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B 6 Accuracy and utility of aircraft flux measurements

Timothy L. Crawford and Ronald J. Dobosy (revised 21 July 00 + CK)

B 6.1 Introduction

Strategies to assess long-term atmosphere-ecosystem exchange of CO_2 and H_2O must deal not only with time trends but also with spatial variability. Flux-towers, always limited in number, efficiently measure time trends but the representativeness of a tower site - or the significance of spatial variation between sites - is best addressed through flux measurements from small aircraft. Recent technological advances in aircraft and instruments allow airborne flux measurements to be made with enhanced precision, greater ease and lower cost. Challenges remain, however, in all aspects of the activity: instrumentation, data processing, and data interpretation.

Airborne eddy-flux observations obtained with modern instruments properly installed and operated on appropriate aircraft, will give results no less accurate than from a careful flux-tower operation. The primary difference is in how the data must be interpreted (Mahrt, 1998). Tower data form a time series relying on mean wind to advect the turbulence past the sensors. An airplane, because of its speed, experiences turbulence more as a space series. The computed fluxes match best (as we will show) when conditions are homogeneous and stationary. However, spatial and temporal variations are the rule and thus drive spatial and temporal averages apart. It follows, therefore, that the best use of airborne data is to examine the rich spatial structure between and beyond towers, and to estimate non-local terms, such as advection, in the energy and mass budgets.

With the recent availability of low-cost systems on light aircraft, airborne measurements promise to become more prevalent. Nevertheless, they are only practical primarily during daylight hours in brief, intensive field campaigns; extrapolation of day-time spatial-structure to night-time conditions or as long-term information remains for now the province of models. The development and validation of such models will be enhanced greatly by the increased availability of airborne observations of spatial structure.

B 6.2 Technology of airborne flux measurement

As with towers, sampling of air-surface exchange from aircraft requires an accurate, undisturbed, high-frequency record of winds (u, v, w) and scalars (temperature, pressure, mass concentrations) just above the canopy. However, airborne sensors are constantly in rapid complex motion, both linear and rotational, in an environment of flow distortion. Wind velocity and scalar parameters that can be measured directly on a tower have to be derived from multiple measurements on an airplane. Errors in magnitude or timing of these feeder data propagate through derived winds and scalars into computed fluxes. Though sensors of sufficient accuracy for this work are readily available commercially, their proper installation and use are major issues. In finding the optimum configuration, vehicle costs, flexibility, imposed flow distortion, frequency response, flight speed and operational altitudes all have to be considered. Considerable complexity in data processing can be avoided through careful selection of airframe and sensor configurations. An accurate common time reference for all data is critical.

Wind measurement from an airplane is simple in concept, difficult in detail, and vital to the flux computation. Mathematically, the central problem is to convert airflow, measured from a moving airplane, to winds in fixed earth coordinates. Most of the sensed airflow arises from the airplane's own motion, which must be measured and removed to determine the wind. Strictly, we need to know the motion of the sensors, not of the airplane. This realisation can lead to important optimisation. In the 1980s, inertial navigation systems (INS) were the most accurate way to measure the sensors' motion. The INS achieved good wind accuracy but availability was limited because of cost and size. Further, it measured the motion of that part of the aircraft where it was mounted. The airflow sensors' velocity was found by extrapolation, a complex, error-inflating process. With the introduction of small, low-cost differential GPS and micro-accelerometer technology, the sensors' motion can now be measured directly. The mathematics has become simpler and more robust.

Flow distortion is a universal consideration in accurate flux measurement. On a tower, flow is distorted by the blockage and drag of the sensors and their support structure. On an airplane such incidental distortion is augmented by powerful flow distortion generated intentionally to provide propulsion and lift. Good airborne installations, like good tower installations, minimise distortion by minimising the disturbance and then placing the sensors as far away from it as is practical. A small, low-drag airframe, rear-mounted engine, and long instrument boom have clear advantages (Crawford and Dobosy, 1992). A rear-mounted engine not only removes the propeller's disturbance from the nose, but also shifts the centre of mass aft, moving the wings aftward as well.

The farther aft the wings, the weaker the upwash at the nose. Upwash is the forward part of the circulation generated by the wings in producing lift. Its magnitude is positively correlated with the vertical wind velocity being measured (Crawford et al., 1996). Thus, upwash contamination, if unaccounted, causes fluxes to be overestimated. Characteristic upwash ranges from 0.5 to 2.5 m s^{-1}, depending on the wing loading, flight speed, and forward distance from the wing to the measurement location. Pressure-radome installations, being generally close to the wing, experience strong upwash relative to sensors mounted on long probes. Smaller airplanes with light wing loading generate less upwash.

Flight speed, being at least a factor of ten greater than the wind being measured, imposes strict accuracy limits. A 1% error in the sensors' or the relative airflow's velocity produces at least a 10% error in wind. Fortunately, modern technology has facilitated these measurements and associated computations, increasing their accuracy while greatly reducing their cost.

Flight speed also affects turbulence measurements in other ways. The faster the flight, the more the turbulent information is compressed in time, improving the sample. This is useful close to the surface, where the turbulence is rich with character driven by surface forcing. It must, however, be accompanied by proportionally faster and more accurate sensors. Further, fast aircraft close to the surface are less manoeuvrable and more intrusive to humans. For low-altitude work (10 - 15 m above ground), 50 m s^{-1} is a practical airspeed, collecting 50 samples per second. With increased altitudes, the surface signal becomes obliterated by turbulent blending. Also, measured flux departs from its surface value as storage and advection beneath the aircraft become more significant (Betts et al.,1990). Further, the horizontal scale of the turbulence increases with height above ground, requiring longer flight tracks to obtain a statistically stable covariance (Lenschow et al.,1994). Fast, higher-flying aircraft are more suited to larger regions where surface detail is less resolved (e.g. Oncley et al., 1997).

The airplane's aerodynamic characteristics correlate its flight speed with vertical wind velocity. For example, when an airplane enters an updraught, constant altitude is maintained by lowering the nose. As the airplane pitches downward, it accelerates. The opposite occurs when descending air is encountered. The airplane thus travels more rapidly through updraughts and more slowly through downdraughts. A constant-rate times series provides a biased sample, with more observations during downdraughts. Constant altitude sampling of other organized flow structures (roll vertices, micro-fronts, slope flows, etc.) may also modulate the airplane's speed, introducing bias into time averages relative to the space average. Such bias can be as much as 15% on small aircraft, though much less on large aircraft. Estimating the ensemble-average eddy flux from observed airborne time series thus requires conversion to a space series, as discussed by Crawford et al. (1993).

B 6.3 Accuracy of Airborne measurements

Typical GPS technology can now define sensors' attitude, velocity, and position in earth coordinates to an accuracy of 0.05°, 0.02 m s^{-1} and 0.01 m respectively. The better GPS receivers report ten times per second but achieve the stated accuracy up to about 1 Hz. Extension to higher frequencies is readily accomplished by measuring accelerations, which increase in amplitude with increasing frequency. Pitch, for example, is found as the second integral of its angular acceleration. This is measured as the difference between vertical accelerations at a known separation along the longitudinal axis of the airplane. Error accumulates rapidly in these integrals, but not in the first two seconds with accelerometers of ordinary good quality. This is adequate because of the high accuracy of GPS at frequencies up to 1 Hz. Figure B.13 shows the quality of the match between pitch angles determined by GPS and by accelerometers. The raw GPS measurement (dashed line through trough) is filtered to remove frequencies above 0.5 Hz (circles). Integrated accelerations are filtered to remove frequencies below 0.5 Hz (solid line about zero). The sum of these filtered signals (solid line through the trough) is more accurate over the whole frequency range than the GPS alone. The two curves, which would obliterate each other, are mutually offset for visibility. The raw GPS trace is noisy in comparison, but the noise is generally within about 0.1° (dashed line about zero). At an air-speed of 50 m s^{-1} an error of only 0.1 m s^{-1} would result from straight use of GPS for pitch.

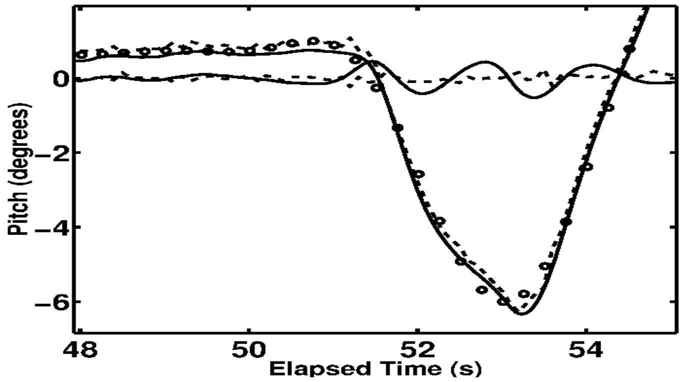

Figure B.13 Pitch angle by GPS, extended by accelerometers

GPS accuracies are still improving with the adoption of dual frequency receivers, more powerful embedded microprocessors and advanced firmware. Airborne wind measurements have the potential accuracy of 0.02 m s^{-1} horizontally and 0.03 m s^{-1} vertically. Unfortunately, adoption of this new technology has been slow. For various reasons, none of the current airborne wind systems achieves this accuracy in mean wind observations. However, mean wind accuracy is rapidly improving. We believe the residual contamination due to unresolved platform motion to be less than 0.2 m s^{-1} horizontally and much less for vertical winds. The accuracy of turbulent wind should be greater than that for the mean wind because its energy occurs in spectral regions higher than most aircraft motion.

Assessment of the overall accuracy of airborne flux measurements can be made by intercomparisons in the field. Comparison among airborne systems, as during the BOREAS experiment (Dobosy et al., 1997) show the overall precision of measurement. A more recent comparison, after upgrades to the Long-EZ's GPS receivers, yielded a further improved match. In particular, the variance of vertical velocity was brought into close agreement through the use of the Twin Otter of the Canadian National Research Council, as can be seen in Figure B.14.

Compared to surface fluxes reported from towers, airborne measurements initially produced flux estimates systematically low, by 15% or more (Shuttleworth, 1991). Through multiple passes over the same track at lower altitudes (30 m or less) the match has been markedly improved. The surface must, of course, be sufficiently homogeneous to ensure similar footprint character. Figure B.14 shows the quality of match that was achieved by the Long-EZ / Twin Otter combination about a tower operated by S. Verma as part of the AmeriFlux programme funded by the Southern Great Plains Regional Office of the US Department of Energy's NIGEC programme.

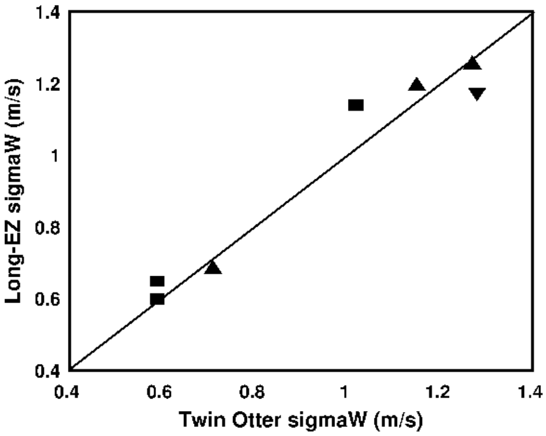

Figure B.14 Variance of vertical wind component, measured from two airplanes

B 6.4 Utility of airborne flux measurement

Some important lessons have been learnt as the technique of airborne flux measurement has evolved during its application in the series of Integrated Terrestrial Experiments. The utility of the technique derives from both transit speed and freedom of track. Being versatile in space but limited in temporal coverage, airborne flux measurements complement naturally the measurements from fixed towers. The best experiment designs deploy airborne flux measurements between tower sites or along paths passing over at least one fixed tower comparable in height to the flight altitude. Shorter paths traversed frequently are better than long paths traversed rarely. Several important experiments illustrate airborne deployment.

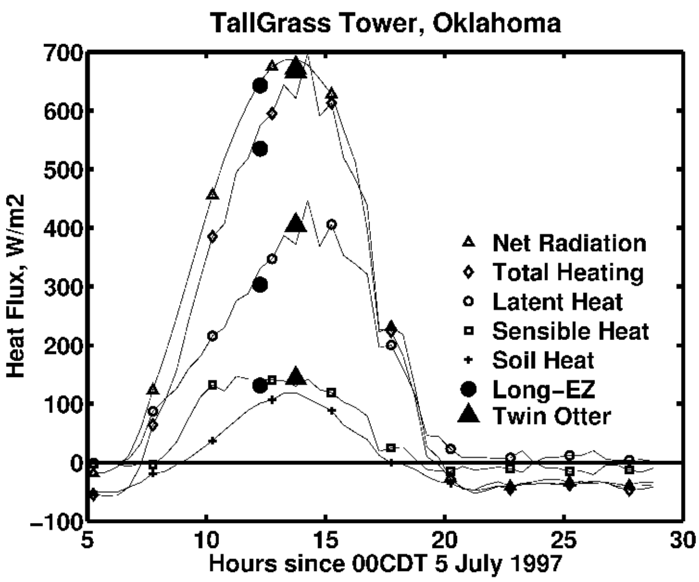

Figure B.15 Flux airplanes and tower under homogeneous conditions in Oklahoma

The Hydrologic Atmospheric Pilot Experiment, Modélisation du Bilan Hydrique (HAPEX-MOBILHY, André et al., 1988) observed the hydrological budget on a 100 km square in southwest France, with an intensive period (IOP) in 1986. The heterogeneity of the landscape was covered by measuring micrometeorological and hydrological parameters at locations representative of the major vegetation communities. The King Air of the US National Center for Atmospheric Research (NCAR) flew a 150 km flight track during the IOP at several depths in the boundary layer, estimating surface fluxes from passes at 100 m altitude. These fluxes, computed over 10-km segments of the path were somewhat low compared to tower measurements. But they showed internal consistency and documented clearly the change in energy partition between agriculture and forest.

The European Field Experiment in a Desertification-Threatened Area (EFEDA) occurred in June 1991 in eastern Spain. The Falcon airplane of the Deutsches Zentrum für Luft- und Raumfahrt (DLR) flew L-shaped patterns at three altitudes from 400 m to 2500 m above ground. Michels and Jochum (1995) found links between the pattern of surface fluxes and the boundary layer's character over its whole depth in this arid and partially irrigated agricultural region. Fluxes sampled at 400 m were, however, sometimes significantly different from those at the surface. The latent heat flux on 23 June 1991 tended to increase at 400 m between Barrax on the east and Tomelloso on the west, opposite to the surface pattern. Modelling reproduced this result and related it to mesoscale moisture advection from the Mediterranean Sea, 200 km to the east (Noilhan et al., 1997).

HAPEX-Sahel extended the observations to the Sahel region of Africa in 1992. The Météo-France Merlin IV aircraft flew 50-km overlapping rectangles over the surface array (Saïd et al., 1997). Of interest to airborne flux measurements, they determined the behaviour of the latent heat flux to be quite variable, compared with that of the sensible heat flux. For the drydown season, an averaging length of 30 km was required to achieve stable statistics, but only 7 km for sensible heat.

In the Boreal Ecosystem-Atmosphere Study (BOREAS) of 1994, surface towers were deployed similarly to HAPEX-MOBILHY. Two study regions of 100-km scale were defined in the Canadian boreal forest, including disturbed areas, lakes, and mixed forest stands. Four flux airplanes flew predetermined transects connecting the fixed towers and extending over a broader range of the heterogeneity of the region (Dobosy et al., 1997; Desjardins et al., 1997). Figure B.16 shows how the uptake of CO_2 varies strongly between active aspens to the west and less productive pine and fir to the east. The three lakes (106.1°W, 105.4°W, and 105.1°W) are marked by their minimal uptake of CO_2. It was found important to the design that these transects be flown repeatedly, since heterogeneity implies multiple populations from which samples are drawn. A single 100 km pass over such a surface may represent an averaging time of 30 minutes, but the sample time over each constituent of the path is considerably less.

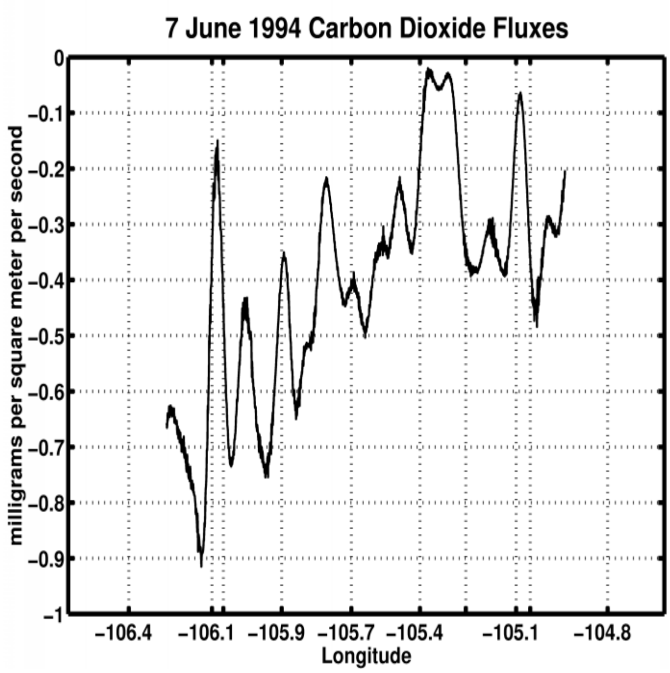

Figure B.16 CO_2 uptake in Sasketchewan during BOREAS, from Long-EZ. Negative values indicate uptake, so smallest uptake is at the top of the plot. Indicated longitude delineates surface cover. Halkett Lake at 106.1°W is flanked by aspen on both sides. Candle Lake at 105.4°W has mixed deciduous and coniferous trees on the west but coniferous trees on the east. White Gull Lake at 105.1°W is flanked on both sides by coniferous trees.

Measurements were made during the Southern Great Plains Experiment of 1997 (SGP97) using two primary flux airplanes. The goal of this experiment was to examine the influence of heterogeneities in soil moisture, as observed by an innovative passive microwave radiometer intended ultimately for satellite use. One important aspect of the study was the effect on the development of the convective boundary layer. The two flux airplanes flew missions at low levels to sample the influence of the surface moisture heterogeneity on the low-level fluxes. This allowed interpolation between measurements at surface towers, located as appropriate in homogeneous subregions. The airplanes, however, were also able to sample near the base of the entrainment zone at the top of the mixed layer, as had Michels and Jochum (1995). Again, repeated passes were important because of the large spatial scale of the motions near the top of the mixed layer (Dobosy and MacPherson, 1999, MacPherson et al., 1999).

Airborne measurements are well suited to remote land areas. Arctic work has been greatly expanded by their flexibility and range (Brooks et al., 1996, Oechel et al., 1998).

Secondary circulations, forming on scales from 10 km to 100 km, can have profound influence on dispersion of admixtures to the air and on the transport of moisture, heat, and momentum. Airborne turbulence measurements are uniquely capable of sampling the flow structures in such circulations as sea breezes and atmospheric frontal structures. Again, it is necessary to make repeated passes over defined lines to ensure proper sampling. (Sun, et al., 1997; Eckman, et al., 1999).

B 6.5 Conclusions

The advent of small specialized flux airplanes has increased the capabilities and greatly reduced the cost of airborne flux measurement. We have found it best to fly as low as possible, repeating the same track as often as possible, when relating observed fluxes to the underlying surface. Fluxes are thus better determined along paths than over areas. Proper choice of the path(s) maximises effectiveness. Today's smaller, cheaper airplanes also make multiple deployments more tractable. Such deployments have been found to be highly effective in the BOREAS and SGP97 experiments.

, not exhaustive, shows a growing number of organisations making airborne flux measurements. The number of new entries with small airplanes shows a potential for a greater availability of low-cost airborne flux measurements. Larger airplanes will remain important for the more unusual or complex measurements, but we expect a growing set of capabilities to be derived from small airplanes as technologies mature.

Table B.4 Organisations making airborne flux measurements

Organisation	Airplane(s)	Size	Example Reference
Airbourne Research Australia	Grob 109	S	Lyons *et al.*, 1993
MetAir (Switzerland)	Stemme S10	S	Neininger *et al.* (1999)
National Research Council (Italy)	Sky Arrow	S	Delivery September 2000
Air Resources Lab (NOAA, USA)	LongEZ	S	Crawford *et al.* (1996)
San Diego State Univ.	Sky Arrow	S	Brooks and Dumas (2000)
University of Lund (Sweden)	Sky Arrow	S	Delivery July 2000
Univ. of Manchester (UK)	Cessna 182	S	Wood *et al.* (1999)
Airbourne Research Australia	Cessna 404	M	Matthews *et al.* (2000)
Institut National des Sciences de l'Univers (France)	Fokker 27	M	Durand *et al.* (1998)
Météo-France	Merlin IV	M	Durand *et al.* (1998)
National Research Council (Canada)	Twin Otter	M	Mailhot *et al.* (1998)
NOAA/ARL	Twin Otter	M	Luke *et al.* (1998)
University of Wyoming	King Air	M	Dobosy *et al.* (1997)
National Center for Atmospheric Research (USA)	Electra C130	L L	Oncley *et al.* (1997) Wang *et al.* (1999)

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B 7 Boundary Layer Budgeting

David R. Fitzjarrald

B 7.1 Introduction

Vigorous mixing in the lower atmosphere is often confined within a relatively shallow planetary boundary layer (PBL), into which the surface fluxes of atmospheric constituents converge. The horizontal scale of mixing - and hence the degree of spatial averaging performed by the boundary layer turbulence - is proportional to the thickness of the layer *h*. This thickness ranges from 100s of metres for stable boundary layers (SBLs) to 1-3 kilometres for convective boundary layers (CBLs). The intensity of the mixing depends on the surface buoyancy flux, and this in turn determines the thickness of the boundary layer. Turbulent mixing at these scales blurs local gradients set up by contrasting land surface types. By using boundary layer (BL) budgets to estimate surface fluxes one exploits the horizontal averaging property of this turbulent mixing. The surface flux is found as a residual; one estimates all transport through the sides and top of the box. The BL budget method is an approach with more advocates than true practitioners. Its potential inspires many to instruct the community on the virtues of the continuity equation, as it is applies to field observations.

The budget method represents an alternative to the recently popular eddy flux tower approach (e.g., Ameriflux, Euroflux) or chamber methods. Fluxes measured from towers are constrained to represent a time-varying area whose diameter in most cases is often less than a kilometre or two, and chambers, which are used to sample tiny surface areas (approximately 1 m^2) (e.g., Mosier, 1989). Artificial stirring is needed to homogenize even such small cham-