JKAU: Met., Env. & Arid Land Agric. Sci., **Vol. 20,** No. 2, pp: 77-93 (2009 A.D. / 1430 A.H.)

Estimation of Roughness Parameters and Sensible Flux in the Hada Al-Sham Area, Makkah

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Abstract. Examples of computed roughness length $z_\circ$ (m) in the Hada Al-Sham were presented as: Between Jumad El-Awwal, 6th and 12th except on 9th, the peak value was 1.6m at 1900 h, lower values of $z_\circ$ were observed and remained very close to an average of 0.03m between 1100-2000 h when the wind direction was nearly SW with an average wind direction of 255º. The higher friction velocities u_* (ms^{-1}) were found in the afternoon with an average of about 0.4 ms^{-1} with less effect of winds. Examples of maximum values of u_* on J. El-Awwal 9th attained up to 0.8 ms^{-1}at about 1900 h, on J. El-Awwal 12th 1.0 ms^{-1} at 2100 h and on J. El-Awwal 15th 1.7 ms^{-1}at 1730 h. The higher friction velocity on J. El-Awwal 9th, was probably due to the change of the wind direction from SW (~223°) which was recorded at 1900 h to westerly wind at 1930 h (275º).

The maximum value of sensible heat flux was found as 1118 Wm^{-2} at 1400 h on J. El-Awwal 15th. Another maximum value of *H* was found as 1200 Wm^{-2} at 1200 h on J. El-Awwal 21th. The afternoon peak values of *H* were found between 550 Wm^{-2} and ~ 700 Wm^{-2} from J. El-Awwal 6th until J. El-Awwal 13th.

Introduction

Steeneveld, *et al*. (2005), referred to Businger, *et al*. (1971) that flux-profile relationships based on turbulent flux and vertical profile observations above prairie grassland over horizontal homogeneous terrain in Kansas, U.S.A. After some adaptations, these relationships are known as the Businger–Dyer relations (Dyer, 1974; Businger, 1988 and Hogstrom, 1988), and are read as:

$$\phi_h = \phi_m^2 = \left(1-16\frac{z}{L}\right)^{-1/2} \quad (1)$$

In which ϕ_h and ϕ_m^2 are dimensionless gradients of temperature and wind speed, z the height above the surface, and *L* the Obukhov length. The Kansas experiment in 1968 was set up to verify the Monin-Obukhov similarity theory (MOST). A theory that is based on the assumption that in the atmospheric surface layer (ASL) z and *L* are the only relevant turbulent length scales. Consequently, according to MOST, the height of the convective boundary layer (CBL), h, does not play a role in the ASL (Holtslag and Nieuwstadt, 1986). Moreover, the Kansas dataset was confined to conditions with $-z/L$ smaller than 1. For large values of $-z/L$, in particular in the so called free convection region where the influence of friction velocity, u_*, is expected to vanish, there is still no unanimity in the literature on the flux gradient relations. The Businger-Dyer relationships do not fulfill the relations found from similarity theory assuming that only the buoyancy flux ($\frac{g}{\theta}\overline{w\theta}$ if humidity effects are ignored) and the actual height z are of relevance only. There is a growing interest in the boundary-layer community to improve the widely used Equation (1) by accounting for additional phenomena. This is a challenging task owing to the scatter of most datasets. Recently, Halldin, *et al*. (1999) and Johansson, *et al*. (2001) found that ϕ_m depends on h/L. Panofsky, *et al*. (1977) already found that the boundary-layer depth is a scaling parameter for the horizontal velocity variances under convective conditions in the surface layer.

The surface energy partitioning has a great influence on regional and local climates. Surface energy, mass and momentum are changing with climatic warming and may have direct and/or indirect feedbacks to the climate (Giolia, *et al*., 2004; Gu, *et al*., 2005; Eugster, *et al*., 2000 and Yao, *et al*., 2008).

The instabilities generated through the convection as well as wind shear are mainly responsible for the transfer of momentum and heat. Over the land surface, a mixing of heat and momentum occurs mainly through the turbulence which is associated with frictional velocity (Patil, 2006). The sensible heat flux is maximum in the noon h and of the order of 300 Wm^{-2} in summer, 200 Wm^{-2} in monsoon and about 150 Wm^{-2} in winter. The frictional velocity is reduced in the night h. A scaling temperature T^* is greater than frictional velocity u_* in highly unstable conditions while u_* decreases in stable conditions (Patil, 2006).

The Objective

As we know due to the inconstancy in planning, the Hada Al-Sham area is classified as a village with scattered habitants and farms. The typical Hada Al-Sham farm and the Hada Al-Sham area must be represented as a special place and well investigated for future planning of a modern village. The area witnesses jumble or strong turbulence of winds because it is surrounded by high mountains, high altitude trees and many obstacles. It is required to study surface and boundary layer of the area. Also knowledge and computation of the energy fluxes and meteorological parameters are very crucial to carry out the purpose.

Data and Method

Site and Data Selection

The mast is located in a farm area in the Hada Al-Sham Valley. The mast belongs to the Faculty of Meteorology, Environment and Arid Land Agriculture (west of Makkah) (21°48' N and 39°40' E), in the west of Saudi Arabia. The distance from Makkah to this station is ~25km. The mast levels at heights 2.5, 3.5 and 5.5m above the ground were installed in a place (there are tiny and very short, scattered dry grass remaining on the surface surrounding the mast) which can be recognized as leveled surface land to light wavy surface. There are so many natural plants dominating all around the Hada Al-Sham Valley, either big or small trees or short grass (Fig. 1, Al-Toukhy, 2005). In the neighboring fields Lucerne plants dominate and are irrigated with an axial irrigator once every two days to the North and NW of the mast. To the west a raw of Sisyphus trees of 2m high and 10m space between them, lays at distances of 200m from the mast and to the southeast further, a farm of a condense Hibiscus and Egyptian Cotton plants of ~ 40cm high. On the eastern side, the mast faces a condensed Jojoba farm at 2.5m to 3m height. Behind this farm there are *Myoporum serratum* raw trees (6-7m high) planted to prevent any effect of strong winds. A chart shows the topographic elevations of the Hada Al-Sham area surrounded by mountains (Fig. 2).

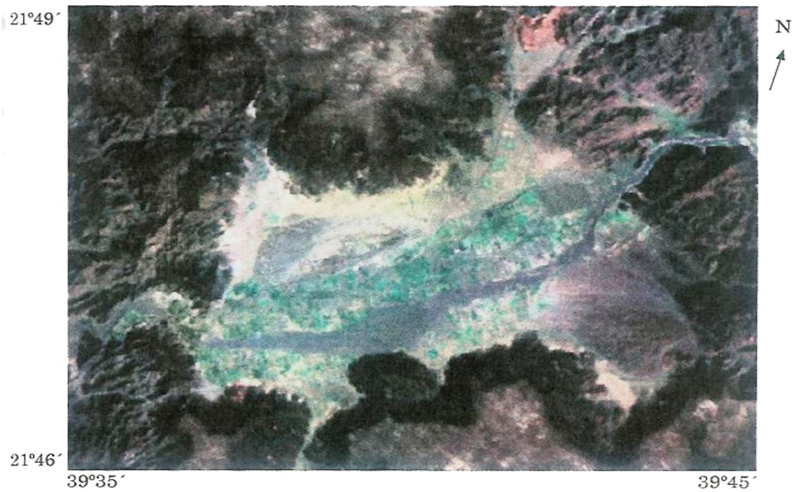


Fig. 1. Aerial photo showing the Hada Al-Sham Valley near Makkah surrounded by mountains, longitudes and latitudes are in degree and minutes.

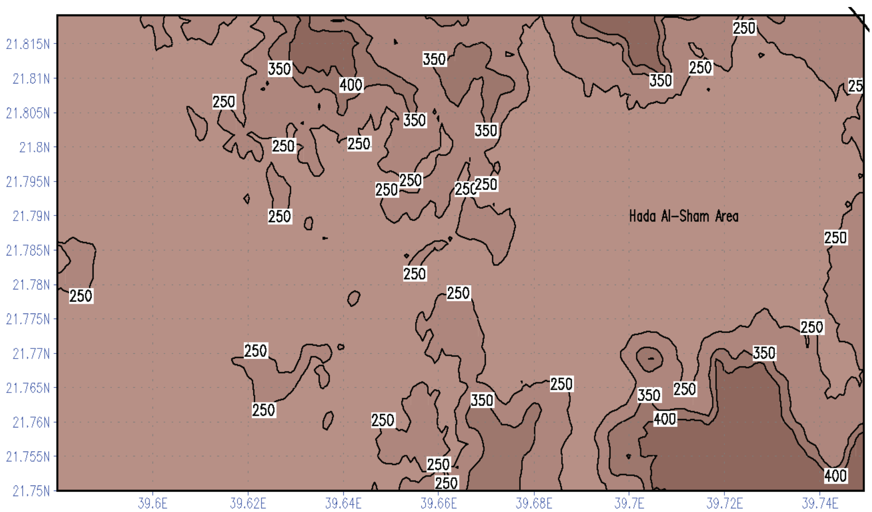


Fig. 2. A chart showing the topographic elevations of the Hada Al-Sham Valley near Makkah, surrounded by mountains, longitudes and latitudes are in degree.

Method of Calculation

Data were obtained from the sensors used for measuring air temperature and wind speed installed on a mast erected in the farm area of the Hada Al-Sham at three heights: 2.5, 3.5 and 5.5m above the ground surface. The data will be used for calculation of the sensible flux.

Surface parameters and energy fluxes were computed from vertical profiles of wind speed and air temperature measurements, the stability parameters based on (MOST) were also computed. Half hourly measurements of wind speed and air temperature were used in a special profile method program for calculating the surface parameters and energy fluxes [sensible heat flux H (Wm^{-2})].

Sozzi, *et al*. (1998) noted that in a generic stability condition within the surface layer (whose vertical extension is of the order of magnitude of the Monin-Obokhov length), for a flat terrain in near stationary conditions, the Monin-Obokhov similarity theory describes the vertical profile of wind speed. In particular, wind speed u varies with altitude z according to the similarity law:

$$\frac{u_z}{u_*} = \frac{1}{k}\left[\ln\left(\frac{z}{z_\circ}\right) - \Psi_M\left(\frac{z}{L}\right)\right] \tag{2}$$

$$\frac{\theta_z - \theta_\circ}{\theta_*} = \frac{1}{k}\left[\ln\left(\frac{z}{z_\circ}\right) - \Psi_H\left(\frac{z}{L}\right)\right] \tag{3}$$

$$\frac{q_z - q_\circ}{q_*} = \frac{1}{k}\left[\ln\left(\frac{z}{z_\circ}\right) - \Psi_E\left(\frac{z}{L}\right)\right] \tag{4}$$

Ψ_M , Ψ_H and Ψ_E are stability functions for momentum, sensible and latent heat respectively. k is von Karmen constant (k = 0.4). The friction velocity is defined by $u_* = (\tau/\rho)^{1/2}$ (Patil, 2006).

Sozzi, *et al*. (1998) added that functions Ψ_M are the wind speed vertical profile universal similarity functions, which assume values depending on stability parameter z/L. A non dimensional length scale, z/L, z being the height where measurements were done and L (m) is the Monin-Obukhov length, is used as stability parameter in the atmospheric surface layer (Patil, 2006). The Monin-Obhukov length *L* is defined as:

$$L = \frac{-u_*^3 \rho}{kg\left(\frac{H}{\theta C_p}\right)} \tag{5}$$

where the acceleration of gravity g = 9.8 ms^{-1}, θ is potential air temperature and C_p is the specific heat (Sánchez, *et al*., 2008). In unstable conditions *L* is negative ($\mathrm{L} \prec 0$), in stable conditions positive ($\mathrm{L} \succ 0$). With strong thermal effects (large heat flux and weak wind) *L* is small; in conditions approaching neutral, *L* becomes infinity large ($L \rightarrow \infty$). Prueger, *et al*. (2004) indicated that the Monin-Obukhov length defines the surface boundary layer stability in terms of turbulent fluxes of heat and water. Equation (2) indicates that vertical wind speed profile is described by the logarithmic law where it can add a correction based on the level of atmospheric stability. The validity of this similarity equation has been experimentally tested in a very wide stability interval ($-2 < z/L < 10$) (Beljaars and Holtslag, 1991), based on results obtained during experimental campaigns. Moreover, Condie and Webster (1997) clarified that

$$\theta_* = -H/(\rho C_p u_*) \tag{6}$$

The similarity functions are given by Paulson (1970), and Sánchez, *et al*. (2008):

$$\Psi_H = \Psi_E = \Psi_M = -5\frac{z}{L} \qquad \frac{z}{L} \geq 0 \tag{7}$$

$$\Psi_M\left(\frac{z}{L}\right) = \ln\left[\left(\frac{1+\varphi_M^{-2}}{2}\right)\left(\frac{1+\varphi_M^{-1}}{2}\right)^2\right] - 2\tan^{-1}\varphi_M^{-1} + \frac{\pi}{2} \tag{8}$$

Estimation of roughness length z_0 (m), friction velocity u_* (ms^{-1}), potential temperature scale θ_* (K) and q_* (g/kg) are achieved by fitting iteratively the profiles 2 and 3 to measured wind velocity and temperature data based on Monin-Obokhov Similarity Theory (MOST). The calculation of H from surface layer profile measurements of temperature, specific humidity and wind speed uses the (MOST) to describe the mean and turbulent structure of the surface layer of the Hada Al-Sham area.

The sensible heat flux H (Wm^{-2}) mentioned by Yao, *et al.* (2008) can be computed as follows:

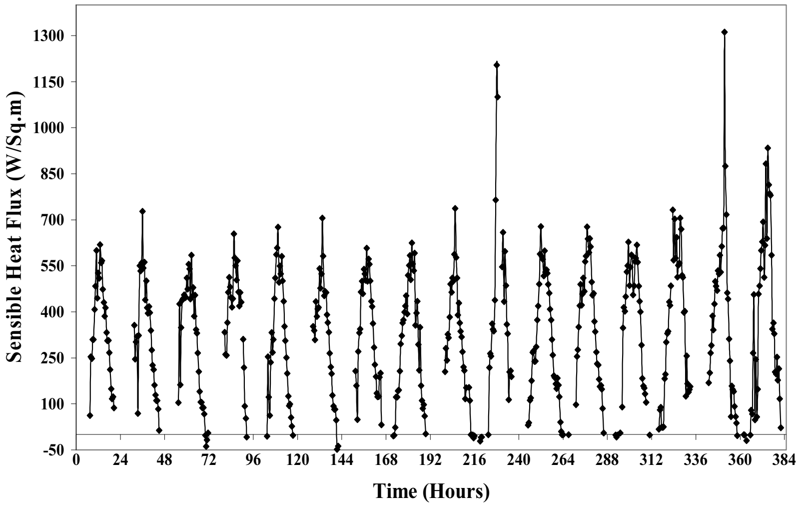
$$H = -\rho c_p u_* \theta_* \tag{9}$$

with ρ the density of air and c_p the specific heat of air at constant pressure, q_* air humidity scale that is the analogue of θ_*. In Eq. 6, we have taken into account ρ =1.2 kg/m^3, c_p = 1004 J $kg^{-1}K^{-1}$ for calculation of the heat flux H. The latent heat of vaporization L_v used in Eq. 18 is 574.7 cal/g at about 40°C, and the latent heat L_v at 0°C is 597.3 cal/g (Rogers, 1983).

Results and Discussion

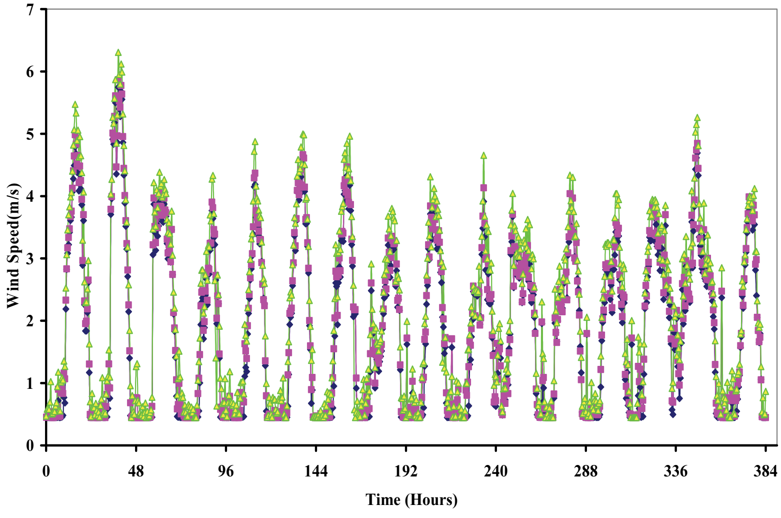
The calculated sensible heat flux H (Wm^{-2}), roughness and stability parameters were investigated. The values H are shown in Fig. 3 for the period between J. El-Awwal 6th, 1423H (July 16th, 2002) and J. El-Awwal 21th, 1423H (July 31st, 2002). Data of wind speed (ms^{-1}) taken from the three levels mast of the Hada Al-Sham at three heights: 2.5m (u_1), 3.5m (u_2) and 5.5m (u_3) between J. El-Awwal 6th and J. El-Awwal 21st, can be seen in Fig. 4. It is noticed that all three values of wind speed u_1, u_2 and u_3 were consistent. The higher values of wind speed u_3 were at 5.5m above the ground but the wind speed u_2 at 3.5m high was lower than u_3 values. The lowest values of wind speed were u_1 at 2.5m high above the ground (Fig. 4).

The daytime sensible heat H (Wm^{-2}) for two weeks is depicted in Fig. 3. These values were computed according to profile method program and the results can be explained as follows:



J. El-Awwal 6 8 10 12 14 16 18 20

Fig. 3. Time series of twenty days of sensible heat flux densities computed between J. El-Awwal 6th, 1423H (July 16th, 2002) and J. El-Awwal 25th, 1423H (August 4th, 2002) in the Hada Al-Sham area, Makkah.



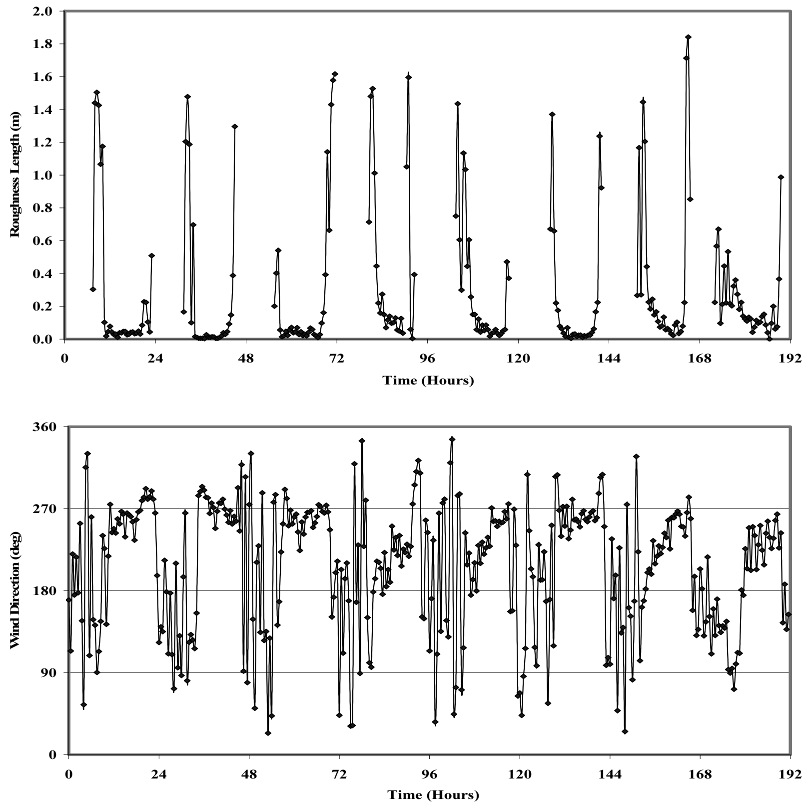
J. El-Awwal 6 8 10 12 14 16 18 20

Fig. 4. Time series of the wind speed from the mast measurements at 3 heights: 2.5m (blue line), 3.5m (pink line) and 5.5m (green line) between J. El-Awwal 6th, 1423H (July 16th, 2002) and J. El-Awwal 30th, 1423H [August (ogst) 10th, 2002] in the Hada Al-Sham area, Makkah.

1. The maximum value of sensible heat flux H was found to be as 1118 Wm^{-2} at 1400 h on J. El-Awwal 15th, 1423H (July 25th, 2002). Another maximum value of H was found as 1200 Wm^{-2} at 1200 h on J. El-Awwal 21th (August 1st).

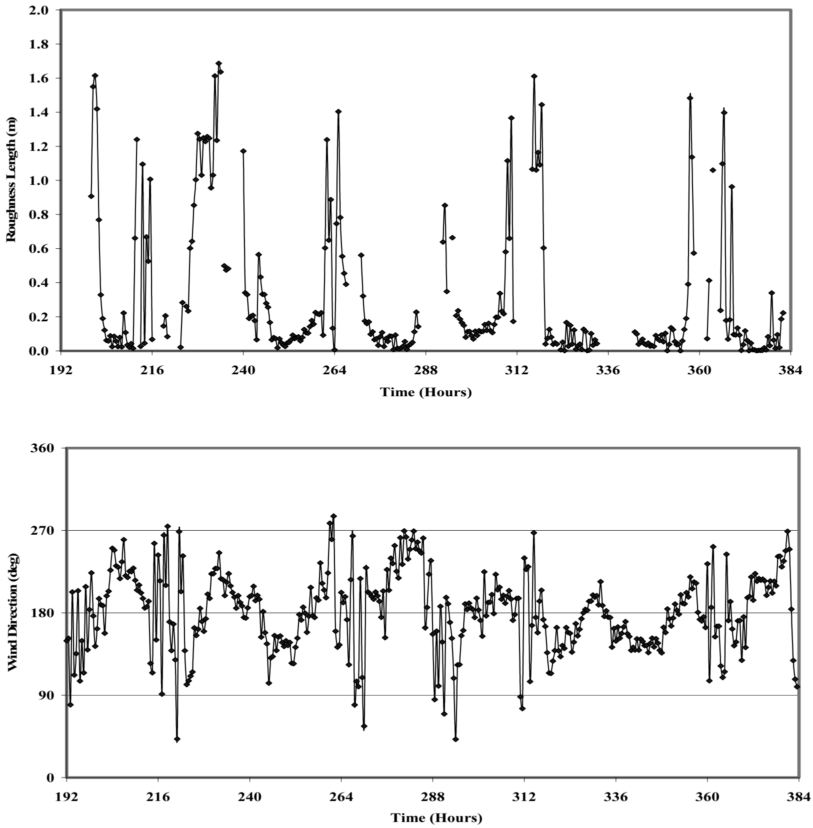
2. The afternoon peak values of H were found between 550 Wm^{-2} and ~ 700 Wm^{-2} [J. El-Awwal 6th (July 16th) until J. El-Awwal 13th (July 23rd)], while other peaks of H were observed between 600 Wm^{-2} and ~ 700 Wm^{-2} [J. El-Awwal 16th (July 26th) until J. El-Awwal 18th (July 28).

The computed values of roughness lengths $z_\circ(m)$ and thee encountered measured values of wind direction at the same mast are shown in Fig. 5 and 6.



J. El-Awwal 6th J. El-Awwal 8th J. El-Awwal 10th J. El-Awwal 12th

Fig. 5. Computed roughness length and measured wind direction between J. El-Awwal 6th and 12th in the Hada Al-Sham area.



J. El-Awwal 14th J. El-Awwal 16th J. El-Awwal 18th J. El-Awwal 20th

Fig. 6. Computed roughness length and measured wind direction between J. El-Awwal 14th and 21st in the Hada Al-Sham area.

The following can be discussed:

1. On J. El-Awwal 6th and 7th (July 16th and 17th), between 0800 until 0830 h, the higher values of roughness lengths $z_\circ$ found to be as high as 1.5m, may be attributed to ~SE winds (average of 129º) where a high altitude trees and a soil barrier of 2-3 high are located to the SE of the mast [Oke, (1978) classified $z_\circ$ (1.0m-6.0m) as forests which means that these values are for high level obstacles]. Between J. El-Awwal 6th to 12th except the peak value of 1.6m at ~1900 h on 9th, lower values of $z_\circ$ were observed and remained very close to an average of 0.03m between 1100-2000 h when the wind direction was nearly SW with an

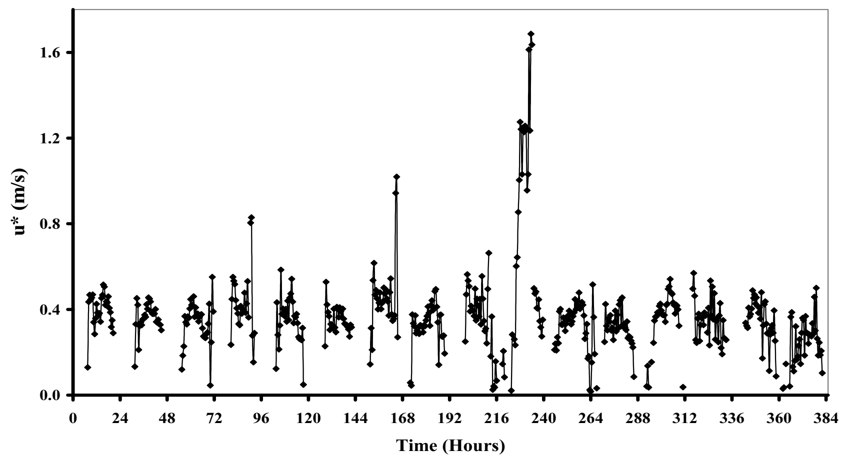
average wind direction of 255º (Fig. 5). An increase in $z_{\circ}$ on both J. El-Awwal 7th and 8th was found, the late evening high values of about 1.5m (2200 h to 2330 h) were probably due to SW (~200 deg.).

2. It was noticed that the fluctuated part of roughness lengths (0730-1000 h) on J. El-Awwal 10th, 11th and 12th encounters the wind direction fluctuation (Fig. 5). An increase in $z_{\circ}$ at 0900 (1.4m) on J. El-Awwal 11th may be due to sudden change of the wind direction from 250° to 120º. A similar situation was observed as in Fig. 5 from J. El-Awwal 10th to 13th after midday until evening (~ 2000 h) when the values of $z_{\circ}$ were very low (0.06m), most probably because of SW winds (Fig. 5). The higher $z_{\circ}$ values on both J. El-Awwal 11th and 12th at about 2100 h were found as 1.2m and 1.8m respectively (Fig. 5).

3. Both J. El-Awwal 14th and 15th in Fig. 6 at about 0900 h, show the high amplitude of $z_{\circ}$ (~1.6m) which can be attributed to S and SE winds. Again, low values of $z_{\circ}$ (average 0.1m) between 1200 and 1900 h were found, probably because of the SW winds effect. On J. El-Awwal 16th, lower values of $z_{\circ}$ between 0730 and 1700 h (average 0.07m) were found, showing that the winds moved to SW direction (Fig. 6). The same as on J. El-Awwal 17th, the average $z_{\circ}$ (0.05m) between 1000 and 2000 h showed the same effect of SW winds.

4. On J. El-Awwal 18th, $z_{\circ}$ was 0.85m at 0500 h, wind direction SE (~150º), while at 0700 h, $z_{\circ}$ was still high (0.66m) and the SE wind direction (~124º) (Fig. 6). The values of $z_{\circ}$ remained low and the winds maintained their direction after 0800 h until midday 1230 h with southerly winds. This probably means that the area might be under the effect of the wind traversing a farm of a condense Hibiscus and Egyptian cotton plants of ~ 40cm high. Same as on J. El-Awwal 18th, the higher value of $z_{\circ}$ was 1.6m in the early morning at 0500 h on J. El-Awwal 19th. The values remained high until 0600 h with average winds of 165º. The values of $z_{\circ}$ dropped to 0.06 (average 170º) after 0700 h until 2130 h.

Mostly on J. El-Awwal 20th, the average value of $z_{\circ}$ was found as 0.06 between 0700 to 1930 h (average wind direction ~170º) (Fig. 6). The fluctuated part of the roughness lengths (0530-1000 h) on J. El-Awwal 21st encountered the wind direction fluctuation (Fig. 6). It also appears in Fig. 6 that $z_{\circ}$ in their lower values sometimes were found close to zero, probably affected by SW winds (average~ 200º between 1000 to 1830 h). It can be generally concluded that most days show an increase in their roughness lengths not exceeding 1.8m with SE winds affected by high altitude trees and a soil barrier of 2-3 m high. The contrary is true, lower values of $z_{\circ}$ were found between midday until early evening, sometimes very close to zero with mostly SW winds. Figure 7 shows the computed values of friction velocity u_* (ms^{-1}). Values of friction velocity u_* were drawn for the period between J. El-Awwal 6th and J. El-Awwal 21st.



J. El-Awwal 6 8 10 12 14 16 18 20
July 16 18 20 22 24 26 28 30

Fig. 7. Time series of friction velocities u_* (ms^{-1}) calculated between J. El-Awwal 6th (July 16th) and J. El-Awwal 21st (July 31th) in the Hada Al-Sham area, Makkah.

The higher daily calculated friction velocities u_* (ms^{-1}) were found in the afternoon with an average of about $0.4\,ms^{-1}$ with less effect of winds unless the wind retarded to approach the site of the experiment. The above days had normal sensible heat between 600-700 Wm^{-2} except the days J. El-Awwal 15th, 20th and 21st (Fig. 3). The maximum scattered values of u_* were observed in Fig.10 as follows: On J. El-Awwal 9th attaining up to $0.8\,ms^{-1}$ at 1830 and 1900 h, on J. El-Awwal 12th $1.0\,ms^{-1}$ at 2100 h and on J. El-Awwal 15th $1.7\,ms^{-1}$ at 1730 h.

The higher friction velocity on J. El-Awwal 9th, was probably due to the change of the wind direction from SW (~223°) which was recorded at 1900 h to westerly wind at 1930 h (275°). The peak friction velocity values on J. El-Awwal 12th, were probably due to the sudden change of the wind direction from nearly west at 2030 h (266°) to NW at 2100 h (283°). The winds on J. El-Awwal 15th at 1700 h were recorded as 216° then deviated to 200°. This might be referred to the high friction velocity which took place.

To examine the stability condition on a specific day J. El-Awwal 21st, M-O length *L* was drawn in Fig. 8. The signs of scale length *L* from 0730 h until 2130 h were negative (unstable conditions) when the sunrise was at 0548 h and set at 1907 h in Makkah. The signs of evening *L* values after 2130 h were positive (stable conditions). Similarly, it is expected that all measurements of *L* were negative signs during the daytime, while the evening values could be positive.

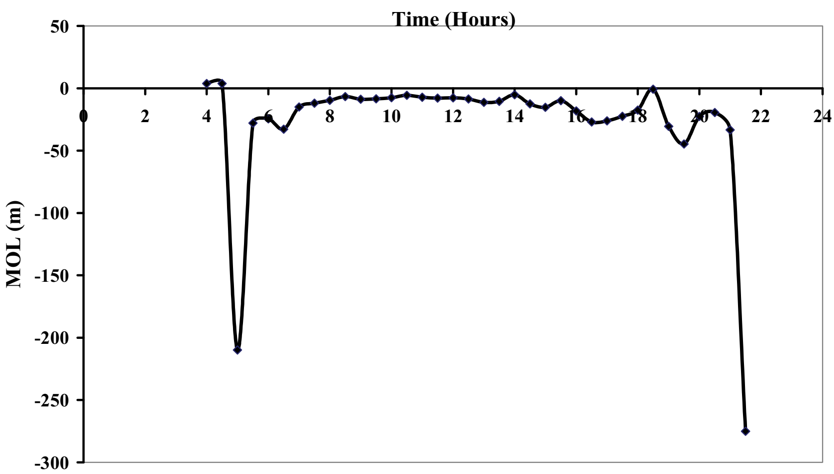


Fig. 8. Monin Obokhov length (MOL) on J. El-Awwal 11th, 1423H.

Conclusion

The higher values of sensible heat calculated on most days of the experiment (600-700 Wm^{-2}) in the afternoon except the days (J. El-Awwal 15th, 20th and 21st) showed fluxes between 850 and 1200 Wm^{-2}.

The higher daily friction velocities calculated u_* (ms^{-1}) were found in the afternoon with an average of about $0.4\,ms^{-1}$. The maximum scattered values of u_* were observed in Fig. 7 as: on J. El-Awwal 9th attained up to 0.8 (ms^{-1}) at 1830 and 1900 h, on J. El-Awwal 12th attained up to 1.0 ms^{-1} at 2100 h and on J. El-Awwal 15th attained up to 1.7 ms^{-1}at 1730 h.

The turbulent eddies transport sensible heat and turbulent kinetic energy upward, eroding the layer of stable air lying above at the same time as the convective boundary layer depth increases (Garcia, *et al.*, 2002). It may be concluded that heat is well mixed systematically during the daytime through the unstable layer.

Acknowledgment

The author would like to thank the Meteorology department, King Abdulaziz University, Jeddah who provided me the data of Hada Al-Sham mast station for use in the field work.

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تقدير عناصر الاحتكاك وفيض الحرارة المحسوسة في منطقة هدى الشام، مكة المكرمة

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المستخلص. قدمت أمثلة للأطوال الاحتكاكية على قيم $z_{\circ}$م التي تم حسابها في منطقة هدى الشام الزراعية بين ٦ و ١٢ جمادى الأولى ١٤٢٣هـــ، حيث كانت قيم $z_{\circ}$ منخفضة وقريبة من الصفر (٠,٠٣م)، بين الساعة ١١٠٠ صباحًا وحتى الساعة ٢٠٠٠ مساءً، بسبب تأثير الرياح الجنوبية الغربية، بحيث كان متوسط اتجاهها ٢٥٥°. أما في يوم ٩ جمادى الأولى فكانت أقصى قيمة للطول $z_{\circ}$ هو ١,٦م عند الساعة ١٩٠٠ مساءً. أما بالنسبة إلى قيمة السرعة الاحتكاكية $u*$ بمتوسط ٠,٤م/ثانية بعد الظهر، فقد وجدت مرتفعة مع تأثير أقل للرياح ما لم يعُق وصولها أشجارعالية. مثال على حساب أعلى قيمة للسرعة الاحتكاكية $u*$ بلغت قيمتها ٠,٨م/ثانية يوم ٩ جمادى الأولى عند الساعة ١٩٠٠ مساءً، بينما كانت أقصى قيمة للسرعة الاحتكاكية $u*$ يوم ١٢ جمادى الأولى ١م/ثانية عند الساعة ٢١٠٠ مساءً، أما يوم ١٥جمادى الأولى بلغت $u*$ ذروتها بقيمة ١,٧م/ثانية عند الساعة ١٧٣٠ مساءً. ربما كانت القيمة العالية للسرعة الاحتكاكية التي وجدت في ٩ جمادى الأولى نتيجة اتجاه الرياح عندما تحولت من جنوبية غربية (٢٢٣°) عند الساعة ١٩٠٠ مساءً، إلى غربية عند الساعة ١٩٣٠ مساءً (٢٧٥°).

أقصى قيم لفيض الحرارة المحسوسة H هي ١١١٨ (وات/ م٢) يوم ١٥ جمادى الأولى عند الساعة ١٤٠٠ ظهرًا، و١٢٠٠ (وات/ م٢) يوم ٢١ جمادى الأولى عند الساعة ١٢٠٠ ظهرًا. أما القيم القصوى العادية لفيض الحرارة المحسوسة للأيام من ٦ جمادى الأولى حتى ١٣ جمادى الأولى فكانت بين ٥٥٠ و٧٠٠ (وات/ م٢).