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ESTIMATION OF BULK TRANSFER COEFFICIENTS OF MOMENTUM AND SENSIBLE HEAT FROM A HUMID TROPICAL BARE SURFACE

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ABSTRACT

The bulk transfer coefficients of momentum (C_D) and sensible heat (C_H) were determined from the field observation carried out on Nigerian Micrometeorological Experimental (Nimex_1) field, Ile-Ife, Nigeria. Direct determination of the transfer coefficients was done using the eddy correlation method. Analytical method was also used to compute the transfer coefficients with the use of bulk transfer algorithms. The C_D and C_H values obtained from eddy covariance method were higher than those from analytical method. Usage of the transfer coefficients obtained from analytical method will lead to slight underestimation of the fluxes. The atmospheric stability parameter z/L values were positive at nights (stability) but negative during the day (instability). The C_D and C_H values were higher during the day (instability) and lower at nights (stability). Whenever z/L was positive the sensible heat flux was negative.

Keywords: Bulk transfer coefficient of momentum, bulk transfer coefficient of sensible heat, stability, instability, atmospheric stability parameter.

INTRODUCTION

The bulk transfer coefficients of momentum and sensible heat over land surface controls the flux of sensible heat from the earth's surface. Atmospheric numerical models and energy budget studies require the bulk transfer coefficients of momentum (C_D) and sensible heat (C_H) to estimate the surface fluxes of momentum and sensible heat (H), (Jordan *et al*., 1999; Briegleb *et al*., 2004). The bulk transfer coefficients vary with regions and dynamics of the atmosphere (Stull, 1988) and accurate bulk transfer coefficients are necessary for numerical models. Hence the need for the validation of existing bulk transfer algorithm with values obtained from direct measurement of fluxes of momentum and sensible heat.

Values of C_D and C_H determined from other places are mostly employed in this part of the tropics since little or no work has been done in this area to determine the values. Errors set in when constant values are used throughout all the hours of the day, so diurnal values are needed.

Micrometeorological experiments are scarce in this part of the tropics and Nigerian Micrometeorological Experiment (Nimex_1) is one of the most comprehensive experiments in this area. The first phase of Nimex measurement started from15 February to 10 March 2004 at Ile-Ife Nigeria. The bulk transfer coefficients of momentum and sensible heat fluxes were not known in this part of the tropics, hence the need for this investigation.

Study Area

The data used in this investigation were collected at Nimex_1 site. The site is situated in southwestern Nigeria, at Obafemi Awolowo University, Ile-Ife ($7^0 33'$N, $4^0 33'$E). This is a tropical area where there are two main seasons viz: wet (April to October) and dry (November to March). The tropical climate is influenced by two air masses: the rain-bearing southwest monsoon originating from the Atlantic Ocean and the dry northeasterly continental air mass passing over the Sahara desert. The position of the Intertropical Convergence Zone (ITCZ) controls the amount, seasonal distribution and type of rainfall as well as the length of the wet season at any location in Nigeria. The region south of the ITCZ, depending on its distance from ITCZ, usually receives more rainfall while the region north of it experiences dryness. The ITCZ gets to its most northern position in July- August and its most southern position in December- February, at which time the dry season sets in (Balogun, 1981). The investigation at the Nimex_1 site was done during the transition period in-between the dry and wet season in 2004 to capture the dry and wet scenarios.

MATERIALS AND METHODS

Meteorological Measurement

The Nimex_1 field was located on an agricultural farm land at Teaching and Research farm, Obafemi Awolowo University Ile-Ife, Nigeria. The elevation of the field is 288 m.a.s.l. It is more or less a bare ground with canopy height less than 0.3 m as the bush on the experimental area was cleared just before the commencement of the

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project. Eddy covariance system comprising of a three dimensional ultrasonic anemometer (model USA-1) and a Krypton hygrometer (model KH2O) were deployed on the field. The ultrasonic anemometer was sampled at 16Hz giving the turbulent wind components, u, v, w and sonic temperature, T_s. The Krypton hygrometer was sampled at 8Hz giving the turbulent absolute humidity. The data were analysed and turbulent fluxes were calculated. The details of the analyses of turbulent fluxes were as presented in Mauder *et al*. (2007), Jegede *et al*. (2004a) and Jegede *et al*. (2004b).

The ground heat flux and net radiation were measured for the determination of the available energy. A self calibrating heat flux plate was used to measure ground heat flux at 0.02m, 0.05m, 0.1m and 0.3m depths. The Kipp and Zonen CNR1 net radiometer was used to measure net radiation.

Profile measurements of wet and dry bulb temperature at 0.9m, 4.9m and 10m height were done using Frakenberger Psychrometer; wind speed was measured at heights 0.7 m, 1.2 m, 2.2m, 3.3m, 5.2m, 7.2m, 10.2 m, and 14.8m with cup anemometer (A101M1/A100L2) and the wind direction was measured at 14.8m level using a rotating vane. Soil surface temperature was measured by Infrared Pyrometer KT 1582D. Soil temperature at depths 0.05 m, 0.1m, and 0.3m was measured by PT-100Ω Thermistor Thermocouple. Campbell Scientific CR10X data- loggers were used in storing the data. The details of the equipment used are stated in table 1.

Day of year (DOY)s 63, 66 and 67 were considered for this investigation. The profile and eddy covariance data were complete for DOYs 66 and 67 while there were data from 0700hr to 2400hour for DOY 63. The DOYs were chosen due to their relatively complete data for both eddy covariance and profile data.

Data analysis and quality control test

The effective fetch in percentage of the theoretical fetch from the field computed according to Gockede *et al*. (2006) were greater than 90 under unstable stratification for most wind directions, greater than 80 under neutral condition and the least was 62 for stable stratification with wind direction of 150^0 (SSE), Mauder *et al*. (2007). On daily basis the quality of profile of meteorological data from 15 m mast was checked by simple visual test according to (Foken, 2003). The quality of the eddy covariance data was checked using TK2, a software package written by Mauder and Foken (2004). It was developed at Obafemi Awolowo University, Ile-Ife, Nigeria and the University of Bareuth during the period of the experiment (Nimex_1). The guides for surface flux measurement and analysis given by Lee *et al*. (2004) were considered by Mauder and Foken (2004). The values that were not physically possible were removed before the calculation of the variances and covariances using the spike detection method of Vickers and Marhrt (1997) that was based on Hojstrup (1981). Cross correlation analysis was done for each averaging interval of the sonic anemometer and Krypton hygrometer that were sampled at different frequencies. This was done to determine the time delay between the two sensors. The method applied for cross wind correction for the correction of sonic temperature was that of Liu *et al*. (2001). Coordinate transformation was done using the planar fit method of Wilczak *et al*. (2001). Spectral models of Kaimal *et al*. (1972) and Hojstrup (1981) were employed for spectral corrections following Moore (1986). The buoyancy flux was converted into sensible heat flux following Schotanus *et al*. (1983). The latent heat flux was also corrected for fluctuations in density and mean vertical mass flow according to Webb *et al*. (1980). Test for steady state conditions and well- developed turbulence was carried out according to Foken and Wichura (1996) and Foken *et al*. (2004). All the above tests and analysis were incorporated

Table 1. Equipment deployed on Nimex_1 site.

Parameter	Sensor	Accuracy
Data acquisition	Campbell Scientific Data-logger CR10X	Not applicable
Wind direction	Vector Instruments Wind vane W200P	$\pm 2^0$
Wind speed	Vector Instruments Cup anemometer A101ML/A100L2	1^0
Wet and dry bulb air temperature	Theodor Friedrichs FrakenbergerPsychrometer	$\pm 0.05\ ^0$C
Soil surface temperature	Heitronics Infrared Pyrometer KT1582D	$\pm 0.5^0$C
Soil temperature	Campbell Scientific Thermistor Thermocouple	$\pm 1^0$C
Soil heat flux	Hukseflux HFP01SC self calibrating Heat flux plate	±3%
Net radiation	Kipp and Zonen CNR1 net radiometer	±10% of daily total
3D wind speed	Metek USA-1 3-D ultrasonic anemometer	$0.01ms^{-1}$
Water vapour content	Campbell Scientific KH20 krypton hygrometer	$0.15m^3g^{-1}cm^{-1}$(sensitivity)

into (Mauder *et al*., 2007).

Parameterization of bulk transfer coefficient of momentum and sensible heat

The bulk momentum (τ) and sensible heat fluxes are given by:

$$\tau = \rho C_D U^2 \quad 1$$

and

$$H = \rho C_p C_H U(T_g - T_a) \quad 2$$

where ρ is the density of air

C_p is the specific heat of air at constant pressure

U is the mean horizontal velocity

T_g is the soil surface temperature, and

T_a is the air temperature

The bulk transfer coefficients are computed as: [3]

$$C_D = \tau / \rho U^2 \quad 3$$

$$C_H = H / \rho C_p U(T_g - T_a) \quad 4$$

$$C_H = (\overline{w'T'}) / U(T_g - T_a) \quad 4b$$

where w = vertical wind speed, and T = air temperature from sonic system .

The turbulent momentum flux and the friction velocity (u_*) are given by McPhee (2002) and Stull (1988) as:

$$\tau = \rho((\overline{u'w'})^2 + (\overline{v'w'})^2)^{1/2} \quad 5$$

$$u_*^2 = [(\overline{u'w'})^2 + (\overline{v'w'})^2]^{1/2} \quad 6$$

Bulk flux Algorithm

The bulk transfer coefficients of momentum and heat were computed from Garratt (1992) and Stull (1988) as:

$$C_D = k^2 / (\ln(z/z_0) - \psi_m)^2 \quad 7$$

$$C_H = k^2 / [(\ln(z/z_0) - \psi_m)(\ln(z/z_0) - \psi_h)] \quad 8$$

Where z is the height of measurement

z_0 is the momentum roughness length

ψ_m and ψ_h are the integral form of the Monin Obukhov similarity functions ϕ_m and ϕ_h which are dimensionless wind shear and temperature gradients respectively given by Zeng (1998) as:

$$\phi_m = \begin{cases} (1 - 16\zeta)^{-1/4} & \zeta < 0 \\ (1 + 5\zeta) & 0 < \zeta < 1 \end{cases} \quad 9$$

$$\phi_h = \begin{cases} (1 - 16\zeta)^{-1/2} & \zeta < 0 \\ (1 + 5\zeta) & 0 < \zeta < 1 \end{cases} \quad 10$$

The values of ϕ_m and ϕ_h under very unstable conditions were given by Kader and Yaglom (1990) as:

$$\phi_m = 0.7 k^{2/3} (-\zeta)^{1/3} \quad 11$$

$$\phi_h = 0.9 k^{4/3} (-\zeta)^{1/3} \quad 12$$

Under very unstable conditions, the similarity functions were described by Hostlag *et al*. (1990) as

$$\phi_m = \phi_h = 5 + \zeta \quad 13$$

Utilizing equations (9) to (13), ψ_m and ψ_h will take the form:

$$\psi_m = \begin{cases} 2\ln\left(\frac{1+x}{2}\right) + \ln\left(\frac{1+x^2}{2}\right) - 2\tan^{-1} x + \frac{\pi}{2} & , for \ -2 < \zeta < 0 \\ -5\zeta & , for \ 0 \le \zeta \end{cases} \quad 14$$

$$\psi_h = \begin{cases} 2\ln\left(\frac{1+x^2}{2}\right) & , for \ -2 < \zeta < 0 \\ -5\zeta & , for \ 0 \le \zeta \end{cases} \quad 15$$

with

$$x = (1 - 16\zeta)^{1/4} \quad 16$$

Equations (14) to (16) were substituted into equations (7) and (8) to calculate C_D and C_H for the parametric determinations of the respective coefficients.

RESULTS AND DISCUSSION

Diurnal variation of C_D values

The wind direction recorded during the period of this investigation was north easterly which conforms to the expected prevailing wind at the transition period from dry to wet season. The wind speed was low (< $3ms^{-1}$) throughout with night values lower (< 2 ms^{-1}). Half hourly meteorological and eddy covariance data were used; the resulting half hourly C_D values obtained from the eddy covariance and analytical methods were different. The mean daily values obtained from the analytical method were one order lower than those obtained from the eddy covariance method. The maximum diurnal values obtained from the eddy covariance method were higher, higher C_D values from eddy covariance method has been reported (Zhang *et al*., 2002). The analytical method gave the daily mean of C_D of 1.66 x 10^{-3} with standard deviation of 8.62 x 10^{-3} while the eddy covariance method gave a mean value of 2.28 x 10^{-2} with standard deviation of 1.71 x 10^{-2} for DOY 63. On DOY 66 analytically obtained C_D had a daily mean of 1.54 x 10^{-3} with standard deviation of 4.75 x 10^{-4} while the mean daily C_D value obtained from eddy covariance method was 1.24 x 10^{-2} with standard deviation 5.86 x 10 $^{-3}$. On DOY 67 the mean daily values for analytical and eddy covariance methods were respectively 2.70 x 10^{-3} and 2.52 x 10 $^{-2}$. The standard deviations were 6.78 x 10 $^{-3}$ and 6.33 x 10 $^{-2}$ for analytical and eddy covariance methods respectively, showing that eddy covariance computed values were

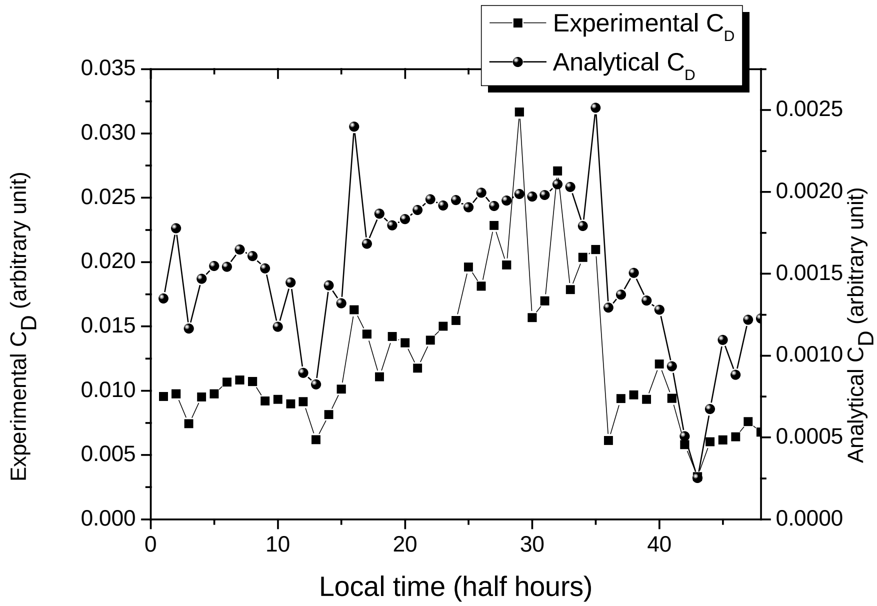

Fig. 1. Diurnal variation of bulk transfer coefficient of momentum, C_D for DOY 66.

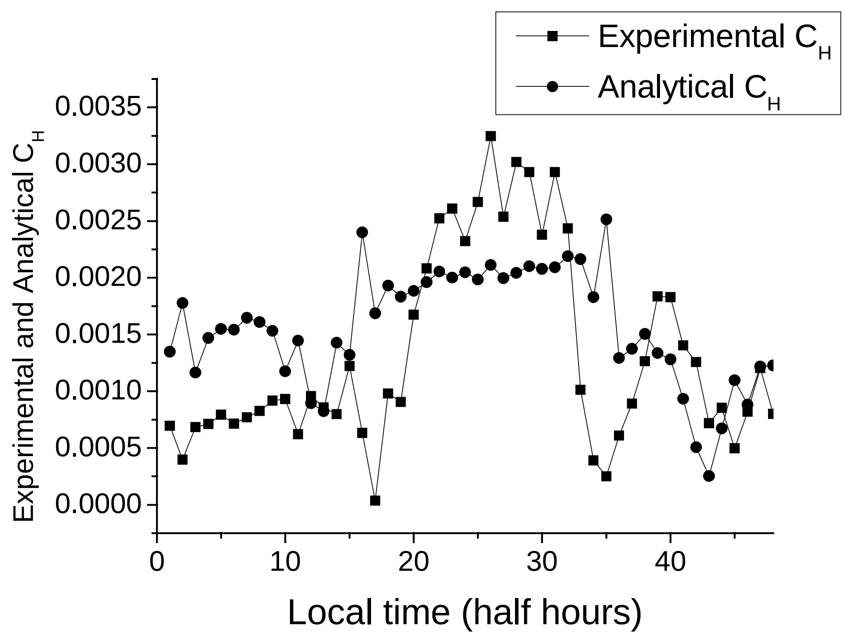

Fig. 2. Diurnal variation of bulk transfer coefficient of sensible heat (C_H) for DOY 66 (in arbitrary unit).

more scattered than the analytically computed ones. Diurnal variation is clearly seen in C_D values with maximum around noon and low values at night and morning hours figure 1.

Diurnal variation of C_H values

Diurnal variation of C_H was similar to that of C_D with maximum at noon and low values at evening, night and early in the morning, figure 2. The C_H values obtained from analytical and eddy covariance methods were comparable, the values were in the same order. Higher daily maximum and mean C_H values were obtained from eddy covariance method. On DOY 66 daily mean 1.57 x 10^{-3} and 1.32 x 10^{-3}, maximum 2.50 x 10^{-3} and 3.25 x 10^{-3} and standard deviation 5.05 x 10 $^{-4}$ and 8.56 x 10 $^{-4}$ were found respectively for analytical and eddy covariance methods. The maximum C_H was higher than the value obtained by Ishikawa and Kodama (1994) on snowmelt

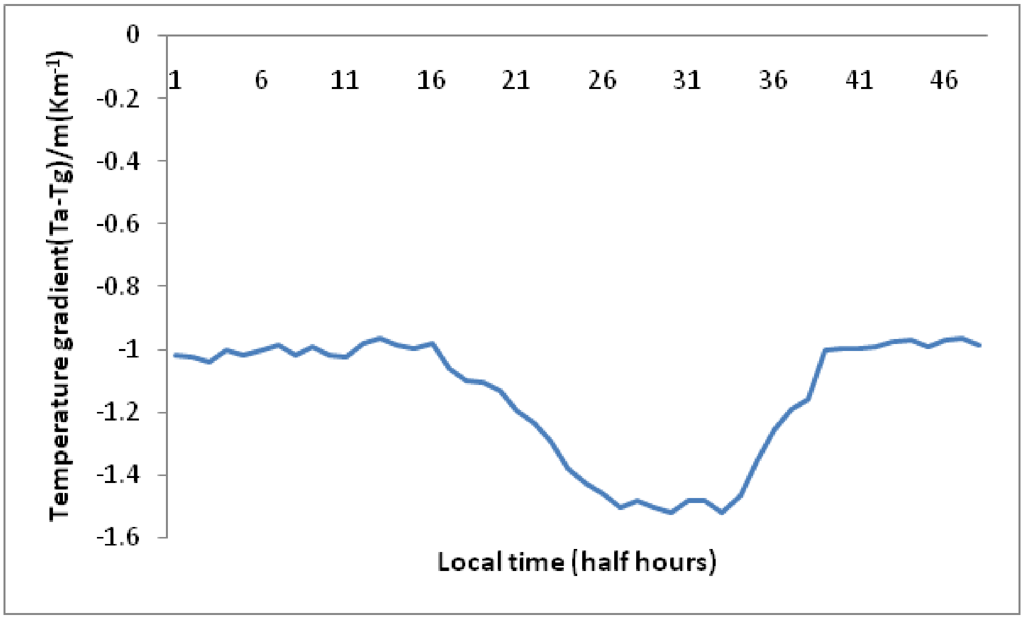

Fig. 3. Diurnal variation of temperature gradient for DOY 66.

surface (2.30×10^{-3}). The values obtained fitted well into the typical range of values for C_H (Stull, 1988).

On DOY 67 the analytical and eddy covariance methods respectively gave mean daily C_H values of 1.70×10^{-3} and 2.52×10^{-3}, maximum C_H values of 7.65×10^{-3} and 1.31×10^{-2} and standard deviations of 1.36×10^{-3} and 2.50×10^{-3}.The eddy covariance computed C_H values had more scatter than the analytically computed values. The maximum C_H values obtained on DOY 63were 3.78×10^{-3} and 6.22×10^{-3} for analytical and eddy covariance methods respectively.

Comparison of the C_D and C_H values obtained from eddy covariance and analytical methods

The C_D and C_H values obtained from the eddy covariance method were taken to be more reliable since they were from directly measured friction velocity and covariance of vertical wind and temperature. Assumptions were made in the derivation of equations (9) to (15); variable meteorological conditions were not included in the analytical equations. The values obtained from eddy covariance method were generally higher than those from the analytical method since variable stability conditions were assumed uniform in the analytical method. (Zhang *et al*., 2002) also obtained higher C_D and C_H values from eddy covariance method than from the other methods.

The temperature gradient $(T_a\text{-}T_g)$ m^{-1} was found to be

Diurnal variation of temperature gradient

negative both during the day and at night during the transition period contrary to the expectation of positive values at nights. The negative gradient implies a positive difference between soil surface temperature and the air temperature at any height up to 10 m $(T_g\text{-}T_a)$ (Fig. 3); possibly due to the strong stability at night and high value of temperature in this area. It has been reported that $(T_g\text{-}T_a)$ was positive at night when the temperature was high but negative when the temperature was low, in 82% of the stations considered in Alpine areas; only in few of the stations did thermal inversion occur, at night Colombi *et al*. (2007). The night time values of T_g were also found to be close to or lower than T_a, (Prigent *et al*., 2003). Temperature is always high in this part of the tropics so soil surface temperature may be higher than the air temperature even at night when there is strong stability. In the early hours of the day, evening and nights $T_g\text{-}T_a$ reduced greatly since there was no input from the sun but it never went below zero, as the case may be in cold regions. The C_H was positive throughout all the hours of the day and night in most published literature. The sign of the temperature difference between the ground and the air $(T_g\text{-}T_a)$; which is positive during the day while it is negative at night, controls the sign of the sensible heat flux in most places. Generally, in this part of the tropics, during the transition period from dry to wet season, the ground temperature was always higher than the air temperature making the temperature difference (Tg-Ta) to be positive throughout the day and night. This makes the sign of C_H to change to negative whenever the value of sensible heat flux is negative. This occurs when the stability parameter z/L is positive, when the atmosphere is stable, this is so at nights and before sunrise. To keep the sign of C_H positive throughout, negative sign was used to multiply the value of sensible heat flux. When the profile of air temperature was considered from 1m to 10 m; there

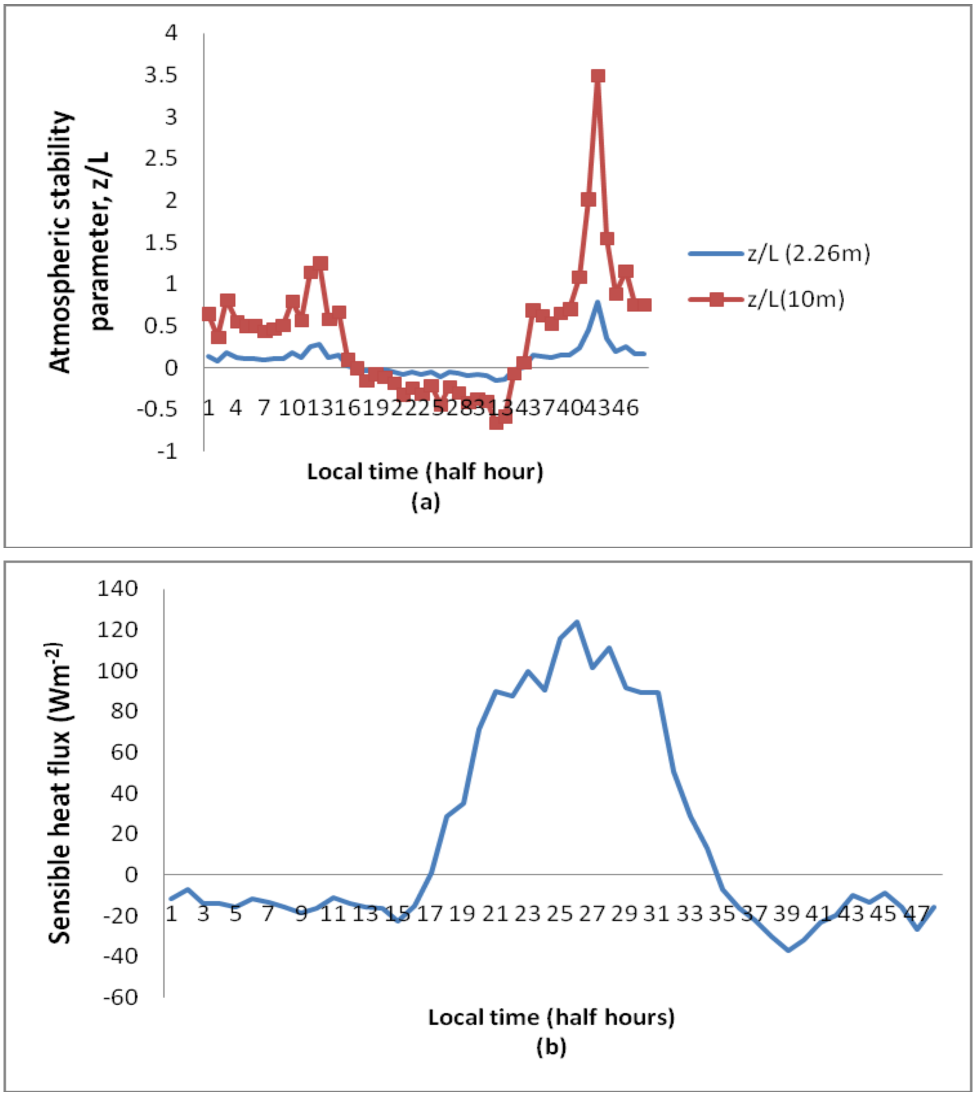

Fig. 4. Diurnal variation of (a) stability parameter, z/L at z= 2.26 m and 10 m and (b) sensible heat flux on DOY 66.

was always inversion at nights with temperature at 1m being the minimum, this is in agreement with existing observation that the minimum temperature on calm, clear and strongly stable night on grass, snow and bare surfaces was between 1 and 50 cm, (Oke, 1970). The minimum was not on the surface.

Diurnal variation of sensible heat flux and stability parameter, z/L

The sign of the sensible heat flux was opposite to the sign of z/L. When z/L was positive, the value of sensible heat flux was negative. The z/L is generally positive at nights, in the evening and early in the morning, at this time the atmosphere is stable so transfer coefficient is reduced. The positive sign of the temperature difference necessitates adding a negative sign to the sensible heat flux whenever z/L is positive to maintain the positive value of the turbulent bulk heat transfer coefficient. Sensible heat flux can be underestimated when the C_H values obtained from analytical method are used to compute it. The sensible heat flux will also lack diurnal variation when a constant bulk transfer coefficient is used for all the hours of the day (Fig. 4).

CONCLUSION

The importance of diurnal C_H and C_D values in modeling the energy budget of the earth and their unavailability in this part of the tropics led to their determination using both analytical and experimental methods. The experimental method was used to validate the analytical method. The experimental method gave lower diurnal C_H and C_D values with higher standard deviations. The obtained values were in the same range as those obtained for other areas, Stull (1998), Zhang *et al*. (2002) and Ishikawa and Kodama (1994). These results can serve as a data base for this area.

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REFERENCES

Balogun, EE. 1981. Seasonal and spatial variations in thunderstorm activity over Nigeria. Weather. 36:192-197.

Briegleb, BP., Bitz, CM., Hunke, EC., Lipscomb, WH., Holland, MM., Scharamm, JL. and Moritz, RE. 2004. Scientific description of the sea ice component in the Community Climate System Model, version three. NCAR Tech. Note NCAR/TN-463+STR.pp70.

Colombi, A., De Michele, C., Pepe, M. and Rampini, A. 2007. Estimation of daily mean air temp from MODIS LST in Alpine areas. EARSeL e Proceedings. 6(1):38-46.

Foken, T. 2003. Angewandte Meteorologie. Mikrometeorologische Methoden. Heidelberg. Springer. pp289.

Foken, T., Go¨ckede, M., Mauder, M., Mahrt, L., Amiro, BD. and Munger, JW. 2004. Post-field data quality control. In: Handbook of micrometeorology. A guide for surface flux measurements. Eds. Lee, X., Massman, WJ. and Law, BE. Dordrecht: Kluwer. 181-208.

Foken, T. and Wichura, B. 1996. Tools for quality assessment of surface-based flux measurements. Agric Forest Meteorol. 78:83-105.

Garratt, JR. 1992. The Atmospheric Boundary Layer. Cambridge University Press. pp316.

Go¨ckede, M., Markkanen, T., Hasager, CB. and Foken, T. 2006. Update of footprint-based approach for the characterization of complex measurement sites. Bound-Layer Meteor. 118:635-655.

Højstrup, J. 1981. A simple model for the adjustment of velocity spectra in unstable conditions downstream of an abrupt change in roughness and heat flux. Bound-Layer Meteor. 341–356.

Højstrup, J. 1993. A statistical data screening procedure. Meas Sci Technol. 4:153-157.

Hostlag, AAM., de Bruijn, EIF. and Pan, HL. 1990. A high resolution air mass transformation model for short-range weather forecasting. Monthly Weather Review. 118:1561-1575.

Ishikawa, N. and Y. Kodama, 1994. Transfer coefficients of sensible heat on a snow melt surface. Meteorology and Atmospheric Physics. 53(3-4):233-240. doi:1007/BF01029614.

Jegede, OO., Okogbue, EC. and Balogun, EE. (eds.) 2004[a]. Proceedings of the Workshop on the Nigerian Micrometeorological Experiment (Nimex-1) July 15 2004, Ile-Ife, Nigeria.

Jegede, OO., Mauder, M., Okogbue, EC., Foken,T., Balogun, EE., Adedokun, JA., Oladiran, EO. , Omotosho, JA., Balogun, AA., Oladosu, OR., Sunmonu, LA., Ayoola, MA., Aregbesola, TO., Ogolo, EO., Nymphas, EF., Adeniyi, MO., Olatona, GI., Ladipo, KO., Ohamobi, SI., Gbobaniyi, EO. and Akinlade, GO. 2004[b]. The Nigerian Micrometeorological Experiment (NIMEX-1): An overview. Ife Journal of Science. 6(2):191-202.

Jordan, RE., Andreas, EL. and Makshtas, AP. 1999. Heat budget of snow-covered sea ice at North Pole 4. J Geophys Res. 104:7785-7806.

Kader, BA. and Yaglom, AM. 1990. Mean fields and fluctuation moments in unstable stratified turbulent boundary layers. J Fluid Mech. 212:637-661.

Kaimal, JC.,Wyngaard, JC., Izumi, Y. and Cote, OR. 1972. Spectral characteristics of surface layer turbulence. Quart J Roy Meteor Soc. 98:563-589.

Lee, X., Massman, W. and Law, BE. (eds). 2004. Handbook of micrometeorology. A guide for surface flux measurement and analysis. Dordrecht: Kluwer Academic Press. pp250.

Liu, H., Peters, G. and Foken, T. 2001. New equations for sonic temperature variance and buoyancy heat flux with an omnidirectional sonic anemometer. Bound-Layer Meteor. 100:459-468.

Mauder, M. and Foken, T. 2004. Documentation and instruction manual of the eddy covariance software package TK2. Arbeitsergebnisse, Universitat Bayreuth, Abt. Mikrometeorologie. 26:44.

Mauder, M., Jegede, OO., Okogbue, EC., Wimmer, F. and Foken, T. 2007. Surface energy balance measurements at a tropical site in West Africa during the transition from dry to wet season. Theor. Appl. Climatol. 89:171-183.

McPhee, MG. 2002. Turbulent stress at the ice/ocean interface and bottom surface hydraulic roughness during the SHEBA drift. J Geophys Res. 107(C10):8037. (10.1029/2000JC000633).

Moore, CJ. 1986. Frequency response corrections for eddy correlation systems. Bound-Layer Meteor. 37:17-35.

Oke, TR. 1970. The temperature profile near the ground on calm clear nights. Quart J Roy Meteor Soc. 96(407):14-23. doi: 10.1002/qj.49709640703.

Prigent, C., Aires, F. and Rossow, WB. 2003. Land surface skin temperatures from a combined analysis of microwave and infrared satellite observations for an all weather evaluation of the differences between air and skin temperatures. J Geophys Res. 108(D10):4310, doi:10. 1029/2002JD002301.

Schotanus, P., Nieuwastadt, FTM. and DeBruin, HAR. 1983. Temperature measurement with a sonic anemometer and its application to heat and moisture fluctuations. Bound-Layer Meteor. 26:81-93.

Stull, RB. 1988. An introduction to boundary layer meteorology. Kluwer Acad. Publ., Dordretch, Boston, London. 262-263.

Vickers, D. and Mahrt, L. 1997. Quality control and flux sampling problems for tower and aircraft data. J Atmos Oceanic Technol. 14:512-526.

Webb, EK., Pearman, GI. and Leuning, R. 1980. Correction of the flux measurements for density effects due to heat and water vapour transfer. Quart J RoyMeteor Soc. 106: 85-100.

Wilczak, JM., Oncley, SP. and Stage, SA. 2001. Sonic anemometer tilt correction algorithms. Bound-Layer Meteor. 99:127-150.

Zeng, X., Zhao, M. and Dickinson, RE. 1998. Intercomparison of bulk aerodynamic algorithms for the computation of sea surface fluxes using TOGA COARE and TAO data. J Climate. 11:2628-2644.

Zhang Q., Wei, G., Huang, R. and Cao, X. 2002. Bulk transfer coefficients of the atmospheric momentum and sensible heat over desert and Gobi in arid climate region of Northwest China. Science in China (Series D). 45(5):468-480.

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