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Measuring in-canopy advection of carbon dioxide using a new transect measurement system (TRAM)

Steven P. Oncley*[1], Karl Schwenz[1], Jielun Sun[1], Sean P. Burns[1,2], and Russell K. Monson[2]

[1]National Center for Atmospheric Research,† Boulder, Colorado
[2]University of Colorado, Boulder, Colorado

1 Introduction

Since the real world rarely is homogeneous, sampling at multiple locations is required in order to determine quantities that represent the state of the atmosphere close to the Earth's surface. Real-world inhomogeneities often exist over a wide range of spatial scales, especially for processes that involve multiple scientific disciplines, e.g. meteorology, biology, and hydrology. Furthermore, some of the spatial scales are dynamic and change with temporally varying quantities such as wind direction and atmospheric stability. To address this sampling need, we have developed a sensor platform that traverses a fixed cable.

Moving a sensor package between several locations has been done for many years and is required when only one sensor is available and/or when sufficient accuracy between independent sensors cannot be guaranteed. Cable-based trams have been operated traversing between two fixed supports (Dabberdt, 1967) and recent tram systems have mostly been used for radiation measurements (Baldocchi, 1984a & b, Lee and Black, 1993, Chen et al., 1997, Privette et al., 1997, and Blanken et al., 2001). The system described here is able to run along a closed path (a loop) and is able to measure both spatially-varying wind velocity and scalar quantities (and thus scalar advection). The system has been designed so that multiple sensor packages could be operated simultaneously on the same path in order to reduce sampling errors. If wind is measured at more than two positions on a closed path, flow divergence could be calculated continuously.

One problem that appears to require this type of sampling is quantification of carbon exchange in forest ecosystems. Sun et al. (1998) present evidence of subcanopy horizontal transport of CO_2 in forests, associated with nocturnal drainage flows. More recently, a series of experiments focused on this problem have been carried out at the Niwot Ridge AmeriFlux site near the University of Colorado Mountain Research Station (CU/MRS) that have supplemented routine observations (Sun et al., 2007 and Burns et al., 2008). The measurements suggest that the topography associated with the local water drainage, Como Creek, does alter the subcanopy CO_2 spatial distribution, with horizontal gradients observed at scales of 100 m.

Here we describe the first use of our TRAnsect Measurement (TRAM) system at Niwot Ridge to determine if finer spatial and temporal scales are important in the subcanopy transport of CO_2 and if Como Creek impacts this transport.

2 TRAM Description

2.1 Mechanical

The TRAM system is functionally like a toy electric train, with a trolley driven by an electric motor along a fixed, closed-loop track that also provides power to the motor. The majority of the TRAM track is segments of tensioned cable. There are two cables for each path segment – a "suspension cable" that supports the trolley and is the electrical ground connection and a "power" cable. Since these cables obviously are straight (except for the catenary droop), "turns" fabricated from bent tubing are required to make the track change direction (see Fig. 1). Cables from one track segment enter from one side and slip into the suspension and power tubing of the turn. After a short distance, the cables exit through slots in the tubing and are tensioned using ratchet straps to support tubes. A mirror set-up on the other side of the turn connects to the next cable segment. An alignment flange prevents the trolley from hitting the support tube as it negotiates the turn. The turns themselves are attached to a set of guyed towers.

The trolley (Fig. 2) used in this study had two wheel clusters connected by a flexible link. (The link allows the trolley to negotiate turns.) There are five wheels in each cluster. Three press against the suspension cable from different directions to hold the cluster captive to

*Corresponding author address: Steven P. Oncley, NCAR/ATD, P.O. Box 3000, Boulder, CO 80307-3000.

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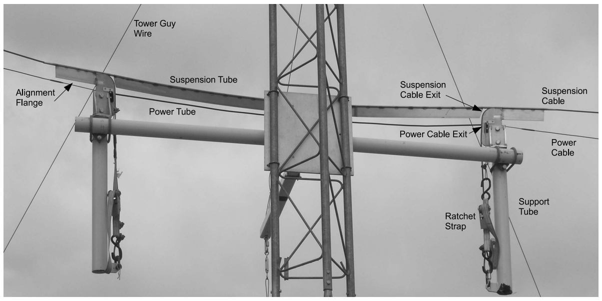

Figure 1: One of the TRAM turns installed on a tower.

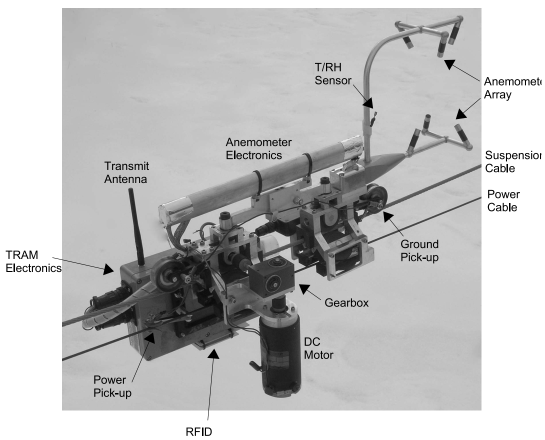

Figure 2: The TRAM trolley with key components labeled.

the cable. The other two wheels follow a guide rail that is built into the turns to prevent the trolley from hitting structural elements while transiting the turn. All but the top suspension wheel in each cluster are mounted on spring-loaded pivots to adjust for the somewhat different diameters of the suspension cable and support tubing and to allow some "play" as the trolley follows each turn.

A DC motor is mounted to one side of the rear wheel cluster and is connected via a 90-degree 2:1 reduction gear box to the topmost wheel of the cluster. Thus, the trolley is driven from the back along the suspension cable. A plastic box containing electronics (some instrumentation, the data system, and power conditioning) is mounted on the rear cluster on the opposite side of the wheel to offset the weight of the motor. The motor and electronics box are mounted to the rear cluster so that the anemometer (mounted to the front wheel cluster) is as far as possible from objects causing flow blockage. If more carrying capacity (bulk or weight) were needed, more wheel clusters could be added.

Spring-loaded copper wheels attached ahead of the front cluster and behind the rear cluster roll along the suspension cable to provide the electrical contact to ground and to help align the trolley to the cable. Spring-loaded carbon brushes contact these wheels to complete the electrical connection. A spring-loaded copper clip slides along the power wire on a two-axis pivoting arm riding behind the trolley to provide the positive power connection to the trolley.

Power is provided to the cables by connecting a bench-style power supply to one or more of the turns. The particular supply we are using has a serial port that allows our data system both to monitor and to control the TRAM power. At present, we have only implemented a "watchdog" function which shuts down all TRAM power if the trolley becomes stuck (detected by the power supply current not changing), however we could use this functionality to supply more power to the trolley to get it through parts of the track with greater drag.

2.2 Sensors

The sensor complement for TRAM is intended to be flexible to accomodate a wide variety of applications. Since the first use of TRAM was to study advection, measurements of carbon dioxide and wind were required along with temperature and humidity. To avoid making the first trolley too large, sensors were chosen to be relatively small and light.

TRAM uses an RMT Ltd. DX6100 closed-path (single cell) infrared gas analyzer for CO_2 which is only 100 mm$\times$86 mm$\times$35 mm and weighs 276 g. The noise level in CO_2 is 5 μmol mol^{-1} at 10 sample s^{-1}, which is somewhat large. However, the intent of the advection study is to identify pools of CO_2 with rather large concentrations (10–100 μmol mol^{-1} higher than ambient) and a modest amount of averaging is possible. This sensor was calibrated in situ by comparison to the NCAR HYDRA system (Burns et al., 2008) that has 18 spatially-distributed inlets connected to a LI-COR LI-7000 infrared gas analyzer that was continually-calibrated against four secondary standard gases. Six of these inlets were placed on TRAM towers and two towers had inlets at the two TRAM heights (see below). The gain of the DX6100 was assumed to be constant and was determined by comparing vertical gradients measured by it and HYDRA. The value that was determined was within 10% of the manufacturer's calibration. The offset had large amplitude temporal variations, presumably due to temperature changes that affect the response of the DX6100. It was determined by comparing the DX6100 measurements to those from HYDRA and applied by linearly interpolating between the comparison times.

Measurement of wind from any moving platform is a combination of determining the air motion relative to the platform and subtracting the platform motion relative to the Earth (e.g. Lenschow, 1986). We chose to use a sonic anemometer to measure the wind relative to TRAM due to its good performance in low wind conditions. We constructed our own transducer array to minimize both internal flow distortion and weight, based on the "UW" design of Zhang et al. (1986) and mounted it on top of the front wheel cluster. We used a pathlength of 15 cm because larger arrays deformed when the trolley moved through turns due to the large torque. Distortion of the air flow (and thus error in the wind measurement) by the array itself is known to be large for winds coming from behind this type of array. Thus, the trolley must move faster than the wind to keep the relative wind direction ahead of the array. Since previous tower data showed that the in-canopy flow never exceeded 2 m s^{-1} and the nominal trolley speed is 3–5 m s^{-1}, array flow distortion was not expected to be a problem. We also examined distortion of the flow by the entire trolley body, including the electronics box and motor, by running the trolley in the NCAR wind tunnel through a modest range of azimuth angles. All of the measurements had speed reductions of less than 3%, which is comparable to the level of flow distortion that has been found for the array itself. Thus, no correction for flow distortion was applied. The sonic anemometer data taken during this project were quite noisy, but were satisfactorily filtered using a simple despiker.

Determining the trolley motion was a harder problem than anticipated. The trolley has a GPS receiver, but GPS reception inside the canopy was poor and 70% of the time no satellites were available. Thus, we have simply used the difference in time for the trolley to go between known positions. By the end of the study, radio-frequency identification (RFID) markers were read at several of the towers to identify exactly when the trolley passed them and increases in current reported by the TRAM power supply indicated when the trolley was in a turn. However, at the beginning of the study neither of these signals were available, so we used the reported trolley heading to determine trolley position. With these estimates of the times when the trolley entered and exited each turn, the average speed along each track segment (cable or turn) could be calculated.

The difference between the relative air motion and the trolley motion produces the ground-referenced wind in trolley coordinates, assuming no "crab" angle of the trolley on the track and negligible cable motion. Both are reasonably good assumptions. To convert from trolley coordinates to Earth-referenced coordinates, the winds need to be multiplied by a rotation matrix calculated for every sample based on the heading, pitch, and roll of the trolley measured by a 3-axis fluxgate compass.

Temperature and relative humidity were measured by an SHT-75 solid-state sensor deployed near the sonic anemometer. The SHT-75 can only be sampled at 2 samples s^{-1} before self-heating errors become large, but this is fast enough to resolve many of the spatial features described below. Data from this sensor also were somewhat noisy – probably a data transmission issue – but were readily despiked.

2.3 Data System

A simple 8/16-bit microprocessor (PIC18F252) acquired data from the above instrumentation. Five discrete serial ports (UARTs) and several digitial I/O lines received data from all the sensors. Data were retransmitted through a pair of 2.4 GHz radio modems to a fixed data system. This radio link allowed real-time monitoring and archiving of all TRAM data without complicating the mechanical design. The radio link also allowed the operator to command the trolley. At present, this capability has been used only to stop the trolley, however, it is envisioned that this capability could allow multiple trollies to operate along the same track while maintaining a constant separation.

3 Deployment

The first field deployment of TRAM at Niwot Ridge was during summer and fall of 2007 (NIWOT07). Within a 1 km radius, the slope at this site is relatively uniform, with a slope of about 6 deg., falling to the East (Fig 3). The entire slope is drained by Como Creek, which is about 2 m across, and is fed by seasonal smaller drainages as the winter snow melts. The vegetation is mostly lodgepole pine (height about 11 m), with fir and spruce also present. There are some small groves of aspen and shrubs, especially near the Creek. See Monson et al. (2002) and Turnipseed et al. (2002) for more details about this site.

The TRAM transect crossed Como Creek. A loop was formed by having the trolley travel South at 5 m above ground (nominally in the middle of the canopy), make a 180 degree turn, return along the same set

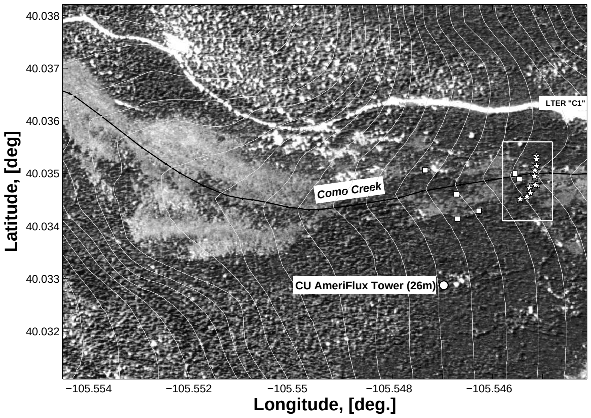

Figure 3: Image of the region near the Ameriflux site at Niwot Ridge. The eleven TRAM towers are shown as stars inside a box on the right. The lighter areas on the left side of the image indicate marsh regions, whereas most of the rest of the image is coniferous forest. The thick white curve near the top of the image is the site access road.

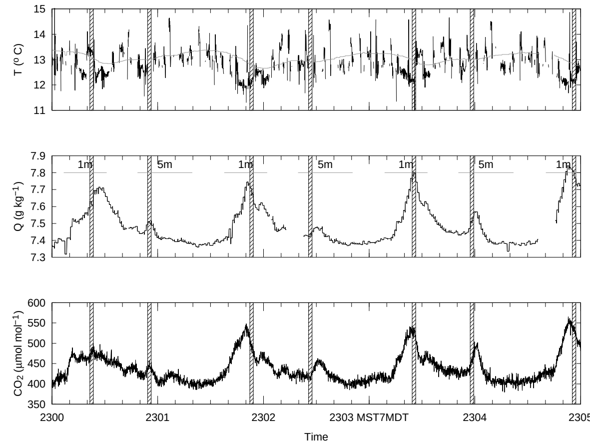

Figure 4: Example time series of some TRAM signals. The upper panel shows data from both the slow-response sensor (dotted line) and the sonic anemometer (solid line, with gaps during the turns). Cross-hatching indicates when the trolley was over Como Creek. Times when the trolley was at 1 and 5 m are indicated in the middle panel.

of towers heading North at 1 m above ground (nominally the trunk space), then turn 180 degrees again. The transect was approximately 120 m long, forming a 240 m total loop. The transect crossed Como Creek about 40 m South of the Northern tower.

The trolley drive wheel has been found to slip when the track is wet and eventually can be destroyed, so it was necessary to have an operator monitor TRAM at all times. This, along with the weather itself, limited the amount of data that were collected. Nevertheless, during August and September 2007 almost 60 hours of data were collected during 12 outings. The trolley typically completed a lap in 90 s, so more than 2000 laps around the track were sampled. These data were taken at various times of the day and night, so that every hour of the diurnal cycle was sampled on 2–6 outings. The longest outing was about 12 hours and the longest continuous run was almost 4 hours.

4 Results

An example time series from TRAM is shown in Fig. 4 over about three laps along the transect. Clearly, the data are periodic. In this example during the night of 17 August, CO_2 concentrations become almost 80 μmol mol^{-1} higher during the few seconds when the trolley was sampling near Como Creek at the 1 m height than anywhere else along the track. (This case was the largest CO_2 gradient observed by TRAM.) A secondary maximum appears when the trolley crosses the Creek at 5 m. Specific humidity varies similiarly to CO_2 and temperature is generally anticorrelated with both Q and CO_2. This is a consistent pattern as seen in Fig. 5, which shows two-hourly averages of CO_2 concentration as a function of track position for this night. Note that during the day, CO_2 appears to be well mixed and no change along the track is observed. This signature – well-mixed CO_2 during the day and a build-up at the Creek at night – was seen consistently in all of the TRAM data and agrees with observations taken in 2004 at this site (Burns et al., 2006).

Figure 6 presents a subset of the data from this night as a time-distance cross-section. Clearly, the placement of the maximum CO_2 concentration at the Creek seen in Fig. 5 is an artifact of temporal averaging. Panel (e) of Fig. 6 shows that "blobs" of CO_2-rich air concentrate close to the surface (1 m height) in the general vicinity of the Creek, though their exact position shifts with time, more-or-less following the wind trajectory. These blobs appear to be on the order of 20 m wide, 100–600 m long, and mostly less than 5 m high. However, the relatively large temporal changes in amplitude indicate that these are not "rivers" of CO_2-rich air. A clear relation between the fine-scale structure of these blobs and the (three-dimensional) wind velocity is not apparent, suggesting that turbulent mixing does not control how they are organized, though larger-scale effects were seen (see below).

Panels (d,f) in this figure show that these blobs are generally cool and moist, though there is not a perfect

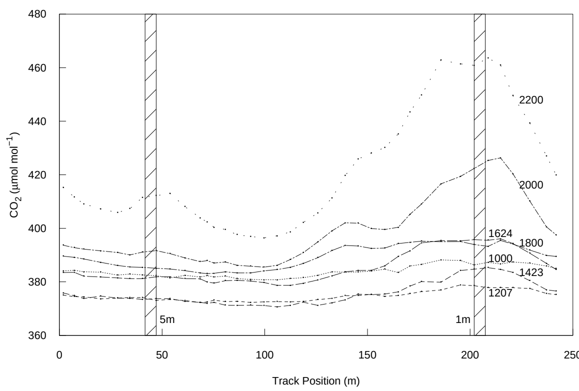

Figure 5: Composites of TRAM CO_2 data for the outing on 17 August, with values averaged over 2-hour periods for each position along the track. Line labels are the start time (MDT) of each period. Track positions 0–127 m are for the trolley traversing southward at a height of 5 m and 127–245 m for the northward return at 1 m. As with Fig. 4, cross-hatching indicates Como Creek.

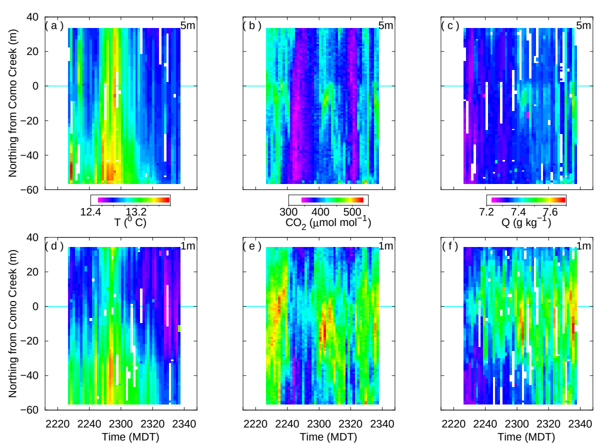

Figure 6: Time-distance cross-sections of temperature (a,d), carbon dioxide concentrations (b,e), and specific humidity (c,f) measured by TRAM. Distances are the position north of Como Creek. (The Creek is indicated by the horizontal blue line.) Measurements made at a height of 5 m are shown in the top panels (a–c) and at 1 m in the bottom panels (d–f). Each TRAM circuit produces a vertical stripe in this plot.

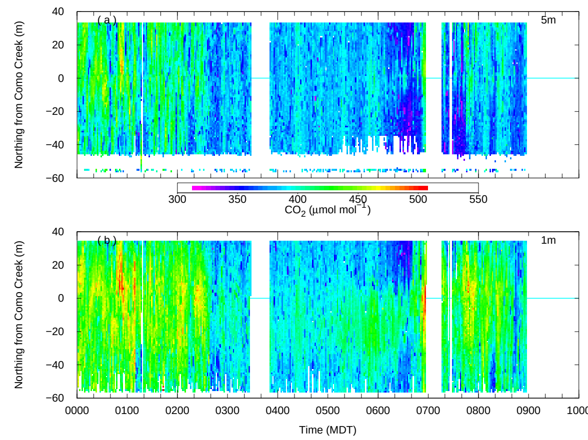

Figure 7: Similar to Fig.6 for values of CO_2 concentration for the morning of 8 September. Missing data at the bottom of panel (a) and to a lesser extent in panel (b) are due to a loose antenna connection on this day.

correlation between the spatial variations of these three scalar quantities. The general correlation seen between CO_2 and Q was observed during all of the nocturnal outings. The relatively fine-scale structure seen in the fields of CO_2 concentration and Q are not observed in temperature.

Finally, panel (b) shows that the CO_2 concentrations were much lower at night in the mid-canopy space just 4 m higher than the data shown in panel (e). This behavior has been observed by others at this site. The blobs that have the greatest CO_2 concentration at 1 m appear to extend vertically up to 5 m, whereas a lesser-amplitude blob at 2320 MDT in the 1 m data does not appear at 5 m. Again, CO_2 concentration and Q appear to be more-or-less correlated and CO_2 and T are vaguely anti-correlated.

Figure 7 presents a longer duration case in which a similar pattern of meandering blobs of CO_2 disappeared at 0240 MDT in a matter of minutes with the pattern reappearing about four hours later. This change is associated with a shift in wind direction (from 270 to 295 degrees), a doubling of wind speed (from 0.5 to 1.0 m s^{-1}), and a factor of 3 increase in the variance of w (from 0.003 to 0.011 m^2 s^{-2}) during this four-hour period. Thus, the decrease of CO_2 during these four hours is due either to enhanced vertical mixing (which would transport CO_2 to higher levels of the canopy or above) or to horizontal advection of air with lower CO2 concentration (or both). For the west winds before and after this period, air would have come from a wetland 400 m to the west of the TRAM location (see Fig. 3). Wetlands generally are assumed to have relatively high respiration rates due to higher amounts of soil organic

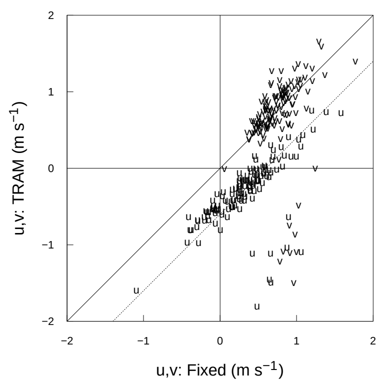

Figure 8: Comparison of wind measurements from TRAM versus those made by a fixed sonic anemometer. The dotted reference line indicates an offset of 0.6 m s^{-1}.

matter, though we have no data that verifies this assumption and the CO_2 flux to the atmosphere likely is different due to the lack of a tall canopy. For more northerly wind directions, the fetch is from the slope of Niwot Ridge itself where soils would be expected to have less organic matter. If advection is dominant, much of the nocturnal CO_2 build-up that was observed would not be from local sources.

A comparison of TRAM wind measurements with those from a fixed anemometer deployed on one of the TRAM towers is shown in Fig. 8 for the outing on 7-8 September. Each point in this figure is the median of 1.8 s of data when the trolley was approaching the fixed anemometer. The wind components are presented in trolley coordinates, so the v component is simply the measurement from TRAM's anemometer whereas the u component also includes the derived trolley motion. An offset of about 0.6 m s^{-1} is seen in u. The most obvious explanation for this offset would be the determination of the trolley motion, however the values that were used (averaging 3.7 m s^{-1}) appear to be reasonable given the measured times passing known positions. Thus, we suspect that this represents a "cycle-slip" due to mistriggering of a weak transducer in the sonic anemometer for this path while the trolley was in motion. The scatter in the data (with a standard deviation of about 0.12 m s^{-1} for each component) presumably represents real differences due to the different sampling in space, though the measured trolley motion contained in u also has an uncertaintly of about this magnitude.

5 Summary and Future Work

We have constructed a new tool for measuring especially horizontal gradients of atmospheric variables over spatial scales of 1–100 m and temporal scales on the order of minutes. The variables currently measured are wind velocity, temperature, humidity, and CO_2 concentration. In our initial use of TRAM, most measurements had problems at least some of the time for a variety of reasons. We are currently working to resolve these issues.

The variation of CO_2 that was found was consistent with tower-based observations made previously at this site, however the limited spatial extent had previously been unknown. Future work will calculate a CO_2 budget for the area by synthesizing TRAM observations with soil respiration, HYDRA CO_2 gradient, and tower CO_2 flux and concentration observations made at this site during the same period. Finally, we plan to add sensors for photosynthetically-active radiation (PAR), ozone, and aerosol size distribution to allow TRAM to be used for other applications.

Acknowlegements

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