FLUX MEASUREMENTS FROM A TALL TOWER IN A COMPLEX LANDSCAPE

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Abstract

The accuracy and representativeness of flux measurements from a tall tower in a complex landscape was assessed by examining the vertical variability of the ratio of wind speed to momentum flux and the vertical angle of the wind. The 30-60 m ratios were consistent with theoretical predictions which indicate well-mixed flux footprints. The difference in the vertical angle of the wind for north and south winds suggests the presence of a terrain discontinuity at the tower or internal boundary layers The latter will complicate the interpretation of the flux measurements.

Introduction: The eddy covariance (EC) 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 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 create internal boundary, layers. IBL's. The presence of IBL'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 surface discontinuities may also induce local circulations compariable in size 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 evaluating the vertical angle of the mean wind.

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 areas 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).

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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/15, Verhoef (1997).

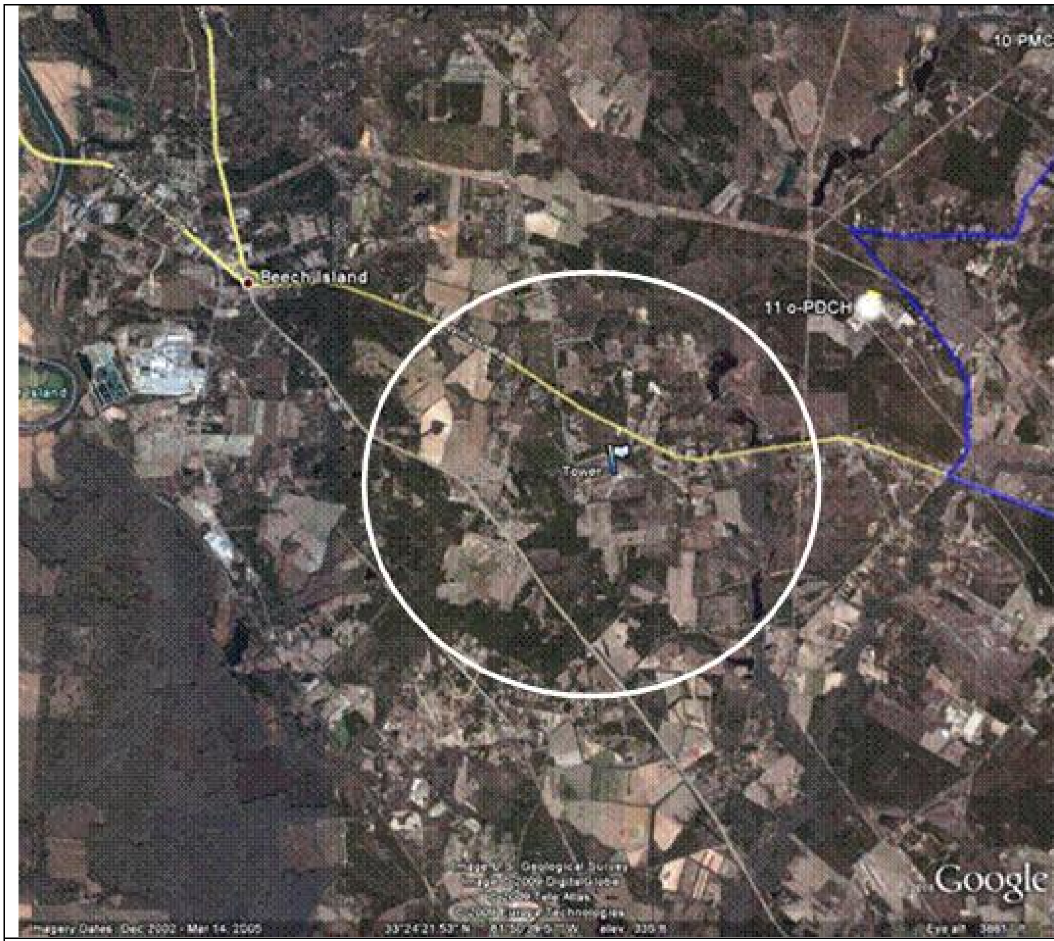

Fig. 1: Google image of the WJBF tower site within a 5 km diameter circle.

Vegetation description	Percentage within 5 km	Roughness length, m	Vegetation height, m	Displacement height, m
1. Scrub pine/oak	10	0.3	7	4.5
2. Pasture/crops	20	0.02	0.5	0.3
3. Managed pine forest	30	0.9	20	13.5
4. Forest/residential	40	0.9	1-30	13.5

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

The assumption that zo = d/15 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.

The WJBF TV tower is instrumented with sonic anemometers at 10, 30, 61 and 304 m and with LICOR water vapor/CO_2 analyzers on 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 friction velocity. 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

$$u/u^* = [\ln((z-d)/zo) + \Psi(z-d//L)]/k \qquad (1)$$

where d and zo are the displacement height and Ψ(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'). Since the (u'w') decreases with height, the measured value was increased to estimate the corresponding surface value. The multiplication factors for 30, 61 and 304m were 1.03, 1.06, 1.3 for convective conditions, 1.06, 1.10, 1.5 for neutral conditions, and 1.1, 1.15, and 1.7, for stable conditions. The momentum fluxes were derived from hourly-averaged data in streamline coordinates.

Fig. 2 shows the ratio of u/(u_*, estimated) for stable conditions. Also shown is the value derived from Monin-Obukhov theory. A discontinuity in the inferred surface roughness is seen between 10m and 30m, with a linear change above 30m. The ratio at 10m is consistent with scrub oak/pine and with forest or forest/residential above 10m, as expected.

The vertical variation of /(u_*, estimated) is shown in Fig. 3 and 4 for neutral and unstable conditions, respectively. The neutral result is similar to the stable result while the unstable data show consistent results for 10 and 30m. This latter is partly the result of the smaller upwind footprint for unstable conditions and the smaller role of surface friction in the vertical change in momentum flux and wind speed.

Figs. 2 to 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 small compared to the footprint size. Height ranges where the observed curve diverges from the theoretical curves suggest regions where the upstream footprint is changing and hence subject to greater uncertainty.

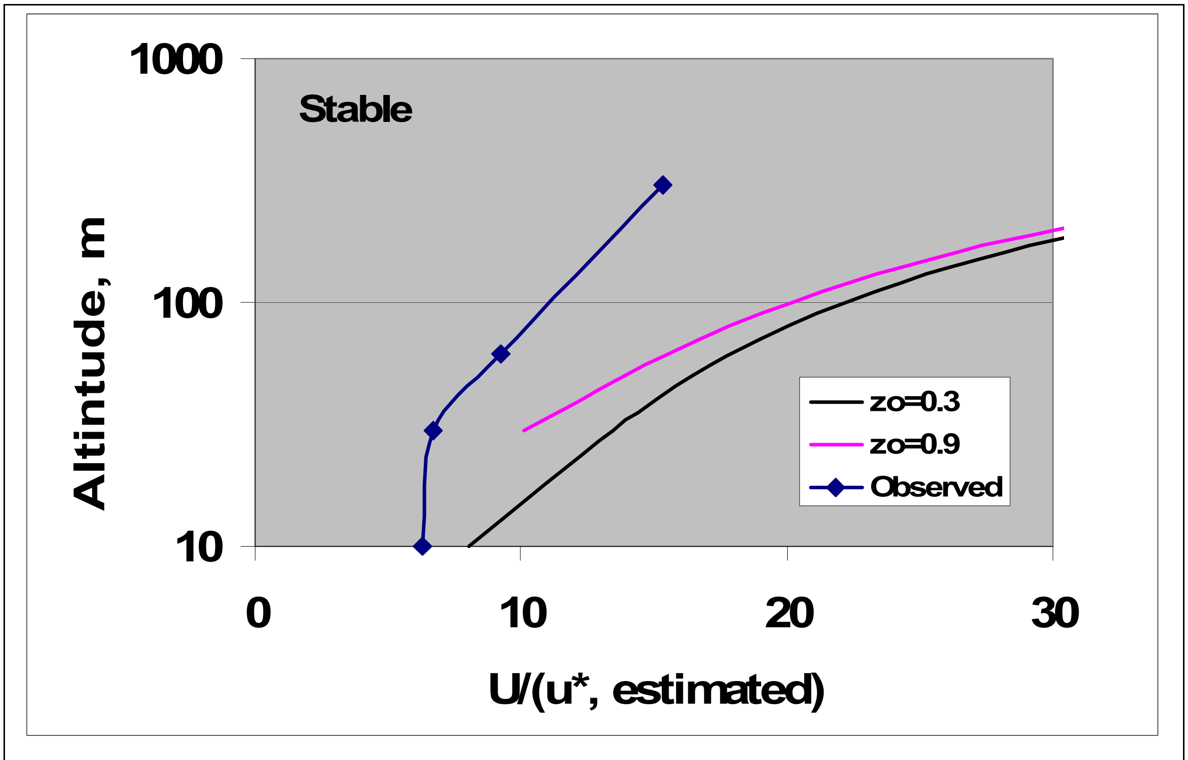

Fig. 2: The ratio of mean wind speed to friction velocity as a function of height for stable stability. Solid lines are for zo=0.3 and 0.9m.

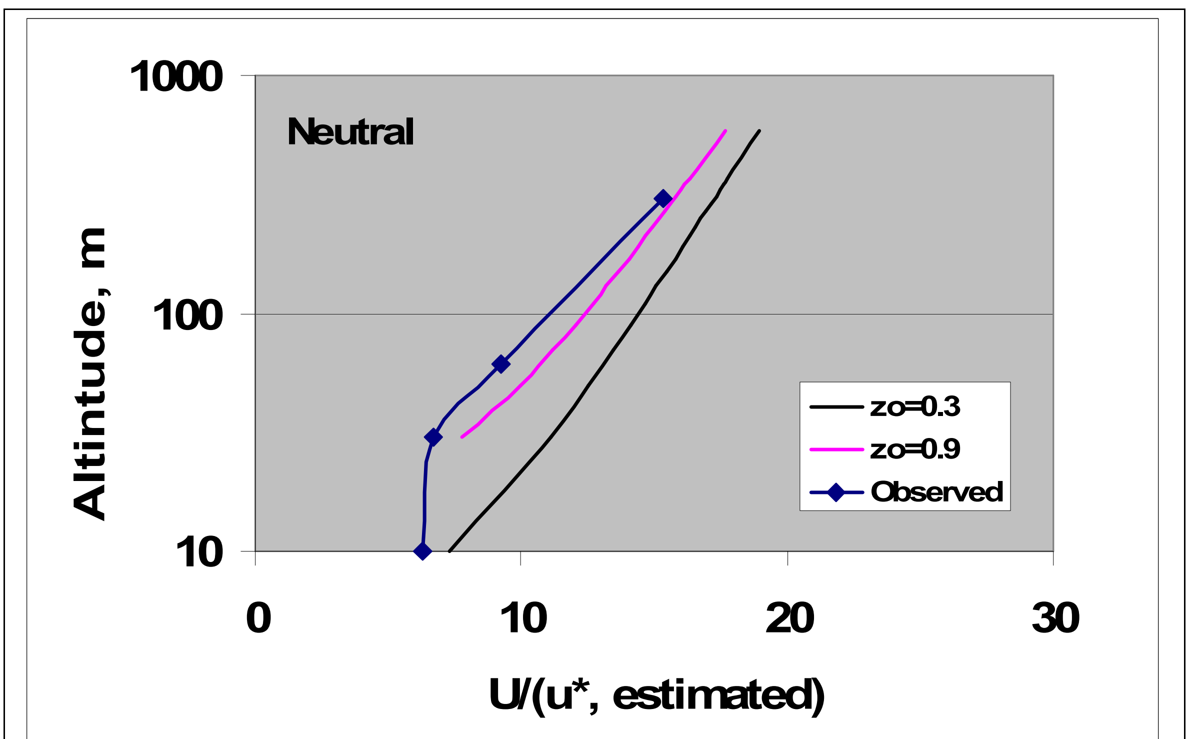

Fig. 3: As in Fig. 2 but for neutral stability

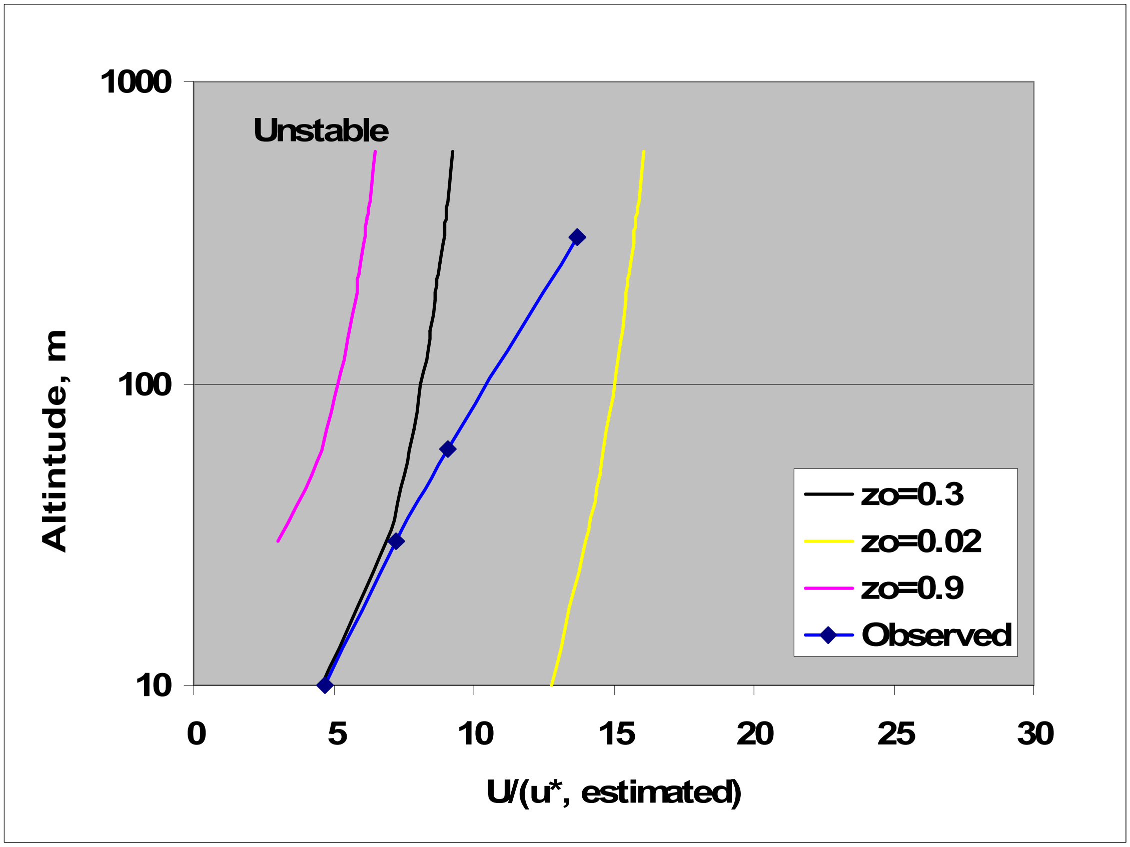

Fig. 4: As in Fig. 2 but for unstable stability

The figures show good blending above 30m, consistent with the vegetation types 3 and 4 of Table 1. The ratio at 10 m is consistent with vegetation type 1 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.

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 angle of the mean wind with respect to the horizontal.

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.

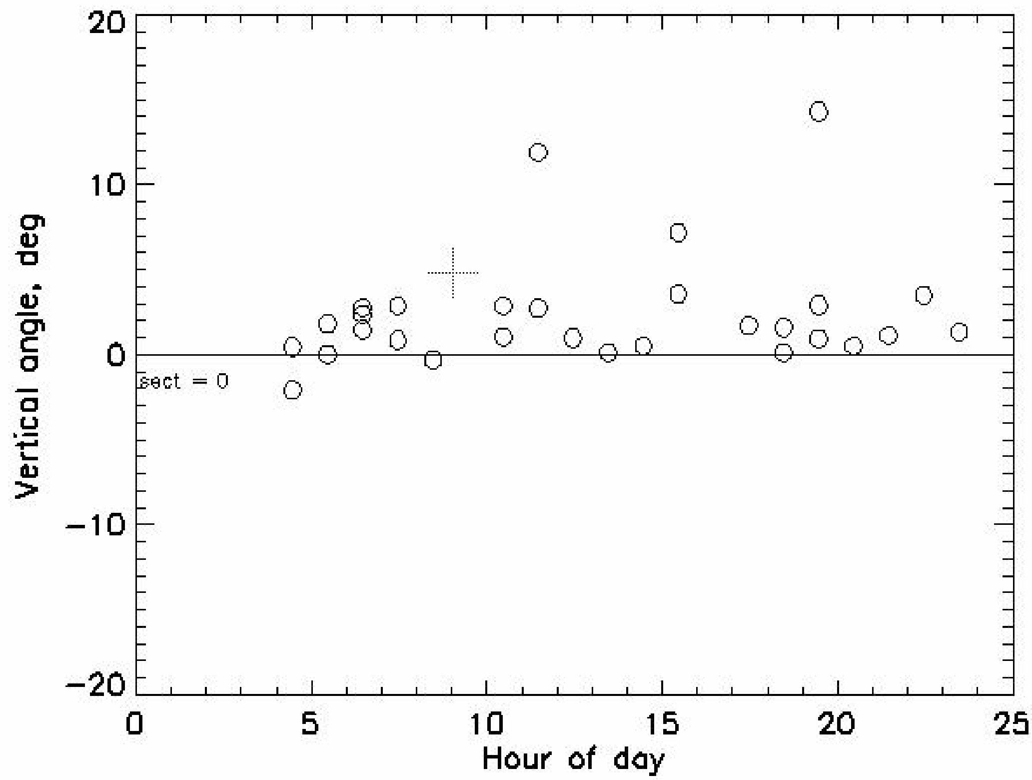

Fig 5: Angle of the wind with the vertical for north winds as a function of time of day..

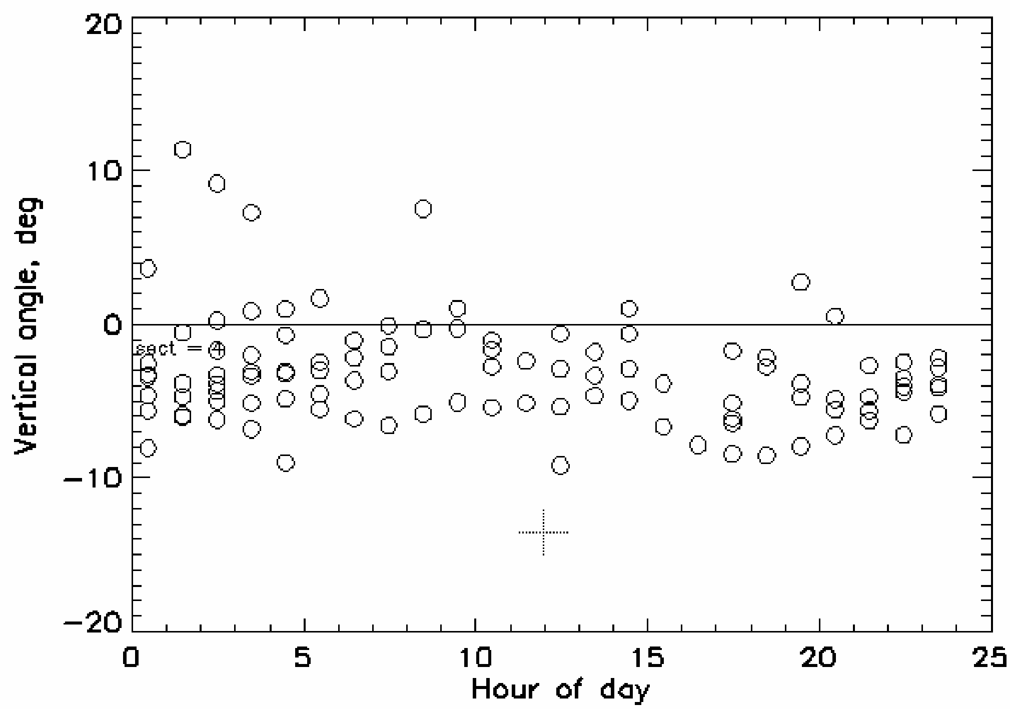

Fig 6: As in Fig 5 but for south winds.

In flat terrain or in a heterogeneous landscape with radial symmetry around the tower, the planar fit normal coordinate should be vertical with the average vertical angle of the wind of zero. For a tilted plane, the vertical wind angle is expected to be the negative of that for winds of opposite direction.

Figs. 4 and 5 show the vertical direction at 30 m for south winds and north winds, respectively, in planar coordinates, as a function of time of day. As can be seen, the vertical angle of the wind is ~+2 degrees for north winds but ~ -4 degrees for south winds. This angle is independent of time of day (stability) . This suggests a discontinuity in slope or the presence of internal boundary layers near the tower.

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 above 30m but departures below 30 were observed. Thus good mixing is implied in the > 30m 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 angle of the wind with the vertical. A difference of 2 degrees was found between the vertical angle of the wind for winds from the south and north. This suggests either a discontinuity in the slope at the tower, or the presence of internal boundary layers. The latter will lead to increased uncertainty in the accuracy of the measured fluxes.

References

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