J3.8 The influence of stability on the turbulent transfer of heat, moisture and momentum fluxes in the surface layer over an agricultural farmland at a tropical location

Balogun A. Ahmed*
Meteorology Department, Federal University of Technology, Akure, Nigeria

O.O, Jegede, and E.O, Aregbesola
Physics Department, Obafemi Awolowo University, Ile-Ife, Nigeria

M. Mauder, and Th. Foken
Department of Micrometeorology, University of Bayreuth, Germany

1. Introduction

The Nigerian Micrometeorological Experiment (Phase I), termed NIMEX-1 was conducted at Ile-Ife (7.55°N, 4.56°E), Nigeria during the period 15th February and 10th March, 2004. This is a low wind tropical location, with mean wind speed, $U < 1.5\ ms^{-1}$, and intense surface heating, net radiation greater than 750 Wm^{-2}. Much research has been done on the processes governing the turbulent transfer of momentum, heat and water vapour in the lowest layers of the atmosphere (surface layer) and generalizations about the flux-gradient relationships under near neutral conditions are well established. However, there still exist some uncertainties for the more prevalent diabatic conditions (Kondo et al, 1978 and Högström, 1988) and data for low wind tropical locations are very few. This paper presents some results of the analysis of the influence of stratification on eddy transfer at a low wind tropical site.

2. Site and Instrumentation

The measurement site chosen for the study is an agricultural farmland in Ile-Ife (7.55^{o}E, 4.56^{o}E), south-western Nigeria, left fallow at this time. The measurement surface is flat and open over an area of approximately 1000 meters by 300 meters, with a mean roughness length z_0, of about 1.0 cm, determined for near neutral conditions and shows a variation with time and wind direction (Balogun et. al., 2004). Beyond this surface is the forested area which is typical of the natural vegetation of the area.

The vertical profile of temperature, moisture and wind up to 15m-height were measured using sensitive cup anemometers at levels 0.5,1,2,3,5,7,10 and 15m, Frankenberger-type psychrometers at levels 1, 5 and 10m and a wind vane at 15m. While turbulent fluxes of heat, moisture and momentum were measured directly with an eddy covariance system, consisting of an ultrasonic anemometer and a krypton hygrometer.

***** Present Affiliation: Department of Geosciences, College of Arts and Sciences University of Missouri, Kansas City, Missouri 64110-2499, USA

The slow systems were sampled every 1sec. and stored subsequently as 1 min. averages for all the measured parameters. The fast response system was made up of an ultrasonic anemometer (USA-1 manufactured by METEK, Germany) and a krypton hygrometer (KH20 manufactured by Campbell Scientific). The sonic anemometer was placed at height of 2.48m and sampled at a frequency of 16Hz, while the krypton hygrometer used for the measurements of turbulent fluctuations of humidity was sampled at 8Hz. Both fast response systems were logged with laptop computers while the slow systems were logged with Campbell Scientific data logger (model CR10X). The data acquisition/reduction and processing programs were developed by scientists at the Obafemi Awolowo University, Ile-Ife, Nigeria. A comprehensive software package "Turbulenzknect" developed by scientists at the University of Bayreuth, Germany was used for quality control and post processing of the turbulence data, producing quality assured turbulence fluxes. The capabilities of this software include identification of spikes in the raw data; quality control tests on the calculated turbulence fluxes, crosswind correction of sonic temperature, planar fit coordinate transformation, density, oxygen and spectral corrections among others. See

http://www.oauife.edu.ng/research/nimex/index.htm and http://www.bayceer.uni-bayreuth.de respectively for details.

3. Theoretical Background

In order to investigate the influence of stratification (characterized here as the gradient Richardson number, Ri) on the scale of turbulent transfers of heat, moisture and momentum in the surface layer, this parameter needs to be evaluated. But because we do not know the local gradients, this has been approximated by the bulk Richardson number, using the vertical wind and temperature profiles. Ri (the ratio of the buoyancy to the mechanical production/dissipation of turbulence) indicates the stratification of the atmosphere, i.e. unstable (Ri

< 0), stable (Ri > 0) or neutral (Ri $\simeq$ 0) and can be estimated from a two level measurement of wind and temperature as:

$$Ri = \frac{g}{\overline{\theta}_v} \frac{\Delta\overline{\theta}_v \Delta z}{\left(\Delta\overline{U}\right)^2 + \left(\Delta\overline{V}\right)^2} \qquad (1)$$

where g is acceleration due to gravity, $\overline{\theta}_v$ is mean virtual potential temperature and ΔU and ΔV are the changes in horizontal wind components across the layer Δz. . The height layer 1-5 m has been used in this analysis. The interval 5-10 m was not used as the wind differences in this interval were not resolved due to the very weak winds, typically less than the accuracy of the anemometers (0.2 ms^{-1}). To minimize errors in the computations differences less than or equal to the above have not been used.

Two other important parameters are the friction velocity, u_* and the Obukhov length, L evaluated from eddy correlation measurements ($\overline{u'w'}$, $\overline{w'\theta'}$):

$$u_* = \sqrt{-\overline{u'w'}} \qquad (2)$$

$$\frac{z}{L} = -\frac{kgHz}{\rho c_p \overline{\theta}_v u_*^3} \qquad (3)$$

The importance of u_* lies in its relationship with shear stress and mechanical mixing in the surface layer, while L is proportional to the height above the surface at which buoyancy dominates over shear. Defining the fluxes we have

$$\frac{\tau}{\rho} = u_*^2 = -\overline{u'w'} = K_m \frac{\partial\overline{u}}{\partial z} \qquad (4)$$

$$\frac{H}{\rho c_p} = \overline{\theta' w'} = -K_h \frac{\partial\overline{\theta}}{\partial z} \qquad (5)$$

$$\frac{E}{L_v \rho} = \overline{q' w'} = -K_w \frac{\partial\overline{q}}{\partial z} \qquad (6)$$

where τ is the shearing stress (rate of vertical transfer by turbulence of horizontal momentum per unit mass of air), H the sensible heat flux, E the latent heat flux, *k* is von Karman's constant (0.4), z is height, L_V, latent heat of vaporization, while c_p and ρ are the specific heat and air density respectively. The turbulent transfers of momentum, heat and water vapour are determined from the eddy diffusivities K_m, K_h and K_w respectively.

4. Results

4.1 Friction velocity, u_*

The friction velocity, u_* is an important velocity scaling parameter in the surface layer, particularly during wind shear induced mechanical production of turbulence and it is strongly dependent on wind speed. Winds are generally weak at Ile-Ife ranging between 0 and 3.5 ms^{-1} with an average of about 1.5 ms^{-1}.

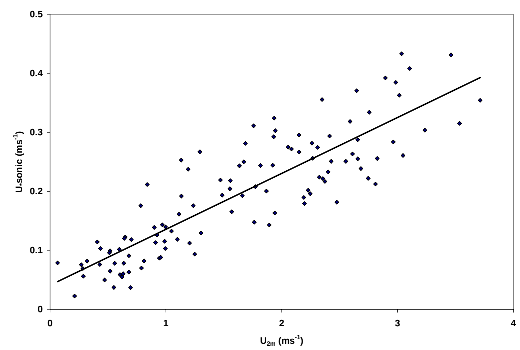

Fig.1. Relationship between sonic derived friction velocity and winds at 2m for all conditions.

Fig. 1. Shows the relationship between winds at 2m with u_* determined from sonic measurements using the eddy correlation method for all conditions. Though with a large scatter. The straight line is obtained from a least square fit to the data points:

$$u_* = 0.094\, u_{2m} + 0.04 \qquad (7)$$

Its values range from 0.07 – 0.43 ms^{-1}.

The influence of stability on friction velocity is clear and can be seen in Fig.2. It decreases rapidly with increasing stability as turbulence is damped under these conditions.

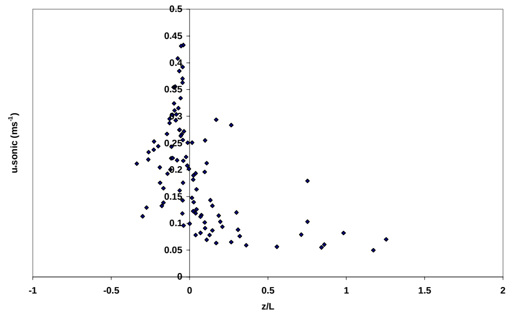

Fig.2. Variation of eddy covariance derived friction velocity with stability.

4.2 Momentum and heat fluxes

The momentum flux was observed to vary from very small values to a maximum of about 0.22 Nm^{-2}. Fig.3. show the diurnal variation for the 4^{th} of March 2004.

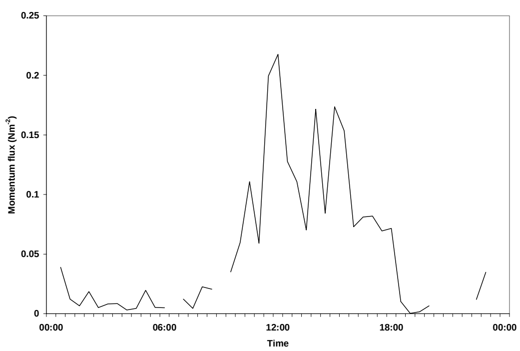

Fig.3. Diurnal variation of momentum flux on 4^{th} March 2004.

Because for some of the days, eddy covariance (EC) measurements of the sensible and latent heat fluxes were only available during the daytime, these fluxes were also determined using the Bowen ratio energy balance (BREB) method. Flux estimates from the two methods were in very good agreement as the variation between them was typically less than 10% for both sensible and latent heat fluxes. Energy closure balance was also very good about 93%. See fig. 4. For the periods when eddy covariance data are not available BREB fluxes have been used to determine the eddy diffusivities of heat.

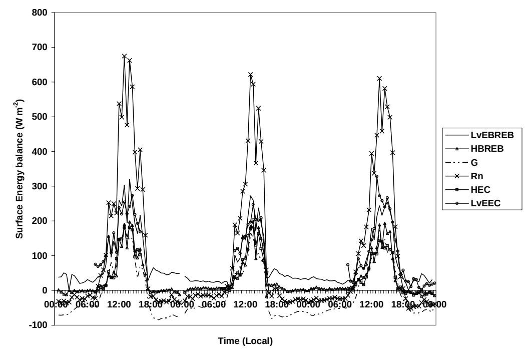

Fig.4a. Surface energy balance with a comparison of the heat fluxes determined directly using eddy correlation covariance and the Bowen ratio energy balance methods for 1st – 3rd March, 2004.

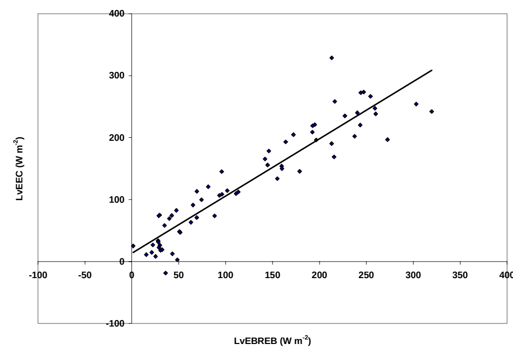

Fig.4b. Comparison of EC and BREB latent heat fluxes.

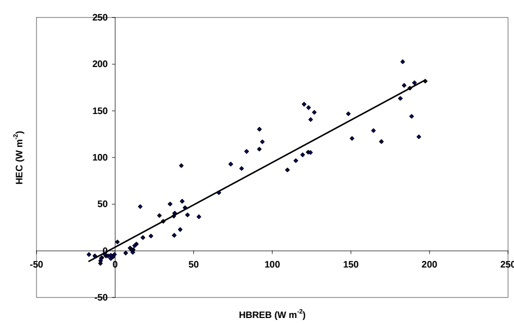

Fig.4c. Comparison of EC and BREB sensible heat fluxes.

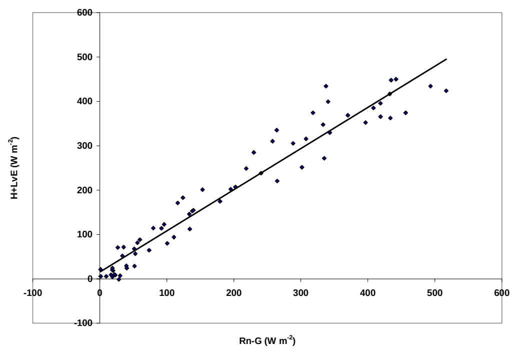

Fig. 4d. Surface energy balance closure at the site.

The linear least-squares correlation of the data points are:

$$L_vE_{EC} = 0.92L_vE_{BREB} + 13.14 \quad (8)$$

$$H_{EC} = 0.91H_{BREB} + 3.93 \quad (9)$$

$$H+L_vE_{EC} = 0.93Rn\text{-}G + 15.33 \quad (10)$$

4.3 Variation of K_m, K_h, K_w and K_h /K_w with stability

The eddy diffusivities of momentum (K_m) and heat (K_h and K_w) show strong sensitivity to stability variations. Fig. 5 shows the variation of Km, K_h and K_w with stability.

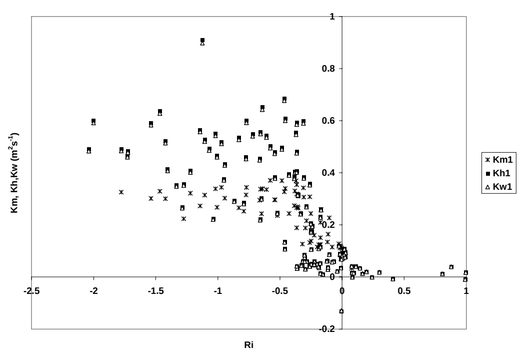

Fig.5. Variation of K_m, K_h and K_w with stability.

Observation shows that, there exists a sharp decrease in the eddy diffusivities as stability increases. This is in agreement with theory and observation (Yagüe and Cano, 1994). The highest values of turbulent transfers are produced in unstable conditions under strong convection associated with strong surface heating and mixing during the day. It is interesting to note that under inversions (strong stability conditions when Ri > 0) turbulence was literarily damped out as K_m tend to vanish and approaches zero even before $Ri_{critical} = 0.25$. The limiting value observed is Ri = 0.08 for this height interval, see Fig.5. Following in the same fashion K_h and K_w decreases rapidly with increasing stability and for Ri > 0.2, K_h and K_w were very small with values of the order of 10^{-4} m^2s^{-1} and are sometimes negative, see Fig.5. This suggests that turbulent mixing is negligible and vertical eddy transfer of heat and water vapour is suppressed by the stable stratification. Though it was observed that K_h and K_w were actually equal during neutral and stable conditions and tends to diverge slightly from unity as instability increases, see Fig. 5. But for practical applications it is acceptable to assume equality as the difference between them was observed not to be more than 2%.

The ratio of the diffusivities of heat, K_h and momentum, K_m ($\alpha = \frac{K_h}{K_m}$) give an indication of the nature of the turbulent eddy exchange processes going on in the surface layer. When $\alpha > 1$ ($K_h > K_m$), the transfer of heat is greater than that of momentum. If on the other hand $\alpha < 1$ ($K_h < K_m$), the transfer of momentum is greater than that of heat. Generally, it is observed that α decreases with increasing stability. Though not much data were available for stable conditions due to the weak winds and very small values of the eddy diffusivities, it was however observed that α is not always equal in stable conditions and less than 1 (Kondo et al., 1978; Carlos and Cano, 1994), but that it is sometimes less than

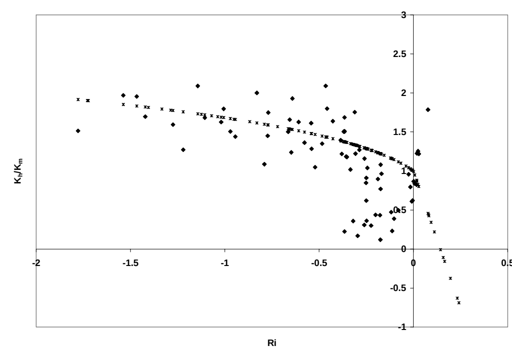

Fig.6. The variation of α with Ri.

1 also under weak instability conditions in the range - 0.005 > Ri > 0.5, see Fig.6. This implies that the decrease of K_h is more than that of K_m, indicating a much higher transfer of momentum than of heat.

Fig.6. also show a tentative suggested empirical fit that appears to predict the behaviour of α for this data set. These relationships are given below.

Unstable conditions:

$$\frac{K_h}{K_m} \approx \frac{K_w}{K_m} = (1 - 9Ri)^{0.25} \qquad (11)$$

Stable conditions:

$$\frac{K_h}{K_m} \approx \frac{K_w}{K_m} = (1 - 7Ri) \qquad (12)$$

5. Conclusion

The evaluation of the effects of stratification on the transfer of the fluxes of heat and momentum in the surface layer during NIMEX-1 at a low wind tropical location in Nigeria has been carried out using Bowen ratio energy balance and direct eddy covariance techniques.

Preliminary results show that there exists a significant dependence of u_*, K_h, K_w and K_m on the surface layer stability, with a sharp decrease of these turbulence parameters with increasing stability. In the free convection regime (of low wind speed, U < 1.5 ms^{-1}, and intense surface heating, net radiation greater than 750 Wm^{-2}), the behaviour of the ratio of eddy diffusivities K_h/K_m with the stability parameter, Ri is unlike that predicted from earlier studies. An empirical relationship that appears to fit the observed behaviour has been suggested. Further studies are in progress to evaluate the modified wind and temperature flux-gradient relationships after Högström, 1988, with this data set.

6. References

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