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An Airborne Study of Boundary Layer Heat and Moisture Fluxes for Project FIFE

Final Report

Robert D. Kelly
Principal Investigator

Department of Atmospheric Science
University of Wyoming
P.O. Box 3038
Laramie, Wyoming 82071–3038

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1. Introduction

This document is the final report describing the University of Wyoming participation in project FIFE, under NASA Grant NAG 5–913.

Following is a brief summary of work accomplished during the First ISLSCP Field Experiment. More detailed descriptions may be found in previous status reports and in the publications and presentations listed in the final section of this report.

2. 1987 Field Operations

The Wyoming King Air participated in IFCs 3 and 4 in 1987, committed to a combination of airborne sensible and latent heat flux measurements and soil moisture mapping with the University of Kansas X–band SLAR (side–looking airborne radar). [See any reports from Gogineni, University of Kansas, for results from SLAR.] In all, 9 flux missions were flown, using several different flight designs. The simplest of these were vertical stacks of horizontal passes along a fixed flight path, allowing construction of flux profiles and extrapolation estimates of surface fluxes. As the experiment progressed the flight designs were changed, first to allow removal of time trends in the flux data, and then to allow full analysis of boundary layer heat and moisture budgets.

A critical decision in the first round of aircraft flux analysis, agreed to by all the flux aircraft investigators, was to pass the aircraft data through a high–pass filter prior to the eddy–correlation flux calculations. The reasoning here was as follows: Since flight legs in FIFE were limited to 15 km, and since many convective structures in the upper 2/3 of an inversion–topped boundary layer have horizontal scales of 5–10 km (Kelly, 1984), we felt that the longer wavelengths of flux would be noticeably undersampled. Such undersampling can and will lead to sizeable errors (+ or –) in flux estimates. The decision to high–pass filter the data, with a cutoff wavelength of 5 km, was simply an attempt to reduce the magnitude of the errors (+ and –) imposed by the relatively short flight legs. Thus, the first round of studies and publications using the aircraft data were based on the filtered data.

3. Submission of data to the FIFE archive (FIS)

Data from the flux flights of 1987 have been submitted to FIS twice. In the first submission all the eddy correlation fluxes and related statistics were based on data after it had been passed through the 5–km high pass filter. The second submission contains fluxes and related statistics based on three different treatments of the time–series data: 1) unaltered, 2) linearly detrended, and 3) high–pass filtered.

4. Boundary layer budget analysis

Full boundary–layer sensible and latent heat budgets were examined using data from the Wyoming King Air and the NAE Twin Otter for three cases from 1987 (20 Aug., 8 and 13 Oct.), and published by Betts, Desjardins, MacPherson, and Kelly (1990). In these cases, both budget estimates and profile extrapolations of surface sensible heat flux were about 40% below the site–wide average surface flux measurements reported for corresponding periods. Estimates of surface latent heat flux were, similarly, about 30% below the site–wide average surface measurements. Initial suggestions were that the discrepancies between the aircraft estimates and surface measurements could have resulted from several sources, including 1) undersampling of short–wavelength fluxes, and 2) loss of information on the long–wavelength fluxes due to the short flight legs or the filtering or both.

At some time following publication of this paper, it was discovered that most of the surface flux measurements, as archived and as used in the budget comparison, were too large. The combined surface sensible and latent heat flux measurements from 13 of the 16 Bowen ratio sites were subsequently revised downward by approximately 10%, after a new calibration of the reference net radiometer applicable to those 13 sites.

5. Objective analysis of BL advection

As was noted in the first budget analysis publication (Betts *et al.*, 1990), significant errors are expected in measuring the horizontal advection terms of the boundary layer sensible and latent heat budgets. Such errors stem from several sources, including: 1) the short (15 km) flight legs used in FIFE, so that horizontal gradients of temperature and water vapor mixing ratio are very small, 2) the effects of local terrain features, and 3) changes in all variables that occur during the time needed for aircraft measurements (e.g., 1.5–2 hours for budget flights). This question was examined further by estimating the horizontal advection of heat and moisture over the FIFE site using objective analysis of NWS radiosonde data from the region around FIFE and comparing these estimates with the advection terms measured by the aircraft. The detailed results were presented in status report 5 (Sept. 1989) for two cases (20 Aug. and 8 Oct.).

Briefly, the advection terms were calculated as

$$SH = \bar{\varrho} C_p \vec{v} \cdot \vec{\nabla}\theta \text{ and } LH = \bar{\varrho} L_v \vec{v} \cdot \vec{\nabla} r,$$

where θ is the potential temperature and r is the water vapor mixing ratio. The objective analysis and aircraft values of SH and LH are listed in the table below.

Source	SH	LH
Obj. anal., 8 Oct.	–0.113 W m^{-3}	–0.0724 W m–3
King Air, 8 Oct.	0.90	—
Twin Otter, 8 Oct.	0.005	–0.226
Obj. anal., 20 Aug.	–0.142	0.317
King Air, 20 Aug.	0.029	—
Twin Otter, 20 Aug.	0.025	–0.101

On both days the regional wind directions and temperature gradients indicate positive sensible heat advection (SH<0), as shown by the objective analysis but not by the aircraft. Similarly, the objective analyses of latent heat advection agree with the regional patterns, whereas the aircraft values are of different sign and/or magnitude.

These discrepancies remain largely unresolved. There were no measurements available during FIFE on a spatial scale between that of the 15–km FIFE site and the 400–km spacing between the NWS radiosonde sites or on a time scale corresponding to the FIFE experiments. Thus, it is not possible to decide whether or not the discrepancy was due to errors in the aircraft measurements, local effects over–riding the regional trends, or some other cause. It is only hoped that future, similar experiments can include measurements at these intermediate scales, since horizontal advection is an important component in BL budget analysis.

6. Comparison of aircraft and surface measurements for all 1987 flux profiles

As noted in section 3, the BL budget studies for 3 cases in 1987 showed aircraft estimates to be 40% and 30% less than the surface measurements for sensible and latent heat fluxes, respectively. Correction of the errors found in the Bowen ratio stations then reduced these numbers to about 30% and 20%, respectively.

A more exhaustive examination of aircraft and surface measurements was then undertaken in order to compare fluxes measured at the surface, calculated as area– and time–averages of the data collected at the surface stations, with values extrapolated from BL flux profiles determined by the aircraft. These extrapolations were accomplished by simple linear regression of flux against height above the surface, based on aircraft fluxes measured over repeated, constant–altitude flights at 2–4 levels in the BL. In all, 32 profiles were analyzed for the period June 26–October 13, 1987, which encompassed IFCs 2–4, using data collected by the Twin Otter and the Wyoming King Air. The surface data from as many as 22 surface stations, corresponding to the times of the aircraft profiles, were taken from the continuous set of surface data, provided by several different scientific groups. This comparison was carried out for two complete sets of aircraft fluxes: those in which the time series had been detrended and those in which the time series had been high–pass filtered.

Several general conclusions were drawn from this study:

1. BL profiles of sensible and latent heat fluxes from FIFE were usually linear, in agreement with theoretical predictions (Lenschow, 1974) and other observations in convectively active BLs (Stull, 1988).

2. High–pass filtering applied to the aircraft data apparently did not add to the disagreement between the profile–predicted and surface average fluxes, although this was mentioned as a possibility in previous analyses (see section 3). However, high–pass filtering did have the intended effect of reducing the uncertainty associated with measurements of long–wavelength fluxes, thus reducing the scatter and increasing the linearity of the flux profiles without changing the magnitude or sign of the general disagreement.

3. Drawing on results from other projects (Kaimal *et al.*, 1976), undersampling by the aircraft at high frequencies could have accounted for as much as a 15% underestimate of the surface fluxes. Drawing on the disagreements quoted above, this would leave unexplained differences of about 15% and 5% for the sensible and latent heat fluxes, respectively.

4. The disagreement between the aircraft and surface latent heat fluxes changed sign between the summer and fall. This may have been due to changes in patterns of evapotranspiration and to a change in the error of of the surface flux values.
5. Neither the magnitude nor the sign of disagreement between the aircraft and surface fluxes varied systematically with BL depth or with the height of the aircraft profile.
6. Bowen ratios from both detrended and filtered aircraft data agreed with surface values much better for the moist, summer cases (IFCs 2, 3) than for the dry cases (IFC 4).

Several different possible sources of error in flux measurement have been examined. It is worth noting that it is unrealistic to assume that even 10% agreement between the two sets of values could be ever be achieved, given the fact that the 15–km flight path lengths used in FIFE will lead to uncertainties much greater than 10% in estimates of the long–wavelength fluxes (Lenschow and Stankov, 1986). The most plausible explanation for the remaining 5–15% disagreement would be undersampling at long wavelengths and uncertainties in the surface averages due to variations in terrain and vegetation.

7. Participation in 1989 field operations (IFC 5)

This investigator participated in the IFC 5 field operation in 1989, with responsibilities for providing operational weather forecasts and in the design of flux aircraft operations. The forecasting experience is summarized in a conference presentation (Prater and Kelly, 1990).

Processing of the 1989 King Air data has been completed for three cases, which will form the core of a BL budget analysis similar to that presented by Betts *et al.* (1990). The cases of interest are 27 July, with a "+" shaped flight pattern; 6 August, with a "T" shaped pattern; and 7 August, with an "L" shaped pattern over the FIFE site. In all three cases the double stacks of horizontal passes were arranged in a time–centered sequence, to allow removal of time trends from the data. The primary difference between these flights and the time–centered "double stacks" used in 1987 is that both N–S and E–W legs were included, so that gradients of temperature, humidity, wind, etc. for both directions can be determined with the same degree of error. Another important difference in the present analysis is that the aircraft fluxes will be based on detrended, but unfiltered, time series of the various variables.

In general, the flux profiles from 1989 were consistent with what one would expect to see in a clear–sky boundary layer over a vegetated surface. The sensible heat fluxes were positive (>100 W m^{-2}) at the surface, and decreased almost linearly with height, to become negative near the top of the BL. The latent heat fluxes was similarly positive at the surface and but constant with height through the BL. These data have also been examined for the effects of filtering (see status report of 31 July 1991).

8. Other responsibilities

Besides participating in the 1987 and 1989 field operations, as director of Wyoming King Air operations in 1987 and as forecaster and ABL group member in 1989, this investigator also served as the chairman of the ABL focus group from 1988 through 1992. Responsibilities stemming from this position included preparation of ABL group reports at and following each of the FIFE workshops and field operations planning sessions, coordination of ABL data submissions to the FIFE Information System (decisions about data formats, etc.), several "general" presentations and one publication reviewing and summarizing the ABL research efforts in FIFE, and coordination and review of the ABL group submissions for the upcoming JGR issue dedicated to FIFE.

9. Continuing analysis

Further study planned includes 1) continued spectral and cross–spectral analysis of the 1987 and 1989 data, to further quantify the origins of the aircraft–surface differences noted in the 1987 results, and 2) finishing the budget analyses of the 3 time–centered flights conducted in 1989.

10. Publications and presentations to date

Betts, A. K., R. L. Desjardins, J. I. MacPherson, and R. D. Kelly, 1990: Boundary layer heat and moisture budgets from FIFE advection studies. *Bound. Layer Meteor., 50,* 109–137.

Betts, A. K., R. L. Desjardins, J. I. MacPherson, and R. D. Kelly, 1989: Boundary layer heat and moisture budgets. Spring 1989 meeting of Amer. Geophys. Union, May 7–11, 1989, Baltimore.

Betts, A. K., R. D. Kelly, and R. L. Desjardins, 1989: Boundary layer energy and heat budgets in FIFE. AMS Symposium on the First ISLSCP Field Experiment (FIFE), 70th AMS Annual Meeting, Feb. 7–9, 1990, Anaheim, Calif.

Kelly, R. D., 1990: Design and operation: Atmospheric boundary layer studies in FIFE. AMS Symposium on the First ISLSCP Field Experiment (FIFE), 70th AMS Annual Meeting, Feb. 7–9, 1990, Anaheim, Calif.

Prater, E. T., and R. D. Kelly, 1990: Weather forecasting for FIFE operations: Approach, problems, and recommendations. AMS Symposium on the First ISLSCP Field Experiment (FIFE), 70th AMS Annual Meeting, Feb. 7–9, 1990, Anaheim, Calif.

Kelly, R. D., and E. T. Prater, 1990: Field use of Unidata PC–McIDAS in project FIFE: An evaluation. Sixth Intl. Conf. on Interactive Information and Processing Sys. for Meteor., Ocean., and Hydrology, Feb. 5–8, 1990, Anaheim, Calif.

Kelly, R. D., E. A. Smith, and J. I MacPherson, 1991: A comparison of surface sensible and latent heat fluxes from aircraft and surface measurements in FIFE 1987. Accepted for publication in the *J. Geophys. Rsch.* special issue.

Kelly, R. D., 1991: Atmospheric boundary layer studies in FIFE: challenges and advances. Accepted for publication in the *J. Geophys. Rsch.* special issue.

MacPherson, J. I., R. L. Grossman, and R. D. Kelly, 1992: Intercomparison results for FIFE flux aircraft. Accepted for publication in the J. Geophys. Rsch. special issue.

11. Other references

Kaimal, J. C., J. C. Wyngaard, D. A. Haugen, O. R. Cote, and Y. Izumi, Turbulence structure in the convective boundary layer, J. Atmos. Sci., 33, 2152–2169, 1976.

Kelly, R. D., 1984: Horizontal roll and boundary–layer interrelationships observed over Lake Michigan. *J. Atmos. Sci., 41*, 1816–1826.

Lenschow, D. H., Model of the height variation of the turbulence kinetic energy budget in the unstable planetary boundary layer, J. Atmos. Sci., 31, 465–474, 1974.

Lenschow, D. H., and B. B. Stankov, Length scales in the convective boundary layer, J. Atmos. Sci., 43, 1198–1209, 1986.

Stull, R. B., An Introduction to Boundary Layer Meteorology, Kluwer Acad. Pub., Boston, Mass., pp. 97–104 and 368, 1988.