Contract No. and Disclaimer:

This manuscript has been authored by Savannah River Nuclear Solutions, LLC under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting this article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for United States Government purposes.

Flux Measurements from a tall tower in a complex landscape

R. J. Kurzeja, A. H. Weber, S. R. Chiswell, M. Parker
Savannah River National Laboratory

Abstract

The accuracy and representativeness of flux measurements from a tall tower in a complex landscape was assessed by examining the vertical and sector variability of the ratio of wind speed to momentum flux and the ratio of vertical advective to eddy flux of heat. The 30-60 m ratios were consistent with theoretical predictions which indicate well mixed flux footprints. Some variation with sector was observed that were consistent with upstream roughness. Vertical advection was negligible compared with vertical flux except for a few sectors at night. This implies minor influence from internal boundary layers. Flux accuracy is a function of sector and stability but 30-60 m fluxes were found to be generally representative of the surrounding landscape.

Introduction: The eddy covariance technique is a powerful method for measuring the exchange of momentum and scalars (heat, moisture, CO2) with the surface that is most reliable when applied to flat, homogeneous landscapes with stationary turbulence. The flux from heterogeneous landscapes can be found by installing flux towers in each of the vegetation types and summing the component fluxes.

However, perfectly homogeneous landscapes are uncommon since soil moisture, rainfall and clouds create time-varying vegetation properties. Moreover, measurement of fluxes from individual patches is laborious and can not account for mixed vegetation patches and nonlinearities at patch boundaries. Finally, much of the landscape is a patchwork of vegetation types and a method to measure the net flux is desirable.

Flux measurements from tall towers are uncommon and difficult to interpret because the greater measurement height increases the chance of a heterogeneous footprint and because the sensors often extend above the surface layer where turbulence behavior is less predictable. Tall towers are also located for commercial rather than scientific reasons.

Complex landscapes are defined by topography or vegetation type. The latter is believed to be the more important consideration for the SRNL (WJBF) tall tower and is the focus of this study. Kaimal and Finnigan (1994) and Garrett (1990) have discussed flow over inhomogeneous surfaces. Roughness changes and thermal boundaries initiate internal boundary, Bill's. The presence of Bill's is inconsistent with the basic assumptions of the EC method because the eddy fluxes will vary with height and because IBC's grow with height downstream of their formation before eventual merging. In addition, measured fluxes are complex functions of downwind distance and discontinuity properties and may also induce local circulations that compete with the EC flux... Significant advective transport violates EC assumptions and also raises the possibility that the measured fluxes from the tower may not be representative of the surrounding landscape.

This paper will study flux data from a 300 m tower, with 4 levels of instruments, in a complex landscape. The surrounding landscape will be characterized in terms of the variation in the ratio of mean wind speed to momentum flux as a function of height and wind direction. The importance of local advection will be assessed by comparing vertical advection with eddy fluxes for momentum and heat.

Tower and data

A Google image of the WJBF tower is shown in Fig. 1. The figure shows a typical Southeast US landscape with pastures, mixed pine hardwood forest, and rural residential in patches ~1/4 to 1 km in size. The tower is located on high ground with elevation variations of 30m within 5 km of the tower. Vegetation around the tower can be grouped into four broad categories (Table 1). The scrub pine/oak biome is concentrated around the base of the tower while pasture (crops) and residential areas become more common beyond 2 km. The roughness length, vegetation height, and displacement height were obtained by estimating the vegetation height, h, and then assuming that displacement height, d =0.7h, and roughness length zo=d/14 Verhoef (1997).

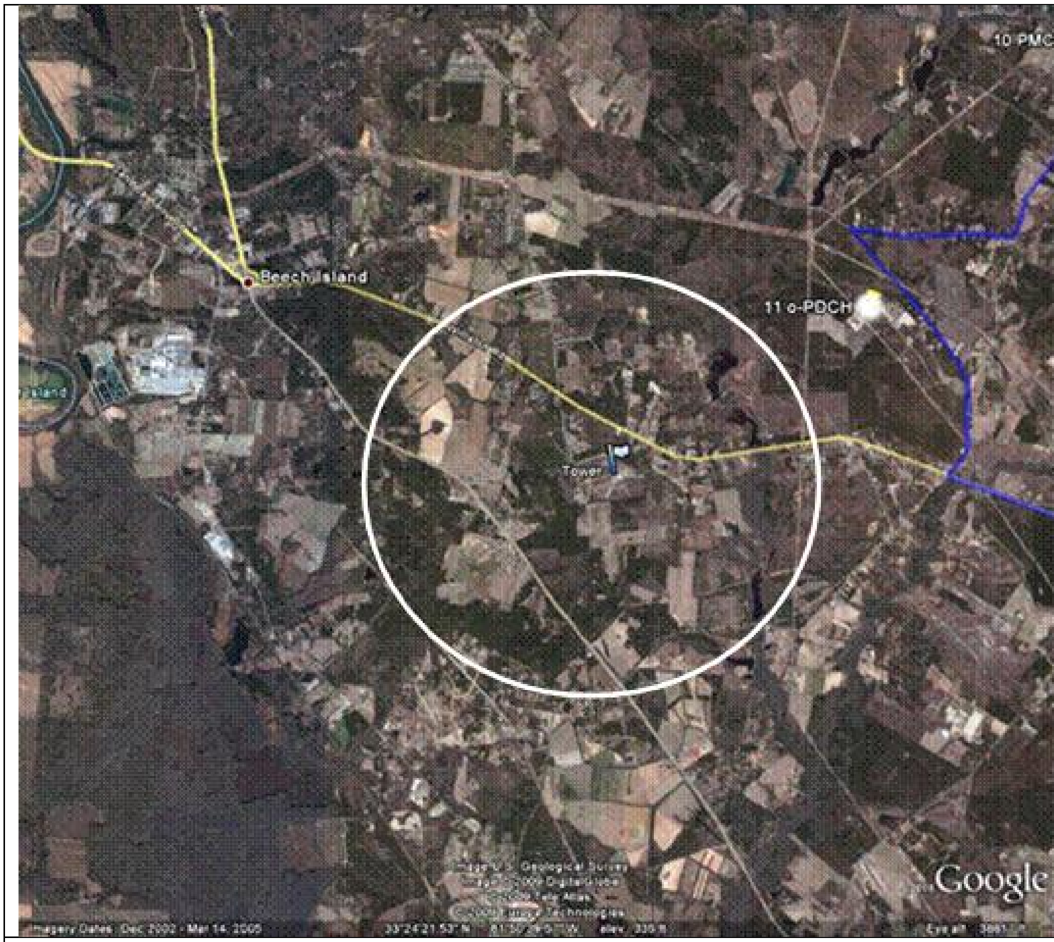

Fig. 1: Google image of the WJBF tower site within a 5 km diameter circle.

The assumption that zo = d/14 is reasonable for uniform vegetation - the first three categories of Table 1 - but is only a crude approximation for mixed vegetation patches, e.g., forest/residential. However, it is a useful approximation since it permits estimation of zo and d with data at one level and one stability.

Vegetation description	Percentage within 5 km	Roughness length, m	Vegetation height, m	Displacement height, m
1. Scrub pine/oak	10	0.3	7	5
2. Pasture/crops	20	0.21	0.5	0.35
3. Managed pine forest	30	0.9	20	14
4. Forest/residential	40	0.9	1-30	14

Table 1: Vegetation types and roughness length, zo, vegetation height, h, and displacement height, d, within 5 km of the tower.

.

The WJBF TV tower is instrumented with sonic anemometers at 10, 30, 61 and 304 m and with LICOR water vapor/CO2 analyzers at the top 3 levels. The top three levels are shadowed by the tower to the northeast while the 10 m level is obstructed to the east-northeast. Land use within 500 m of the tower is dominated by pasture to the north, and scrub pine/oak in other quadrants.

Method

The analysis will focus on heterogeneity in surface properties as seen in the vertical variation of wind speed normalized by the momentum flux. The data can be understood in terms of four idealized cases.

Case 1: Radial homogeneity this situation is denoted by uniform upwind fetch but variation with wind direction. For this case we should expect that tower flux parameter profiles to follow theoretical profiles with height but be offset from each other.

Case 2: Sector homogeneity. This case is when roughness varies with upwind distance but not with sector. Tower sector profiles for this case should be identical but all will depart from theoretical profiles as a function of height.

Case 3: Small patches. This case is called 'blended' Mahrt (1995) and denotes a situation where the vegetation patch size is small compared with the flux footprint. Vertical flux parameter profiles for this case should be parallel to theoretical values but displaced. Fluxes at upper level will tend to be blended because of their larger flux footprints.

Case 4: Large patch asymmetry. This case combines Cases 1 and 2. For example, when a tower is located off-center within a circular clearing we should expect local circulations generated by the roughness change to depend on the wind direction.

Results:

A useful indicator of surface properties that affects each level is the ratio of the wind speed to the vertical momentum flux. According to Monin-Obukhov theory this ratio is given by

$$u/(u'w')^{1/2} = [\ln((z-d)/zo) + \Psi(z-d//L)]/k \qquad (1)$$

where d and zo are the displacement height and $\Psi(z-d//L)$ is the M-O stability correction, and k=0.4

The eddy flux in this equation is usually taken to be the surface friction velocity. However, since we assume that each measurement level corresponds to a different surface footprint, we use the eddy flux measured at each level when computing the ratio $u/(u'w')^{1/2}$. The mean data were derived from hourly mean fluxes and winds in streamline coordinates.

Fig. 2 shows the quantity $u/(u'w')^{1/2}$ as a function of stability for 10 and 30 m for winds from the NNW and SSW sectors.

The vertical variation of $u/(u'w')^{1/2}$ is shown in Fig. 3 and 4 for stable and neutral conditions, respectively. Also shown in these figures is the expected value from Eq. 1 calculated with the average stability from the data points. Each point is an average of all the data for that sector and height.

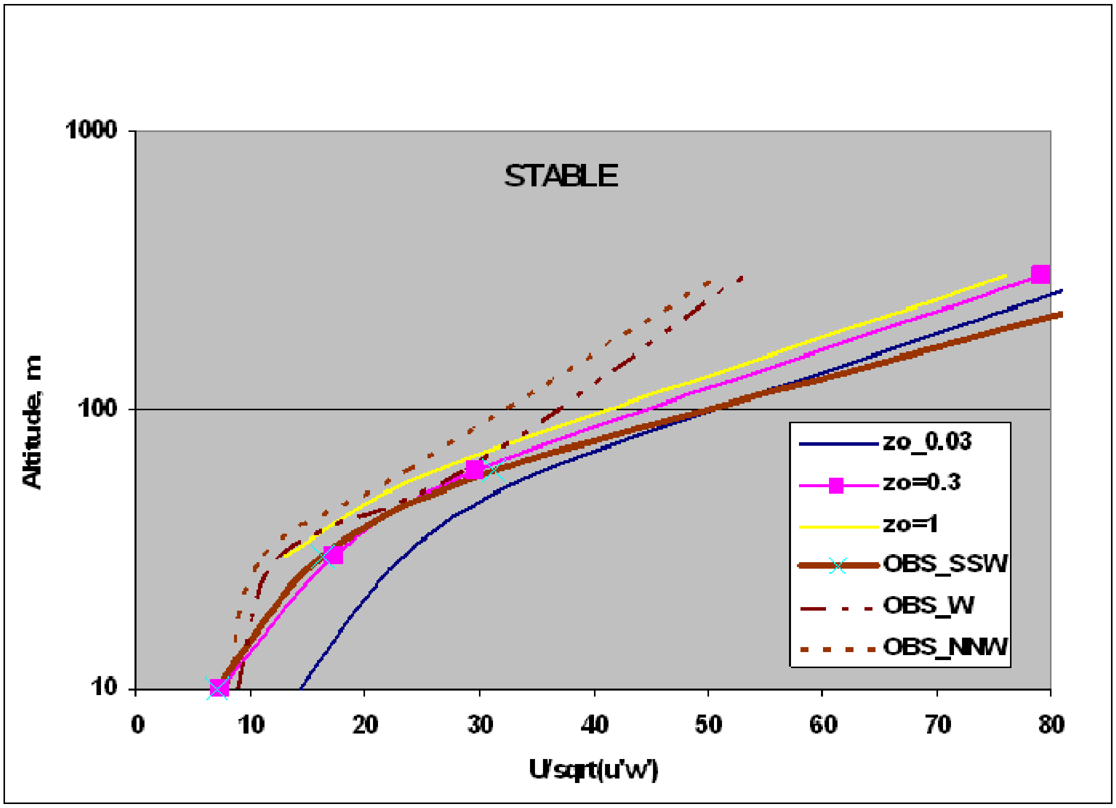

Fig. 2: The ratio of mean wind speed to friction velocity as a function of height for stable stability for the SW, W and NNW sectors. Solid lines are for zo=0.03, .3 and 1.0.

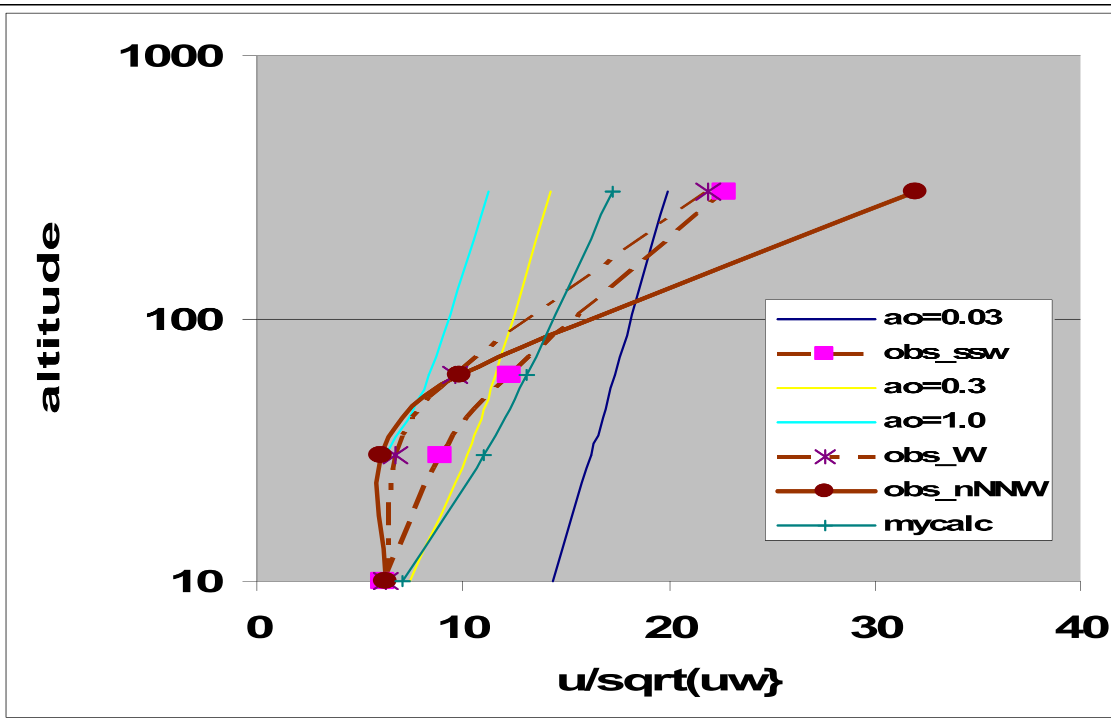

Fig. 3: As in Fig. 2 but for neutral stability

Figs. 3 and 4 can be used in a semi-quantitative analysis of the fluxes measured at each level. Height ranges where the observed curve is parallel to the theory correspond to blended footprints. i.e., footprints with vegetation patches are small compared to the footprint size. Height ranges where the observed curve diverges from the standard curves suggest regions where the upstream footprint is changing and hence subject to greater uncertainty.

The figure shows good blending between 30 and 60m with a ratio consistent with the vegetation types 3 and 4 of Table 1. The ratio at 10 m is consistent with vegetation types 1 and 2 as expected, since the 10m footprint is small and close to the tower base. The ratio at 300 m departs from theory because it is near the top of the surface layer. The implied roughness to the west is much less than to the south or north, probably because the terrain is flatter, with more pasture to the west. Also, significant in Fig. 3 and 4 is the similarity in implied roughness between the 30 and 60m levels. As suggested in Table 1 this is probably due to the similar roughness of the commercial pine forests and mixed pine/hardwood/residential vegetation types.

As noted in the Introduction, in ideal (homogeneous) conditions advection by local circulation will be negligible. This will not be true, however, near surface in homogeneities where local IBC's and circulations are possible. A measure of the departure from ideal conditions is given by the magnitude of the advection terms compared to the flux terms. Horizontal gradients can not be measured at a single tower, but because of mass continuity, vertical advection can be compared with eddy fluxes.

Since the vertical velocity is identically zero in streamline coordinates, vertical advection must be evaluated in instrument or planar fit coordinates. The vertical velocity in planar fit coordinates is calculated with respect to a horizontal plane adjusted so that the long-term vertical velocity is zero. Thus, it can be interpreted as a long term baseline which responds to fluctuations of several hours.

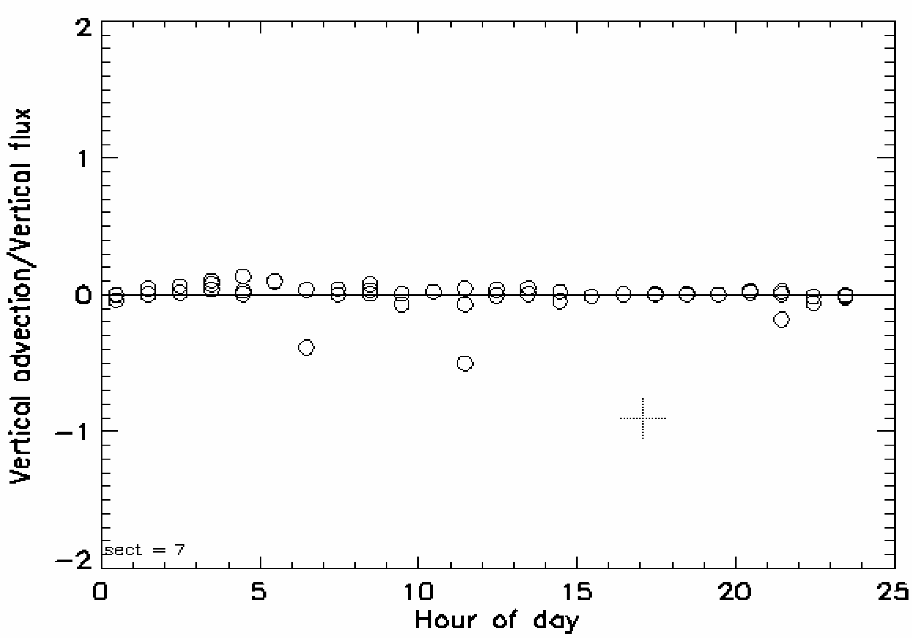

Fig 4: Ratio of the vertical sensible heat advection to the vertical eddy flux at 30m for the NNW sector.

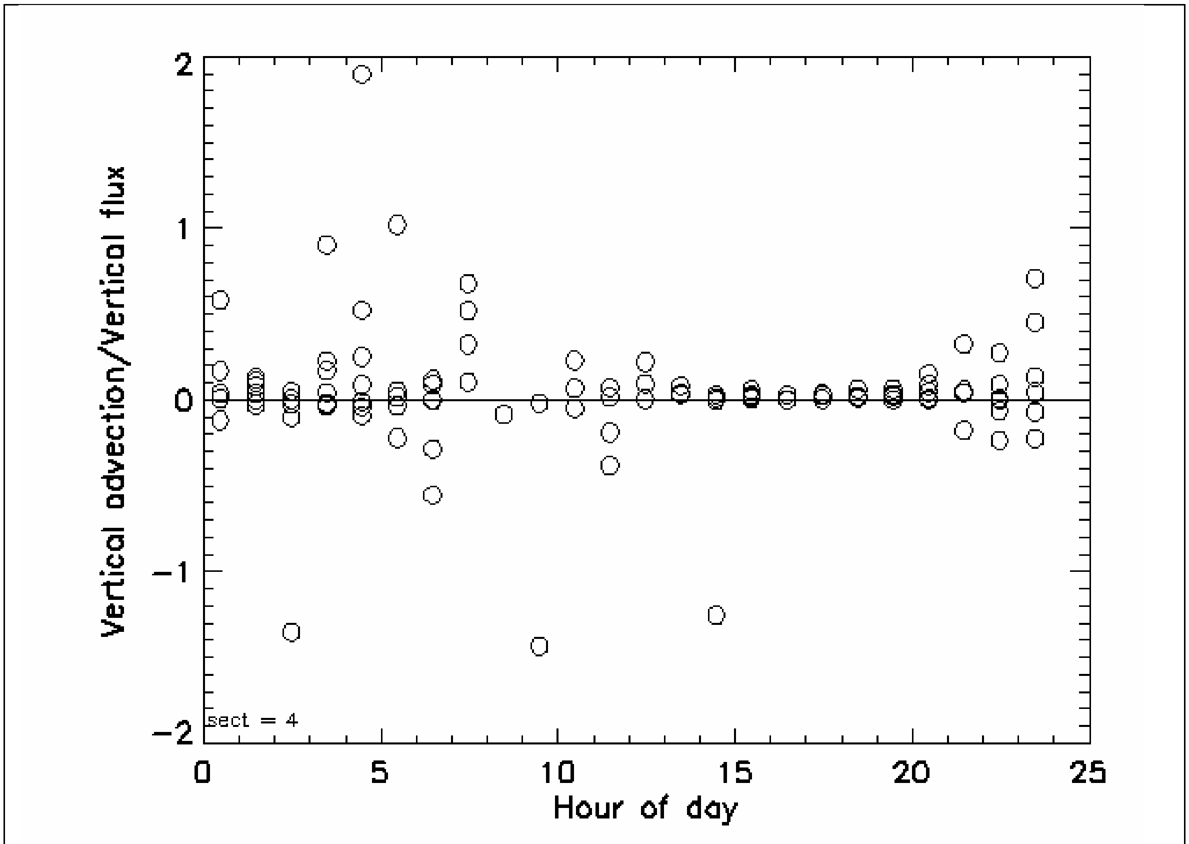

Fig 4: As in Fig 4 but for the SSW sector

In ideal flat
conditions or in a heterogeneous landscape with radial symmetry around the tower the planar fit normal coordinate should be vertical.

Figs. 4 and 5 show the average vertical heat flux in planar coordinates for winds from SSW sector and from the NNW sector. As can be seen, vertical advection is small compared with vertical eddy flux during the day in both sectors but not at night. Vertical advection is more important at night in the SSW sector but the ratio average is approximately 1. This suggests that the absence of a persistent internal boundary layer.

Conclusions

The effect of landscape heterogeneities on fluxes was examined by comparing the vertical variation of the ratio of the mean wind to the momentum flux compared with values derived from Monin-Obukhov theory.

The profiles of U/u^* were parallel to the theoretical curves and consistent with each other between 30 and 60 m but departures below 30 and above 60 m were observed. Thus good mixing is implied in the 30-60m range with the likelihood that the flux form upwind footprints is a weighted sum of fluxes from the various vegetation types. The 10m level ratio was consistent with roughness properties near the base of the tower and the 10-30 m level corresponds to a footprint transition region...

The effect of possible internal boundary layers around the tower was examined by comparing the ratio vertical advective change to vertical eddy fluxes. It was found that in daytime, sensible heat advection was negligible compared to the vertical flux, which implies no significant effect from local circulations. On the other hand, vertical advection at night was more important in some wind directions. This implies that nighttime eddy fluxes may not be representative of the area around the tower for these conditions and the eddy flux is more uncertain.

References

Garrett, J. R., 1990: The internal boundary layer, *Bound. Layer Meteor*., **50**, 171-203.

Kaimal, J.C., and J.J. Finnigan, 1994: *Atmospheric Boundary Layer Flows,* Oxford University Press, 289pp.

Mahrt, L, 1995, the bulk aerodynamic formulation over heterogeneous surfaces. *Bound. Layer Meteor*., **96**, 87-119.