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IMPROVED TURBULENT FLUX CALCULATIONS

Dean Vickers* and L. Mahrt
Oregon State University, Corvallis, OR

1. INTRODUCTION

Eddy correlation flux calculations from tower data require the researcher to choose a time scale τ (or a length scale for aircraft data) to represent the local time mean. The calculated flux includes all scales of motion from the smallest resolved by the instrumentation up to the specified averaging time scale τ, and therefore, the calculated flux depends on the choice of τ. Since the atmosphere typically contains motions and coherent vertical transports (fluxes) on a wide range of time scales, the selection of τ is not always straightforward. The choice of τ varies in the literature, where a typical value is 30 minutes. Differences in τ may contribute to some of the differences between studies, especially for the stable boundary layer. The choice of τ may be influenced by the goal of the particular research. For example, while studying similarity relationships, one might attempt to remove all non-turbulent contributions to the fluxes, while for balancing surface energy budgets one might want to include heat fluxes at larger time scales, regardless of their origins.

The scale dependence of the flux often reveals a cospectral gap region that separates the turbulent scales of the cospectra from the mesoscale transport (Smedman and Högström, 1975). These mesoscale types of flow can include deep convection, large roll vortices and local circulations due to topographical or surface heterogeneity. In stable flows, mesoscale motions can include internal gravity waves, drainage flows and other less well known motions. Mahrt et al. (2001) found a spectral gap delineating turbulence and mesoscale motions by examining spectra (variances) of the wind components for a variety of different tower data sets.

Mesoscale motions do not obey similarity theory and are poorly sampled on time scales of a few hours or less (Mahrt et al., 2001), and including mesoscale transport in calculated fluxes potentially degrades similarity relationships (Smedman, 1988). This degradation is expected to be most significant for stratified conditions, where the turbulent fluxes are small and inadvertent inclusion of the mesoscale contribution can dramatically change the magnitude and even the sign of the calculated flux.

In this study, apply multi-resolution decomposition to turbulence data to identify the cospectral gap region. A simple height and stability dependent model is developed to predict the gap time scale. We compare fluxes and similarity relationships using the new gap scale model to those calculated using the traditional approach of a constant averaging time scale.

2. DATA

The primary tower data is from the Cooperative Atmosphere-Surface Exchange Study - 1999 (CASES99) grassland site in Kansas, USA, during October. This data set includes sixteen different sonic anemometers of either Campbell CSAT or ATI K-probe design, deployed on nine different towers tightly clustered in a circular region of diameter 600 *m* centered on a main 60 *m* tower. The sonics were deployed at a number of vertical levels ranging from 0.5-55 *m* above ground. Auxiliary tower data sets include: *a)* three Kaijo Denki sonic anemometers at 2, 10 and 20 *m*, and a Gill Solent sonic at 7 *m* above ground over a low heather canopy in the Borris Moor of Jutland in Denmark for one week in July 1995 (BORRIS95), and *b)* two ATI K-probe sonic anemometers at 3 and 10 *m* above Kansas grassland during March 1995 (MICROFRONTS). We use the auxiliary tower data sets to test the generality of the conclusions based on CASES99 results.

For the purpose of characterizing the stability dependence of the cospectral gap scale in the next section, we prefer the bulk Richardson number to z/L. R_b is calculated independent of the fluxes, while the Obukov length L is defined by the fluxes. A bulk Richardson number is calculated as

$$R_b = \frac{(\theta_z - \theta_{sfc})gz}{\theta_z U_z^2} \qquad (1)$$

with $z = 15$ *m*, θ_{sfc} the surface radiative temperature, and where all quantities are 1-hour time averages. Using surface radiative temperature measurements over land is often problematic due to irregularities in surface cover and differences between the the radiometer footprint and the flux footprint. However, in CASES99, these problems are reduced by averaging the radiative temperature

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**corresponding author address:* Dean Vickers, College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR; *email*: vickers@oce.orst.edu

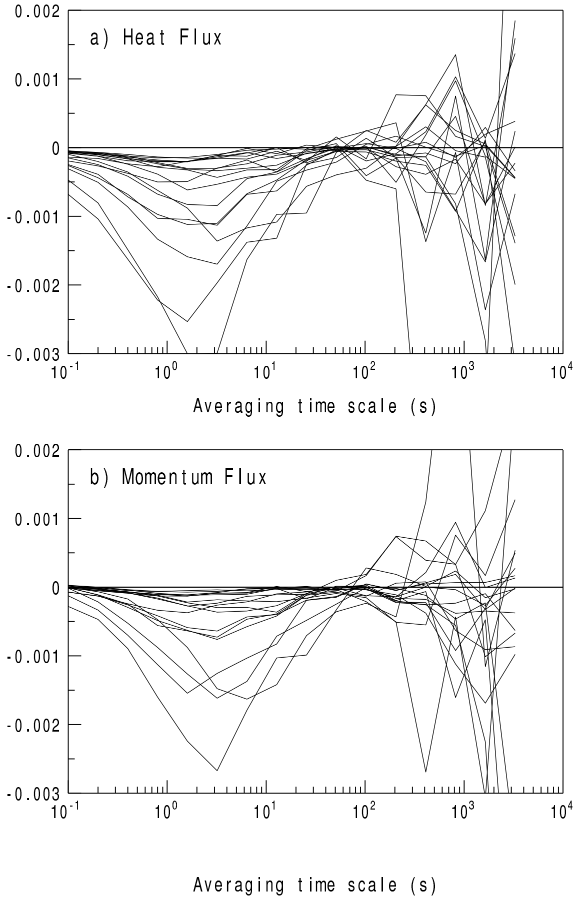

Figure 1: Averaging time scale dependence of the a) sonic heat flux ($ms^{-1}C$) and b) alongwind component of the momentum flux (m^2s^{-2}), for CASES99 5-m sonic data for 18 stable one hour periods on 12 nights.

estimates from six different locations all with similar surfaces (grassland). U_z is taken as the vector average wind speed and θ_z from an aspirated and shielded temperature measurement.

3. COSPECTRAL GAP SCALE

The cospectral gap scale was examined by studying multi-resolution cospectra of the momentum and heat flux for each 1-hour period. Unlike Fourier decomposition, the scale dependence based on multi-resolution decomposition depends on the scale of the fluctuations and not the periodicity (Howell and Mahrt, 1997). In most stratified nocturnal cases, a gap region was clearly evident in the cospectra (Figure 1). The fluxes of heat and momentum at time scales larger than the gap scale ($\sim 60\ s$) are often erratic, a strong function of averaging time and can be of either sign. A gap region was not always evident for unstable daytime periods where the distinction between large convective eddies that scale with boundary-layer depth and mesoscale motions becomes blurred.

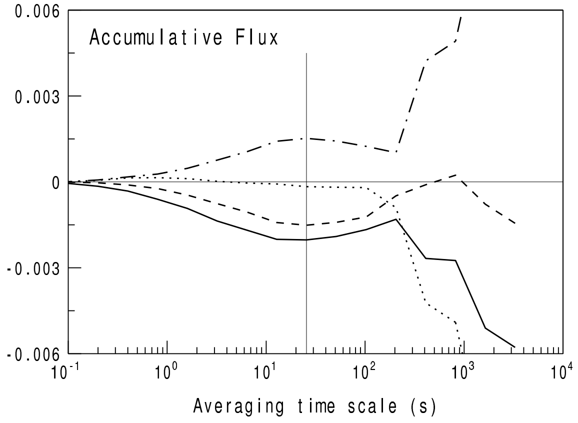

Figure 2: Accumulative flux (sum of cospectra) for CASES99 5-m sonic data for one stable period around midnight for the sonic heat flux (solid line), alongwind component of momentum flux (dash), crosswind momentum flux (dot), and magnitude of momentum flux (dash-dot). The vertical line is the gap detection algorithm time scale (26 *s*).

For time scales slightly larger than the gap, the cospectra for both the alongwind component of the momentum flux and the heat flux typically change sign. As a result, the accumulative flux, or equivalently the eddy correlation flux, is a local maximum at the gap scale (Figure 2). In the region around the gap (20 to 40-second averaging time scale), the accumulative flux curve is flat, and the flux is not a strong function of averaging time. By contrast, for longer time scales outside the gap region, the accumulative fluxes in this example increase rapidly with increasing averaging time, and therefore are not well posed. At averaging time scales 5 minutes and longer, the crosswind component of the momentum flux dominates the magnitude of the momentum flux vector. In the region of the cospectra associated with turbulence, the crosswind component of the momentum flux is much smaller than the alongwind component.

An automated algorithm was developed to objectively find the gap time scale. Individual cospectra for 1-hour time series are first smoothed with a 1-2-1 filter to remove potential noise which can sometimes trick the algorithm. Because the random sampling error of the cospectra for an individual 1-hour record is large, we averaged the gap scale over the entire experiment to reduce random error and then developed relationships between the average gap scale and height above ground and bulk stability.

In addition to height above ground and stability, which are the influences we will explicitly consider, the gap scale may also be related to boundary-layer depth. Shallow boundary layers could suppress the largest turbulent eddies and reduce the gap scale. At night, the gap scale may be related to the location and intensity of the low level jet, which was commonly observed in CASES99. The observations needed to test the boundary-layer depth and low level jet influences were not routinely available in our data sets and will not be available in many anticipated applications.

The gap time scale and gap length scale (using Taylor's hypothesis) generally increase with height in near neutral and unstable conditions due to the presence of the ground which inhibits the turbulent eddy size. The neutral gap length scale increases approximately linearly with height in the lowest 20 *m*, but increases at a rate much less than linear above 20 *m*, possibly due to the influences of boundary-layer depth. In stable conditions, no clear height dependence of the gap time scale is observed. A possible explanation is that in stable conditions the larger turbulent eddies are limited by the temperature stratification such that height above ground becomes a secondary influence.

To assess a length scale from tower data one needs to assume Taylor's hypothesis, which has two potential problems: a) the theory may not apply because the eddies do not move with the mean wind speed or they evolve significantly during the time required to pass the tower, and b) the eddies generally become more elongated in the wind direction with stronger winds. Given that there is no available alternative, we chose to empirically model the gap time scale directly to improve turbulent flux calculations. We select a form for the gap time scale of

$$\tau = \alpha_r (z/z_r)^p f(R_b) \tag{2}$$

where α_r is the neutral gap time scale (seconds) at arbitrary reference height $z_r = 10$ *m*, and $f(R_b)$ is a stability function equal to unity for neutral flow. The CASES99 neutral data yield $\alpha_r = 540$ *s* and *p*= 1/3.

Despite considerable scatter between the different sonic anemometers, a good relationship was found between the gap time scale and stability as measured by the bulk Richardson number. A fit to the stability dependence based on all the CASES99 data is given by

$$f(R_b) = (1 - 50R_b)^{1/4}; R_b < 0 \tag{3}$$

$$f(R_b) = (1 + 100R_b)^{-1/2}; R_b > 0 \tag{4}$$

where the stability function was found by first removing the neutral height dependence. Some of the scatter is due to the stability dependence of the height dependence, which for simplicity has been excluded from the model. For extreme positive or negative bulk Richardson numbers, where $f(R_b)$ either vanishes or becomes very large, we constrain the gap time scale to be no smaller than 30 *s* and no larger than 1200 *s*. The model (Eqs. 2-4) based on CASES99 data compares favorably with the independent data sets from BORRIS95 and MICROFRONTS.

The gap scale model is applied to the calculation of eddy correlation fluxes as follows. The bulk Richardson number is estimated from the 1-hour average wind speed and the 1-hour average temperatures. The gap time scale is evaluated using the height and stability-dependent model (Eqs. 2-4). Quantities such as the vertical velocity w and temperature T are decomposed into a mean and a fluctuating part, as in standard Reynold's decomposition, using the gap time scale to define the local averaging time and therefore the fluctuations (e.g. w' and T'). The fluxes (e.g. $w'T'$) are then averaged over one hour to reduce random sampling errors.

4. IMPLICATIONS FOR SIMILARITY THEORY

The expectation of applying the gap scale model is that the calculated fluxes will better represent turbulent transport and be more tightly coupled to the local wind shear and temperature stratification. That is, the scatter in similarity relationships should be reduced using the gap scale fluxes. This result is not guaranteed however because there is considerable scatter in the gap time scale for a given height and bulk stability. In this section, we focus on the measurements made at and below 10 *m* above ground in CASES99. We will address the systematic influence on the fluxes first and then examine scatter in similarity relationships.

Averaging over the entire experiment, the friction velocity u_* increases slightly with increasing averaging time scale. For unstable conditions, the friction velocities are generally larger (smaller) when using a 30 (5) minute time scale compared to using the gap scale model, where the model time scale ranges between 10 and 20 minutes depending on R_b. This systematic relationship between the friction velocity and the averaging time scale was observed for all of the sonic anemometers at or below 10 *m* in CASES99. One factor responsible for the systematic increase in u_* with averaging time is the potential for an increase in the crosswind component of the momentum flux with averaging time (e.g. Figure 2).

Small but systematic differences were also found for the sonic heat fluxes. During daytime convective periods, the upward heat flux increases with increasing averaging time scale such that heat fluxes based on 30-minute or 1-hour averages are slightly greater than the gap scale heat fluxes, which are 20 minutes or less. Larger upward heat fluxes normally improve the surface energy budget. Here the intention is to include only the turbulent heat flux.

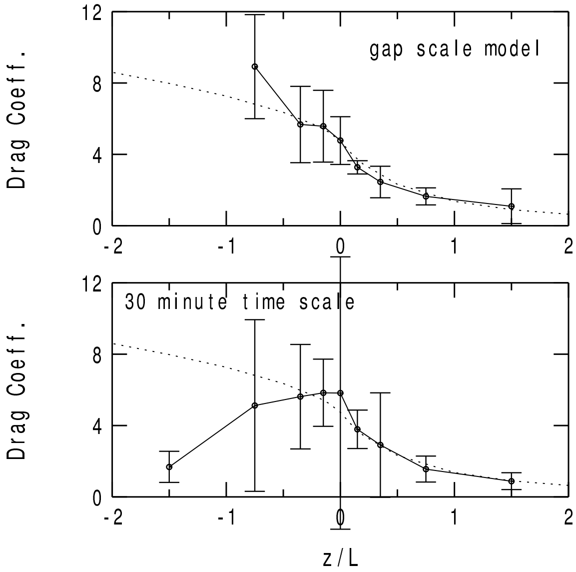

Figure 3: Stability (z/L) dependence of the drag coefficient (C_d x 1000) for fluxes calculated using a) the gap scale model, and b) a constant 30-minute averaging time for the CASES99 10-*m* sonic data. The error bars show plus and minus one standard deviation. The dashed line is the similarity theory prediction. $C_d(z/L)$ for a constant 5-minute averaging time (not shown) is similar to that for a 30-minute averaging time.

For stable conditions, the systematic heat flux difference is small and the scatter is large, especially on a percent basis.

Use of the variable averaging time scale, as compared to the common approach of using a constant averaging time scale, reduces the scatter in stable boundary-layer similarity relationships as measured by the correlation between R_b and z/L. The scatter is reduced by excluding mesoscale contributions to the calculated fluxes. These mesoscale fluxes are typically not related to the local wind shear or temperature stratification in a systematic way and are poorly sampled.

In the stable boundary layer, fluxes calculated using the shorter averaging time of the gap model lead to systematically larger values of the stability parameter z/L. This is primarily due to a smaller estimate of the friction velocity for the shorter averaging time (a few minutes or less) of the model. The momentum fluxes at scales larger than the gap scale are commonly dominated by the crosswind component, even when there is little directional shear of the mean wind. The crosswind component of the stress is associated more with large scale meandering of the wind and possibly gravity waves than with turbulence.

Numerous cases are found where the heat flux calculated using a 5 minute or longer time scale is upward in the stratified nocturnal boundary layer, contrary to the similarity prediction. For these same cases, the heat flux cospectra show a downward flux at shorter time scales. The gap scale captures the downward heat flux by excluding the upward flux at longer time scales and significantly reduces the number of apparent counter-gradient heat flux cases by a factor of 2 to 4, depending on the level and sonic anemometer considered.

Use of the adjustable averaging time scale reduces the bias and the scatter in the z/L dependence of the drag coefficient compared to use of a constant averaging time (Figure 3). Use of fixed averaging time scales for calculating the fluxes can lead to an erroneous decrease in the mean drag coefficient with increasing instability (Figure 3b) due to the incorrect sign of the heat flux resulting from contamination by mesoscale motions.

5. ACKNOWLEDGMENTS

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