sonic anemometer measurements at locations A (blue), B (green), C (lower level in black, higher level in red). A is the site closest to the ocean. Flow circulation occurred under weak synoptic forcing conditions.

4. CONCLUSIONS

Evening transition observations at two geographically different locations were discussed in this paper, one site an inland site and the other a coastal site. At the inland site, the transition observations resembled the theoretical picture proposed by Hunt et al. (2003), where a stagnation front with strong overturning turbulent motions is formed at a given location, followed by a katabatic flow in lower layers while remnants of anabatic flow persist at high levels for a period of time. The initiation of katabatic flow occurs when the transition front starts moving downward as a gravity current. In coastal (urban) regions in complex terrain, however, the evening transition mechanism is modified by the presence of pressure gradients due to the urban heat island effect and ocean-land pressure (temperature) gradients. In this case, the transition occurs along the lower valley simultaneously and the flow stagnation lasts for several hours. This extended stagnation has implications for evening pollution that builds up in urban coastal valleys.

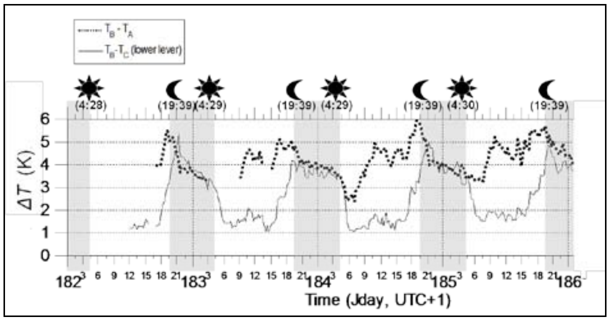

Figure 9: 20-min averaged virtual temperature differences ΔT between site B and A (T_B-T_A; dashed line) and the lower level of site C (T_B-T_C; solid line)

5. REFERENCES

Brazel, A. J., H. J. S. Fernando, J. C. R. Hunt, N. Selover, B. C. Hedquist, and E. Pardyjak, 2005: Evening transition observations in Phoenix, Arizona. *J. Appl. Meteor.*, **44**, 99 – 112.

Doran, J. C., J. D. Fast, and J. Horel, 2002: The VTMX 2000 campaign. *Bull. Amer. Meteor. Soc.*, **83**, 537 – 551.

Fernando, H. J. S., 2010: Fluid dynamics of urban atmospheres in complex terrain. *Annu. Rev. Fluid Mech.*, **42**, 365 – 389.

Hunt, J. C. R., H. J. S. Fernando, and M. Princevac, 2003: Unsteady thermally driven flows on gentle slopes. *J. Atmos. Sci.*, **60**, 2169 – 2182.

Lee, S. M., W. Giori, M. Princevac, and H. J. S. Fernando, 2006: Implementation of a stable PBL turbulence parameterization for the mesoscale model MM5: nocturnal flow in complex terrain. *Bound.-Layer Meteor.*, **119**, 109 – 134.

Monti, P., H. J. S. Fernando, M. Princevac, W. C. Chan, T. A. Kowalewski, and E. R. Pardyjak, 2002: Observations of flow and turbulence in the nocturnal boundary layer over a slope. *J. Atmos. Sci.,* **59**, 2513 – 2534.

Princevac, M., and H. J. S. Fernando, 2008: Morning break-up of cold pools in complex terrain. *J. Fluid Mech.*, **616**, 99 – 109.

——, J. C. R. Hunt, and H. J. S. Fernando, 2008: Quasi-Steady katabatic winds over long slopes in wide valleys. *J. Atmos. Sci.,* **65**, 627-643.

Verhoeff, B., 2006: Evening transition in complex terrain: the Phoenix transition flow experiment (TRANSFLEX). MS thesis, Dept. of Mechanical and

Aerospace Engineering, Arizona State University, 102 pp.

Whiteman, C. D., 1990: Observations of thermally developed wind systems in mountainous terrain. *Atmospheric Processes Over Complex Terrain*, *Meteor. Monogr.,* **23** (No. 45), Amer. Meteor. Soc., 5 – 42.

——, 2000: *Mountain Meteorology: Fundamentals and Applications*. Oxford University Press, 355 pp.