THE OASIS EXPERIENCE: COMPARISON OF AIRCRAFT- AND TOWER- BASED FLUX MEASUREMENTS

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ABSTRACT

The OASIS experiment, undertaken in October 1995 in New South Wales, Australia, employed aircraft to estimate the spatial variability of surface-atmosphere exchanges of heat, moisture and CO₂ and to interpolate these variables between a small number of surface micro-meteorological stations. This study describes a comparison between tower-based measurements at one of these sites and aircraft measurements from a number of dedicated low-level flights. Confidence in the surface measurements is assured by the closure of the surface energy budget. Good agreement between the independent measures of mean temperature, wind speed and wind direction was achieved. Aircraft measurements of the standard deviation of the vertical wind speed and absolute humidity show no bias but some scatter compared to the tower measurements while the aircraft standard deviation of air temperature is less than the tower measurement by, on average, a factor of 1.6. Latent heat fluxes from the aircraft appear to be slightly larger than tower values but somewhat scattered whereas the aircraft sensible heat flux clearly underestimates tower values by a factor of 2. Net radiation measured from the aircraft was approximately 20% higher than the tower data. These results are consistent with previous aircraft-surface comparisons. If windtunnel tests confirm our suspicions that the underestimation of temperature variance and sensible heat flux is due to the poor high-frequency response of the aircraft temperature sensor, then the results will demonstrate that aircraft and tower based data are directly comparable provided care is taken with instrument calibrations, response times, and footprint differences.

INTRODUCTION

In recent years, there has been considerable interest in modelling the earth’s climate, mainly to predict its response to increasing levels of greenhouse gases. This has stimulated research into surface-atmosphere exchange processes occurring at scales up to 250 - 500 km, since these are not explicitly resolved by current climate models and must therefore be parameterised. At the same time, research attention has turned away from the examination of exchange processes over homogeneous surfaces, formerly extensively studied because of their ‘relative’ simplicity, to those occurring over more typical, heterogeneous areas. The conjunction of these two interests has led to several large-scale boundary layer experiments, eg. FIFE, HAPEX, concerned with measurements over moderately heterogeneous areas of ~10 to ~100 km², using both aircraft and ground-based systems to provide information on the spatial variability of surface-atmosphere processes. Full utilisation of this data requires assessment of the degree to which data from different platforms agree.

Such an experiment, Observations at Several Interacting Scales (OASIS), was undertaken in October 1995 near Wagga Wagga, New South Wales, Australia. Its aims
were to characterise land-atmosphere exchanges of water, energy and trace gases at regional scales. The experimental domain, comprising a heterogenous landscape of mixed cereal cropping and pastural farming, was some 100 km in linear extent. OASIS was coordinated by scientists from the CSIRO Centre for Environmental Mechanics and involved a number of teams from Australian and New Zealand research institutions. It differed from previous land-atmosphere interaction studies in having a greater emphasis on trace gas and stable isotope exchange (Raupach et al., 1994). Within OASIS, aircraft measurements were employed to estimate spatially-averaged surface fluxes and to interpolate between a small number of ground-based micro-meteorological stations. The current study deals with a comparison of aircraft and ground-based measurements at one of these stations to assess the compatability of aircraft and tower measurements.

Previous attempts at similar comparisons have met with indifferent success. Schuepp et al. (1987) claim some success with CO₂ and latent heat fluxes (λE) while Desjardins et al. (1989) found their aircraft measurements to underestimate ground-based measurements of sensible heat flux (H) by some 58%. The latter claimed that underestimates of this order have been repeatedly observed “and no sources of errors in aircraft flux measurements of sensible heat have been detected to account for this difference.” That the aircraft measurements of both H and the standard deviation of air temperature were underestimated by a comparable percentage suggests there may have been a loss of high frequency information from the temperature measurement but this observation was not noted by the authors. Similar results for aircraft/ground-based comparisons were obtained in FIFE (Kelley et al 1992) and HAPEX-Sahel (Lucotte and Said 1996).

The objective of this paper is to present comparisons of aircraft and surface-based measurements at one site within the OASIS experimental domain. To this end, a series of dedicated low level flights was undertaken in the vicinity of two ground based eddy correlation (EC) systems. By operating at very low heights (~6 m AGL), it was hoped to eliminate the influence of flux divergence with height and to minimise footprint differences between the aircraft and tower-based measurements. Statistical variability in the fluxes was reduced by making repeated passes (10 to 14) over the fields containing tower-mounted EC sensors. Confidence in the surface-based measurements is suggested by closure of the surface energy budget.

**EXPERIMENTAL**

Data presented in these comparisons were recorded near Lockhart, ~50 km west-southwest of Wagga Wagga. The area is flat and devoted to cereal cropping (wheat, oats and barley) interspersed with some pastural farming. Typical field dimensions are ~1 km.

Site layout is indicated in Figure 1. Mean crop heights for the two instrumented paddocks were 1.15 m for the wheat and 1.35 m for the oats. Unlike the oats, the row structure was more clearly evident in the case of the wheat and when looking down from the intrument masts, the underlying soil was still visible through the canopy. Surrounding paddocks were also either in cereals, having similar crop heights, or grazed pasture. The nearest farm buildings and trees were approximately 500 m NW of the experimental site (see Figure 1). There was no irrigation of the experimental site or nearby areas.

![Figure 1: Schematic of Lockhart experimental site showing layout of paddocks, equipment and flight paths of the FIAMS motorised glider. The E/W flight path was 1230 m long and the N/S flight path 1615 m in length.](image-url)
The original intention had been to compare the aircraft data with that from a large aperture scintillometer (McAneney et al. 1995). Unfortunately, the combination of the late arrival of the aircraft and failure of the scintillometer light source the following day meant that there was insufficient overlapping data. Instead, data from the ground based EC instruments installed in support of the scintillometer has been used.

2.1 Ground-based measurements

In the wheat field, EC instruments were mounted at a height of 4.5 m AGL. Instruments deployed were a 1-dimensional sonic anemometer/fine thermocouple combination (Campbell Scientific Inc.), krypton hygrometer (CSI), and a 2-dimensional drag anemometer (Green et al., 1994). A similar suite of instruments, excluding the drag anemometer, were mounted at 2.3 m AGL in the oats field. These instruments provided measurements of fluxes of sensible and latent heat, and friction velocity ($u_*$) with a frequency response of 10 Hz or better. For the latent heat flux, water vapour concentration was derived from the output of the krypton hygrometers and corrected for $O_3$ absorption using the method of Tanner et al. (1993). Raw fluxes were then corrected for density effects following Webb et al. (1980).

A net radiometer (Model Q6.1: Radiation and Energy Balance Systems Inc.) was mounted 1 m above the wheat crop on a tripod some 5 m north of the meteorological mast with a similar instrument mounted above the oats.

Climatological instruments for the measurement of air temperature, wind speed and direction were mounted at a height of 4.5 m on a second meteorological mast in the wheat field (see Figure 1). Away from the base of this mast, two soil heat flux plates (HFT 3.1: REBS) were buried at a depth of 6 cm for estimation of the soil heat flux ($G$) following the method recommended by Watts et al. (1990). Fluxes were corrected for heat storage above the plates with the soil water content in the top 10 cm being measured once daily by Time Domain Reflectometry (Soil Moisture Measurement Corp.), soil temperature measured continuously at 2 and 4 cm, and a differential thermocouple measurement of the undisturbed temperature gradient (ie. away from the flux plates) at 6 cm depth.

Data collection and analysis procedures were the same as those described in previous publications (eg. McAneney et al. 1995). The averaging time for all calculations was 30 minutes with measurements confined to day time hours. Data were rejected for periods of rain; poor angle of attack, major wind shifts, and when net radiation was negative.

2.2 Aircraft Measurements

The aircraft used in this experiment was the Flinders Institute for Atmospheric and Marine Sciences (FIAMS) Grob 109b motorised glider. The three components of the wind field are calculated as the difference between the true airspeed of the aircraft, as measured by a 5-hole probe, and its ground speed in earth coordinates derived from inertial navigation and GPS data. Air temperature is measured by a PT100 sensor, wound from 25 micron wire and mounted in a reverse flow housing. Water vapour concentration was measured using an open-path infra-red gas analyser (IRGA) described by Auble and Meyers (1992). The four components of the radiation budget were measured using Eppley radiometers mounted on the aircraft canopy and beneath the right wing. All other sensors described above are mounted on or near an instrument pod under the left wing. A description of the instrumentation and data processing can be found in Hacker and Schwertfeger (1988).

The low height of the dedicated comparison flights (~6 m AGL) raises concerns about the loss of high frequency information due to finite sensor response times. For an instrument like the IRGA, with a time response of 0.05 seconds, the relatively low airspeed of the 109b, (40 m s$^{-1}$), means that the minimum resolvable wavelength is about 4 m. According to Panofsky and Dutton (1984) (their Figure 8.26), this can be expected to result in a negligible loss of power in the measured covariances at a height of 6 m. Similar reasoning indicates that sensor separation should not contribute significant loss of cospectral information. Additional effects of the low aircraft height, eg. suppression of the wing tip vortices ('ground effect'), are also not expected to significantly influence data presented here.
Nine dedicated flights consisting of 10 to 14 passes, oriented either north/south or east/west, were carried out over 7 days. For the north/south flights, the total flight path was about 1600 m over two wheat fields, the southern most of which contained a ground-based EC system. In the east/west flights, the pass length was about 1200 m, the western extremity of which was pasture, the middle being oats containing a ground-based EC system and the eastern extremity being the wheat field containing the primary EC station. A typical pass lasted 35 seconds with a flight of 10 passes yielding 6 minutes of data spread over 30 minutes.

2.3 Fetch considerations

In order to estimate the extent of upwind source contributions to the various measurements, we utilise the simple expressions given by Schuepp et al. (1990) together with measurements from the drag anemometer in the wheat field. These imply a maximum sensitivity for the wheat-field flux instruments (z = 4.5 m) to source contributions 50 m upwind of the tower and that 50% of the flux originates within a distance of 140 m. Comparable figures for the aircraft measurements are 70 and 390 m.

3. RESULTS & DISCUSSION

Table 1 gives the overall meteorological conditions during the comparison flights where U and D are the wind speed and direction, T is the air temperature, $R_N$ is the net radiation and L is the Monin-Obukhov length. The comparisons took place with stabilities ranging from neutral/slightly stable (19/10/95) to extremely unstable (23/10/95 and 24/10/95). Cloud cover varied considerably from day to day, modulating $R_N$. The air temperature ranged over 15°C with the trend reflecting the passage of a cold front that brought rain to the area on the 20th, 21st and 22nd October.

3.1 Ground-based measurements

The degree to which the energy budget is closed provides a check on the EC measurements. Figure 2 shows that the sum $H + \lambda E + G$ balanced $R_N$ on average, giving confidence in the independently measured energy budget components. The slope of

<table>
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<th>D</th>
<th>T (°C)</th>
<th>$R_N$ (W m(^{-2}))</th>
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Table 1: Meteorological conditions during the comparison flights
regression line is 1.006 and the residual standard deviation about this line is 64 Wm$^{-2}$.

Measurements made over the oats show no significant differences in $R_n$ (slope of regression $0.996 \pm 0.003$) and only small differences in sensible heat ($H_{\text{OATS}} - 0.93H_{\text{WHEAT}}$) (data not shown). Thus for the purposes of energy budget, and in particular for $H$, the two instrumented fields may be regarded as being very similar. For comparison with aircraft covariance
measurements, mean values of the wheat and oats serve as the reference for East-West flights whereas the wheat alone are used for North-South passes. In the case of variances and mean quantities, we employ measurements over the wheat as these were made closer to the height of the aircraft.

**3.2 Aircraft - surface comparisons**

Figures 3 to 11 compare the aircraft and tower based data. On each figure are shown the 1:1 line (solid), the best fit line (dashed), the equation and correlation coefficient of the
best fit, the mean difference ("b") and the root mean square difference ("RMS"). For the standard deviations and fluxes, the statistics are for the best fit line through the origin.

3.2.1 Wind components

Figure 3 shows good agreement between the aircraft and wheat field mean wind speeds (U), but the reason for the bias of 0.4 ms\(^{-1}\) is not known. Figure 4 shows the comparison between the aircraft and tower based measurements of the mean wind direction (D). Apart from three outlying points, all for periods when the wind speed was less than 2 ms\(^{-1}\) and wind direction poorly defined, the agreement is reasonable. Excluding these points reduces the bias from -20 to -9 degrees.

Figure 5 shows that the two estimates of the standard deviation of vertical velocity (\(\sigma_w\)) are in very good agreement with high correlation. The ground-based measurements have been extrapolated to the height of the aircraft using the correction for stability given in Panofsky and Dutton (1984).

3.2.2 Temperature and Humidity

The two measurements of the mean air temperature (T), Figure 6, show a very close correlation but the aircraft measurements underestimate with respect to the tower based by 0.9\(^\circ\)C on average. This small discrepancy is likely to be due to calibration uncertainties and radiation errors for the tower instrument.

The aircraft standard deviation of air temperature (T), Figure 7, attains on average only 60\% of the value recorded by the tower-based fine thermocouple. The most likely explanation for this is the smoothing of high frequency temperature fluctuations by the aircraft temperature sensor due to a slow response time. This would be particularly noticeable here because the flights were carried out at very low levels where more of the turbulent energy is expected to be at higher frequencies. Wind tunnel tests are currently being performed to determine the response time of the temperature sensor used on the aircraft and will be published separately.

No ground-based measure of mean humidity was made but Figure 8 shows general agreement between ground and aircraft measurements of the standard deviation of absolute humidity (q). Whilst the scatter is reasonably large, there is no significant bias in the comparison. This supports the hypothesis that the underestimation observed in the \(\sigma_T\) comparison is due to the temperature sensor response time, since that for the water vapour instrument, used on the aircraft, is known to be short, typically 0.05 second, (Auble and Meyers, 1992).

3.2.3 Net Radiation, Sensible and Latent Heat Fluxes

Where appropriate, tower based values of net radiation, sensible and latent heat fluxes have been calculated as weighted composites of adjacent time periods (N/S and E/W passes) and data from instruments in the ots and wheat fields (E/W passes only).

Figure 9 shows the net radiation (R\(_n\)) comparison where the aircraft values are about 20\% greater than those from the ground based instruments. This could be due to small errors in the calibrations of either instrument suite, although the closure, on average, of the energy budget by the ground based observations suggests the problem lies in the aircraft data. The degree of scatter is reassuringly small, given the cloudy conditions (see Table 1) that prevailed for most of the comparison flights.

The sensible heat flux (H) comparison, Figure 10, shows that the aircraft values
underestimate those from the tower based instruments by about a factor of two. This substantial underestimate is consistent with, but slightly larger than, the aircraft underestimate of $c_r$, evident in Figure 7 and again is felt to be mainly due to an inadequate temperature sensor response time combined with a loss of low frequency contributions due to the method of processing the aircraft data, see below. The latent heat flux ($\lambda E$) comparison, Figure 11, shows considerable scatter but with general agreement between the ground based and aircraft data. Outlying points, indicated by open circles, correspond to measurements underneath broken cumulus cloud cover. Without these, the aircraft appears to slightly overestimate with respect to the ground based data.

3.2.4 Effect of aircraft data processing

To obtain a single value for aircraft data for each multiple pass flight, the overall covariance was estimated as the mean of the covariances for each pass plus the covariance of the pass means. However, during the processing of the aircraft data, the mean vertical wind speed is set to zero for each pass, in accordance with standard techniques (Lenschow 1986). This is done because alignment errors, flow distortion and inertial navigation system offsets lead to small but potentially overwhelming mean wind vertical velocity values from aircraft data. Normally, this practice leads to little error when used over long (> 5km) aircraft flights since the mean wind vertical velocity in the boundary layer is close to zero when averaged over sufficiently long times or distances. While the aircraft passes used here were very short, typically 1200 to 1600 m, it is felt that the extremely low height of the passes justifies a similar assumption.

This setting of the mean vertical wind speed to zero for each pass also forces the second term in the compositing of the fluxes, the covariance of the means, to zero. This is the same as applying a high pass filter to the fluxes, with a cutoff equal to the pass length, between 1200 and 1600 m in our case. According to Panofsky and Dutton (1984), this is expected to lead to a loss of between 8 and 25% of cospectral information and consequent underestimation of the fluxes. While this may explain part of the underestimation of $H$ by the aircraft, it is not consistent with the small overestimation of $\lambda E$ by this platform. It is possible, however, that these larger values of $\lambda E$ result from higher evaporation rates from the non-instrumented fields sampled by the aircraft.

It is important to remember that the above applies only to the covariances because of the practice of forcing the mean vertical wind speed to zero for each pass. With variances composited from the mean of the pass variances plus the variance of the pass means, the short pass length is not expected to lead to bias in the variances, only to an increase in scatter.

**SUMMARY**

This experiment was undertaken to ascertain the degree of agreement between aircraft and ground based measurements of micro-meteorological variables during the OASIS experiment of 1995. Complications due to flux divergence and footprint differences were minimised by making the aircraft measurements close to the height of the tower instruments and repeatedly flying over the same fields. Closure of the surface energy budget gives confidence in the surface flux measurements, at least to the degree that the instrumented fields are representative of the surrounding areas seen by the aircraft.

The results suggest that under carefully controlled conditions where height and footprint differences have been minimised, aircraft and tower-based mean wind speeds can be expected to agree to within 0.5 ms$^{-1}$, directions to within $10^\circ$, temperatures to within 1.0°C and net radiation to within 20%. These limits, particularly the last two, can probably be reduced by more careful calibration of aircraft and tower-based sensors.

Comparison of the standard deviations of vertical velocity and absolute humidity show little bias but some scatter with RMS differences of 0.07 ms$^{-1}$ and 0.35 gm$^{-3}$ respectively. Similarly, latent heat fluxes are in general agreement but somewhat scattered with an RMS difference of 46 Wm$^{-2}$. In this experiment, the aircraft underestimated the standard deviation of temperature and sensible heat flux by about a factor of two. This is likely due to an inadequate sensor response time, a hypothesis which is currently being checked. Analogy with the water
vapour measurements suggests that at these heights (~6 mAGL), response times of the order of 0.05 seconds are required.

Even with perfect sensors, agreement between aircraft and tower-based measurements is limited by the conflicting requirements of minimising footprint differences while still ensuring adequate averaging lengths. In this study, the averaging length for the aircraft fluxes was only 1200 to 1600 m but still results in the aircraft sampling air influenced by an area roughly 10 times that influencing the tower instruments, so even small scale differences between adjacent fields will bias any comparisons. This serves as an important reminder of the limited extent to which tower based measurements represent their surroundings.

REFERENCES


