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AIRBORNE MEASUREMENT OF MASS AND ENERGY EXCHANGE FROM AGRICULTURAL LANDS

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Abstract

This paper describes the airborne measurement of mass and energy exchange from agricultural lands around the Ottawa area, in the 2003 field campaign, using the NRC¹ Twin Otter atmospheric research aircraft. The aircraft was instrumented to measure the vertical fluxes of sensible and latent heat, momentum, carbon dioxide, ozone and nitrous oxide, along with supporting meteorological and radiometric data. A total of 32 project flights were flown, accumulating 50 hours of flight data from two agricultural tracks southeast of Ottawa. This paper details the instrumentation system in the NRC Twin Otter, along with descriptions of the aircraft operation during this 2003 field campaign. Measured fluxes and supporting meteorological and radiometric data are presented and discussed.

1. INTRODUCTION

This field campaign was conducted over two tracks in the Ottawa area, over the period of March to October 2003. The objective was to use the NRC Twin Otter atmospheric research aircraft (Figure 1) to accurately measure the fluxes of greenhouse gases from agricultural lands.

Over 30 project flights were conducted between 26 March and 10 October 2003, based out of Ottawa. The fluxes of heat, water vapour, carbon dioxide, ozone and nitrous oxide were measured along a height of approximately 200 feet above ground level (agl) on repeated passes over two tracks, each approximately 5 nautical miles (nm) in length.



Figure 1: NRC Twin Otter Atmospheric Research Aircraft

This paper documents the Twin Otter flight operations in this project, and includes descriptions of the aircraft instrumentation, software, recorded and archived parameters, and procedures used in the analysis of the data. Measured fluxes of sensible and latent heat, carbon dioxide, ozone and supporting meteorological and radiometric data are presented for all of the approximately 340 flux runs flown by the Twin Otter in this experiment.

2. INSTRUMENTATION SYSTEM

Figure 2 is a schematic diagram of the Twin Otter showing the mounting locations of the instruments flown in this project.

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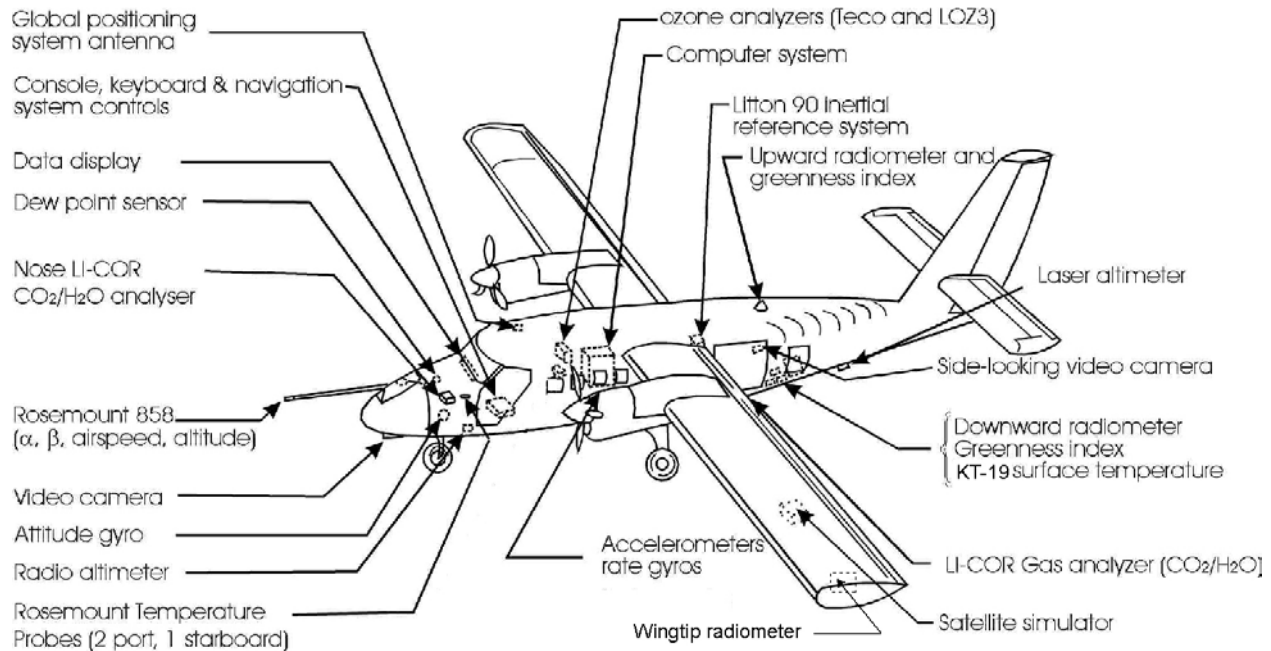


Figure 2: NRC Twin Otter Configured to Measure Flux

2.1 Position and Altitude

The Twin Otter is equipped with a Trimble Model TNL-8100 GPS navigation system, which was used for flying accurate tracks and for recording aircraft position and velocity data.

To fly the desired tracks for flux-measuring runs, GPS navigation was used, with heading and cross-track deviation fed to the pilot's flight director in the instrument panel. A second, more sensitive display, featuring track-angle error in addition to cross-track deviation, was mounted atop the coaming of the instrument panel, well within the pilot's heads-up scan. This display was driven by the airborne microprocessor and had a full-range deviation of ± 0.5 nautical miles.

Aircraft position data were also available from the LTN90-100 Inertial Reference System. This system is subject to the Schuler Oscillation, in which the indicated position can drift in error up to approximately two nautical miles per hour. Finally, a third set of position data was provided by the NovAtel RT-20 GPS. Data recorded from the NovAtel included height above sea level, but as the GPS was not operated in the differential mode with an accompanying ground station, this height was only accurate to approximately 5-10 m.

Three other height measurements were recorded during the project. Absolute height above the terrain was measured by a Sperry AA-200 radio altimeter, which was limited to altitudes below approximately 940 m, but adequate for all of the flux runs. A pressure height above sea level was computed from the measurement of static pressure corrected for altimeter setting. Finally, the height above sea level of the underlying terrain was computed from the difference between the pressure height and the radio-altimeter height. This parameter was set to zero when the radio-altimeter was off-scale (i.e., above 940 m).

2.2 Wind and Turbulence Data

The Twin Otter is instrumented to measure the three orthogonal components of atmospheric motion over a frequency range from 0 to 10 Hz. The true wind velocity is derived from the vector difference between the air velocity relative to the aircraft and the aircraft 'inertial' velocity relative to the ground (strictly speaking, the rotating Earth is not an inertial frame of reference, but for ease of expression the term 'inertial' in this paper will mean 'relative to the Earth').

Air motion relative to the aircraft is measured by a nose-mounted gust boom; which incorporates a

Rosemount 858AJ28 5-hole probe. This device and the associated pressure transducers measure static pressure (altitude), dynamic pressure (airspeed) and the angles of attack and sideslip. A second altitude/airspeed system employs a separate set of pressure transducers connected to the fuselage-mounted pitot and static ports.

The primary system on the aircraft for the measurement of the inertial velocity vector is a Litton LTN-90-100 Inertial Reference System (IRS). For this project, the on-board VME-based microprocessor computed and recorded three sets of winds, differing primarily in the methods used to determine the inertial velocity. They are the following:

- 1) **Litton winds:** The true airspeed (TAS) vector is resolved into earth-fixed axes using the attitude angles and heading from the LTN-90 IRS. The 3-axis inertial velocities from the IRS are then subtracted from the TAS components to derive the 3-axis winds. This is the method used on most atmospheric research aircraft. It is subject to the Schuler Oscillation phenomenon, which affects mainly the horizontal components of the inertial velocities measured by the IRS, and consists of a time-varying bias with a period of approximately 84 minutes. This is reflected in the computed north and east components of the wind velocity, with typical errors of up to 1-2 m/s. The NRC Flight Research Laboratory (FRL) has developed a Kalman filtering and smoothing technique that combines IRS data with redundant navaid data (e.g. GPS, VOR/DME) to correct the IRS velocity, position, heading and attitude data for these oscillations (Leach, 1991). This procedure was not applied to the data from this project, since it was not deemed to be essential.
- 2) **Primary Back-up GPS winds:** The NovAtel RT-20 GPS system measured position and inertial velocities to a greater accuracy than the Trimble GPS. The NovAtel inertial velocities are normally used in the aircraft software and in the ground-based playback system to compute a second set of 3-axis wind velocities. These are referred to in this paper as the 'NovAtel Winds'. In this project, however, the NovAtel GPS data recording had an interface problem, and therefore was unavailable for the majority of the flights.

- 3) **Secondary Backup winds:** In the vertical velocity computation, the aircraft software employs a complementary filtering routine in which the low frequency contribution to the inertial velocity is provided by the rate of change of pressure altitude, and the high frequency components are derived from the MP-1 Motion-Pak containing three-axis accelerometers and rate gyros. The horizontal wind components are derived using the north and east components of the Trimble GPS-measured groundspeed. Although the horizontal components of this set of wind velocities are less accurate than those in (1) and (2) above, the time histories of the vertical component are nearly identical to those computed in (1).

Further details on these wind computation methods are given in MacPherson (1990), along with the equations used to derive the wind and gust components and the fluxes. The backup winds are computed and recorded to provide wind data in case the Litton-90 IRS fails. There were no such problems in this project, thus the primary Litton wind data were used in the calculation of all of the fluxes given in this paper.

2.3 Temperature and Dew Point

Three temperature probes were carried on the Twin Otter during this project, including an unheated fast-response Rosemount 102EAL temperature probe mounted on the port side of the nose and two 102DJ1CG heated probes, one on each side of the nose. The unheated probe has a slightly faster frequency response than the heated probes. In the Twin Otter cockpit, Function Switch #5 on the computer console is used to select which temperature probe is used in the airborne software to derive true airspeed and static temperature. The unheated probe was selected throughout this project and its data were used in the data archive.

Dew point temperature was measured using an E,G & G Model 137 Cambridge dew point sensor mounted on the starboard side of the Twin Otter nose. Dew point temperatures were also derived and recorded from the H₂O data measured by the two LI-COR CO₂/H₂O analysers on the aircraft.

2.4 Carbon Dioxide and Water Vapour

One of the long-standing policies for the instrumentation system on the Twin Otter is that

most parameters are measured by at least two separate instruments. Thus the aircraft carries two LI-COR CO₂/H₂O analysers. One of these is a LI-COR LI-6262 analyser that is mounted in the nose bay of the aircraft. Its sample air is drawn through a 3/8-inch plastic tube from an inlet on the side of the nose-boom fairing 2.1 m behind the tip of the gust boom, thus minimizing the lag between measurement of the vertical gust component and the CO₂/H₂O concentration. The inlet consists of a rear-facing bent tube, a change from an earlier design, in which an empty casing for a Rosemount total temperature probe served as the inlet. This new reverse inlet design was used in the SMACEX (Soil Moisture-Atmosphere Coupling Experiment) project (MacPherson, 2002) and proved to be an improvement in terms of the inflow into the tube being uncorrelated with changes in aircraft dynamic pressure.

The second CO₂/H₂O analyser (referred to as the 'cabin LI-COR') was mounted in the rear instrumentation rack, with its sample air drawn from an inlet atop the fuselage via a 3/8-inch plastic tube. In early 2002, the LI-COR LI-6262 unit previously occupying this location was replaced with a new LI-COR LI-7000 unit, which features improvements in both accuracy and frequency response. The LI-7000 offers much more flexibility, in that the trade-off between frequency response and the signal/noise ratio can be programmed within the unit. During this project, the LI-7000 was set for 20-Hz response for all of the flights.

Processing the data from the two models of LI-COR analyser now requires different subroutines in the software in the airborne and playback computing systems. In the case of the LI-6262 (nose), its maximum frequency response (>2 Hz) is only achievable if the raw millivolt signals are recorded, with the conversion to ppm CO₂ and ppt H₂O handled during the data processing. For the LI-7000, the conversion from raw to processed data takes place within the LI-7000 at the selected, programmable rate. Thus the ppm CO₂ and ppt H₂O values can be recorded directly with the highest possible frequency response, and then subsequently converted to mixing ratios, etc. The LI-7000 also offers the output of these parameters and other derived variables in a digital format via an RS-232 interface. For this project, LI-7000 data were recorded in the digital format.

The aircraft was fitted with an airborne calibration system for the cabin LI-COR CO₂ signal. On

activation by the cabin crew, two reference gases were passed sequentially through the analyser for 30 seconds each. The first was pure nitrogen (N₂) gas with zero ppm of CO₂, the second was a laboratory standard mixture of known CO₂ concentration (364 ppm for the 2003 project). As part of the daily pre-flight preparations of the aircraft, the zero and span of the water vapour and CO₂ channels of both LI-COR analysers on the aircraft were calibrated. The zeroes were adjusted using pure nitrogen as the reference gas. The CO₂ span was set using the 364-ppm reference sample, while the water vapour span was set against an air sample that had its humidity controlled and measured by a dew point generator.

Despite these efforts, the *absolute values* of the CO₂ concentrations from the two analysers did not always agree in the flight data – the nose LI-COR concentration usually exceeded the cabin value by about 10 ppm. There were also day-to-day variations of 5–10 ppm in the recorded mean concentrations of both analysers. Although the absolute values of the CO₂ concentrations may be suspect, the two instruments agreed well in measuring the fluctuations in the CO₂ concentrations, and thus produced nearly identical CO₂ fluxes.

2.5 Ozone Analysers

The Twin Otter carried two ozone analysers, one slow-response unit for mean concentrations and one fast-response analyser to measure ozone fluxes and deposition velocities. The Air Quality Processes Research Division of the Meteorological Service of Canada (MSC) provided a TECO-49 UV-absorption ozone analyser to measure mean absolute ozone concentrations on the Twin Otter. This was mounted on rack-1 in the aircraft cabin with sample air drawn from an inlet extending above the cabin roof. Its signal was digitally recorded to a resolution of 0.1 ppb per bit over a range of zero to approximately 200 ppb. The TECO operates using two cells, one a reference and one a sample cell. At an interval of 10 seconds, a new analysis reading is output and the cells reverse functions. Consequently, the output signal only appears to update at an interval of 10 seconds. It is not useable for flux measurements.

The second ozone analyser flown was a Scintrex LOZ-3 Ozone Detector, which detects the chemiluminescence produced when ozone encounters a surface wetted with a specially

formulated solution of Eosin-Y. This unit has a time constant of approximately one second, and requires a lag adjustment of 1.56 seconds when used in a flux calculation on the Twin Otter. Resulting cospectra have shown little contribution at wavelengths shorter than 50 m, so fluxes can be expected to be slightly under-estimated at the lowest flight levels.

2.6 Radiometers

The incident and reflected solar radiation were measured with Kipp and Zonen CM-11 pyranometers with a 305-2800 nm spectral range. The upward-facing radiometer was mounted on the aft fuselage of the aircraft (see Figure 2), which is tapered. It was mounted so that its sensing axis is canted forward 3 degrees relative to the IRS vertical axis to compensate for the mean pitch angle of the aircraft in flight. In the data analysis routine, software has been developed to continuously correct the upward radiometer reading for its mounting alignment and for variations in the heading and the pitch and roll attitudes of the aircraft, throughout each flight (MacPherson, 1990). The procedure utilizes the recorded GMT, pitch and roll attitude, heading, latitude and longitude. The only terminal input required is the sun declination angle for that day of the year (Table 169 of List, 1951).

This procedure was applied to all of the clear or mostly clear sky cases in processing the data; it was not applied in the analysis of flights flown on cloudy and overcast days. The calibration of these radiometers is dependent on the temperature within the radiometer housing. In 1999, these installations were upgraded with the addition of a temperature measurement within the radiometer housings. The calibration correction equations for the two radiometers are applied in subroutines in the Twin Otter airborne program and in the post-flight analysis program.

Radiometric surface temperature was measured on the Twin Otter by a Heitronics KT-19 infrared pyrometer. The KT-19 provides a digital output through an RS-232 interface board and features a stable calibration, and a wide operational temperature range, and programmable settings for frequency response and signal/noise ratio. The KT19 unit was programmed for a 30 ms response time. It has a 2.7 deg field of view.

In the past, there had been no direct measurement of net radiation, R_n , on the Twin Otter. Rather, it

was calculated at each 1/32-second using the measured incident and reflected solar radiation (R_{up} and R_{dn}), with long-wave contributions derived from the KT-19 surface temperature (T_s in °K) and air temperature (T_a in °K) in the following equation:

$$R_n = R_{up} - R_{dn} + [1.20 \cdot \sigma \cdot T_a^4 - 171.0] - [0.98 \cdot \sigma \cdot T_s^4] \quad (1)$$

where, the last two terms represent estimated incident and reflected long-wave components, using the Stephan-Boltzmann Constant $\sigma = 5.6924 \times 10^{-8}$ and a surface emissivity of 0.98. In past experiments, this computed value of net radiation has agreed quite well with tower measurements (SGP97, Table 3, MacPherson, 1998 and BOREAS, Tables 16-17, MacPherson, 1996).

In 2002, a Kipp and Zonen CNR-1 Net Radiometer, housed in a specially modified port wingtip (Figure 2) was installed. For this installation, the case of the CNR-1 also had to be modified to increase its thickness to match that of the wingtip, i.e., to ensure each radiometer had a 180-deg field of view. The CNR-1 consists of two CM3 pyranometers (18 s time constant, 305-2800 nm spectral range) and two CG3 pyrgeometers (18 s time constant, 5000-50000 nm spectral range). It can be wired to measure the four separate outputs from the radiometers, or to measure *only* the net radiation. The latter mode was chosen for the Twin Otter, since it was net radiation that was required, and the incident and reflected solar radiation were already measured by the CM11 pyranometers mounted atop and beneath the fuselage. Furthermore, when wired to output net radiation only, the measured internal temperature of the CNR-1 does not have to be recorded. This temperature is required in the derivation equation for the individual incident and reflected infrared components, but cancels out of the equation when only net radiation is sought.

The experience gained with the CNR-1 net radiometer during SMACEX revealed a couple of interesting points. First, there was a heading-related bias in the wingtip R_n values, a variation of approximately $\pm 30 \text{ W/m}^2$ dependent mostly on whether the aircraft was flying away from or towards the sun's azimuth. Although the upward radiometers were canted forward about 3 degrees to account for the average pitch attitude of the aircraft, it would appear that a slightly higher angle may have been required. Also, flight-averaged R_n values from the wingtip radiometer tended to be larger than the R_n (calc) derived from Equation 1 by about 50 W/m^2 . Analysis of the data from the SMACEX

project showed that the wingtip Rn from the CNR-1 provided the better match with the tower data (MacPherson, 2002), and thus has been used in the summary and archive files for this project.

For this project, the Twin Otter carried both an upward- and downward-looking Skye Industries Vegetation Greenness Indicator, which measures a ratio of near infrared (730 nm) to red (660 nm) radiation. The downward reading can be correlated with the density of green vegetation beneath the aircraft. The upward-facing unit was installed to allow a possible normalization of the downward reading to remove small changes seen in past projects associated with the variations in total solar radiation, such as those encountered in the shadows of clouds. Although the greenness index is a good indicator of *relative* changes in vegetative cover, caution should be exercised in comparing the *absolute* value of the greenness index with data collected in previous projects.

A downward-looking Exotech 100BX Satellite Simulator was mounted within the port wing of the Twin Otter (Figure 2). This simultaneously measures reflected radiation over four wavelength bands, and can be configured to simulate two modes of LandSat operation (MSS and TM), as well as the French satellite SPOT (three channels only). It has a faster response than the other radiometers discussed above, and considerable flexibility in terms of viewing angles and output signal voltage ranges. It was configured in the LandSat TM mode with the following wavelength bands: Channel A, 457-521 nm; Channel B, 523-595 nm; Channel C, 630-687 nm; and Channel D, 762-897 nm. In the analysis software, a greenness index is also computed from the ratio of the Channel D to Channel C signals, which has a faster response and shows more structure than that provided by the Skye Industries device discussed above. It should be noted that the Satellite Simulator was operated with a 15-deg field of view in this project.

2.7 Event Marker

A multi-level event marker was recorded with a 16-bit word, which also incorporated the positions of eight function switches on the cockpit console. These were used to set flags in the airborne and playback software. In this experiment, the unheated temperature probe was used for all flights, so function switch #5 was always selected OFF. Of most interest in the data analysis is bit-14, the event

marker that denotes that a flux-measuring run (or other special test) was in progress.

2.8 Data Acquisition, Display and Recording

The computer system on the Twin Otter is based on the industry-standard VME backplane. The processor used is a Motorola MVME167, built around the 68040 CPU chip running at 33 MHz. There are also a number of commercial I/O boards that interface to the many different input and output devices on board the aircraft. These include: RS-232 serial boards, Arinc 429, DR11W, analog to digital, digital to analog, synchro, digital I/O, SCSI and VGA graphics. The real-time operating system is Microware's OS-9, Version 3.0.

A user interacts with the computer in three ways. The first is through a keyboard with a 16-line LCD console. This is used only to get the computer booted and the airborne program (i.e., the data acquisition master program) loaded and running. The second is through a number of function switches, which control the majority of the operations and options of the airborne program (e.g., select the temperature used in the airspeed calculations, activate the LI-COR calibration procedure, select winds displayed in magnetic or true degrees, etc.). The final way the user interacts with the computer is through a VGA LCD 640x480 flat panel display, on which most of the data being computed are displayed in real time, including wind and flux information. A second flat panel display was mounted in the aircraft cabin to display these data to the crewmember occupying the rear station in the aircraft.

The airborne program is not a single executable program, but is comprised of a number of separate executable programs that communicate via shared memory and events. The main process of the data acquisition programs runs at 32 Hz and reads all of the synchronous data. The asynchronous data are collected by separate processes and passed to the main program via shared memory. The core of the system is driven by the A/D converters. The analog signals are conditioned with a two-phase filtering process. First the signals pass through hardware signal conditioning where each signal is low-pass filtered at 100 Hz, amplified and biased. The signal is then digitally sampled at a rate of 256 Hz. A digital 47-point 10 Hz low-pass finite input response (FIR) filter is applied, and the data are decimated down to 32 Hz. The 10 Hz low pass filter implies that, at a nominal true airspeed of 55-60 m/s, the

minimum resolvable wavelength of the Twin Otter measurements is about 6 m.

The data from the VME computer is broadcast on a network connection to a laptop computer mounted at the forward crew station, where the data is recorded. On landing the data file is copied from the laptop to the removable hard drive. Post flight, the data from the removable hard drive is then used to create the CD-ROM that is used in the subsequent flux analysis and archiving. The format of the data is specified in a header block that is written to the data file when the program first starts up. This allows for a variable size data block that can be easily changed as needed for a project. The parameters are stored in engineering units for maximum precision.

2.9 Playback and Archive Software

Immediately after the flight, the aircraft data file is read from the removable hard drive into a portable PC and the data are reformatted and written to a CD-ROM. Three types of files are stored on the CD:

- 1) A direct copy of the entire flight data file with all parameters at 32 Hz.
- 2) A file written in the FRL's 'Playback' format for all parameters at 1 Hz. This file is used primarily for 'quick-look' purposes to ensure data quality, and to produce flight track plots, tephigrams and hodographs from soundings, and analog plots of selected parameters.
- 3) For all segments of the flight for which the event marker was selected ON (i.e., each flux run and sounding), a separate file is written in 'Playback' format for all parameters at 32 Hz. These files are subsequently used in the flux analysis program 'ARCPOKNEW'.

The main flux analysis program 'ARCPOKNEW' is written in Visual Fortran and runs on a PC using the 32-Hz data files from the CD-ROM and series of control files stored on the PC's hard disk.

A variety of output files are produced by 'ARCPOKNEW'. The primary ones include a number of ASCII files summarizing the run-average wind and flux data. The 'PLTDAT' files are the principal archive datasets of 32-Hz data for all parameters selected by the 'outflag'. They include the raw, linearly detrended, and high-pass filtered time histories of all parameters used in the flux calculations as well as the subsequent instantaneous flux contributions (e.g., the product of vertical wind times mixing ratio fluctuations that

represent the latent heat flux). These 'PLTDAT' files are stored on CD-ROM and are processed by subsequent analysis software to produce analog plots, spectra and co spectra. MacPherson (2003) gives further details on the data archived from this project, and from other Twin Otter flux-measuring projects dating back to 1991.

2.10 Flux Calculations

The principal equations used in ARCPOKNEW to compute wind components and fluxes from Twin Otter data are given in MacPherson (1990).

Three sets of fluxes were computed for CO₂, sensible and latent heat; these used (1) raw, (2) linearly detrended, and (3) high-pass filtered time series at 32 Hz. The high-pass filtering routine used a third-order algorithm with a breakpoint set at 0.005 Hz, which corresponded to a wavelength of approximately 11 km at the usual flight speed of the Twin Otter of about 55-60 m/s. Only the linearly detrended fluxes are presented in this paper.

On the Twin Otter (and other flux aircraft), there is a physical displacement between the primary sensor for the vertical gust velocity at the tip of the nose-boom, and the other sensors providing data for the flux calculations. In using the eddy covariance technique to compute fluxes, the data must be adjusted for the transport time for a parcel of air to pass from the nose-boom to the other sensors. This adjustment is particularly important for runs at low altitude, where the spacing of the sensors can become a significant fraction of the typical turbulent eddy size.

By means of an optional input in the playback software, the time histories for fluctuations in temperature, CO₂, H₂O, and ozone can be advanced a selectable number of data intervals (lags) prior to being multiplied by the vertical gust velocity to derive the fluxes. To verify the predicted time lags, data from low-altitude runs can be analyzed with a range of lags. The resulting computed correlation coefficients are then plotted versus lag, with the maximum of the curve defining the appropriate lag for use in the subsequent data analyses. Another benefit of this technique is that the lag derived for each instrument is a combination of delays resulting from both the physical separation of the sensors and the differences in the response times of the sensors.

2.10.1 Sensible Heat Flux (H)

In the playback software ARCPOKNEW, the run-averaged sensible heat flux H (in W/m²) was calculated for each of the three temperature measurements using the following equation:

$$H = 4.1876 \cdot \rho \cdot C_p \cdot 1/N \cdot \sum_{i=1}^N w(i)' \cdot \theta(i)' \quad (2)$$

where, w(i)' represents fluctuations from the run-mean in the vertical wind component,

$\theta(i)'$ represents fluctuations from the run-mean in the potential temperature, time-adjusted for the lag discussed above,

ρ is the run-average air density in kg/m³,

N is the number of data points (at 32 Hz) in the run

C_p is the specific heat of air at constant pressure

4.1876 is the conversion factor from cal/s to Watts

$$C_p = 240 \cdot (1.0 + 0.84 \cdot R/1000) \quad \text{cal/kg/deg.K} \quad (3)$$

where, R is the water vapour mixing ratio in gm H₂O per kg dry air.

The potential temperature in degrees K is derived from the following equation:

$$\theta = (T_s + 273.16) \cdot (1000/P_s)^{2.7} \quad (4)$$

where T_s is the air temperature in deg C

P_s is the static pressure in mb

On average, the sensible heat flux from the unheated probe, with its slightly better frequency response, was approximately 5-10 % greater than the estimates from the two heated probes. Fluxes derived using data from the heated probes usually agreed within 5 W/m² with one another.

2.10.2 Latent Heat Flux (LE)

The latent heat flux LE (in W/m²) was computed using the time-adjusted fluctuations in the water vapour mixing ratio, r(i)', from the LI-COR analysers in the following equation:

$$LE = 4.1876 \cdot \rho \cdot L_v \cdot 1/N \cdot \sum_{i=1}^N w(i)' \cdot r(i)' \quad (5)$$

Where, L_v , the latent heat of vaporization in cal/ kg, is given by:

$$L_v = 597.3 - 0.564 \cdot T_s \quad (6)$$

2.10.3 CO₂ Flux (WC)

Similarly, the CO₂ flux (WC, in mg/m²/s) was computed using fluctuations in the lag-adjusted LI-COR CO₂ mixing ratio, r_c(i)' (in mg CO₂ per kg of dry air), and the equation:

$$WC = \rho \cdot 1/N \cdot \sum_{i=1}^N w(i)' \cdot r_c(i)' \quad (7)$$

The LE and CO₂ fluxes were calculated using data from both the nose and cabin LI-COR data, after correcting for lags of 14/32 and 27/32 seconds respectively. There was very good agreement in the latent heat fluxes and CO₂ fluxes derived from the two analysers. Despite the higher frequency response capability of the cabin analyser, the nose analyser, with its inlet positioned close to the gust boom, gave latent heat (LE) and CO₂ fluxes on average 2-3 % greater than the cabin analyser.

2.10.4 Ozone Flux (WOz)

The ozone flux is derived using data from both the TECO and the LOZ-3 analysers on the Twin Otter. The LOZ-3 analyser has the faster response of the two devices, but the TECO has the better measurement of the absolute ozone concentration. A 3-step process is used in ARCPOKNEW to compute the ozone flux, following the procedure given in detail in Section 3.2.1 of MacPherson (1992).

First, a raw ozone flux estimate is computed using the w(i)' signal and the lag-adjusted ozone fluctuations of the LOZ-3 signal in ppb. That is:

$$WOz = A_{oz} \cdot 1/N \cdot \sum_{i=1}^N w(i)' \cdot LOZ(i)' \quad (8)$$

$$\text{where } A_{oz} = \rho \cdot 48.0/28.97 \quad (9)$$

A_{oz} is used to convert the LOZ(i)' signal from ppb to $\mu\text{g}/\text{m}^3$ using the run-averaged air density ρ and the ratio of molecular weights for ozone/air, so that the ozone flux is in units of $\mu\text{g}/\text{m}^2/\text{s}$.

Ozone fluxes are often reported in terms of the deposition velocity Vd, the mean vertical transport velocity for the ozone, positive towards the surface, i.e.

$$Vd = -100 \cdot WOz/[A_{oz} \cdot C_{LOz}] \quad (10)$$

where, Vd is in cm/s and C_{LOz} represents the run-mean ozone concentration in ppb from the LOZ-3 analyzer. As described in more detail in

MacPherson (1992), the corrected ozone flux, WO_{Zc} , can then be derived using the computed Vd and the ratio of the run-mean concentrations from both the LOZ-3 and TECO analysers. Equation (10) is reversed to solve for the corrected WO_{Zc} using the derived Vd from the fast-response LOZ-3, but the **mean** concentration from the more accurate TECO analyzer.

$$WO_{Zc} = -A_{O_3} * Vd * C_{TECO}/100 \quad (11)$$

And then substituting (10) into (11)

$$WO_{Zc} = WO_Z * C_{TECO}/C_{LOZ} \quad (12)$$

2.10.5 N_2O Flux:

Fluxes of nitrous oxide were measured using the Relaxed Eddy Accumulation (REA) technique, which is described in detail in section 3.

2.11 Video

The Twin Otter carries a VHS video recording system with two cameras, one mounted under the nose with a view along the flight path, the other mounted in the window of the cabin door providing a view to port at right angles to the flight path. A toggle switch on the cockpit console is used to select which camera is being recorded. Each flight is recorded in its entirety. For most of the time, the forward-looking camera is selected, with the side camera used primarily to document the upwind view representative of the flux footprint during crosswind runs. A data block is superimposed on the video image listing the GMT, aircraft altitude, heading and geographical position, and the state of the event marker flag. The audio channel on the VHS tape records all crew conversation on the aircraft intercom, as well as all radio transmissions.

3. THE EDDY ACCUMULATION SYSTEM (EAS)

Aircraft platforms have proven highly successful at measuring turbulent trace gas fluxes by eddy covariance at the regional scale ($>100 \text{ km}^2$) (Desjardins, 2000). However, the lack of a portable, self-contained, fast-response analyzer for N_2O constitutes, at present, a major obstacle to airborne eddy covariance N_2O fluxes. The Relaxed Eddy Accumulation technique (Businger, 1990) allows the measurement of scalar fluxes based on the same fundamental principles as eddy

covariance, without the need for a fast response analyzer. This technique has already been successfully applied to the airborne measurement of turbulent fluxes of agrochemicals (Zhu, 1998) and volatile organic compounds (Zhu, 1999).

The concept of Eddy Accumulation was originally suggested by Desjardins (1972), whereby air from updrafts and downdrafts were to be collected in two separate reservoirs, depending on the sign of the vertical component of wind (w) measured in real time, and at sample flow rates proportional to w . The air samples thus collected may then be analyzed later in the laboratory. Businger and Oncley (1990) suggested a relaxation of this method, where the sample flow need not be proportional to w . Rather, a constant sample flow rate is used for both updrafts and downdrafts, and the REA trace gas flux estimate (F_χ) is proportional to the difference in trace gas concentration (χ) between the two reservoirs and to the standard deviation of vertical wind (σ_w), such that:

$$F_\chi = A\sigma_w(\chi^+ - \chi^-) \quad (13)$$

where, the + and - superscripts denote ascending and descending air, respectively. The constant A may be determined by simultaneous *in-situ* measurements of eddy covariance turbulent fluxes ($\overline{w'\chi'}$) of a trace species for which a fast-response analyzer is available, e.g. CO_2 , so that A is simply obtained from the following:

$$A = \frac{\overline{w'\chi'}}{\sigma_w(\chi^+ - \chi^-)} \quad (14)$$

In the usual application of the REA technique, A is applied as a constant, which is dependent on the magnitude of the dead-band, used in the sampling system (see below). For example, if a dead-band of 0.1 m/s is selected, $A \approx 0.57$ should be used (MacPherson, 1991).

3.1 The NRC Twin Otter REAS

The REA device used in this study has been extensively described in Zhu *et al.*, (1998, 1999) and Flēchard *et al.*, (2001), although trapping methods have varied depending on the trace gas sampled. A schematic of the REA system

adapted for trace gas flux measurement is presented in Figure 3.

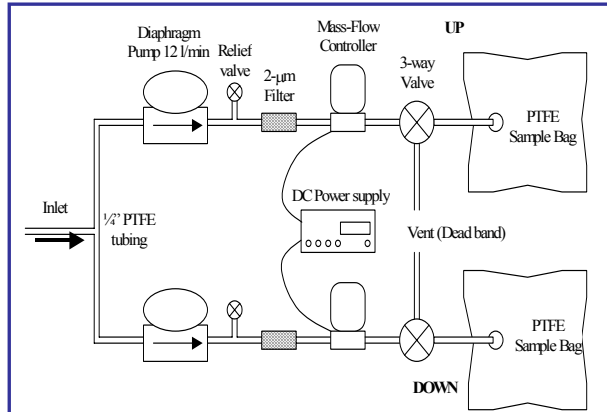


Figure 3: Schematic of the REAS in the NRC Twin Otter

Basically, air is drawn through a common 3/8" PTFE (poly-tetra-fluoro-ethylene) inlet by two diaphragm pumps, and is then split between the Up and Down channels. After passing through 2- μm stainless steel filters, the airflow is maintained at a constant 12 L/min in each line by 2 mass-flow controllers and a 4-channel power supply/readout unit. Two relief valves are used between the pumps and the mass-flow controllers to prevent over-pressurization. Two fast-response switching 3-way valves allow the flow to be directed either to PTFE sample bags or to the vent line.

Three sampling modes are defined according to the sign and magnitude of vertical wind speed w :

- 1) $w > w_0$: Up valve opens to the Up bag and Down valve opens to vent;
- 2) $w < -w_0$: Down valve opens to the Down bag and Up valve opens to vent;
- 3) $-w_0 < w < w_0$: both valves are open to vent so that no sampling takes place (dead-band);

where: w_0 is a positive set value (typically 0.1 m/s). The use of a dead-band helps to increase the lifetime of the valves and also enhances the concentration difference between the two bags.

The REAS assembly was mounted in the rear cabin of the NRC Twin Otter aircraft as shown in Figure 4. The w signal controlling the switching of the valves is high-pass filtered in real time to remove any bias in sampling due to aircraft weight changes and small calibration offsets.



Figure 4: The REAS installed in the NRC Twin Otter

3.2 N_2O analysis

Air samples collected using the aircraft were analyzed in the laboratories of Agriculture and Agri-Food Canada (AAFC) for N_2O concentration differences using a Tunable Diode Laser (TDL) Trace Gas Analyzer (TGA100). The TDL was set up in the gradient mode to measure concentration differences between the Up and the Down bags of individual pairs previously sampled in flight. To avoid a bias in the concentration difference due to a possible drift, the analyzer switches between the two bags of one pair back and forth every 6 seconds and outputs an average concentration difference at the end of each minute. The IR-emitting laser is cooled in a liquid nitrogen dewar and is simultaneously temperature (88 K) and current (400 mA) controlled to produce a linearly modulated wavelength which is centered on a single N_2O absorption line (2205/cm). The IR radiation is passed through reference and sample absorption cells and the transmitted power is detected by Peltier-cooled mercury cadmium telluride detectors.

Tests conducted during an earlier program to determine the detection limit of the TDL in the concentration difference mode, showed that in the context of REA (Eq. 13), a 10-pptv N_2O concentration difference with a σ_w of 0.5 m/s is equivalent to a flux density of 5 ng N_2O / m^2/s at 10°C and 1013 mbar (Flechar, 2001).

All pairs of PTFE bags were flushed with ambient air then vacuumed, three times, prior to sampling, in order to prevent hysteresis / memory effects.

Also, the bags were prepared in this manner just prior to being used on the flight (typically on the morning of the flight day), to prevent inadvertent contamination. For the same reason, the bag samples were usually analyzed within a few hours after the samples had been collected. The results from the analyses of the bag samples from each flight were then used to compute nitrous oxide fluxes (equation 13).

4. SUMMARY OF FLIGHT OPERATIONS

4.1 Sampling Areas

Initially, three 5-nm (≈ 9 km) flight tracks for the N_2O sampling flights were selected over Eastern Ontario, viz. Casselman, Morewood and Larose Forest. The Casselman and Morewood tracks represent areas of intensive agriculture with relatively high N input, typically forage crops, pasture, corn and soybean. The Larose Forest, by contrast, is representative of low N-input or natural ecosystems. Therefore, it was decided not to fly over the Larose Forest track and only the other two tracks were retained for the 2003 experiment. Three measurement campaigns took place as follows:

1. during the Spring thaw (March-April) of 2003,
2. throughout the summer of 2003, through planting, fertilization, growth and harvest,
3. in the Fall (September-October) of 2003.

Flights always took place around mid-day and lasted typically two hours. Two repeated passes over each flight track (about 5-6 minutes) were generally needed to fill the sample bags, depending on the sample flow rate and on turbulence levels, *i.e.* what percentage of the time the REA system was in the dead-band mode. Most runs were flown at about 65m (200 feet) above ground level (agl).

In order to be able to relate the aircraft-measured fluxes to the underlying vegetation, it is desirable to make measurements at a height of approximately 40m (130 feet) agl. However, Transport Canada (TC) rules forbid operation of an aircraft within 500 feet, vertically or horizontally, of persons, occupied buildings, and vehicles. Grazing animals are also to be avoided. A compromise solution was devised, whereby the project tracks were flown at a mean height of 60m (200 ft) agl, with the proviso that when it appeared that flying directly over people or animals was

unavoidable, the aircraft would “pop-up” to a height of 500 feet over them. During these pop-ups, the sampling was temporarily paused.

To capture the long-wavelength contributions to the fluxes, runs at least 5 km in length are required. Furthermore, each of the tracks should be flown several times in a row to improve the statistical reliability of the flux estimates. It is these repeated passes that can accentuate the problem if a resident is irritated by the passage of a low flying aircraft, and this can lead to a call to TC and possible curtailment of the experiment.

A total of 49 flight hours were flown on 32 project flights. All of the flights were flown in the mid-day period when the boundary layer was building.

4.2 Data Summary

As indicated in previous sections, most parameters on the Twin Otter are measured at least twice by individual instruments. For example, for this project there were three temperature probes, two GPS systems, two LI-COR CO_2/H_2O analyzers, two ozone analyzers and a primary wind system with two backups. Therefore, when producing the final data archives and summary tables, choices have to be made to ensure that the best possible data are used. In this project, there were very few problems with the primary wind system (Section 2.2), and the fast-response unheated temperature probe data were used for all archived air temperature measurements and sensible heat fluxes. For the archived GPS and CO_2/H_2O data, however, some instrument problems required a selection on an individual flight basis.

After every flight, AAFC personnel would take the bagged samples collected back to their lab for analysis. Results from the TDL analysis of the bagged samples were reported back as the concentration difference between the ‘up’ and ‘down’ bags in ppt (parts per trillion). This is converted to concentration in ng/m^3 and then combined with the standard deviation of the vertical gust velocity using Equation 13 to derive the N_2O flux. The flux is expressed as both $ng/m^2/s$ and $mg/m^2/day$, with a positive sign indicative of emission from the surface.

Another important metric used to quantify the exchange of energy and trace gases between the surface and the atmospheric boundary layer is the

residual energy flux ratio, given by $(R_n - H - LE) / R_n$. This is the proportion of the net radiation (R_n) not measured by the aircraft as an upward flux of total energy, i.e., sensible (H) plus latent heat (LE). This 'lost' energy includes the flux of heat into the ground and the flux divergence, i.e., the heat used to heat the atmosphere between the surface and the flight altitude (typically $10-20 \text{ W/m}^2$ for these low flight altitudes). This ratio is not the same as the traditional 'closure ratio', which includes the soil heat flux (could not be measured in this experiment). The residual energy flux is high at the beginning of the experiment, as a significant portion of the sun's energy is used to melt snow or to heat standing water on the surface. A typical value of this ratio for summertime flights is about 0.2, representative of the soil heat flux and the flux divergence component.

5. OBSERVATIONS AND DISCUSSION

In this section, we present an initial interpretation of the Twin Otter flux data collected during this project. More intensive treatment can be expected to appear in focused papers and journal articles when the aircraft measurements are combined with data from the flux tower and other meteorological databases.

5.1 CO₂ Flux

Figure 5 shows the CO₂ flux in $\text{mg/m}^2/\text{s}$ plotted versus the day of the year. Each point represents the average of all runs flown on the individual tracks on each flight.

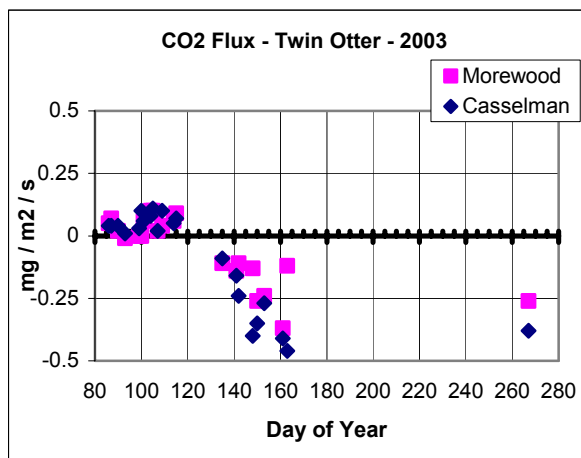


Figure 5: CO₂ Flux measured over the 2 agricultural tracks

For the flights flown in March and April (Days 85-115), the CO₂ flux showed consistent small positive (upward) values indicative of respiration from the surface. When flights resumed in the middle of May (Day 135), CO₂ fluxes were downward and increased with time as the vegetation along the flight tracks grew. During this period, the CO₂ fluxes on the Casselman track were consistently higher than those for Morewood, corresponding to the higher Greenness Index readings for the Casselman track.

Examination of the Satellite Simulator data from flights near the end of May (e.g. Day 148) indicates that more than half of the Morewood track remained essentially bare and unplanted, while only about a third of the Casselman track was fallow.

5.2 Energy Fluxes

Figures 6 and 7 show the sensible heat flux (H) and the latent heat flux (LE) for both flight tracks flown in this project, plotted versus day the year.

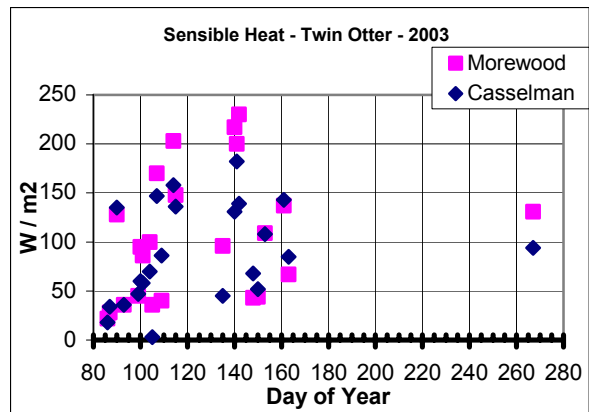


Figure 6: Sensible Heat Flux measured over the 2 tracks

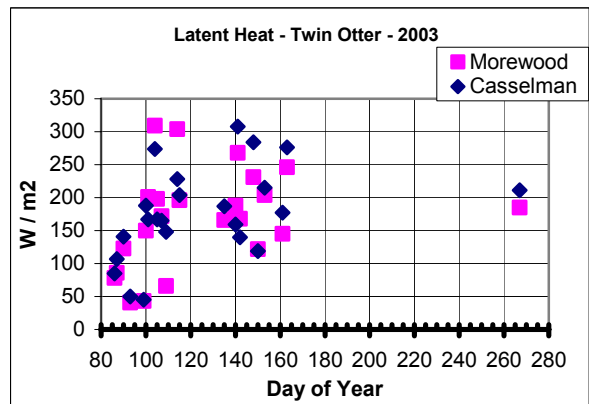


Figure 7: Latent Heat Flux measured over the 2 tracks

Figure 8 shows the surface temperature measured over the runs. The surface temperature appears to be slightly higher over the Morewood track than over the Casselman run in most cases, a reflection of the greater proportion of bare ground observed on the Morewood track.

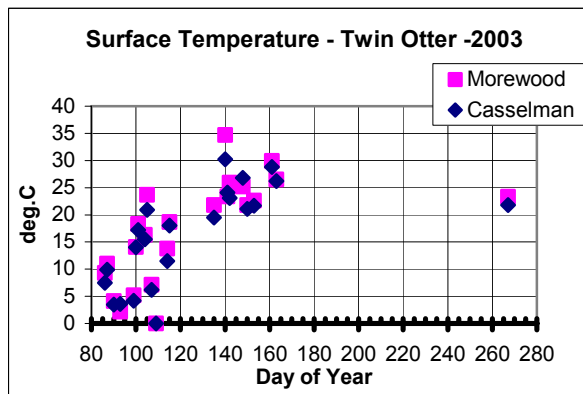


Figure 8: Surface Temperature measured at the 2 tracks

5.3 Ozone Flux

Figure 9 shows the O₃ flux in $\mu\text{g}/\text{m}^2/\text{s}$, plotted versus the day of the year, for the Morewood and Casselman tracks. Note that in this presentation, the sign of the ozone flux has been reversed, consistent with the convention for ozone deposition velocity, so that the plot essentially displays ozone uptake by the surface, i.e., positive values represent downward flux.

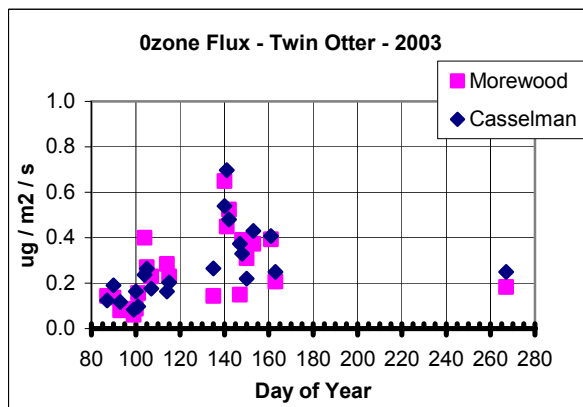


Figure 9: O₃ Flux measured over the 2 tracks

The largest ozone fluxes occurred on Days 140 and 141, which corresponded to the days with the highest sensible heat flux (Figure 6). Ozone concentrations in the atmosphere are known to

vary depending on the source of the air mass over the test area. Ozone fluxes can therefore also depend on the atmospheric ozone concentration, which has been added in Figure 10 to the plot of fluxes for the spring period of the project.

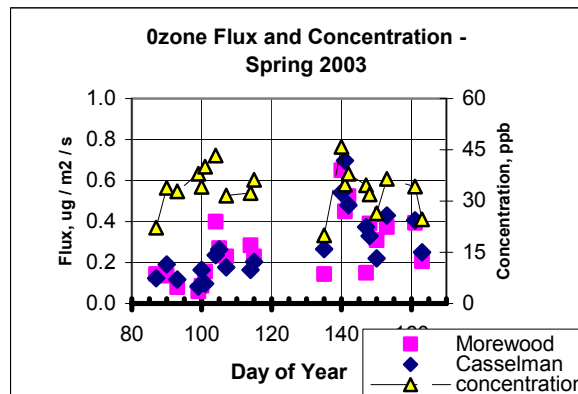


Figure 10: O₃ Flux and Concentration for Spring 2003

The ozone concentration was measured by the TECO analyzer on the Twin Otter, which was not on the aircraft for the flight on Day 267. The largest ozone concentration was measured on Day 140, which was a warm day (23 C) with strong southwest winds, suggesting that the air mass originated in industrial areas of Southern Ontario and the Ohio Valley. The magnitude of the ozone flux does not appear to be related to the N₂O fluxes. The ozone uptake does not appear to differ significantly between the Morewood and Casselman tracks, unlike the CO₂ fluxes after Day 135. This is consistent with Twin Otter measurements made over bare and vegetated fields in the San Joaquin Valley of California (MacPherson, 1992). Although vegetated surfaces absorb both ozone and CO₂, bare fields (especially if recently ploughed) still take up ozone, but emit CO₂.

5.4 N₂O Flux

The interpretation of the N₂O flux data is currently ongoing. The N₂O flux data obtained from the Twin Otter in this 2003 field campaign will be correlated with other information, such as the timing and extent of fertilizer application along the Casselman and Morewood tracks, precipitation events and results from tower-based N₂O flux measurements made on the AAFC Experimental Farm property in southwest suburban Ottawa. The detailed results of this investigation will be reported in the near future.

6. CONCLUDING REMARKS

The Twin Otter provided high-quality meteorological and flux data from 49 flight hours over 32 project flights between March and October of 2003. This paper has summarized the 2003 Flux Measuring Field Campaign, detailing the instruments flown, listing the best estimates of the run-averaged fluxes, and presenting a number of graphical presentations to assist in the interpretation of data collected. Further analysis of the data collected during this project is ongoing and will be the subject of subsequent reporting.

7. ACKNOWLEDGMENTS

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