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SEPARATING THE CORN FROM THE BEANS: CONDITIONAL SAMPLING FROM AIRBORNE TURBULENCE MEASUREMENTS TO ASSESS THE CONTRIBUTION OF INDIVIDUAL COMPONENTS TO THE BULK FLUX.

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1. INTRODUCTION

Ecosystem models and the real atmosphere each aggregate air-surface fluxes as some sort of weighted average of the contributions from each type of surface present. Getting these weights to match is one of the major challenges of ecosystem modeling. For example, patches of contrasting surface can influence each other's microclimate in ways that affect fluxes and that vary with conditions (Anderson *et al.*, 2003). Models must account for this. Direct measurement of the fluxes' heterogeneity over multiple landscapes under multiple conditions is thus an important contributor to models' evolution. Early in the history of airborne eddy-correlation measurements, the allure of reducing the sampling lengths to the level of homogeneity led to shortened definitions for the base state's length. Grossman (1992) found such analysis to miss the larger scales of turbulence to the detriment of accuracy. Yet agricultural landscapes usually have fine-scale granularity. Crops strikingly different in their characteristic air-surface exchange can inhabit neighboring fields. Of central Illinois's two dominant crops, corn absorbs CO_2 in early summer at twice or more the rate of soybeans. Thus the challenge and allure remain. We present in this paper a sampling concept that we call the "flux fragment" method. This method looks promising for representing the small-scale heterogeneity often present in agricultural landscapes.

The eddy-correlation technique splits a flow into two parts, a deterministic base state component and a stochastic eddy component, deterministic only in bulk. The flux is the net transport by the eddies; it is the covariance between fluctuations in velocity (usually vertical) and in the transported scalar. The landscape's heterogeneity can have important deterministic influence if its scale is much greater than that of the boundary layer's turbulence or if it contains such strong contrasts as between land and water. One must always be careful, however, to make a complete sample of the boundary layer's larger stochastic components. Grossman (1992), for a flight altitude of 150 m, recommended defining the base state as a trend over at least 15 km.

The notion to separate pieces out of a time series of airborne measurements for eddy correlation has been around for a long time. LeMone *et al.* (2003) recently analysed airborne flux data from Kansas using averaging lengths from 1 km to 4 km to tease out the data's spatial and temporal variations. They addressed the larger turbulence scales by defining the base state to be the trend over entire flight paths, considerably longer than the averaging lengths they used to analyse the heterogeneity. Over the relatively large fields of rural Kansas straight flight paths of acceptable length were possible. Over the denser population of central Illinois obstacle avoidance requires polygonal paths such as shown in Figure 1. The requisite turns between segments introduce gaps of up to five minutes' length in the datastream, fluxes not being reliably measured in turns. Thus forced to deal with intermittent data, we found conditional sampling to be a natural extension, clearly useful to our pursuit of separately identifying component fluxes in a landscape of small-scale (500 m) heterogeneities.

2. FLUX FRAGMENT METHOD

The fundamental hypotheses of the our flux fragment method are

1. The organized mesoscale features are minimal or can be captured by proper definition of the base state
2. Selecting individual blocks from a

Figure 1: Flight track used in 2005 June in Illinois. Towers have eddy-correlation flux measurement

time/space series (*i.e.,* a flight transect) without regard for where they occur is still capable of capturing the large-scale features of the turbulence.

3. A few surface types (corn and beans in Illinois) are apportioned roughly equally and account for the bulk of the land cover of the study region

At our flight altitude 20 m above ground level (AGL), eddies affecting vertical mixing are smaller than those at 150 m AGL considered by Grossman (1992). Although the base state may thus have shorter length, we found it convenient to use a full transect, about twenty minutes. The trend was a low-order polynomial fit by least squares to the data as a function of path length through the air, a total of 50 km. Using path length instead of time accounts for variations in the airplane's true airspeed (Crawford *et al.* 1993). As a function of path length the data appear in bunches corresponding to the segments seen in Figure 1. The turns between segments appear as gaps, during which a constant airspeed is assumed. Early-morning warming and moistening of the boundary layer, and its depletion of CO_2, accounted for the strongest trends. However, the trend was not simply linear. Especially in the early-morning flights a cubic polynomial better fit the trend hinting at some mesoscale activity, of interest but not yet identified.

The flux fragments themselves are integrals with respect to the path length of products , of velocity's departure from the base state with departure values of a scalar Q. They each have one second's data, nominally 40 m of flight path. Integration is through the air, not over the ground because the turbulence is only loosely linked with the ground. They are integrals, not averages, to facilitate their accumulation into samples selected according their associated surface type or some other condition. Dividing by the sample's accumulated length provides the estimator of the ensemble average. As additional information about of the sample's character, the integrals of the individual departure quantities themselves are included among the flux fragments. In a valid sample these add to zero within acceptable limits. Further discussion is given below.

Each fragment includes information from all scales of the turbulence, since it is comprised of departures from the overall base state. LeMone *et al.* (2003) note the concentration of flux by large eddies. Other parts of large eddies disperse the flux. A proper estimate of the ensemble-average flux requires a sample large enough to ensure proportional representation from all parts of the larger eddies, yet not so large as to include members outside the ensemble. The most straightforward sample is simply all fragments in sequence over the time defined by the base state. Except for the gaps this is the standard Reynolds average. All sums of departure quantities are exactly zero by construction. More generally, the fragment technique facilitates conditional sampling.

The condition for the current sampling is the nature of each fragment's area of influence (footprint) on the upwind ground. The simplified footprint model of Kljun *et al.* (2003) provides a crosswind integral of the probability distribution at each point along the centerline of each fragment's footprint. Typically this line crosses fields of both corn and beans. For each point along the line we define an indicator function for corn, unity if the point is in corn, zero otherwise. Likewise we define an indicator function for beans. Integrating each indicator function along the footprint's centerline, weighted by the crosswind-integrated probability of influence yields a number between zero and one for each surface type. These numbers express the likelihood that each surface influenced this fragment. A tradeoff is then possible between likelihood of influence by a given surface and sufficiency of sample size. For the 2005 data from Illinois 70% likelihood was chosen, by which nearly half of the fragments associated with beans and nearly half with corn.

The regularity of the landscape minimizes, though does not eliminate, mesoscale organizations. Operating away from fronts, squall lines and the like helps further. The patchwork nature of the heterogeneity makes hopeless the shorter averaging lengths that might show promise for flight at 20 m over such broader-scale heterogeneity as Oklahoma's (*e.g.*, LeMone *et al.,* 2003). Yet the same patchwork is an invitation to a conditional sampling scheme.

3. DID WE GET A PROPER SAMPLE?

Lenschow *et al.* (1994) derived estimates of what constitutes a sufficient sample for airborne flux measurements, based on the integral scale of the turbulence. Spatial samples sufficiently long compared to this scale incorporate sufficient degrees of freedom to approximate ensemble averages. If a single pass over a path is insufficient, repeat passes over the same path may be combined so long as the total time does not exceed about 10% of the diurnal cycle.

We have not yet applied this test to the current data because estimating the integral scale of the turbulence is not straightforward. Fourier transforms, the normal tool for this estimation, are intolerant of gaps. The multi-resolution decomposition discussed by Howell and Mahrt (1997) may be able to address the issue.

Table 1: Reynolds-Average Check Values
2006 June 18

Run	avg(w')	avg(Th')	avg(LH')	avg(A')	
A12	5%	13%	26%	-34%	Corn
	3%	2%	-7%	9%	Beans
A34	5%	9%	20%	-28%	Corn
	6%	1%	9%	19%	Beans
B12	-3%	-4%	9%	-23%	Corn
	7%	19%	-3%	16%	Beans
B34	-8%	-1%	11%	-21%	Corn
	14%	15%	1%	10%	Beans

Another test of adequate sampling is to compare with independent estimates derived from samples recognized to be sufficient. Here we present the data from 2005 June 18 beginning just after sunrise and continuing nearly to local noon. These are plotted in Figures 2 - 4 along with traces of daytime fluxes measured at three towers, two in beans and one in corn. The tower in corn and one of the towers in beans (green line in the figures) are located at the point marked “Tower” midway along the flight track in Figure 1. The second tower in beans is at the east end. The match for CO_2, latent heat, and sensible heat is remarkable, both in bulk flux and in fluxes derived from conditional samples in corn and beans. The most striking difference between corn and beans is, as expected, in CO_2 flux. Latent heat flux does not much distinguish corn from beans whether measured from tower or airplane. Curiously, the towers' sensible heat flux hardly distinguishes corn from beans, but the airborne sensible heat fluxes are clearly stronger over beans once the sun gets up. This is plausible given the considerably larger leaf area index for corn in mid-June. Beans had not yet closed their canopy leaving some bare soil exposed.

Table 1 lists the averages of the relevant departure quantities for these flux estimates. The designations ”A” and “B” indicate morning and midday flights. Each flight has four passes over the path in Figure 1. For the conditional sampling the passes are taken in pairs. The averages are reported relative to a measure of the variability of the particular departure quantity: vertical motion, temperature and so forth. Explicitly they are a percent of the standard deviation. Zero indicates that the subsample for corn or for beans drew as many positive departures as negative. The mean over all departure quantities in all fragments is zero by definition.

In Table 1 the corn samples in all four runs exhibit more CO_2 depletion relative to the average over all fragments, while the bean samples exhibit less CO_2 depletion than the average over all fragments. In latent heat content the corn samples’ values are biased above the average, while the bean samples’ values tend to be below or about the same as the average. In potential temperature, the corn samples for the mid-

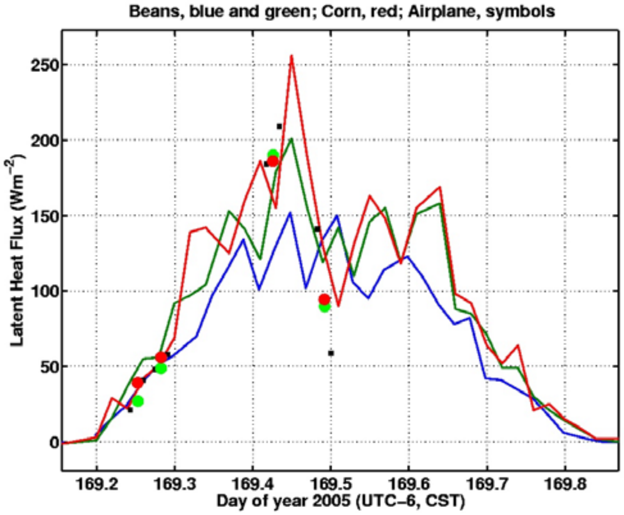

Figure 2: Latent heat flux at towers and airplane. Red and green traces both come from midway on the track in Figure 1. Blue is at the east end. Black spots are the airplane's bulk fluxes. Red spots are corn, green are beans.

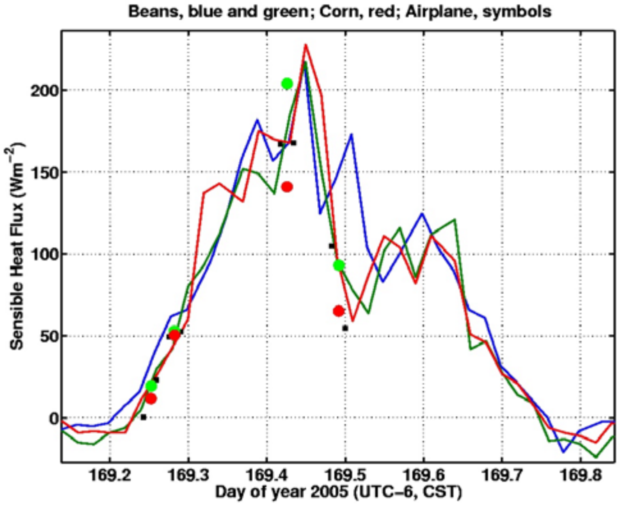

Figure 4: Sensible heat flux, otherwise same as Figure 2.

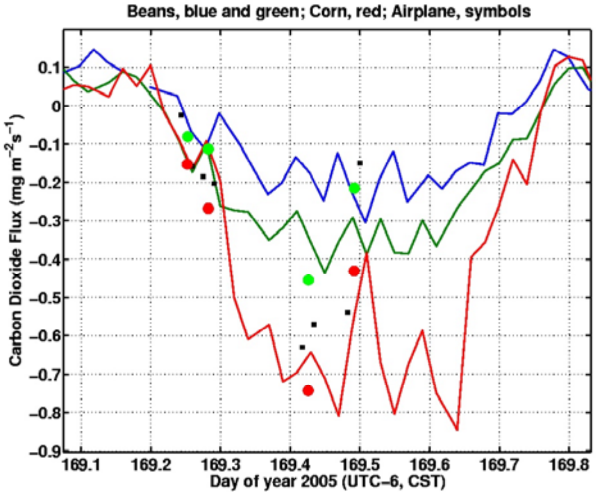

Figure 3: Carbon Dioxide flux, otherwise same as Figure 2.

day runs have a warm bias relative to the average over all fragments. These results are consistent with the plots and give promise of the ability to identify the origin of a sample of fragments by its mean departure values. Such ability is useful to assessing the validity of a footprint model. If one candidate's "corn" sample has greater CO_2 depletion on average than another, it is evidence to favor that model's footprint estimates because we expect greater CO_2 depletion in air which has come from corn.

4. IMPLICATIONS

An inference from the apparent success in discerning corn from beans in the airborne data is that the flight altitude was well below the blending height (Claußen, 1995, Mahrt, 2000). This promises an opportunity to explore the mechanism of obliteration of horizontal heterogeneity in the real atmosphere's mixing. Except for Mahrt's (2000) work over Oklahoma, this concept is primarily derived from models. Opportunity to sample fluxes both below and above the blending height in the atmosphere allows treatment of some significant questions. How are footprint models useful for airborne measurements at altitudes where the signal of horizontal heterogeneity has been lost from the fluxes? Can flux measurements be valid and useful estimates of air-surface exchange when made sufficiently high in the boundary layer (maybe 150 m) to allow regional samples of flux? Many questions surround such samples. This situation promises a relatively simple case minimizing the influence of factors other than the obliteration of horizontal signal with height.

Besides its utility to blending height studies, this set of data provides opportunity to test the flux fragment technique in its native setting before expanding to less favorable conditions to test its resilience to departure from its hypotheses.

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