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A field study of the mean surface layer structure in Sub-Saharan West Africa: The pre-monsoon (Dry) season

OLUWAGBEMIGA O. JEGEDE*

Deptt. of Physics, Obafemi Awolowo University, Ile-Ife, Nigeria

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सार — नाइजीरिया के ओस (7° 26′,4 ° 35′ पू.) में एक 23 मीटर ऊँचे स्तम्भ पर लगे उपकरणों से लिए गए माइक्रो मौसम वैज्ञानिक प्रेक्षणों के आधार पर पश्चिमी अफ्रीका के उपसहारा क्षेत्र में अधिकतम शुष्कता के समय (जनवरी-फरवरी) भूतल सतह की औसत अविसंरचना के संबंध में प्रमुख स्थलीय अध्ययन की सूचना प्राप्त हुई है। इन परिणामों से क्षैतिजीय वायु और तापमान तथा नेट विकिरण के मिश्रित उर्ध्वधर प्रोफाइलों का पता चला है। दैनिक पद्धति पर भी चर्चा की गई है। प्रक्षोभ तीव्रता $\sigma\mu/<u>$ प्रवण रिचर्डसन नम्बर Ri तथा संवेग और उष्मा के फलक्सों के आकलनों को प्रोफाइल डाटा से समाकलित किया गया।

केवल दिन के समय में जब ऊपरी सतह पर सौर उष्मा प्रायः तीव्र होती है तब सतह प्रवाह को प्ररूपित करने वाली मन्द पवनों (<3 m/s) के कारण भूतल सतही प्रक्षोभ ही प्रमुख होता है। रात्रि के समय प्रक्षोभ अत्यंत अवरुद्ध तथा अंतरायिक हो जाता है। अस्थिर धरातलीय सतह में आनुभविक फलक्स प्रोफाइल सम्बद्धों द्वारा संवेग तथा उष्मा के लिए समान कार्यकलापों को सुस्थापित किया गया है। तथापि स्थिर अवस्थाओं के लिए यह उपयुक्त नहीं है। इस अध्ययन के प्रमुख परिणामों से धरातल सतह की विशेषताओं और निम्न अक्षांश पर धरातलीय सतह के आनुभविक सम्बद्धों की जाँच की उपयुक्तता के संबंध में विस्तृत विवरण प्रस्तुत करने में सहायता मिलेगी।

ABSTRACT. A major field study of the mean surface layer (SL) structure at the peak of the dry season (January-February) in the sub-Saharan West Africa is reported from micro-meteorological measurements conducted on an instrumented 23m mast at Osu (7°26′N, 4°35′E), Nigeria. The results presented comprised of the vertical profiles of horizontal wind and temperature, and the net radiation. Also, the diurnal patterns were discussed. Estimates of the turbulence intensity $\sigma u/<u>$, the gradient Richardson number R_i, and the fluxes of momentum and heat were deduced from the profile data.

Due to the weak winds (<3m/s) that typified the near-surface flow, the SL turbulence was prominent only for daytime when solar heating of the surface is usually intense. At night time the turbulence is highly suppressed and intermittent. In the unstable SL, the similarity functions for momentum and heat are well fitted by empirical flux-profile relationships, however, this is not valid for the stable conditions.

The major result of this study represents a contribution towards explaining in detail, the surface layer characteristics and testing applicability of SL empirical relationships at the low latitudes.

Key words - Temperature profile,, Turbulence, Net radiation

1. Introduction

The sub-Saharan (tropical) region of West Africa is located between the equator and reaching a northward extent of about latitude 20°N. The area experiences tropical climate such that the year can roughly be divided into two seasons: wet (April-October) and dry (November-March). This change of seasons occurs in association with the meridional movement of the Inter-Tropical Discontinuity (ITD) line which represents the demarcation at the surface, between the southwesterly and the northeasterly winds over the sub-continent (Adejokun, 1966). Based on the latitudinal positions of the ITD are the well recognized weather zones within the sub-region (Hamilton and Archbold, 1945).

The vertical structure of the tropical boundary layer is quite distinct from that observed at both the mid and high latitudes. The layer extends from the surface up to the trade-wind inversion level, which is very stably stratified such that it impedes the vertical transfer of energy and

*Present affiliation: Meteorologisches Observatorium, Lindenberg, 15864 Lindenberg, Germany

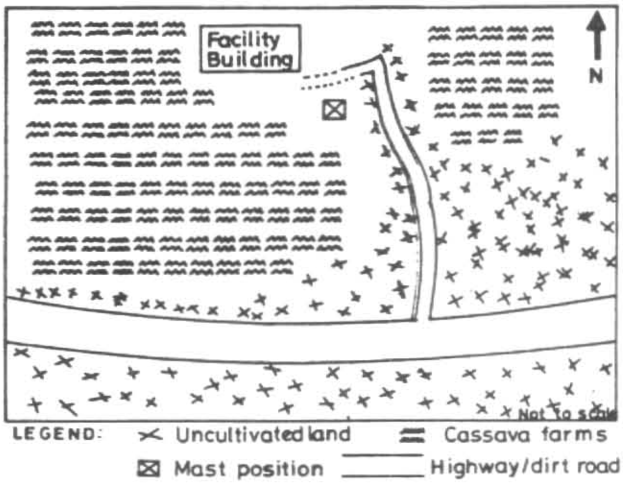


Fig.1. Sketch of the experimental site

momentum, thereby providing a lid on the cumulus convection (McBean *et al.* 1979). The lowest few tens of meters of the boundary layer represent the surface layer (SL), where turbulent fluxes and stress vary by less than 10% of their magnitude at the surface (also termed as the constant flux layer). Typically, the tropical SL depth varies between 20 and 100m, and it shows a slight decrease in potential temperature with height but a stronger decrease in the moisture content.

Due to the proximity of the SL layer to the earth's surface, it has been studied extensively through several micro-meteorology field measurement programs (see Haugen, 1986). So far, only few profile measurements of the SL structure have been conducted in tropical regions including the GATE field programme which focuses on the ocenic surface layer. Therefore, there are still many outstanding questions pertaining to the specific roles of tropical SL in the near surface energy exchange processes remaining to be answered. Added to this is the need to re- evaluate existing SL parameterizations in the tropics, since many of the well quoted empirical relationships are based on the data sourced mostly from the mid-latitudes (see Van Ulden and Holtslag, 1982).

Profile measurements of windspeed and temperature reported in this work have been obtained from a micrometeorological station established at Osu, Nigeria (7°26′N, 4°35′E), at the following four levels 5.44, 7.82, 11.29 and 15.37m covering the two-month period: January and February, 1995. In addition, both the windspeed and direction were measured at 22.31m, and also the net radiation at 6m, all on the same mast. All variables were stored as 10 min averages. Humidity was not among the variables presently recorded and it is deemed that this omission will not severely impair the profile measurements being analysed since it is expected that during the dry season the effects of water vapour on buoyancy will be very minimal.

2. Experimental site : location and preparation

A suitable location for the field study was found at the outskirts of Osu (7°26′N, 4°33′E), a semi-rural town, in the southwestern part of Nigeria. Installed at the site is an abandoned 50m mast, originally constructed to serve as a communication tower for a microwave radio link. The terrain at the measurement site is plain (lowlands), but gently sloping in an east-west direction. The land use pattern in the immediate vicinity of the mast position is that of small-scale subsistence farming practices (cassava farms of average height about 2 m), and patches of uncultivated land. It is devoid of any tall obstacles, such as big trees and hills for at least 500m radius from the base of the mast (except for the building housing communication equipment positioned about 20m north-west of the mast). There are a few dwelling houses clustered together about 1.5km southwest to the mast position. The average roughness length at the site was estimated to be about 0.2m. About 1 km south of the experimental site is a group of small hills (average elevation about 50m). There also exists a highway with a very low traffic density running in an east-west direction 200m south of the installations. A small dirt road, which is rarely used, branches off the highway and leads directly to the experimental site. A sketch of the experimental site is shown in Fig.1.

Details about the measurement programme and equipment can be found in Jegede (1994, 1995). The array of sensors comprises only slow response instruments (times of 30s or less). The wind and temperature transducers on the mast were spaced apart logarithmically. The first level of measurement was 5.44m and chosen to confirm with the theoretical requirement that at the lowest measurement height $z > 20z_0$ (here, z_0 has been estimated to be about 0.2m). The other measurement levels were 7.82, 11.29 and 15.37m. At the top, which was 22.31m, both the windspeed and direction were recorded. The net radiation was measured at 6m. The position of the sensors on the mast (drawn from photograph) is shown in Fig.2.

Windspeed at five levels on the mast (specified above) was measured with photoelectronic cup anemometers (manufactured by Vector Instruments, U.K., model A101ML). The distance constant for the instrument is 5m(2.3m) and it has a threshold windspeed of 0.15m/s. A potentiometer windvane (Vectors Instruments, model W200P) with a distance constant of 2.3m was employed for measuring the wind direction. Four mechanically aspirated platinum resistance temperature transducers (Vector Instruments, model T302) were utilised to measure the temperature profile in a bridge circuit connection for the temperature difference with an accuracy of ±0.05°C. The net radiation

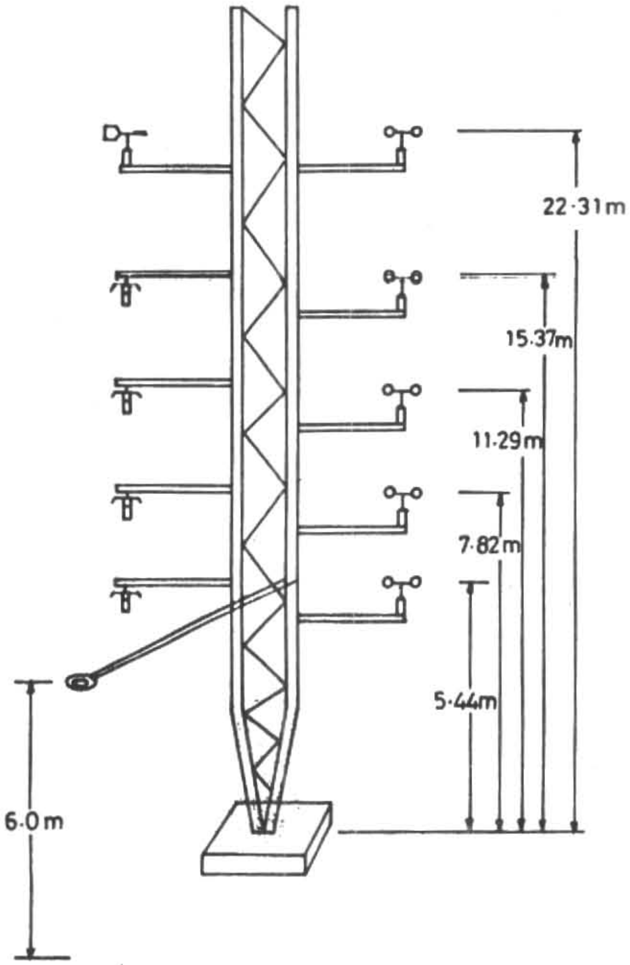


Fig.2. The position of the sensors on the mast

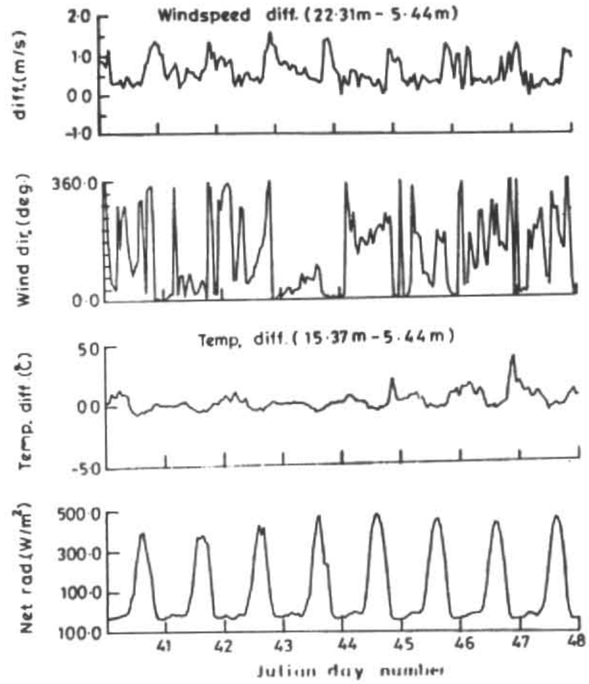


Fig.3. A sample time series during the period: Julian day 40-47

difference with an accuracy of ±0.05°C. The net radiation was measured with a Campbell Scientific double-dome net radiometer (model Q7). The net radiometer was positioned to be well above the vegetative surface cover so that the net radiation measurements can truly reflect the areal average.

All the sensors were wired directly to a datalogger (Campbell Scientific, model CR10) which was programmed to store data in two operating modes: (a) intensive, producing 1min. averages and (b) normal, producing 10min. averages of all the measured variables. The data was retrieved regularly for processing and throughout the period of data collection: January-February, no malfunctioning of any piece of the equipment occurred.

The field data acquired was further subjected to a series of quality control procedures. First, the data was scrutinized to check for existence of spurious measurement values which could probably be due to the malfunctioning of any of the sensors. No such error was present in the data from the visual inspection of time series plots of all the variables. In computing the fluxes of momentum and heat, wind measurements with recorded values of less than 1m/s were rejected to reduce errors contamination of low wind speeds (near calms). The Monin-Obukhov similarity theory of the SL is known also not to work well in cases of low winds (Arya, 1988). Furthermore, the information based on the wind direction was used to isolate the periods when the windflow could be obstructed considerably (flow modification) by the nearby 10m- high instrument building. In addition, values of windspeed differences between the successive levels, Δu less than 0.1 m/s was excluded. This was done to reduce errors larger than the actual wind speed differences due to variation in the response characteristics or differences in the calibration of independent wind speed sensors. Also temperature differences, ΔT of less than 0.05°C, were rejected to reduce considerably instrumental measurement errors. Finally, the data was reduced to hourly averages.

3. Field observations at the Osu experimental station

Continuous 10-minute average records of wind and temperature profile measurements, and net radiation for the months of January and February were analysed in this study. The data capture was 100% with the data integrity reliable since there was no occurrence of any faulty or damaged instruments within the measurement period. A sample time-series plots of the windspeed difference (22.31-5.44m), wind direction at 22.31m, temperature difference (15.37-5.44m) and net radiation at 6m recorded during the period: Julian day 40-47, is shown in Fig.3.

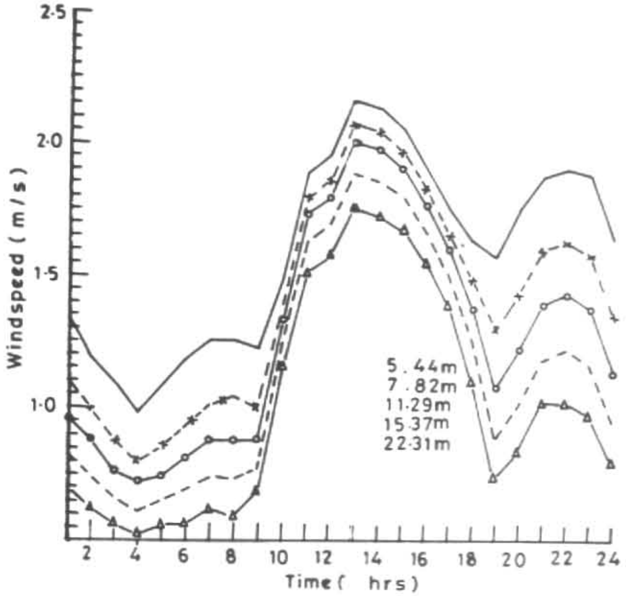


Fig.4. Diurnal wind patterns at selected heights for Osu station during January-February 1995

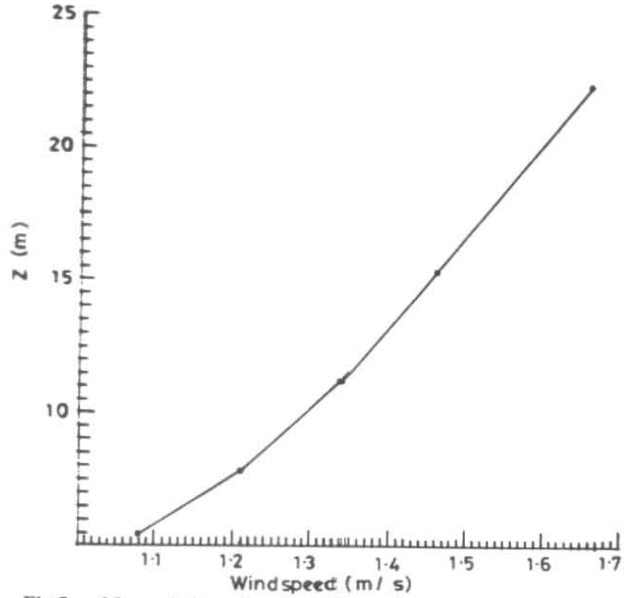


Fig.5. Mean windspeed profile at Osu station during January- February 1995

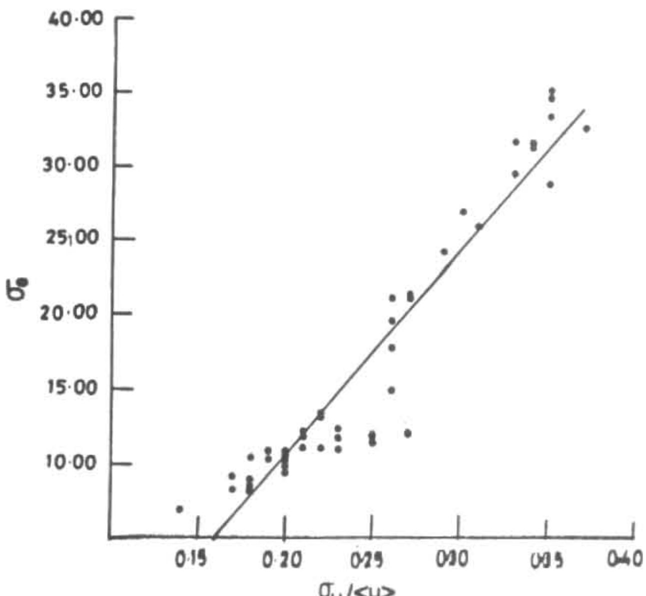


Fig.6. Horizontal wind direction fluctuation against turbulence intensity, January-February Osu stations data

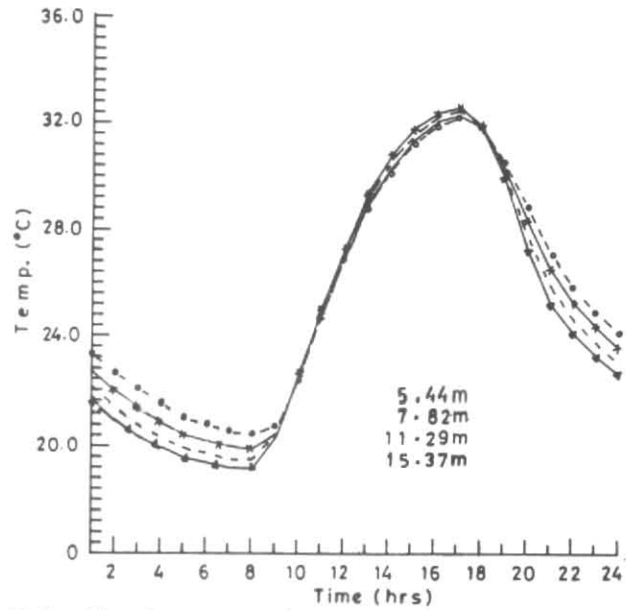
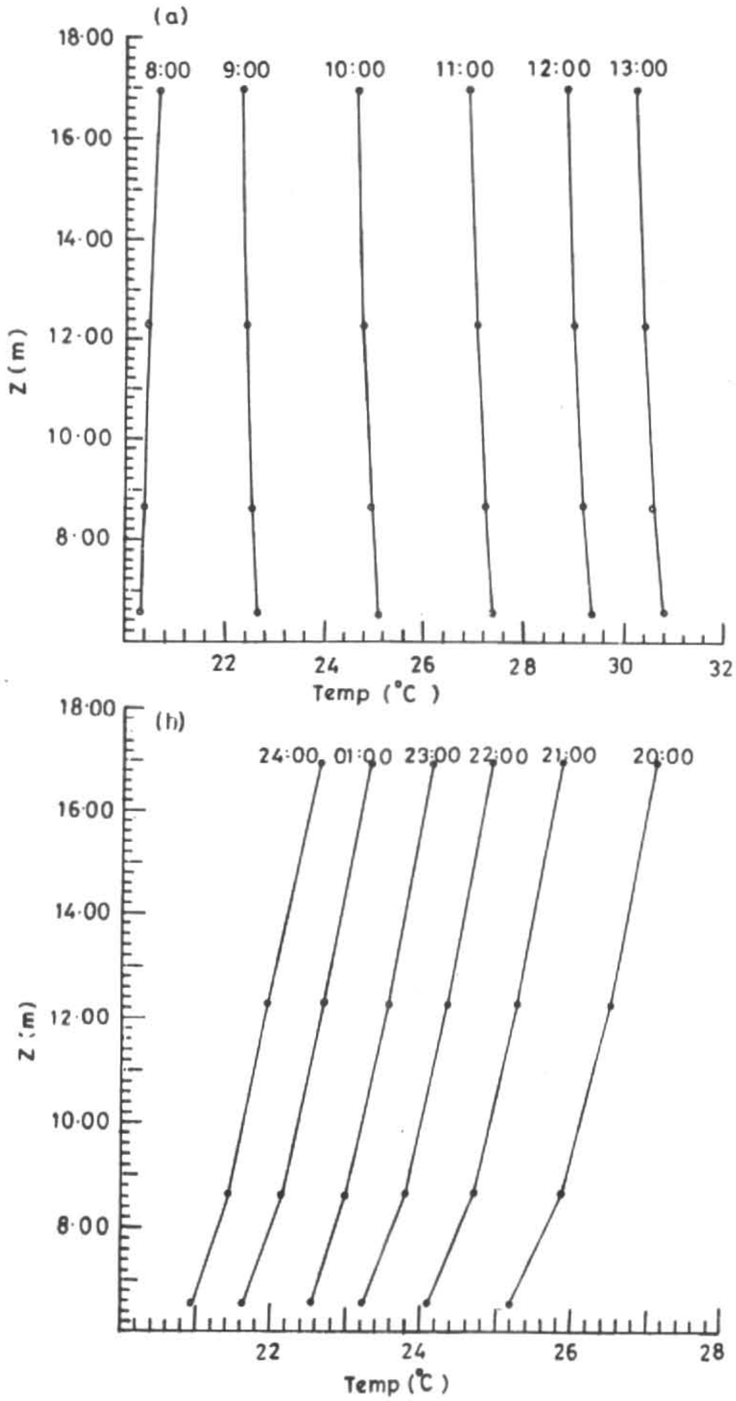


Fig.7. Diurnal temperature patterns at selected heights for Osu station, January-February 1995

3.1. *The near-surface mean wind flow characteristics*

The diurnal patterns of near surface wind flow at Osu during the period is shown in Fig.4. The surface layer winds was generally weak (<3 m/s), which during the dry season is typical of the continental areas in sub-Saharan West Africa (Hamilton and Archbold 1945). It is believed that the low wind speeds recorded at about this time (January/February) are associated with the absence of vigorous convective activity (such as thunderstorms, squall lines and other mesoscale disturbances) in the areas. Also, the very dry (arid) conditions that prevail at this time bring about a drastic reduction of the latent heat energy that can be released to sustain the local/regional circulation.

At the surface, the windspeed varies from near calm conditions early in the mornings to reach peak values of about 2.5 m/s in the afternoons. The diurnal trend is characteristic since by the afternoons the environment would have become fully buoyant as a consequence of the typically high solar radiation input (day time net radiation is about 500 Wm^{-2}) that is received. It is the prominent solar heating of the surface that is responsible for the increase in intensity of local circulations which die out in the early evenings as the sun falls below the horizon.



Figs.8(a & b). Surface layer temperature profiles at Osu (a) daytime and (b) night time cases during January-February 1995

The vertical wind profile in the surface layer in Fig.5 shows that the windspeed increases logarithmically with height from about 1m/s at 5.44 to 1.6m/s at 22.31m, portraying a weak windshear ($\partial u/\partial z \sim 0.03\ s^{-1}$). From the wind power law formula:

$$U_2/U_1 = (z_2/z_1)p \quad (1)$$

where U_1, U_2 represent the mean wind speed at heights z_1 and z_2 respectively, and the exponent p depends on stability. Applying the data to the above relationship, gives the mean value of the power law exponent p to be 0.28.

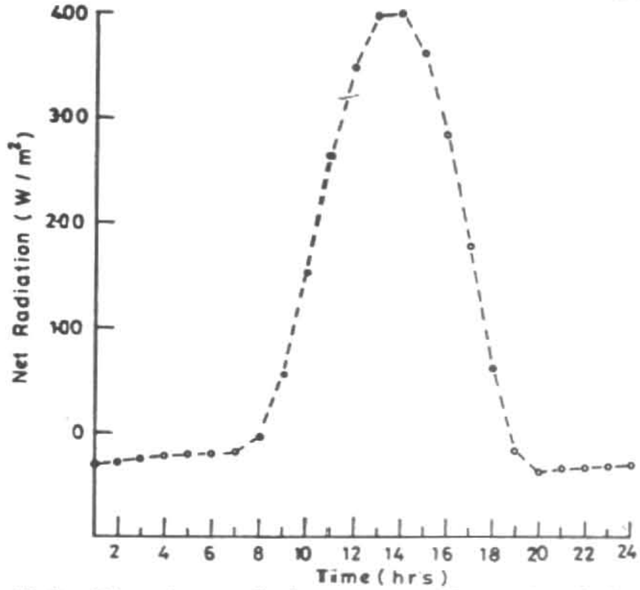


Fig.9. Diurnal net radiation pattern at Osu station during January-February 1995

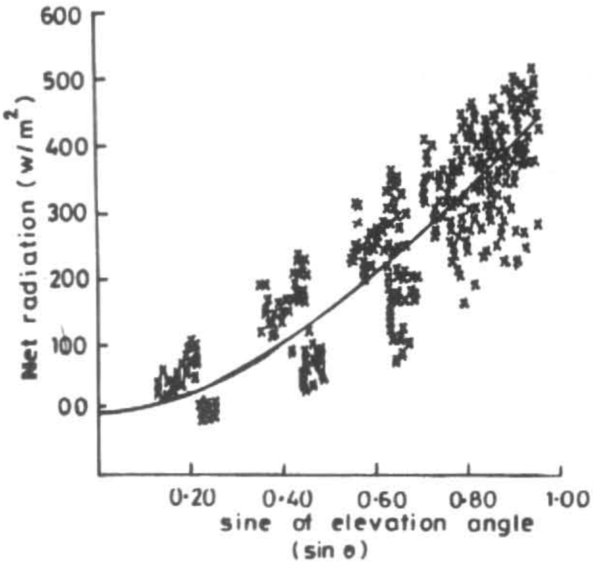


Fig.10. Net radiation plotted against sine of solar elevation angle at Osu station during January-February 1995

In Fig.6, the horizontal wind direction fluctuations σ_θ, show a linear relationship with the turbulence intensity, σ_u/U, which can be expressed in simple form:

$$\sigma\theta = A(\sigma u/U) + B \tag{2}$$

where A and B are empirical constants. From the least squares fitting to the data, values of the empirical constants obtained A=137.6, and B=-16.9. Empirical relationship in Eqn.(2) above has the practical utility in air pollution dispersion modelling, specifically to determine the Cramer's turbulence classes.

3.2. *The surface layer temperature profiles*

The diurnal variation of the near surface temperatures is shown in Fig.7. At the lowest measurement level (5.44m), the temperature shows a minimum in the early mornings (~7 a.m.) of about 19°C to reach a maximum of 33°C in the afternoons (~3p.m.). The pattern is similar at the other levels in Fig.7. The SL temperature profiles for different stability conditions are shown in Fig.8. During the day time the SL was frequently super-adiabatic with lapse rate values of 0.022°C/m. This is evident because the weather at daytime was mostly hot and dry (maximum day time temperatures was about 38°C. At early morning and night time, the surface based inversion layer is found to be well established with an average lapse rate of about 105°C/m. The (near) neutral stability conditions occurred only at the transition times (that is, at dawn or dusk), but very short-lived (less than or about one hour).

3.3. *The net radiation*

The diurnal pattern of the net radiation is shown in Fig.9. Peak value of 400Wm^{-2} at about 14.00 hours (local time=UTC+1) was recorded. At night time, the value of net radiation was fairly constant and negative (about -40Wm^{-2}). In Fig.10, the net radiation (daytime) was plotted against the sine of solar elevation angle (sinθ). The line of best fit to the experimental data is a polynomial of degree 3 which is of the form:

$$R = a_0 + a_1\sin\theta + a_2\sin^2\theta + a_3\sin^3\theta \tag{3}$$

The regression coefficients obtained from Eqn.(3) irrespective of the sky conditions (degree of cloudiness, turbidity, etc.) for the period were: a_0 = -3.6; a_1 = 46.1; a_2 = 607.1; and a_3 = -194.6. Eqn.(3) above is similar to that obtained in Nielsen *et al.* (1981), except that the third term on right hand side was dropped due to its relatively small magnitude. Since the net radiation is not routinely recorded at any of the local meteorological stations, therefore, the above relationship is of use to obtain a fairly reliable estimate of net radiation in these regions.

3.4. *Surface layer turbulence characteristics*

The vertical profile of horizontal SL turbulence intensity, $\sigma u/\langle U\rangle$ is shown in Fig.11. Close to the surface, the parameter has a value of 0.33 which decreases exponentially with height to about 0.22 at 22.31m. The vertical turbulence structure can be described by the relationship :

$$z = Ae^{-Bx} \tag{4}$$

where $x=\sigma_u/\langle U\rangle$, and A,B are the empirical constants. From curve fitting to the data, the values obtained for the constants were A=347.6 and B=12.5.

The roughness elements around the site have average height of 2m. The averaged roughness length z_0 was, thus, estimated from visual inspection to be approximately 0.2m, except for the wind sector 325-350° corresponding to the

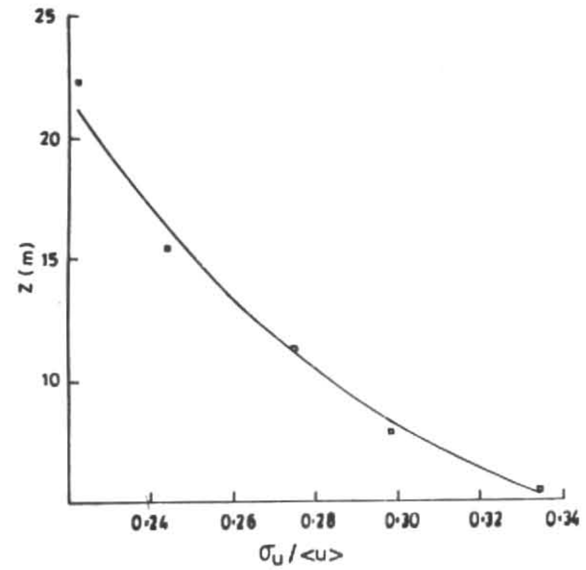


Fig.11. Mean turbulence profile at Osu station during January- February 1995

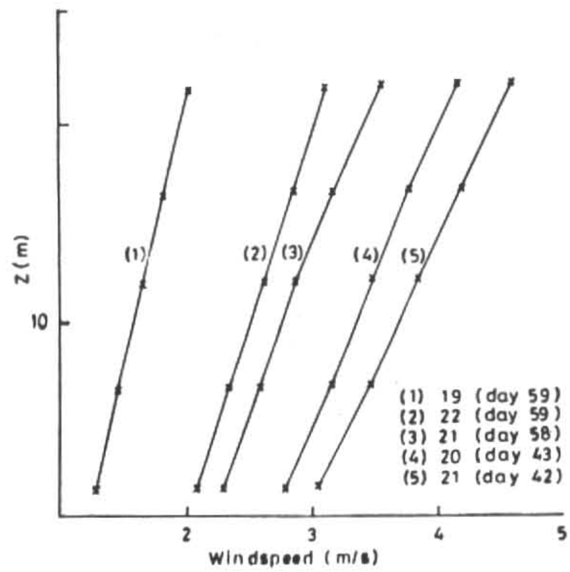


Fig.12. Neural wind profiles at Osu station during February 1995

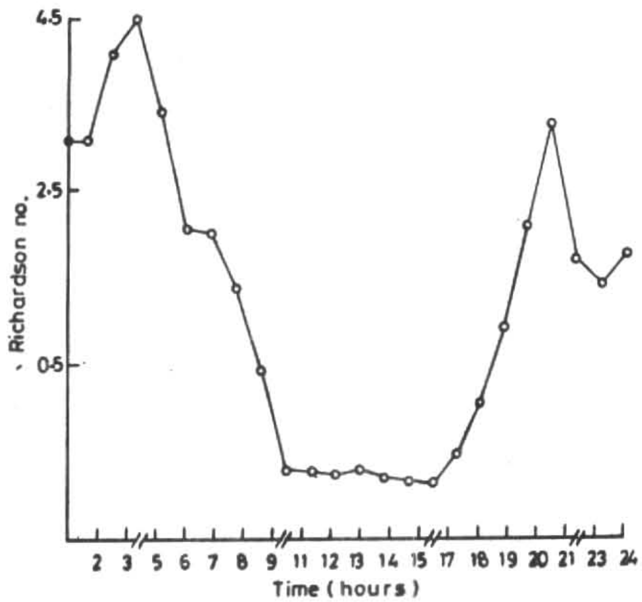


Fig.13. Diurnal variation of gradient Richardson number at Osu station during January-February 1995

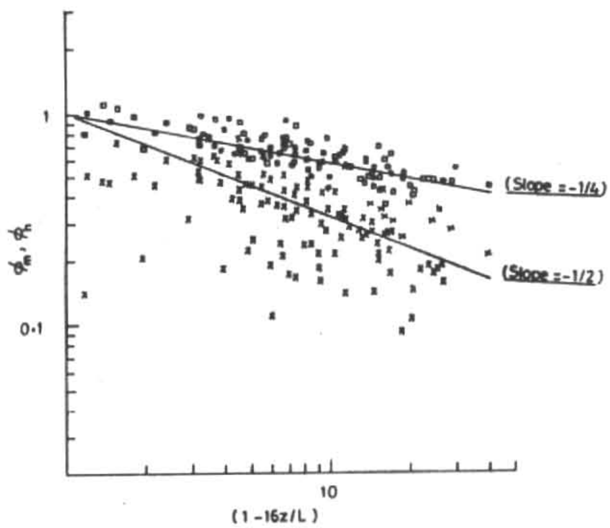
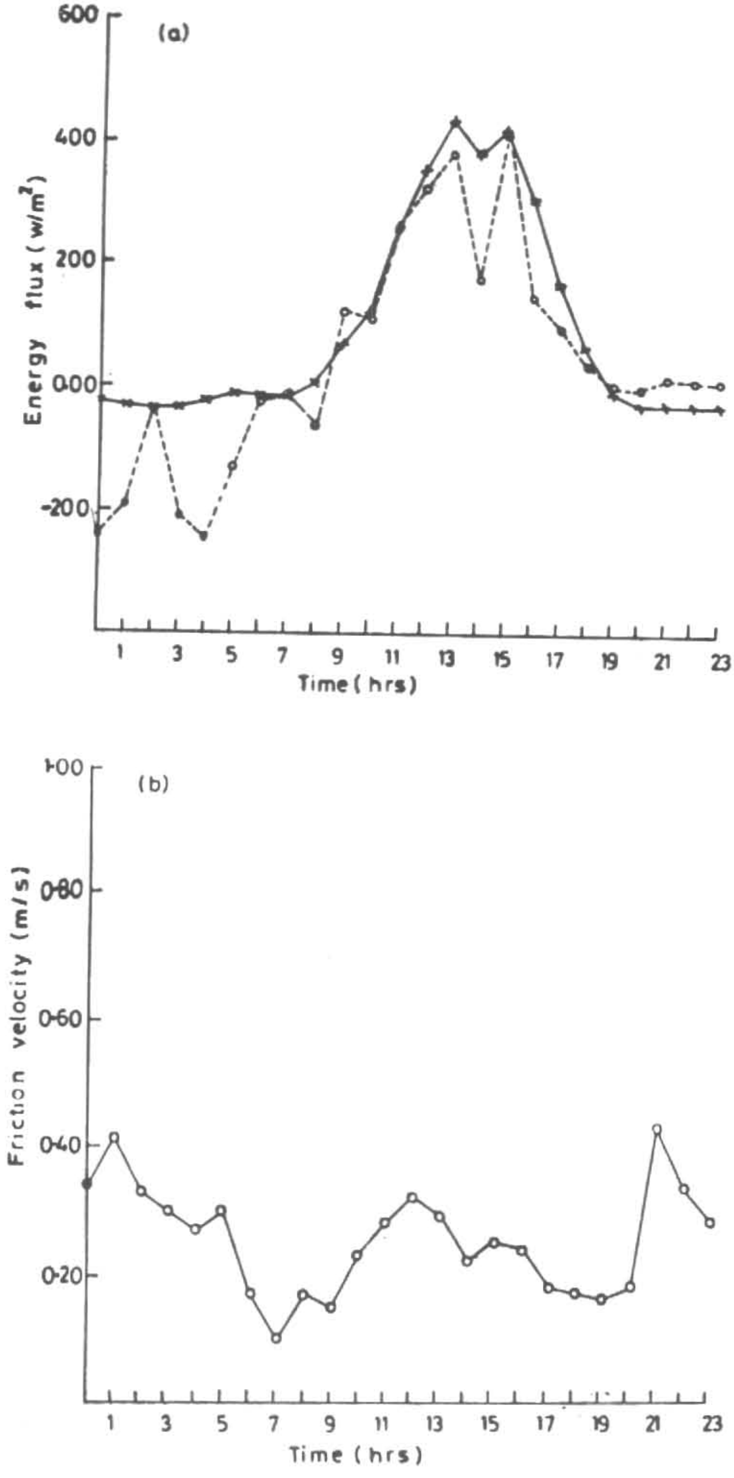


Fig.14. Function for stable conditions at Osu station

direction where the facility building was positioned. In this sector, we assume a roughness length value of 1m. In addition, due to the considerable height of the vegetative cover around the site, a displacement length d, was estimated to be 1.4m (being roughly 70% of the actual height of the roughness element).

Using the vertical temperature profiles, periods corresponding specifically to near neutral conditions ($|\Delta T|$ <0.05°C and gradient Richardson number (see below), $|R_i|$ < 0.05) were selected to use in plotting in z against U so as to determine the z_0 from the intercept Fig.12 shows the selected wind profiles for (near neutral cases from which representative values of the roughness length in the area surrounding the mast have been estimated. Due to the non-homogeneity of the area surrounding the mast (partly caused by the obstruction created by nearby structures), the estimates of the roughness length obtained for the site can be expected not to be constant, since it is dependent on the particular wind direction sector (see Table 1 below). Values estimated ranges from 0.12 and 0.15m.



Figs.15(a & b) . (a) Diurnal variation of net radiation (solid line) and sensible heat flux (dashed line) at Osu station: Julian day 42
(b) Diurnal variation of friction velocity at Osu station: Julian day 42

A quantitative description of the SL turbulence characteristics during the observation period at the Osu station, was obtained from the gradient Richardson number, R_i

$$R_i = g/T_0 \{(d\theta/dz)/(dU/dz)^2 \quad (5)$$

using the mast profile data. In order to estimate the R_i, the measurement heights z_1 = 5.44m and z_2 = 15.32m were

TABLE 1

	z(m)	U(m/s)	U(m/s)	U(m/s)	U(m/s)
	5.44	3.05	2.78	2.28	2.08
	7.82	3.47	3.15	2.58	2.34
	11.29	3.85	3.49	2.88	2.63
	15.32	4.20	3.79	3.18	2.87
	22.31	4.62	4.19	3.58	3.14
Richardson no.		0.01	0.01	0.05	0.04
z_0(m)		0.14	0.12	0.12	0.10
wind direction		3°	10°	19°	19°
local time (hrs)		21	20	21	22

chosen to conform to the specification that z_2/z_1=2 to 4 (see Arya 1988), so that the differences in velocities and temperatures may be well resolved. The diurnal variations of R_i is shown in Fig.13., in the day time (ΔT <0) such that turbulence was fully developed (R_i <0) and sustained, whereas at night time (ΔT>0), the turbulence in the stable SL was found to be highly suppressed and intermittent. For most of the night time, it was found that $R_i > R_c$, where R_c is the critical Richardson number with a numerical value of 0.25. This trend is probably due to the strong inversion (about 0.105°C/m) that was usually present and also the very weak winds (which varies between calms and about 1 m/s) about this time during the day.

Some of the various forms of the flux-profile relationships have been tested with the SL profile data gathered from Osu to obtain the plots of the dimensionless wind shear and heat gradient using empirical relationships (see Dyer and Hicks 1970, Businger *et al.* 1971). The results are shown in Fig.14 only for the unstable SL (ξ <0) all of which portray good fit of the mast data to the above quoted empirical relationships. It is observed from the Osu data set that the universal function ϕm shows good agreement with both the Businger *et al.* (1971) and Dyer and Hicks (1970) empirical relationships. However, when the Osu data was tested for the ϕh function, the profile relationship given by Dyer and Hicks (1970) proved to be superior to the formulations by Businger *et al.* (1971).

In general, fitting of the Osu SL data with the functional relationship for the dimension less wind shear agrees well with the empirical relationship of the form:

$$\phi m(\xi) = (1-16z/L)^{-1/4} \quad (6)$$

Similarly, the adopted relationship for the non-dimensional heat gradient of the form:

$$\phi H(\xi) = (1-16z/L)^{-1/2} \quad (7)$$

is also justified for use (see Fig.14). Both Eqns(6) and (7) are the same as in Dyer and Hicks (1970) and are found to perform better than the Businger profiles.

During stable conditions, the characteristic functions, ϕm and ϕh could not be suitably organised based along the commonly prescribed empirical relationships. A plausible explanation for this may be inferred from the knowledge that values of the gradient Richardson number computed at these periods, $R_i > R_c$ which suggests that the turbulence was not fully developed, probably existing intermittently and in very small magnitudes. Another important reason is that the Monin-Obukhov similarity theory is known not work well in situations in which the winds are near calm which typified the flow conditions in the evenings/early mornings periods as seen in Fig.4. Added to this is the knowledge that the surface based inversion is strong which greatly suppresses turbulence. Consequently, none of the above quoted relationships was found to be valid during the stable SL conditions.

The fluxes of momentum and sensible heat can be estimated through the use of the following relationships :

$$\tau = \rho u^{*2} = \rho[u'w'^2 + v'w'^2]^{1/2} \quad (8)$$

and

$$H = -\rho c_p u^* \theta^* \quad (9)$$

where τ is the shearing stress and u', v', w' are the fluctuating components of the mean wind Eqns.(8) and (9) above has been applied to study the diurnal characteristics of the fluxes for the Julian day #42 during the measurement period. The result is shown in Figs.15(a) and (b). In Fig.15(a), estimated values of the sensible heat are compared with measurements of the net radiation. There is a good correlation observed between the variables such that same features are present. In Fig.15(b), the momentum flux (represented by friction velocity), gives values between 0.12 and 0.42.

4. Conclusions

The micro-meteorological data set gathered from this phase of the field experiment provide some important initial results for detailed explanation of the SL structure and surface energy exchange mechanisms in the sub-Saharan (tropical) environment during the pre-monsoon (dry) season. Analysed for the months of January and February, were both the mean wind and temperature profiles (from near surface to about 23 m) and net radiation measurement at a single level.

Diurnal patterns of the surface wind show that during the period, the field was generally weak (<3ms^{-1}), which increases to a maximum in the early afternoons. Temperature profiles indicate that the day time was frequently superadiabatic, which helps to sustain the SL turbulence (though buoyancy as convective turbulence) despite the rather low winds. At night time, the surface-based inversion was found to be strong enough as to effectively suppress turbulence within the stable SL (R_i > 0.25).

The empirical flux-profile relationships listed by several authors have been tested, and those obtained by Dyer and Hicks (1970) have been shown to be valid for the unstable SL, particularly of the dimensionless temperature gradient. However, due to the very weak winds at night time and strong temperature inversion (both of which characterise the stable SL), none of the empirical relationships tested was found useful to fit the empirical forms for the universal function ϕm and ϕh.

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