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

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Abstract

Data from the Nigerian Micrometeorological Experiment (NIMEX-1) recently conducted between 15th February and 10th March 2004, at a tropical agricultural field site in Ile-Ife (7.55°E, 4.56°E), south-western Nigeria have been used to investigate the effects 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. The vertical profile (at several levels) of temperature, moisture and wind up to 15m-height measured using sensitive cup anemometers, Frankenberger-type psychrometers, and a wind vane were sampled at every 1 sec. and stored subsequently as 1 min. averages. The turbulent fluxes of heat, moisture and momentum were measured directly with an eddy covariance system, consisting of an ultrasonic anemometer and a krypton hygrometer (sampled at 16 *Hz* and 8 *Hz* respectively). The friction velocity, u_* and eddy diffusivities for heat (K_h), moisture (K_w) and momentum (K_m) were also obtained from the data. The results obtained showed 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.

Introduction

The Nigerian Micrometeorological Experiment (Phase I), termed NIMEX-1 was conducted at Ile-Ife (7.55oN, 4.56oE), 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 (Dyer and Hicks 1970, Businger et al. 1971, Pruitt et al. 1971, Kondo et al, 1978 and Högström, 1996) and data for low wind tropical location 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.

Site and Instrumentation

The measurement site chosen for the study is an agricultural farmland in Ile-Ife (7.55°E, 4.56°E), south-western Nigeria, left fallow at this time. The measurement surface is flat and open over an area of approximately 1000 metres by 300 metres, 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 are 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

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ultrasonic anemometer and a krypton hygrometer.

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 datalogger (model CR10X). The data acquisition/reduction, quality control and processing programs were developed by scientists at the Obafemi Awolowo University, Ile-Ife, Nigeria and the Department of Micrometeorology, University of Bayreuth, Germany. See Nigerian Micrometeorological Experiment, NIMEX-1 URL at http://www.oauife.edu.ng/research/nimex/index.htm for details.

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 need to be evaluated. This has been done 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:

$$Ri = \frac{g}{\overline{\theta}_v} z_m \ln \frac{z_2}{z_1} \frac{\Delta\theta}{\left(\Delta U\right)^2} \qquad (1)$$

where g is acceleration due to gravity, $\overline{\theta_v}$ is mean virtual potential temperature and zm = $(z_1 z_2)^{1/2}$ represent the geometric mean height, $\Delta\theta = \theta_2 - \theta_1$ and $\Delta U = U_2 - U_1$ represent the potential temperature and wind speed differences between the two levels respectively. The intervals 1-5 m and 1-10 m have 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 m/s). To minimize errors in the computations differences less than or equal to the above have not been used. The logarithmic function used in Equation (1) is realistic in the sense that profiles of mean variables within the surface layer are more linear with respect to the logarithmic function of the height

Two other important parameters are the friction velocity, u_* and the Monin-Obukhov stability parameter (z/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.

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 L is the Obukhov length, 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.

Results

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 m/s with an average of about 1.5 m/s.

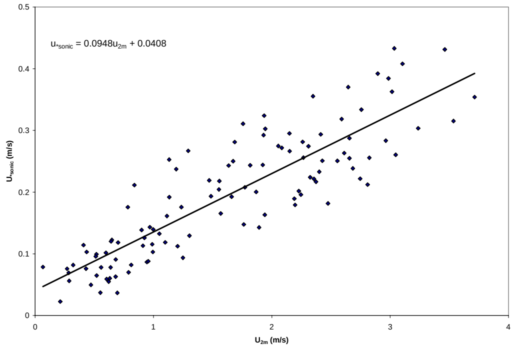

Fig.1. Relationship between sonic derived friction velocity and winds at 2m for all conditions.

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:

$U_* = 0.0948u_{2m} + 0.0408$

Its values range from 0.07 – 0.43 m/s.

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.

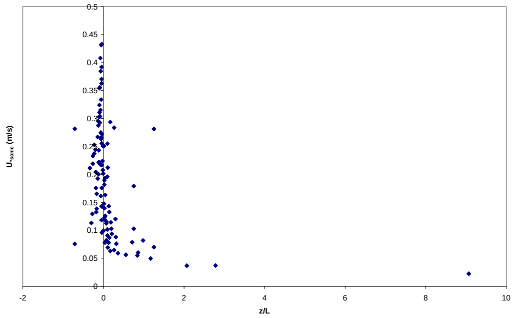

Fig.2. Variation of eddy correlation derived friction velocity with stability.

Heat and Momentum fluxes

Fig.3. shows a comparison of the friction velocity determined directly using eddy correlation (U_{*sonic}) and the Monin-Obukhov (MO) similarity theory using the Businger-Dyer (Dyer, 1970; Businger et al., 1971) flux profile relationships (U_{*Fp}) at a geometric mean height of 3.16m (1-10 m interval).

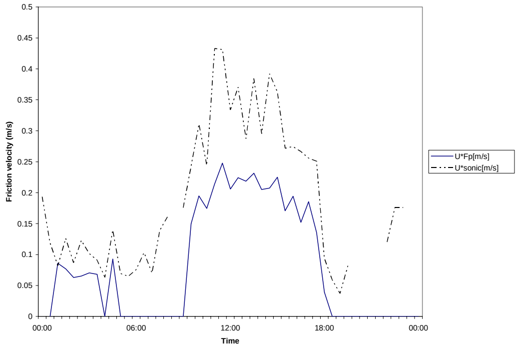

Fig.3a. Diurnal variation of the friction velocity determined directly using eddy correlation and Businger-Dyer flux profile relationships on 4th March, 2004.

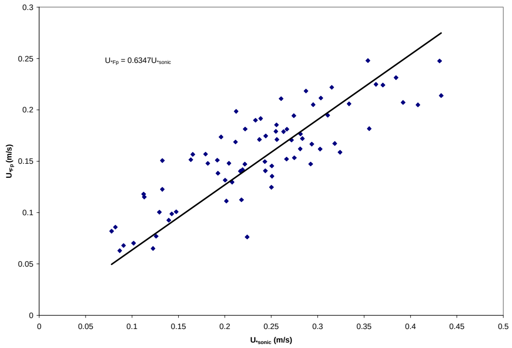

Fig.3b. Comparison of the friction velocity determined directly using eddy correlation and the Businger-Dyer flux profile relationships.

Observation shows that they both follow the same trend, see Fig.3a. However, U_{*Fp} was consistently lower than U_{*sonic} by about 30-35%. This is reasonable, considering instrumental error and the fact that the full requirement for the (MO) similarity theory may not have been met. Further analysis, with tests with other flux profile relationships (Högström (1996) will answer the question above and also determine whether a better performance can be achieved with this data set.

Because for some of the days, eddy correlation (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 only about 10 – 20% for H and about 15 - 25% for LE. Energy closure was about 80%. See fig. 4. For the periods when eddy correlation data are not available BREB fluxes have been used to determine the eddy diffusivities of heat.

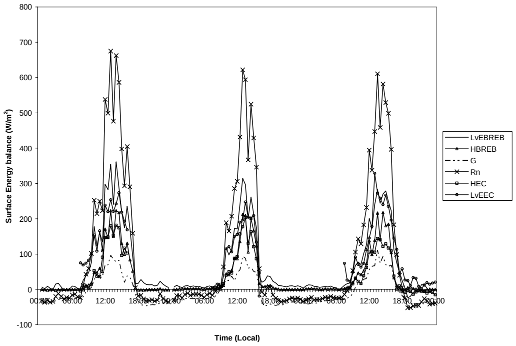

Fig.4a. Surface energy balance with a comparison of the heat fluxes determined directly using eddy correlation and the Bowen ratio energy balance methods for 1st – 3rd March, 2004.

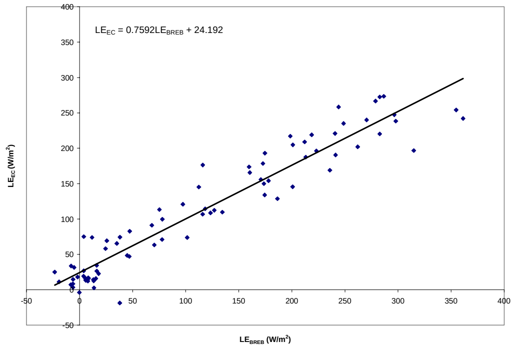

Fig.4b. Comparison of EC and BREB latent heat fluxes.

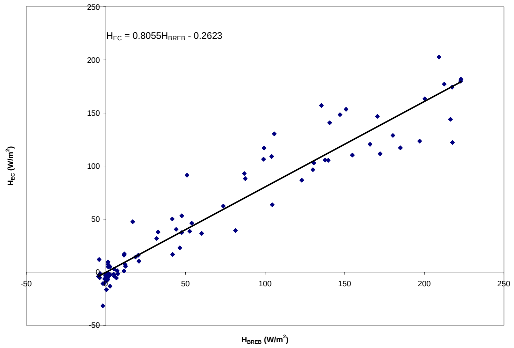

Fig.4c. Comparison of EC and BREB sensible heat fluxes.

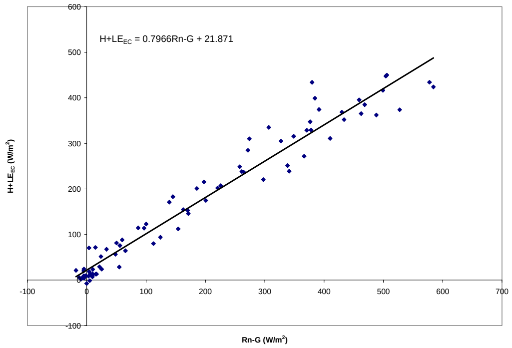

Fig. 4d. Surface energy balance closure at the site.

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

$LE_{EC} = 0.7592LE_{BREB} + 24.192$

$H_{EC} = 0.8055H_{BREB} - 0.2623$

$H+LE_{EC} = 0.7966Rn-G + 21.871$

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

The eddy diffusivities of momentum (Km) and heat (Kh and Kw) show strong sensitivity to stability variations. Fig. 5 shows the variation of Km, Kh and Kw with stability for the height intervals 1 – 5 m and 1 – 10 m. Due to the very weak wind no meaningful gradients were obtained from the 5 – 10 m height interval.

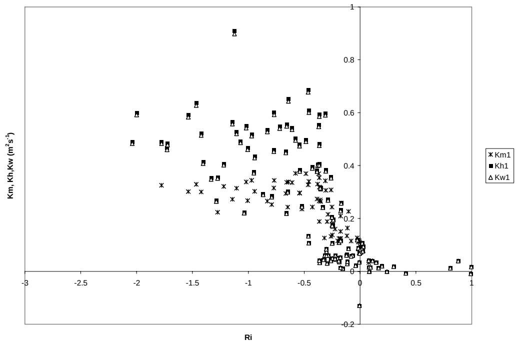

Fig.5a. Variation of Km, Kh and Kw with stability for the height interval 1 – 5 m.

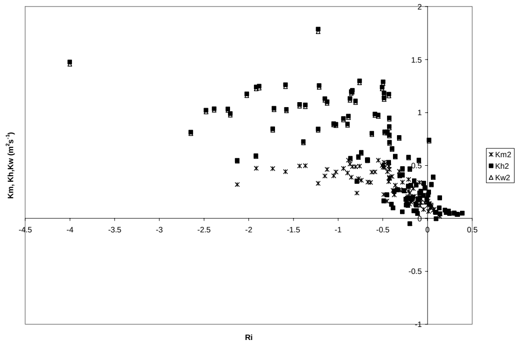

Fig.5b. Variation of Km, Kh and Kw with stability for the height interval 1 – 10 m.

Observation shows that, there exists a sharp decrease in the eddy diffusivities as stability increases. It is also observed that they reach larger maxima for the higher level interval. 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 Km tend to vanish and approaches zero even before $Ri_{critical}$ = 0.25. The limiting values observed are Ri = 0.08 and Ri = 0.14 for the lower and higher height intervals respectively, see fig.5. Similar results have been obtained by Oke, 1970 and Kondo et al., 1978. Following in the same fashion Kh and Kw decreases rapidly with increasing stability and for Ri > 0.2, Kh and Kw 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 Kh and Kw 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 eddy diffusivities of heat, Kh and momentum, Km ($\mu_K = \frac{K_h}{K_m}$) give an indication of the nature of the turbulent eddy exchange processes going on in the surface layer. When μ_K > 1 (Kh > Km), the transfer of heat is greater than that of momentum. If on the other hand μ_K < 1 (Kh < Km), the transfer of momentum is greater than that of heat. Generally, it is observed that μ_K 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 μ_K 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 1 also under weak instability conditions in the range - 0.005 > Ri > 0.5, see fig.6. This implies that the decrease of Kh is more than that of Km, indicating a much higher transfer of momentum than of heat.

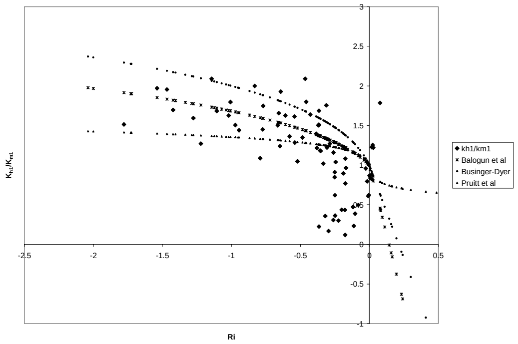

Fig.6a shows the variation of μ_K with Ri for the height interval 1 – 5m.

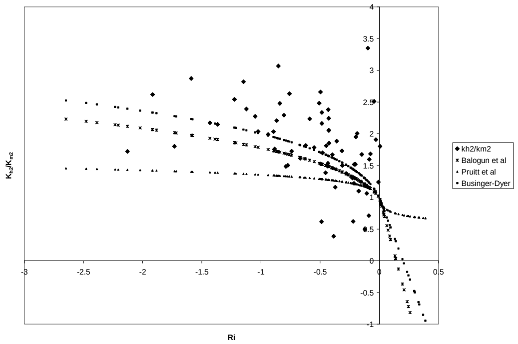

Fig.6b shows the variation of μ_K with Ri for the height interval 1 – 10m.

Some results regarding the empirical fits to μ_K from earlier investigations (Businger et al., 1971, Dyer and Hicks, 1970 and Pruitt et al., 1973). These indicate that these relationships do not agree with this data set. A tentative suggested empirical fit appears to predict the behaviour of data better, at least for the lower level height interval 1-5 m. These relationships are listed below.

Unstable conditions:

$$\frac{K_h}{K_m} \approx \frac{K_w}{K_m} = (1-16Ri)^{0.25} \tag{a}$$

$$\frac{K_h}{K_m} \approx \frac{K_w}{K_m} = (1-15Ri)^{0.25} \tag{b}$$

$$\frac{K_h}{K_m} \approx \frac{K_w}{K_m} = (1-60Ri)^{0.074} \tag{c}$$

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

Stable conditions:

$$\frac{K_h}{K_m} \approx \frac{K_w}{K_m} = (1-5Ri) \tag{a}$$

$$\frac{K_h}{K_m} \approx \frac{K_w}{K_m} = (1-4.7Ri) \tag{b}$$

$$\frac{K_h}{K_m} \approx \frac{K_w}{K_m} = (1-95Ri)^{-0.11} \tag{c}$$

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

Where a and b are credited to Dyer and Hicks 1970 and Businger et al. 1971, c is that of Pruitt et al., 1973, while d is the suggestion by the authors of this paper. None of these relationships appears to fit the data well for the 1 – 10 m height interval, and tend to fall below the data points, see fig.6b. The reason for this may be that the gradient at this higher level may not be equilibrium with the surface, indicating the presence of an internal boundary layer and influence of fluxes from other source areas at this level. Further analysis including flux foot print analysis may shed some light on this.

Conclusion and further Research

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 aerodynamic flux-gradient relationships, Bowen ratio energy balance and direct eddy correlation 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 behaviour better has been suggested.

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