10.3 THE DECAY OF CONVECTIVE TURBULENCE DURING EVENING TRANSITION PERIOD

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1. INTRODUCTION

Local meteorology and dispersion of contaminants in the lower troposphere is greatly affected by turbulence in the atmospheric boundary layer (ABL). The structure and intensity of turbulence in ABL, in turn, is determined by the diurnal heating and cooling of the ground as well as flows driven by synoptic pressure gradients. During transition periods wherein the nature of diurnal forcing changes the flow becomes non-stationary and its structure becomes complex. Only a few studies have been reported on such periods, mainly because of observational, theoretical and modeling difficulties. The morning transition is typically defined as the time for the convective boundary layer (CBL) to grow to ~ 200m against nocturnal inversion. During the evening transition, a surface inversion is formed accompanied by the dissolution of the CBL. Numerous processes associated with transition periods have been identified and descriptions of them have been attempted (Atkinson 1981; Whiteman 1990, 2000), yet the state of understanding on such processes leaves much to be desired.

The transition in flat terrain is perhaps the simplest. During morning transition the nocturnal inversion gradually weakens due to warming, first becoming susceptible to turbulent erosion by shear-generated turbulence and then by the CBL turbulence. The evening transition initiates a few minutes to one hour before sunset and the dissolution of the CBL and the development of stable stratification is said to occur within minutes. LES studies carried out with impulsive removal of the driving heat flux from CBL have identified the time scale of decay as $\tau_d = h / w_*$ (Nieuwstadt & Brost 1986), where w_* is the initial convective velocity scale. If the heat flux is slowly decreasing with a time scale greater than w_* / h, then τ_d can be larger (Cole & Fernando 1998).

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Transitions in complex terrain are more complex and involve reversals of up and down slope/valley flows as well as evolution and dissolution of inversion layer and CBL. A limiting case is where the width of the valley is much larger than the height, whence some processes on the slopes and the valley can be considered approximately independent of each other and can be studied separately (Bader & McKee 1985). During evening transition, the mean flows are weak due to the switching of flow from up-slope to down-slope, and thus the decay of turbulence is expected to be not much different from that on flat terrain. In this paper, the evening decay of convective turbulence in complex terrain is studied using data taken during the Vertical Transport and Mixing eXperiment (VTMX) conducted in the Salt Lake City and the first Phoenix Air Flow Experiment (PAFEX-1). The aim is to document turbulence decay characteristics upon slow subsidence of solar radiation. A simple theoretical model is advanced to predict the decay process, and relevant decay time scales are identified.

2. EXPERIMENTS

The VTMX field campaign is described in Doran et al. (2002). The VTMX measurements analyzed here were taken at three locations: ASU Cemetery site in the east valley (latitude 40^o 45’ 11’’ N, longitude 111^o 50’ 55’’ W, 1410 m above sea level, slope 4^0), Shay’s Lounge (40^o 37' 25" N, 111^0 54' 50" W, 1330 m above sea level, at the valley bottom) and in a slope site (40^o 32’ 11’’ N, 112^o 00’ 47’’ W, 1466 m above sea level, slope 1.58^0) in the west valley. Because the measurements were made away from buildings and trees, the data can be considered as free from the immediate effects of obstacle wakes. The measurements taken by sonic anemometers were analyzed to evaluate the time decay of turbulent fluctuations, but the sites in point were instrumented with an array of meteorological instruments against which the measurements could be counter checked. Because the interest was on days with minimum synoptic influence, only Intense Observational Periods (IOP’s) with well-developed slope flows were used in the analysis. Although most IOPs took place from

1700 LST (2300 UTC) to 1000 LST (1600 UTC) of the following day, the sonic anemometer data were taken continuously. Data files were logged at 10 Hz on all three sites. The heights of sonics were 13.9 m for the ACS site, and 8.5 m for the Shay's Lounge and slope site.

The PAFEX-1 field campaign was conducted in the Phoenix metropolitan area during the period January 15 to February 1, 1998. Detailed measurements were carried out at the Grand Canyon University (GCU, 33^o 30.83' N, 112^o 7.82' W, 347 m above sea level, slope ~ 0.003), located in the central part of the valley approximately 9 km north-west of downtown Phoenix. From January 29 to February 1, turbulent measurements of sensible heat and momentum fluxes were also made with a sonic anemometer mounted on a mast at a fixed height of 9.5 m above the surface (Fernando et al. 2001). For flux and turbulence statistics, a 60-minute averaging time was employed. At ACS/VTMX and PAFEX-1 sites, the short wave and net radiation, soil heat flux and temperatures, and barometric pressure were also recorded (Monti et al. 2002).

3. THEORETICAL CONSIDERATIONS

In the absence of significant mean winds, the turbulent kinetic energy (k) decay can be written as

$$\frac{\partial k}{\partial t} = \overline{b^{'} w^{'}} - \varepsilon , \qquad (1)$$

where $\overline{b^{'} w^{'}}$ is the buoyancy flux and ε the dissipation. If the decay of k occurs in a series of quasi-steady steps, and if the bottom buoyancy flux changes as *Q(0,t),* the distribution of buoyancy flux with height (z) at a time t is given by

$$Q(z,t) = Q_o(0,t)\left[1 - \frac{z}{H}\right], \qquad (2)$$

where $Q(z,t) = \alpha g \overline{T^{'} w^{'}}$, $\overline{T^{'} w^{'}}$ is the heat flux, $\alpha = \theta_R^{-1}$ and θ_R is a reference temperature. Substitution of (2) in (1), averaging of variable quantities over a suitable volume, parameterizing the volume-averaged dissipation $<\varepsilon>$ using the volume-averaged kinetic energy $<k>$ and the depth of the mixed layer H as $<\varepsilon> = C_\varepsilon <k>^{3/2}/H$, and assuming that the surface buoyancy flux decreases as

$$Q_o(0,t) = Q_m \cos\frac{\pi t}{2\tau_f} , \qquad (3)$$

where τ_f is a time scale of the decay heat flux and C_ε is a constant (Nieuwstadt & Brost 1986), we obtain

$$\frac{\partial <k>}{\partial t} = \frac{Q_m}{2}\cos\left(\frac{\pi t}{2\tau_f}\right) - C_\varepsilon \frac{<k>^{3/2}}{H}. \qquad (4)$$

By normalizing (4) using the scales $k_0 \left(= w_*^2\right)$ for *<k>,* where w_* is the convective velocity at the beginning of the decay *(t=0)*, and $t_0 = H/w_*$ for time, we obtain

$$\frac{\partial k^*}{\partial t^*} + C_\varepsilon k^{*3/2} = \frac{1}{2}\cos At^* \qquad (5)$$

where $k^* = <k>/k_0$, $t^* = t/t_0$, and $A = \pi H/2(w_* \tau_f)$. Based on the field and laboratory experimental results, we may take, at $t = 0,\ k^* = <k>_{t=0}/w_*^2 \approx 0.3$.

4. RESULTS

Figure 1 shows a composite of normalized turbulent kinetic energy as a function of the normalized time for the ACS site. The time variation of the turbulent energy for the case of steady forcing $\tau_f = \infty$, for $\tau_f = 4.35$ considered numerically by Sorbjan 1997) and for instantaneous removal of the source ($\tau_f = 0$) considered numerically by Nieuwstadt & Brost 1986) are also shown. The theoretical predictions correspond to the solutions for (5) given above, where τ_f and the initial convective velocity w_* necessary for the predictions were evaluated for each day using the direct measurement of ground heat flux. A typical set of such supporting meteorological variables used in the analysis and the cosine curve fitted to the heat flux measurements to obtain τ_f are shown in Figure 2. The time corresponding to the maximum of the curve was used as time $t = 0$, where the decrease of solar insolation begins. The height of the convective layer H was estimated from the potential temperature profiles taken by radiosondes. In Figure 3, C_ε = 2.5 was used, as it gave the best fit to all of the curves corresponding to different days. This is close to $C_\varepsilon \approx 2.0$ used by Nieuwstadt and Brost (1986). Also shown in Figure 3 are the data taken from PAFEX-1 together with prediction based on (5); a reasonable agreement can be seen, indicating that (5) has general applicability.

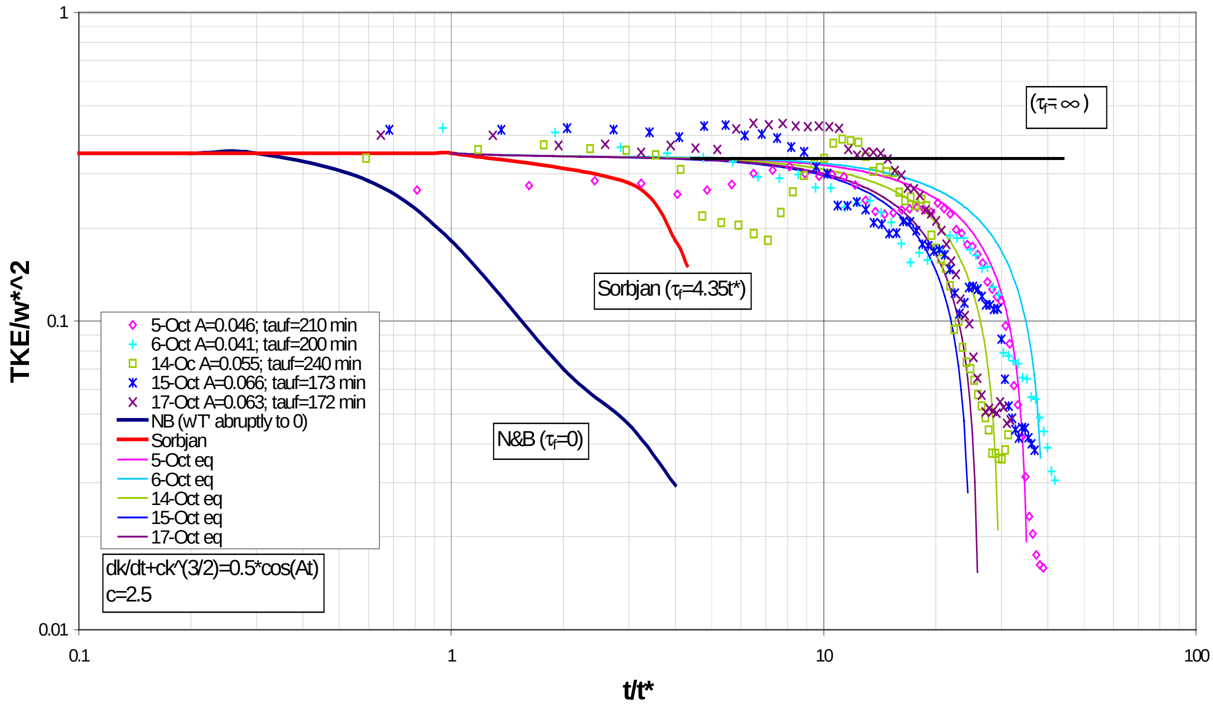

Figure 1. Normalized turbulent kinetic energy as a function of the normalized time from the ACS site together with the theoretical predictions correspond to the solutions for (5)

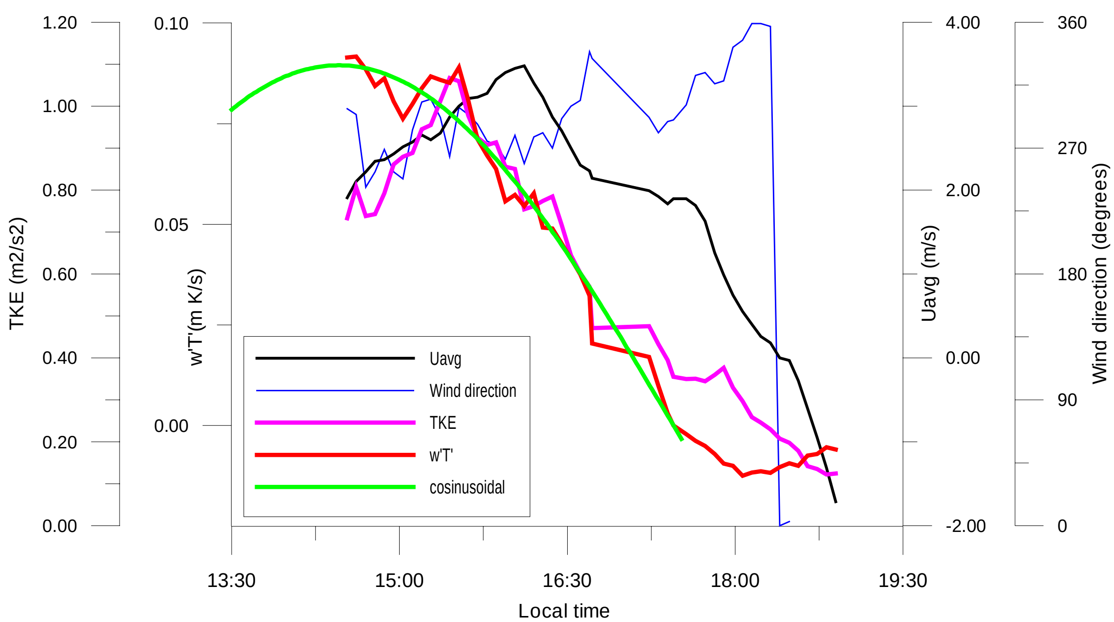

Figure 2. Typical set of supporting meteorological variables used in the analysis and the cosine curve fitted to the heat flux

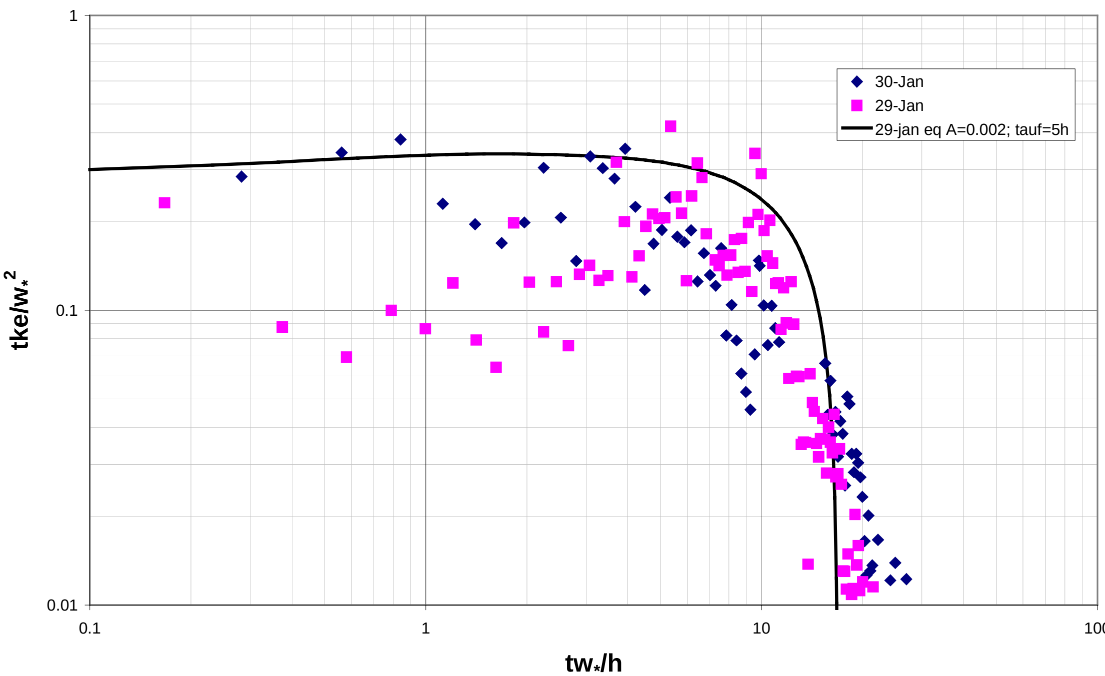

Figure 3. Data taken during PAFEX-1 experiment together with prediction based on (5)

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