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Measurement of the diurnal cycle of temperature, humidity, wind, and carbon dioxide in a subalpine forest during the 2004 Carbon in the Mountains Experiment (CME04)

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I. Introduction:

Near-surface atmospheric conditions in mountainous terrain are often determined by large-scale differences in surface heating (or cooling) that create complex slope-driven katabatic or anabatic flows (Whiteman, 2000). Forest-covered slopes add additional physical and biological complexity to quantifying the budgets of scalars such as water vapor and carbon dioxide (due to plants acting as biological sources and sinks as well as the effect of trees on the airflow). Meteorological data collected during the CME-04 are used to examine the mean diurnal conditions at the site (Figures 1 and 2). The standard deviation of the data within each half-hour bin is a measure of the "day-to-day" variability for each parameter. Over the two months of our observations the day-to-day variability is typically 10-20% of the mean value, except for WS where the variability is on the same order as the mean.

Several distinctive features of the diurnal cycle are highlighted here (a more complete description can be found within the extended abstract). At night katabatic (downslope) flows were present above the canopy over 90% of the time (during August and September), while during the daytime the occurrence of upslope or downslope flows was nearly equal (50%). The specific humidity typically reached a maximum in the early evening (around 18:00 MST) and gradually decreased throughout the night until reaching a minimum just before sunrise (at 5:00 MST). This pattern for q is due to the advection of drier air from higher elevation down past the tower and also the shutting down of plant transpiration as the stomates of plants close at night (effectively cutting off one of the inputs of water vapor to the atmosphere). (During the plant-dormant period of the year (October-March) there is not a dramatic decrease of q throughout the night as there is in the summer months.) CO_2 is well-mixed during the daytime (due to unstable atmospheric conditions and photosynthetic uptake of CO_2). At night the uptake of CO_2 by leaves is reduced to negligible levels, but heterotrophic respiration of CO_2 by soil microbes and autotrophic CO_2 respiration by roots continues to occur. These biological factors combined with stable atmospheric conditions resulted in a large increase of CO_2 near the ground at night (Figure 1d).

The magnitude of the WS gradually increased at night which is typical of downslope flows due to the decoupling of the surface and air aloft. At the tower location there was a tendency for increased turbulent activity just before midnight as evidenced by a sharp increase in the day-to-day variability of the vertical velocity variance between 22:00-24:00 MST (Fig. 2d). This is indicative of the occurrence of turbulent bursts (due, in part, to the increased vertical WS shear and accompanying breakdown into intermittent turbulence as well as large scale disturbances passing by the site.)

Figure 1: *Half-hourly binned mean (left) and standard deviation (right) of measurements from August and September, 2004 at the Aspen Tower for (a) net radiation R_{net}, (b) air temperature T_a, (c) specific humidity q, and (d) carbon dioxide CO_2. Five-minute mean data are used for R_{net}, T_a, and q while 15-minute data are used for CO_2.*

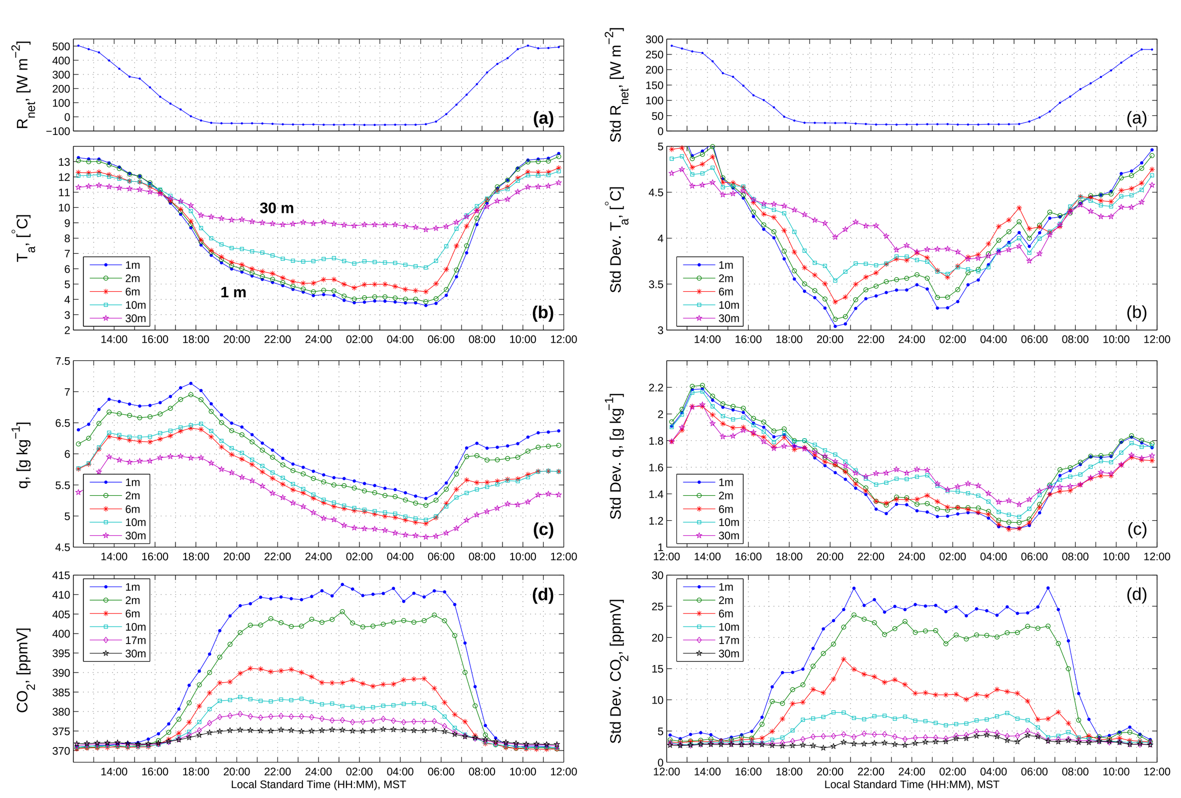
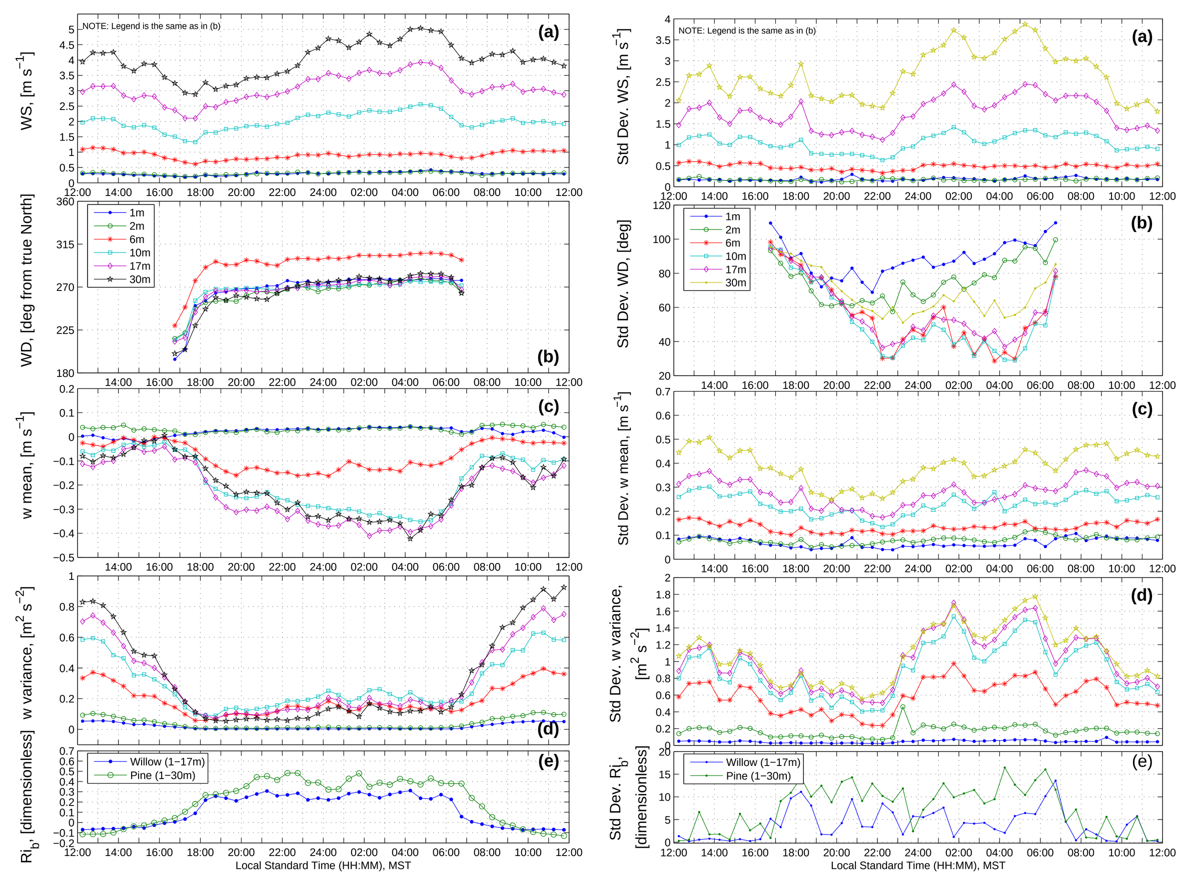
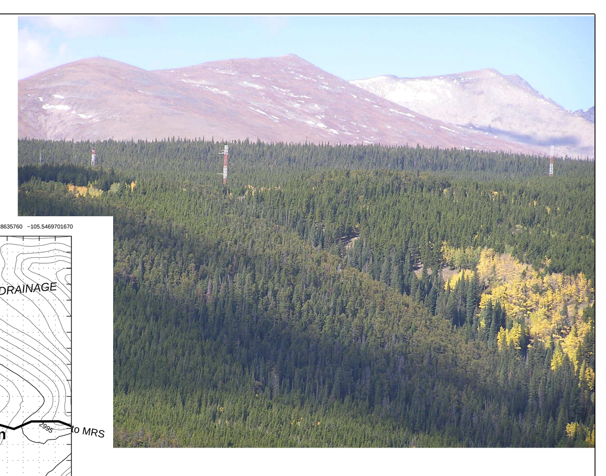


Figure 2: *As in Fig. 1, except for (a) wind speed WS, (b) wind direction WD, (c) 5-min vertical wind (mean), (d) 5-min vertical wind variance, and (e) bulk Richardson number. Daytime WD is not shown because the distribution is bi-modal.*

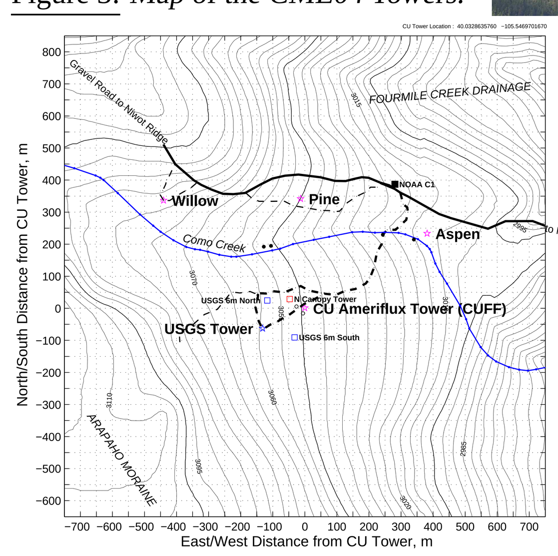


II. Carbon in the Mountains Experiment Details:



As part of the 2004 Carbon in the Mountains Experiment (CME04), the NCAR Earth Observing Laboratory (EOL) installed three towers ("Pine", "Willow", and "Aspen") in a subalpine mixed-conifer forest near the existing University of Colorado (CU) and U.S. Geological Survey (USGS) Ameriflux towers. These five towers were located in a relatively flat area (~4-10 percent slope) about 10 km east of the continental divide near Niwot Ridge, Colorado (Figure 3). The EOL towers loosely followed the drainage of a small creek. One tower ("Willow") was in a open area while the other four towers were in either aspen or mixed-conifer forest. The average canopy height within the forest is around 11 m. The tree density around the CU Tower is around 0.4 trees m^{-2} with a leaf area index (LAI) of 3.8-4.2 m^2m^{-2} (Turnipseed et al., 2002). The sites in order of increasing tree density are: Willow (no canopy), Aspen, USGS, CUFF, and Pine. The Aspen tower was located closest to Como Creek in a relatively open area dominated by willows and shrubs that are around 3-4 m tall interspersed with a few larger conifers that are 10-15 m tall.

Figure 3: *Map of the CME04 Towers.*



III. Bulk Richardson Number:

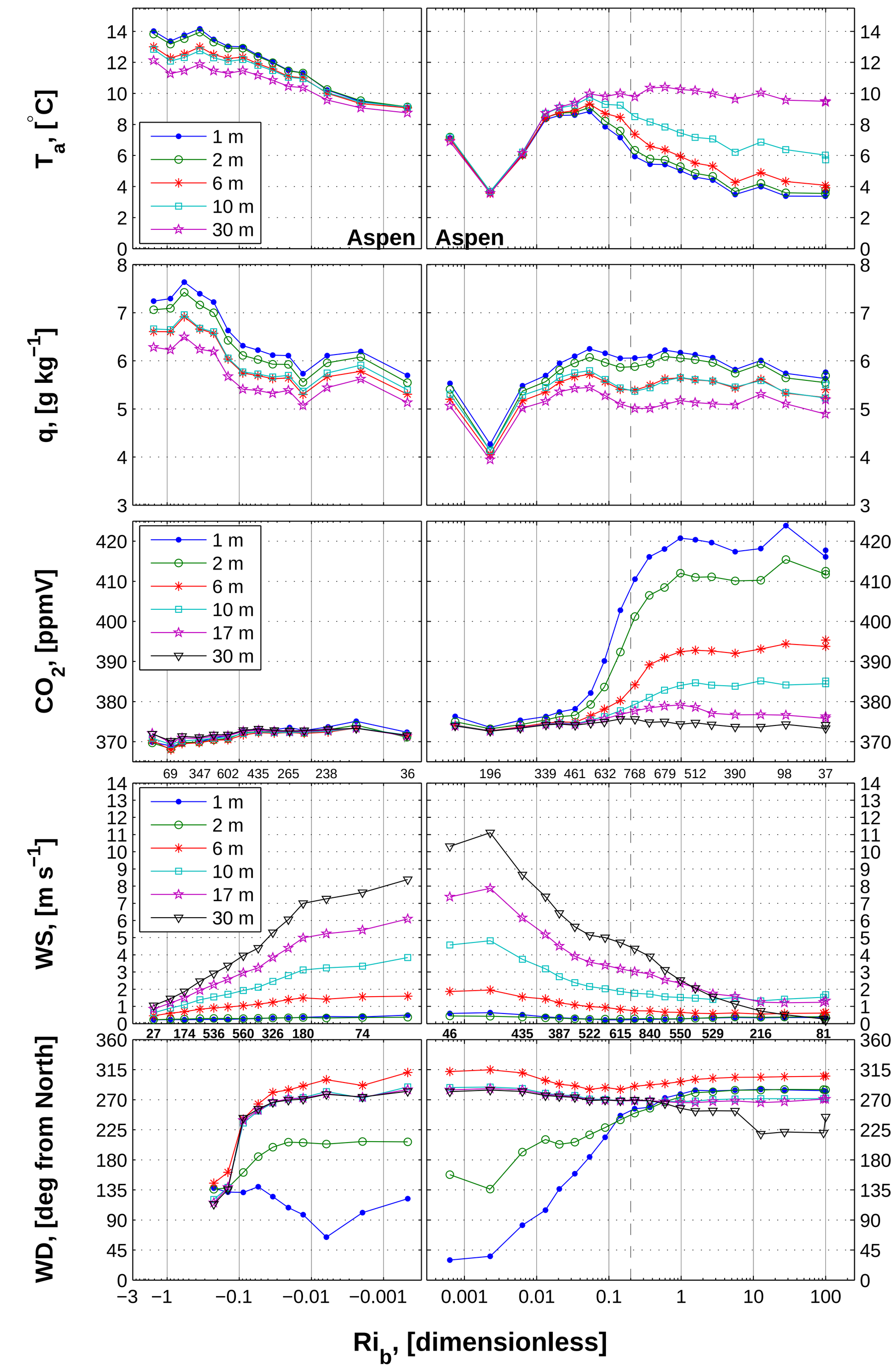
Wind shear near the ground is a constant source of turbulence in the atmosphere. With increased turbulence, there is an increase in mixing of scalars. If the ground surface is cooler (or warmer) than the overlying atmosphere the mean buoyancy gradient can act to reduce (or enhance) the turbulence in the atmosphere. The Richardson number compares the ratio of the shear production and buoyant destruction (or production) of atmospheric turbulence and is a widely used parameter for examining the stability of the atmosphere (Kaimal and Finnigan, 1994). Large and negative Ri values indicates unstable atmospheric conditions, Ri near zero indicates near-neutral conditions, and large positive Ri indicates a strongly stable atmosphere. When the Richardson number exceeds a certain "critical" value (typically taken to be around 0.2), turbulence is greatly suppressed and the flow can be considered laminar. For the CME-04 tower data the bulk Richardson number (Ri_b) was calculated between the lowest and highest measurement levels at each tower using:

$$Ri_b = \frac{g}{\overline{T}_a}\frac{(\theta_2-\theta_1)(z_2-z_1)}{(U)^2},$$

where z_2 and z_1 are the upper and lower heights of the layer, $\overline{T}_a$ is the mean air temperature in the layer, θ is the potential temperature, and U is the wind speed measured at the top of the layer. Since the vertical gradients of wind and temperature within the canopy can be very small we have chosen the lower level (z_1) to be within the canopy layer and the upper level (z_2) to be above the canopy (for sites with a canopy).

If the mean measurements at the Aspen tower are binned by Ri_b, it can be observed that Ri_b of ~ 0.1 is a good indicator of the conditions when the mean gradients of CO_2 and T_a start to develop (Figure 4). Also, under conditions of very strong stability (e.g., $Ri_b > 2$) a WS maximum, or jet, forms at the mid-levels on the tower. There are also some interesting dynamical effect on the WD where the in-canopy directions can be over 90 degrees different than the above-canopy WD for high-WS conditions (note that the Aspen tower is located near the separation point between two different canyons). Figure 5 shows the vertical gradients at each tower binned by Ri_b. With this partitioning of the data, the effect of the different height of the maximum canopy density is revealed by the CO_2 gradients. A more complete description of these observations is within the extended abstract.

Figure 4: *Mean measurements at Aspen Tower binned by the bulk Richardson number Ri_b. The vertical dashed line represents the approximate location of the critical Richardson number (Ri_b = 0.2)*



IV. Conclusions:

The diurnal cycle and bulk-Richardson-number-based composites at a mountain location are presented. The katabatic winds reveal themselves in the diurnal cycle as a gradual increase of WS throughout the night accompanied by a steady "drying out" of the atmosphere (as drier air from higher elevation gets advected by the study site and the trees reduce the transpiration of water vapor). Binning vertical gradients by Ri_b helps to establish a criteria for conditions that are conducive to flow separations. We find a transition away from well-mixed turbulence at a critical Ri_b of approximately 0.1-0.3. Further intercomparisons between the measurements at the CME04 towers are on-going and can be used to better understand the effect of surface heterogeneity on the measurements.

References:

Kaimal, J. C. and J. J. Finnigan, 1994: *Atmospheric Boundary Layer Flows: Their Structure and Measurement.* Oxford University Press, 289 pp.

Turnipseed, A.A., et al. 2002: Energy balance above a high-elevation subalpine forest in complex topography.*Agric. For. Meteorol.*, **110**, 177-201.

Whiteman, C.D., 2000: *Mountain Meteorology: Fundamentals and Applications.* Oxford University Press, 355 pp.

Figure 5: *The vertical gradients of (from left to right): air temperature T_a, specific humidity q, carbon dioxide CO_2, and wind speed WS binned by the bulk Richardson number Ri_b.*