P2.9 AN AIRBORNE DISJUNCT EDDY COVARIANCE SYSTEM: SAMPLING STRATEGY AND INSTRUMENT DESIGN

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1. INTRODUCTION

Various surface layer flux measurement techniques have been developed to study the exchange of trace gases between the surface and the atmosphere. Of these methods the eddy covariance (EC) and eddy accumulation (EA) methods are also applicable for airborne measurements. The EC method has several advantages over the EA methods. However the conventional continuously sampling EC (CEC) method requires a fast analyser, as the high-frequency variations of the trace gas concentration have to be measured.

The disjunct eddy sampling, also called intermittent or periodic sampling, relaxes the requirement for a fast analyser when applied to the EC method (Dabberdt et al. 1993; Lenschow et al. 1994; Rinne et al., 2001). In disjunct eddy covariance (DEC) only a subset of the continuous time series is used to obtain the flux, i.e. in equation (1),

$$F_s = \langle w's' \rangle = \frac{1}{n}\sum_{i=1}^{n} w'(t_i)s'(t_i)\,, \qquad (1)$$

there is a considerable interval between t_i and t_{i+1}.

The DEC flux measurements are conducted by taking air samples very quickly (0.1 s) and analysing them relatively slowly (10-30 s). This method has been used to measure hydrocarbon emissions from vegetation (Rinne et al., 2001; Warneke et al., 2002). The DES approach has also been applied to the disjunct eddy accumulation technique (Rinne et al., 2000).

We are currently developing an airborne DEC system. As a part of this program we have been studying different possible designs for an airborne DES and the requirements for DEC. This includes quantification of the uncertainties in the flux values due to the disjunct eddy sampling. An airborne DEC system would add a powerful new tool for measurements of surface-atmosphere trace gas exchange, especially in remote areas.

The various sources of uncertainty of fluxes measured by a DEC method include the sub-sampling of the time-series, sample carry-over, insufficient time response of the sampler, and the displacement of the sampler from the wind sensor. Some results addressing the first two sources, which are specific for the DEC method, are presented. Various potential designs for an airborne DES are discussed as well as the sampling strategy.

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2. POTENTIAL DESIGNS FOR AN AIRBORNE DES

There are few possible designs for airborne DES. The first is based on the ground-based system presented by Rinne et al. (2001). In this system the sample is taken by opening a high flow conductance valve (α-valve) into a pre-evacuated rigid wall intermediate storage reservoir (ISR). The ISR is evacuated between each sample by a vacuum pump. The air intake would be a short tube sticking outside the aircraft, possibly with the α-valve. The rest of the system would be inside the aircraft.

A second possible design uses a soft-walled bag as an ISR. The sample intake would be directed towards the flight direction so that when opening the α-valve the pressure would push the air into the ISR. The ISR would be evacuated, but no big vacuum pump would be needed. A kind of mixture of the rigid wall ISR and soft-walled ISR DES has been previously tested at NCAR (A. C. Delany[1], pers. comm.).

A third possible design for DEC utilises so-called flow-through ISR. In this design air flows through a tube, parallel to the flight direction and open at both ends. The sample is captured by simultaneously closing the valves at both ends of the tube. Also this design has been tested at NCAR (W. A. Cooper[2], personal communication). In this design no pump is needed to evacuate the ISR. A tower-based flow-through DES, in which the flow was created by pump, was tested at NCAR during the summer 2001.

A kind of disjunct eddy covariance technique is the virtual DEC, in which a proton-transfer-reaction mass-spectrometer (PTR-MS), with a response time of around 0.1 s, is used to scan through a set of compounds thus generating a disjunct time-series of each compound. This method has been used to measure hydrocarbon emissions from vegetation by Karl et al. (2002).

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3. SPECIFICATIONS FOR DES STRATEGY

3.1 Simulation of DES

To specify the best strategy for airborne DEC measurements a series of measurement simulations were conducted using high frequency data from ground-based and airborne experiments. The effect of DES was studied by sub-sampling the time series of high-frequency turbulence data with sampling intervals between 0.75 and 300 s. The data used for the simulations included four days of 10 Hz three dimensional wind (u, v, w) and temperature (T) data recorded 3.2 m above an alfalfa field in Fort Morgan, Colorado in August 2000 (Rinne et al., 2001; Warneke et al., 2002), hereafter called FM00; and 25 Hz 3-D wind, temperature and specific humidity (q) data recorded during five flights in the boundary layer onboard Merlin aircraft of Météo-France above Beauce plain, France, during TRAC98 experiment in 1998 at flight levels 100 m to 2000 m (Campistron et al., 1999), hereafter called M98.

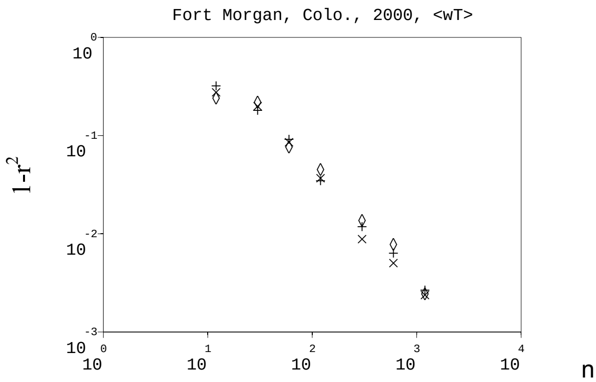

Figure 1: The number of observations (n) used for DEC flux calculation vs. correlation (r^2) between DEC heat fluxes and CEC heat fluxes. Simulated by FM00 data using three different averaging periods: 15 min (crosses), 30 min (diagonal crosses), and 60 min (diamonds).

The DES was simulated by taking samples from time series at various intervals and calculating fluxes using these subsets. This was conducted ten times for each half hourly period, each time moving the starting point of the sampling one tenth of the sample interval ahead. Also integral time-scales of *w'T'* and *w'q'* and their variances, as well as r^2 between *w'* and *T'* and *q'*, were calculated. The fluxes were calculated using averaging times of 15 min, 30 min and 60 min for FM00 data. The flight legs on M98 data were 10 minutes long, i.e. about 60 km, which was used as integration time.

The effect of the sample carry-over from one sample to another was also simulated. The carry-over is due to the inability of certain disjunct eddy sampling systems to totally flush the previous sample from the ISR. In this simulation each sample was simulated to be composed of 0-20% of the previous sample, the rest being of the current sample.

Ruppert (2002) and Ruppert et al. (2002) have also simulated various flux measurement methods, including DEC, using high frequency data of 3D wind, *T*, *q* and CO_2 concentration.

3.2 Results of the simulations

No bias was observed between the simulated DEC and CEC fluxes. This was expected since the turbulence in the surface layer or in the daytime unstable boundary layer generally does not have wave-like motions, which could coincide with the sampling interval of DEC. However, wave motions are often observed in the stably stratified boundary layer, and this introduces a possible source of systematic error to the fluxes measured aboard an aircraft flying in the boundary layer.

Figure 1 presents the correlation coefficient between heat fluxes calculated using DEC with various sample intervals and CEC, for three integration times (FM00 data). Only one realization of DEC per each averaging interval is used here. When the correlation coefficients are plotted against the number of observations used for the DEC flux, as in the figure, instead of sample interval, they fall onto the same line. As the integral time-scales of *w'T'* were only a few seconds, and thus much shorter than the typical sample intervals of a DES, it is not surprising that the number of samples proved to be the governing parameter for the correlation between DEC and CEC.

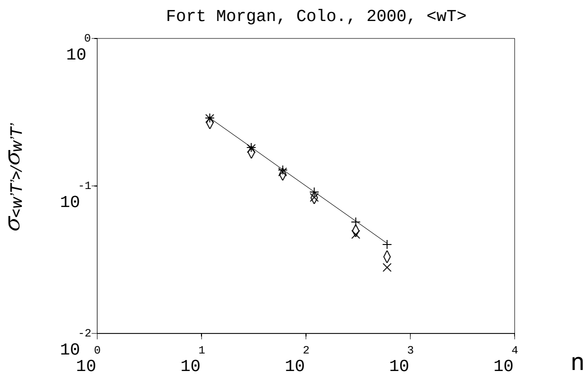

Figure 2: Number of observations (n) used for the DEC flux vs. $\sigma_{<w'T'>}/\sigma_{w'T'}$, FM00 data. Line: predictions by Eq. (3); crosses: Eq. (2) with N=18000; diagonal crosses: Eq. (2) with N calculated by Eq. (4); open diamonds: calculated from DEC simulations.

To quantify the uncertainty caused by the DES we used standard statistical methods. The standard deviation of the mean, $\sigma_{<w's'>}$, calculated from a sample taken from a population of *w's'*s with standard deviation $\sigma_{w's'}$ can estimated by:

$$\sigma_{\langle w's' \rangle} = \sqrt{\frac{N-n}{N-1}} \frac{\sigma_{w's'}}{\sqrt{n}}, \qquad (2)$$

where N is the population size and n the sample size. The standard deviation of the mean of *w's'*s can be used as a measure of the uncertainty of the flux, <w's'>, calculated as a mean of the sample generated by the disjunct eddy sampling. The term $\sqrt{(N-n)/(N-1)}$ is close to unity when n is small compared to N. When n/N<0.1 this term can be ignored and the standard deviation of the mean can be estimated by Eq. (3),

$$\sigma_{\langle w's' \rangle} \approx \frac{\sigma_{w's'}}{\sqrt{n}}. \qquad (3)$$

A half-an-hour time series of 10 Hz data contains 18000 data-points. However, these are not independent as there is a positive autocorrelation of *w's'* for a few seconds in the surface layer. To take this into account the effective size of the populations was estimated by Eq. (4),

$$N = \frac{T_{ave}}{\tau_{w's'}}, \qquad (4)$$

where T_{ave} is the length of the averaging period and $\tau_{w's'}$ the integral time-scale of *w's'*.

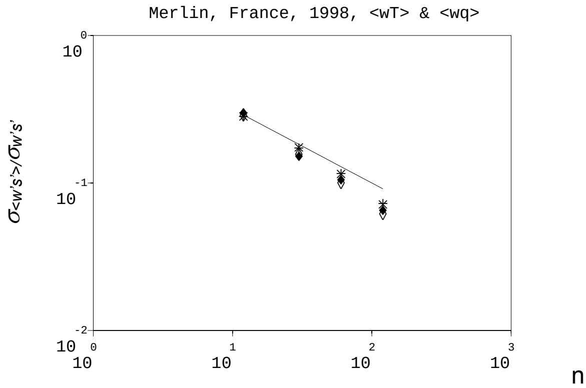

Figure 3: Same as figure 2 but using M98 data, for both water vapour and temperature. Line: predictions by Eq. (3); crosses and diagonal crosses: Eq. (2) with N calculated by Eq. (4) for temperature and for water vapour, respectively; open and filled diamonds: calculated from DEC simulations using water vapour and temperature, respectively.

The uncertainty of *<w'T'>* was estimated for each half-an-hour averaging period of FM00 data as the standard deviation of ten different DEC realisations from the CEC flux value for each period. These results, normalized by $\sigma_{w'T'}$, are shown in Figure 2. As can be seen, the simple Equation (3) predicts the uncertainty reasonably well, although with slight overestimation. The Equation (2) with N=18000 gives practically the same results as Eq. (3). If N is calculated by Equation (4) the uncertainty estimate is closer to the observed.

In Figure 3 the uncertainty estimates described above are conducted for the M98 data. As can be seen the uncertainty of heat and humidity fluxes behave the same way and the same equations can be used to quantify them.

As can be seen equation (2) or its simpler forms can be used to estimate the uncertainty introduced to the measured fluxes by the DES. In the simplest equation only information on the standard deviation of *w's'* and number of samples are needed.

The results of the simulation of sample carry-over using M98 and FM00 data can be seen in the Figure 4. Even 10 % carry-over from a sample to the next one causes relatively small flux under-estimation.

4. CONCLUSIONS

As was expected the fluxes calculated by disjunct eddy covariance did not have any bias compared to the fluxes calculated using continuous time series. The uncertainty, although considerable for low sample numbers, was random in nature.

As the sample intervals we are interested are much longer than the integral timescale of the corresponding w's', it is not surprising that the number of samples used for DEC flux calculation proved to be a governing parameter for uncertainty caused by sub-sampling the time-series. The parameter $\sigma_{w's'}/\sqrt{n}$ can be used to estimate the uncertainty caused by DES.

A phenomena causing systematic underestimation to the fluxes measured with certain types of DE-samplers is sample carry-over. The effect of the carry-over seems, however, to be relatively small and could be corrected for.

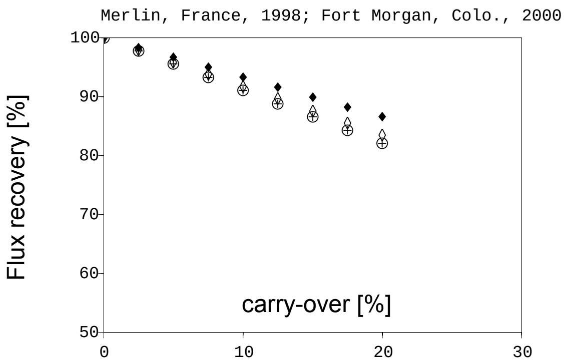

Figure 4: Simulation on the effect of sample carry-over to the flux underestimation using M98 data. Open diamonds: water vapour M98; filled diamonds: temperature M98; crossed circles: temperature FM00.

As the research aircraft typically have airspeed of around 300-400 km/h, the typical leg-lengths for turbulence measurements have been around 10 minutes. For longer straight-forward legs the surface heterogeneities become a problem. Ten minutes is a very short time to gather enough data-points with a DEC system with its sampling interval usually fixed by the response time of the analyser used. A solution is to fly back and forth, or in a circular pattern over the same source area at the same height to collect samples required for the specified flux accuracy.

Instrument noise in the concentration measurement can be highly degrading to the quality of the DEC flux measurements. In the CEC the effect of the noise gets averaged out due to the high number of concentration measurements, but in DEC high quality concentration measurements are needed.

Finally, the choice between the different designs of the DEC, as well as between different flux measurement methods, depends strongly on their technical feasibility. For a measurement system to be a powerful tool for trace gas flux measurements we have to be able to make it work in various, often difficult, environmental conditions.

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