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Fluxes of sensible heat and momentum in the surface layer estimated from the profile measurements of wind and temperature at a tropical station

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RESUMEN

En este estudio han sido estimados los flujos en la capa superficial para la cantidad de movimiento como para el calor sensible en un lugar tropical; Osu, Nigeria (7°26' N, 4°35' E), usando mediciones de perfiles de viento medio y temperatura, llevadas a cabo en la estación anterior al monzón (enero-marzo).

Debido a los vientos débiles de superficie que generalmente existen en el área (para el periodo de estudio $\overline{U}$ era 1.24 $m.s^{-1}$) y a la fuerte insolación, el SL de tiempo diurno se encontró con frecuencia que estaba dentro del régimen de convección libre. Típicamente en el tiempo diurno el flujo de calor sensible era H~200 $W.m^{-2}$ y la velocidad de fricción u_* ~ 0.2 $m.s^{-1}$. En el tiempo nocturno la inversión de temperatura con base en la superficie era muy pronunciada (>0.33°C. m^{-1}) en tal forma que la intensidad de la turbulencia en el SL nocturno era más débil, menos alta, esporádica y menos prolongada (H~ -5.0 $W.m^{-2}$; u_* < 0.2 $m.s^{-1}$).

También se discute la distribución de la frecuencia de estos flujos derivados (y las variables medias) para el periodo observado.

ABSTRACT

In this study the surface layer fluxes for both the sensible heat and momentum have been estimated at a tropical location; Osu, Nigeria (7°26' N, 4°35' E), using profile measurements of mean wind and temperature realized within the pre-monsoon season (January - March).

Due to the weak surface winds that commonly exist in the area (for the study period, $\overline{U}$ was 1.24 $m.s^{-1}$) and strong insolation, the daytime SL was frequently found to be within the free convection regime. Typically in the daytime, the sensible heat flux H~200 $W.m^{-2}$ and the friction velocity u_* ~ 0.2 $m.s^{-1}$. At nighttimes, the ground-based temperature inversion was very pronounced (>0.33°C.m^{-1}) and it is such that the intensity of the turbulence in the nocturnal SL was weaker, shallower, sporadic and unsustained (H~ -5.0 $W.m^{-2}$; u_* < 0.2 $m.s^{-1}$).

The frequency distribution of these derived fluxes (and the mean variables) for the observation period is also discussed.

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1. Introduction

The new generation or the advanced-type of operational air pollution models receive as input deterministic surface layer parameters such as roughness length, sensible heat flux, and surface stress in order to estimate the dispersion of effluents within the boundary layer (BL). The better performance of such newer models over those based on the traditional Pasquill-Gifford-Turner (P-G-T) stability classes typing schemes rest wholly on the fact that the advanced models incorporate more detailed boundary layer physics in their formulations of σ_y and σ_z for the dispersion processes (Berkowicz *et al.*, 1985).

However, direct measurements of the fluxes of sensible heat and momentum are tob cumbersome to be carried out routinely for operational air pollution dispersion modelling purposes. What is done in practice is to estimate the surface layer fluxes indirectly from basic meteorological data (e.g., surface wind, temperature, net radiation, etc.) using a meteorological preprocessor (van Ulden and Holtslag, 1985). The fluxes thus obtained are then used as input into these models.

The flux-profile method (Arya, 1988) has been adopted for this study to estimate the sensible heat and momentum fluxes for a tropical location in west Africa during a pre-monsoon season (January-March) in 1995. Also discussed is the frequency distribution of the mean wind and the derived fluxes. The implication of this result for air pollution estimation in the area is mentioned.

2. Details of the field measurements

The field measurements reported in this study were conducted at Osu (7°26' N, 4°35' E), Nigeria, during the period: January - March, 1995. This was the dry season in most parts of the west African sub-region. The topography of the surrounding areas is low land (230 m a.m.s.l.) and is characterized by very rough surface elements (small round hills, tall shrubs and trees). The terrain at the measurement site is flat, but is slightly sloping towards the west. And in the vicinity were cassava farms (sparsely grown) of average height of 2 m interspersed by patches of uncultivated land (overgrown with shrubs). If observed at far distance, then the height of the roughness elements of the site was uniform. For the measurement area, the roughness length, z_o has been estimated to be 0.24 m (Wieringa, 1993; Jegede *et al.*, 1996). A sketch of the experimental location is shown in Figure 1.

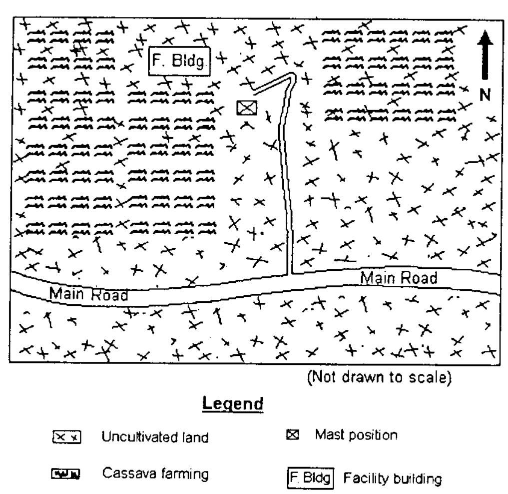

Fig. 1. A schematic layout of the experimental site

A slender 50 m mast positioned at the site was instrumented up to a height of 23 m for the profile measurements. The mast data consisted of mean wind speed, and temperature recorded at the following heights 5.44 m; 7.82 m; 11.29 m; 15.37 m; and 22.31 m (Note: only the mean wind vector was measured at the topmost height). The data also included a single level net radiation measurement at 5 m. Light-weight, photoelectronic 3-cup anemometers (Vector Instruments A101ML) with a distance constant of 2.3 m and a threshold speed of 0.15 $m.s^{-1}$ and potentiometer-type wind vane (Vector Instruments W200P) were employed. The temperature transducer (Vector Instruments T302) used was a mechanically ventilated platinum-resistance thermometer with trippled walled housing and a large fibre-glass hat to prevent radiation heating errors. These were connected in a bridge circuit to measure temperature differences with an accuracy of ± 0.05 °C. The sampling rate selected for both the wind speed and direction measurements was 10 secs, while for the temperature it was chosen as 30 secs. The mast data were measured and stored as 10-minute averages with a datalogger (Campbell Scientific CR10). The positioning of the transducers on the mast is sketched in Figure 2.

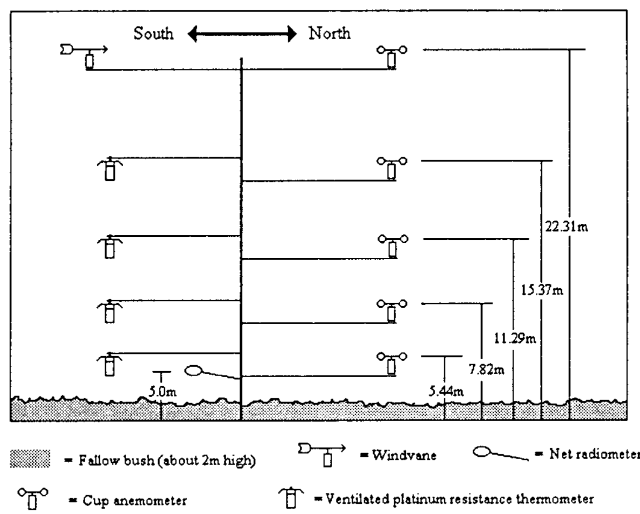

Fig. 2. Arrangement of transducers on the meteorological mast

Due to logistics problems, it was not possible during the conduct of the experiment to include the measurement of atmospheric humidity. However, it is of note that all measurements reported here were made during a dry season when arid conditions persisted throughout. It is believed that non-inclusion of water vapour will not seriously impair our flux estimates since it can be expected that during the dry period, such effects on buoyancy will be very minimal (Busch, 1973). It is also recognized that large errors could arise in the estimation of wind speed differences (especially in our study area with weak surface winds), since this requires the use of two independent wind sensors (Irwin and Binkowski, 1981). To reduce such errors in the estimations, independently determined roughness length value for the site (Jegede, 1996) was used along with a single-level wind measurement.

3. Methodology

The flux-profile method that was used to estimate fluxes of sensible heat and momentum in this study, is based on the Monin-Obukhov similarity theory of the surface layer (Berkowicz and Prahm, 1982; Arya, 1988). Essentially, the theory assumes that the mean flow and its turbulent characteristics depend on the following scaling variables: the height above the surface z, the friction velocity u_*, the surface kinematic heat flux $H_o/\rho c_p$, and the buoyancy variable g/T_o. All of the above quantities are related together as a measure of the dynamic stability condition within the SL, ζ ($\equiv z/L$), where L is the Monin-Obukhov length and is expressed below as:

$$L = \frac{-\rho c_p T_o U_*^3}{kgH_o}, \tag{1}$$

Above, ρ represents the mean air density, c_p is the specific heat capacity at constant pressure, g is the gravitational constant, and k is the von Karman's constant (value 0.4).

With this method, the value of L can be easily calculated from a multi-level (at least three) measurement of mean wind and temperature as line of best fit of the geometric mean height, z_m plotted against the gradient Richardson number, R_i. Depending on the SL stability, for unstable conditions ($R_i < 0$), z_m is plotted against R_i, while for stable conditions ($0 < R_i < R_c$, where R_c is the critical Richardson number), z_m is plotted against $\{R_i/(1\text{-}5\ R_i)\}$. The value of L thus obtained is used in a suitable SL empirical flux-profile relationship such as from the Kansas data (Businger *et al.*, 1971) to determine the fluxes of momentum and sensible heat. Major limitations to using the profile method arise from measurement errors, inhomogeneities of the underlying surface and the selection of the appropriate universal functions in relevant profile equations. (See Berkowicz and Prahm, 1982).

4. Results and discussions

4.1 Characteristics of the mean wind and temperature at the surface

The diurnal courses of the mean wind speed and temperature in the near surface (at 5.44 m) for the monitoring period: January - March, 1995 is shown in Figure 3. From the figure, it can be observed that

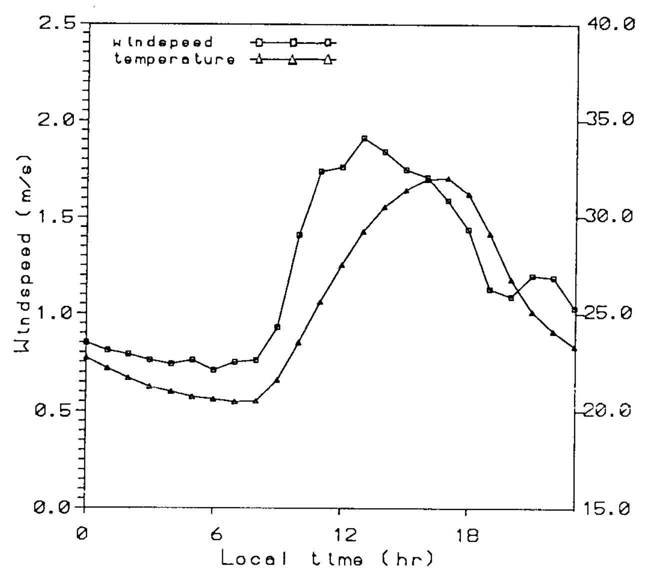

Fig. 3. Diurnal variations of wind speed and temperature at the Osu station. January - March, 1995.

the mean surface flow was weak ($\overline{U}$ = 1.24 m.s^{-1}) and its daily maximum occurred at about 13 h local time (which is GMT+1 hr). In the nighttime, at about 21 h, a second but not as well developed wind maxima is also observed. This feature is being associated in the area, with occurrences of the nocturnal low-level jets which is a common feature of the tropical boundary layers (McBean *et al.*, 1977). In whole of the study period, wind speeds up to 3 m.s^{-1} (and higher) were seldomly recorded. When such winds were found, it can be linked to passages of transient weather disturbances over the monitoring area. The persistently low-wind feature is attributable to the synoptic conditions prevailing at about this period of the year. That is, a large scale air mass subsidence existed over the sub-region which is brought about by the positioning of the sub-tropical high pressure belt. An additional fact is the very rough nature of the surrounding area (distant hills and tall trees) which consequently reduced the strength of the near surface flow.

The magnitude of the vertical wind shear estimated was smaller than 0.03 s^{-1} in all stability conditions. This indicates a relatively small horizontal momentum flux being transported downwards (which could also be inferred from the estimates of the friction velocity obtained below). From the hourly averaged wind data, the dispersion of the wind direction, σ_θ plotted against the standard deviation of the mean wind speed, σ_u is shown in Figure 4. A simple linear relationship of the form:

$$\sigma_\theta = 44.54\sigma_u \tag{2}$$

is found (r = 0.93). The above relationship has practical applications for air pollution estimations since it can be used to determine the Cramer's turbulence classes (Hanna *et al.*, 1982) when σ_θ is not measured.

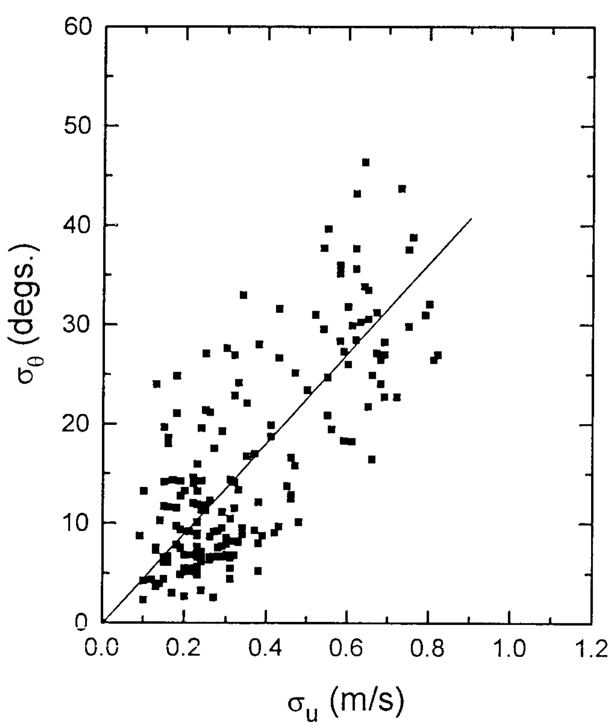

Fig. 4. Horizontal wind dispersion against standard deviation of horizontal wind speed.

In the same period, the air temperature (at 5.44 m) increased from about 20.8 °C (nighttime minimum), to reach a maximum of about 31.8 °C at around 16 h (Fig. 3). Since a strong insolation and weak winds exist during the daytime, the SL was usually found to be superadiabatic (strong convective instability). Except for the transition hours (at dawn and dusk), it was common to find in the nighttime hours that the vertical temperature gradient was very pronounced ($\left|\frac{dT}{dz}\right| \geq 0.3$ °C/m). That is, a very stable SL exists due to the strong surface-based temperature inversion layer (formed mainly as a result of the nocturnal radiative cooling). The prominent lapse rate at the nighttime is responsible for suppressing levels of active turbulence within the SL.

The net radiation measurements recorded at a height of 5 m indicated peak values of about 470 $W.m^{-2}$ in the daytime (around 14 h). This is especially so during days when the sky condition is cloudless or breaks between the spells of hazy weather. At the nighttime, the upwardly directed net radiation was observed to be fairly constant and has values of about 30 Wm^{-2} (negative values).

4.2 Estimation of turbulent fluxes in the tropical surface layer: A case study

As a case study of the surface layer characteristics (mean and fluxes) at the Osu monitoring station, Figure 5 displays for the period: January 01 - 09, 1995, traces of the time series of the wind at two heights (speed, direction and the standard deviations), the air temperature and its gradient, and the net radiation.

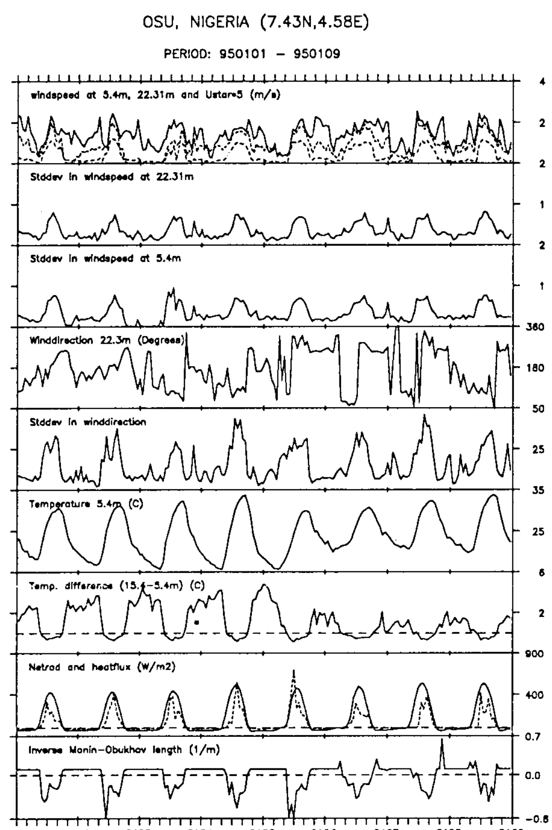

Fig. 5. Composited time series plots of the measured and estimated parameters in the surface layer. Case studies for period: January 01 - 09, 1995.

Also shown in the same graph are the estimated fluxes: sensible heat, friction velocity and the Monin-Obukhov length, all of which have been deduced from the flux-profile method explained in section 3 above.

In Figure 5, in the afternoons, the wind dispersion increases towards large amplitudes ranging between 25° and 45°. The σ_θ trace can be observed in the same figure to correlate fairly well to the standard deviation for the horizontal wind speed, σ_u (see also Fig. 4). From the estimates, values of the friction velocity (the kinematic momentum flux) increased from about 0.1 m.s^{-1} at nighttimes to 0.3 m.s^{-1} during the daytime. The low values for the friction velocity is suggestive that the mechanical contribution to the SL turbulence was minimal which is consequent from the rather weak wind fields noticed in the area. Also from Figure 5, it can be observed that the estimates of the sensible heat flux compared reasonably with the magnitudes of the measured net radiation. The values of Monin-Obukhov lengths plotted in the same figure suggests that the nighttime is definitely seen as stable (1.5 m $<L<$ 10.0 m), while the most of the daytime was strongly unstable (-8.0 m $<L<$ -1.25 m).

4.3 Frequency distributions of the surface layer parameters

A total of 2112 hours of SL data all falling within the period: January - March, were collated and later presented as frequency analyses for each of the following surface layer parameters: the wind speed and direction, air temperature, Pasquill-Gifford-Turner (P-G-T) stability classes, friction velocity, the Monin-Obukhov length, sensible heat flux, and the net radiation. The joint frequency distribution of the wind speed and direction (at 10m) is shown in Table 1. Wind speeds greater than 4 m.s^{-1} were almost absent from the records and represented about .08% of the total. The wind speed class: 1.0 - 2.0 m.s^{-1} was seen to be the most prominent at the station, which represented a total of 41.8% from all the wind directions. Substantially, the winds from the north and northeast, a combined total of 29.7 % was found. This is not at all surprising since during the pre-monsoon season, the continental northeasterly flow (known locally as the Harmattan) is the prominent surface flow (Hamilton and Archbold, 1945). Calms represented about 12.6% of the wind conditions at the station of the whole time.

Table 1. The joint frequency distribution of the wind speed and direction at the Osu station. January - March, 1995.

wind directions	wind speed classes (m.s^{-1})					Total
	<1.0	1.0 - 2.0	2.0 - 3.0	3.0 - 4.0	>4.0	
N	0.026	0.079	0.046	0.014	0.003	0.168
NE	0.016	0.051	0.047	0.013	0.001	0.129
E	0.020	0.042	0.014	0.001	0.000	0.076
SE	0.022	0.033	0.010	0.001	0.000	0.065
S	0.000	0.082	0.000	0.000	0.000	0.082
SW	0.028	0.047	0.050	0.004	0.001	0.130
W	0.040	0.047	0.012	0.006	0.001	0.106
NW	0.019	0.037	0.014	0.002	0.002	0.075
all directions	0.215	0.418	0.193	0.041	0.008	0.874
calms						0.126

Noting that sharp contrasts exist between daytime and nighttime conditions of the tropical SL (McBean *et al.*, 1977), the estimated fluxes have been separated into daytime cases (880 hours) and nighttime cases (704 hours). The transition hours at dawn and dusk were not included.

(a) Daytime cases The frequency distribution of P-G-T stability classes obtained during the daytime is shown in Figure 6a. Here, the stability class A alone accounted for about 77.6% of the cases studied. This justifies the assertion already made above that with the strong insolation and weak surface winds, the daytime SL was highly unstable. Inclusive of the classes B and C, the total frequency of unstable conditions in the daytime SL increases to about 80% thus indicating a high occurrence of instability for the daytime tropical boundary layer when the clouds are absent (which is a common feature during the pre-monsoon season). The balance (~20%) represents varying degrees of stable conditions in SL and were found during brief periods when the effects of large scale advection dominated the local circulation in the area (outbreaks of cold air). The frequency distribution of the friction velocity, u_* is shown in Figure 7a. It can be observed from the estimates that values of u_* rarely exceed 0.3 $m.s^{-1}$ and account for less than 5% of the whole period. The u_* class: 0.1 - 0.3 $m.s^{-1}$ class was the most prominent (~90%). Therefore, it can be inferred from the low values of u_* that mechanical contribution to the surface layer turbulence is small.

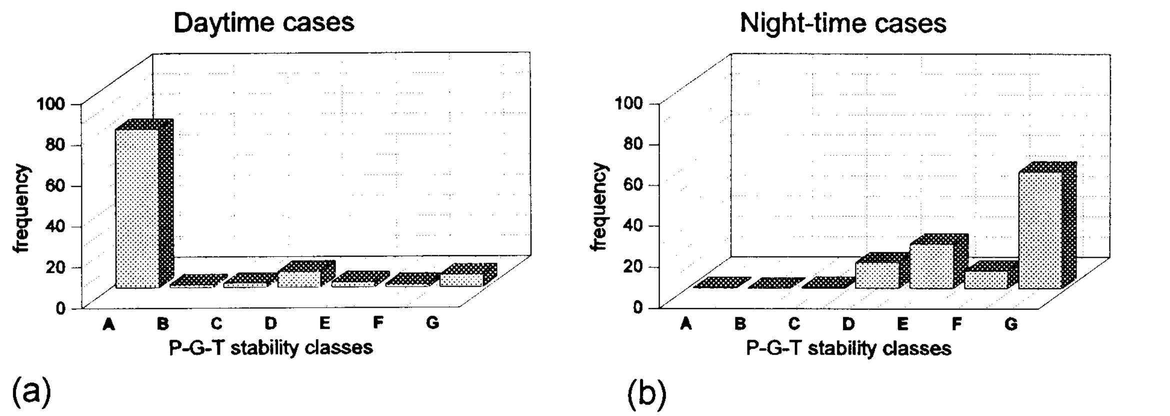

Fig. 6. Frequency distribution of the daytime P-G-T classes at Osu station. January - March, 1995 (a) Daytime cases and (b) Nighttime cases.

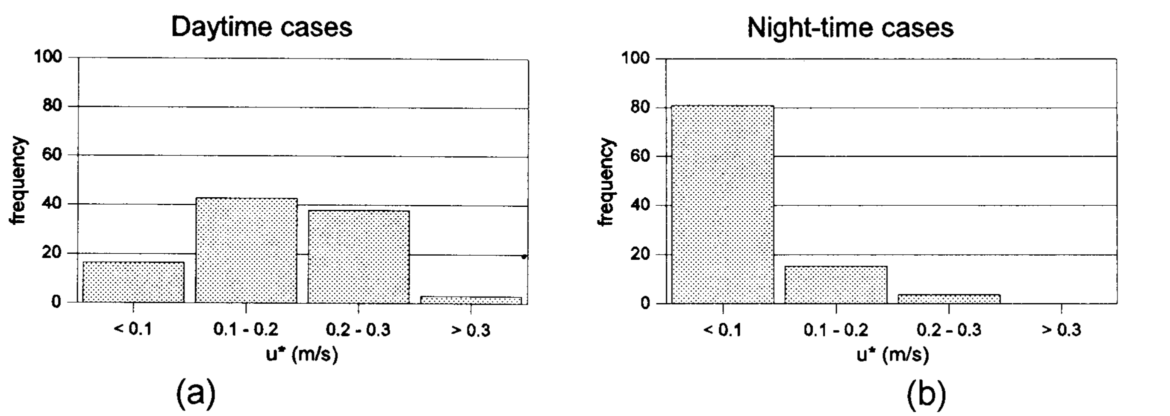

Fig. 7. The same as in Figure 6 but for the friction velocity.

Estimates of the Monin-Obukhov length displayed in Figure 8a suggest that roughly 80% of the values fall within the (dynamic) stability category: -50 m $<L<$ 0, also showing that the daytime conditions was largely unstable. The frequency distribution of the daytime sensible heat flux is shown in Figure 9a. The distribution is one-tailed with the heat flux class: 0-100 $W.m^{-2}$ being the most frequent (about 47%).

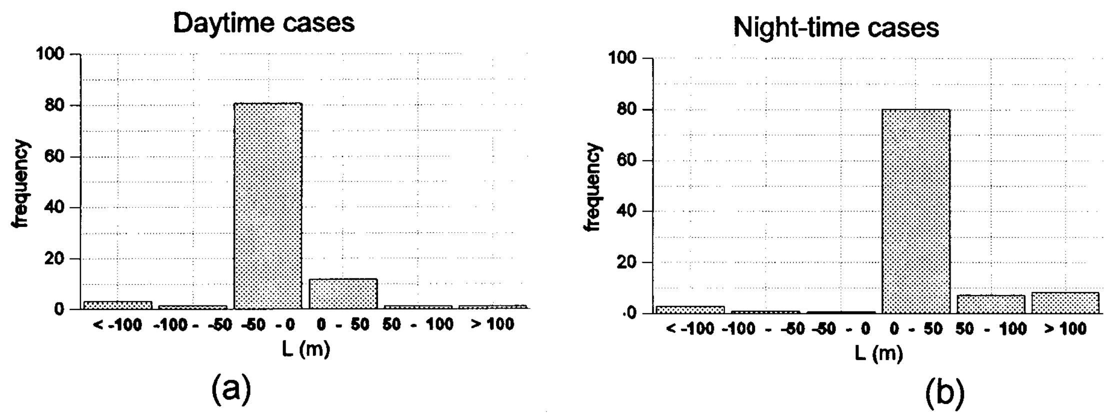

Fig. 8. The same as in Figure 6 but for the Monin-Obukhov length

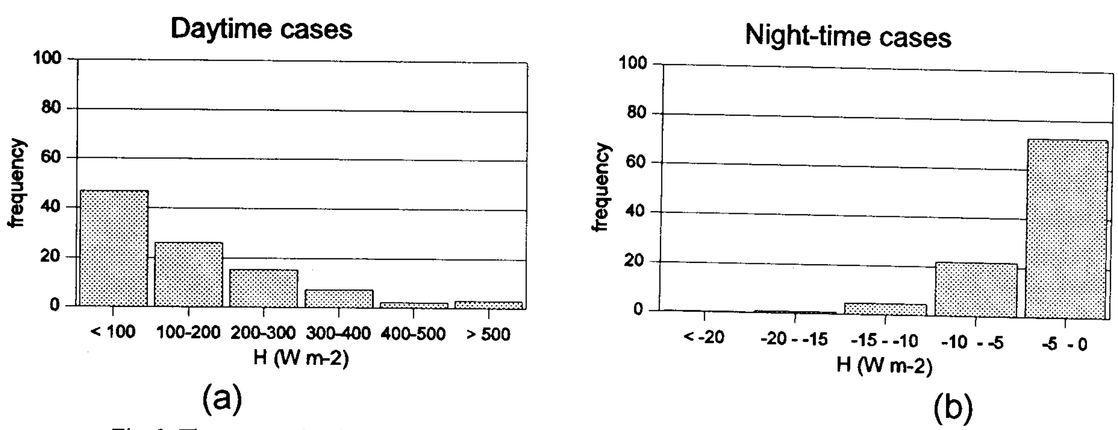

Fig. 9. The same as in Figure 6 but for the sensible heat flux.

(b) Nighttime cases The frequency distribution of the nighttime cases for the P-G-T stability classes is shown in Figure 6b. Here, the strongly stable condition (class G) is most prominent and accounted for about 60% of all the cases observed. For all stable categories (classes E, F, and G), a combined total of 87.2% is realized. The estimated values of the friction velocity, u_* shown in Figure 7b portrayed rather negligible values for the nighttime with almost 96% of the estimates having values less than 0.2 $m.s^{-1}$. This observation suggests that active turbulence was non-existent in the nocturnal SL. In Figure 8b, the Monin-Obukhov lengths obtained for the nighttime cases showed that almost 81% fall within the stable category: 50 m $>L>$ 0. The frequency distribution of the nighttime (negative values) sensible heat flux is shown in Figure 9b. The estimates indicate that the magnitude of sensible heat loss by the surface at nighttime is very small, mostly, -5 $W.m^{-2}$ $<H<$ 0 (about 75% of the cases).

5. Conclusions

From the mean profile measurements conducted at the Osu field station during this study, weak winds were observed to persist within the lowest levels of tropical SL. For the whole period, the mean wind speed measured at 5.44 m was 1.24 $m.s^{-1}$. This low-wind regime coupled with the strong insolation renders the daytime SL conditions to be convectively active. Prominency of the temperature inversion layer during the nighttime was found to be effective in suppressing the levels of turbulence within the SL. The low values of friction velocity obtained ($u_* \sim 0.2$ $m.s^{-1}$) is indicative that the mechanical contribution to SL turbulence is minimal. The magnitudes of the net radiation and sensible heat (which was estimated by the use of profile method) were found to be comparable. The deficit is to be accounted mainly as the soil heat flux. The latent heat term (its contribution to the surface energy balance equation) was assumed to be minimal during the pre-monsoon period due to the arid nature of the surface. It should be mentioned here that the observed SL conditions strongly indicate a high probability of occurrence of air pollution episodes in the area for emissions from low sources since the dispersal effects by the mean wind flow was very limited.

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