Diurnal Course of Carbon Dioxide Mixing Ratios in the Urban Boundary Layer in Response to Surface Emissions

B. CRAWFORD, A. CHRISTEN, AND I. MCKENDRY

Department of Geography, The University of British Columbia, Vancouver, British Columbia, Canada

(Manuscript received 26 February 2015, in final form 20 October 2015)

ABSTRACT

Observations of carbon dioxide (CO₂) mixing ratios in the urban boundary layer (UBL) are rare, even though there is potential for such measurements to be used to monitor city-scale net CO₂ emissions. This work presents a unique dataset of CO₂ mixing ratios observed in the UBL above Vancouver, British Columbia, Canada, by means of a tethered balloon system over a continuous 24-h summertime period. Vertical profiles of CO₂ mixing ratios are found to vary according to UBL thermal structure and mechanical dynamics (development of convective and nocturnal boundary layers, vertical mixing from mechanical turbulence, horizontal advection from land–sea thermal breezes, and vertical entrainment). A box model is applied to quantify net city-scale surface emissions to the UBL volume using the measured rate of change of UBL CO₂ mixing ratios and estimated CO₂ advection and entrainment fluxes. The diurnal course of city-scale net emissions predicted by the model is similar to simultaneous local-scale eddy-covariance CO₂ flux measurements, although there are relatively large uncertainties in hourly model calculations of horizontal advection and vertical entrainment fluxes due to inputs of regional background CO₂ mixing ratios. Daily city-scale emissions totals predicted by the model (20.2 gC m⁻² day⁻¹) are 35% larger than those measured simultaneously on an urban local-scale eddy-covariance flux tower and are within 32% of a spatially scaled municipal greenhouse gas inventory. However, these methods are not expected to agree exactly because they represent different spatial source areas and include different CO₂ source and sink processes.

1. Introduction

Although a majority of global anthropogenic carbon dioxide (CO₂) emissions originate from urban areas (e.g., Satterthwaite 2008), few studies have investigated CO₂ mixing ratios in the urban boundary layer (UBL). Observations are challenging because heights of tower platforms that could support in situ CO₂ mixing ratio measurements in urban areas are often too low (located in the surface layer) and airborne measurements tend to be labor intensive and expensive. Satellite-based remote sensing techniques show promise, but instruments are not yet sensitive enough to resolve variations in CO₂ mixing ratios that result from relatively small changes in surface emissions (Kort et al. 2012). Nevertheless, observations in the UBL are useful because CO₂ mixing ratios here are representative of city-scale airsheds because of the spatial averaging properties of atmospheric turbulent mixing. Therefore, column-based measurements over urban areas are likely to yield more information about urban-scale fluxes than a near-surface measurement because they represent a larger source area of influence (McKain et al. 2012). This means there is potential to infer city-scale net CO₂ emissions from mixing ratio time series in the UBL in order to monitor emissions and validate municipal emissions inventories and models.

Two general approaches have been commonly used to infer net emissions at city scales from concentration or mixing ratio measurements. The first uses mixing ratio observations together with inverse atmospheric transport modeling to derive upwind source areas and surface fluxes. Examples include the Stochastic Time-Inverted Lagrangian Transport (STILT) model (Lin et al. 2003) coupled with wind fields generated by a three-dimensional meteorological mesoscale model. An example study using this approach was conducted around Salt Lake City, Utah, where mixing ratio observations at several near-surface locations were used to detect

Corresponding author address: B. Crawford, Dept. of Geography, The University of British Columbia, 1984 West Mall, Vancouver, BC V6T 1Z2, Canada. E-mail: bencrawf@gmail.com

DOI: 10.1175/JAMC-D-15-0060.1

© 2016 American Meteorological Society
changes in anthropogenic CO$_2$ emissions of greater than 15% on monthly time scales (McKain et al. 2012). In Los Angeles, California, a similar inverse modeling approach was used to determine the minimum density of surface-based observation sites required to resolve anthropogenic CO$_2$ emissions at 8-week and 10-km resolutions (Kort et al. 2013). In Heidelberg, Germany, atmospheric transport modeling was combined with a 5 min $\times$ 5 min–resolution CO$_2$ emissions model to predict observations from a stationary network of CO$_2$, CO, and radon sensors (Vogel et al. 2013). Another example of this approach was conducted in Paris, France, where a network of CO$_2$ mixing ratio measurements was used to model surface CO$_2$ fluxes on 6-h time scales. Bréon et al. (2015) concluded that inversion modeling techniques that rely on CO$_2$ upwind-downwind gradients perform better than those that simply use raw CO$_2$ mixing ratios. In Boston, Massachusetts, McKain et al. (2015) used an inverse modeling approach and tower-based measurements to quantify annual methane emissions from natural gas infrastructure.

The second common approach is to formulate a box model based on mass conservation principles. Box models generally need only mixing ratio measurements in a convective boundary layer to represent regional fluxes, in addition to measurements or models of boundary layer depth (Cleugh and Grimmond 2001). An important assumption is that of a well-mixed boundary layer that has fully adjusted to the underlying urban surface. Following scaling arguments by Raupach (1995) and Cleugh and Grimmond (2001), the downwind distance $X$ (m) required for boundary layer adjustment during convective conditions is related to the convective time scale $t_b$ (s), horizontal wind velocity in the mixed layer $U$ (m s$^{-1}$), and convective velocity scale $w_*$ (m s$^{-1}$):

$$X = z_i U / w_* ,$$  

where $z_i$ is the boundary layer height and $w_*$ is

$$w_* = \left( \frac{g F_{HV} z_i}{\theta_v} \right)^{1/3} ,$$  

where $F_{HV}$ is the kinematic virtual heat flux $(Q_H + 0.07 Q_E / \rho C_p)$ and $\theta_v$ is the virtual potential temperature in the well-mixed convective boundary layer. The sensible and latent heat fluxes (W m$^{-2}$) are $Q_H$ and $Q_E$, respectively, and $\rho$ and $C_p$ are the density and heat capacity of air, respectively.

The convective time scale for a surface signal to reach the top of the boundary layer is

$$t_b = X / U = z_i / w_* .$$  

It then follows that a convective boundary layer will be fully mixed over lengths greater than $X$ and times longer than $t_b$. If the scale of horizontal heterogeneity of surface fluxes is much less than $X$, boundary layer concentrations will be representative of the average of the surface source–sink processes underlying the boundary layer.

Studies using a boundary layer budget approach in urban areas must take into account the unique ways that urban areas modify the overlying boundary layer structure. In idealized daytime conditions with clear skies and a regional background wind, an internal boundary layer grows downwind with distance from the upwind urban edge until it occupies the entire planetary boundary layer. This internal boundary layer is the UBL and strong heating of the urban surface relative to the surrounding nonurban areas (e.g., from the urban heat island effect and modification of the surface energy balance toward higher Bowen ratios) drives buoyant convection that propels the UBL higher than the surrounding nonurban boundary layer (Oke 1987). The lowest 10% depth of the UBL is classified as the surface layer and is characterized by steep vertical gradients of scalar atmospheric variables. In the overlying 90% of the UBL (the mixed layer), strong mixing from convective turbulence is expected to result in near-uniform vertical profiles of wind speed, water vapor, potential temperature, and suspended air pollutants (e.g., Oke and East 1971).

Overnight in nonurban areas, cooling of the urban surface after sunset creates a layer of stable air that acts to suppress vertical mixing and transport. Over urban areas, a shallow, slightly unstable surface layer (SL) has often been observed as a result of increased mixing from storage heat releases, anthropogenic heat emissions, and greater urban surface roughness (e.g., Oke and East 1971; Uno et al. 1988). Above the slightly unstable SL is an elevated temperature inversion and stable nocturnal boundary layer (NBL) along with an overlying residual mixed layer (RL). The RL is a near-neutrally stable layer of residual turbulence, heat, and pollutants from the previous day capped by a temperature inversion. Nocturnal profiles of potential air temperature are expected to be roughly constant from the surface through the SL, increase in the NBL, then become roughly uniform with height in the RL (e.g., Oke and East 1971). Vertical profiles of pollutants with active nocturnal surface sources, such as CO$_2$, are expected to decrease with height above the nighttime SL as a result of near-surface buildup below the temperature inversion and lack of vertical mixing (e.g., Oke and East 1971).
Several studies have used aircraft-based measurements of CO₂ mixing ratios to calculate the city-scale net CO₂ flux using a box model formulation. In Indianapolis, Indiana, measurement flight paths were conducted through the depth of the boundary layer downwind of the city. A spatially interpolated vertical plane of CO₂ mixing ratio values normal to the prevailing wind direction downwind of the city was then used to attribute net emissions to an upwind urban spatial area. Fluxes calculated using this method showed high temporal variability (mean 19.2 ± 15.4 μmol m⁻² s⁻¹), but mean values were not statistically significantly different from an independent spatial surface emissions model (Mays et al. 2009). In London, United Kingdom, a measurement campaign used aircraft-based observations to estimate urban CO₂ fluxes and found daytime averages of 46–104 μmol m⁻² s⁻¹. These flux magnitudes are statistically similar to synchronous measurements from local-scale urban eddy covariance (EC) flux towers and emissions inventories (Font et al. 2015). In Rome, Italy, airborne measurements and mass budgeting techniques were used to estimate city-scale fluxes that ranged from 2.5 to 14.7 μmol m⁻² s⁻¹ (Gioli et al. 2014). These estimates were compared with concurrent CO₂ emissions inventories and the largest differences between the model and inventories were associated with greater wind speed and direction variability during measurements.

Tower-based CO₂ mixing ratio measurements have also been used in urban box model studies. In Vancouver, British Columbia, Canada, Reid and Steyn (1997) used a series of eight boxes describing UBL growth combined with a surface emissions model to predict CO₂ mixing ratios at a single measurement location located 28 m above the urban surface. A similar approach was developed in Salt Lake City, Utah, using a total of 162 boxes and a near-surface CO₂ monitoring network comprising seven stations (Strong et al. 2011). These studies rely on mixing ratios measured at a single tower height near the surface, rather than integrated measurements over the depth of the UBL.

To date, neither boundary layer budget approaches nor inverse modeling techniques are able to monitor emissions in near–real time nor resolve hourly scale urban-scale fluxes. Additionally, there is a lack of UBL CO₂ mixing ratio data against which to test urban-scale emissions and atmospheric transport models. The primary objective of this work is to measure and describe vertically resolved CO₂ mixing ratios observed in the UBL column over Vancouver and explain observations in terms of UBL dynamics. To our knowledge, no previous study has directly sampled CO₂ mixing ratios in the urban environment through the depth of the UBL over the diurnal course. The second objective is to apply a box model to retrieve hourly city-scale CO₂ surface fluxes from the UBL profile measurements. Results from the model are compared to local-scale eddy covariance measurements from a network of three flux towers within the metropolitan Vancouver area and to emission inventory data.

2. Methods

a. Observations of CO₂ in the urban boundary layer

1) Study location and period

During 14–15 August 2008, vertical profiles of CO₂ mixing ratios in the UBL were observed with a measurement system mounted on a tethered balloon. Measurements took place in Memorial Park cemetery (49.2362°N, 123.0392°W), located within the built-up metropolitan area of Vancouver (Fig. 1). The Vancouver metropolitan area includes a population of 2.37 million people with estimated annual greenhouse gas emissions from transportation, buildings, and solid waste sources of 10.35 Mt of CO₂-equivalent per year (Metro Vancouver 2010).

The tethered balloon launch site has an elevation of 80 m MSL and is located approximately 5.0 km from downtown (at a heading of 340°), 10 km away from the Strait of Georgia (270°), and 7.0 km away from Vancouvers International Airport (YVR; 230°). The cemetery is approximately 0.5 km × 1 km in area and is bounded by arterial roads to the east (Fraser Street) and south (49th Avenue) with daily vehicle loads upward of 20,000 vehicles per day. Land cover in the cemetery is primarily clipped and irrigated grass. The cemetery is interspersed with individual trees of up to 25 m height, although no trees were within 100 m of the observation site.

Observations are representative of a synoptically calm situation characterized by weak horizontal pressure gradients (low regional wind speeds) and primarily clear skies (high solar radiation input during day, strong radiative cooling overnight). At the nearby “Vancouver-Sunset” flux tower (section 2b), the mean air temperature recorded during the 24-h period at 24.8 m AGL was 24.9°C, with a minimum of 21.0°C at 0800 LST (LST = Pacific standard time) and a maximum of 30.2°C at 1800 LST. The total solar irradiance measured at the flux tower was 23.49 MJ m⁻² day⁻¹ and the observed net radiation was 13.02 MJ m⁻² day⁻¹. A scattered layer of stratus clouds (~4500 m) and a thin, high layer of cirrus clouds (~7000 m) were observed on the morning of 15 August 2008 from 0000 to 1000 LST (Environment Canada 2013). Sunset on 14 August was at 1930 LST, and sunrise on 15 August was at 0505 LST.
This observation period was selected in order to sample a representative diurnal cycle of morning–afternoon convective boundary layer development, evening boundary layer collapse, and nocturnal development of a stable surface layer and residual layer aloft. Weekday conditions (Thursday–Friday) were selected to be representative of weekday CO₂ emissions. Though this particular set of atmospheric conditions is not typical for this area (e.g., not representative of winter or during passage of synoptic-scale systems), these conditions make for a nearly ideal setting to observe specific processes operating at the city scale, such as the formation of a stable NBL, development of a daytime convective mixed layer, and onset of thermally driven land–sea breezes.

2) INSTRUMENTATION

UBL CO₂ mixing ratios were measured with a GMM220 CO₂ sensor (Vaisala, Inc.) and recorded on a CR1000 datalogger (Campbell Scientific, Inc.). A lightweight sensor (200 g) was required because of the payload restrictions of the balloon (<2 kg). Air temperature and relative humidity were measured with a HMP50 temperature–relative humidity (T–RH) sensor (Vaisala), and air pressure, wind velocity, and wind direction were measured using a Kestrel 4500 Weather Tracker (Nielsen-Kellerman Co.). The accuracy of air temperature measurements is ±0.4°C (at 20°C) and accuracy of relative humidity is ±3% (Campbell Scientific 2015). The Kestrel 4500 is factory calibrated and the wind speed accuracy is ±1.04%, wind direction is accurate within ±5°, and pressure accuracy is ±0.02%. All instruments were sampled at 5-s intervals. The measurement system was suspended 0.5 m below a 5-m³ volume meteorological balloon (Vaisala TTB series) inflated with helium. Wind direction measured by the Kestrel 4500 was determined by the balloon’s orientation (always aligned with the mean horizontal wind direction). The balloon’s altitude was controlled by an electric winch and the balloon was authorized to measure up to a height of 400 m AGL by air traffic control. During the 24-h period from 1100 UTC 14 August to 1100 UTC 15 August, 48 vertical profiles were measured in total. Each profile was completed in 30 min (i.e., two profiles per hour, one going up, one coming back down) and were timed to

![Map of CO₂ and wind measurements in Vancouver during July–August 2008. Mean wind vectors observed during selected afternoon (1200–1600 LST) and overnight (0200–0500 LST) during the balloon observation campaign are superimposed on the map. Metropolitan Vancouver land-use data are from 2006 (City of Vancouver 2006), and elevation contours are in 100-m intervals above sea level (MSL), with the 500- and 1000-m MSL contours thickened for reference.](https://example.com/map.png)
coincide with 30-min CO₂ flux-averaging periods at three EC towers in operation in the region (see section 2b).

Voltage signals from the GMM220 CO₂ sensor recorded by the CR1000 logger were converted to CO₂ mixing ratios using results from an in-house calibration against an Li-7000 closed-path infrared gas analyzer (Li-Cor Biosciences). During the calibration, the GMM220 and Li-7000 intake valve were placed in a sealed chamber in which the CO₂ mixing ratio was varied from 440 to 970 ppmv. Mixing ratios were kept constant at six different values and 10-min averages from the two sensors were compared.

Additional tests were performed on the GMM220 sensor under controlled laboratory conditions to quantify sensor drift, sensor precision, temperature dependence, and pressure dependence (Christen and Nesic 2015). For these tests, four GMM220 sensors, including the ones used in this study, were placed in a temperature- and pressure-controlled sealed container (0.35 m³) with the CO₂ mixing ratio held constant. Temperature dependence was tested over the range of 28°C–36°C and pressure dependence was tested from 900 to 1000 hPa. These tests showed that absolute sensor drift over a 24-h period is on average 0.34 (±0.40) ppm; the sensor responds linearly to pressure at a rate of 0.77 ppm hPa⁻¹ and responds linearly to temperature changes at −5.44 ppm K⁻¹ at ≈400 ppm. These results confirm the temperature and pressure dependences given by the manufacturer calibration (Campbell Scientific 2015). Sensor precision (defined as the standard deviation during the averaging period) is found to be dependent on the length of the averaging period. During the balloon observation period, the sensor sampled every 5 s and there were, on average, 12 individual samples per 10-m-height layer (section 2a(3)) resulting in a 60-s sample averaging period per ascent or descent. During the balloon observation campaign, the mean standard deviation of the sensor error during each 60-s sample period is 4.2 ppm. Sensor response time is 30 s.

Raw CO₂ mixing ratios from the balloon observation system were corrected for air temperature and atmospheric pressure dependences for each 10-m vertical increment (section 2a(3)) using the confirmed manufacturer supplied algorithms (Vaisala 2014). Before corrections were applied, the overall mean uncertainty during individual runs from temperature, pressure, precision, and drift was ±33.3 ppm (±8.5% of mean measured CO₂). After temperature and pressure corrections were applied, the overall uncertainty was reduced to 4.2 ppm (±1% of the mean measured CO₂).

3) DATA PROCESSING

Hourly vertical profiles of CO₂ mixing ratio, air temperature, wind direction, relative humidity, and wind velocities used for subsequent analysis were obtained by averaging 50-s samples (cᵅ) from two individual, consecutive 30-min profiles (one going up, one coming back down) in 10-m vertical increments:

\[ \bar{c}_{m,z} = \frac{\sum c_{m,z}}{n_z}. \]  

where \( \bar{c}_{m,z} \) is the mean CO₂ mixing ratio of \( n_z \) individual 5-s samples (cᵅ) at 10-m-height increment (z). Using this method, the balloon passes through each 10-m-height increment twice per hour, though the time interval between passes is not constant with height. Regions near the top of the profile have a shorter interval between measurements (≈5 min), while regions near the surface have longer intervals (up to 60 min). Profile-averaged CO₂ mixing ratio values (\( \langle cᵅ \rangle \)) reported in this work are the mean of the 10-m vertical increment (Δz) averages for a height range from \( z_1 \) (m) to \( z_2 \) (m):

\[ \langle cᵅ \rangle = \frac{\sum_{z_1}^{z_2} \bar{c}_{m,z}}{(z_1 - z_2)/\Delta z}. \]  

This procedure [Eqs. (4) and (5)] is also applied to potential air temperature \( \theta \) and the horizontal components of the wind vector (u, v) to retrieve profile-averaged values of potential air temperature \( \langle \theta \rangle \), wind velocity \( \langle U \rangle \), and wind direction \( \langle WD \rangle \), respectively.

b. Auxiliary measurements

During the tethered balloon observations, there were three micrometeorological towers within 20 km of the balloon launch site equipped with eddy-covariance instrumentation to measure local-scale CO₂, energy, and water fluxes (Fig. 1; Table 1). The aforementioned Vancouver-Sunset tower was located 1.9-km distance to the southeast of the balloon launch site (143°) in a residential neighborhood, the “Vancouver-Oakridge” tower was located in a residential neighborhood 3.0 km to the west (250°), and the “Westham Island” site was established as a rural reference station located 18.5 km away to the southwest (200°). Additionally, CO₂ mixing ratios were measured above the UBL at a forested offshore ski resort on Cypress Mountain at 1100-m elevation above sea level (“Cypress Mountain”; Fig. 1; Table 1).

At the Vancouver-Sunset flux tower, net mixing ratios and fluxes of CO₂ (\( F_C \)) were continuously measured
from July to August 2008 at an effective height of 24.8 m AGL. The Sunset neighborhood where the tower is located is classified as local climate zone 6 [LCZ-6 or “open lowrise”; Stewart and Oke (2012)] and is primarily residential area with an average population density of 63.1 persons per hectare. Over 90% of buildings are single, detached, residential structures with a mean building density of 12.8 buildings per hectare and mean building height of 5.1 m (van der Laan 2011). Plan-area land cover fractions in a 1900 m × 1900 m area centered on the tower are 29% building, 11% tree, 24% lawn, and 35% impervious.

EC has been established as a robust method for measuring net CO2 in urban environments, provided that strict siting requirements are met [e.g., instruments are mounted above the roughness sublayer and the surrounding local-scale surface area is uniform in its roughness and thermal characteristics (Grimmond et al. 2009)]. The neighborhood surrounding the Vancouver-Sunset flux tower has been identified as structurally homogenous at local scales of EC measurements (in 45° segments around the tower, sector mean roughness length \( z_0 = 1.23 \) m, minimum \( z_0 = 0.87 \) m, and maximum \( z_0 = 1.69 \) m) and has been used extensively to investigate turbulence, energy balance, and water balance in urban environments (e.g., Cleugh and Oke 1986; Schmid et al. 1991; Grimmond and Oke 1991; Roth and Oke 1995). This tower and surrounding neighborhood have also been the site of a number of previous measurement campaigns designed to investigate CO2 concentrations and fluxes (Reid and Steyn 1997; Walsh 2005; Christen et al. 2011; Kellett et al. 2013; Crawford and Christen 2014; Crawford and Christen 2015). The roughness length \( z_0 \) is calculated from sonic anemometer data during neutral stability conditions (Grimmond 1998):

\[
z_0 = (z - z_d) \exp \left( -\frac{U_* k}{u_w} \right),
\]

where \( z \) is measurement height, \( U_* \) is mean wind speed measured at height \( z \), \( k \) is the von Kármán constant, \( u_w \) is the measured friction velocity, and \( z_d \) is the displacement height. The quantity \( z_d \) is estimated morphometrically as 0.67 times the mean height of canopy roughness elements (trees and buildings) in a 1900 m × 1900 m lidar elevation dataset centered on the tower (Grimmond and Oke 1999).

A ceilometer (Vaisala CL31) was also in operation at Vancouver-Sunset during the balloon observations (McKendry et al. 2009) and is used to estimate daytime convective boundary layer heights (\( z_i \)) through remote sensing of vertical aerosol structure (van der Kamp and McKendry 2010). The ceilometer-measured backscatter profiles at 15-s resolution in 5-m vertical increments up to 7.5 km. For analysis of the daytime UBL height, 10-min averages were used for heights above 50 m (van der Kamp and McKendry 2010).

The Vancouver-Oakridge tower was in operation from June to August 2008. EC instrumentation was mounted at 29 m on a guyed hydraulic mast located in the Oakridge neighborhood (LCZ-6, open lowrise). The tower is 0.5 km from arterial roads and a park composed of grass recreational fields (approximately 250 m × 250 m) is located immediately east of the tower. Based on analysis of satellite imagery, land cover fractions in a 1000-m radius about the tower are 23% building, 21% impervious, and 56% vegetation.

<table>
<thead>
<tr>
<th>Station</th>
<th>Operator</th>
<th>Measurements</th>
<th>Coordinates (°)</th>
<th>Elev (m MSL)</th>
<th>Height (m AGL)</th>
<th>LCZ classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vancouver-Sunset</td>
<td>UBC</td>
<td>( F_{CO_2 \text{, wind}} )</td>
<td>49.2261°N, 123.0784°W</td>
<td>90</td>
<td>24.8</td>
<td>6; open lowrise</td>
</tr>
<tr>
<td>Vancouver-Oakridge</td>
<td>UBC</td>
<td>( F_{CO_2 \text{, wind}} )</td>
<td>49.2306°N, 123.1329°W</td>
<td>100</td>
<td>29.0</td>
<td>6; open lowrise</td>
</tr>
<tr>
<td>Westham Island</td>
<td>UBC</td>
<td>( F_{CO_2 \text{, wind}} )</td>
<td>49.0863°N, 123.1768°W</td>
<td>0</td>
<td>1.8</td>
<td>D; low plants</td>
</tr>
<tr>
<td>Cypress Mountain</td>
<td>UBC</td>
<td>( CO_2 )</td>
<td>49.3915°N, 123.2120°W</td>
<td>1100</td>
<td>2.0</td>
<td>B; scattered trees</td>
</tr>
<tr>
<td>Vancouver-UBC (1108487)</td>
<td>UBC</td>
<td>( CO_2 \text{, wind} )</td>
<td>49.250°N, 123.2500°W</td>
<td>78</td>
<td>2.0</td>
<td>9; sparsely built</td>
</tr>
<tr>
<td>YVR (71892)</td>
<td>Environment Canada</td>
<td>Wind</td>
<td>49.19472°N, 123.1833°W</td>
<td>4.3</td>
<td>10.0</td>
<td>8; low large use</td>
</tr>
<tr>
<td>Sandheads (71209)</td>
<td>Environment Canada</td>
<td>Wind</td>
<td>49.2559°N, 123.3034°W</td>
<td>11</td>
<td>10.0</td>
<td>G; water</td>
</tr>
<tr>
<td>Point Atkinson (71037)</td>
<td>Environment Canada</td>
<td>Wind</td>
<td>49.3303°N, 123.2647°W</td>
<td>14</td>
<td>10.0</td>
<td>G; water</td>
</tr>
</tbody>
</table>


TABLE 1. Vancouver measurement network stations. WMO climate station identification numbers are given in parentheses for stations operated by Environment Canada, and hourly data were downloaded from the Environment Canada historical data archive (Environment Canada 2013). An Environment Canada identification number is given for the Vancouver-UBC station. Elevation refers to height of the station base above sea level (MSL), and height is the measurement height above ground level (AGL). Station surroundings are classified according to the local climate zone (LCZ) scheme of Stewart and Oke (2012). CO2 measurements are of concentration.
TABLE 2. Neighborhood characteristics for Vancouver-Sunset and Vancouver-Oakridge. Vancouver-Sunset values are for a 1900 m × 1900 m area centered on the flux tower, and Vancouver-Oakridge values are for an area with 1000-m radius around the tower.

<table>
<thead>
<tr>
<th></th>
<th>Vancouver-Sunset</th>
<th>Vancouver-Oakridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation plan area fraction (%)</td>
<td>35</td>
<td>56</td>
</tr>
<tr>
<td>Impervious plan area fraction (%)</td>
<td>35</td>
<td>21</td>
</tr>
<tr>
<td>Built plan area fraction (%)</td>
<td>29</td>
<td>23</td>
</tr>
<tr>
<td>Building density (buildings per hectare)</td>
<td>12.8</td>
<td>8.0</td>
</tr>
<tr>
<td>Population density (persons per hectare)</td>
<td>63.1</td>
<td>27.6</td>
</tr>
<tr>
<td>$F_C$ (gC m⁻² day⁻¹)</td>
<td>16.13</td>
<td>2.29</td>
</tr>
</tbody>
</table>

(both trees and lawn) (Tooke et al. 2009). Population density within 1000-m radius is 27.6 persons per hectare, and the built density is 8.0 buildings per hectare, with a mean roof height is 5.8 m. This location is structurally similar to Vancouver-Sunset (i.e., primarily detached two-story residential homes organized into city blocks and interspersed with mature vegetation), though the population and built density are lower than at Vancouver-Sunset and the vegetation density is higher (Table 2). Because of the lower population and built densities, greater vegetation coverage, and greater distance to arterial roads, the mean daily total $F_C$ observed at Vancouver-Oakridge (2.29 gC m⁻² day⁻¹) is 85% lower than at Vancouver-Sunset (16.13 gC m⁻² day⁻¹) during July–August 2008 (Table 2) (Crawford et al. 2009). The neighborhood surrounding the tower is structurally homogeneous at local scales (in 45° segments around the tower, sector mean $z_0 = 1.38$ m, minimum $z_0 = 0.99$ m, maximum $z_0 = 1.65$ m) and is also appropriate for EC measurements.

A rural reference EC tower (Westham Island) was located in the Fraser River delta, 18 km south of the urban Vancouver-Sunset and Vancouver-Oakridge sites. The tripod tower was installed in a flat, unmanaged, nonirrigated grass field in a region characterized by intensive agriculture. The local-scale turbulent flux source area is classified as LCZ-D (low plant cover) and grass heights ranged from 10 cm in winter to 1.75 m in summer. Grass was 1.60 m high during August 2008 (Liss et al. 2010). EC instrumentation was mounted at 1.8 m AGL and the tower was located 300 m horizontally away from the Strait of Georgia.

All three flux sites measured CO₂ fluxes using a sonic anemometer (CSAT 3-d; Campbell Scientific) and an open-path infrared gas analyzer (IRGA; Li-7500 from Li-Cor, Inc.). Each IRGA was calibrated in house every 6 months according to standardized procedures (Li-Cor 2015) against reference tanks from Environment Canada. The accuracy of the Li-7500 is ±1%, and its precision is 0.16 ppm (Li-Cor 2015). At all sites, three-dimensional wind velocities and CO₂ mixing ratios were recorded at 20 Hz and subject to several quality control procedures (e.g., filtered for interference from precipitation, realistic maximum–minimum thresholds). Fluxes were then calculated from block-averaged means of 30-min periods and a 2D coordinate rotation was performed to align the coordinate system with the mean wind direction (Crawford et al. 2010).

Additional measurements of CO₂ mixing ratios were taken during July–August 2008 at Cypress Mountain (Fig. 1). This station used a Vaisala GMM220 sensor that sampled every 5 s and recorded 10-min averages. This sensor was also included in the independent calibration and testing procedures described in section 2a(2), and sensor precision during the 10-min-averaging period is ±2.8 ppm. The sensor was located at the peak of a ski run at 1100-m elevation and was mounted at 2 m AGL above rocky soil with sparse vegetation, including mature coniferous trees within a 30-m radius. The station was 21-km horizontal distance (33° heading) away from the balloon launch site.

c. CO₂ box model

Surface CO₂ fluxes are inferred from UBL measurements using a boundary layer budget approach applied to a single-box model construct. This approach is chosen because of its relative simplicity in terms of data input requirements and for its potential to resolve fluxes at hourly time steps. To calculate the surface flux, the model uses observations of CO₂ mixing ratios in the urban boundary layer and explicitly calculates values for vertical entrainment and horizontal advection fluxes. The remainder of this section describes the basic assumptions, develops the model framework, and discusses various inputs to the model, specifically CO₂ mixing ratios outside of the model domain and urban boundary layer height.

This model construction assumes a column of air being advected along the surface at the mean wind speed and that CO₂ emissions from the surface are evenly mixed throughout the boundary layer depth $z_l$ during time $t$ (60 min). During hours when there are convective conditions, $t$ is greater than $t_w$ [Eq. (3)], indicating the UBL is well mixed through depth $z_l$ (Table 3). Additionally, the estimated upwind distance the air has traveled during the 60-min period (estimated as $(U)t$) is much larger than the horizontal length scale $X$ [Eq. (1)] required for the boundary layer to adjust to the surface conditions (Table 3). For the box model application, mixing ratio observations $c_m$ are converted to molar densities $c = c_m \rho M_{\text{air}}$, where $M_{\text{air}}$ is molecular mass of air.
We then begin with the general conservation equation for a scalar $c$ in Einstein notation (Stull 1988):

$$\frac{\partial c}{\partial t} + \mathbf{u} \cdot \nabla c = - \frac{\partial (\mathbf{u}c)}{\partial x} + \mathbf{S}_c - \frac{\partial (\mathbf{w}c)}{\partial x} \cdot \mathbf{j},$$

(7)

where all terms have units of micromoles per meter cubed per second (molar flux divergence). The first term on the left-hand side (lhs) represents the change in storage of the scalar $c$ and the second term on the lhs represents advection. On the right-hand side (rhs), the first term describes the molecular diffusion, the second term is an in situ source term (such as a chemical reaction), and the third term describes turbulent fluxes.

This equation can be simplified for CO$_2$, as there are no sources or sinks within the UBL (inert, long-lived gas), so that $\mathbf{S}_c = 0$. The mean molecular diffusion is also ignored because the diffusion term in a turbulent boundary layer atmosphere is several orders of magnitude smaller than the other terms (Stull 1988). Assuming that the mean wind direction is along the $x$ axis reduces the problem to two dimensions (i.e., lateral homogeneity of flow, where $\mathbf{v} = 0$ and $\mathbf{w} = 0$), and simplifies the equation to

$$\frac{\partial c}{\partial t} + \mathbf{u} \cdot \nabla c = - \frac{\partial (\mathbf{u}c)}{\partial x} + \mathbf{S}_c - \frac{\partial (\mathbf{w}c)}{\partial x} \cdot \mathbf{j},$$

(8)

where the first term on the lhs is the storage change and the second term is the mean horizontal advection in the along-wind direction ($\mathbf{u}$). On the rhs, the first term represents the horizontal along-wind turbulent flux, the second term is the crosswind turbulent flux, and the third term is the vertical turbulent flux. Next, because CO$_2$ emissions sources and sinks are located at the surface, fluxes are primarily vertical so that $\mathbf{w}c \gg \mathbf{u}c$ and $\mathbf{v}c$. Thus, $\mathbf{u}c$ and $\mathbf{w}c$ can be neglected (Stull 1988). In discrete form, the model was written for a one-dimensional column with a layer thickness $\Delta z$ that is set to 10 m:

$$\frac{\Delta \xi}{\Delta t} + \xi \frac{\Delta \xi}{\Delta x} = - \frac{\partial (\mathbf{u}c)}{\partial x} + \frac{\partial (\mathbf{w}c)}{\partial y} + \frac{\partial (\mathbf{w}c)}{\partial z},$$

(9)

where $\Delta (\mathbf{w}c)$ is the turbulent flux difference between the top and bottom of the box. Note that all units in this column model are expressed by unit area (i.e., $\mu$mol m$^{-2}$ s$^{-1}$).

---

**Table 3. Profile averages from UBL measurements (0–400 m AGL) during the 24-h observation period.** The upwind distance that air influencing measurements has traveled during each hour is given as $(U)t$ (km) (where $t$ is the 3600-s temporal averaging period), the horizontal distance required for boundary layer adjustment to the surface during convective conditions is $X$ (km) [Eq. (1)], and the convective time scale indicating the circulation time of the boundary layer scale eddies is $t_w$ (min) [Eq. (3)]. Hours without values (—) are the result of negative kinematic surface heat flux observations from Vancouver-Sunset (i.e., stable, nonconvective conditions).

<table>
<thead>
<tr>
<th>Hour</th>
<th>$\langle c \rangle$ (ppm)</th>
<th>$\langle \theta \rangle$ ($^\circ$C)</th>
<th>$\langle U \rangle$ (m s$^{-1}$)</th>
<th>$\langle WD \rangle$ ($^\circ$)</th>
<th>$(U)t$ (km)</th>
<th>$X$ (km)</th>
<th>$t_w$ (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td>387.5</td>
<td>22.5</td>
<td>1.79</td>
<td>258</td>
<td>6.45</td>
<td>0.63</td>
<td>5.85</td>
</tr>
<tr>
<td>1200</td>
<td>387.4</td>
<td>23.1</td>
<td>2.42</td>
<td>260</td>
<td>8.70</td>
<td>0.69</td>
<td>4.68</td>
</tr>
<tr>
<td>1300</td>
<td>385.7</td>
<td>24.0</td>
<td>2.95</td>
<td>228</td>
<td>10.63</td>
<td>0.91</td>
<td>5.07</td>
</tr>
<tr>
<td>1400</td>
<td>383.2</td>
<td>25.2</td>
<td>2.76</td>
<td>228</td>
<td>9.93</td>
<td>0.82</td>
<td>4.89</td>
</tr>
<tr>
<td>1500</td>
<td>384.0</td>
<td>26.5</td>
<td>2.97</td>
<td>219</td>
<td>10.69</td>
<td>0.94</td>
<td>5.29</td>
</tr>
<tr>
<td>1600</td>
<td>381.1</td>
<td>27.2</td>
<td>3.48</td>
<td>220</td>
<td>12.54</td>
<td>1.07</td>
<td>5.04</td>
</tr>
<tr>
<td>1700</td>
<td>376.5</td>
<td>28.1</td>
<td>3.18</td>
<td>232</td>
<td>11.44</td>
<td>1.03</td>
<td>5.28</td>
</tr>
<tr>
<td>1800</td>
<td>377.2</td>
<td>29.3</td>
<td>2.53</td>
<td>220</td>
<td>9.10</td>
<td>0.85</td>
<td>5.23</td>
</tr>
<tr>
<td>1900</td>
<td>384.1</td>
<td>28.1</td>
<td>2.59</td>
<td>354</td>
<td>9.33</td>
<td>0.61</td>
<td>4.53</td>
</tr>
<tr>
<td>2000</td>
<td>390.0</td>
<td>27.4</td>
<td>2.89</td>
<td>0</td>
<td>10.39</td>
<td>0.36</td>
<td>7.00</td>
</tr>
<tr>
<td>2100</td>
<td>393.2</td>
<td>27.0</td>
<td>2.25</td>
<td>40</td>
<td>8.11</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2200</td>
<td>397.1</td>
<td>26.6</td>
<td>2.56</td>
<td>101</td>
<td>9.22</td>
<td>2.03</td>
<td>12.27</td>
</tr>
<tr>
<td>2300</td>
<td>400.7</td>
<td>25.9</td>
<td>2.40</td>
<td>103</td>
<td>8.64</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>0000</td>
<td>400.0</td>
<td>25.1</td>
<td>1.98</td>
<td>99</td>
<td>7.14</td>
<td>1.16</td>
<td>9.65</td>
</tr>
<tr>
<td>0100</td>
<td>398.7</td>
<td>24.5</td>
<td>1.30</td>
<td>31</td>
<td>4.68</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>0200</td>
<td>402.7</td>
<td>23.7</td>
<td>1.10</td>
<td>338</td>
<td>3.95</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>0300</td>
<td>406.1</td>
<td>23.4</td>
<td>1.08</td>
<td>82</td>
<td>3.88</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>0400</td>
<td>405.1</td>
<td>23.1</td>
<td>1.63</td>
<td>92</td>
<td>5.87</td>
<td>0.82</td>
<td>7.65</td>
</tr>
<tr>
<td>0500</td>
<td>405.7</td>
<td>23.2</td>
<td>1.41</td>
<td>66</td>
<td>5.06</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>0600</td>
<td>404.2</td>
<td>22.5</td>
<td>1.55</td>
<td>326</td>
<td>5.57</td>
<td>0.45</td>
<td>5.00</td>
</tr>
<tr>
<td>0700</td>
<td>402.8</td>
<td>22.8</td>
<td>2.50</td>
<td>153</td>
<td>8.99</td>
<td>0.70</td>
<td>7.32</td>
</tr>
<tr>
<td>0800</td>
<td>397.0</td>
<td>23.3</td>
<td>2.85</td>
<td>194</td>
<td>10.25</td>
<td>0.25</td>
<td>2.90</td>
</tr>
<tr>
<td>0900</td>
<td>399.3</td>
<td>23.2</td>
<td>2.24</td>
<td>170</td>
<td>8.07</td>
<td>0.50</td>
<td>5.06</td>
</tr>
<tr>
<td>1000</td>
<td>396.1</td>
<td>24.3</td>
<td>1.77</td>
<td>172</td>
<td>6.36</td>
<td>0.55</td>
<td>5.53</td>
</tr>
<tr>
<td>24-h mean</td>
<td>393.6</td>
<td>25.0</td>
<td>2.26</td>
<td>175</td>
<td>8.13</td>
<td>0.80</td>
<td>6.01</td>
</tr>
</tbody>
</table>
Summing all layers from ground to height $z_i$, we get

$$
\sum_{z=0}^{z_i} \Delta z \frac{\Delta x}{\Delta t} + \sum_{z=0}^{z_i} \Delta z \frac{\Delta x}{\Delta t} = \left( -\overline{w'C_{z_i}} - \overline{w'C_{z(0)}} \right), \tag{10}
$$

where $\overline{w'C_{z(0)}}$ is the surface flux ($F_C$) and $\overline{w'C_{z_i}}$ is the entrainment flux.

Integrating the concentration change from surface to height $z_i$ and solving for the surface flux results in

$$
F_C = z_i \frac{\Delta z}{\Delta t} + \sum_{z=0}^{z_i} \Delta z \frac{\Delta x}{\Delta t} + \overline{w'C_{z_i}}. \tag{11}
$$

The entrainment flux can be approximated by

$$
\overline{w'C_{z_i}} = (\overline{\tau} - \overline{\tau}_b) \frac{\Delta z_i}{\Delta t}, \tag{12}
$$

where $c_b$ is the background mixing ratio above the UBL. This results in an overall model equation of

$$
F_C = z_i \frac{\Delta z}{\Delta t} + \sum_{z=0}^{z_i} \Delta z \frac{\Delta x}{\Delta t} + (\overline{\tau} - \overline{\tau}_b) \frac{\Delta z_i}{\Delta t}, \tag{13}
$$

where the first term on the rhs is the molar density change measured by the balloon system, the second term is the horizontal advective flux (with the horizontal CO2 gradient approximated as $\overline{\tau} - \overline{\tau}_b$), and the third term is the entrainment flux. The $\Delta t$ value is the model time step (1 h), $\overline{\tau}$ is measured by the balloon system up to height $z_i$, and $\overline{\tau}$ and $\overline{\tau}_b$ are measured by the balloon system at each $\Delta t$ increment.

The $z_i$ value is determined by the ceilometer measurements at Vancouver-Sunset during daytime convective conditions (van der Kamp and McKendry 2010). Overnight, the NBL height $z_i$ cannot be determined directly from ceilometer measurements because non-physical, semiperiodic backscatter signal fluctuations below 50 m obscure the definition of the NBL depth (van der Kamp and McKendry 2010). Instead, the height of the NBL was estimated using three different methods. First, $z_i$ is defined as the height at which $\theta$ is 90% of the difference between $\theta$ in the residual layer (defined here as the measured average from 350 to 400 m AGL; this layer provides a representative sample above the likely height of the NBL and below the maximum height of the previous day’s convective boundary layer) and the surface layer (defined here as 0–20 m AGL). This is an ad hoc method based on observed nighttime temperature profiles (Fig. 2) that defines $z_i$ at a height where the potential temperature profile stops increasing with height and becomes roughly uniform. The second method relies on the assumption that mechanical forces dominate near-surface mixing relative to buoyancy.

Mean wind speeds at 10 m (measured by the balloon system) are used to determine $z_i$ based on empirical relations described by Benkley and Schulman (1979), where $z_i = 125U_{10}$. This model was specifically designed for 10-m wind speeds because this is the WMO standard wind speed measurement height and accounts for potential decoupling between the stable NBL and overlying RL conditions. The third method describes the growth of the stable NBL in terms of cumulative surface cooling with time (Stull 2000):

$$
z_i = 5(aU_{RL}^{3/4}t^{1/2}), \tag{14}
$$

where $a$ is a constant set to 0.15 m$^{1/4}$ s$^{1/4}$ (Stull 2000), $U_{RL}$ is the mean wind speed in the RL (defined here as the mean of the balloon-system measurements from 350 to 400 m), and $t$ is time since sunset in seconds.

An upwind horizontal CO2 mixing ratio gradient is needed to calculate the advection term, along with $z_i$ and $\overline{\tau}$ [Eq. (11)]. This gradient is determined as the difference between the measured advection term, along with $z_i$ and $\overline{\tau}$ [Eq. (11)]. This gradient is determined as the difference between the measured $\overline{\tau}$ for each layer and the upwind background CO2 mixing ratio ($c_b$) across the horizontal distance $\Delta x$. The $c_b$ input is set to two different values: (i) 375 ppm (average 24-h value measured during July–August 2008 at the nonurban Cypress Mountain and Westham Island monitoring sites; see Fig. 1) and (ii) a dynamic value set to the hourly difference between the Westham Island and UBL profile-averaged CO2 mixing ratio during the observation period. This method assumes a well-mixed boundary layer and vertically homogenous distribution of CO2 mixing ratio upwind of the urban area. Mixing ratios are converted into molar densities using the air density measured in 10-m height increments by the balloon system and the molecular weight of the air.

The advection term is added to $F_C$ only during individual hours and $\Delta t$ layers when wind directions are from $200^\circ$ to $270^\circ$. When winds are from this sector, marine air with relatively low-CO2 content is expected to influence the model domain. The $\Delta x$ input to calculate the gradient $(\overline{\tau} - \overline{\tau}_b)/\Delta x$ is set to the mean upwind horizontal distance to the ocean–urban edge (10.5 km) in the $200^\circ$–$270^\circ$ sector, beyond which it is assumed there exists a well-mixed $c_b$. When winds are from $270^\circ$ to $200^\circ$, the horizontal gradient is influenced by the extensive urban landscape upwind of the measurement site and so $\Delta c$ is assumed to be negligible. This procedure assumes that the horizontal CO2 gradient (and thus advection) with upwind ocean fetch ($200^\circ$–$270^\circ$) is much greater than when wind directions are from other sectors. This simplification ignores horizontal gradients and advection from other wind directions and is a source of model uncertainty.
The entrainment flux term uses the two values of $c_b$ described earlier and a third value set to the average CO$_2$ mixing ratio in the layer ranging from $z_i$ to $z_i + \Delta z$, measured by the balloon system [when $(z_i + \Delta z_i) < 400$-m measurement height]. Mixing ratios are converted to molar densities using air density measured by the balloon system and the molecular weight of air. When there is boundary layer collapse ($\Delta z_i \leq 0$), the entrainment term is set to zero. In this situation, there is not a negative entrainment value (which would imply clean air is removed from the UBL); instead this layer $(z_i - \Delta z_i)$ becomes a residual layer aloft. Use of the measurements from Cypress Mountain in the entrainment term introduces uncertainty into the model because these values are not expected to be necessarily representative of the free atmosphere above the UBL. Atmospheric observations at mountain peaks are expected to be frequently influenced by the planetary
boundary layer through thermo-topographic winds during summer conditions (Gallagher et al. 2011) and CO₂ observations are additionally affected by local and microscale surroundings (e.g., plant CO₂ sequestration and soil and vegetation CO₂ respiration). The advantage of this station is that it is located outside and above the UBL and is expected to approximate the lower bound of possible $c_b$ values and, thus, the largest magnitudes of entrainment. Use of the dynamic hourly difference between the mixing ratio at Westham Island and the UBL profile-averaged CO₂ mixing ratio during the observation period assumes a vertically homogenous distribution of CO₂ mixing ratio above the UBL identical to that found upwind of the urban area.

Measurements were limited to 400 m by air traffic control, but ceilometer measurements indicate UBL heights extend up to 540 m during the afternoon of 14 August. During hours when $z_i > 400$ m, individual 10-m layers from 400 m to $z_i$ are assigned the mean value of measurements of CO₂, wind speed, and wind direction for that hour in the 20–400-m layer, based on the assumption of a well-mixed UBL.

In summary, the box model uses measured values of hourly changes in CO₂ mixing ratio and explicitly modeled values of vertical entrainment and horizontal advective fluxes to solve for $F_C$. The model uses inputs of the background CO₂ mixing ratio to calculate advection and entrainment and NBL height during nighttime stable conditions. Three different values of background CO₂ mixing ratio and three methods for estimating the NBL height are used to test the model sensitivity.

3. Results and discussion

a. UBL dynamics and CO₂ mixing ratios

During the 14–15 August observation period, the measured CO₂ mixing ratios up to 400 m AGL range from 372 to 456 ppm. The lowest mixing ratios (372–384 ppm) at individual height layers in the UBL are observed during the late afternoon from 1600 to 1800 LST and the highest (420–456 ppm) are observed overnight and during the early morning (2000–0700 h) below 50 m AGL (Fig. 2; Table 3). Observed profile-averaged CO₂ mixing ratio and three methods for estimating the NBL height are used to test the model sensitivity.

Increases from 22.5°C at 1100 LST to 29.3°C at 1800 LST. After sunset (1800–1900 LST), $\theta$ near the surface ($<50$ m) rapidly cools from 29.9°C to 25.9°C.

Observed wind directions and velocities conform to a pattern of diurnally reversing land–sea-breeze thermal circulations typical in this area during summertime (Fig. 3; Table 3). During the afternoon (1100–1800 LST), wind directions above 10 m are from the west and southwest and profile-averaged wind speeds are 2.6 m s⁻¹. Maximum daytime wind speeds are 4.2 m s⁻¹ at 140 m AGL at 1600 LST. After sunset, the thermal circulation reverses and the observed wind directions shift to the northeast. From 1900 to 2000 LST, there is directional wind shear with height, with easterly winds observed at 100–250 m, and westerly winds from 250 to 400 m. By 2200 LST the flow at all heights up to 400 m was from the east, with a maximum velocity of 3.9 m s⁻¹ at 140 m. Overnight, winds shift from the northeast, and the observed wind directions shift back toward the southwest and velocity increases to 2.5 m s⁻¹ below 100 m at 0500 LST near sunrise. After sunrise, onset of the sea-breeze front is observed at 0700–0800 LST as wind directions shift back toward the southwest and velocity increases to 4.5 m s⁻¹.

Near-surface winds showed moderate regional spatial variability (Fig. 1). At YVR, Sandheads, Westham Island, and Vancouver-University of British Columbia (Vancouver-UBC), the mean afternoon winds from 1200 to 1600 LST are from the northwest and range from 2 to 4 m s⁻¹. At the same time, Vancouver-Oakridge, Vancouver-Sunset, and the balloon system (20–30-m height) record wind directions from the southwest, west, and west, respectively. This backing is expected as winds
The observed UBL CO$_2$ mixing ratios are strongly influenced by the thermal structure of the UBL. Initial backscatter measurements from the ceilometer show a UBL height of 540 m at 1100 LST (Fig. 4). This is the maximum UBL height measured during the observation period, and from 1100 to 1300 LST the UBL height fluctuates about 500 m before falling to 400 m by 1600 LST as a result of the reduced surface heating and less vigorous vertical mixing (Fig. 4). The observed pattern of convective UBL development and the magnitude of the UBL heights are consistent with long-term summertime measurements obtained from the ceilometer operated at this site from 2006 to 2008 (van der Kamp and McKendry 2010).

Vertical profile measurements during the afternoon show a well-mixed UBL with nearly uniform potential temperatures and CO$_2$ mixing ratios with height (Fig. 2). During late afternoon (1500–1800 LST), the profile-averaged CO$_2$ mixing ratio up to 400 m AGL is 380.2 ppm and the mean vertical gradient is $-0.1$ ppm dam$^{-1}$ (Fig. 5). The profile-averaged potential air temperature during the same period is 30.0°C, with a mean vertical gradient of 0.085 K dam$^{-1}$. During this time, measurements by the EC system at Vancouver-Sunset indicate dynamically unstable conditions (mean $z' / L = -0.70$). The Obukhov length $L$ is defined as $L = -\theta u'_{*}/kw'$, where $\theta$ the friction velocity ($u_{*}$), and the covariance $w'\theta'$ are measured at the Vancouver-Sunset flux tower.

Beginning before sunset, three methods were used to estimate the growth of the stable nocturnal boundary layer during the night of 14/15 August 2008 (Fig. 4). The cumulative cooling method [Eq. (14)] estimates an NBL height of 104 m at 2000 LST, approximately 30 min after sunset. This estimate rises to 212 m at 0100 LST. This peak is explained by the increase in RL wind speeds from 2200 to 2300 LST (Fig. 3). After 0200 LST, the NBL height rises steadily to a maximum peak of 232 m by 0700 LST. The empirical estimate based on 10-m wind speeds fluctuates through the night between 15 m (2000 and 0300 LST) and 181 m (1800 LST). This estimate is directly scaled to the observed fluctuations in nocturnal wind speeds at 10 m as measured by the tethered balloon system (Fig. 3). The NBL height estimate using the ad hoc method based on the $\theta$-gradient rises to 80 m by 1900 LST. The rest of the night shows a steady upward growth to 130 m at 0700 LST. The mean maximum NBL height of all three methods at midnight (3.5 h after sunset) is 123 m and at 0600 LST (9.5 h after sunset) is 158 m. Overall, the $\theta$-gradient method appears to yield the most stable results throughout the night (i.e., no large fluctuations) relative to the other methods and also uses measurements directly related to the thermal structure of the NBL.

Vertical profile measurements overnight (0000–0400 LST) show that the profile-averaged potential air temperature has cooled to 25.7°C, with a mean vertical gradient of 0.2 K dam$^{-1}$ and a maximum gradient of 1.0 K dam$^{-1}$ from 20 to 40 m (Fig. 5). During these same hours, the profile-averaged CO$_2$ has risen to 403.8 ppm and the mean vertical gradient is $-1.6$ ppm dam$^{-1}$ with a

![Figure 4](unnamed.png)
the steepest negative gradient of $-15.0$ ppm dam$^{-1}$ from 20 to 40 m. Above the NBL, potential temperature profiles indicate the presence of a neutrally stable RL with roughly uniform CO$_2$ mixing ratios with height.

In contrast to measurements of NBL structure over other urban neighborhoods [e.g., in Montreal, Québec, Canada (Oke and East 1971), and Sapporo, Japan (Uno et al. 1988)], there is no observed shallow thermally unstable layer at this site, though these studies are representative of different types of local-scale neighborhood surfaces. Instead, the nocturnal potential temperature inversion begins very near to the surface, presumably because of minimal storage and anthropogenic heat releases from the microscale park setting of the measurements and the surrounding low-density residential neighborhood. There is also a clear increase in CO$_2$ mixing ratios in the NBL, which is evidence of vertical mixing of CO$_2$ injected into the stable NBL from nocturnal canopy layer sources (e.g., human, soil, and vegetation respiration, as well as fossil fuel combustion from traffic and cooking). Because there is no indication of buoyant thermal turbulence production, this mixing must instead be dominated by mechanical processes (i.e., turbulence generated by wind shear and from flow over buildings and trees).

Beginning after sunrise (0505 LST), ceilometer backscatter measurements show the rise of the convective UBL up to a height of 350 m by 1000 LST. During this time, CO$_2$ mixing ratios below 100 m show a decrease from 421.3 to 402.4 ppm. This indicates vertical flushing of accumulated CO$_2$ in the NBL during growth of the convective UBL, in addition to entrainment of relatively low-CO$_2$ content air from the overlying residual layer.

The pattern of overnight CO$_2$ buildup and morning flushing of accumulated CO$_2$ in the NBL observed by the balloon-based system is consistent with observations of CO$_2$ mixing ratios and potential air temperatures measured in the urban canopy layer (UCL) in the Vancouver-Sunset neighborhood (Crawford and Christen 2014). In this study, there was an observed increase in UCL CO$_2$ mixing ratios in the hour after sunset, followed by microscale horizontal advection along topographic gradients (i.e., cold-air pooling) during the night. Just after sunset, CO$_2$ mixing ratios were observed to rapidly decrease throughout the UCL.

![FIG. 5. The (left) CO$_2$ mixing ratio and (right) potential air temperature in the UBL during afternoon unstable conditions (light blue) and overnight stable conditions (dark blue).](image-url)
The diurnal course of the profile-averaged CO₂ mixing ratio from 0 to 400 m is compared with CO₂ mixing ratios measured at three locations in the metropolitan Vancouver area (Fig. 6). The highest CO₂ mixing ratios throughout the study period are observed at Vancouver-Sunset (mean of 406.7 ppm, maximum of 444.6 ppm, and minimum of 375.8 ppm) and the lowest values are at Westham Island (mean of 375.8 ppm, maximum of 393.6 ppm, and minimum of 366.1 ppm). During the afternoon (1100–1800 LST), the mean UBL values measured by the balloon-based system are within 0.9 ppm (0.2%) of the measurements at Vancouver-Sunset and within 4.5 ppm (1.2%) of the measurements at Vancouver-Oakridge, measuring 24.8 and 29 m, respectively. Overnight (1800–0800 LST), the 0–400-m average is lower than at Vancouver-Sunset by 23.6 ppm (−5.5%) and lower by −8.0 ppm (−1.9%) at Vancouver-Oakridge, on average. This result suggests that urban tower-based measurements are representative of the entire UBL depth during unstable, well-mixed conditions. At night, however, the tower-based mixing ratio measurements diverge from the profile average, suggesting the decoupling of urban surface-layer conditions from the overlying RL (Crawford and Christen 2014).

Ensemble mean CO₂ mixing ratios measured by the CO₂ observation network during July–August 2008 indicate the CO₂ content during the 24-h experimental period was unusually high overnight and during early morning (Fig. 6). At Vancouver-Sunset, the mean CO₂ mixing ratio from 2000 to 0600 LST during the experiment was 429.5 ppm, as compared with the July–August ensemble mean of 387.4 ppm for the same hours (8.3% difference). Hourly CO₂ mixing ratios from 2000 to 0500 LST at Vancouver-Sunset during the experiment were in the top 10th percentile of all July–August 2008 values for each hour. At the Vancouver-Oakridge tower, observed mixing ratios during the experiment were 3.8% higher than the July–August average. In contrast, overnight mixing ratios were −2.2% below average at the nonurban Westham Island site, although typically nighttime CO₂ mixing ratios at Westham Island are higher than those at Vancouver-Sunset by 6.6 ppm (1.7%). During the daytime, all sites are within 2.2% of their respective July–August ensemble means.

The likely reasons for the above-average CO₂ mixing ratios during this night are enhanced thermal stability and reduced mixing and advection from mean winds. This night was characterized by more negative sensible heat flux ($Q_H$) and lower wind speeds than average at Vancouver-Sunset. Overnight from 0000 to 0400 LST, the mean $Q_H$ measured at Vancouver-Sunset was $−4.9 \text{ W m}^{-2}$, as compared with a July–August

Fig. 6. Hourly mean CO₂ mixing ratios measured by the observation network (Fig. 1) during the balloon campaign on 14–15 Aug 2008 (solid lines) and ensemble means during July–August 2008 (dashed lines). Values from Cypress Mountain are not available during the balloon observation period. The balloon measurement (dark blue) is a column-average value from 0 to 400 m ($\bar{C}_{\text{cm}}$).
2008 ensemble average of 0.7 W m\(^{-2}\). For the same hours, the wind speed at Vancouver-Sunset was 2.0 m s\(^{-1}\) during the experimental period, as compared with a July–August 2008 ensemble average of 2.4 m s\(^{-1}\). More negative \(Q_H\) implies greater heat loss from the surface, leading to more stably stratified conditions than usual, and lower wind speeds imply reduced vertical mixing and horizontal advection, resulting in above-average CO\(_2\) mixing ratios during the experimental period. This implies that observations obtained during this period are representative of a specific set of synoptic and regional atmospheric conditions (e.g., summertime high pressure system, large daytime solar heat input, and weak synoptic horizontal pressure gradient). The advantage of using observations during this set of conditions is that important processes such as the development of the nocturnal UBL, daytime convective UBL, and the onset of thermal land–sea-breeze circulation patterns are more clearly developed.

b. Modeled regional-scale \(F_C\)

Urban-scale CO\(_2\) fluxes were modeled using Eq. (12). Three variations of background CO\(_2\) mixing ratios were used to determine the sensitivity of the calculation to the choice of different vertical and horizontal gradients for entrainment and advection fluxes. Further, three variations of the stable NBL height were explored to estimate \(z_i\) and \(\Delta z_c\) during nighttime hours. For the period 1200 LST 14 August–1200 LST 15 August 2008 \(F_C\) was modeled and the diurnal course of \(F_C\) is plotted to be centered at noon (Fig. 7).

The box-model results are compared to EC observations and scaled greenhouse gas inventories; however, these methods are not expected to agree exactly. This is primarily because the box model, EC measurements, and scaled inventories are each representative of different spatial source areas with different surface CO\(_2\) source–sink configurations. Furthermore, the scaled inventory neglects biogenic CO\(_2\) processes (photosynthesis and respiration), while the reported CO\(_2\)-equivalent emissions totals also include methane and nitrous oxide and are given for an entire year. Differences between methods are discussed in further detail throughout the following section. Though perfect agreement is not expected, a comparison between methods is still worthwhile as a check on the plausibility of the modeled results. We expect that although the magnitude of the hourly \(F_C\) and daily exchange totals will differ, results from each method (and corresponding spatial scale) should follow the same general diurnal pattern and be of the same order of magnitude.

The total flux for the 24-h observation period calculated from the box model is 20.2 g C m\(^{-2}\) day\(^{-1}\), compared to local-scale EC measurements of 7.25 g C m\(^{-2}\) day\(^{-1}\) observed at Vancouver-Sunset, 1.07 g C m\(^{-2}\) day\(^{-1}\) measured at Vancouver-Oakridge, and \(-2.87\) g C m\(^{-2}\) day\(^{-1}\) measured at Westham Island (Fig. 7; Table 5). Mean hourly uncertainty for the modeled fluxes is \(\pm 0.08 \mu mol m^{-2} s^{-1}\), compared with a mean hourly flux of 19.5 \(\mu mol m^{-2} s^{-1}\). For measured EC fluxes at Vancouver-Sunset, the mean hourly variability is \(\pm 0.08 \mu mol m^{-2} s^{-1}\), compared with the hourly mean of 15.4 \(\mu mol m^{-2} s^{-1}\).

Box-model results are also compared with spatially averaged EC fluxes. Spatial averaging of the EC measurements is necessary because spatial heterogeneity of the surface CO\(_2\) source and sinks can introduce location bias into the measured CO\(_2\) emissions when attempting to calculate long-term or spatially integrated emissions totals. It is also important to note that only a small percentage of the city of Vancouver is sampled by the EC measurement tower (Crawford and Christen 2015). Two methods are used to spatially average EC measurements. The first uses directionally averaged fluxes calculated as the equal-weighted average of individual hourly mean \(F_C\) values from four wind direction quadrants (0°–90°, 90°–180°, etc.) during July–August 2008 following the procedure suggested by Christen et al. (2011). The July–August 2008 24-h directionally averaged total flux measured at Vancouver-Sunset was 16.3 g C m\(^{-2}\) day\(^{-1}\), it was 2.3 g C m\(^{-2}\) day\(^{-1}\) at Vancouver-Oakridge, and it was \(-1.7\) g C m\(^{-2}\) day\(^{-1}\) at Westham Island.

A second method uses statistical models to calculate spatially averaged fluxes representative of an entire neighborhood at Vancouver-Sunset based on measured environmental variables (e.g., soil temperature, incoming solar radiation, time of day) and land cover characteristics of modeled turbulent flux source areas (e.g., plan area proportion of vegetation and busy roads). Using this method (described in detail in Crawford and Christen (2015)), the spatially averaged mean \(F_C\) for the Vancouver-Sunset neighborhood during the 24-h balloon observation period is 15.0 g C m\(^{-2}\) day\(^{-1}\) (Table 5). The box model predicts higher emissions than either of the spatially averaged EC flux methods. This likely reflects the influence of CO\(_2\) emissions from commercial and industrial sources and high traffic volume roads and highways that are not present in the residential local-scale EC flux source areas.

The modeled daily total of 20.2 g C m\(^{-2}\) day\(^{-1}\) is compared with the scaled greenhouse gas inventories for the city of Vancouver and its metropolitan region (Metro Vancouver 2010). “Metro” Vancouver (1672 km\(^2\)) contains the city of Vancouver (100 km\(^2\)). Comparison with both the city of Vancouver and the metro Vancouver
inventories is useful because the box model is representative of areas that include both city and metropolitan areas. For both the city of Vancouver and metro Vancouver, inventories were conducted in 2007 and 2010 and provide annual total emissions totals, as well as the fraction from motor vehicle traffic sources, building sources, and solid waste sources (Table 4). Because of seasonal variations in the local emissions from natural gas combustion for building heating and traffic volume, and day of week variations in commuter traffic volume, annual emissions totals have been scaled to be representative of weekday emissions in August.

For traffic, the monthly traffic emissions scaling factors are calculated based on modeled emissions from traffic counts and trip diaries for the Vancouver-Sunset neighborhood (Christen et al. 2011). These scaling factors are applied to the annual inventory traffic emissions totals to produce monthly traffic emissions totals. Weekday and weekend differences are then calculated based on EC observations at Vancouver-Sunset of reductions in weekend traffic emissions of 42% relative to weekdays (Christen et al. 2011). Although emissions factors are calculated specifically for the Vancouver-Sunset neighborhood, it is assumed that weekly and monthly patterns are representative of the entire city of Vancouver and metro Vancouver.

For building emissions, monthly scaling factors are determined for the Vancouver-Sunset neighborhood from building energy model (BEM) simulations and local climate data (Christen et al. 2011). The BEM results include local emissions due to natural gas combustion for both space-heating and water-heating purposes. Some uncertainty is introduced when these scaling factors are applied to the area of the city of

---

**Fig. 7.** Boundary layer budget calculations of $F_C$ during 14–15 Aug 2008. The mean of all model variations is shown as the black line; error bars are maximum and minimum values of individual model runs with varying background CO$_2$ and stable boundary layer height inputs. Also shown are observations from the Vancouver-Sunset (light blue), Vancouver-Oakridge (light brown), and Westham Island (light green) flux towers (Fig. 1) during the balloon observation period (dashed line) and for July–August 2008 (shaded areas; dotted lines). Note the x-axis hour range differs from previous plots.
Vancouver and the metro Vancouver area because BEM models are calibrated for the specific residential housing stock found in the Vancouver-Sunset neighborhood and may not be representative of all building types (e.g., high-density apartment blocks or commercial buildings). This uncertainty is expected to be minor because the emissions factors are monthly fractions of total annual emissions that are assumed to be similar across building types, rather than emissions totals, which are expected to vary. Additional error is introduced because this approach does not consider variations in emissions from industrial processes.

Table 4. Summary of scaled community energy and emissions inventories for metro Vancouver and the city of Vancouver, 2007 and 2010.

<table>
<thead>
<tr>
<th></th>
<th>City 2007</th>
<th>City 2010</th>
<th>Metro 2007</th>
<th>Metro 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total annual emissions (Mt CO₂-equivalent)</td>
<td>2.46</td>
<td>2.33</td>
<td>10.8</td>
<td>10.4</td>
</tr>
<tr>
<td>Building emissions (%)</td>
<td>49</td>
<td>48</td>
<td>43</td>
<td>42</td>
</tr>
<tr>
<td>On-road vehicle emissions (%)</td>
<td>46</td>
<td>46</td>
<td>52</td>
<td>53</td>
</tr>
<tr>
<td>Solid waste emissions (%)</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Population (persons)</td>
<td>610136</td>
<td>642843</td>
<td>2237220</td>
<td>2374628</td>
</tr>
<tr>
<td>Land area (km²)</td>
<td>100.02</td>
<td>100.02</td>
<td>1671.88</td>
<td>1671.88</td>
</tr>
<tr>
<td>Population density (persons per hectare)</td>
<td>61.0</td>
<td>64.2</td>
<td>13.8</td>
<td>14.2</td>
</tr>
<tr>
<td>Annual per capita emissions (t CO₂-equivalent)</td>
<td>4.0</td>
<td>3.6</td>
<td>4.8</td>
<td>4.4</td>
</tr>
<tr>
<td>Annual per area emissions (gC m⁻² day⁻¹)</td>
<td>18.4</td>
<td>17.4</td>
<td>4.8</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Table 5. Modeled boundary layer budget $F_C$ compared with values measured during the 24-h observation period by eddy covariance. ST is the Vancouver-Sunset flux tower, OR is the Vancouver-Oakridge flux tower, and WI is the Westham Island flux site (Fig. 1). Italicized values are data gaps that have been linearly interpolated. The overbar signifies the ensemble mean flux from July to August 2008 for each tower, and $(ST)$ is the spatially modeled flux (section 3b) in the Vancouver-Sunset neighborhood using methods developed in Crawford and Christen (2014a). Units for all values are micromoles per meter squared per second. Note that the hour column is different than in Table 3.

<table>
<thead>
<tr>
<th>Hour</th>
<th>$F_C$ (gC m⁻² day⁻¹)</th>
<th>ST</th>
<th>OR</th>
<th>WI</th>
<th>$(ST)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>-3.0</td>
<td>2.71</td>
<td>0.02</td>
<td>-12.08</td>
<td>9.57</td>
</tr>
<tr>
<td>0100</td>
<td>-1.6</td>
<td>5.57</td>
<td>-2.14</td>
<td>-12.06</td>
<td>6.06</td>
</tr>
<tr>
<td>0200</td>
<td>7.6</td>
<td>9.78</td>
<td>-2.03</td>
<td>13.53</td>
<td>4.45</td>
</tr>
<tr>
<td>0300</td>
<td>8.6</td>
<td>0.53</td>
<td>-4.78</td>
<td>11.63</td>
<td>4.51</td>
</tr>
<tr>
<td>0400</td>
<td>-1.5</td>
<td>8.12</td>
<td>-12.93</td>
<td>9.28</td>
<td>5.28</td>
</tr>
<tr>
<td>0500</td>
<td>0.8</td>
<td>1.53</td>
<td>-2.19</td>
<td>4.03</td>
<td>6.11</td>
</tr>
<tr>
<td>0600</td>
<td>5.2</td>
<td>12.86</td>
<td>12.11</td>
<td>4.77</td>
<td>11.43</td>
</tr>
<tr>
<td>0700</td>
<td>0.3</td>
<td>-6.76</td>
<td>10.82</td>
<td>-5.67</td>
<td>19.80</td>
</tr>
<tr>
<td>0800</td>
<td>37.4</td>
<td>5.14</td>
<td>-7.18</td>
<td>-12.07</td>
<td>20.55</td>
</tr>
<tr>
<td>0900</td>
<td>53.0</td>
<td>19.23</td>
<td>-4.66</td>
<td>-14.17</td>
<td>27.86</td>
</tr>
<tr>
<td>1000</td>
<td>43.2</td>
<td>14.36</td>
<td>-1.20</td>
<td>-18.35</td>
<td>17.32</td>
</tr>
<tr>
<td>1100</td>
<td>41.1</td>
<td>-0.44</td>
<td>-3.29</td>
<td>-13.55</td>
<td>28.37</td>
</tr>
<tr>
<td>1200</td>
<td>39.0</td>
<td>3.98</td>
<td>2.88</td>
<td>-14.27</td>
<td>17.26</td>
</tr>
<tr>
<td>1300</td>
<td>45.3</td>
<td>3.86</td>
<td>-5.33</td>
<td>-12.63</td>
<td>19.02</td>
</tr>
<tr>
<td>1400</td>
<td>28.4</td>
<td>1.03</td>
<td>10.53</td>
<td>-12.19</td>
<td>26.63</td>
</tr>
<tr>
<td>1500</td>
<td>51.7</td>
<td>10.80</td>
<td>7.47</td>
<td>-11.07</td>
<td>18.98</td>
</tr>
<tr>
<td>1600</td>
<td>38.9</td>
<td>5.80</td>
<td>4.34</td>
<td>-7.85</td>
<td>19.92</td>
</tr>
<tr>
<td>1700</td>
<td>2.3</td>
<td>2.47</td>
<td>8.59</td>
<td>-2.50</td>
<td>21.02</td>
</tr>
<tr>
<td>1800</td>
<td>21.7</td>
<td>3.94</td>
<td>6.29</td>
<td>0.34</td>
<td>18.82</td>
</tr>
<tr>
<td>1900</td>
<td>12.5</td>
<td>3.43</td>
<td>-1.62</td>
<td>0.79</td>
<td>15.59</td>
</tr>
<tr>
<td>2000</td>
<td>3.3</td>
<td>32.75</td>
<td>-1.29</td>
<td>15.17</td>
<td>15.01</td>
</tr>
<tr>
<td>2100</td>
<td>9.3</td>
<td>22.68</td>
<td>6.19</td>
<td>29.55</td>
<td>14.85</td>
</tr>
<tr>
<td>2200</td>
<td>10.5</td>
<td>2.19</td>
<td>4.95</td>
<td>-6.30</td>
<td>12.69</td>
</tr>
<tr>
<td>2300</td>
<td>13.4</td>
<td>2.16</td>
<td>-0.78</td>
<td>-24.89</td>
<td>11.91</td>
</tr>
<tr>
<td>24-h total (gC m⁻² day⁻¹)</td>
<td>20.2</td>
<td>7.25</td>
<td>1.07</td>
<td>-2.87</td>
<td>16.13</td>
</tr>
</tbody>
</table>
higher-elevation mountainous area north of the city of Vancouver) based on land-use fractions listed in the inventories. The city of Vancouver’s total land area is downscaled by 13% and metro Vancouver is downscaled by 42%. The box-model daily total of 20.2 gC m\(^{-2}\) day\(^{-1}\) is 32% higher than the scaled inventory from the city of Vancouver for 2007 (13.8 gC m\(^{-2}\) day\(^{-1}\)) and 35% higher than 2010 (13.1 gC m\(^{-2}\) day\(^{-1}\)). Possible reasons for the discrepancy between the box-model and inventory approaches are errors in building and traffic inventory discrepancies between the box-model and inventory approaches. This is because the inventories are from different years than the balloon: emissions at this time is from 1700 LST, and the model predicts a rapid increase in \(F_C\) up to 53.0 µmol m\(^{-2}\) s\(^{-1}\) at 0900 LST. The timing and shape of this peak are similar to the July–August 2008 mean \(F_C\) measured at Vancouver-Sunset, but the magnitude is larger (27.86 µmol m\(^{-2}\) s\(^{-1}\) at 0900 LST at Vancouver-Sunset). The measured UBL wind direction at this time is from 170°, indicating the surface area influencing the measurements includes predominantly urban residential land cover, heavily trafficked commuter highways leading into Vancouver, and industrial zones along the Fraser River (Fig. 1). Higher \(F_C\) relative to the residential Vancouver-Sunset site could result from industrial sources and the relatively higher traffic density within the upwind source area.

On average, the magnitude of entrainment during 0700–1100 LST is \(-33.1\ \mu\text{mol m}^{-2}\ \text{s}^{-1}\) (Fig. 8) as the height of the convective UBL rises rapidly after sunrise to 540 m by 1100 LST (Fig. 4). Mean uncertainty due to the different background CO\(_2\) mixing ratios used is \(\pm 25.2 \mu\text{mol m}^{-2}\ \text{s}^{-1}\) (Fig. 8). When observed CO\(_2\) values in the RL are used as the \(c_b\) input, the mean flux during these hours is 4.9 µmol m\(^{-2}\) s\(^{-1}\), with individual hours showing negative emissions (i.e., uptake) \((-12.3 \mu\text{mol m}^{-2}\ \text{s}^{-1}\) at 0800 h). This appears to underestimate the actual emissions based on traffic counts and EC tower observations that indicate a peak in daily emissions at this time. When Cypress Mountain is used for \(c_b\), the average modeled emissions during this time are 44.9 µmol m\(^{-2}\) s\(^{-1}\) (peak of 7.65 µmol m\(^{-2}\) s\(^{-1}\) at 0900 LST), which is higher than expected based on comparison to local-scale EC measurements. In addition to uncertainties resulting from the choice of \(c_b\) input, the uncertainty in modeled \(F_C\) during this time can also be attributed to the influence of horizontal advection. During these hours, mean wind directions are predominantly from the SE (150°–170°) where there is a mix...
of agricultural land (and potentially significant horizontal CO₂ gradients) within 10 km of the balloon observation site.

Additional model uncertainties related to entrainment are generated because the single-box model construct used in this study assumes a spatially homogeneous rise in convective UBL height across the entire model domain. Though this is certainly a simplification, the assumption is supported by modeled mixed layer depths for eight individual boxes, each with an alongwind length of 1900 m (cumulative length is 15.2 km) extending westward from Vancouver-Sunset to the shoreline of the Strait of Georgia (Reid and Steyn 1997). This study modeled the mixed layer depth in June over each individual box using a parameterized surface sensible heat flux, inversion intensity, mixed layer temperature, and subsidence velocity (Reid and Steyn 1997; Steyn and Oke 1982). After sunrise, the mixed layer depths over all boxes are modeled to rise at the same rate up to nearly 600 m until 1100 LST.

From 0900 to 1700 LST, the mean modeled $F_C$ steadily decreases from 53.0 to 2.3 μmol m⁻² s⁻¹. As the diurnal sea-breeze circulation is established and wind directions veer toward the SW, advection begins to play an important role (Fig. 8). From 1100 to 1600 LST, the magnitude of the advection term is $-47.1 \mu$mol m⁻² s⁻¹ on average, enough to offset $F_C$. The average hourly uncertainty range of modeled advection resulting from the input of different upwind background CO₂ mixing ratios is $\pm 14.6 \mu$mol m⁻² s⁻¹ (Fig. 8). Further uncertainty in the model could result from spatially inhomogeneous changes in the UBL depth after 1100 h. After the sea breeze is established in mid-morning, higher UBL heights are expected farther downwind of the sea–urban edge in part because the cooler marine air being advected onshore acts to suppress the UBL depth closer to shore (Reid and Steyn 1997). Additionally, the western part of the city is more vegetated than the east, which favors a greater proportion of latent heat ($Q_L$) to sensible heat ($Q_H$) (i.e., lower Bowen ratio). In the more vegetated Vancouver-Oakridge neighborhood (56% plan area vegetation fraction), the measured mean $Q_H$ during 1100–1600 LST is 189.29 W m⁻², as compared with 297.45 W m⁻² observed in the less vegetated Vancouver-Sunset neighborhood (32.1% plan area vegetation fraction). Here,
Vertical profiles of the CO₂ mixing ratio, potential air temperature, wind speed, and wind direction were measured in the urban boundary layer of Vancouver, British Columbia, Canada, over a continuous 24-h period in August 2008. Observations were used to model integrated urban-scale surface CO₂ fluxes at hourly time scales using a boundary layer budget calculation with a box-model construct. Model results were compared to observations from three local-scale EC towers in operation during the UBL observation period in the greater Vancouver region. The box-model 24-h emissions total of 20.2 gC m⁻² day⁻¹ is 35% higher than simultaneous spatially averaged local-scale fluxes from the Vancouver-Sunset neighborhood (15.0 gC m⁻² day⁻¹) and is higher by 32% of a scaled inventory total (13.8 gC m⁻² day⁻¹) from 2007 for the city of Vancouver. A possible reason the box model produces higher estimates of daily emissions totals is a bias toward busy roads and industrial areas in the balloon system measurement source area—although exact agreement between the box model, EC measurements, and scaled inventory is not expected. This is mainly because the EC measurements, the box model, and inventories are representative of different spatial scales and source areas. Additional discrepancies arise between methods because the inventory includes additional greenhouse gases (methane, nitrous oxide), neglects biogenic carbon processes (soil respiration, vegetation uptake), and uncertainties are introduced when annual inventories are scaled to be representative of the study period. The box-model output is also highly sensitive to entrainment and advection fluxes whose magnitudes are comparable to or exceed the magnitude of surface emissions.

**4. Conclusions and future directions**

Vertical profiles of the CO₂ mixing ratio, potential air temperature, wind speed, and wind direction were measured in the urban boundary layer of Vancouver, British Columbia, Canada, over a continuous 24-h period in August 2008. Observations were used to model integrated urban-scale surface CO₂ fluxes at hourly time scales using a boundary layer budget calculation with a box-model construct. Model results were compared to observations from three local-scale EC towers in operation during the UBL observation period in the greater Vancouver region. The box-model 24-h emissions total of 20.2 gC m⁻² day⁻¹ is 35% higher than simultaneous spatially averaged local-scale fluxes from the Vancouver-Sunset neighborhood (15.0 gC m⁻² day⁻¹) and is higher by 32% of a scaled inventory total (13.8 gC m⁻² day⁻¹) from 2007 for the city of Vancouver. A possible reason the box model produces higher estimates of daily emissions totals is a bias toward busy roads and industrial areas in the balloon system measurement source area—although exact agreement between the box model, EC measurements, and scaled inventory is not expected. This is mainly because the EC measurements, the box model, and inventories are representative of different spatial scales and source areas. Additional discrepancies arise between methods because the inventory includes additional greenhouse gases (methane, nitrous oxide), neglects biogenic carbon processes (soil respiration, vegetation uptake), and uncertainties are introduced when annual inventories are scaled to be representative of the study period. The box-model output is also highly sensitive to entrainment and advection fluxes whose magnitudes are comparable to or exceed the magnitude of surface emissions.

This study also finds the vertical distribution of CO₂ is regulated by the thermal structure of the UBL. Over-night, measured vertical profiles of potential air temperature show the development of a stable NBL with an overlying neutral RL beginning just after sunset. Measured vertical profiles of CO₂ mixing ratio during this same time period show a clear buildup of CO₂ in the stable NBL. Three estimates of NBL height were used and the average NBL 3.5 h after sunset is 123 m. Vertical potential temperature profiles and EC measurements from the nearby Vancouver-Sunset tower indicate vertical mixing CO₂ in the NBL is dominated by mechanical processes. The model predicts positive hourly FC on average overnight (average 4.9 μmol m⁻² s⁻¹ from 2100 to 0500 LST), though individual hours show unrealistic negative FC due to advective and entrainment effects not captured by the model. Overall, the mean uncertainty overnight due to differences in NBL height is ±1.8 μmol m⁻² s⁻¹.

After sunrise from 0600 to 1100 LST, there is rapid growth in UBL height while the CO₂ mixing ratios decrease in the NBL as a result of the flushing of accumulated overnight CO₂ and entrainment from above. The modeled FC during this time rises to a peak at 0900 LST (53.0 μmol m⁻² s⁻¹). The timing and shape of the increase in FC are similar to EC measurements at Vancouver-Sunset, though the magnitude of the measurements is not as large (27.86 μmol m⁻² s⁻¹). Entrainment of the low-CO₂ mixing ratio air from above is an important process during this time (average 48% of hourly CO₂ budget) and the model is sensitive to the choice of background CO₂ mixing ratio input (mean uncertainty is ±20.0 μmol m⁻² s⁻¹).

Throughout the afternoon (1100–1800 LST), the observed profile-averaged CO₂ mixing ratios continue to decrease even though the surface is expected to be a net source of CO₂. Measurements show a well-mixed UBL with roughly vertically uniform profiles of potential air temperature and CO₂ mixing ratios. During this period, advection from upwind low-CO₂ mixing ratio marine air is an important process (average 56% of the hourly CO₂ budget). Though the modeled FC magnitude is realistic from 1100 to 1600 LST, there is large uncertainty because of advection (hourly average ±16.2 μmol m⁻² s⁻¹) resulting from different background CO₂ mixing ratio model inputs.

In summary, the model realistically simulates the diurnal course of city-scale FC. Phenomena such as the growth of the nocturnal stable boundary layer and growth of the convective UBL are spatially simplified in this single-box formulation and the largest model uncertainties result from the choice of background CO₂ mixing ratio used to calculate the advection and entrainment. Improved measurements or input of upwind CO₂ mixing ratios used to calculate the horizontal and vertical gradients, as well as increased model spatial resolution (i.e., increased number of upwind boxes), would likely improve the model results. Quantification of additional processes, such as ocean–air CO₂ exchange and recirculation of urban CO₂ from landsea and topographic circulations would also be helpful for future research to better resolve vertical profiles of CO₂ outside of the urban area.

Additional measurements, such as observations of carbon isotope ratios Δ¹³C and δ¹³C, could help distinguish between the advection of marine air with CO₂
originating primarily from biogenic sources and urbanized air with CO₂ primarily from fossil-fuel sources (e.g., Pataki et al. 2007). Measurements of gases such as carbonyl sulfide (COS) or methyl iodide (CH₃I) could also potentially be used as tracers for marine air (e.g., Bell et al. 2002; Kettle et al. 2002).

Given the complex coastal meteorology at this site (e.g., sea-breeze circulation, spatial heterogeneity of UBL dynamics, recirculation of CO₂), a comparison of model performance using a high-resolution inverse atmospheric transport modeling approach would provide more detailed insights. Such a comparison would be especially interesting during the afternoon period when several meteorological processes (entrainment; advection) are interacting simultaneously with surface CO₂ source–sink processes to influence CO₂ mixing ratios in the UBL. A more sophisticated treatment of the upwind source area influencing the UBL measurements using an inverse modeling approach would also likely yield insights into urban-scale CO₂ fluxes.

This work also has implications for the monitoring of urban-scale CO₂ emissions using CO₂ mixing ratio measurements. Tower-based CO₂ mixing ratio observations in the surface layer are representative of the entire well-mixed UBL during convective situations and below the stable NBL height overnight during this 24-h observation period. This implies future research, using either a box-model approach or inverse atmospheric modeling, could take advantage of long-term (multiyear) mixing ratio measurements from towers to estimate urban-scale CO₂ fluxes. Repeated measurements averaged over many days in varying atmospheric conditions would result in more robust emissions estimates.

Acknowledgments. The current research was funded by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) as part of the Environmental Prediction in Canadian Cities (EPiCC) network [principal investigators (PIs): T. R. Oke, UBC, and J. Voogt, UWO] and by an NSERC discovery grant (“Direct measurement of greenhouse gas exchange in urban ecosystems”; PI: A. Christen, UBC). Research infrastructure was supported by NSERC, CFI, and BCKDF (PI: A. Christen). We acknowledge the support of the city of Vancouver and Environment Canada for providing additional data and BC Hydro and the city of Vancouver for granting access to the EC tower and balloon sites. We further acknowledge the significant scientific, technical, and administrative support of staff and students at the UBC, especially Rick Kettler, Eric Leinberger, Kate Liss, Zoran Nesic, Chad Siemens, and Derek van der Kamp.

REFERENCES


Li-Cor, 2015: Li-7500RS open path CO2/H2O gas analyzer instruction manual. Li-Cor Tech. Rep., 190 pp. [Available online at https://www.boxerentec.net/s7yf0flzgn9iezkq1i3b1]


Tooke, T., N. Coops, N. Goodwin, and J. Voogt, 2009: Extracting urban vegetation characteristics using spectral mixture analysis


