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APPLICATION OF BUSINGER-DYEAR AND BRUTSAERT'S STABILITY FUNCTIONS FOR ESTIMATION OF THE SENSIBLE HEAT FLUX ON SOME MEASURED DATA IN THE HADA AL-SHAM AREA, MAKKAH, SAUDI ARABIA

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Abstract

Micrometeorological measurements on the Hada Al-Sham region near Makkah were used for determination of the fluxes of sensible heat and momentum by applying profile method derived from Monin-Obukhov similarity theory. Samples of data were selected in a very unstable conditions (summer seasons) in the Hada Al-Sham area, Makkah. Two code programs written according to both Brutsaert (1992) and Businger-Dyear were used. Sensible heat values using the stability correction functions used by Businger-Dyer (B-D-F) were found to be higher (10-14%) than the stability correction functions used by Brutsaert (B-F) between 1100 and 1700 hours (noon and afternoon) on days of September 2002 and June 2003. The roughness lengths Z_0 show higher values (0.3-0.5m) using (B-F) on most days for the easterly and SE winds due to the effect of very high rough area (medium height buildings, hills). The roughness length Z_0 was found to be related with wind direction. It was noticed from the experiment that the roughness length using the stability correction functions by (B-F) and was more sensitive to any change in wind direction than that used by (B-D-F). The more the sudden change of the wind direction by (B-F) version the more the fluctuations in the roughness length values occure.

Finally, the stability correction functions used by (B-D-F) for calculating sensible heat fluxes and stability parameters are more preferable than using the stability correction functions by (B-F) one.

1. Introduction

Grachev et al (2000) described the integral forms of the Flux-Profile Relations, the integral forms of the universal functions

$$\frac{d\overline{U}}{dz} = \left(\frac{u_*}{k\,z}\right)\varphi_u(\zeta)\ , \qquad \frac{d\overline{\theta}}{dz} = \left(\frac{\theta_*}{k\,z}\right)\varphi_t(\zeta) \tag{1}$$

where $\theta_* = \frac{-\overline{w'\theta'}}{u_*}$ is the temperature scale; dimensionless velocity, $\varphi_u(\zeta)$ and temperature, $\varphi_t(\zeta)$, gradients are the presumably universal functions of a non-dimensional stability parameter $(\zeta = z/L)$. The von Karman constant k is defined such that for neutral conditions.

Cahill et al (1997) reported that the roughness length for temperature, z_{oh}, is simply an integration constant defined by the Monin-Obukhov similarity theory which quantifies the height above the surface (*z* = *0*) where the temperature is taken to be equal to T_s. Note that z_{oh} is the surface intercept of the atmospheric surface layer temperature profile in the same way that the momentum roughness length z_{om} is the zero velocity intercept for the surface layer velocity profile,

$$\bar{u} = \frac{u_*}{k}\left[\ln\left(\frac{z}{z_{om}}\right) - \Psi_m(\zeta)\right] \tag{2}$$

where $\bar{u}$ is the mean wind speed, z is the measurement height, and $\Psi_m(\zeta)$ is the similarity function for momentum.

The Monin and Obukhov (1954) describe similarity model for temperature can be written as

$$T_s - T_a = \frac{H}{k u_* \rho c_p}\left[\ln\left(\frac{z}{z_{oh}}\right) - \Psi_h(\zeta)\right] \tag{3}$$

where *H* is the sensible heat flux, z_h is the measurement height for temperature in the surface layer of the atmospheric boundary layer (ABL), *k* = (0.4) is von Karman's constant, $u_* = (\tau_o / \rho)^{1/2}$ is the friction velocity, τ_o is the surface shear stress, ρ is the air density, c_p is the specific heat of air, T_s and T_a are the surface and air temperatures, respectively, z_{oh} is the roughness length for temperature, and Ψ_h is the similarity function for temperature. The similarity function depends on the dimensionless variable ζ, defined as z_h / L, where L is the Obukhov length.

Parlange and Brutsaert (1993) considered $u_* = (\tau_o / \rho)^{1/2}$ as one of the essential variables in Monin-Obukhov similarity theory to describe turbulence in the surface sub-layer or inner region of the atmospheric boundary layer (ABL).

Universal functions of a non-dimensional stability parameter $(\zeta = z / L)$ in Eq.(1) can be written as

$$\frac{d\overline{U}}{dz} = \frac{u_*}{k(z - d_o)}\,\varphi_m(II) \tag{4}$$

where d_o is the (zero-plane) displacement height; $\varphi_m = \varphi_m(II)$ is the Monin-Obukhov stability function, in which $II = (z - d_o) / L$.

For unstable conditions the stability function ~ *m* has been the subject of numerous experimental studies. Until a few years ago, the consensus based on the field observations was that the Businger-Dyer formulation (e.g., Dyer, 1974; Businger, 1988 and Högstrom, 1988), in a general form

$$\varphi_m = (1 - C\,II)^{-1/4} \tag{5}$$

where *C* is a constant, gives a good description of the available data. However, almost all of the field studies on which (3) was based produced data for (–*II*) smaller than 2.0; thus little was known about the behaviour of φ_m for large values of (–*II*), which represent strongly unstable conditions for measurements at higher elevations in the surface layer. More recently, following a theoretical analysis by Kader and Yaglom (1990) with a data collection with values of (–*II*) up to 20, Brutsaert (1992) suggested as an interpolation function

$$\varphi_m = \left[(a + b\,x^n)/(a + x^n)\right] + c\,x^{1/3} \qquad (6)$$

where $x = -II$, and *a*, *b*, *c* and *n* are constants, to be specified below. In practical applications, the wind speed profile, which is the integral of (4), is often written in the form the looks like Eq.(2)

$$u = \frac{u_*}{k}\left[\ln\left(\frac{z - d_o}{z_o}\right) - \Psi_m(II)\right] \qquad (7)$$

The stability correction function $\Psi_m(II)$ is defined by

$$\Psi_m(II) = \int [1 - \varphi_m(z)]\,dz/z \qquad (8)$$

Parlange and Brutsaert (1993) added that it can be readily integrated using the two φ_m functions. Thus the correction function derived from the Businger-Dyear formulation (5) is

$$\Psi_m(II) = \int_{z_o/L}^{II} \ln\left[\frac{(1+u)^2(1+u^2)}{(1+u_o)^2(1+u_o^2)}\right] - 2\tan^{-1}(u) + \tan^{-1}(u_o) \qquad (9)$$

where $u = (1 - C\,II)^{1/4}$ and $u_o = (1 - C\,z_o/L)^{1/4}$. The value of *C* was selected as 16, which is typical for *k = 0.4*. In the integration of (8) with (6), two sets of constants were used. In the first implementation, the constants in (6) were chosen to produce a close fit with the data of Kader and Yaglom (1990). The result was the following (for *k = 0.4*) (Brutsaert, 1992);

$$\Psi_m(II) = 0 \quad \text{for} \quad II > -0.0093$$

$$\Psi_m(II) = 1.72\ln\left[\frac{\left(0.37 + x^{0.72}\right)}{0.37 + \left(0.0093 + x_o\right)^{0.72}}\right] - 1.5\left(x^{1/3} - (0.0093 + x_0)^{1/3}\right) \qquad (10)$$

For $II \le -0.0093$

where, again, $x = -II$ and $x_o = -z_o/L$. In the second implementation of (6), the constants were selected as a compromise between the data set of Kader and Yaglom (1990) and the several earlier data sets for small (–*II*), as exemplified by Högstrom (Brutsaert, 1992). They proposed the following:

$$\Psi_m(II) = 0 \quad \text{for} \quad II > -0.0059$$

$$\Psi_m(II) = 1.47\ln\left[\frac{\left(0.28 + x^{0.75}\right)}{0.28 + \left(0.0059 + x_o\right)^{0.75}}\right] - 1.29\left(x^{1/3} - (0.0059 + x_0)^{1/3}\right) \qquad (11)$$

For $-0.0059 \geq II \geq -15.025$

$$\Psi_m(II) = \Psi_m(-15.025) \quad \text{for} \quad II = -15.025 \ . \qquad (12)$$

Figure (1) shows the momentum stability correction functions Ψ_m given from Equations (9-11) plotted versus *–II*.

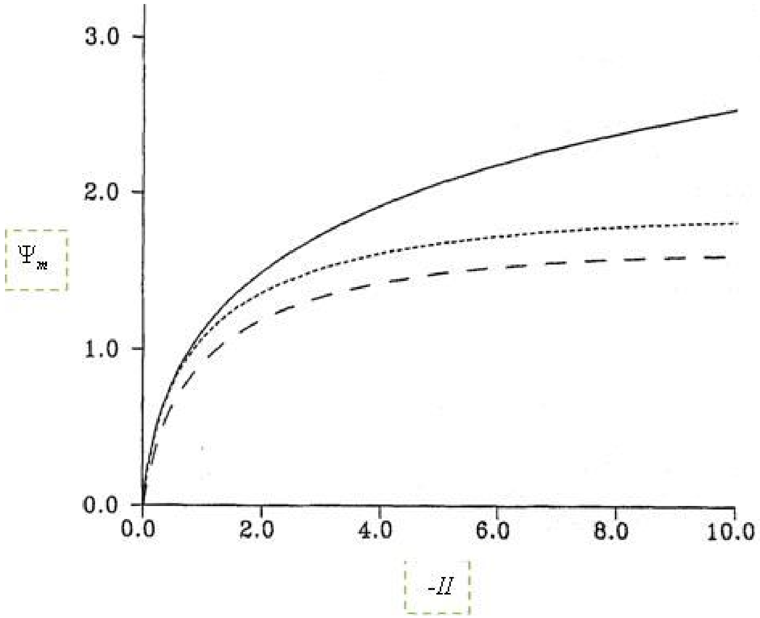

Figure (1): The momentum stability correction functions $\Psi_m(z_o = 0)$; Eq.(9), solid line; Eq.(10), long dashed line; Eq.(11), dashed line (Parlange and Brutsaert, 1993).

Brutsaert (1992) applied number of formulas depending on the basis of a combination of the proposal of Kader and Yaglom (1990) and the analysis of Högstrom (1988) for unstable atmospheric conditions (mentioned above). They are for sensible heat,

$$\Psi_h(II) = 1.2\ln\left(0.33 + II^{0.75}\right)/\,0.33 \qquad (12)$$

Both Parlange and Brutsaert (1993) continued that as an illustration, the three forms of Ψ_m, namely (9), (0), and (11) $(II_o = 0)$, are plotted for $z_o = 0$ in Figure(1). The surface-layer similarity scheme (1) has been developed and tested primarily for relatively smooth and homogeneous terrain. Moreover, most experiments on which (5) and (6) are based, were conducted at the field scale with measurements at a few meters above the ground and effective fetches in the order of a few hundred meters, at most.

Brutsaert (2005) presented Eq.(7) as similar to scheme (1) in the form

$$\bar{u} = \frac{u_*}{k}\left[\ln\left(\frac{z-d_o}{z_o}\right) - \Psi_m\left(\frac{z-d_o}{L}\right) + \Psi_m\left(\frac{z_o}{L}\right)\right] \qquad (13)$$

and Eq.(3) as

$$\theta_s - \bar{\theta} = \frac{H}{k u_* \rho c_p}\left[\ln\left(\frac{z-d_o}{z_{oh}}\right) - \Psi_h\left(\frac{z-d_o}{L}\right) + \Psi_h\left(\frac{z_{oh}}{L}\right)\right] \qquad (14)$$

where $\bar{u}$, $\bar{\theta}$ refer to mean values of wind speed and potential temperature respectively, θ_s is surface potential temperature.

It is important to mention the following that Businger-Dyear relationships which have been found between φ_m and z/L (Dyer 1974, Garratt 1992) can have the criteria as

Stable conditions $(z/L > 0)$: $\varphi_h = \varphi_m = 1 + 5\,z/L$ (15)

Unstable conditions $(z/L < 0)$: $\varphi_h = \varphi_m^2 = (1 - 16\,z/L)^{-1/2}$ (16)

Note that we should generally restrict the application of these relationships to $z < |L|$. From φ_m we can calculate u_* in stable conditions as written in Eq.(13), where $\Psi_m(z/L) = -5\,z/L$ in stable conditions. In unstable conditions one can still use this form

$$\Psi_m\left(\frac{z}{L}\right) = 2\ln\left(\frac{1+u}{2}\right) + \left(\frac{1+u^2}{2}\right) - 2\tan^{-1}(u) + \frac{\pi}{2} \qquad (17)$$

Here the dimensionless parameter φ_h, which turns out to be equal to φ_h in stable conditions (Eq. 15) but equal to φ_m^2 in unstable conditions (Eq. 16).

Salomons (2001) noticed that from Businger-Dyear relations, it can be driven expressions for the wind profile $\bar{u}$ and the potential temperature profile $\bar{\theta}$; the profiles called Businger-Dyear profiles

$$\bar{u} = \frac{u_*}{k}\left[\ln\left(\frac{z}{z_o}\right) - \Psi_m\left(\frac{z}{L}\right)\right] \qquad (18)$$

and

$$\bar{\theta} = \bar{\theta}_o = \ln\left(\frac{z}{z_T}\right) - \Psi_h\left(\frac{z}{L}\right) \qquad (19)$$

where z_T the roughness length for temperature, and is usually less than the aerodynamic roughness length z_o .

By fitting iteratively the profiles (18 and 19), one can be computed z_o, u_* and θ_* using measured wind velocity and temperature data. After determining u_* and θ_*, heat fleur (H) can be estimated by:

$$H = \rho c_p u_* \theta_* \, . \tag{20}$$

2. Site and data Selection

Micrometeorological measurements on the Hada Al-Sham region near Makkah (Fig. 2) were used for determination of the fluxes of sensible heat and momentum by applying profile equations derived from Monin-Obukhov similarity theory.

Figure (2): Map of Saudi Arabia.

The data were taken from a mast located in an 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 ~25 *km*. The mast cover levels at heights 2.5, 3.5 and 5.5 *m* 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 levelled surface land to light wavy surface.

3. Results and Discussion

The micrometeorological measurements on the Hada Al-Sham area were used to estimate both fluxes of sensible heat H and of momentum by applying profile method with two different stability correction functions for momentum Ψ_m and sensible heat Ψ_h. In general, *H* values derived from profiles with the stability functions of Brutsaert (1992) and *H* values when the Businger-Dyear functions were used. For sensible heat flux using Brutsaert functions was compared with Businger-Dyear functions drawn in this section. If we scrutinize at the method of calculating the sensible heat from temperature profiles, it was found that a relatively not large difference between the *H* values derived with these two different versions of the stability correction functions were caused by the small differences for Ψ_h values and by larger differences for Ψ_m values. This result stems from the strong sensitivity of the resulting *H* values on the choice of Ψ_h.

3.1 Data analysis on 2002-2003

It was noticed that in Fig.(3) on 17th August 2002 at Hada Al Sham area, several fluctuated roughness length z_0 values computed using Brutsaert's stability correction functions appeared and they had their own significant meaning. They never exceeded 0.5 *m* during the day time (Fig. 4). The first peak of z_0 occurred at 1000 hours with value of 0.4 *m* when the wind direction suddenly turned from 185° to 137°, second peak of 0.33 *m* occurred at 1100 hours with wind direction of 165°. Third peak of z_0 with value of 0.3 *m* found at 1330 hours and with reasonable wind direction of 191° (SSW). Both peaks of 0.5m one at 1600 and the other at 1730 hours occurred with wind direction of 211° (SW), but in contrast Businger-Dyear has its maximum value of z_0 of 0.15 *m* (Fig. 4). On the other hand Businger-Dyear roughness length eventually had a sudden peak value of 0.36 *m* at 1930 hours and with wind direction of 167° (Fig. 4). Actually, it was noticed that the Businger-Dyear roughness lengths between 0900 and 1230 hours have an average value of 0.1 *m*. Due to the lower values of z_0 from 0700 and 1200 hours, the sensible heat *H* was relatively close to each other (Fig. 2) at this period of time.

The situation on 18th August 2002 was as follows: Fig.(5) shows that both sensible heat H at their maximum values of 525 Wm^{-2} and 485 Wm^{-2} using (B-D-F) and (B-F) respectively, have a relatively not large differences between the *H* values derived with these two different versions of the stability correction functions (mentioned above). Between 1000 and 1130 hours, there are abnormal values of *H* by applying the stability correction functions (B-F) (Fig. 5), probably because of the sudden change of the SW (230°) to SSE (148°) winds at 1000 hours, then gradually returned to normal values of *H*. Referring with z_0 for both functions (Fig. 6), two peaks of z_0 were appeared one at 1030 hours and the other peak at 1200 hours.

These peaks only appeared; in case of using (B-F), the sudden change of the SW (230°) to SSE (148°) winds at 1000 hours affecting this higher value of roughness length (~1.9 *m*) while the other peak of z_0 at 1200 hours was 0.9 *m* (Fig. 6), Table (1).

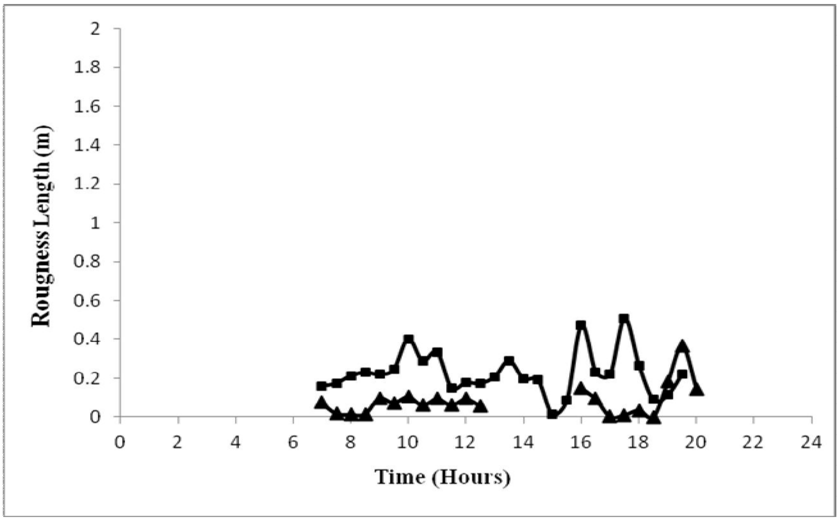

Figure (3): Businger-Dyear (—▲—) roughness lenngth $z_0(m)$ and Brutsaert's version (—■—) on 17th August 2002 at Hada Al Sham area.

Table (1): Abnormal values of z_0 for Brutsaert's version of stability correction functions.

	$z_0(m)$	W.D. (Deg.)	$z_0(m)$	W.D. (Deg.)	$z_0(m)$	W.D. (Deg.)
Date (2002)						
18-08	1.9 at 1000 h	148	1.9 at 1000 h	184	-------	-------
08-09	0.5 at 1100 h	145	1.0 at 1230 h	175	1.4 at 1430	160
Date (2003)						
1-6	0.6 at 1430 h	251	0.7 at 1700 h	270	--------	--------
6-6	0.5 at 1100 h	190	0.8 at 1800 h	261	0.56 at 1930 h	231

On 4th September 2002 the following can be explained: the calculated sensible heat *H* using the stability correction functions (B-D-F) and (B-F) shows that there are not large differences between the H values derived with these two different versions of stability functions. This difference was found to be as 14%. The reason of very low values of z_0 between 1330 and 1930 hours, is probably because of the effect of

SSW (~203). The roughness length z_0 values computed using Brutsaert's stability correction functions (B-F) and using the stability functions (B-D-F).

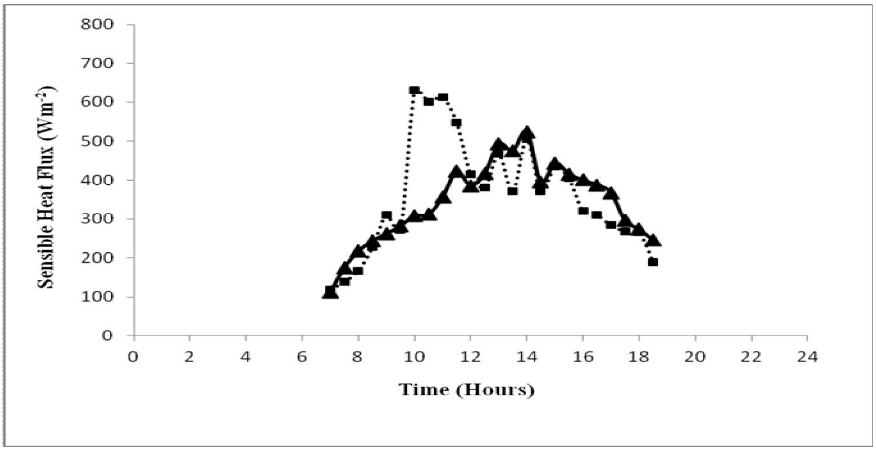

Figure (4): Businger-Dyear functions ψ (─▲─) and Brutsaert's version of the ψ functions (··■··), both stability functions used to calculate the sensible heat flux on 18th August 2002 at Hada Al Sham area.

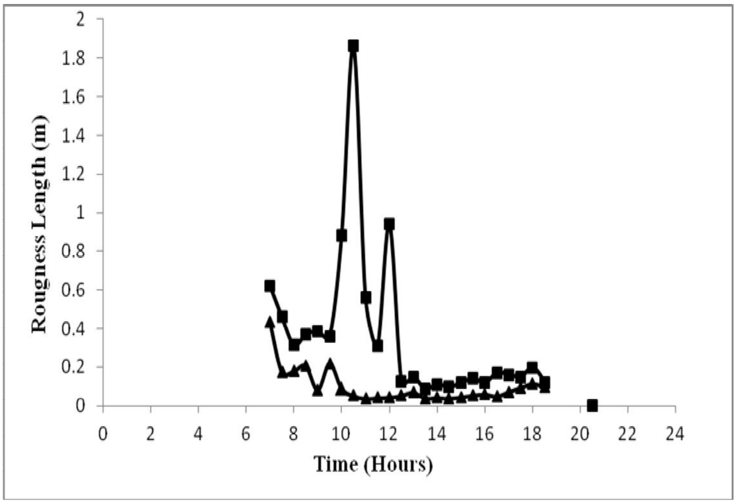

Figure (5): Businger-Dyear (─▲─) roughness length $z_o(m)$ and Brutsaert's version of the (─■─) on 18th August 2002 at Hada Al Sham area.

On 8th September 2002, Fig.(7) shows the sensible heat flux values which have been calculated using the stability functions (B-D-F), represented by dotted line. The dotted line curve seems a pretty and smooth ever in our experiment.

On 8th September 2002, Fig.(9) shows that two peaks were observed using Brutsaert's stability correction functions (B-F). Every peak has a certain significant meaning. The first peak occurred at 1100 hours with a roughness length of 0.5 *m* when suddenly the wind direction turned from 145° to 175°. The second peak occurred at 1230 hours showing also the same wind direction 175° but with higher value of z_0 of 1 *m* which could be affected by high trees located to the SE of the mast which holding the meteorological instruments. The last peak which occurred at 1430 hours also showed the highest value of $z_0 = 1.4m$ and with 160° (Fig. 10, Table 1). Both Businger-Dyear and Brutsaert's z_0 between 1500 and 2000 hours show normal values without any effect of the surface obstacles and with nearly SSW wind (~200°).

It was revealed that the values of z_0 and sensible heat *H* are lower than in 2002 probably because of the wind direction blowing across the smooth roughness.

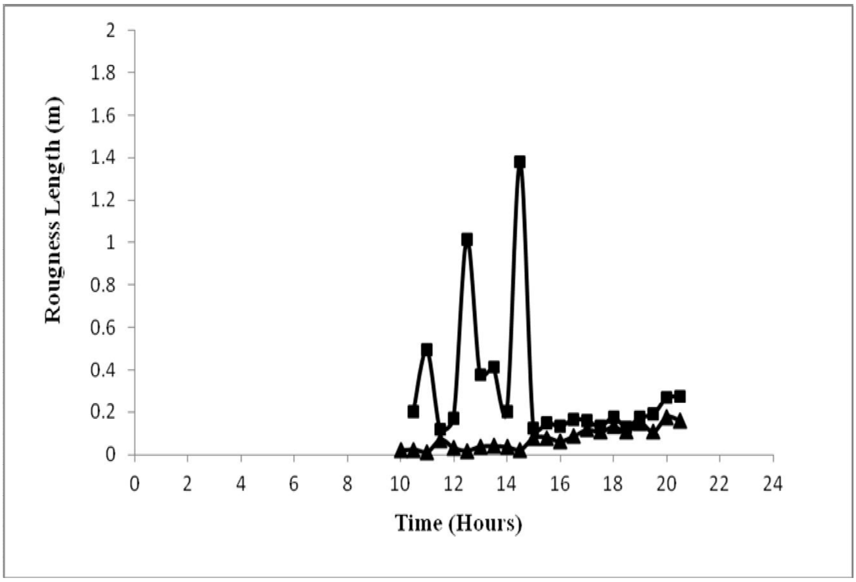

Figure (6): Businger-Dyer (—▲—) roughness lenngth $z_o(m)$ and Brutsaert's version of the (—■—) on 8th September 2002 at Hada Al Sham area.

On 1st June 2003 at Hada Al Sham area, there was not large difference in *H* between 0900 hours and 1330 hours. Only two peak values were seen at 1430 hours and 1630 hours (Fig. 7). As for roughness length values, in general, very low values were found on the whole day when z_0 was calculated using the stability functions (B-D-F). The reason may be because of the wind which blown starting SSW in the morning hours, turning gradually turned to SW at noon and afternoon, while in the late afternoon found to be nearly W. Two peak values (Fig. 8) are likely to follow the same trend as the sensible heat; one with the value of 0.6 *m* at 1430 hours and the other one with the value of 0.7 *m* at 1700 hours (Table 1), when using Brutsaert's stability correction functions (B-F).

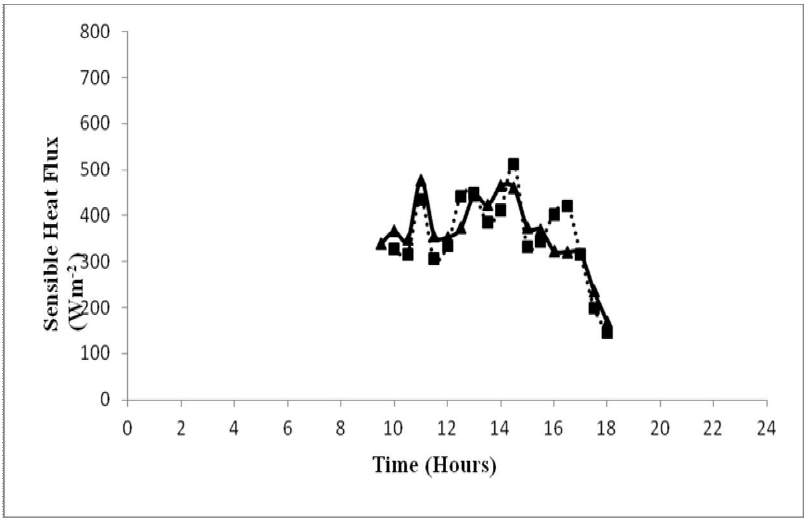

Figure (7): Businger-Dyer functions ψ (—▲—) and Brutsaert's version of the ψ functions (••■••), both stability functions used to calculate the sensible heat flux on 1st June 2003 at Hada Al Sham area.

These peaks appeared because of the sudden change of wind direction from SW winds to westerly winds. All day the winds were mostly SW and not affected with large obstacles.

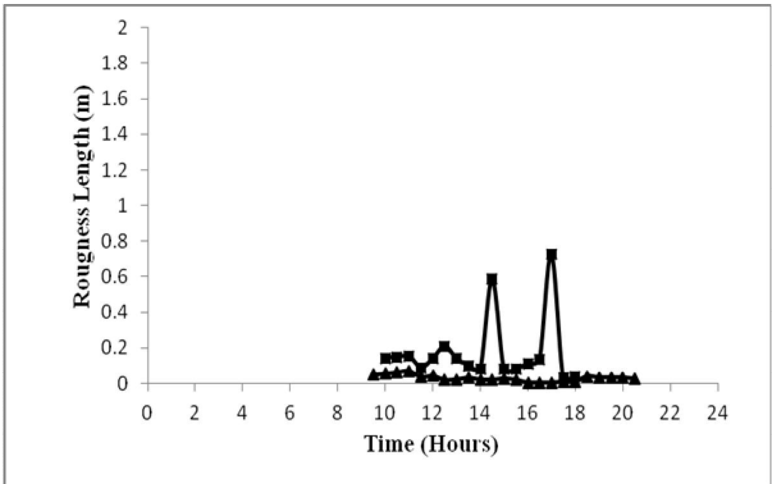

Figure (8): Businger-Dyer functions ψ (—▲—) roughness lenngth $z_o(m)$ and Brutsaert's version of the (—■—) on 1st June 2003 at Hada Al Sham area.

On 5th June 2003 at Hada Al Sham area, generally, there was not large difference in *H*. Abnormal value was found at 1130 hours with *H* of 650 Wm^{-2} when the wind was turned at 1100 hours from 200° to 183° at 1130 hours (Brutsaert's version) while the rest values after that were under the effect of SSW to SW until 1700 and with a very unstable condition of the surface layer (Fig. 9). There is a peak value following the peak value in *H* of 650 Wm^{-2} and z_0 of 0.6 *m* (Fig. 9). The values of *H* (Brutsaert's version) matched with the values (Basinger- Dyer's version) between 1800 and 2030 hours. Same as on 1st June 2003, the roughness length values were very low on the whole day when z_0 was calculated using the stability functions (B-D-F). The reason may be because of the wind which blown starting from SSW, SW and W.

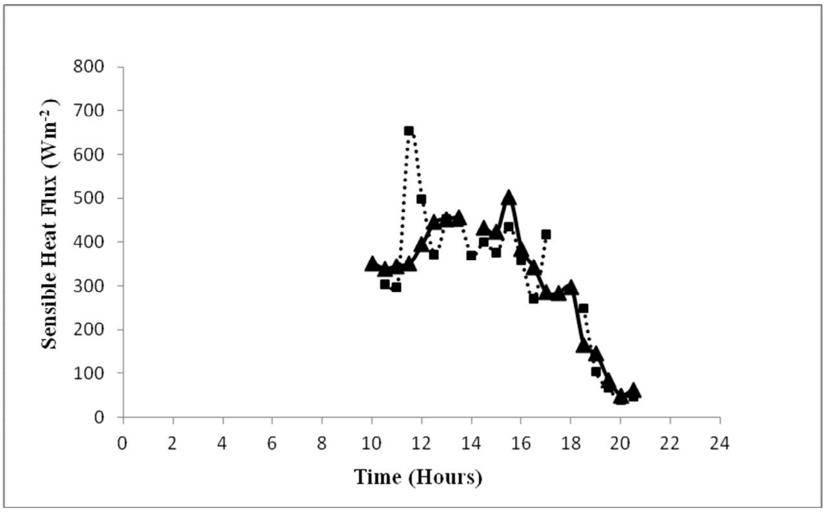

Figure (9): Businger-Dyear functions ψ (—▲—) and Brutsaert's version of the ψ functions (••■••), both stability functions used to calculate the sensible heat flux on 5th June 2003 at Hada Al Sham area.

On 11th June 2003 at Hada Al Sham area (Fig. 10), the abnormal value was appeared when using (Brutsaert version) for calculating the flux *H*. The highest value of *H* was 654 Wm^{-2} at 1300 hours when the wind was turned at 1230 hours from 260° to 274° at 1300 hours (Brutsaert's version, Fig. 10). The sensible heat values using the stability correction functions used by Businger-Dyear (B-D-F) were higher (12%) than the stability correction functions used by Brutsaert (B-F) between 1100 and 1700 (Fig. 10). This is the first time in our experiment (Fig. 11), that both values of z_0 using the stability correction functions used by Businger-Dyear (B-D-F) and the stability correction functions used by Brutsaert (B-F) are nearly matching each other (Fig. 11). The wind directions on this day were SSW between 0900 to

1000 hours, then SW until midday and about westerly between 1200 and 1930 hours (sunset).

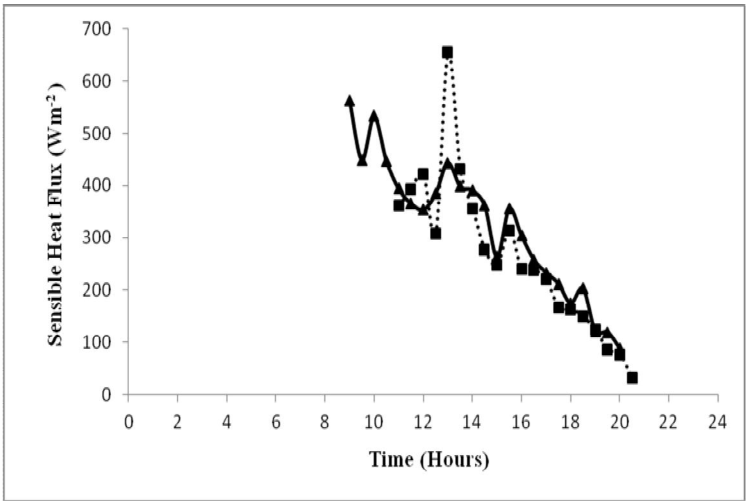

Figure (10): Businger-Dyear functions ψ (—▲—) and Brutsaert's version of the ψ functions (··■··), both stability functions used to calculate the sensible heat flux on 11th June 2003 at Hada Al Sham area.

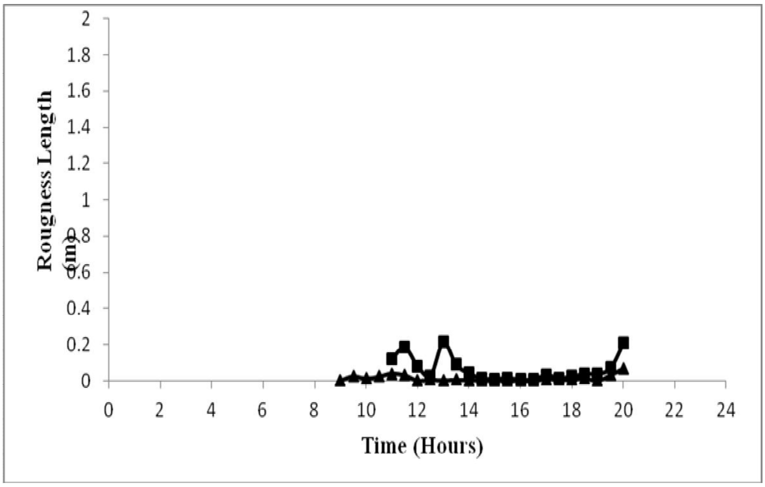

Figure (11): Businger-Dyear functions ψ (—▲—) roughness length $z_0(m)$ and Brutsaert's version of the (—■—) on 11th June 2003 at Hada Al Sham area.

Conclusion

The sensible heat flux values derived from temperature profiles with the stability functions of Brutsaert (1992) and compared with the flux values when the Businger-Dyear functions were used to drive them under strongly unstable conditions.

It is concluded that the sensible heat values using Businger-Dyear functions (B-D-F) were higher 14% than Brutsaert functions (B-F) between 1100 and 1700 hours (noon and afternoon) on 17, 18 August , 4 September 2002 and on 8th September 2002. The flux values *H* using Businger-Dyear functions were higher 16% than Brutsaert functions in the afternoon, same as on 8th September 2002, but on both 1st and 5th June 2003, the flux values (B-D-F) higher ~10% than the flux values (B-F), on 1st June 2003, the flux values (B-D-F) higher ~12% than the flux values (B-F), where unstable condition was predominant unlike the findings of Sugita et al (1995) under the same situation.

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