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Aircraft vertical profiling of variation of CO_2 over a Canadian Boreal Forest Site: a role of advection in the changes in the atmospheric boundary layer CO_2 content

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ABSTRACT

During the period of July 8–13, 2002, we collected vertical profiles by aircraft of meteorological variables and atmospheric CO_2 over the OBS (old black spruce) site located in Boreal Ecosystem Research and Monitoring Sites in Northern Saskatchewan, Canada. We have used the data from the morning and afternoon flights to calculate the regional daily afternoon CO_2 flux for the days July 8–11. These daily fluxes were then compared to those obtained by the boundary layer budget method and by the eddy covariance measurements on the tower at the OBS site. We identified the importance of changes in the CO_2 concentration by advection to the flux estimates. In addition, we provide arguments to suggest that subseasonal temporal averaging might not, at least in some cases, eliminate advective bias contribution to the flux estimates. Because the advective influence is large and highly directional, even on seasonal and interannual timescales, it is advisable that flux estimates based on CO_2 concentration change at a site contain dynamic description of an air parcel transport history.

1. Introduction

A notable effort is applied currently in the carbon cycle community to obtain regional scale (on the order of 10^4–10^6 km^2) source/sink estimates in order to link smaller scale surface net flux measurements with those calculated on a larger scale. Methodologies exploiting the properties of the atmospheric boundary layer (ABL) as a natural regional integrator of highly inhomogeneous land surface carbon fluxes are widely used to obtain regional carbon flux estimates (e.g. Raupach et al., 1992; Denmead et al., 1996; Levy et al., 1999; Kuck et al., 2000; Lloyd et al., 2001; Bakwin et al., 2004). These approaches have applied simple mass balance principles to evaluate atmospheric boundary layer budget (BLB) of CO_2 mixing ratio to generate regionally averaged estimates of its flux. However, these BLB methods have limitations and must be applied only under certain conditions. It is not uncommon that the assumptions used in the derivation of the BLB mass balance equation are not met. These assumptions include (1) height invariant CO_2 mixing ratio in ABL, (2) space and time invariant CO_2 in the free troposphere above the boundary layer and (3) constant known vertical velocity of the ABL growth (w_+), and known ABL height. In reality, quite often there are not enough observational measurements to constrain the values of the terms that appear in the mass balance budget equation.

Alternatively, a more direct estimate of the net exchange of CO_2 between the atmosphere and the biosphere can be obtained from an integration of sequential vertical profiles of CO_2 in ABL and the layer of free troposphere right above it. In the early work of Wofsy et al. (1988) vertical CO_2 profiles in ABL over Amazon forest were measured with non-dispersive infrared (NDIR) analyser. Using these data the decline in the CO_2 columnar content was estimated and used to evaluate the rate of carbon dioxide assimilation by the forest. Later a direct integration of aircraft CO_2 vertical profiles was applied by a number of other researches (e.g. Lloyd et al., 2001; Styles et al., 2002) to derive regional flux estimates. We designate this approach of calculating regional CO_2 flux as the aircraft profile integration (API) method. In this paper, we present daytime CO_2 flux estimates calculated by integrating the areas under the vertical profiles of CO_2 obtained during the morning and afternoon flights during the period July 8–13, 2002 over the Fluxnet-Canada Boreal Ecosystem Research and Monitoring Sites (BERMS) site in northern Saskatchewan,

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Canada. The results from the API method will be compared to those from the BLB method in which we use the aircraft measurements to constrain as much as we can the variables in the BLB equation. We also compare the estimates of the flux into a vertical ABL column from these approaches with eddy covariance (EC) flux measurements from BERMS to identify and highlight the importance of advection.

In the API and BLB approaches, the effect of the horizontal exchange of CO_2 across the sidewalls of a chosen air column on the CO_2 mixing ratio inside the air column is ignored or assumed to be negligible. It is assumed that 'the sidewall exchange can be ignored if the convective boundary layer (CBL) is growing over a large area which is horizontally homogeneous at length scales comparable with or larger than the length scales of the CBL turbulence' (Lloyd et al., 2001). This allows, so it is assumed, the smoothing by the atmospheric mixing of small-scale surface source heterogeneity. When the length scale of the CBL turbulence is considered, the associated timescale for mixing is probably from several hours to a few days. A number of researchers (e.g. Levy et al., 1999, Kuck et al., 2000, Lloyd et al., 2001, Styles et al., 2002) have thus focused on a CO_2 budgeting for the subsynoptic timescale.

2. Methodology

Measurements of the CO_2 vertical profiles (using a Cessna 172 light aircraft) were made over the BERMS Old Black Spruce (BERMS-OBS) tower (53°59′N, 105°07′W) near Prince Albert, Saskatchewan from July 8 to 11, 2002 (Fig. 1). The vegetation is mostly black spruce, but approximately 15% of the forest consists of deciduous-type larch. The height of these trees reaches approximately 15 m. Ground level vegetation consists mostly of moss and Labrador tea. This type of forest is quite boggy, and has many small pockets of standing water. Old Black Spruce is important as a research site because this type of forest accounts for over 70% of boreal forest cover in Canada (http://berms.ccrp.ec.gc.ca).

Weather permitting, the aircraft measurements included one flight in the morning and one flight in the afternoon each day with two ascents over the tower in each flight. The maximum altitude achieved by the plane on each flight was around 700 mb. The CO_2 concentration was measured continuously with onboard LiCor 6251 NDIR analyser. The pressure in both sample and reference cells of the analyser was stabilized at the level slightly above the surface pressure (∼100 kPa for flights over the BERMS area). The air for continuous measurements was pumped through a magnesium perchlorate water trap for drying and a 7 mkm Nupro particle filter to the sampling line flow controller. The flow controller was set at a flow rate of 400 ml min^{-1}. The reference line of the analyser was continuously flushed with the reference CO_2-in-air gas from a small-volume high-pressure (1 *l*, 15 MPa) aluminum gas cylinder at a flow rate of 10 ml min^{-1}. The reference gas flow was regulated by an independent flow controller. To maintain the measurement precision to better than 0.3 ppm, an in-flight calibration of the instrument was made every 10 min using a set of three calibration gas standards with CO_2 concentrations in the atmospheric range. These standards are traceable to WMO Mole Fraction Scale for CO_2 (Zhao et al., 1997). Continuous CO_2 data were logged with 0.5 Hz frequency. An independent sampling line was used to collect pressurized dried air samples for subsequent analysis in the laboratory for CO_2, CO, N_2O, CH_4, SF_6, ^{13}C and ^{18}O in CO_2. A good agreement (∼0.3 ppm on average) between CO_2 concentrations from the NDIR measurements with the concentration values determined in the laboratory analysis of the simultaneously taken air samples provided an independent evidence for the quality of our CO_2 measurements. Meteorological parameters such as ambient air temperature, pressure and humidity, wind speed and direction, as well as the aircraft position, were also measured with AIMMS-10 aircraft meteorological system (Aventech Research Inc.) and logged every 2 s. The same meteorological parameters were measured continuously at the surface on the tower. The eddy covariance CO_2 flux measurements for the study period were obtained from the BERMS-OBS tower, where the flux measurements have been conducted since 1999 (Griffis et al., 2003)

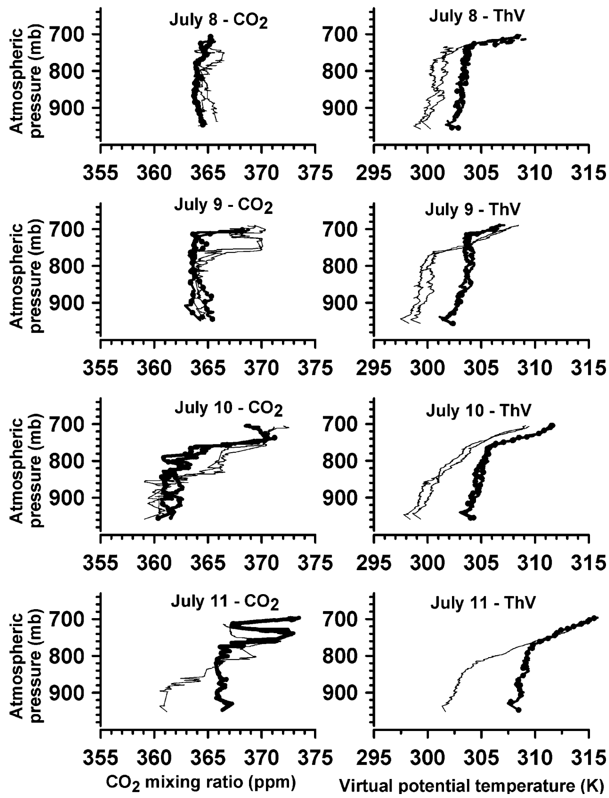

Fig 1. Vertical profiles of CO_2 and potential temperature over BERMS OBS tower in July 2002. Thin lines—morning profiles, thick line—afternoon profiles.

The amount $N_{CO_2}(z_{top})$ of CO_2 moles in the air column from the surface to the level z_{top} per unit area may be calculated as

$$N_{CO_2}(z_{top}) = \frac{\mu_{CO_2}}{\mu_{air}} \int_0^{z_{top}} C\,(z) \frac{p(z) - e(z)}{p(z)} \rho(z) \mathrm{d}z. \quad (1)$$

Or using the pressure vertical coordinate

$$N_{CO_2}(p_{top}) = -\frac{\mu_{CO_2}}{\mu_{air}} \int_{p_0}^{p_{top}} C(p) \frac{p - e(p)}{p} \frac{\mathrm{d}p}{g} = -\frac{1}{g} \int_{p_0}^{p_{top}} C_{mass}(p) \frac{p - e(p)}{p} \mathrm{d}p, \quad (2)$$

where p_{top} and p_0 are the pressure at the top and at the bottom of the integrated air column, $\rho(z)$ is the CO_2 molar density, $C(z)$ and $C(p)$ are the CO_2 volume mixing ratios of dry air at level z and p, respectively, $C_{mass}(p)$ is the mass mixing ratio of CO_2 in dry air at level p, $e(z)$ and $e(p)$ are the water vapour partial pressures at level z and p, respectively, μ_{air} and μ_{CO_2} are the molecular weights of dry air and CO_2 respectively, the term $(p - e)/p$ accounts for the height-dependent moisture content in the moist atmospheric air. Difference in the CO_2 amounts, calculated for two sequentially measured vertical profiles of CO_2 in the air column, divided by the time between the measurements of these profiles, is equal to an average flux into the air column required to cause the observed net CO_2 change in the column. This net flux is a sum of the surface flux, exchange flux through the top and through the walls of the air column. If we choose integration boundaries for the two profiles of a day at a same isobaric surfaces instead of two fixed height levels, the effects of air density changes (due to temperature change in ABL with time) and large scale subsidence (see Styles et al., 2002) may be neglected. We fix the top of the air column at the isobaric surface p_{top}. If the level p_{top} is chosen above the ABL top then the hydrostatic approximation may be applied, providing a good base for the assumption of zero air-flow through the top of such an air column. If we also choose two profiles with the same CO_2 concentration $C(p_{top})$ at the isobaric surface p_{top} we can assume that CO_2 exchange flux through the top of the column over the time between the two profiles measurements may be neglected. Thus, if we have an estimate for the surface flux from eddy covariance measurements, the advection contribution to changes of the CO_2 amount in the column could be estimated as a difference of the net flux into the column and the surface flux. To account for the change of the air amount in the column because of the changes in near-surface pressure we choose the bottom boundary of the column also at the isobaric surface p_0, with p_0 equalling to the lowest pressure for the time period for which an estimate is calculated. Then a small correction was applied to the surface flux data to adjust the surface source/sink to the level p_0 .

In the BLB approach it is suggested that regionallyaveraged flux into CBL may be estimated from the changes in concentration of CO_2 and in the size of the CBL. We followed the formulation for the CBL budget-based CO_2 flux estimates from the paper of Lloyd et al. (2001).

$$\langle R - A \rangle = \frac{\left(M_{B(1)} - \langle W_+ \rangle T\right)\left(C_{B(1)} - C_+\right) - M_{B(0)}\left(C_{B(0)} - C_+\right)}{T}. \quad (3)$$

As Lloyd et al. (2001) defined in eq. (3), A is the rate of CO_2 assimilation by the photosynthesizing vegetation below, R is the corresponding ecosystem respiration rate, $M_{B(0)}$ and $M_{B(1)}$ the CBL air content at times t_0 and t_1 correspondingly. $M_B = \rho_B h$, where h is the CBL height and ρ_B is the mean molar density of air in the CBL, thus units for M_B are moles per unit surface area. C_B is the mean over CBL molar fraction of CO_2, C_+ is the CO_2 molar fraction in the free troposphere above, $W_+ = \rho_h w_+$ is the molar flux of air across a stationary plane at height h, w_+ is the vertical velocity at height h induced by large-scale atmospheric motion, T is the time period between the two states of developing CBL, $T = t_1 - t_0$, and angular brackets denote averaging between t_0 and t_1.

When measured vertical profiles for CO_2, temperature and humidity are available the values for M_B, C_B and C_+ can be calculated from these data. For estimating w_+ a formula from Levy et al. (1999) was used:

$$w_+ = \frac{h}{z}\left(\frac{\mathrm{d}\theta_z/\mathrm{d}t}{-\gamma_z}\right) \quad (4)$$

where θ_z is potential temperature at height z, γ_z is the gradient in potential temperature at height z, z reference height above and not influenced by the CBL. This approximation was suggested by Gryning and Batchvarova (1999) and is based on the assumption that horizontal divergence is constant with height, so that w_+ is proportional to the height above surface. If warming of the air at some reference height z, which is high enough above the CBL, is assumed to be a result of subsidence, the mean vertical velocity just above the CBL, w_+ can be estimated from eq. (4), using again the aircraft data for calculating parameters in the equation.

3. Results and discussion

Both the API and the BLB methods assume uniformity of atmospheric CO_2 concentration and its temporal change over the region where CO_2 flux is being calculated. Given the notorious heterogeneity of the ecosystem (and therefore CO_2 flux) over a large region, this assumption is very difficult to satisfy in practice. Moreover, homogeneity in ecosystem properties is not sufficient for uniformity of the boundary layer CO_2 concentration field. The modelling study of Chan et al. (2004) indicates that over a boreal region in Canada the atmospheric CO_2 concentration field in summer is heterogeneous and dynamic, characterized by CO_2 gradients of 5–15 ppm over distances on the order of 100 km or more and changing on a timescale of a day. In CO_2 Budget and Rectification Airborne (COBRA) study (Stephens et al., 2000; Gerbig et al., 2003a,b; Lin et al., 2004) gradients of CO_2 of the same order were observed and large variations in biosphere–atmosphere exchange due to modulation of the downward radiation with moving cloud systems were noted. We are going to show in this section that our experimental data reveal spatiotemporal variability in the CO_2 distribution in the ABL of similar magnitude but happening on a shorter timescale of a few hours and at a short distance on the order of 10–20 km. Unless one can obtain a detailed knowledge of the history of the CO_2 concentration of the air parcels when they have been advected over the region (Lagrangian framework – see e.g. Raupach et al., 1992, Gerbig et al., 2003a,b; Lin et al., 2004), the API and the BLB approaches have limited potential as tools for estimating regional CO_2 fluxes.

Figure 2 shows the tower measurements of meteorological parameters and CO_2 at the BERMS-OBS site from July 8 to 13, 2002. Included in the bottom panel showing the CO_2 time-series are the eddy covariance CO_2 flux measurements obtained at the site. It is evident from the figure that a weak warm frontal passage occurred over a 2-d period (July 10 and 11). Beginning on July 10, the atmospheric pressure started to fall as the specific humidity gradually rose. We also see the corresponding rise in the air temperature and a shift in the wind direction. It is interesting to note that, in comparing the time-series of the CO_2 flux measurements and the atmospheric CO_2 values, the changes in these time-series are not in agreement with each other, particularly during the daytime. This is primarily due to the influence of horizontal advection.

In the afternoons of July 8 and 9 the concentration growth period started only when CO_2 flux became positive (biospheric source). However, on July 11 the concentration increased by about 5 ppm in approximately 1.5 h in the early afternoon, while the eddy covariance (EC) measurements continued to show a strong negative CO_2 flux (biospheric sink). Morning and afternoon CO_2 profiles for the day showed that CO_2 is well mixed in the ABL before and after the observed concentration rise (see

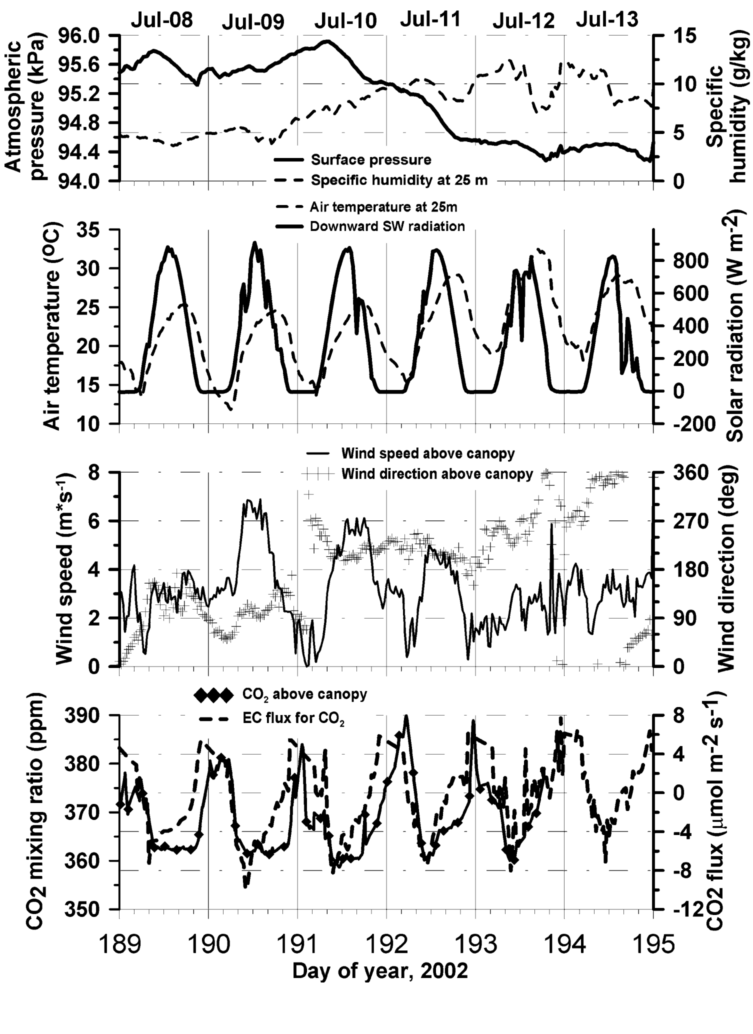

Fig 2. Meteorological parameters, CO_2 mixing ratio and CO_2 flux measured at the top of BERMS-OBS tower in July 2002.

Fig. 1). If we assume that the observed increase in CO_2 did occur in the whole depth of the convective ABL then equivalent surface source of CO_2 would have to be 40–50 mol m^{-2} s^{-1} to develop such a magnitude of the concentration growth in the layer - one order of magnitude higher than fluxes measured with EC technique in this boreal ecosystem. Thus, the advection of the CO_2-enriched air seems to be the only feasible explanation. This advected air from regions near the OBS tower was likely of biospheric origin and not localized anthropogenic source since there was no associated increase in the CO concentration on that day (not shown). In fact, the CO/CO_2 ratio slightly decreased from July10 (0.26–0.34 ppb CO ppm^{-1} CO_2) to July 11 (0.20–0.30 ppb CO ppm^{-1} CO_2) (Doug Worthy, personal communication, 2005).

3.1. Flux estimates and the role of advection

Flux estimates from the API and the BLB methods are shown in Fig. 3. To calculate the estimates of flux into the ABL column using the aircraft vertical profile information in eq. (2), we select daily pairs (morning and afternoon) of the CO_2 profiles shown in Fig. 1. Each of the CO_2 daily profile pair satisfies the condition of having a level above ABL where CO_2 concentration values of the two profiles are in close agreement. We assign the highest altitude where this occurs to the upper height limit p_{top} in eq. (2) and calculate estimates of the CO_2 flux into the ABL column, as described in Section 2.

The advantage of the BLB approach is the ability to produce an estimate of a regional CO_2 flux with limited information on the CO_2 vertical distribution in the ABL and above it. The quality of such an estimate depends on the validity of the assumptions formulated in the Introduction section above. Information on the CO_2, temperature and humidity vertical profiles in the ABL and above it from the aircraft measurements provides an opportunity to generate better estimates of the parameters in the eq. (3), such as the average ABL CO_2 concentration (C_B), the ABL air content (M_B), CO_2 concentration just above the ABL (C_+), and the vertical velocity of the large scale atmospheric motion (w_+), than the values commonly used in the absence of such data (e.g. Raupach et al., 1992; Denmead et al., 1996; Levy et al., 1999). We evaluated the input parameters for eq. (3) (i.e. $M_{B(0)}$ and $M_{B(1)}$, $C_{B(0)}$ and $C_{B(1)}$, C_+ and w_+) using available detailed information from the aircraft measurements of CO_2, temperature and humidity profiles within ABL, CO_2 concentration and potential temperature gradient above the ABL and the height of the ABL dynamics. Although we tried to provide the best possible values for the input parameters in eq. (3), based on information available from the aircraft measurements (see Table 1), it is interesting to note in Fig. 3 that the flux estimates obtained by the BLB method can differ from those obtained by the API method sometime by as much as 100%. We assume that the API estimates are more reliable, because in the BLB method, the assumptions regarding the CO_2 flow through the top of ABL (entrainment) play important roles in eq. (3) and parameters for this part of equation – especially w_+ – is difficult to estimate. In the case of API, the choice of the upper integration level at the same isobaric surface above the ABL for both integrated profiles allows the application of the hydrostatic approximation. By choosing this isobaric level with the same CO_2 concentration further simplifies the problem as the vertical exchange of CO_2 through this level may be neglected. The difference would be greater if such detailed information on the vertical properties of the parameters in eq. (3) were not available; unfortunately, this is often the case and the errors associated with the BLB method is significant.

The daytime averaged flux estimates into an air column obtained from the API method and the BLB method correspond to the time period between the morning and the afternoon aircraft profiles. The CO_2 surface flux for each day obtained from the EC measurements, also shown in Fig. 3, corresponds to the same time period. For the period of July 8–10, there is an agreement, at least in sign, between the API and BLB flux estimates and the average surface flux; the differences are probably reflecting advection signal which may contribute in this case anywhere from 15 to 110% of the average EC flux. On July 11, the API flux estimate shows a large positive value, indicating a large regional source somewhere upstream of the OBS site. The API flux value reflects the observed increase in the CO_2 concentration due to the advection of CO_2-rich air from the southerly direction (Fig. 2) to the OBS tower site through a substantial part of the ABL column. The API flux magnitude reached ∼320% of the EC flux that remained negative (biospheric sink) with its magnitude remaining similar to those in previous days. The difference between the EC flux from the tower measurements and the flux estimate derived

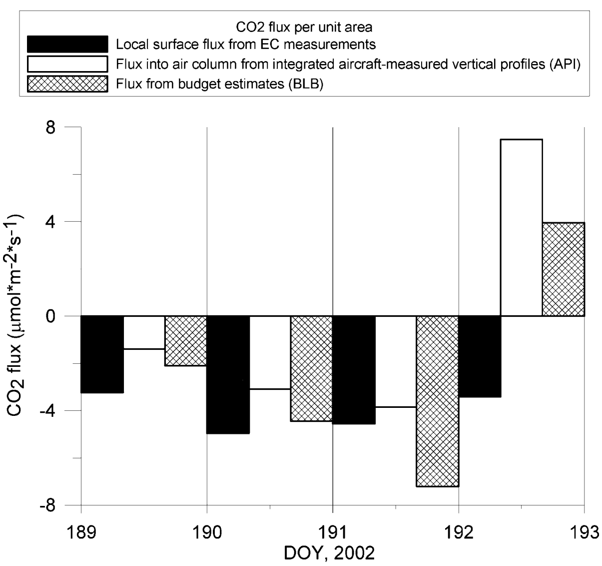

Fig 3. Comparison of the CO_2 surface flux measured with eddy covariance technique (EC) with the estimated flux into ABL column (API and BLB techniques).

Table 1. Values for parameters in the BLB equation (eq. (3)), estimated from the measured aircraft profiles (reference case).

Date in 2002	Average time for flight (h LT)	Boundary layer height (from measured vertical profile of potential temperature) (m)	Average over height air molar density in ABL (mol/m^3)	Average over height CO_2 concentration in the ABL (ppm)	Averaged between morning and afternoon CO_2 concentration in the free troposphere above ABL (ppm)	Vertical velocity of large-scale atmospheric motion estimated with eq. (4) from measured (m/s)
8 July	11.4	1830	0.037	364.6	366.0	0.033
8 July	19.3	2303	0.034	364.1		
9 July	11.1	1890	0.037	364.3	368.4	0.033
9 July	17.8	2550	0.035	364.1		
10 July	10.7	1125	0.038	360.6	369.0	0.035
10 July	17.3	1968	0.036	362.2		
11 July	10.1	1195	0.038	362.3	369.2	0.035
11 July	17.4	1870	0.036	366.4		

from changes in the ABL column CO_2 content provides an indication of the degree of advective contribution to the flux near the tower. The BLB flux estimates follow the same sign as the API estimates, but differ in magnitude to within a factor of 2. These results reaffirm the idea that it is potentially dangerous to extrapolate a local EC flux to a regional scale. Furthermore, advection results from a directional movement of airmass whose CO_2 concentration is dependent on its history, that is, on its history of contacts with different ecosystems along its path. It is therefore inappropriate to talk of a 'regional' flux estimate derived from a concentration change observed at a point in space.

Another example of strong mid-ABL advection contribution into the air column balance was observed in our aircraft campaign over Fraserdale tower in Northern Ontario (49°52′N, 81°37′W) in July 2000. The site is about 210 m above sea level with a 40 m tower located on the top of a small hill. A 2 km × 2 km region around the site is characterized mainly by forest (50%), the Abitibi river (18%) and logged area. Of the forested region, mature black spruce (51%) and poplar (26%) about 10 m height are the dominant tree species; other species are jack pine, birch, white spruce and balsam fir. The landscape around the site is also characterized by a number of small wetlands to the south and southwest. On the Fraserdale tower the high precision measurements of CO_2 and other trace gases concentrations were carried out since 1990 until now (Higuchi et al., 2003). Meteorological parameters (atmospheric pressure, air temperature and humidity, wind speed and direction at several levels on the tower) were also monitored during the period. No eddy covariance flux measurements were made at the site.

Aircraft measurements were carried out over Fraserdale from July 25 to July 29, 2000 using the same instrument and methodology as described in section 2. The measurements consist of morning and afternoon vertical profiles to a 3 km height of continuous CO_2 concentrations and meteorological data, as well as flask samples collected for CO_2, other trace gases and CO_2 stable isotopes. Meteorological conditions from the tower measurements (see Fig. 4) indicate a weak cold front passage on July 27 (day 209). The corresponding change in the vertical profiles of CO_2 and potential temperature is clearly seen in the Fig. 5. The profiles were measured twice a day - in the morning (9–11 LT) and in the afternoon (15–17 LT). For each flight, there are up to four profiles corresponding to a sequence of ascents and descents, with each ascent or descent taking approximately 30 min. The CO_2 concentration from the tower measurement is plotted as the lowest point of each profile. The observations were not taken on July 27 (day 209), the day of the frontal passage. However, the sequence of the profiles shows the shallow ABL in the cold sector with large gradients across the ABL-free troposphere boundary (the afternoon profiles on July 28 (day 210)), in contrast to the deep warm sector ABL with small transitional gradients (the afternoon profiles on July 26 (day 208). Within the warm sector, the sequence of morning profiles on July 25 (day 207) showed the advection of higher CO_2 concentration air to Fraserdale above the 900 mb level. For a typical wind speed of 10 m s^{-1}, the profiles capture the movement of air with a CO_2 gradient of about 5 ppm per 100 km. By comparing the July 25 (day 207) afternoon profiles to the July 26 (day 208) morning profiles, there is evidence of an overnight advection of air with about 5 ppm lower CO_2 concentration in the ABL residual layer (between 900 and 800 mb).

There are prominent surface maxima in the CO_2 profiles on the morning of July 29 (day 211). On that morning, fog formed in the stable surface layer produced by the strong overnight radiative cooling. The ground fog delayed the surface warming

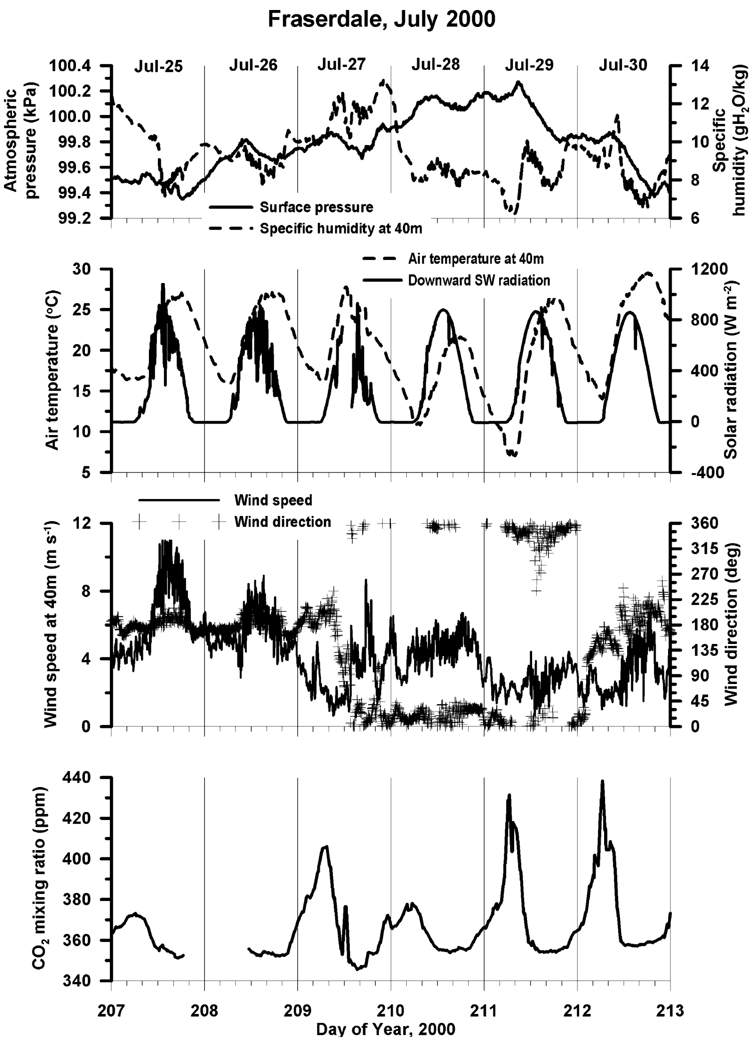

Fig 4. Meteorological parameters and CO_2 mixing ratio measured at the top of Fraserdale tower in July 2000.

in the morning and the destruction of the stable nighttime surface layer. Also, the fog reduced the surface solar radiation and photosynthetic draw down. Thus the large buildup of nighttime respired CO_2 in the stable surface layer remained visible as the large surface CO_2 maxima in the Figure. The surface CO_2 values (from the tower data) for the profiles were about 400 ppm.

The condition of a well-mixed ABL is not valid for the morning CO_2 profiles of the July 2000 aircraft campaign over Fraserdale. Thus, the BLB methodology could not be applied to estimate the daytime net CO_2 flux into the ABL vertical column, basing on the morning and afternoon flights. Also EC flux measurements were never performed on the FRD tower. As a result we were not able to generate the same set of estimates as for the aircraft campaign over BERMS OBS site in July 2002 (see Fig. 3 and associated discussion). Nevertheless, we considered it useful to include in this section comparison of the API-based estimates for the flux into the vertical column of ABL with the surface flux near the Fraserdale tower, estimated with BEPS (Boreal Ecosystem Productivity Simulator) ecosystem model (Liu et al., 1997) to provide another example of a strong advection signal. A number of papers on the comparison of different model performances with experimental data (e.g. Amthor et al., 2001; Grant et al., 2005) showed that typically model-simulated CO_2 fluxes are within the range of $\pm$50% of the eddy-covariance flux measurements. Also, to evaluate the performance of the BEPS model we did calculate the CO_2 net exchange flux for the BERMS OBS site (not shown here) and get the same agreement within $\pm$50% with the EC measurements on the OBS tower. Therefore, the BEPS simulated flux may serve as a semi-quantitative estimate of the EC flux in this comparison to API estimate. The comparison of API flux estimate to BEPS flux in Fig. 6 indicates that there was strong advection of high CO_2 concentration air into the column on day 208 (one day before the weak cold front passage). In contrast, on days 207 (warm air sector), 210 and 211 (cool air sector), there were strong advective contributions of depleted CO_2 air into the column. Although these three episodes represent advections of low CO_2 concentration air, they have quite different meteorological conditions (warm versus cool air sectors);

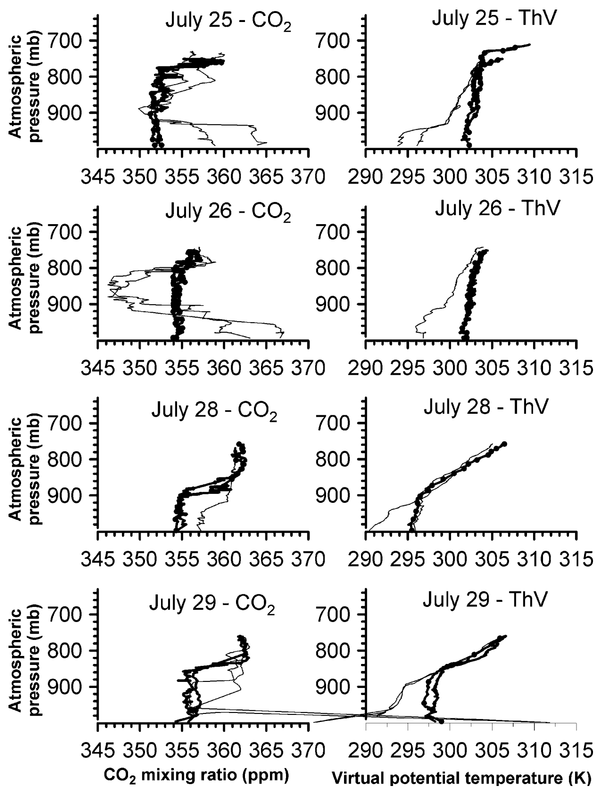

Fig 5. Vertical profiles of CO_2 and potential temperature over Fraserdale tower in July 2000. Thin lines—morning profiles, thick line—afternoon profiles

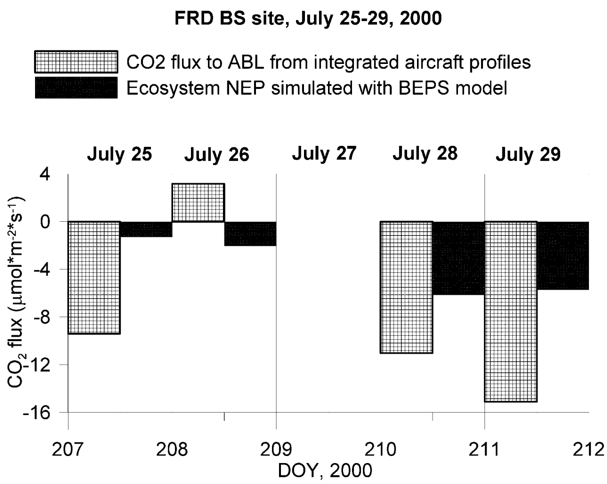

Fig 6. Comparison of the CO_2 surface flux estimated with BEPS ecosystem model with the estimated flux into ABL column (API technique).

also their wind directions were in opposite directions according to Fig. 4 with different upwind vegetation types and distributions. This suggests that there is no simple relationship among advection, meteorological conditions and vegetation types; their fully coupled interactions are important in determining the space–time distribution of the CO_2. These results indicate that advection of high and low concentrations of CO_2 air are quite common and highly variable.

Our analysis shows that the horizontal transport contribution cannot be neglected in the ABL mass balance equation for CO_2 on a subsynoptic timescale. The degree of significance of the contribution depends on the degree of heterogeneity of the atmospheric CO_2 concentration field that is produced by the heterogeneous distribution of the biospheric sources/sinks and their response to changing meteorological drivers. The advective influences we saw in our campaign measurements are relatively ubiquitous. The horizontal heterogeneity in the ABL CO_2 concentration field can be seen in the horizontal ferry flights in the campaign. The ferry flights CO_2 measurements were collected between Toronto (aircraft home base) and Prince Alert, and between Prince Albert and BERMS site. The ferry flights measurements were made at the pressure level of approximately 850 mb. Figure 7(a) shows horizontal changes in atmospheric CO_2 observed during the ferry flights between the BERMS site and the Prince Albert airport during the two consecutive days of the July campaign. Both days were characterized with developed convective mixing at least to 1 km in the time of the morning flights and to about 2 km height for the afternoon flights (see Fig. 1). The surface vegetation surrounding Prince Albert is agricultural and natural grassland. On the 80 km ferry flight from the Prince Albert airport to the BERMS area, the grassland is replaced by a forest at a half-way point (~40 km from the PA airport). One can readily see from Fig. 7(a) that even in the afternoons the CO_2 gradient between Prince Albert and the OBS tower changed sign from negative 2 ppm to positive 2 ppm per 80 km in 1 day. The maximum difference in the CO_2 concentration measured over the same route reached ~10 ppm (forested area near 53,6° N latitude in the Fig. 7a).

Figure 7b shows a similar picture, but for the ferry flights between Toronto and Prince Albert. The ferry flights were performed in daytime on sunny days when convection mixing was already well developed. In July 2002 the observed gradients of CO_2 in the mid-ABL were as large as ~20 ppm per 100 km. A study by Chan et al. (2004) using a three-dimensional atmospheric dynamic regional model coupled to an ecosystem model showed simulated ABL CO_2 concentration field over Canada with gradients of the same order of magnitude as were observed in our long-range aircraft transects. The simulated gradients were the results of the atmosphere–biosphere interaction, the primary effect is the synoptic and mesoscale cloud patterns induced radiation variation on photosynthesis. The features related to the static surface distribution of the ecosystems were less pronounced.

4. Conclusions

In this study, we have presented aircraft data of vertical profiles in ABL taken during the period July 8–11, 2002. These profiles

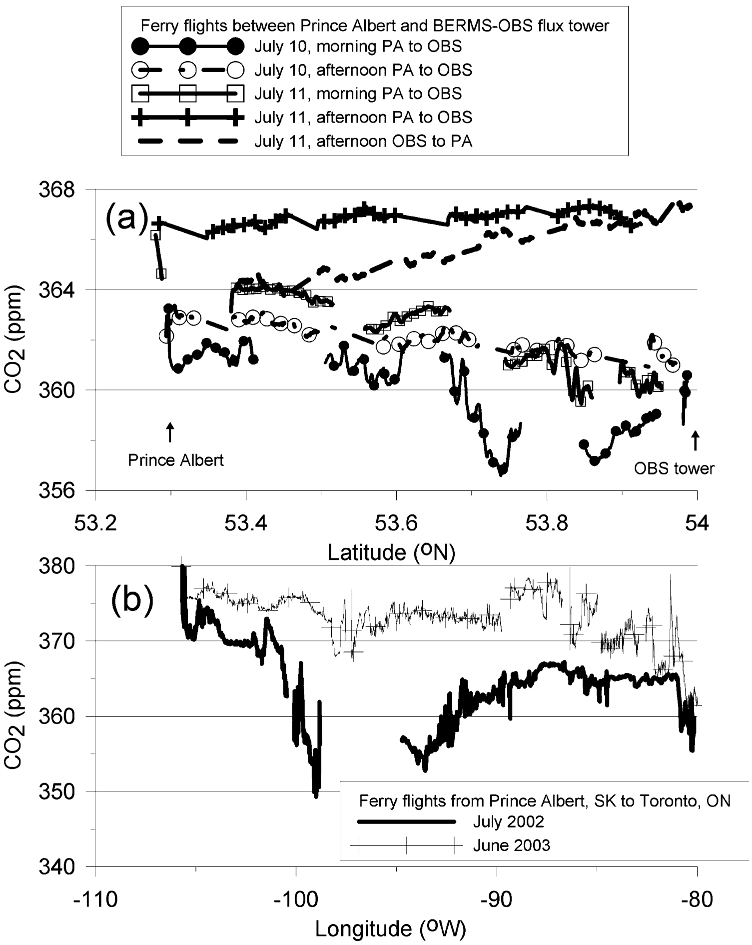

Fig 7. CO2 mixing ratio variability in mid-ABL(~0.8-1.2 km above surface). (a) ferry flights between Prince Albert airport and BERMS-OBS tower in July 2002 and (b) ferry flights between Prince Albert, Saskatchewan and Toronto, Ontario in July 2002 and June 2003.

were taken during the morning and afternoon flights in each day over the BERMS-OBS site in northern Saskatchewan, Canada. Surface measurements of pressure, temperature, humidity and wind indicated passage of a weak warm front on July 11. The winds shifted to southerly during July 10 and 11, and eventually returned to northerly on July 13. The difference in the diurnal variation between the CO_2 concentration and eddy covariance flux measurements on the tower each day at the site indicated the importance of advective influence on the concentration measurements at the tower on a subsynoptic timescale. This difference became quite obvious during the passage of the warm front on July11, with a strong transport through the depth of ABL of air enriched in CO_2. Using the API and the BLB methods, flux estimates changed sign from negative (sink) on July 8, 9, 10 to positive (source) on July 11. This contrasted with the EC flux which remained negative and with similar magnitude as on previous days. The advection of air with a higher concentration by about 5 ppm was translated as a regional source of CO_2 by both the API and the BLB methods. In this case study the advection contribution varied from about 20 to 400% of the EC surface flux, measured at the site. We presented another example of strong advective contribution into the CO2 ABL content, measured in July 2000 over Fraserdale tower in Northern Ontario, Canada.

We have also shown, with evidence from the aircraft ferry flights between Toronto and Prince Albert, as well as between Prince Albert and BERMS, and from a modelling study (Chan et al., 2004), that over the boreal region in Canada the atmospheric CO_2 concentration field in summer is heterogeneous, characterized by CO_2 gradients of up to 20 ppm over distances on the order of 100 km or more. These differences are dynamic, reflecting not only distribution of the surface biospheric sources/sinks but also their temporal variability in response to synoptic and mesoscale changes in meteorological conditions. The advective flux component makes an important contribution to the changes in the ABL column CO_2 concentration on synoptic to subsynoptic timescales. On longer timescales, it has been suggested by other investigators (e.g. Bakwin et al., 2004) that the advective contribution to the flux estimate over a region can be eliminated by some suitable averaging time, say a month or even a season. But since transport is highly directional with time (e.g. Higuchi et al., 2003), it is our opinion that there will always remain seasonal and even interannual advective bias in the flux estimates based on atmospheric CO_2 concentration measurements. Establishing this on a more quantitative footing requires further investigation.

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