Linking near surface turbulence under stable conditions to regional flow stability, and geometric and surface cover properties of the landscape

Luiz E. Medeiros[1,2] , and David R. Fitzjarrald[1]
[1]University at Albany, State University of New York
[2]Current affiliation: Universidade Federal de Santa Maria

Abstract: Averaged surface heat and momentum fluxes obtained from a network of surface flux stations in a heterogeneous landscape are found as function of a regional Richardson number (Ri_{br}). The results indicate that the need for extra mixing above a critical bulk Richardson number (Ri_{cr} = 1/4) in numerical weather prediction models (NWP) to avoid unrealistic cooling at surface is a consequence of spatial averaging. Network-averaged flux persists when the regional flow stability is well above critical ($Ri_{br} >> Ri_{cr}$). We found that there are preferential places for the occurrence of strong turbulence under same stability conditions of the mesoscale flow. Further, we identify two most prominent local landscape characteristics near observation stations that signal the likely occurrence of turbulence, terrain concavity and site sheltering. Site sheltering was determined using Fujita's 'transmission factor' and surface concavity by determining the Laplacian ($\partial^2/\partial x^2+\partial^2/\partial y^2$) of a quadratic surface (s = s(x,y)) fitted to the local topography. Each site characteristic exerts systematic influences on nocturnal heat and momentum fluxes, with sheltering being more influential under windy conditions (> 5m s^{-1}) and concavity under weak windy conditions.

1. Introduction - The Stable boundary layer (SBL) forms usually during the night over land primarily due the air contact with the cold surface, which is established as consequence of long-wave radiation divergence. Turbulence mixes the air near the surface increasing the cooling of the air. NWP models have difficulties on dealing with very stable boundary layer, which happens over land under light winds and clear skies. Under these conditions the turbulence near the surface is intermittent and not spatially continuous (Acevedo and Fitzjarrald 2003, hereafter AF2003). This problem arises because NWPs adopt a classical concept of the SBL, in which there is continuous turbulence close to the ground. In many cases, a first order closure *K-theory* schemes are used to obtain the surface fluxes (McCabe and Brown, 2007). Turbulent diffusion coefficients are usually based on stability functions that depend on a bulk Richardson number (Ri_b). Different kinds of stability functions are used to adjust the turbulent diffusion coefficients for momentum K_m and heat K_h. In modeling (Delage, 1997) it has been found necessary to allow mixing to occur even for grid-cell with $Ri_b > ¼$ (the critical Richardson number Ri_{cr} = ¼). In practice, it is done using different types of stability functions. Given ideal surface conditions (e. g. flat surface with homogeneous roughness) bursts of turbulence could plausibly occur randomly across the landscape, however more realistic landscapes have heterogeneous landscapes whose effects should be considered when analyzing near surface turbulence. Thus the objective here is to identify how near surface turbulence is distributed across a heterogeneous landscape, and find out if unphysical extra mixing, necessary to improve the models forecast, under very stable conditions ($Ri_b > Ri_{cr}$) can be attributed to real extra mixing observed at certain parts of the domain.

2. Data - The data used is from the Hudson Valley Ambient Meteorology Study (HVAMS) and corresponds to the period between mid September 2003 and end of

October 2003, with a network of ten surface flux stations, one weather station, one aircraft, and one wind profiler (Fig. 1).

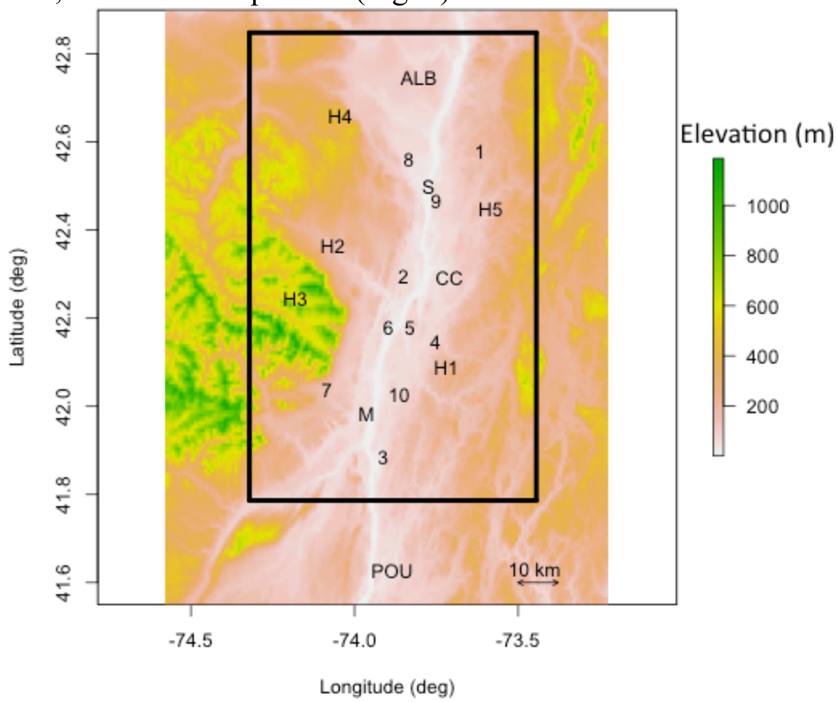

Figure 1: Topography of the HVAMS region. Numbers from 1 to 10 refer to surface flux stations, ALB to soundings and hourly surface weather data, POU to hourly surface weather data, and M to the 915 MHz Doppler radar (wind profiler).

3. Results - A regional Richardson number (Ri_{br}), intended to evaluate the stability of the regional flow, was developed based on sounding and surface station data. The network average momentum and sensible heat fluxes have a clear dependence in terms of Ri_{br} for the range $0 < Ri_{br} < 50$ (Fig. 2). The more notable result is that there is appreciable network average flux when $Ri_{br} > Ri_{cr}$. This can justify the practice of allow mixing in models when $Ri_{br} > ¼$. It also illustrate that the $Ri_{cr} = ¼$ cutoff for turbulence is not suitable for heterogeneous terrain. The shot-tailed stability functions, which do not allow mixing for $Ri_{br} > Ri_{cr}$, perform better in weak stable conditions, while long-tailed ones (which allow mixing when at supercritical) perform well in strong stability conditions.

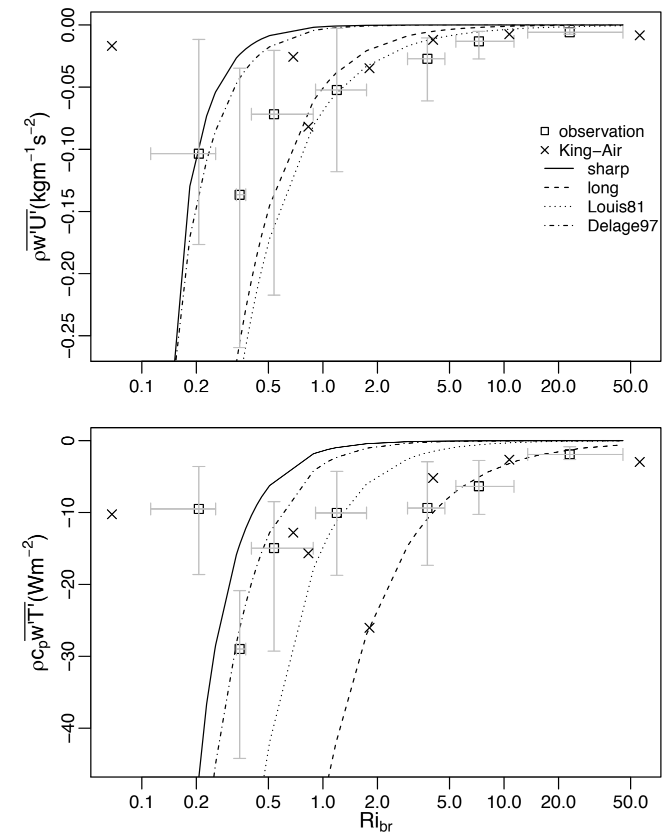

Figure 2. Upper panel is momentum flux vs. Ri_{br} and lower panel is sensible heat flux *vs.* Ri_{br}. Squares refer to the observed network average flux as function of Ri_{br}, which depends on sounding, network, and 915 MHz wind profiler data. The solid, dashed, dotted, and dashed-dotted lines are, respectively, the predicted theoretical momentum using sharp-tail, long-tail, Louis81, and Delage97 stability functions. Each observation point (square) represents five nights bin-average of nighttime network flux average, and the "*x's*" to the nighttime network flux average when there was aircraft data available. The horizontal bars represent the range of Ri_{br} and vertical bars the range of fluxes within each bin.

Figure 3 shows that under same stability conditions of background flow (Ri_{br}), the different stations have different momentum and heat exchanges. There are preferential sites for occurrence of mixing. As all stations had different site surface characteristics e. g. exposure, slope, concavity and elevation, this result shows that spatial heterogeneity influences the turbulence activity locally.

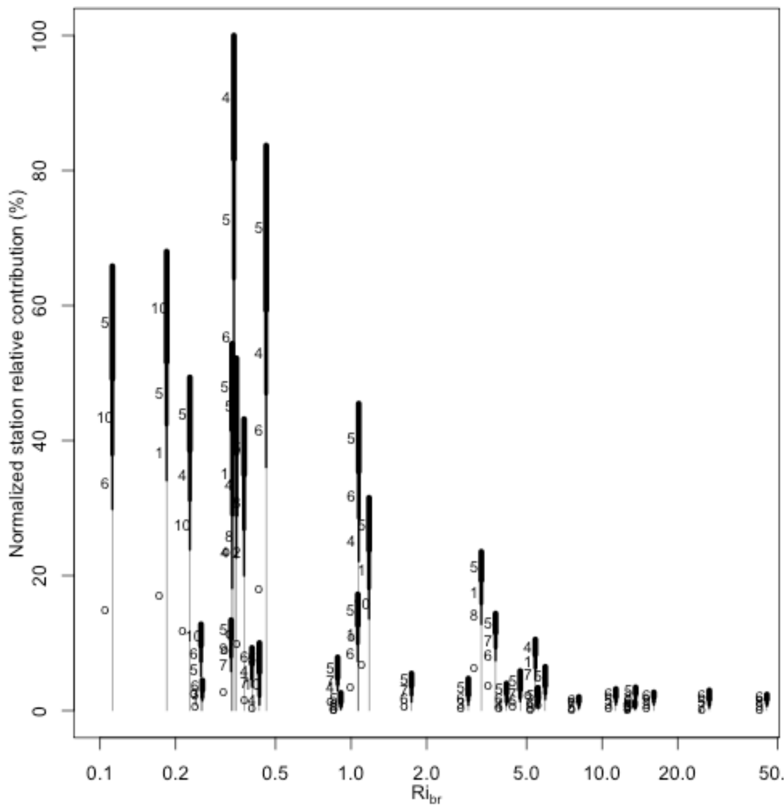

Figure 3: Normalized relative station contribution to the nightly network average momentum flux vs. *Ri_{br}*. Length of the each bar is normalized by the maximum network average momentum flux during the IOP. The widths indicate different stations (thickest = 1st dominant station, second thickest = 2nd dominant station, second thinnest = 3rd dominant station, and thinnest = all other stations); the length indicates the individual contributions of each station. Only the dominant stations for the nights are shown, all others stations fall into others contribution "o".

The results indicate that the absolute magnitude of the momentum and sensible heat fluxes (result not shown) must also depend on terrain concavity (Figures 4). Fluxes become more negative with decreasing concavity. At the extreme values of the concavity range this relation seems most clear. However, within the sub-range of values [-0.0004, 0.0004] (m-1) this behavior is complex. Flux dependence with concavity is best defined for calm conditions, and least defined for windy conditions. There is a larger spread, and the coefficient of determination r^2 of the adjusted cubic curve $ax^3 + b$ decreases from calm to windy conditions for the momentum and sensible heat fluxes. The fitted cubic curve somewhat resembles how the fluxes should vary with concavity. We do not expect it accurately describes the fluxes in terms of concavity (Figure 5) and *TF* (Figure 5) because it has no physical basis, but we use it as first attempt to describe the fluxes in terms of this quantities for the different classes of background wind and cloud cover. When comparing clear sky with overcast conditions for same background wind regime, it is not clear that the flux dependence with concavity is higher for clear skies than for overcast skies. In certain instances r^2 increases from overcast to clear, which seems a more physical behavior because of enhanced stability at concave places but in other cases it is not observed.

Mean wind directions found for the same periods for which the fluxes are calculated were used to obtain the transmission factors (TFs) (Fujita and Wakimoto 1982) of the particular wind directions accessed during the entire IOP (50 nights). [The TF evaluates how obstructed is one station relative to the wind for a particular direction.] Nights were then sorted out in terms of background wind and cloud cover conditions, and TF and the momentum and sensible heat fluxes are then averaged for the different conditions. As expected, the momentum and heat flux (result not shown) have stronger dependence with TF for windy than calm conditions (Figures 5) and they tend to be higher for winds coming from more open directions. This confirms earlier results from AF2003, who showed that on calm nights the fluxes are overall smaller and flux differences among the directions are minimal. Less obstructed directions are associated with higher flux values. A limitation of using TF to evaluate sheltering around the stations is that the assumption that all stations are subjected to a common "unobstructed" mesoscale wind may not always work for the HVAMS array, particularly during light wind conditions. We used the daytime network wind to determine each station's TF. During daytime convective conditions, mixing is deeper and more vigorous causing the wind field to be more homogeneous across the network.

We suppose that the spread in the fluxes with concavity, and TF comes about because it is difficult to isolate the influences of the local topographic and land cover elements. Only at the extremes of the concavity, and TF ranges do their influences emerge clearly. Future work with many more stations in the network would clarify these uncertainties.

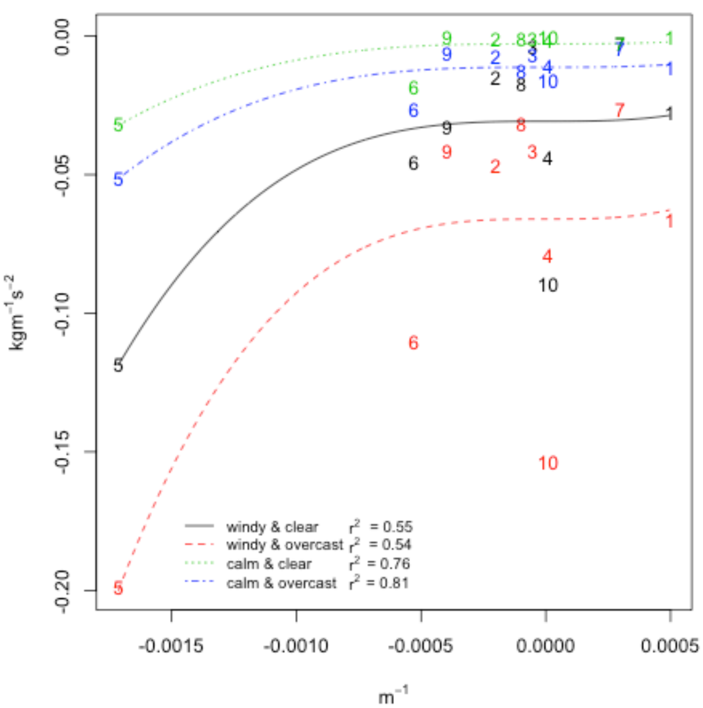

Figure 4: Nocturnal (23 UT – 11 UT) average momentum flux averaged for different mesoscale wind and cloud cover fraction (vertical axis) during the IOP as a function of site concavity (horizontal axis) evaluated by fitting a quadratic surface to an area of ~ 0.3 km x 0.3 km centered at each station. Green for *windy and clear nights*, blue *windy and overcast*, *light blue calm and clear*, and pink *calm and overcast*. Numbers refer to the stations (only flux stations). The colored lines represents a 3rd order polynomial ($ax^3 + b$) fitted by non-

linear least square method to the four different wind and cloud cover conditions. Note that the coefficient of determination (r^2) is given all four atmospheric conditions.

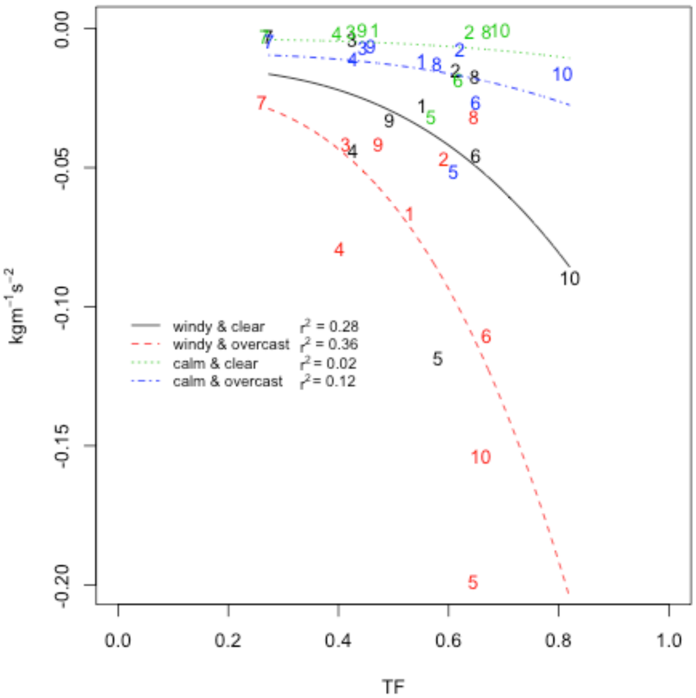

Figure 5: Nocturnal average momentum flux averaged for different mesoscale wind and cloud cover fraction conditions during the IOP versus averaged *TF*. Green for *windy and clear nights*, blue *windy and overcast*, *light blue calm and clear*, and pink *calm and overcast*. Numbers refer to the stations. The colored lines represents a 3rd order polynomial ($ax^3 + b$) fitted by non-linear least square method to the four different wind and cloud cover conditions.

4. Summary -The need for extra mixing above Ri_{cr} in NWP models is justified by the experimental results found. There are still network-averaged fluxes in the regime $Ri_{br} >> Ri_{cr}$. Spatial heterogeneity of landscape forces mixing not to be uniform across the landscape. Places like stations 5, 4, 6 and 10 dominate the regional momentum and sensible heat exchanges. Among the site characteristics used, local surface concavity is the most important factor in determining sensible heat and momentum fluxes under calm conditions, with *TF* being more influential in windy conditions. Under windy conditions the overall fluxes are higher and differences in the fluxes between obstructed and open direction are therefore higher too. The conclusions drawn about the relative importance of different landscape characteristics on nocturnal turbulent exchange are preliminary. The network analyzed here (10 flux-measuring stations and 5 conventional weather stations) was limited by resource availability. However, we believe that our approach lends itself to future application for larger networks.

5. REFERENCES

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