JKAU: Met., Env. & Arid Land Agric. Sci., **Vol. 18** No. 1, pp: 41-57 (2007 A.D. / 1428 A.H.)

Measurements of Momentum and Sensible Heat Flux Using Eddy Correlation Method in the Mina Valley During the Haj Period

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Abstract. Direct measurements of sensible heat flux were made in the Mina valley during Haj Period. Fifteen-minute average of the correlations between the fluctuations of the two signals ($\overline{w' T'}$) and later the vertical turbulent heat flux were computed from a Remtech fluxmeter station. Friction velocity *u* was deduced from the fluxmeter data as well. It was seen particularly on Dhu Al-Hijjah 11 starting from 2100 h until next day at 0200 h on Dhu Al-Hijjah 12, *u* was attained up to 0.8 ms^{-1} at night. This may be interpreted as the direction was easterly to south easterly wind. The wind flowed across obstacles such as tents, shelters, high buildings ... *etc.* It was noticed always that evenings sensible heat had positive values, most probably because at night the long wave radiation doesn't escape outside the valley but collides with vertical walls and slopes of the valley and then reflects to the ground. Thus the contribution of large amounts of long wave and the resulting excessive heat on the floor in addition to thousands of pilgrims standing there keep the warm lower layer of the valley unstable throughout night.

Introduction

Small-scale processes dominate the atmospheric boundary layer up to few tens of meters above the ground living environment for most humans and agricultural crops and creatures (Webb, 1965). The first few meters of the atmosphere are commonly referred to as surface layer. Most of the interactions between the surface layer and overlying atmosphere are important due to the links between boundary forcing at the surface and the atmosphere above it

(Viswandham, *et al.* 1997). Cao and Ma (2005) reported that surface sensible heat flux is important in measuring energy exchange between the surface and the atmosphere. In our case we selected Mina Valley, a relatively rough (bridges, scattered buildings, hills) region. Masts should be used to obtain either wind, temperature and humidity profiles for flux estimates (Anbar Serry, 2001). The sensible heat flux *H* and latent heat flux *LE* have a noticeable diurnal cycle. Day time values are expected to be positive because solar radiation heating of the earth's surface transfers heat to the atmosphere. Without solar heating, the night time fluxes are near zero. Temperature and vertical wind data are used to calculate the sensible heat flux *H* while the specific humidity and vertical wind data are also be used to calculate the latent heat flux *LE.* The direct measurements using rapid-response instruments of *H* and *LE* may be useful in this case. The direct measurements of sensible heat flux using eddy correlation method were obtained from the same mast near the Gamarat Bridge (hundred thousands of people gathering area).

Turbulent Transfer

Atmosphere is generally turbulent, except when the wind is extremely light. This means that generally the flow of air is not smooth, but subject to chaotic fluctuations, made evident by irregular waving of foliage (Webb, 1965). When the instrument of fast response is placed in the atmosphere to measure a wind speed component or temperature or vapour pressure, its indication fluctuates rapidly in a random manner.

Another important characteristic of turbulence is rapid diffusion. Samples of air moving randomly from place to place ('turbulence element' or 'parcels' or 'eddies') transport entities such as heat, momentum, CO_2, *etc.*, so that various properties are spread rapidly from one region of the atmosphere to another. In discussing the essentials of turbulent transfer, the same author considered the atmospheric boundary layer over flat, uniform terrain, so having horizontally uniform conditions, and the net turbulent fluxes of various entities will then be in the vertical direction only. Furthermore, he considered conditions that are steady in time, so that at any given position there is no change with time of the mean properties of the air (*i.e.* ignoring the turbulent fluctuations). The net flux of any entity must be then independent of height above the ground.

The mean value of a quantity is generally indicated by a bar and fluctuating turbulent deviation by a prime,

e.g. temperature $T = \overline{T} + T'$ (1)

The mean is taken over a time period sufficiently long to average out the turbulent fluctuations; the period adopted may typically be from 10 to 30 min. It is customary to take axes x along the mean wind direction, y transverse, and z vertical, the corresponding components of air velocity being denoted by u, v, and w. The mean along-wind speed will be denoted by U, and for all practical purposes the means of the other two components will be zero over level terrain. As an example of a turbulent flux, we can consider the vertical transfer of horizontal momentum. The amount of horizontal momentum per unit volume of air is ρu, so that the instantaneous rate of vertical transfer across a small horizontal area is $\rho w'u$, per unit area and unit time. Here ρ is the air density, taken to be constant. Over a given averaging period, the net turbulent flux of horizontal momentum is therefore $\overline{\rho w'u}$ which, since $\overline{w'} = 0$, may be written $\overline{\rho w'u'}$. It is easily seen that the quantity $\overline{\rho w'u'}$ is negative, and thus represents *downward* transfer. Since the mean wind increases with height, elements moving upwards or downwards (w' positive or negative) generally bring with them, respectively, lower or higher forward speed (u' negative or positive).

Thus there is a steady downward loss of momentum at a rate which must be equal to the horizontal drag of the wind on the ground surface. This drag or shearing stress is taken to be positive. The period to be denoted by τ, and, on the conventional definition of a shearing stress, is taken to be positive.

The vertical fluxes are taken to be independent of height, and are considered positive, *i.e*. the transfer is upwards.

Shearing stress (often called the Reynolds stress), represents momentum flux:

$$\tau = -\rho\overline{w'u'} \tag{2}$$

Heat flux:

$$H = c_p\,\rho\overline{w'T'} \tag{3}$$

Water vapor flux, generally equal to evaporation from the surface:

$$E = \rho\overline{w'q'} \tag{4}$$

In Eq. (3), ρ is the air density and c_p denotes the specific heat of air (at constant pressure). In (4), q denotes the specific humidity, *i.e.*, the mass of water vapor per unit mass of moist air.

Materials and Methods

Remtech Fluxmeter (Alcyon Equipment Company, Swiss) was created for short-term meteorological forecasts in the surface layer. Its application is based on two main components: First, a complete set of highly accurate instruments which sample parameters such as wind, temperature, humidity and pollution concentration (Catalogue of the instrument). Second, a microcomputer that calculates the fluxes on line.

These are the results of various complex computations (digital filtering using decimation technique and correlations between fluctuations) and allow a budget of turbulent eddies to be made. Remtech Fluxmeter includes an 18.5m mast, which supports a tridimensional anemometer, two temperature sensors, one humidity sensor (in our experiment was out of order) and a digital LSI 1103 minicomputer. This offers configuration versatility, which is adapted to user's needs.

Instrumentation

The surface layer measurements of temperature and wind from the mast at 18.5 m high above the ground surface were taken in Mina Valley between Dhu Al-Hijjah 9-12, 1417 H. As above mentioned, Remtech Fluxmeter, the micrometeorological station sampling three dimensional winds, temperature system of and three propeller anemometer sensors were mounted at the top of the mast.

Data Acquisition System

1 – ADAM II microprocessor-based data acquisition system: a data acquisition system samples sensors, transforms their signals into digital values and puts data on a support compatible with computer processing. The program used was specified by Alcyon Equipment for each purpose describing the sequence of operations to be performed.

2 – INTACT Peripheral Data Acquisition System: a remote data concentrating unit for ADAM II. INTACT: Acquisition: sensors convert physical parameters into electrical signals. For example: the three components of wind were converted into electrical pulses (one pulse corresponding to approximately 10 cm wind way, temperature measured by the resistance variation of a platinum wire (Manufactures: Alcyon Equipment Catalogue). The task of a data acquisition system is to adapt incoming signals (counting of pulses, amplification of low level electrical signals, scanning, analogue to digital conversion) and storing them.

3 – MEC and S- MEC Measurement Evaluation Computer: responsible for editing and cassette recording with ADAM II, displaying on 2480 character screen, and interfacing to any usual computer, BASIC programmable.

The Micrometeorological Station Fluxmeter

According to the manufacturer's catalogue, Alcyon Equipment gave all information concerning the evaluation of a pollution situation:

Vertical component

The roughness of the ground and its thermal exchanges with the atmosphere determine the structure of the atmospheric turbulence. The vertical component of the wind is essential in describing these phenomena. The fluxmeter therefore gives information in all three spatial dimensions.

Principle of operation

The fluxmeter samples its sensors every 5 seconds. The data then pass through a series of sophisticated calculations (deconvolution, digital filtering, and correlation of fluctuating terms) and are delivered at regular intervals (*e.g.* l5 min.) as a series of simple terms.

Compression of information

The turbulent fluxes describe locally all turbulent movements that occur in a very large volume (several km^3). These are given at regular intervals of, say 15 min; followed by a compression of information preserving all details of measured phenomena but nevertheless allowing storage of data on cassette with autonomy of up to one week.

In reality, the flow of air within the lower layers of the atmosphere is very complex; essentially it depends on the thermal inversion which is usually at an altitude of a few hundred meters. The ground surface is the main source of all phenomena appearing up to the inversion layer. The sun heats up the ground surface which then transfers its heat to the atmosphere. The analysis of vertical movements thus becomes much important. The ground roughness generates series of vortices in the air, distributed in the same way as crumbs of bread being rolled with hand on a table cloth. The situation becomes more complicated with the addition of other ascending and descending movements due to thermal exchanges with the surface. The outcome of this is a great number of vortices varying in size from a few tens of centimetres to large whirling movements between the ground and the inversion layer (Fig. 1).

Knowledge of all these vortices from the largest to the smallest is essential to understand the turbulent transfer for example.

Compatibility with monitoring networks

The measured parameters (wind, temperature, and humidity or pollutant concentration) can be expressed as (Fig. 2):

$$x = \bar{x} + x' \tag{4}$$

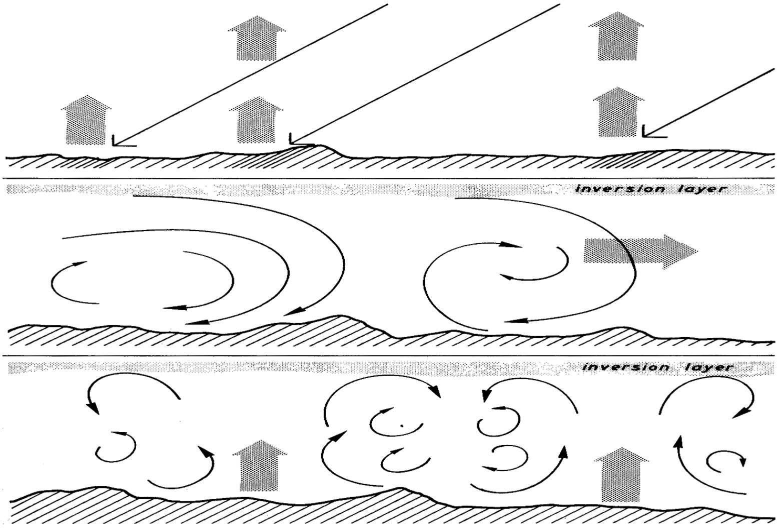

Fig. 1. The ground roughness generates series of vortices in the air, distributed in the same way as crumbs of bread being rolled with hand on a table cloth.

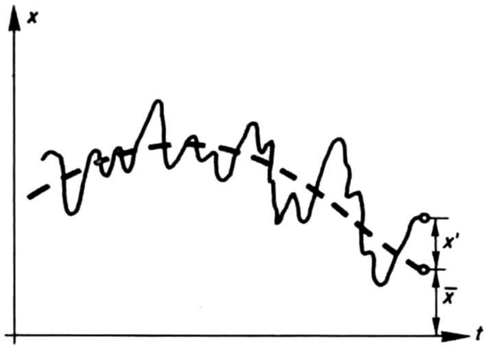

Fig. 2. The slowly varying average value $\bar{x}$ and the fluctuating part x'.

in which

$\bar{x}$ represents the slowly varying average value.

x' the fluctuating part

Synoptic meteorology is concerned with $\bar{x}$ whereas micro-meteorology (*e.g.* pollution studies) is concerned with x'. Thus the instruments and the methods to be used are quite different. Physically $\bar{x}$ and x' are well separated: $\bar{x}$ corresponds to very low frequencies, x' to higher frequencies (Fig. 3). Between them, the spectrum usually displays a hollow, certainly when low and middle range winds exist. This will facilitate the processing, whose first task is to retain

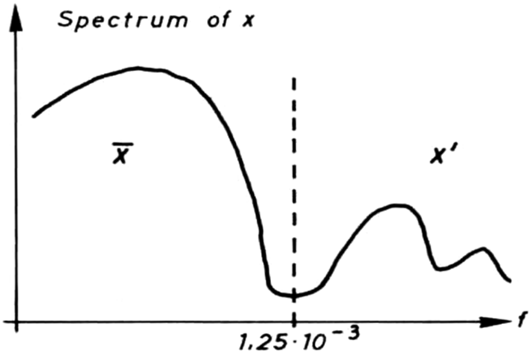

Fig. 3. Very low frequencies $\bar{x}$ and higher frequencies x'.

only the fluctuating term of the measured phenomena. This is obtained by means of a high performance digital filter.

Correlation of fluctuating term

If the laws of conservation of mass, momentum and energy are applied, the volume between the ground surface and the inversion layer, and the separation into $\bar{x}$, x', is taken into account one can obtain terms such as:

$\overline{w'T'}$, $\overline{u'C'}$, $\overline{v'^2}$, *etc.* (product of fluctuating parts). These are sufficient to represent all the turbulent phenomena which occur within the considered volume. Even though they are averages, they are as rich in information as the total of the samples (or instantaneous measurements) used to calculate them.

Data Collection and Analysis

One can obtain:

$u = \bar{u} + u'$ 1st horizontal component of wind speed (5)

$v = \bar{v} + v'$ 2nd horizontal component of wind speed (6)

$w = \bar{w} + w'$ vertical component of wind speed (7)

$T = \bar{T} + T'$ temperature (8)

$RH = RH + RH'$ humidity (9)

Practically, the sensors are sampled every 5s. The values obtained are digitized and stored in memory for 1000s (16min, 40s) which gives 200 groups of 5 parameters *u*, *v*, *w*, *T*, *RH* thus in fact $5 \times 200 = 1000$ values (Fig. 4).

After processing of the raw data (deconvolution, digital filtering for separation of tendencies and fluctuations, correlations of fluctuating terms) there remain only the averages $\bar{u}$, $\bar{v}$, $\bar{w}$, $\bar{T}$ and the turbulent fluxes (Fig. 5):

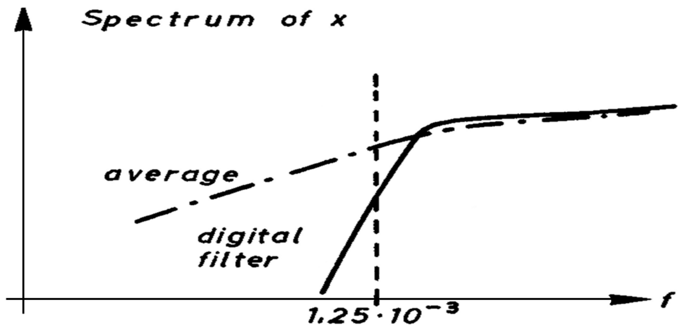

Fig. 4. Very low frequencies $\bar{x}$ and higher frequencies x'.

$\overline{u'^2}$, $\overline{v'^2}$, $\overline{w'^2}$, $\overline{T'^2}$, $\overline{RH'^2}$ variances of fluctuation (also called square sigmas)

$\overline{u'v'}$, $\overline{u'w'}$, $\overline{v'w'}$ turbulent momentum fluxes

$\overline{u'T'}$, $\overline{v'T'}$ horizontal turbulent heat fluxes

$\overline{u'RH'}$, $\overline{RH'T'}$ horizontal turbulent humidity fluxes

$\overline{w'T'}$, $\overline{w'RH'}$ vertical turbulent fluxes of heat and humidity

$\overline{T'RH'}$ cross correlation between temperature and humidity

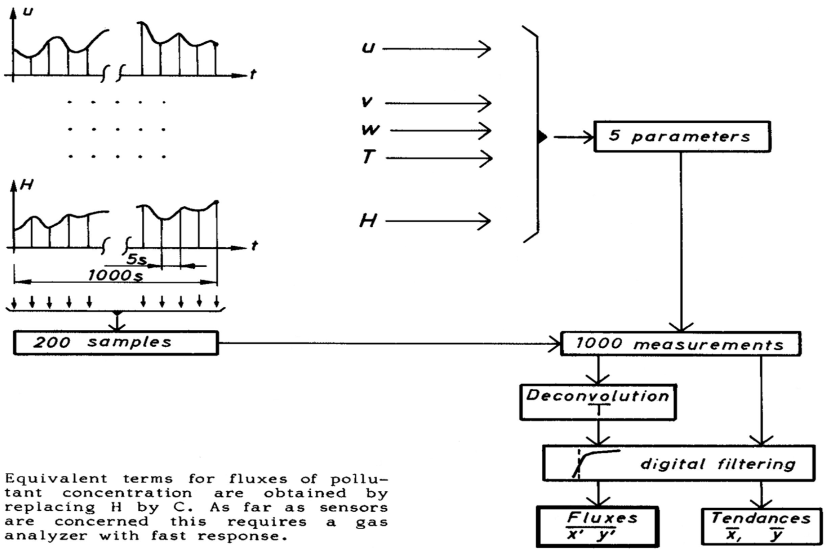

Fig. 5. A diagram showing that the fluxmeter samples its sensors every 5 seconds. The data then pass through a series of sophisticated calculations (deconvolution, digital filtering, and correlation of fluctuating terms) and are delivered at regular intervals (*e.g.* l5 min) as a series of simple terms.

Results and Discussion

Turbulent Flux Data

Direct measurements of sensible heat flux were made in the Mina valley during Haj Period between Dhu Al-Hijjah 9 and Dhu Al-Hijjah 12, 1417H (April 16 and April 19, 1997). Fifteen-minute average of vertical temperature flux ($\overline{C_p \rho w'T'}$) were computed from fluxmeter data.

Eq. (2) was used to calculate the sensible heat flux *H* when the specific heat of air c_p was 1004 J kg^{-1} °C^{-1} and the air density ρ 1.22 kg m^{-3}.

The correlation between the fluctuating parts u' and -w' can be seen in Fig. 6. This figure shows a part of u' and w' between 1000 h to 1200 h on Dhu Al-Hijjah 9 (April 16). It gives an indication that any time u' increases, w' immediately must be decreased and vice versa. When most of the fluctuating part w' > 0, this means that the flux is upward during the day.

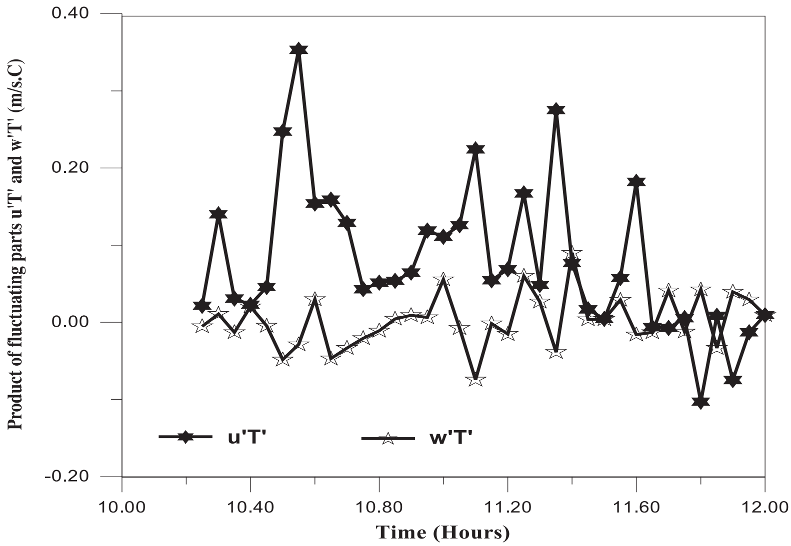

Fig. 6. Variance of first component of horizontal wind and variance of the vertical wind speed between 1000 and 1200 on Dhu Al-Hijjah 9, 1417H (April 16, 1997).

The vertical transfer of sensible heat by eddies can be visualized in Fig. 7. It shows the variation of air temperature (T) and vertical velocity (w) over a period of 3 h as an example on Dhu Al-Hijjah 9 during the daytime unstable period (data from the fast response instruments of the fluxmeter and every 3 minutes interval). The simultaneous record of (T) exhibits the same pattern, and its fluctuations were closely in phase with those of the vertical wind (w). This can be interpreted in unstable conditions as an updraft (positive w) is associated with an increase of T, and a downdraft (negative w) with decrease of T, relative to its

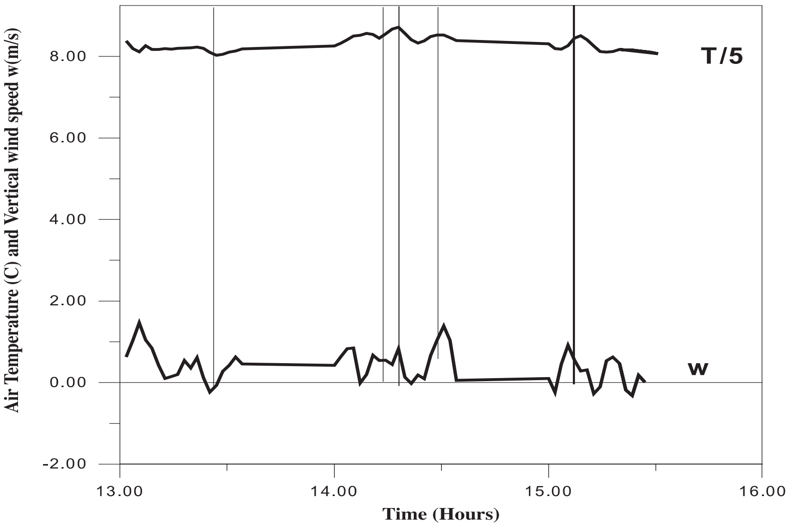

Fig. 7. Vertical wind w and temperature T on Dhu Al-Hijjah 9, 1417H in the Mina Valley.

mean value (Oke, 1978). This occurs because unstable conditions are associated with a lapse rate condition T profile, and an updraft through the measurements level has originated closer to the ground where it is warmer. Conversely, a down-draft comes from higher levels where it is cooler (Oke, 1978). For both situations (up- and down drafts) the net sensible heat is therefore upwards.

Diurnal Variation of Sensible Heat Flux in the Mina Valley

The diurnal variations of sensible heat flux were shown in Fig. 8(A-D). Sensible heat flux increases from the beginning after sunrise at around 0800 h and continues with a large increase to show maximum sensible heat at about 1300 h (afternoon). The maximum value of sensible heat flux on Dhu Al-Hijjah 9, 1417H (Arafat day) was 250 Wm^{-2} at about 1300 h. Higher values of sensible heat flux were observed after sunset on Dhu Al-Hijjah 11 at around 2030 h and continued until next day at ~ 0300 hours probably because of the intensive gathering of people and starting to wait until next day for departure to Mina Valley (this area usually witnesses a large number of pilgrims on the same day every year). Another possibility for these phenomena can be the easterly and south-easterly winds (Table 1) which passed tents and some obstacles such as shelters, governmental building, *etc*... showing a high heat flux. It was also noticed on Dhu Al-Hijjah 10, 1417H at the end of the night an increase in sensible heat which attained its maximum values of about 50 Wm^{-2} between 2000 and 2400 h. The reason for that might be the large number of pilgrims arrived in the central part of the valley near the mast area (Gamarat Bridge) to sleep their first night after returning back from Arafat.

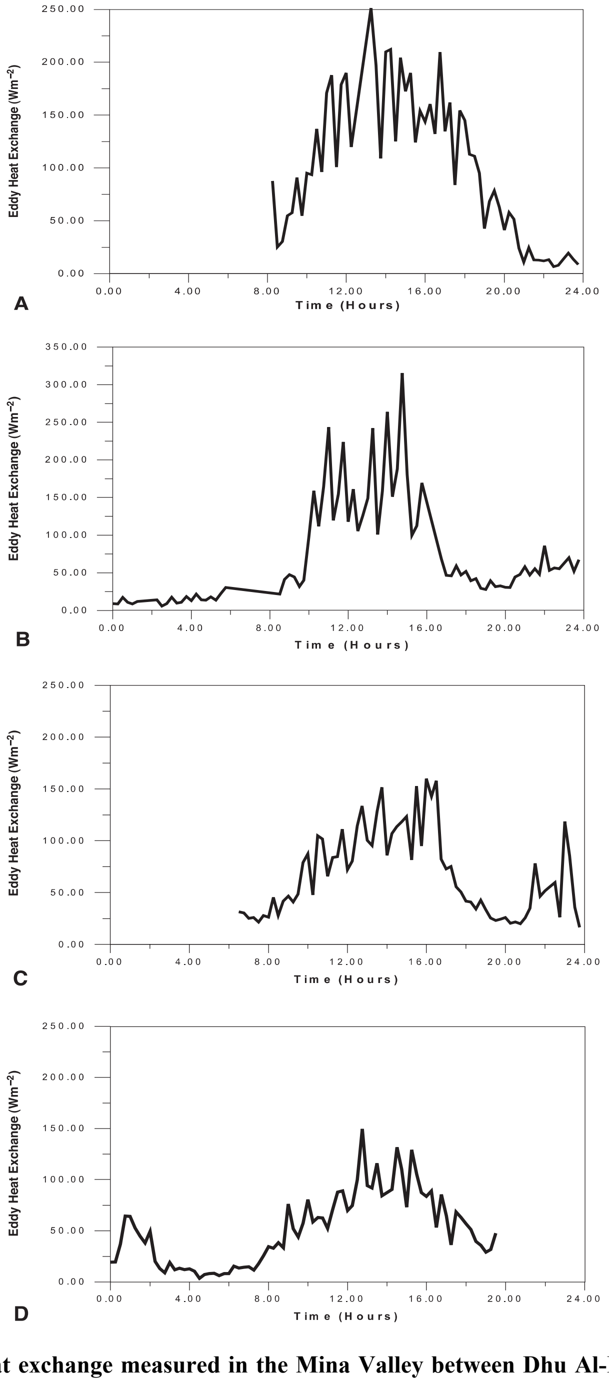

Fig. 8. Eddy heat exchange measured in the Mina Valley between Dhu Al-Hijjah 9, 1417H (April 16, 1997) and Dhu Al-Hijjah 12, 1417H (April 19, 1997) A, B, C and D respectively.

It was noticed always that evenings sensible heat were positive values (Fig. 8A-D) presumably because of :

1) The presence of people most of the nights. As Anbar Serry (2001) mentioned that energy available at the surface was estimated to be ~400 Wm^{-2} during the day and ~150 Wm^{-2} at night (assuming little vehicle use). This energy being merely to supply the sensible and latent heat fluxes. At night the energy sources may be sufficient to keep the boundary layer unstable and to ventilate the surface so improving the comfort of the pilgrims.
2) The light winds might be drained along the slope of the valley to the valley floor without affecting too much on temperature changes at the floor, but the high level strong winds could continue to flow crossing this narrow valley. This surface floor warming plus the effect of peoples gathering keep the valley boundary layer unstable during the Haj period.
3) At night the long wave radiation doesn't escape outside the valley but collides with vertical walls and slopes of the valley then reflects to the ground.

Thus, the resulting excessive heat on the floor from the contribution of large amounts of long wave and the standing of thousands of pilgrims keep the warm lower layer of the valley unstable throughout night (Fig. 9).

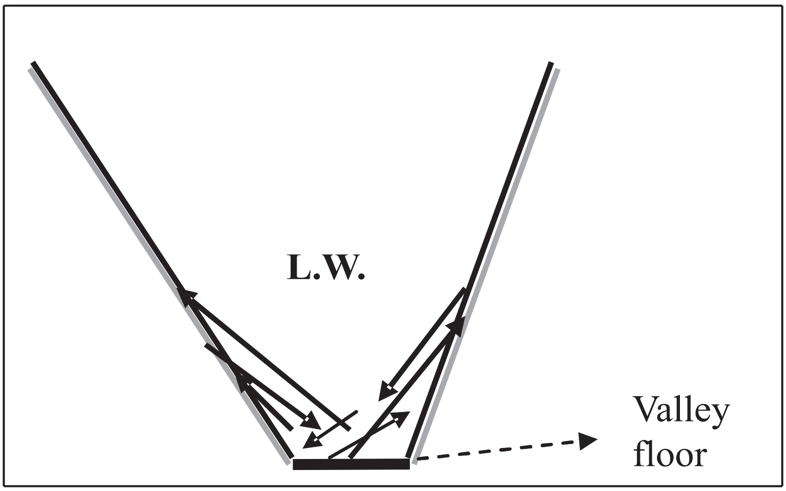

Fig. 9. The long-wave radiation behaviour in the narrow valley at night.

Friction Velocity and Wind Direction

Figures10A-10C, show the friction velocities u_* between Dhu Al-Hijjah 9 and 12, 1417H. Referring to Table 1, it can be noticed that the friction velocities u_* in the early morning between 0000 h to 0500 h were fine. This might be because of the direction of wind when it was westerly to north west with lower

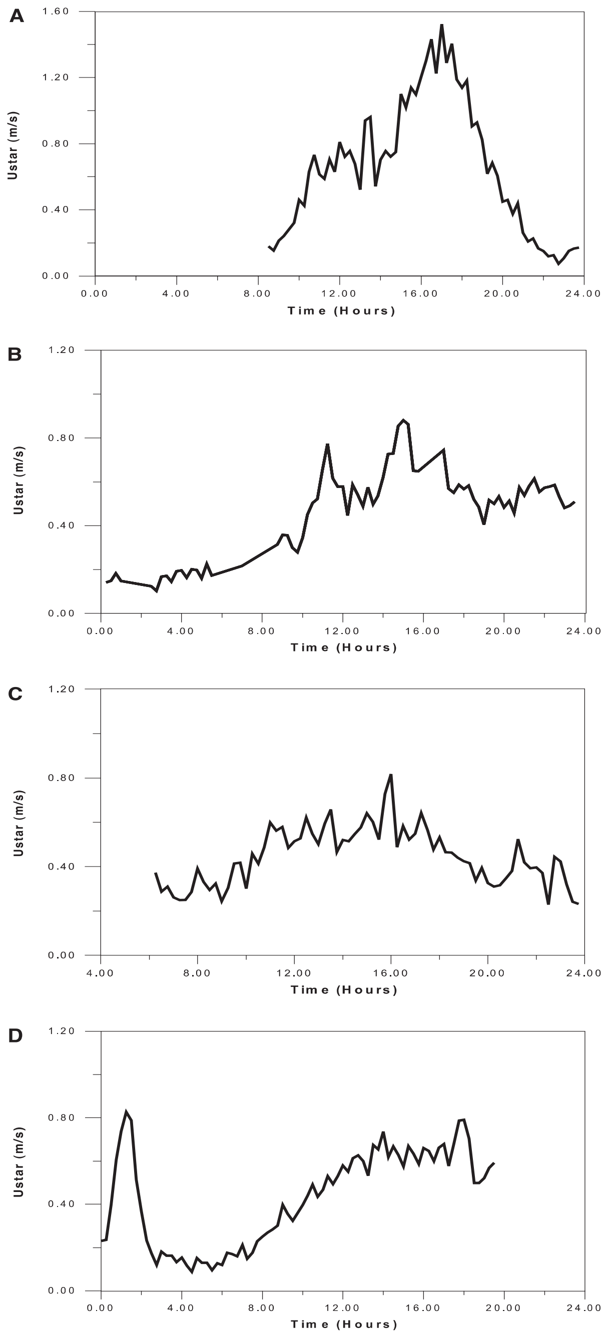

Fig. 10. Computed u_* from the fluxmeter data measured in the Mina Valley between Dhu Al-Hijjah 9, 1417H (April 16, 1997) and Dhu Al-Hijjah 12, 1417H (April 19, 1997) A, B, C and D respectively.

Table 1. Mast wind direction (w.d.) in degree between Dhu Al-Hijjah 9 and Dhu Al-Hijjah 12 and selected friction velocity (ms^{-1}), (Bold numbers mean high friction velocities).

Time (hours)	Hijjah 9	Hijjah 10		Hijjah 11		Hijjah 12	
	w.d.	w.d.	u_*	w.d.	u_*	w.d.	u_*
0	114	193	208		134	0.37	
1.0	115	275	226		173	**0.72**	
2.0	113	209	231		323	0.22	
3.0	105	311	263		248		
4.0	158	310	232		311		
5.0	122	249	245		129		
6.0	119	151	111		137		
18.0	132	118	111		128		
19.0	139	138	0.49	133			126
20.0	129	147	0.51	124		110	
21.0	71	165	**0.57**	94	0.43	91	
22.0	86	154	**0.57**	55	0.37	99	
23.0	118	180	0.49	100	0.26	112	

friction velocity as about 0.2 ms^{-1} (Fig. 10B). The evening values on both Dhu Al-Hijjah 10 and 11 (Fig. 10C and 10D) show that u_* were high as 0.4-0.5 ms^{-1} probably because of the nearly east wind direction. The friction velocity u_* was also found to be 0.8 ms^{-1} at about 0100 h on Dhu Al-Hijjah 12, (Table 1, and Fig. 10D). The sudden drop of u_* to 0.22 ms^{-1} at 0200 h on Dhu Al-Hijjah 12, might most probably be due to the sudden change of wind direction from 173º to 323º between 0100 to 0200 h (Table 1). Moreover, to clarify the increase in friction velocity at about 0100 h on Dhu Al-Hijjah 12, data selected from Fig.10D between 0000 and 0350 h show the relationships between the fluctuating parts w' and T'. The vertical lines in Fig. 11 show that the simultaneous record of air temperature exhibits the same pattern, and its fluctuations are closely in phase with those of w'. Between 2100 h of Dhu Al-Hijjah 11 and around 0200 h (next day) there was nearly unusual high values of sensible heat (unstable condition as seen in Fig. 8C and Fig. 8D) associated with an updraft through the measurement level originating closer to the ground where it is warmer than any other nights due to huge gathering of people different from that in Fig. 8A.

Doran, *et al.* (1989) showed that wind speed affects the extent of turbulent mixing and atmospheric stability. Under conditions of good drainage flow, winds near the valley floor run primarily along the axis of the valley. Thus, turbulent fluxes in such a region are likely to be influenced more by local irregularities of vegetation and topography in the valley floors than by the presence of steep sidewalls. The nearly westerly and north west winds along the axis of the valley in the early morning between 0000 and 0500 h on Dhu Al-Hijjah 10 and 11 and between 0000 to 0200 h and 0500 h on Dhu Al-Hijah 12 show that winds increase almost the dynamical friction velocity (Table 1). Conversely, the early morning friction velocities u_* (ms^{-1}) on Dhu Al-Hijjah 10, were low between 0030 h and 0115 h (Table 2) with nearly south west winds. The early morning friction velocities u_* (ms^{-1}) on Dhu Al-Hijjah 12 were high with sudden change of wind direction (Tables 1 and 2). Finally, the data between 0030 and 0125 h show very high values of the fluctuating part w' in comparison with the rest hours (Fig. 11). It could be concluded that excessive heat and humidity due to the pilgrim's presence during the Haj period could be a significant representing forcing term at the surface.

Table 2. Selected the early morning friction velocities u_* (ms^{-1}) for both days Dhu Al-Hijjah 10 and Dhu Al-Hijjah 12), (Bold numbers mean high friction velocities).

Date Time (h:min)	Hijjah 10	Hijjah 12
	u_*	
00:00	–	0.23
00:15	0.14	0.24
00:30	0.15	**0.40**
00:45	0.18	**0.61**
01:00	0.15	**0.74**
01:15	0.11	**0.83**
01:30	–	0.14

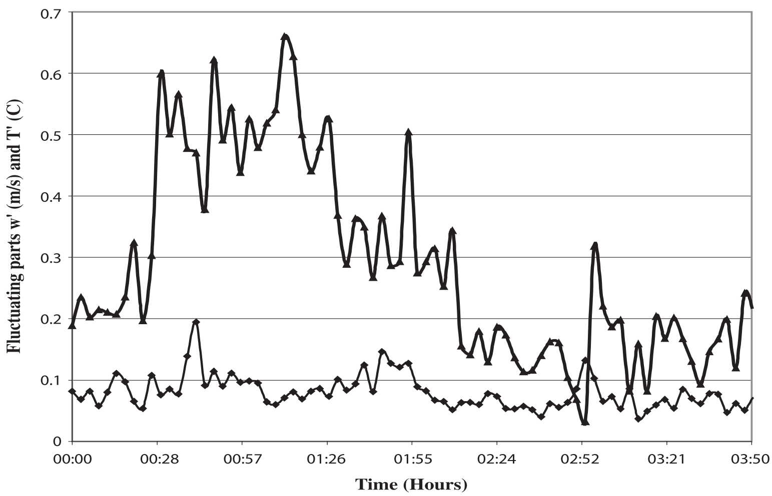

Fig. 11. The relationships between the fluctuating part w' (bold line) and T' (smooth line) resulted from the fast response instruments. Data selected between 0000 h and 0350 h on Dhu Al-Hijjah 12 (April 19).

Acknowledgment

I would like to thank the Meteorology Department, King Abdulaziz University, Jeddah who lent me the full station of Remtech Fluxmeter for use in the field work.

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قياسات القوة الدافعة وطاقة الحرارة المحسوسة باستخدام طريقة الترابط لحركة الدوامات بوادي منى خلال فترة الحج

عمر محمد يعقوب عنبر

قسم الأرصاد - كلية الأرصاد والبيئة وزراعة المناطق الجافة

جامعة الملك عبدالعزيز - جـــدة - المملكة العربية السعودية

المستخلص. تم قياس وتقدير مباشر لكمية الطاقة الحرارية المحسوسة خلال فترة وجود الحجيج بمنى في حج عام ١٤١٧هـ، وذلك من قياسات أخذت متوسط كل ربع ساعة للترابط بين العنصرين المنحرفين ($w'T'$) من المحطة المستخدمة للقياس والتي تسمى Remtech Fluxmeter Station. تم حساب السرعة الاحتكاكية u_* خلال اليوم من المعلومات المتوفرة أيضًا من المحطة المذكورة أعلاه لمعرفة مدى تغيرها خلال اليوم. لوحظت u_* بين الساعة ٢١ يوم ١١ ذي الحجة والساعة ٢ صباحًا من اليوم التالي ١٢ من ذي الحجة أنها ظاهرة بسرعات كبيرة فقد وصلت بقيمة عالية قدرت ٠,٨ ms^{-1} حيث كانت الرياح آتية من الشرق والجنوب الشرقي. هذا يفسر بأن الرياح كانت آتية من مناطق مثل الخيام والمظلات والمباني المرتفعة.

لوحظ أن اتجاه فيض الطاقة الحرارية المحسوسة في الطبقة السطحية بوادي منى دائمًا موجبًا بالليل بعكس ما هو معروف بقيمته السالبة بالليل، والسبب في ذلك يرجع إلى التواجد الهائل للحجاج في فترة الحج (أيام منى)، مع أسباب أخرى، وهي: تجمع كميات من الإشعاع الطويل الموجة المرتدة من الجدران والسفوح بعد استقبالها من السطح السفلى للوادي، مما يجعل هذه الأشعة لا تذهب إلى خارج الوادي بل ترجع إلى السطح السفلى، وهذه بدورها تساهم في تسخين السطح الذي هو أصلا ساخن بسبب وجود العنصر البشرى عليه من الأساس خلال تواجدهم ومكوثهم في الوادي، وهذا يجعل الطبقة الحدية للوادي غير مستقرة بالليل.