Tellus (2003), 55B, 115–125

TELLUS
ISSN 0280–6509

Regional source/sink impact on the diurnal, seasonal and inter-annual variations in atmospheric CO_2 at a boreal forest site in Canada

By K. HIGUCHI*, D. WORTHY, D. CHAN and A. SHASHKOV, *Air Quality Research Branch, Meteorological Service of Canada, 4905 Dufferin Street, Toronto, Ontario M3H 5T4, Canada*

(Manuscript received 2 February 2002; in final form 20 December 2002)

ABSTRACT

Time series of in-situ CO_2 data from Fraserdale (50°N, 81°W) in the northern Ontario boreal forest is described, together with an analysis of observed variations occurring on daily to interannual timescales. Atmospheric CO_2 measurements at Fraserdale reflect a complex interaction between the daily cycle of the vegetative carbon flux and the daily evolution of the boundary layer mixing dynamics. This is particularly evident during the growing season, when CO_2 concentrations are influenced strongly by local and regional biospheric activities. In addition, the atmospheric CO_2 measurements at Fraserdale are greatly influenced by the direction of atmospheric transport, and reflect the complex heterogeneous distribution of ecosystem types around the site. Averaged over the 7-yr period from 1990 to 1996, the seasonal cycle associated with air from west and northwest of the site shows an amplitude of ~19 ppm, while that associated with air from the south and southwest shows an amplitude of ~23 ppm; the seasonal minimum, on average, occurs about a week earlier in the latter case than in the former. This is reflective of the fact that many of the deciduous trees are located to the south and southwest of Fraserdale. Furthermore, its location in the boreal forest causes the seasonal minimum to occur on average in early August at Fraserdale, compared to late August observed at Alert and at many other background stations in the high-latitude Northern Hemisphere. At the Fraserdale site there is no statistically significant indication, during the 1990–1996 study period, of changes in the length of the growing season (as measured by zero crossing points in the seasonal cycle).

1. Introduction

At the present time, the fraction of anthropogenically emitted CO_2 remaining in the atmosphere has been relatively steady at 50–55% of the fossil-fuel CO_2 emission of about 6 Gt C yr^{-1}. With an estimate of an additional 1.6 ± 1.4 Gt C yr^{-1} release from tropical deforestation activities (IPCC, 1996), the actual fractional amount of the total anthropogenically produced CO_2 remaining in the atmosphere comes out to about 40%. One of the main questions facing carbon cycle researchers has always been: What are the relative roles played by the oceans and the terrestrial biosphere in the net uptake of the remaining portion of the CO_2 emission? The most recent estimate calculated from available observed data puts the net oceanic uptake at 2 ± 1 Gt C yr^{-1} (Takahashi et al., 1999). Consistent with the idea put forward by Wong (1978) and Broecker et al. (1979) that the land biosphere on a global basis is either a neutral reservoir (i.e., no net release or uptake of CO_2 from the atmosphere) or a relatively small net sink for atmospheric CO_2, it appears today that an amount of CO_2 almost equivalent to that released by the tropics is being absorbed by the land biosphere in the Northern Hemisphere midlatitudes (Gurney et al., 2002).

In order to increase our quantitative understanding of the role of the Northern Hemisphere midlatitude terrestrial biosphere in balancing the global carbon

*Corresponding author.
e-mail: kaz.higuchi@ec.gc.ca

budget, there is a recognition of the need to establish an increasing number of continental monitoring sites to obtain atmospheric CO_2 measurements to further constrain atmospheric models which are used to obtain regional and hemispheric estimates of biospheric sources and sinks (e.g., Fan et al., 1998; Ciais et al., 2000). At the present time there are only few such sites in the world where such CO_2 measurements are taken (Levin et al., 1995; Bakwin et al., 1998; Haszpra, 1999; Inoue and Matsueda, 2001). In this paper we present a description of continuous atmospheric CO_2 data obtained at a continental boreal forest site in Canada, one of the few in the world with relatively long records. The study focuses on the period 1990–1996.

2. Brief site description and data

Fraserdale (49°52′N, 81°37′W) is located southwest of James Bay in northern Ontario (Fig. 1). The site is about 210 m above sea level, with a 40 m tower located on the top of a small hill at the east end of a large clearing, about 300–400 m across, which is characterised by a relatively smooth shallow valley covered by tall grass and several small willow trees. Immediately to the east of the site flows the Abitibi River, where the Ontario Power Generation company has hydroelectric dam about 200 m north-northeast from the tower. A 2 km × 2 km region around the site is characterised mainly by forest (50%), the Abitibi River (18%) and a logged area. Of the forested region, mature black spruce (51%) and poplar (26%) about 10 m in height are the dominant tree species; other species are jack pine, birch, white spruce and balsam fir. The landscape around the site is also characterised by a number of small wetlands to the south and southwest.

The closest town to the Fraserdale site is Smooth Rock Falls (population ∼2500) located about 70 km south of the site. The closest town to the north is Moosonee (population ∼1500) located about 200 km from the site. Timmins (population ∼50 000) is the closest major city, located about 150 km south of Fraserdale.

Monthly mean temperatures are below 0 °C for about 6 months of the year, with a wintertime mean of about −20 °C (with a range from about −28 to −15 °C) and a summertime mean of about 17 °C (with a range from about 15 to 18 °C). There are about 162 freeze-free days per year, while the growing season (defined as starting after five consecutive days with temperatures above 5 °C) extends on average from 5 May to 15 September (133 d). Thus, biological

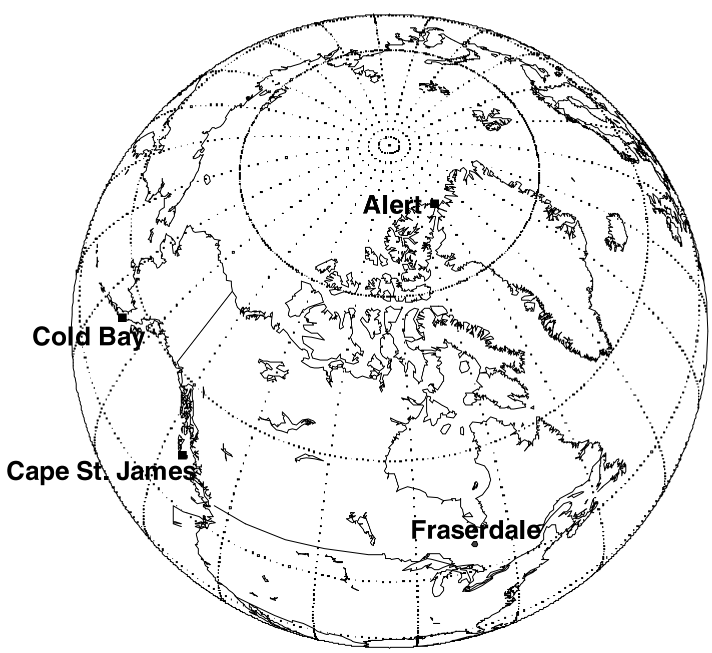

Fig. 1. Geographical location of Fraserdale, relative to Alert, Cold Bay and Cape St. James.

influences on the measurements at Fraserdale start in early May.

Annual precipitation (derived from neighbouring meteorological stations at Mosonee and Timmins) is about 800 mm (water equivalent). Consequently, the forest influencing the measurement site is a wet boreal forest, in contrast to the dry boreal forest west of Ontario. The movement of the Arctic front controls the seasonal precipitation pattern over the Fraserdale region. Thus, higher precipitation values are observed during the summertime (up to 100 mm month^{-1}) when the Arctic front is located just to the north of Fraserdale.

Changes in the position of the Arctic front affect the different air masses that are sampled at Fraserdale. The site is climatologically influenced alternately by Arctic, maritime tropical and modified Pacific air masses (Bryson, 1966), resulting in four main different seasonal circulation patterns: (1) a winter pattern that brings air from the northwest between November and February, (2) a spring pattern that transports air from the north between March and June, (3) a summer pattern that brings air from the north as well as from the southwest between July and September and (4) a short transitional fall pattern that brings air from the west in October. During winter and spring the circulation patterns bring clean air from the north to Fraserdale, while anthropogenic influence on the sampled air is more likely associated with the summer circulation (Jobson et al., 1994).

In February 1990 a continuous monitoring of atmospheric CO_2 was initiated at the top of the 40 m tower at the Fraserdale site. The measurement continued until November 1996, with only a few short interruptions. A second air sample intake was added at the 20 m level in late 1995. Meteorological parameters, such as wind and air temperature, were measured at heights of 1.5, 10, 20 and 40 m on the tower; humidity was taken at 1.5, 20 and 40 m levels. The CO_2 measurement program was re-initiated in late 1998, and continues to the present day. A more detailed description of the Fraserdale site and its measurement program can be found in the Meteorological Service of Canada report (MSC, 1999) and Worthy et al. (1998).

3. Measurement instrumentations and procedures

Atmospheric CO_2 is continuously measured at Fraserdale using non-dispersive infrared (NDIR) methodology. A Siemens Ultramat III spectrometer was used from February 1990 to August 1994 and a Siemens Ultramat V was used from September 1994 to December 1996. Ambient air is supplied to the NDIR at approximately 5 L min^{-1} by a KNF Neuberger (model UN022SV1) vacuum pump that draws air through a 0.95 cm o.d. sample line (Dekoron), which extends to the top of a 40 m triangular steel tower. A 7 μm stainless steel membrane filter is placed just prior to the pump to trap dust and dirt particles. After the pump, the sample air is passed through a pressure relief valve set at 1 atm to release excess pressure (and air) and then through a large bead-filled glass trap immersed in a cryogenic bath, set at -70 °C, to permit the analysis on a dry air basis. The dried airflow is then split between inlets for a methane gas chromatograph and the NDIR analyser. Standard gases are supplied to the NDIR from pressurised gas cylinders (30 L aluminium tanks) equipped with high-purity, two-stage gas regulators. Stainless steel tubing (0.32 cm o.d. $\times$ 0.22 cm i.d.) is used for the standard gases and ambient sample line after the cold trap.

A Campbell Scientific data logger (model CR21$\times$) is used to control the automated operation of the standard tank injection sequences and acquires the raw voltage output. Every hour, a calibrated target gas (approximately 360 ppm) and a zero gas (approximately 310 ppm) are passed through the analyser for 3 min each. Ambient air is passed through the system for the remaining 54 min of each hour. Every 5 h, the target, zero and three working gases (that span the typical measurement range, i.e. 350, 375 and 400 ppm) are passed through the analyser for 3 min each. Every 15 d the working and target gases are calibrated against a set of five station standards. These station standards are calibrated at the site approximately every 6 months against a set of five transfer standards from the central calibration facility in Toronto.

The zero and target tanks and ambient mixing ratios are calculated from a quadratic system response function determined from the calibrated assigned mixing ratios of the three working gases. The target and zero gas evaluations provide a measure of the accuracy and reproducibility of the system. Approximately 90% of the target evaluations are within $\pm$0.3 ppm and 50% within $\pm$0.1 ppm. The analytical precision of the system is estimated to be around 0.05 ppm. The 3 min averaged data values are also manually inspected and examined using quality control routines before being accepted as valid ambient measurements. All measurements are directly traceable to the international CO_2 mole fraction scale maintained by the WMO Central

Calibration Laboratory (CCL) at the NOAA/CMDL facilities in Boulder, Colorado. The Meteorological Service of Canada maintains a set of National Standards that are regularly calibrated by NOAA/CMDL approximately every 2 yr.

4. Results and discussion

In this section we present a discussion on analysis results of the atmospheric CO_2 measurements taken at the 40 m level of the tower. We characterise daily, seasonal and interannual variations of CO_2 at the Fraserdale site.

4.1. *Diurnal and day-to-day variations*

Figure 2 shows hourly concentration values taken at the top of the 40 m tower from 1990 to 1996. Also plotted for reference are the smooth curves fitted to the flask CO_2 data from the background monitoring stations Alert (82°27′N, 62°31′W), Cape St. James (51°56′N, 131°01′W) and Cold Bay (55°12′N, 162°43′W). The Cold Bay data are obtained from the NOAA/CMDL anonymous ftp site (http://ftp.cmdl.noaa.gov/). Also plotted are some aircraft measurements obtained above the planetary boundary layer (PBL) by Ray Desjardins (Agriculture Canada, personal communication) over the BOREAS

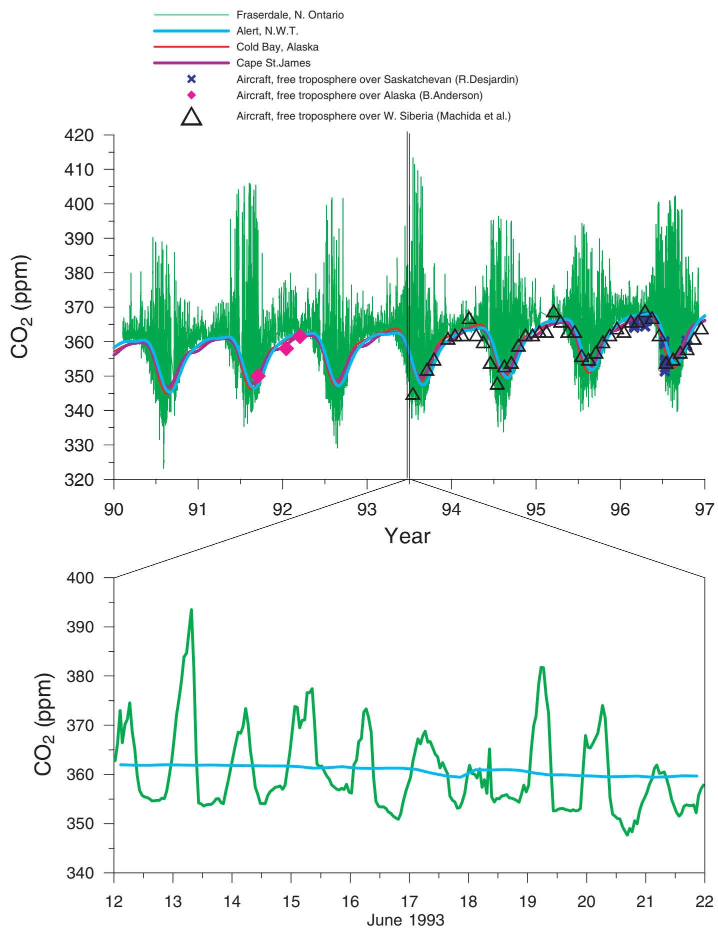

Fig. 2. Hourly CO_2 values (green) taken from the top of the 40- m tower from 1990 to 1996, inclusive. Also shown are smooth curves fitted to flask data from Alert, Cape St. James and Cold Bay, along with the aircraft data. The bottom panel shows a magnified window of the daily cycle at Fraserdale (green) from 12 to 22 June 1993; the blue line is the smoothed Alert concentration curve.

(Boreal Ecosystem–Atmosphere Study) site in northern Saskatchewan, by Anderson et al. (1996) over Alaska and by T. Machida (National Institute for Environmental Science, personal communication) over western Siberia. The smoothed seasonal cycles of the three maritime "background" monitoring stations obtained by applying the curve-fitting procedure of Nakazawa et al. (1997) are also shown in the figure for qualitative comparison with the Fraserdale measurements. (A comparison of the seasonal cycles from Alert, Cold Bay and Fraserdale is given in Fig. 5.). The bottom panel in Fig. 2 shows a magnified view of the variability in the diurnal cycle at Fraserdale from 12 to 22 June 1993. It shows that the night-time concentration contributes significantly to the day-to-day variability in the diurnal cycle, and at times (e.g., 18 and 21 June) the night-time concentration in PBL does not exceed the "background" Alert values. Based on coupled regional atmosphere–ecosystem model simulations (paper in preparation) for the growing season, we have found, on a daily timescale, that the distance of influence (DI) for the atmospheric CO_2 concentration measurements on the 40 m tower at Fraserdale is approximately 500 km during the daytime, and about 200 km during the night. Here, DI is defined as the upwind length of biospheric CO_2 flux contributing about 70% to the CO_2 concentration signal observed at the Fraserdale site.

Strong regional biospheric influence at the Fraserdale site is quite evident during the growing season. Interaction of the daily cycle of the atmosphere/vegetation CO_2 exchange with the daily evolution of the boundary layer mixing regime produces daily variations in the CO_2 mixing ratio on the order of 50 ppm or more. During the growing season, both the CO_2 exchange and the PBL mixing regime experience significant diurnal variations, driven primarily by daily changes in radiative fluxes. Figure 3 shows typical seasonally averaged diurnal changes in atmospheric CO_2 during different seasons. (The data have been detrended for this calculation.) The following descriptive discussion of the diurnal cycle is based on the results obtained from several intensive measurement campaigns (including vertical profiling by aircraft) carried out at Fraserdale from 1998 to 2000. A detailed presentation of the campaign results is now being prepared.

During any particular day in the growing season, activation of photosynthesis and a rapid growth of the surface turbulent layer (due to surface sensible and latent heat fluxes) after sunrise result in a rapid de-

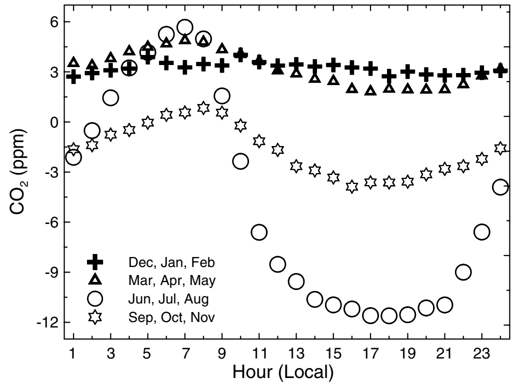

Fig. 3. Seasonally averaged diurnal changes in atmospheric CO_2 for the period 1990–1996. Winter (December–February), spring (March–May), summer (June–August) and fall (September–November).

crease in the PBL CO_2 mixing ratio (see summer in Fig. 3). By early afternoon, the well mixed boundary layer typically reaches 1500–2000 m in height. After that time, the height of the convective boundary layer grows much slower. A combination of the change in the photosynthetic rate during the day and the "maturing" of the convective boundary layer by early afternoon results in a period of quasi-constant CO_2 mixing ratio (the afternoon "plateau") from around mid-afternoon to sunset.

At night, photosynthesis stops and there is a net transfer of CO_2 to the atmosphere from soil (heterotrophic) and plant (autotrophic) respiration. It accumulates in a stable nocturnal boundary layer created by a temperature inversion due to surface radiative cooling, causing a rapid increase in CO_2 mixing ratio in the surface stable layer during the night. The night-time measurements at Fraserdale reflect the CO_2 concentration in this stable layer. The accumulation continues until the stable layer collapses shortly after sunrise. Data from the morning vertical aircraft profiling indicate that the surface layer height at the Fraserdale site is around 100–200 m (well above the height of the tower). This is similar in magnitude to the mean summer minimum height of approximately 345 m derived from a mesoscale atmospheric model constrained by the surrounding upper-air station data (SENES, 1997).

Our coupled atmosphere–ecosystem model simulations (paper in preparation) also show that synoptic weather events also contribute significantly to the day-to-day variability of the diurnal cycle during the growing season. For example, a high-pressure system with relatively clear sky conditions during the daytime allows more intensive photosynthetic assimilation by the vegetation, while calm wind and stable stratification near the surface at night allow a high concentration of CO_2 to accumulate. In contrast, a low-pressure system with cloudy and windy conditions tends to produce smaller diurnal cycle of CO_2 concentration. The impact of interannual variations in weather regimes at Fraserdale on the biospheric flux and the atmospheric mixing makes significant contribution to the interannual variability in the amplitude of the diurnal cycle.

During the non-growing season, there is very little diurnal variation in CO_2 mixing ratio (see winter in Fig. 3); however, there is detectable day-to-day or daily variability. Mean winter maximum and minimum PBL heights over the Fraserdale area are 1200 and 470 m, respectively (SENES, 1997). Although there is some influence by air from anthropogenic regions to the south, Fraserdale is dominated by air masses from the high Arctic in winter; thus, much of the daily variability in the CO_2 concentration is likely due to long-range transport from the Arctic region (Worthy et al., 1998). A Keeling plot calculation of flask samples taken during a period in February 1999 under Arctic air mass gives a $\delta^{13}C$ value of about –28‰, which is an indication of fossil fuel sources (Lin Huang, Meteorological Service of Canada, personal communication). Right after snow melts in spring, and before any significant photosynthesis takes place, nighttime concentrations increase noticeably due to the thawing of the surface soil layer and the subsequent initiation of soil respiration.

4.2. *Seasonal and interannual variations*

In Fig. 4 afternoon (3:00–5:00 pm local time) data from Fraserdale, along with the fitted curve, the trend and the growth rate obtained from the curve-fitting procedure described in Nakazawa et al. (1997), are shown. The growth rate for Alert is added for comparison. The afternoon data are chosen to prevent the contribution of diurnal bias on seasonal and interannual timescales, as well as to obtain a maximum regional representation of biological activities around Fraserale. The fitted curve shows the usual winter bimodal distribution seen at other stations such as Alert and Pt. Barrow in some years (Halter and Harris, 1983; Higuchi et al., 1987). The amplitude of the annual cycle is about 20 ppm, indicative of the stronger influence of a seasonal vegetative cycle than those observed at background stations at similar or higher latitudes. The latter half of the record shows a growth rate near 2 ppm yr^{-1}. The growth rate shows a negative value in 1992, consistent with the global impact on the atmospheric regime caused by the eruption of Mt. Pinatubo in 1991, but also specifically around the Fraserdale site. Both Fraserdale and Alert show negative growth

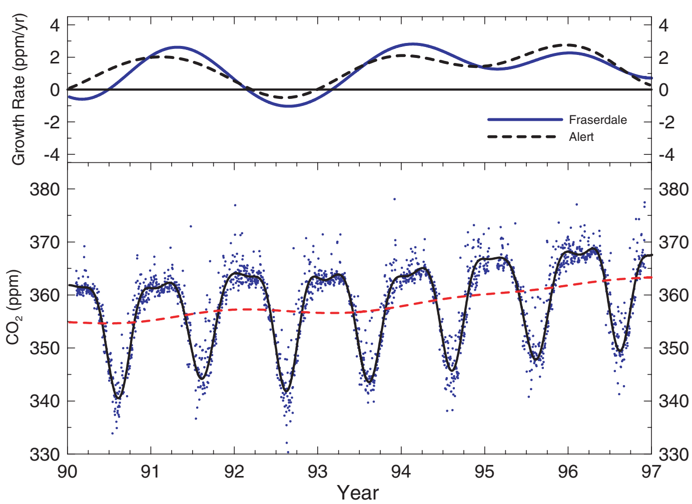

Fig. 4. Daily values using the afternoon data from Fraserdale. Smoothed curves of the seasonal cycle, trend and growth rate are obtained from the digital filtering technique of Nakazawa et al. (1997). The growth rate for Alert is also plotted for comparison.

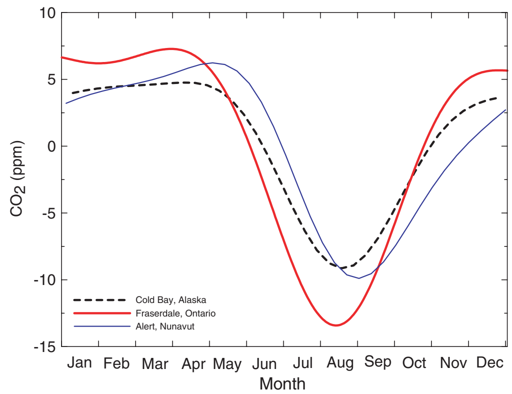

Fig. 5. Comparison of mean seasonal cycles obtained for Alert, Cold Bay and Fraserdale.

rates in 1992. Ito and Oikawa (2000) and Jones and Cox (2001) show that much of this global negative growth in atmospheric CO_2 was due to reduced soil and plant respiration caused by below normal surface temperatures; this resulted in a net transfer of atmospheric carbon to the biosphere in 1992.

Figure 5 shows the 1990–1996 mean seasonal cycle at Fraserdale. Also shown are the mean seasonal cycles at Alert and Cold Bay. The Fraserdale seasonal amplitude of about 20 ppm, as compared to 15 and 13 ppm at Alert and Cold Bay, respectively, is indicative of its location in the biosphere. Also consistent with the larger influence of vegetative activities at the Fraserdale site are (1) the earlier draw-down when photosynthesis becomes greater than respiration (mid-April, as compared to early to late May at Cold Bay and Alert, respectively), (2) the magnitude of the seasonal minimum (4 ppm lower than that at Alert and Cold Bay), (3) the earlier occurrence of the seasonal minimum (about 3 wk ahead of Alert), and (4) higher CO_2 values during the non-growing season. The greater rate of increase of CO_2 observed at Fraserdale than at Alert and Cold Bay after their respective seasonal minima is also indicative of the immediate atmospheric CO_2 response to the growing dominance of respiration over photosynthetic activity in vegetation around the Fraserdale site. Similarity in the phasing (but not in the amplitude) of the seasonal cycles at Fraserdale and Cold Bay reflects the fact that these sites are located in approximately the same mid-latitudinal zone, as compared to Alert in the high Arctic. Latitudinal atmospheric mixing is on the order of a week, while longitudinal mixing is on the order of a month.

4.3. Directional decomposition of afternoon CO_2 data

Atmospheric CO_2 concentration is modified by carbon sources and sinks, as well as by atmospheric mixing, on the way to a monitoring site. Therefore, we perform a 1 d back trajectory analysis of the afternoon CO_2 data, using the Meteorological Service of Canada (MSC) trajectory model (Olsen et al., 1978). One-day back trajectories are comparable to the DI values of the CO_2 measurements at the Fraserdale tower, and thus reflect the regional influence. Also, limiting the back trajectory calculations to 1 d prevents cross-sectorial problems of air mass arrivals with mixed CO_2 source/sink signatures. In order to facilitate the trajectory analysis, we divide the region around Fraserdale into six sectors: Sector 1 = 180–260°, Sector 2 = 260–305°, Sector 3 = 305–0°, Sector 4 = 0–80°, Sector 5 = 80–110° and Sector 6 = 110–180° (Fig. 6). The sectoring of the region around Fraserdale is adopted from Worthy et al. (1998) and is based mainly on a combination of two factors in this study: seasonal wind direction distribution and assumed CO_2 source distribution. For the 1 d back trajectories, deciduous trees dominate Sector 1, while boreal conifers constitute much of Sectors 2. Sector 3 is occupied mainly by non-forested ecosystems (tundra, wetlands, etc.) and Sector 4 is composed of boreal conifers. Influence by winds from Sectors 5 and 6 at Fraserdale is minimal. Figure 7 shows the climatological seasonal distribution of the percentage of air parcels (weighted by angle subtended by each sector) coming from different sectors. On a year-round basis, Fraserdale sees relatively little air coming from the eastern hemisphere (Sectors 4–6). Air parcels from the remaining sectors influence Fraserdale to varying degrees, depending on the season. In winter, winds from Sectors 1–3 are dominant. Summer and fall show similar relative distribution of percentage of "1 d back" air parcels arriving at Fraserdale as winter. In spring, the normalized percentage is relatively evenly distributed among all sectors, with slightly larger percentages in Sectors 2, 3 and 5. Overall, the Fraserdale site is dominated by air from the western half (Sectors 1–3), but particularly from Sector 2. Based on Fig. 7, further analysis of the CO_2 data related to winds from Sectors 5 and 6 has not been carried out.

The curve-fitting technique described in Nakazawa et al. (1997) is applied to a set of CO_2 data associated with each of the trajectory sectors. The resulting seasonal cycle and trend for each of the sectors from 1 to

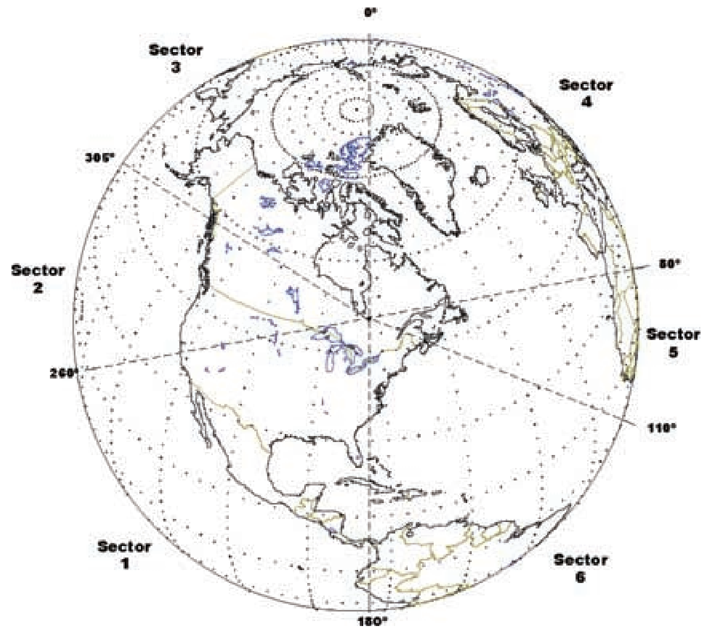

Fig. 6. Division of azimuthal circle around the Fraserdale site into six sectors for trajectory analysis.

4 are shown in Fig. 8. For the period 1990–1996 there are 498 CO_2 data values for Sector 1, 664 for Sector 2, 577 for Sector 3 and 331 for Sector 4. Each sector is characterised by its own seasonal cycle, with Sector 1 showing the largest amplitude. It is interesting to note that the sector trends agree remarkably well with one another for the first 3 yr; however, after 1992 they diverge.

Mean seasonal cycle as a function of sector is shown in Fig. 9 for Sectors 1–4. The seasonal cycles, with amplitudes of ~19 ppm, associated with Sectors 2–4 show similar climatological behaviour in their evolution throughout the year. In contrast, the seasonal cycle associated with air parcels originating in Sector 1 (southwestern sector) shows a larger seasonal amplitude of ~23 ppm, with the annual minimum occurring about a week earlier in August, particularly in

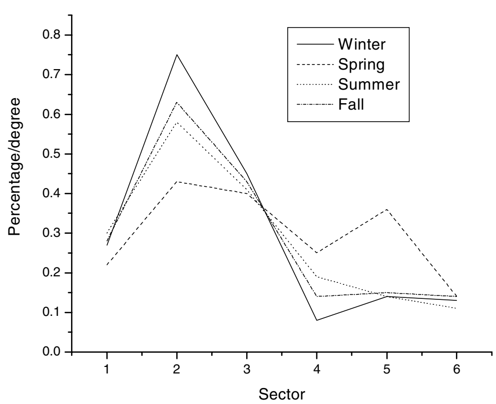

Fig. 7. Climatological seasonal distribution of air parcels coming from different sectors (1–6) in units of percentage degree^{-1}.

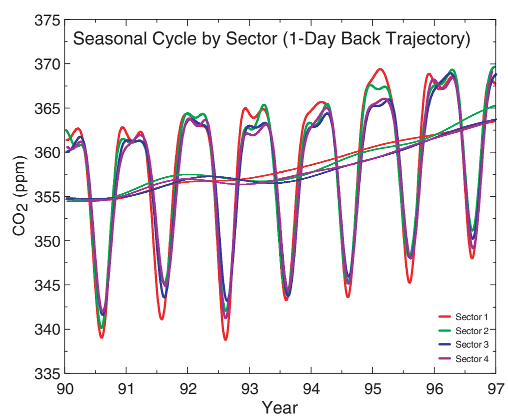

Fig. 8. Seasonal cycle and trend for each of the sectors from 1 to 4.

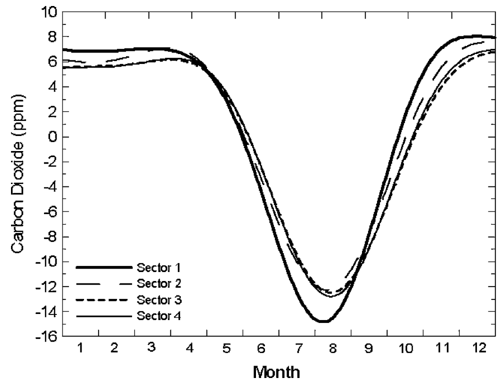

Fig. 9. Mean seasonal cycle for each of the sectors from 1 to 4.

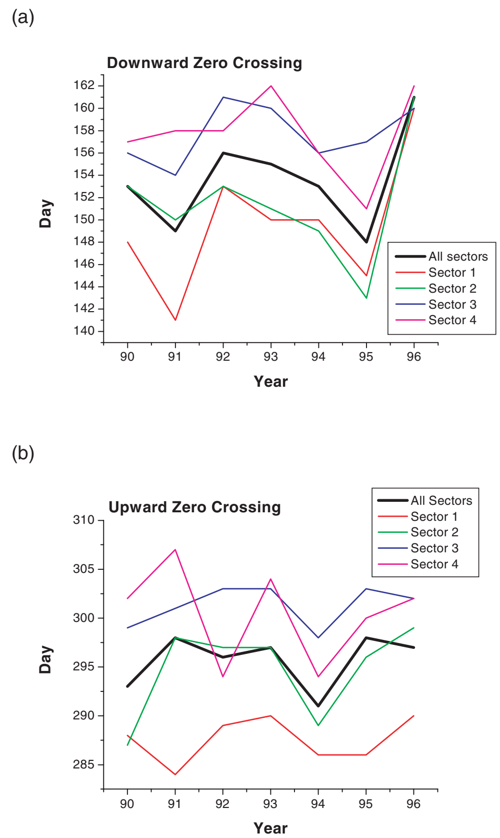

Fig. 10. Downward (a) and upward (b) zero crossing days of the detrended seasonal cycle for each of the sectors from 1 to 4. Zero crossing days designated as 'all sectors' are derived from detrending the seasonal cycle shown in Fig. 4.

relation to Sectors 3 and 4 (north and northeast). This difference in the occurrence of the annual minimum is significantly different at the 0.05 level. The greater annual minimum displayed by the Sector 1 seasonal cycle results from the fact that much of the deciduous trees are located to the south and southwest of the Fraserdale site. Additionally, earlier timings of downward and upward zero crossings displayed by Sector 1, compared to the other sectors, particularly Sectors 3 and 4, are also consistent with the regional ecosystem distribution around Fraserdale.

Changes in the timing of the downward and upward zero crossings from year to year associated with each sector are shown in Figs. 10(a) and (b), respectively. The zero crossing parameter has been used as an indicator of the length of a growing season. Earlier downward crossing indicates an earlier start of the growing season, while later upward crossing implies delayed termination of the growing season (Keeling et al., 1996). The timing of the zero crossing is reflective of the regional biospheric activity, which is influenced by an interactive combination of various processes related to meteorological (temperature, precipitation, radiation, etc.) and ecological (soil temperature and moisture, soil types, plant species, land disturbance, age structure, etc.) parameters. Notwithstanding the shortness of the record, an examination of Fig. 10(a) from 1990 to 1995 shows that there is no statistically significant linear trend in the timing of the decrease in atmospheric CO_2 at the beginning of each growing season in Sectors 1, 3 and 4; Sector 2, however, shows a significant trend towards earlier growing season, from about day 153 in 1990 to about day 143 in 1995. In 1991 and 1995, almost all sectors indicate earlier start of the growing season. An approximate 10 d delay in the downward zero crossing associated with Sector 1 in 1992, compared to 1991, may be related to the effect of Mt. Pinatubo eruption, but it is interesting to note that the timing persists for the following 2 yr. All sectors converge to about day 160 for the downward zero crossing in 1996. The region around Fraserdale experienced a relative cool spring in 1996. The snow melt day usually occurs about day 100 in northern Ontario, but in 1996 it was delayed for over a month.

Year-to-year change in the timing of the upward zero crossing can be used as an indicator of the interannual variation in the termination of the growing season. As can be seen in Fig. 10(b), there is no statistically significant linear trend in this parameter at Fraserdale if all the observed data (i.e., all the sectors) are used. However, there are notable differences among the sectors. Sector 1 shows a gradual delay in the timing of the end in the growing season. Sector 2, which appears to dominate the timing of the upward zero crossing, shows a delay of over 10 d from 1990 to 1991, and of similar magnitude from 1994 to 1996.

We can summarise the data in Fig. 10 by subtracting the downward crossing zero day from the upward crossing day for each year. The difference gives us some indication of the length of the growing season. The average time between the downward and upward zero crossing is about 142 d (with a standard deviation of about 5 d). Although not shown, we find that, not surprisingly, there is no statistically significant linear trend in this parameter for Sectors 2–4. However, Sector 1 shows a decrease in the growing season length by about a week from 1990 to 1996. This is statistically significant at the 90% confidence level due to the 1996 value. If the 1996 value is not used, then the decrease associated with Sector 1 is shortened to about 3 d, resulting in no significant change in the growing season length from 1990 to 1995.

5. Conclusions

In this paper we have characterised daily, seasonal and interannual variations of in-situ atmospheric CO_2 measurements taken at Fraserdale from 1990 to 1996. This continental site located in a boreal forest ecosystem in northern Ontario is dominated mainly by black spruce trees. Atmospheric CO_2 measurements at Fraserdale are greatly influenced by the direction of the transport, and reflect an integrated result of a complex pattern of CO_2 flux associated with highly heterogeneous distribution of different vegetation types and land-use practices (such as logging) in regions around the site.

Interaction of the diurnal cycle of the vegetation CO_2 exchange with the diurnal evolution of the boundary layer mixing regime produces diurnal variations in atmospheric CO_2 on the order of 50 ppm or more. The day-to-day (or daily) variability in the observed diurnal CO_2 amplitude is driven mostly by the nighttime CO_2 concentration, which is determined mainly by the daily changes in the PBL dynamics of synoptic weather systems.

Overall, the Fraserdale site is dominated by air from the western half. On average, the seasonal cycle associated with air from west and northwest of the site shows amplitude of $\sim$19 ppm, while that associated with air from south and southwest shows amplitude of $\sim$23 ppm; the seasonal minimum, on average, occurs about a week earlier in the latter case than in the former. This is consistent with the fact that much of the deciduous vegetation is located to the south and southwest of the Fraserdale site. Climatologically, the seasonal minimum occurs in early August at Fraserdale, compared to late August observed at Alert and at many other background stations in high latitude Northern Hemisphere. This is indicative of the time lag between the behaviour of the biospheric flux of CO_2 and its reflection in the free tropospheric concentration field.

The timing of upward and downward zero crossing in the seasonal cycle has been used as an indicator of the length of biospheric growing season. At Fraserdale, we have found that the average time between the downward and upward zero crossing is about 142 d, and there seems to be no strong evidence to suggest in atmospheric CO_2 concentration that the growing season in northern Ontario boreal forest is changing, at least within the context of carbon cycling.

6. Acknowledgements

We acknowledge the leadership provided by Dr. Neil Trivett during his association with the Meteorological Service of Canada. The measurement program at the Fraserdale site was established under his guidance. We also thank Darrell Ernst, Michele Ernst, Victoria Hudec, Robert Kessler, Lori Leeder, Andrew Platt, Senen Racki and Lori Cook for their valuable technical and logistics support. Ontario Power Corporation has generously provided facilities and partial funding for the measurement program at Fraserdale. Constructive comments and suggestions by two anonymous reviewers have greatly improved the quality of the paper.

REFERENCES

Anderson, B. E., Gregory, G. L., Collins, J. E. Jr., Sachse, G. W., Conway, T. J. and Whiting, G. P. 1996. Airborne observations of spatial and temporal variability of tropospheric carbon dioxide. *J. Geophys. Res.* **101**, 1985–1997.

Bakwin, P. S., Tans, P. P., Hurst, D. F. and Zhao, C. 1998. Measurements of carbon dioxide on very tall towers: results of the NOAA/CMDL program. *Tellus* **50B**, 401–415.

Broecker, W. S., Takahashi, T., Simpson, H. J. and Peng, T.-H. 1979. Fate of fossil fuel carbon dioxide and the global carbon budget. *Science* **206**, 409–418.

Bryson, R. A. 1966. Air masses, streamlines, and the boreal forest. *Geogr. Bull*. **4**, 228–269.

Ciais, P., Peylin, P. and Bousquet, P. 2000. Regional biospheric carbon fluxes as inferred from atmospheric CO_2 measurements. *Ecol. Appl*. **10**, 1574–1589.

Fan, S.-M., Gloor, M., Mahlman, J., Pacala, S., Sarmiento, J., Takahashi, T. and Tans, P. 1998. A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models. *Science* **282**, 442–446.

Gurney, K. R., Law, R. M., Denning, A. S., Rayner, P. J., Baker, D., Bourquet, P., Bruhwiler, L., Chen, Y.-H., Ciais, P., Fan, S., Fung, I. Y., Gloor, M., Heimann, M., Higuchi, K., John, J., Maki, T., Maksyutov, S., Masarie, K., Peylin, P., Prather, M., Pak, B. C., Randerson, J., Sarmiento, J., Taguchi, S., Takahashi, T. and Yuen, C. W. 2002. Robust regional estimate of annual CO_2 sources and sinks. *Nature* **415**, 626–30.

Halter, B. C. and Harris, J. M. 1983. On the variability of atmospheric carbon dioxide concentration at Barrow, Alaska, during winter. *J. Geophys. Res*. **88**, 6858–6864.

Haszpra, L. 1999. On the representativeness of carbon dioxide measurements. *J. Geophys. Res*. **104**, 26 953–26 960.

Higuchi, K., Trivett, N. B. A. and Daggupaty, S. M. 1987. A preliminary climatology of trajectories related to atmospheric CO_2 measurements at Alert and Mould Bay. *Atmos. Environ*. **21**, 1915–1926.

Inoue, H. Y. and Matsueda, H. 2001. Measurements of atmospheric CO_2 from a meteorological tower in Tsukuba, Japan. *Tellus* **53B**, 205–219.

IPCC, 1996. *Climate change 1995. The science of climate change*. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. (eds. J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattengerg and K. Maskell) Cambridge University Press, Cambridge, UK.

Ito, A. and Oikawa, T. 2000. A model analysis of the relationship between climate perturbations and carbon budget anomalies in global terrestrial ecosystems. *Climate Res*. **15**, 161–183.

Jobson, B. T., Wu, Z., Niki, H. and Barrie, L. A. 1994. Seasonal trends of isoprene, C_2-C_5 alkanes, and acetylene at a remote boreal site in Canada. *J. Geophys. Res*. **99**, 1589–1599.

Jones, C. D. and Cox, P. M. 2001. Modeling the volcanic signal in the atmospheric CO_2 record. *Global Biogeochem. Cycles* **15**, 453–465.

Keeling, C. D., Chin, J. F. S. and Whorf, T. P. 1996. Increased activity of northern vegetation inferred from atmospheric CO_2 measurements. *Science* **382**, 146–149.

Levin, I., Graul, R. and Trivett, N. B. A. 1995. Long term observations of atmospheric CO_2 and carbon isotopes at continental sites in Germany. *Tellus* **47B**, 23–34.

Nakazawa, T., Ishizawa, M., Higuchi, K. and Trivett, N. B. A. 1997. Two curve fitting methods applied to CO_2 flask data. *Environmetrics* **8**, 197–218.

Olsen, M. P., Oikawa, K. K. and MacAfee, A. 1978. A trajectory model applied to the long range transport of air pollutants. *Meteorological Service of Canada Internal Report* LRTAP 78-4, Toronto, Ontario, 24 pp.

MSC, 1999. Canadian Baseline Program: Summary of Progress to 1998. Air Quality Research Branch Report, Meteorological Service of Canada, Toronto, Ontario, Canada.

SENES, 1997. A mixing height study for North America (1987–1991). Report prepared for the Atmospheric Environment Service by SENES Consultants Ltd., Richmond Hill, Ontario, Canada.

Takahashi, T., Wanninkhof, R. H., Feely, R. A., Weiss, R. F., Chipman, D. W., Bates, N., Olafson, J., Sabine, C. and Sutherland, S. C. 1999. Net sea–air CO_2 flux over the global oceans: An improved estimate based on the sea–air pCO_2 difference. In: *Proceedings of the 2nd International Symposium CO_2 in the Oceans*, Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan, pp 9–15.

Wong, C. S. 1978. Atmospheric input of carbon dioxide from burning wood. *Science* **200**, 197–200.

Worthy, D. E. J., Levin, I., Trivett, N. B. A., Kuhlmann, A. J., Hopper, J. F. and Ernst, M. K. 1998. Seven years of continuous methane observations at a remote boreal site in Ontario, Canada. *J. Geophys. Res*. **103**, 15 995–16 007.