JP4.7 MEASUREMENTS OF THE DIURNAL CYCLE OF TEMPERATURE, HUMIDITY, WIND, AND CARBON DIOXIDE IN A SUBALPINE FOREST DURING THE CARBON IN THE MOUNTAINS EXPERIMENT (CME04)

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1. INTRODUCTION

As part of the 2004 Carbon in the Mountains Experiment (CME04), three towers were deployed by the National Center for Atmospheric Research (NCAR) Earth Observing Laboratory (EOL) Integrated Surface Flux Facility (ISFF) group in a subalpine forest near the existing University of Colorado (CU) and U.S. Geological Survey (USGS) Ameriflux towers (Detailed descriptions of the CU Ameriflux tower (hereafter called “CUFF”) can be found in Turnipseed et al. (2002, 2003) and Monson et al. (2002)). The towers are located within the Roosevelt National Forest in mountainous terrain below Niwot Ridge, Colorado approximately 8 km east of the Continental Divide. The CUFF tower started collecting data at this location in November, 1998; both the CUFF and USGS towers continue to operate at the present time. The three EOL towers (hereafter called “Willow”, “Pine”, and “Aspen”) were arranged to follow the drainage of a small mountain creek, Como Creek (Fig. 1).

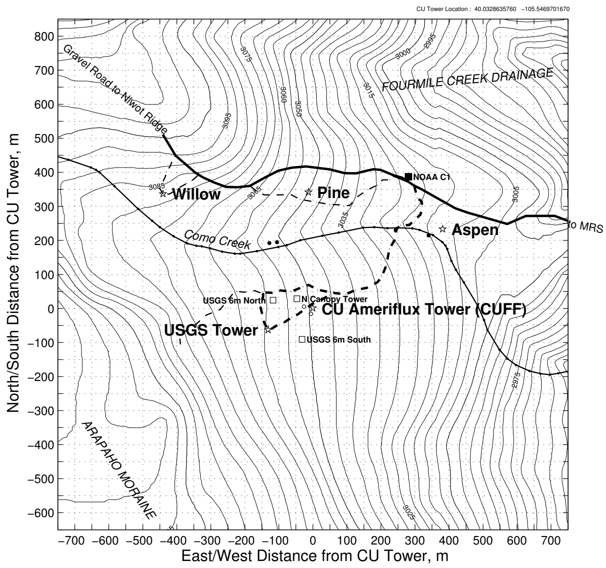

Figure 1: Location of the five towers used in CME04. Elevation contours at 5-m intervals are from the U.S. Geologic Survey 7.5-min DEM. The Como Creek data are from the “Hydrography - Streams” data available from the Boulder County GIS webpage (http://www.co.boulder.co.us/gis/). All tower locations were measured with a Trimble GPS Pathfinder Pro XL system (differentially-corrected). The dashed lines are foot paths.

Air motions in mountains are complicated by abrupt changes in topography, differential heating/cooling of sloped surfaces, orographic lifting, channeling, and the creation of waves and rotors (see Turnipseed et al. (2004) for some specific examples of these events that occur at the Niwot Ridge site). At night air descending downslope converges with air descending from other valleys and ridges to create complicated flow patterns (Simpson 1994). Air motions can also be affected by the presence of surface water (such as lakes) or local heat sources or sinks (Sun et al. 1998). These local air motions interact with synoptic flow to create a wide range of conditions experienced at a single location. The addition of a forest to mountainous terrain creates a layer of protected air that will be more influenced by local topography than the above-canopy winds. This layer of canopy air will generally be slow-moving (for a dense canopy the 5-min average WS will rarely exceed 1 m/s), and the canopy imparts a large drag force on the overlying wind field (Finnigan, 2000). Recent studies (Sun et al. 2006; Yi et al. 2005) have examined the in-canopy drainage flows near the CUFF and USGS towers (on the south side of Como Creek). The observed diurnal cycle of air temperature T_a, specific humidity q, and carbon dioxide CO_2 will help provide some clues as to the interaction of these scalars with the wind field.

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Nominal Height	USGS		Aspen		Pine		Willow		CUFF	
	T/RH[a]	WS/WD[b]	T/RH[a]	WS/WD[b]	T/RH[a]	WS/WD[b]	T/RH[a]	WS/WD[b]	T/RH[a]	WS/WD[b]
30m	33.0 45A	33.0 NA RMY	30.54 50Y	30.54 186.5° csat	29.69 50Y	29.69 163.5° csat				
21m									21.5 35D	21.5 203° csat
17m				17.62 184.7° ati		16.77 162.2° nuw	16.5 50Y	17.0 178.9° csat		
12m										12.5 20° ati
10m	10.0 45A	10.0 - 425A	10.28 50Y	10.28 182.0° ati	9.49 50Y	9.49 160.1° nuw	9.5 50Y	10.0 178.1° ati		9.0 - 425A
8m									8.0 35D	
6m		6.0 - 425A	6.43 50Y	6.43 172.1° ati	5.82 50Y	5.82 161.0° nuw	5.5 50Y	6.0 178.3° ati		5.7 190° csat
3m		3.0 - 425A								
2m	2.0 35		2.26 50Y	2.26 182.7° csat	2.22 50Y	2.22 159.3° csat	1.5 50Y	2.0 179.9° ati	2.0 45D	2.56 196° csat
1m		1.0 - 425A	1.18 50Y	1.18 182.9° ati	1.39 50Y	1.39 158.4° nuw	0.95 50Y	1.0 179.7° ati		1.61 - 425A

[a] T/RH sensors: "50Y" is the Vaisala 50Y Humitter platinum-resistance (PRT) sensor; "35", "35A", "35D", "45A", and "45D" are the Vaisala HMP25, HMP35A, HMP35D, HMP45A, and HMP45D PRT sensors; Sensors on the USGS tower are housed in a naturally aspirated radiation shield (Gill 41000 radiation shield), while sensors on the other towers are mechanically aspirated with either RM Young 43408 aspirated radiation shields (CUFF) or a dual-concentric-cylinder shield designed by NCAR/EOL/ISFF .

[b] WS/WD sensors: "csat" is the Campbell Scientific CSAT-3 3-dimensional sonic anemometer; "425A" is the Vaisala Handar 2-dimensional sonic anemometer; "nuw" is a 3-dimensional sonic designed and built by NCAR EOL/ISSF; "ati" is the Applied Technologies ATI-K 3-dimensional sonic anemometer, and "RMY" is the R.M. Young Wind Sentry Set (model 03001) 3-cup anemometer and wind vane.

Table 1: Details of the temperature, humidity, and wind measurements at each tower during CME-04.

The goals of this study are to (I) present the details of the tower instrumentation during CME-04 (section 2.1), (II) evaluate the quality of the tower measurements (section 2.3), and (III) describe the typical August/September diurnal cycle of T_a, q, and CO_2 measured at the site (section 3.1).

2. MEASUREMENTS

The tower measurements used for this study are from August and September, 2004. The five towers of CME04 were within 400 m of each other to investigate the atmospheric flow and effect of drainage flows on the horizontal advection of CO_2. Though the terrain within 5 km of the towers can be quite steep, the towers were located in a relatively flat area (with a grade ranging from 4-12 percent). As Como Creek passes by the towers it ranges anywhere from 1-5 m wide (depending on the time of year and location). The geographic features that form the Como Creek drainage are Arapahoe Moraine that runs Northwest-to-Southeast, and a slight ridge to the North that separates the drainage of Como Creek from Fourmile Creek. Como Creek drains a small area (3-4 square km) to the west of the towers; after passing the tower location, the creek goes past the CU Mountain Research Station (MRS), turns south, connects with North Boulder Creek, and eventually flows into Boulder Creek and down onto the plains. The site is typically snow-covered from early November to late May with a maximum snow depth of 1.5-2 m. Yearly precipitation is typically 60-70 cm.

The CUFF and USGS towers are located near the side of the Arapahoe Moraine in a relatively dense forest that is composed of sub-alpine fir, lodgepole pine, limber pine, and Englemann spruce. The tree density around the CU Tower is around 0.4 trees m^{-2} with a LAI of 3.8-4.2 $m^2 m^{-2}$ (Turnipseed et al. (2002)). (Further details on the forest canopy structure near CUFF and USGS can be found in Yi et al. (2005).) The Willow tower was located in a approximately 200x100 m-sized marshy area dominated by low shrubs (~1 m high), without any tall trees within 50 m of the tower. The Pine tower was located in a fairly dense conifer forest with a small patch of aspen trees immediately to the west of the tower. 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.

	USGS[a]	Aspen	Pine	Willow	CUFF
System		Aircoa[b] "B"	Hydra[c]	Aircoa[b] "A"	
Levels (m)	1, 3, 6, 10, 33	1, 2, 6, 10, 17, 30	1, 2, 6, 10, 17, 30	0.5, 1, 2, 6, 10, 17	0.5, 1, 2, 5, 10, 21.5
CO_2 Sensor[d]	LI-7000	LI-820	LI-7000	LI-820	LI-6251
Sample Resolution[e]	30 min	15 min	24 min	15 min	6 min
Air Drying Method	None	Nafion	Nafion	Nafion	Magnesium Perchlorate
Calibration Gases[f] (ppmV)	0 and 414.3 (0 and 412.3)	342.10, 370.41, 405.35, 471.23	334.88, 349.27, 398.14, 417.95	344.11, 366.53, 401.75, 474.64	0 and 401.33
Calibration Frequency	2 hrs (full)	3.5 hrs (full) 0.5 hrs (part)	2.5 hrs (full) 0.5 hrs (part)	3.5 hrs (full) 0.5 hrs (part)	4 hrs (full)

[a] The USGS system had inlets located at both the USGS and CUFF towers. The inlets at the CUFF tower were at heights of 1, 3, 6, 10, and 23 m and will be designated as "CUFF/USGS". The CUFF/USGS inlet at 6 m had a problem with the tubing and will not be used.

[b] Aircoa: "Autonomous Inexpensive Robust CO2 Analyzer"; design led by Britt Stephens at NCAR EOL/RAF

[c] Hydra: an Air-sampling system designed by Tony Delany at NCAR EOL/ISFF

[d] All CO_2 Sensors are manufactured by LI-COR Biosciences Inc. (4308 Progressive Ave. Lincoln, Nebraska USA). The model number of the sensor used is shown in the table.

[e] Sample resolution: the minimum time between samples from a given inlet.

[f] The calibration gases used at Pine, Willow, Aspen, and CUFF were pre- and post-calibrated at the NCAR/RAF O_2/CO_2 calibration facility. The USGS calibration gas was changed on Sept 8th, 2004 (from a 414.3 to 412.3 cylinder).

Table 2: Details of the CO_2 measurements at each tower during CME-04. The 1m inlet at CUFF was not used.

2.1 Tower Instrumentation

Each tower was equipped with multiple levels of sensors (or air inlets) for measuring T_a, q, WS, WD, and CO_2. Tables 1 and 2 detail the instrumentation used at each tower. In addition to the multi-level measurements a barometric pressure sensor and radiation sensors were also located at each tower. Other parameters (such as fluxes of heat, water vapor, and CO_2, soil temperature, soil moisture, etc) were also measured at some tower locations, but are not relevant to the present study so will not be discussed here.

There were several different co2 measurement systems taking part in CME04 (see table 2 for the details of each system). The effect of the differences between the systems on the calculated CO_2 measurements will not be explicitly explored here. It is important to note that both the Aircoa and Hydra systems used four calibration gases and had "full" calibrations (using all 4 calibration gases) as well as "partial" calibrations (where only 1 of the 4 calibration gases were used) on a more frequent interval. In contrast, the CUFF and USGS towers used two calibration gases and used only "full" calibrations. All the systems used a similar sampling strategy of periodically switching between different inlets and calibration gases. This creates a non-continuous time series for each inlet and complicates the comparison of CO_2 between systems since there is a variety of time stamps and sampling strategies (the problem is much worse at night when local CO_2 gradients can be large). The calibration gas is at the foundation of the accuracy for all the CME04 CO_2 measurements. For the EOL and CUFF Towers the calibration gases were analyzed at the NCAR/RAF O_2/CO_2 Calibration Facility that reaches an accuracy of 0.05 ppmV (relative to the World Meteorological Organization (WMO) CO_2 scale). The USGS calibration cylinders were processed in a USGS laboratory by using a NOAA Climate Monitoring and Diagnostics Laboratory (CMDL) standard cylinder and a LI-COR LI-6262.

The temperature and humidity (T/RH) sensors at the EOL and CUFF towers were mechanically aspirated and enclosed in a dual-concentric-cylinder shield. At the USGS tower naturally ventilated radiation shields were used. Each T/RH sensor on Willow, Pine, and Aspen was individually calibrated by ISFF and has an estimated field accuracy of about $\pm 0.1°$C. The CUFF T_a data at 8 m has been increased by 0.25°C based on a side-by-side comparison with a "roving" temperature sensor.

Wind speed and direction was primarily measured with either 2-d or 3-d sonic anemometers (Table 1). Almost all the sonics were mounted on booms that were pointing in a southerly direction, so flow through the towers (before reaching the anemometers) should not have been a issue since the winds at the site are primarily flowing in a east-west direction.

The linux-based data system used at the CUFF and EOL towers were designed by EOL/ISFF and use network time protocol (NTP) to insure consistent time tags on all the data. Spot checks of the USGS time showed it to be consistent with the other towers.

2.2 Data Details

Links to most of the data sets used in this study can be found on the ACME/CME "swiki" webpage (http://swiki.ucar.edu/acme/). (ACME is the "Airborne" component of CME.) The temperature, humidity and wind raw data from Aspen, Pine, Willow, and CUFF were recorded at a rate of either 1-Hz, 10-Hz, or 30-Hz; however, for this study, the 5-min statistics (means and variances) are used. The 5-min statistics are part of the data system software designed by the NCAR/EOL/ISFF group. For each field project ISFF reports the details of experiment, provides access to the data, and has a detailed "logbook" from the experiment available via a webpage (Oncley, 2004). The 5-min ISFF data set used in this study were obtained on 16 March, 2005. The CUFF 5-min data were obtained from the CU Ameriflux data webpage (http://urquell.colorado.edu/data_ameriflux/).

The CO_2 data are a bit more complicated since they were sampled at different rates and the systems varied between towers (Table 2). The "Aircoa" CO_2 data from Willow and Aspen were processed by Britt Stephens at the NCAR/EOL Research Aviation Facility (RAF) and the data used herein are the version from 5 April, 2005. The CO_2 data from Pine were collected with the "Hydra" system and version 2 (15 March, 2005) of these data are used. The CUFF CO_2 data (available via the acme swiki) were processed by Sean Burns at the CU Monson Lab. The USGS CO_2 data were obtained via e-mail from Dean Anderson.

Two different strategies were used for analysis of the CO_2 data. One was to match the CO_2 data to a 15-min time stamp; this requires either interpolating or averaging (depending on the data set) the raw CO_2 data to a common 15-min time variable. The other strategy was to take the median of the samples over a 2-hour period which did not require interpolation of any data. The longer averaging period is better for inter-comparing the absolute value of the CO_2 between systems, but some of the fine-scale details are lost in the averaging process. The transport time of the air to flow along the tubing to the instrument was taken into account in the processing.

The data analysis only used time periods when all the data of a specific parameter were available on all towers. In situations where data from one level were missing (due to instrument problems) and the data from other levels were available then a linear interpolation (with height) was used to gap-fill the missing data. [provide more specific details of data quality here].

All results for this study are presented in Mountain Standard Time (MST) which is seven hours behind UTC time.

2.3 Examination of Data Quality

Strong winds tend to mix the atmosphere and minimize the vertical and horizontal gradients in scalars. We use this property of the atmosphere to examine the parameters measured at each tower for data quality. This way of partitioning the data also provides some insight into the atmospheric and biological processes that take place at the site. Figures 2-6 show the windspeed-binned vertical gradients of T_a, q, CO_2, WS, and WD at each tower. The left-hand columns in each figure are the daytime data (11:00-14:00 MST), and the right-hand columns are the nighttime data (22:00-4:00 MST). The time periods were chosen to avoid any effect of the morning or evening transition. Based on these plots the data at each tower appears to be reasonable (with a few exceptions) and some consistent patterns in the tower data emerge. One exception is the 1-m inlet for CO_2 at the Willow tower which displays some erratic behavior as the WS changes (Fig 4). This was a known problem during the field experiment, that was never solved. For this reason, the 1-m CO_2 data from the Willow site will not be used in our study. Also, the 6-m WD from the Aspen tower appears to have a consistent ∼25° clockwise bias that is not observable in the data from any other tower (Fig. 6). The direction of the boom for the 6-m sonic at Aspen was aligned at 172° while all the other sonic booms on the Aspen tower were between 182-186° (see Table 1). Perhaps some correction for the bias needs to be applied to these data before they are used in any analysis (this is still an open question).

In addition to the data quality checks there are several other observations to note in the vertical gradient comparisons. At the sites with the greatest canopy density (USGS, Pine, and CUFF) the vertical gradient of T_a during the daytime is a minimum for the highest and lowest above-canopy WS conditions (Fig. 2c). At nighttime the mean T_a vertical gradient is nearly constant for above-canopy

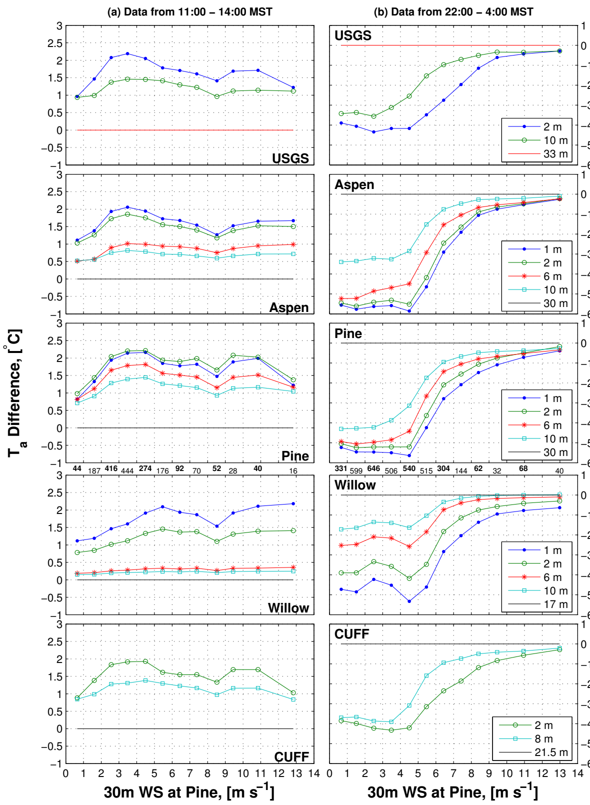

Figure 2: The vertical gradient of air temperature T_a measured at each tower binned by the 30m-WS at the Pine tower (the lower levels are subtracted from the highest measurement level). Note that the y-axis range of the left and right panels differ. The number of 5-min data values for each bin is shown between the panels for Willow and Pine (the number of possible 5-min samples is 2196 for the daytime data and 4392 for the nighttime).

windspeeds less than 5 m s^{-1}, and a non-linear decrease in the magnitude of the gradient as the WS increases beyond 5 m s^{-1} (Fig. 2b). At the largest WS, the sites with canopies have a mean vertical gradient of less than 0.3°C, while the canopy-free site (Willow) still has a gradient greater than 0.5°C (this is because the surface at Willow is not protected from radiative cooling by the presence of a canopy).

For q the air at the upper levels of the towers were typically drier than the air near the ground (Fig. 3). The exception to this is for low-wind conditions at night when the vertical gradients in q become small and the air at the mid-level of the towers was often slightly drier than the air both above and below that level. As with T_a the towers with the most dense canopies reveal large vertical gradients for the greatest above-canopy WS while those without a canopy (Willow) or with a more open canopy (Aspen) show very small gradients in q.

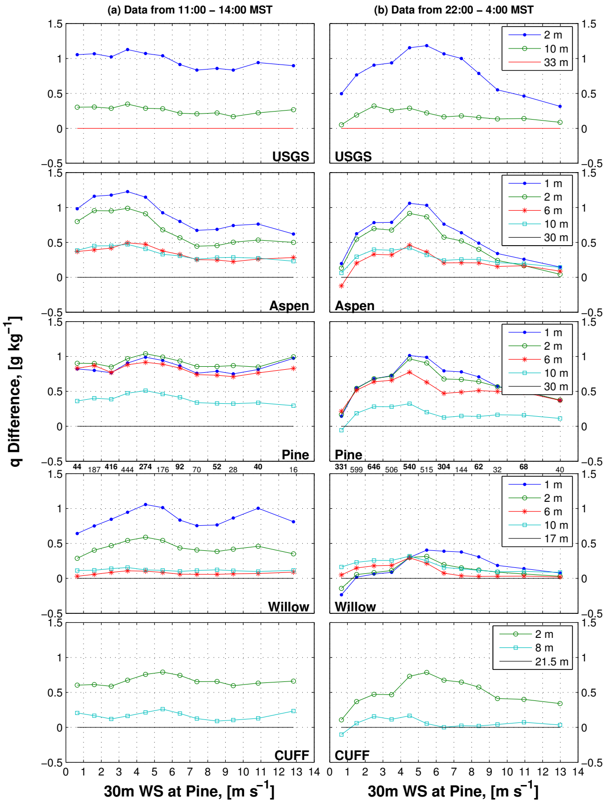

Figure 3: As in Fig. 2, but for specific humidity q.

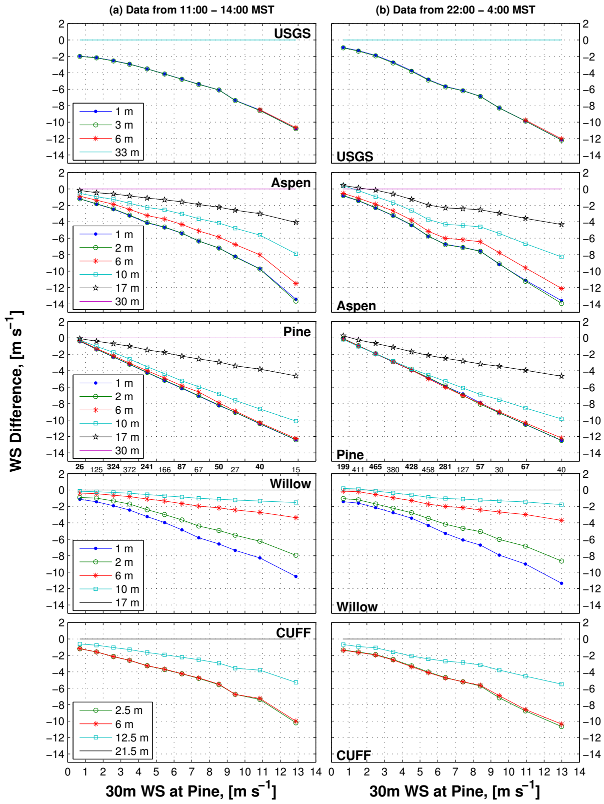

Figure 5: As in Fig. 2, but for wind speed WS.

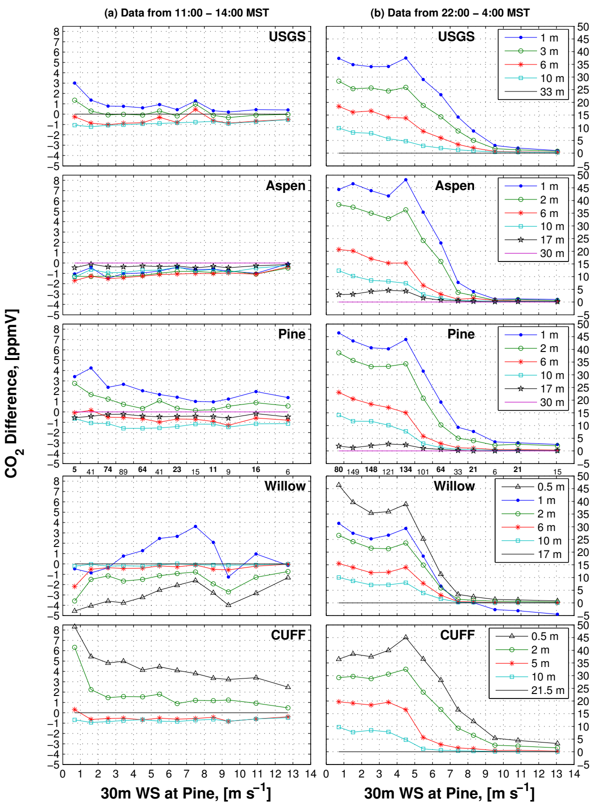

Figure 4: As in Fig. 2, but for carbon dioxide CO_2. For CO_2, the number of 15-min data values in each bin are shown between the panels for Willow and Pine.

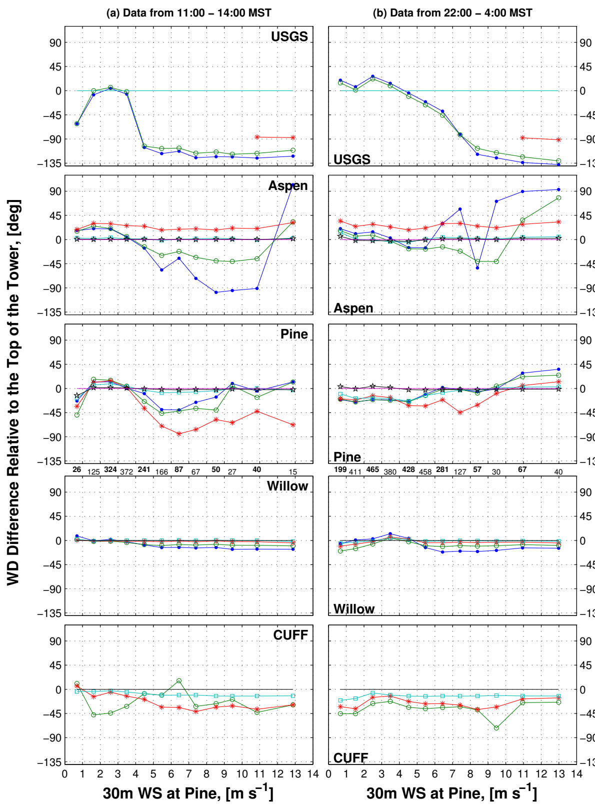

Figure 6: As in Fig. 2, but for wind direction WD. A positive WD difference indicates that the WD is clockwise relative to the top of the tower. The legend is the same as in Fig. 5.

During the day the mid-canopy inlets measure CO_2 values that are around 1-2 ppmV lower than the CO_2 at the top of the towers due to the photosynthetic uptake of CO_2 by the trees (Fig. 4a). The towers with the most dense canopies (CUFF, Pine, USGS) reveal that respiration by soil microbes in the ground generate a surplus of CO_2 that is not fully absorbed by the trees or fully mixed into the atmosphere (even at the highest WS). This feature also persists at night when the WS is large. At the more open or canopy-free sites (Willow and Pine) the ground cover and shrubs near the ground are able to receive much more solar radiation and thus absorb any CO_2 released from the soil. At these locations there is no buildup of CO_2 closer to the ground, instead the CO_2 near the ground is 2-3 ppmV lower than the upper levels (indicating CO_2 uptake is taking place near the ground). This uptake is greatest at the Willow site which is dominated by low plants and shrubs.

For weak nighttime synoptic winds (30-m WS < 1 m s^{-1}) a WS maximum can often be found at Aspen and Pine between the top of the canopy and 30m (Fig. 5). At Willow the WS maximum was found between 10 and 17m. This is probably the "classic" WS maximum that is characteristic of drainage flows (e.g., Whiteman, 2000; Monti et al. 2002). When the synoptic winds aloft are stronger the drainage flow becomes deeper than the height of the CME04 towers (i.e., the maximum WS is found above the tops of the towers) and the total depth of the drainage flow is not known. The low-level WS maximum was not observed at the CUFF and USGS towers and it's difficult to conclude if this is because the other towers didn't have the proper placement of wind sensors to observe this phenomena or because of the different location of the towers at the site.

The vertical WD gradients (Fig. 6) at Aspen and USGS show a large dependence on WS. For the largest WS conditions the WD near the bottom of these towers can be almost 90° different from the direction at the top of the tower. The other towers show more uniform WD, with Willow being the most uniform of all. This is probably because the Willow site has no canopy and it is also in the most level area of any of the towers. WD will be discussed in more detail below.

Up to this point we have been discussing the mean vertical gradients observed at each tower. The mean values binned by WS are also useful to evaluate the atmospheric conditions at the site. The

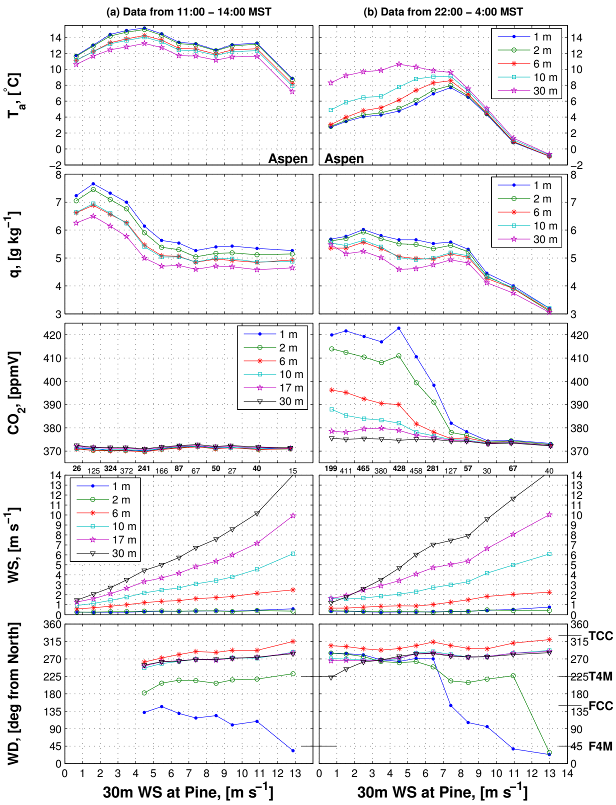

Figure 7: Aspen tower mean air temperature T_a, specific humidity q, carbon dioxide CO_2, wind speed WS, and wind direction WD binned by the 30-m WS measured at the Pine tower. The horizontal lines and text in the WD panels indicate the direction for air flowing toward (TCC) or from (FCC) Como creek and, for air flowing toward (T4M) or from (F4M) the Fourmile creek drainages (these directions are relative to the Aspen tower).

mean Aspen tower data for T_a, q, CO_2, WS, and WD are shown in Fig. 7. For the strongly convective conditions of mid-day the warmest T_a were not experienced at the lowest windspeeds, but, instead occur at a mid-range windspeed of $\sim$4.5 m s^{-1} (Fig. 7, column a). By separating the daytime data into upslope and downslope conditions (Fig. 8) it can be observed that the reason the maximum T_a is at mid-range WS is due to the upslope flows being strongest when the air temperature is at a maximum. The 30-m WS during upslope conditions was rarely greater than 5 m s^{-1} whereas downslope flows had a WS greater than 7 m s^{-1} around 10% of the time.

Similar to T_a, the mean daytime-q shows a distinct peak in atmospheric humidity below about 4.5 m s^{-1} (Fig 7, column a). From Fig. 8 it is clear

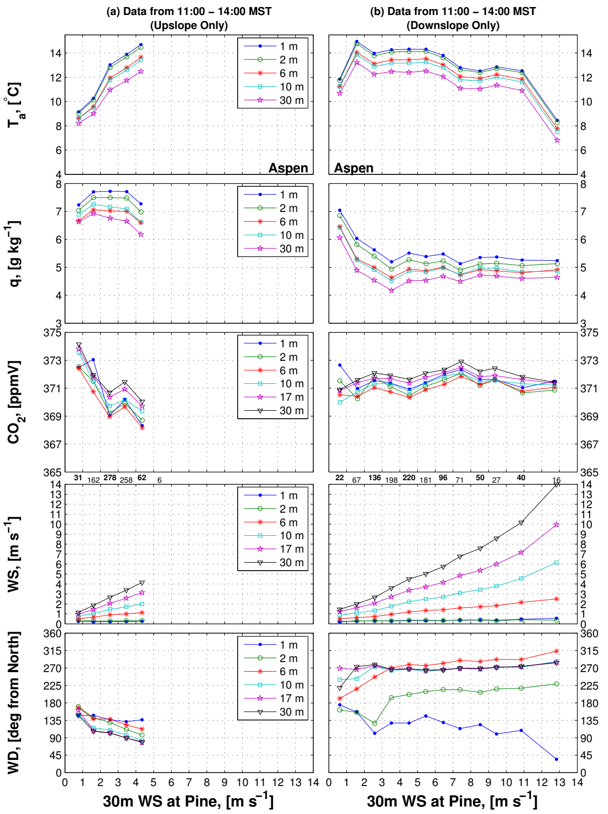

Figure 8: Daytime data from Fig. 7 (column a), but separated into (a) upslope and (b) downslope conditions at 30 m.

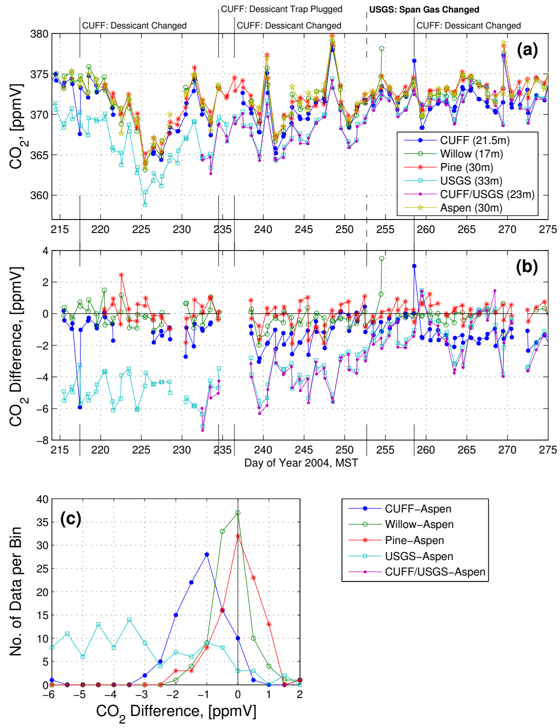

Figure 9: Time series of (a) CO_2 measured between 11:00-14:00 MST from 1 August to 30 September, 2004, (b) the difference in CO_2 between the highest level on each tower (the 30-m CO_2 at Aspen is used as the reference), and (c) the frequency distribution of the difference between the CO_2 measurements. The CO_2 values are 2-hour medians. The vertical lines (and corresponding text) in the top panel specify any changes to the measuring systems.

that the reason for this peak is that the upslope flow is transporting more humid air up to the tower site.

The characteristics of CO_2 are markedly different than either T_a and q. As discussed previously, this is primarily due to the effect of photosynthesis and vertical mixing of the CO_2 during the daytime and the large amount of CO_2 generated by the soil microbes at night (when photosynthesis is not taking place). At night when the 30-m WS is large enough (and the canopy is fairly open as at the Aspen site) this surplus of CO_2 generated in the soil can be mixed into the atmosphere (Figs. 4b and 7b).

Since there were several different CO_2-measuring systems used in CME04, the mid-day 2-hr median data are used to cross-compare CO_2 from each of the various systems (Fig. 9). Figure 9b shows the time series of the differences (using Aspen as the reference) for the 2 months of data used in this study. The vertical lines indicate when changes to the CUFF and USGS systems occurred. There is a low bias of about 5 ppmV on the USGS system until the calibration cylinder is changed on 8 September (day 252). After this date, the comparison between the USGS and the other towers are more reasonable. It should be noted that even though the absolute value of the USGS CO_2 data are biased, error in the relative differences (i.e., measurements of the horizontal and vertical gradients) will be an order of magnitude smaller than any error in the absolute measurement. Changing the dessicant (magnesium perchlorate) in the CUFF system (on day 217 and day 258) caused spikes in the CO_2 difference data for CUFF (Figure 9b). This is most likely due to the relatively long time period (4 hours) between calibrations at the CUFF tower and the rapid change in conditions (primarily temperature) when the box that houses the LI-6251 is opened to service the dessicant trap. In order to get some estimate of the accuracy of the measurements by the various systems the frequency distribution of the mid-day differences are plotted in Figure 9c. It should be

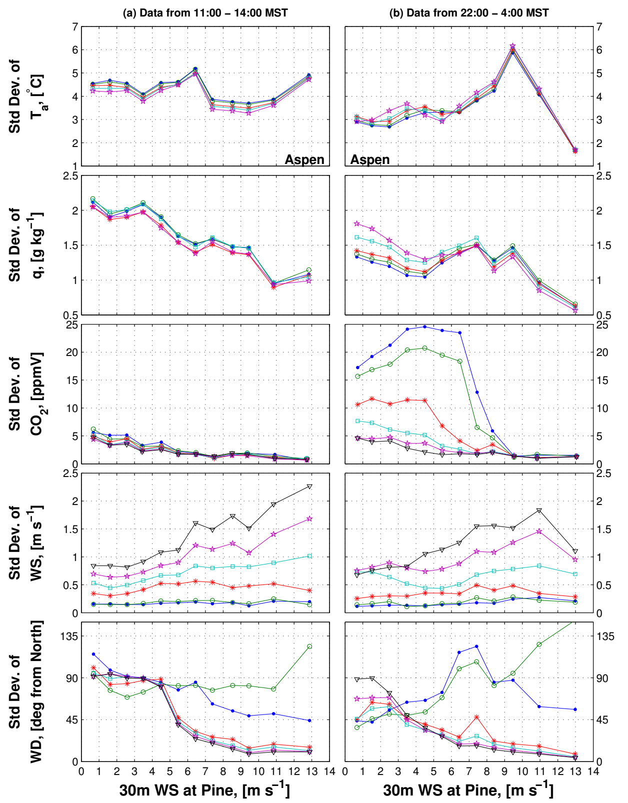

Figure 10: The standard deviation of the data shown in Fig. 7. The legend for each panel is the same as that shown in Figs. 7 and 8.

emphasized that some of these differences could be real due to the different tower locations and different levels of the measurements. The most likely reason for the slightly negative skewness of the Willow data compared to Pine is the difference in height of the Willow and Pine inlets (30 m compared to 17 m).

As shown in Fig. 1, the Aspen tower is located at a location where the air flow can either go down (or come up from) the Fourmile creek drainage (to the North) or use the Como creek drainage (toward the South). The WD binned by 30-m WS shows that for downslope flows the above-canopy winds are usually coming out of the west (270°), but the winds below the canopy are typically moving in a direction (up or down) that is more aligned with the Fourmile creek drainage (Fig 7). When the drainage winds at 30 m were greater than 10 m s^{-1} (which was less than 8% of the time) there appears to be a dynamic effect on the low-level air that causes the flow to be coming up the Fourmile creek drainage. It should be noted that the above-canopy air at

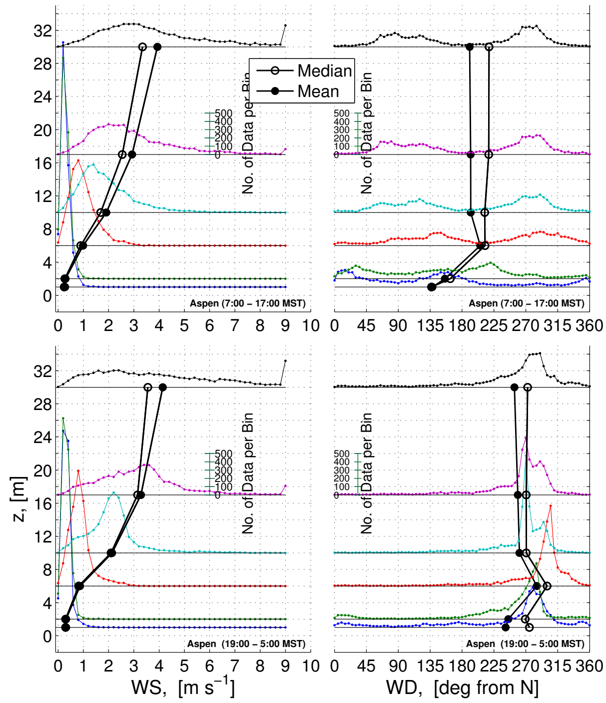

Figure 11: Frequency distributions of (a) wind speed WS, and (b) wind direction WD at different levels on the Aspen tower for daytime (top panels) and nighttime (lower panels).

night is usually heading almost due west at the Aspen tower. This air is most likely going to flow down the Fourmile Creek drainage (and not the Como Creek drainage). The large (25°) bias in the 6-m WD at Aspen was discussed earlier, and there is some question as to whether this is an instrumental issue or a real phenomena.

At this point it may appear that the effect of WS does not "mix" the scalars as well as we originally postulated (e.g., the daytime-q in Fig. 8 appears to be nearly constant for WS greater than 5 m s^{-1}). However, the effect of the WS on these scalars is more evident if the standard deviation of the 5-min data in each WS bin is examined (Fig. 10). For example the standard deviation of the daytime-q in decreases by over 50% over the entire windspeed range (Fig. 10a). CO_2 and WD also show similar decreases in the standard deviation as the WS increases.

3. RESULTS

The mean diurnal pattern measured at the Aspen tower will be presented. Note that the mean patterns shown herein are created by a wide var-

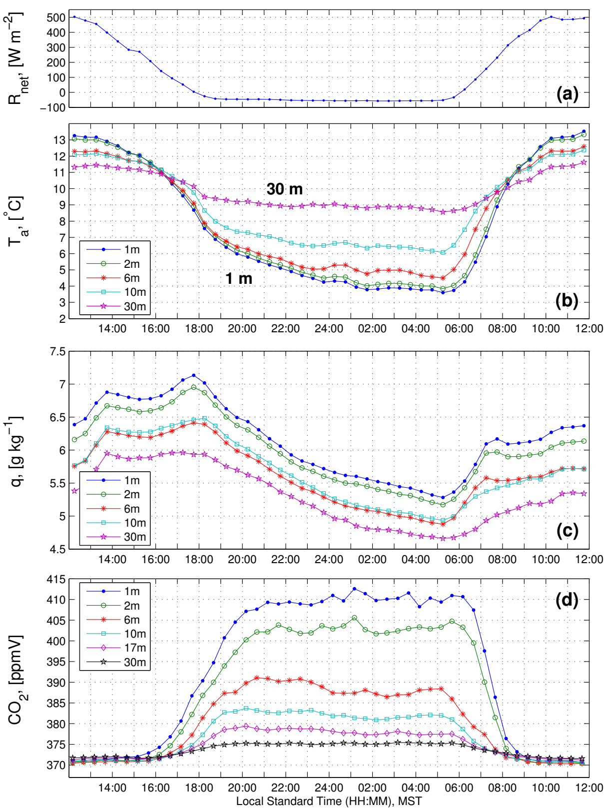

Figure 12: Half-hourly binned mean measurements from August and September, 2004 at the Aspen Tower for (a) net radiation R_{net}, (b) air temperature T_a, (c) specific humidity q, and (d) carbon dioxide CO_2. Five-minute mean data are used for R_{net}, T_a, and q while 15-minute data are used for CO_2.

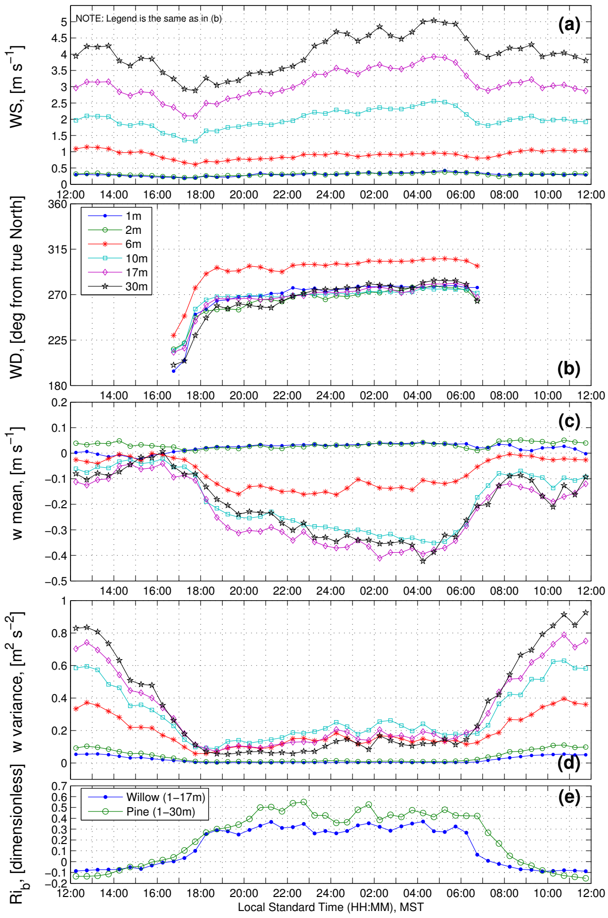

Figure 13: Half-hourly binned mean measurements at the Aspen Tower for (a) wind speed WS, (b) wind direction WD, (c) 5-min vertical wind (mean), (d) 5-min vertical wind variance, and (e) bulk Richardson number.

iety of different atmospheric phenomena (e.g., wave breaking, the effect of clouds, etc) and it is not possible to discern the effect of all these phenomena from the below analysis.

3.1 Typical Diurnal Pattern (Aspen Tower)

As shown in the previous section, the summertime winds at the tower site often experience the typical upslope (daytime) and downslope (nighttime) winds characteristic of sloping terrain (Whiteman, 2000). Figure 11 shows the frequency distribution of 5-minute averaged winds measured at each level of the Aspen tower during the day and night. At the 1 m and 2 m levels (ie, deep within the canopy) the winds never exceed 1 m s^{-1}. The above-canopy WS distributions are somewhat non-gaussian (as evidenced by the difference between the mean and median). During the daytime the above-canopy WD can be either upslope or downslope, while nearly any WD is possible within the canopy (Figs. 11b and 8). Note that if a mean or median is calculated from the binormal distribution of the above-canopy daytime WD the result can be nearly meaningless. At night both the above- and in-canopy WD are typically downslope (Figs. 11c-11d)). However, as mentioned in the previous section, when the above-canopy WS was greater than 7 m s^{-1} the in-canopy WD can be in a very different direction relative to the above-canopy WD. Figure 11c highlights that these higher WS conditions were not very common (around 10% of the time periods for August and September) so it is difficult to generalize this finding based on the somewhat limited number of data samples.

The typical diurnal atmospheric conditions at the site are revealed by the mean-composited parameters shown in Figs. 12 and 13, and the standard deviation of these same parameters shown in Figs. 14 and 15 (the standard deviation is an indication of the how much “day-to-day” variability there is in the measured parameters). Over the two

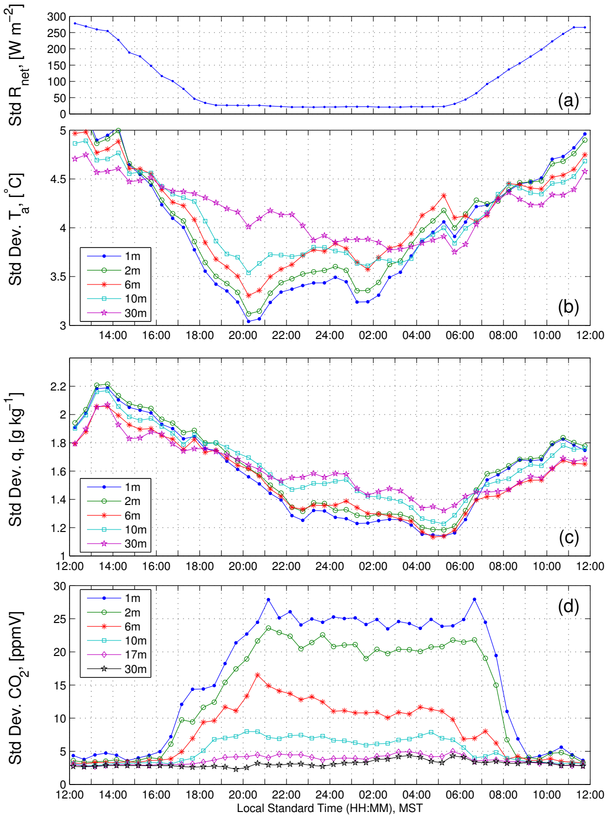

Figure 14: As in Figure 12, except the standard deviation of the data within each bin are shown.

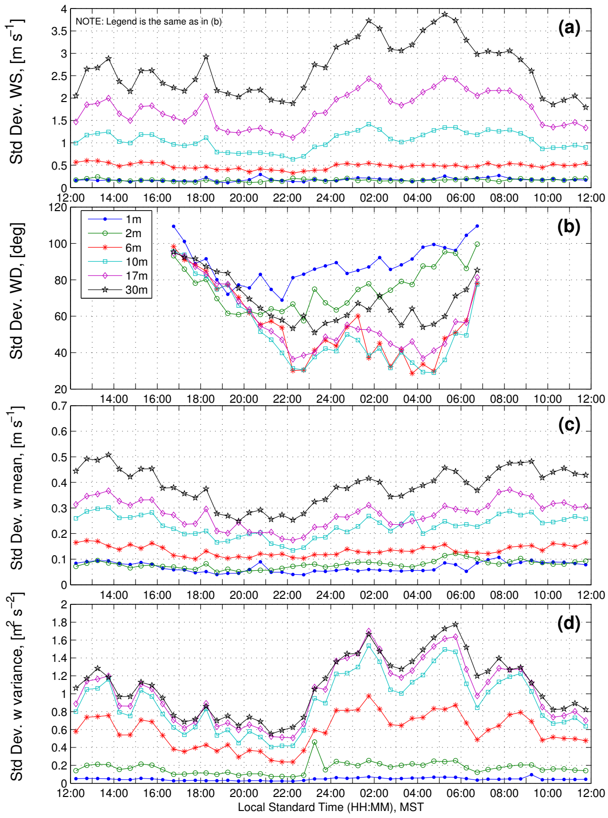

Figure 15: As in Figure 13, except the standard deviation of the data within each bin are shown.

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.

There are several distinctive features of the nocturnal downslope (or katabatic) flow that are highlighted here. The specific humidity gradually decreases throughout the night at the site (Fig. 12c). This is due to several factors: (1) the advection of drier air from higher elevation moves down past the tower site, (2) at night the stomates of plants close and reduce plant transpiration which effectively cuts 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 in the summer months), and (3) though there is typically not a lot of dew formation at the site, there are some nights where condensation occurs which will tend to further extract water vapor from the atmosphere. The peak in q at around sunset (17:00-18:00 MST) occurs at the same time time the WS is at a minimum (Fig. 13a) and the atmospheric stability is changing from unstable to stable. These conditions inhibit the vertical mixing of the air near the ground with higher-level air and effectively "trapping" water vapor near the ground and causing q to increase. At the same time the stability increases a drainage front might be passing by the towers and could force the more humid air near the ground up to higher levels on the tower (Monti et al. 2002). Another factor that leads to greater afternoon atmospheric humidity is the common occurrence of afternoon thunderstorms (primarily in August) that provides a source of water for evaporation.

The well-mixed CO_2 during the daytime (due to unstable atmospheric conditions and photosynthetic uptake of CO_2) and the large increase at night (due to stable atmospheric conditions and heterotrophic respiration of CO_2 by soil microbes) follows previous descriptions of the diurnal cycle of CO_2 (Yi et al. 2001) One reason for the large day-to-day variability of the CO_2 at night is the WS-dependence of the mixing of the vertical gradients mentioned in section 3.2 (Fig. 4b).

The gradual increase of WS throughout the night (Fig. 15a) is typical of downslope mountain flows (Whiteman, 2000) and indicative of the decoupling of the atmosphere from the the ground under stable conditions. As mentioned previously, when the drainage flow is fairly weak there is a maximum in the WS that forms between the 30m level and the top of the canopy (Fig. 5b). For stronger downslope flows the drainage depth extends some unknown distance above the height of the towers. The sonic anemometers were oriented perpendicular to gravity on each of the towers and 5-min mean vertical wind (without any tilt-correction) measured at each level is shown in Fig. 15c. Based on these data there is a clear downward movement of air during the night that is consistent with the downslope wind flows (note, since the sonics are oriented with gravity there is probably some mix of the horizontal "slope-following" wind in the vertical wind data). There also appears to be some periodicity (on a 2-hour scale) in WS (for both the mean and standard deviation, Figs. 15a and 15a). This might be indicative of pulsing flows that are common in mountain environments (e.g., Banta, 2004; Simpson, 1994).

The day-to-day variability of T_a and q are greatest during the day (Figs. 14b and 14c). This is because there is a wide range of incoming solar radiation conditions during the day (e.g, clear days versus cloudy days) whereas the nighttime radiative conditions are more consistent from day-to-day. From 17:00-24:00 MST the day-to-day variability of T_a at 30m is much larger than near the ground. This is because the 30m level is sometimes experiencing synoptic flow and sometimes experiencing drainage conditions (depending on the depth of the drainage flow) while near the ground drainage flow is almost always present. Later in the night (past midnight) the drainage flow has deepened so there is no longer a significant difference.

The day-to-day variability of CO_2 is greatest at night and a minimum during the day (due to the atmospheric mixing and photosynthetic uptake of CO_2 during the day). Also, there is a sharp increase in the day-to-day variability of the vertical velocity variance between 22:00-24:00 MST (Fig. 15d). 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 waves coming off the Continental Divide.). Examination of the bulk Richardson number between the lowest and highest levels at the Willow and Aspen towers show that the flow is in a regime around the critical Richardson number of 0.25 (Fig. 13e).

4. CONCLUSIONS

The mean diurnal cycle of temperature, humidity and wind in a mountainous forest location near Niwot Ridge, Colorado was examined. With a grade of ~4-12% at the site (and much steeper terrain nearby), katabatic flows were present above the canopy over 90% of the time at night (during August and September). During the daytime the ratio of upslope to downslope flows were around 50% (Fig. 11). The katabatic wind 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).

Quality checks on the data were performed by examining the vertical gradients of T_a, q, CO_2, WS, and WD at each tower for a range above-canopy WS conditions from 0-13 m s^{-1}. For the larger WS values there were not enough samples of high-WS conditions for a conclusive analysis, but dramatic changes in the vertical gradients were observed as the WS increases (accompanied by decreases in the variability of the binned data). Using the vertical gradients of CO_2, differences in canopy density can be observed among the various towers. The differences in canopy density have similar impacts on the gradients of q and WS.

The impact of using several different CO_2-measuring systems in CME-04 was evaluated based on final CO_2 measurements. Using multiple, well-calibrated calibration gases and frequent calibrations were found to be critical if CO_2 data from different systems are to be used together to do any analysis. Co-located inlets can be a useful tool for evaluating the accuracy between two different systems. When co-located inlets are not readily available, the mid-day CO_2 values can be compared to get some estimate of the inter-system accuracy (as long as the measurement locations are not too far away from eachother and in a fairly homogeneous area). Based on 2 months of CME04 data, the mid-day CO_2 difference at 30-m between the Pine and Aspen towers was found to have a mean of 0.02 ppmV with a standard deviation of 0.72 ppmV. Future studies that use multiple CO_2-measuring systems systems would be wise to plan for a way to evaluate the accuracy of the measurements between systems.

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.

5. ACKNOWLEDGEMENTS

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