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FLUXES OF ATMOSPHERIC CARBON DIOXIDE OVER A SUBURBAN AREA OF VANCOUVER

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1. INTRODUCTION

Until very recently measurement of atmospheric carbon dioxide fluxes has primarily focused on measurements over simple homogeneous surfaces such as bare soil, agricultural fields or forests whereas urban areas has been largely ignored, probably due to their complexity. Understanding CO_2 fluxes from urban areas is, however, important in order to better understand the interaction of natural and anthropogenic processes that control the role of cities in carbon budgets. A few short-term studies have been conducted at urban sites including a suburban/commercial area of Chicago (Grimmond *et al.,* 2002a), central Edinburgh (Nemitz *et al*., 2002) and Marseille, France (Grimmond *et al.,* 2004), and residential areas of Copenhagen (Soegaard and Moller-Jensen, 2003), Tokyo (Moriwaki and Kanda, 2004), and Basel (Vogt *et al.,* 2004). A long-term field project is currently underway in Baltimore (Grimmond *et al.,* 2002b), but there are relatively few such studies.

Through the combined effects of widespread deforestation, changes in land use and expanding urban development, long-term stores of carbon are being released into the atmosphere, leading to the well known temporal increase in the global CO_2 concentration. Urbanization tends to diminish the terrestrial sink as forests and natural ecosystems are removed to make way for parking lots, buildings and roads. In addition, urbanization introduces major CO_2 sources through the combustion of fossil fuels. Without knowledge of the magnitude of urban atmospheric CO_2 fluxes, and the controls upon them, a significant part of the modern carbon budget scenario is missing. Further, study of carbon dioxide in urban areas, where the majority of anthropogenic sources are concentrated, may provide insight into how ecosystems will react to elevated CO_2 levels.

The goal of this study is to provide long-term (>1 year) measurements of carbon dioxide fluxes from an urban area. Objectives of this research include determination of the effect of emissions and vegetative influences on the flux of CO_2, quantification and description of seasonal variations, and comparisons with results from other urban CO_2 flux research sites.

2. METHODS

2.1 *The Site*

The site (Sunset Site) is located in a suburban district of Vancouver, B.C. The measurement site is situated near the corner of Knight Street and 49th Avenue, Vancouver, within the confines of a BC Hydro substation. A 30-meter open construction lattice tower sits near the southeast corner of the substation. Surrounding topography is relatively even with only slight undulations and a gentle slope southwards towards the Fraser River. Within a 2 km radius, the urban structure is approximately 80% suburban, low density, 1-2 story housing with an average building height of 8.5 m. Based on surveys conducted in the 1980s the plan area consists of 64% greenspace, 24% buildings, and 11% pavement (Figure 1) (Cleugh, 1990). The aerodynamic roughness length is approximately 0.5 m and the zero-plane displacement length is 3.5 m based on morphometric analysis of the urban geometry (Roth, 1991). This suburban area extends at least 1.5 km in all directions from the tower giving relatively homogenous fetch.

Figure 2: Airphoto of the suburban region. Tower location is marked with an X.
(City of Vancouver, 2002)

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2.2 *Field measurements*

Measurements at the tower site were conducted continuously from August 2001 to January 2003.

Standard eddy covariance techniques were utilized to measure and calculate the flux of atmospheric carbon dioxide. A Li-cor 7500 infrared gas analyzer measured the relative densities of carbon dioxide and water vapour, whilst a Gill 3-dimensional asymmetric sonic anemometer measured the horizontal, vertical and crosswind components of wind velocity (u,v and w). These instruments were mounted at 27.0 m above ground on a boom that extended 1.8 m southwest from the tower in order to minimize disruption of airflow by the tower itself. The spacing between the adjacently mounted instruments was 0.5 m from August 2001 to July 30, 2002 and 0.2 m from July 30, 2002 to January 1, 2003. Both set-ups therefore conform with the recommendation of Baldocchi *et al*. (2000) and Meyers (2001) that the distance between the sonic anemometer and the infrared gas analyzer should be less than 0.5 m to minimize flow distortion and lag effects.

Additional meteorological instrumentation was mounted at 27.8 m and included a Kipp and Zonen CNR1 net radiometer to measure the fluxes of incoming and emitted longwave radiation and of incoming and reflected shortwave radiation. An RM Young wind vane and cup anemometer was also mounted at 27.8 m; an HMP 35A temperature and humidity sensor was mounted at 20.1 m.

2.3 *Logging and processing of data*

All data were recorded on a Campbell Scientific Inc. 23X datalogger housed in a camper at the base of the tower. Turbulence, carbon dioxide, and water vapour data were sampled at 10 Hz to ensure adequate sampling of the high-frequency portion of the flux cospectrum (Anderson *et al.*, 1984). Fast response data were automatically downloaded to a computer every 30 minutes. The slow response instruments were sampled at 5-second intervals and data were automatically downloaded every 24 hours to the computer.

10 Hz data were block-averaged for 30 minute periods. All data presented here are based on 30 minute averages with the time stamp indicating the end of the 30 minute period. All times referred to are local time, labeled as Pacific Standard Daylight Time (PSDT). Eddy covariance fluxes were calculated based on methods described in Schmid *et al.* (2000 and 2003) and Offerle *et al*. (2003).

2.4 *Issues to consider when measuring CO_2 over an urban surface*

Measurement height is an important variable to consider when observing meteorological variables over urban areas. Measurements within the roughness sublayer (RSL) are influenced by the micro-scale (Figure 2). Within this layer entities are not well mixed and therefore carbon dioxide concentrations, for example, are likely to be highly variable, and dependent on exactly where they have been measured. Above the RSL, representative of the local-scale, it is possible to capture an integrated (well-blended) response of all surface features located in the upwind source region. This is the constant flux, or inertial sublayer (ISL), and fluxes or heat, mass and momentum are expected to be spatially homogenous throughout the layer. At urban sites, to ensure measurements are within the inertial sublayer, an emerging rule-of-thumb is that instruments be mounted at greater than 2 times the height of the mean roughness elements. The height appears to depend on the density of the elements and the factor may range from 1.5 at very dense sites to 4 with open element spacing (Oke, 2004).

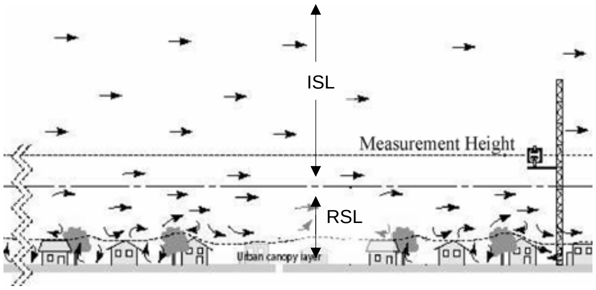

Figure 1: Ideal measurement height over an urban environment (Masson *et al*., 2003)

In addition to mounting instruments at a height that will correctly represent an integrated, well-blended, response from the surface elements, the source area, of each instrument must be considered. The source area is the segment of the surface that influences the sensor. It depends on the mounting height and the process being monitored. Radiative source areas are circles with the tower in the center. On the tower, the downward sensor element of the radiometer projects a field-of-view onto the surface. The radius of this radiative source area is given by:

$$r = \left(\frac{1}{F} - 1 \right)^{-1/2} \qquad [1.0]$$

where F is the view factor and r is the radius of the circular surface disc (Reifsnyder, 1967). For the radiometer on the Vancouver tower, a 0.95 view factor yields a source area radius of 121 m and for a 0.99 view factor the source area radius is 277 m. Source areas or ‘footprints’ of entities carried by turbulent transfer, such as sensible and latent heat or carbon dioxide are more complex and dynamic. In this case the sensor is influenced by a spatially averaged contribution of an elliptical surface patch located upwind from the tower. The shape of a turbulent source area isopleth is given in

Figure 2. Turbulent source areas change in size and position as the wind direction and stability change throughout the day.

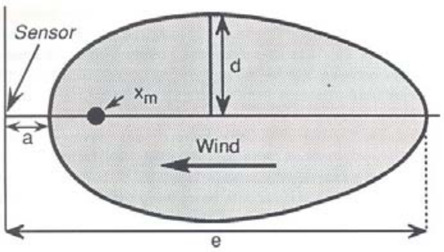

Figure 2. Dimensions of a turbulent source area isopleth. x_m: maximum source location, *a*: downwind edge, *e*: upwind edge and *d*: lateral half-dimension of the source area. (Schmid *et al*., 1991)

3. RESULTS AND DISCUSSION

3.1 *Energy and radiation fluxes*

In addition to the CO_2 fluxes, energy balance and radiation budget components were measured at the site. Fluxes of energy and radiation have been reported from this site as part of many studies since the early 1980s. 2002 was somewhat warmer and drier than average. Low precipitation in the summer forced watering restrictions throughout Vancouver. This prevented irrigation of surface vegetation such as lawns causing vegetation to turn brown early in the season. Also, surfaces within the 95% radiative source area consist largely of impervious ground including asphalt roadways and sidewalks, as well as gravel substrate for the nearby schoolyards and the BC hydro substation.

The annual ensemble results for 2002 are given in Figure 3. The individual day and monthly average results look similar to those measured in previous studies except that the role of the sensible heat fluxes appears to be increasing over time. It is difficult to be certain of this, given the inter-annual variability of the forcing conditions, but if true it would be consistent with the tendency for continued development of building lots and the increase in traffic over time. In addition, there has been a change in technology used for observations.

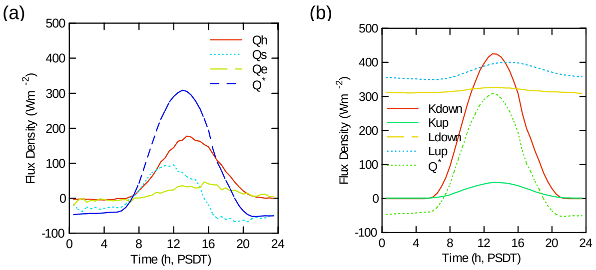

Figure 3: (a) ensemble energy balance for 2002, (b) ensemble radiation budget for 2002

3.2 *Carbon dioxide fluxes*

Here carbon dioxide fluxes are presented as positive if carbon dioxide is being emitted into the atmosphere from the surface, and negative if there is uptake or sequestration of CO_2 by the surface. Our expectation at this suburban site is that at midday fluxes in the summer months are likely to be negative when vegetation sequesters carbon dioxide from the atmosphere via photosynthesis at rates greater than those of emissions (mainly from vehicles). In contrast, in winter we might expect to see positive fluxes when emissions dominate in the absence of the photosynthetic sink. We also expect the positive winter fluxes should be greater due to space heating emissions from residential buildings.

Data from 2002 indicate fluxes of carbon dioxide are variable throughout the year and do not simply follow the expected patterns. The ensemble average diurnal carbon dioxide fluxes, presented by month, show that negative fluxes are virtually absent throughout the year (Figure 4). This indicates that photosynthesis by the substantial vegetation cover sequestered CO_2 from the atmosphere during leaf out, but the vegetative sink was not strong enough to offset CO_2 emissions by respiration and fuel combustion.

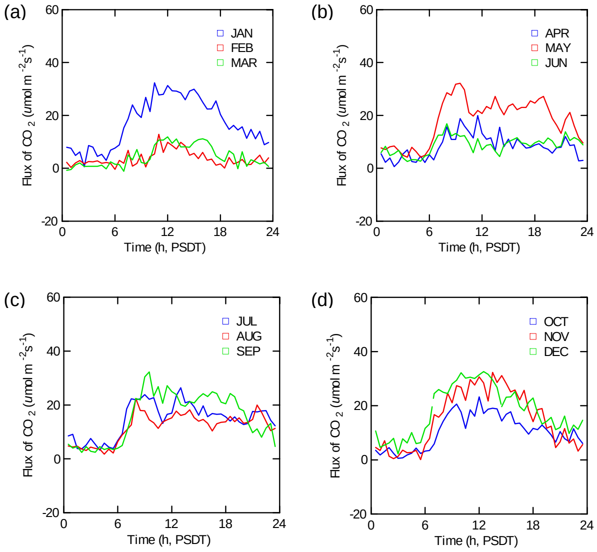

Figure 4: Variability of average daily CO_2 fluxes for the year 2002, (a) Jan-Mar 2002, (b) Apr-Jun 2002, (c) Jul-Sep 2002, (d) Oct-Dec 2002

Further, in individual months the data do not follow expected seasonal trends. For example, the month of May 2002 has a higher midday average flux than would be expected for a month when the trees are in full leaf and photosynthesis should be occurring (Figure 5).

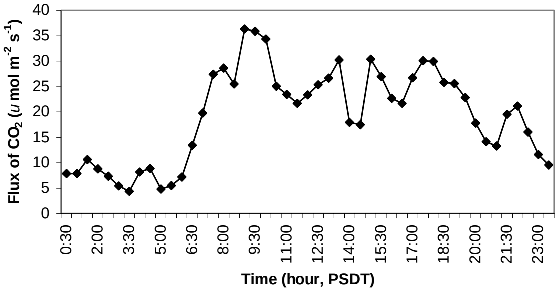

Figure 5: Higher than expected average daily carbon dioxide flux for the month of May 2002

In order to examine anomalies in the data, such as this, shorter time scales must be examined to determine what controls the magnitude of CO_2 fluxes. Manual examination of data revealed a correlation between prevailing wind direction and the magnitude of the carbon dioxide flux. As the wind direction shifts, abrupt changes in carbon dioxide fluxes are often evident.

A closer look at the correlation between wind direction and CO_2 fluxes was achieved by filtering data by wind direction. Eight wind sectors were arbitrarily chosen (Table 1) and the average CO_2 flux from each sector was subsequently calculated for each month.

Wind sector	Wind directions included	Primary surface features in the source area
Sector 1	0-45°	Road, grass, school-yard
Sector 2	46-90°	School-yard
Sector 3	91-135°	Main road, major intersection
Sector 4	136-180°	Main road, major intersection
Sector 5	181-225°	Residential
Sector 6	226-270°	Road, residential
Sector 7	271-315°	Residential
Sector 8	315-360°	Substation, grass

Table 1: Wind sector divisions and primary surface features within each sector

In May, 2002 there was a high frequency of winds coming from Sectors 3 and 4 (Figure 6(a)). The source areas for turbulent fluxes in these sectors are occupied by a major arterial highway intersection (Knight Street and 49th Avenue) including a designated truck route. As a result the flux of carbon dioxide from those directions shows significantly higher values than from most other sectors (Figure 6(b)). A similar pattern of correlation between wind direction and CO_2 fluxes is seen throughout the year (Figure 7). When the wind comes from the direction of the busy intersection (Sectors 3 and 4) CO_2 fluxes are high.

Similar sector analyses of the sensible and latent heat fluxes do not show such directional dependency. This points out the dissimilarity of the spatial nature of the source strength distributions for heat, water vapour and carbon dioxide. Earlier results from this same tower site noted the difference between the source distributions of heat and water vapour; all urban surfaces are sources of heat but not necessarily of water leading to the finding of the inequality of transfer efficiencies for the two entities (Roth and Oke, 1995). Even so previous results from this site have not noted the existence of sectoral bias in the fluxes of heat or moisture. The sources and sinks of carbon dioxide are even more spatially uneven than for water, consisting as they do of a mixture of area and line sources and sinks. In the present case it appears that the intersection of two major line sources creates a strong directional bias. The analysis of data from such a site therefore requires special source area considerations not normally necessary in urban energy balance studies.

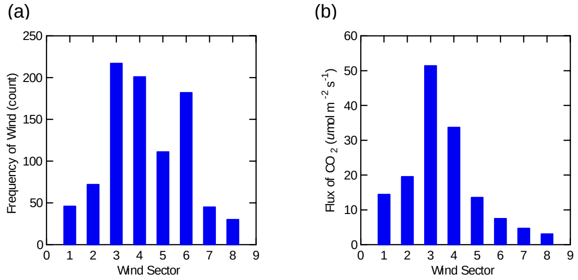

Figure 6: (a) frequency of wind direction from each wind sector, (b) average carbon dioxide flux from each sector; both for daylight hours in May 2002

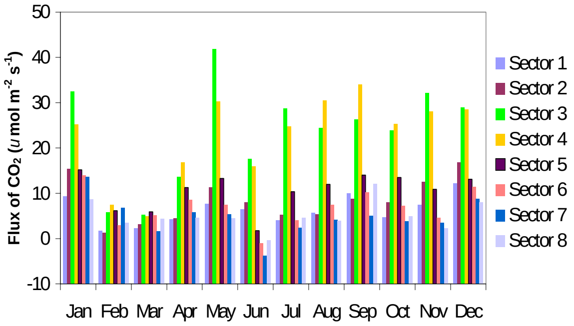

Figure 7: Average flux of CO_2 from each wind sector for 2002

4. SUMMARY

Results of carbon dioxide fluxes for the year 2002 from a suburban site in Vancouver are presented. Analyses indicate that small changes in wind direction result in relatively sharp changes in the fraction of the surface characteristics contributing to sources and sinks of CO_2, which can significantly affect the magnitude of the carbon dioxide fluxes. In particular, high CO_2 fluxes occur when winds are from the direction of the main vehicular routes that pass close to the tower. During the summer the vegetative sink at this site, which is 64% vegetated, is not sufficient to outweigh emissions from the suburban area.

5. ACKNOWLEDGEMENTS

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