

The Relationship between Vertical Kinematic Eddy Heat Flux, Air Temperature and Turbulent Kinetic Energy in Atmospheric Boundary Layer: Baghdad City

Nagham Abbas Mohammed^{1*}

¹Department of Atmospheric Sciences, College of Science, Mustansiriyah University,
10052 Baghdad, IRAQ.

*Contact: setnagham@uomustansiriya.edu.iq

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Abstract

Studying the heat flux in the boundary layer and understanding its relationship to the various atmospheric variables reflects positively on understanding the nature of turbulence in this layer and thus understanding the nature of the spread and movement of pollutants and the transmission and distribution of energy in this layer, also, the vertical heat flux is considered a significant influence on the movement of buoyancy and stability in the boundary layer and its effect on the horizontal wind movement, and therefore it is considered one of the important studies indirectly involved in the estimates of wind energy production, pollutant diffusion, and turbulence. This study involved the calculation of the Eddy Heat Flux and turbulent kinetic energy across Baghdad city. Our investigation revealed a correlation between the Eddy Heat Flux, temperature, and Turbulent Kinetic Energy (TKE). The observations have been made for wind speed with three components (u, v, w) and temperature by using a fast-response anemometer. As for the atmospheric pressure data, it was obtained from the automatic weather station located in the department of Atmospheric Sciences at Mustansiriya University. The range of observations extended through the duration of thirty days for 24 hours from 1st July 2016 to 30th July 2016 every second. The maximum Eddy Heat Flux value was 0.092 J/(m².s) at 10:00 on 23th July 2016, while the minimum Eddy Heat Flux value was -0.013 J/(m².s) at 21:00 hour on 25th July 2016, the negative sign refer to a change in the direction of heat transfer., It was also found that there is a positive relationship between the eddy heat flux and temperatures with a correlation coefficient of 0.93, as well as between the eddy heat flux and the turbulent kinetic energy with a correlation coefficient of 0.8.

Keywords: Eddy Heat Flux, Turbulent Kinetic Energy, potential temperature, boundary layer.

الخلاصة

ان دراسة فيض الحرارة في الطبقة المحاددة وفهم علاقته بالمتغيرات الجوية المختلفة يعكس بشكل ايجابي على فهم طبيعة الاضطراب في هذه الطبقة بالتالي فهم طبيعة انتشار وحركة الملوثات وانتقال وتوزيع الطاقة في هذه الطبقة، كما وان الفيض الحراري العمودي يعتبر مؤثرا أساسيا في حركة الطفو والاستقرارية في الطبقة المحاددة وتأثيرها على حركة الرياح الأفقية. بالتالي تعتبر من الدراسات المهمة بشكل غير مباشر في تقديرات إنتاج طاقة الرياح ، انتشار الملوثات ، و الاضطراب. في هذا العمل تم حساب الفيض الحراري الدوامي والطاقة الحركية المضطربة فوق مدينة بغداد، وتم اختبار العلاقة بين الطاقة الحركية المضطربة ودرجات الحرارة مع القيم المحسوبة للفيض الحراري الدوامي. تم رصد البيانات لسرعة الرياح بمركباتها الثلاث (u,v,w) ودرجات الحرارة باستخدام جهاز قياس سرعة الرياح ذو الاستجابة السريعة Ultrasonic اما بيانات الضغط الجوي فتم الحصول عليها من محطة الطقس الاوتوماتيكية الموجودة في قسم علوم الجوى في الجامعة المستنصرية. امتدت فترة الرصد على مدى ثلاثون يوما لمدة ٢٤ ساعة من ٢٠١٦/٧/١ الى ٢٠١٦/٧/٣٠ في كل ثانية. ان اعلى قيمة للفيض الحراري الدوامي كانت ٠,٠٩٢ J/(m².s) عند الساعة ١٠:٠٠ في يوم ٢٣/٧/٢٠١٦

واقل قيمة له كانت $0.013 \text{ J}/(\text{m}^2.\text{s})$ - عند الساعة ٢١:٠٠ في يوم ٢٠١٦/٧/٢٥ (الاشارة السالبة تشير الى التغير في اتجاه انتقال الحرارة). وكذلك تم التوصل الى وجود علاقة طردية بين الفيض الحراري الدوامي و درجات الحرارة وبمعامل ارتباط يبلغ (٠,٩٣) وكذلك بين الفيض الحراري الدوامي و الطاقة الحركية المضطربة وبمعامل ارتباط يبلغ (٠,٨).

INTRODUCTION

One of the most important basic influences in turbulence is the transfer of heat, which leads to convection processes that directly affect the stability of the atmosphere and thus the horizontal and vertical wind speeds [1].

The transmission of the quantum amount per unit area at a time is known as flux. The flux is frequently associated with moments, heat, mass, humidity, and pollution in the boundary layer. This definition applies to heat transfer and its unit ($\text{J}/(\text{m}^2.\text{s})$)

Due to the difficulty of measuring quantitative quantities while being able to measure the various atmospheric elements (temperature, pressure, humidity, etc.), flux formulas in the atmosphere must be transformed into abstract kinematic forms to become heat flux movement by dividing by the density of moist air. [2] Quantitative amounts are transferred across time and space as a result of fluid movement. It is common knowledge that flow, or fluid movement, consists of two fundamental components: turbulence and rate, and it has been demonstrated that heat is transferred to and from the Earth in the boundary layer, particularly the surface layer, by turbulence [3].

Turbulent Kinetic Energy is one of the most important variables in micrometeorology because it is directly related to the transfer of heat, moisture, and momentum through the boundary layer and can be used to start turbulent diffusion. The physical processes that lead to turbulence can be described using the limits of the turbulent kinetic energy budget equation. The ability of the flow to become turbulent is determined by the relative balance of these processes, which suggests that Turbulent Kinetic Energy and stability are related [4].

The Turbulent Kinetic Energy equation can be used to set some non-dimensional parameters and measures of stability, such as Obkhove Length and Richardson Number. The importance of calculating the turbulent kinetic

energy lies in studying turbulence in the boundary layer, where the air condition in the boundary layer can be assessed (stable, neutral or unstable) [3]. The flow of air can be divided into three types: mean wind, waves, and turbulence. It is possible that these types come separately or collectively through the boundary layer, for example; heat, humidity, momentum, and pollutants are transmitted horizontally by the mean wind and vertically by the turbulent movement. The mean wind is responsible for the rapid horizontal transition which, is called Advection through the boundary layer, as friction makes the rate of wind speed slow near the surface of the earth. The vertical mean wind is much lower and usually ranges from a few millimeters to a few centimeters per second. Turbulence contributes to the movement of moisture, heat, momentum, and pollutants vertically [5].

Turbulence consists of rotational movements called eddies and they are of different sizes. Most of the turbulence in the boundary layer is caused by the effects of the Earth's surface, such as solar heating of the Earth's surface that generates masses or hot air parcels rising. These thermal parcels are great eddies. As for the effect of friction on the air near the surface of the earth, it causes wind shear, which also becomes turbulence [6].

Wave movement is the movement that occurs frequently in the nocturnal boundary layer, as it transmits little heat and moisture, as well as part of the pollutants, Still, it is effective in transferring energy and momentum, as the waves are generated locally from wind shear or the wind running over barriers [7].

Many studies have been done about calculating heat, momentum flux, and turbulent kinetic energy. For example, John D. Albertson et al. (1997) talked about turbulent kinetic energy and its relationship to the momentum flux resulting from the surface and heat. He also tried to design a pair of equations of the second and third orders

to calculate the surface flux through the dissipation ratio [8].

Naghah Abbas (2016) Calculate the Turbulent kinetic energy during the daytime from 7:00. to 13:00. from 22/2/2015 to 13/3/2015 over Baghdad city and test the effect of temperatures and solar radiation on the calculated values of the turbulent kinetic energy. The results show that the maximum Turbulent kinetic energy value was ($5.1 \text{ m}^2/\text{s}^2$) and the minimum Turbulent kinetic energy was ($0.06 \text{ m}^2/\text{s}^2$) [9].

Romi, T.A. (2000) estimates the Monin-Obukhov length and sensible heat flux to calculate the temperature and wind speed at a height of 100m above Baghdad City [10].

Aqeel and Hassan A.F. (2011) employed slow-responding devices for recording the temperature and wind speed at two levels, 20 m, and 15 m, at various times over the duration of a month, between 16:00 LT and 20:00 LST. In order to measure and evaluate an exponential relationship between the Abu-Khov length and the sensible heat flux equation that is utilized under a specific condition, estimation was performed. In this work, Abu-Khov's maximum length was (-249.2), and its minimum length was (-2638.1m). The greatest heat flux value was 19.7 w/m^2 , while 1.9 w/m^2 was the lowest value. w/m^2 [1].

Bing Tong, et al (2022) based on the sonic anemometer data measured at four boundary layer towers in China with contrasting underlying surfaces to investigate the near-surface TKE characteristics under the different convection regimes classified by the ratio of the buoyancy term (BP) to the shear term (SP) the results show that TKE initially increases from unstable to neutral atmospheric stratification conditions and decreases from neutral to stable conditions [11].

MATERIALS AND METHODS

The Location

The Atmospheric Sciences Building at Mustansiriyah University was chosen because of its location at an elevation of 31.7 meters above mean sea level ($33^\circ 22' 2.152'' \text{ N}$, $44^\circ 24' 12.912'' \text{ E}$). On the eastern side of

Baghdad in this location, it mostly consists of various roughnesses from 3-meter-tall houses to 30-meter-tall buildings like government offices. Trees and about 80% of buildings surround the study site [2].

INSTRUMENT

In this study, the ultrasonic anemometer Wind Master Pro 021-MG079141189 PK has been used to record and observe the wind speed in each of the three components (u, v, and w) every second, as well as recording and calculating the temperature of the air and sound speed. The device provides a large quantity of data in a short amount of time. It lies at a height of around 18 meters above the ground. As for the atmospheric pressure values, they were obtained from the automatic weather station located above the building of the Department of Atmospheric Sciences, which gives hourly values for the atmospheric variables. for the same timings and period of observation.

OBSERVATIONS

The observation period was from 1/7/2016 to 30/7/2016, and observations of the temperature and wind speed component (u, v and w) were obtained every second for 24 hours the observations number in this study are 2592000. For the atmospheric pressure values, they obtained from the automatic weather station which gives hourly values for the atmospheric variables for the same timing and period of observation.

Proposed Methodology

The following equations can be used to calculate the vertical movement of the eddy heat flux responsible for heat transfer [3]:

$$H = \overline{w'\theta'} \quad (1)$$

Where:

H: The Eddy Heat Flux

w' : is the turbulent vertical component of wind speed [3], can be calculated:

$$\hat{w} = w_i - \bar{w} \quad (2)$$

w_i : The instantaneous value of the wind speed component (w)

\bar{w} : Average wind speed component (w).

θ : The potential temperature, it can be calculated by the following formula [12]:

$$\theta = T \left(\frac{1000}{P} \right)^{\frac{R}{C_P}} \quad (3)$$

where:

T: The temperature of the air parcel, in Kelvin.

P: Atmospheric pressure.

R: Air's gas constant.

C_P: The air's specific heat when pressure is constant.

$$\frac{R}{C_P} = 0.286.$$

θ' : Is the turbulent in potential temperature, which can be calculated as follows:

$$\theta' = \theta_i - \bar{\theta} \quad (4)$$

θ_i : The instantaneous value of the potential temperature.

$\bar{\theta}$: Average of the potential temperature.

The output signal may be used to determine the direction of heat transfer. Eddy turbulence causes the amount of heat to be transferred to the top if it is $+(w'\theta')$, but if it is $-(w'\theta')$, it causes the amount of heat to be transferred to the bottom.

To calculate the turbulent kinetic energy by the following formula [9]:

$$TKE = 0.5(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \quad (5)$$

where u , v , and w are the turbulent wind speed toward the axes (x, y, and z).

RESULTS AND DISCUSSION

Variation of Eddy Heat Flux

The eddy heat flux values were calculated during the study period using the Eq. (1). It was found that the maximum value of the eddy heat flux ($0.092 \text{ j/m}^2.\text{s}$) at 10:00 on 23rd July 2016, and its minimum value ($-0.013 \text{ j/m}^2.\text{s}$) at 21:00 on 25th July 2016. It appears from the results that the values of the eddy heat flux begin to increase during the daytime to be the maximum values at a time ranging between 8:00 - 14:00, and the flux values decrease after sunset to be the minimum values at a time ranging between 18:00 - 5:00, as shown in Figure 1 (a, b). Figure

1 (c) shows the nature of the daily change in eddy heat flux for the study period, the maximum value of the eddy heat flux ($0.036 \text{ j/m}^2.\text{s}$) on 23rd July 2016, and the minimum value ($0.013 \text{ j/m}^2.\text{s}$) on 21st July 2016.

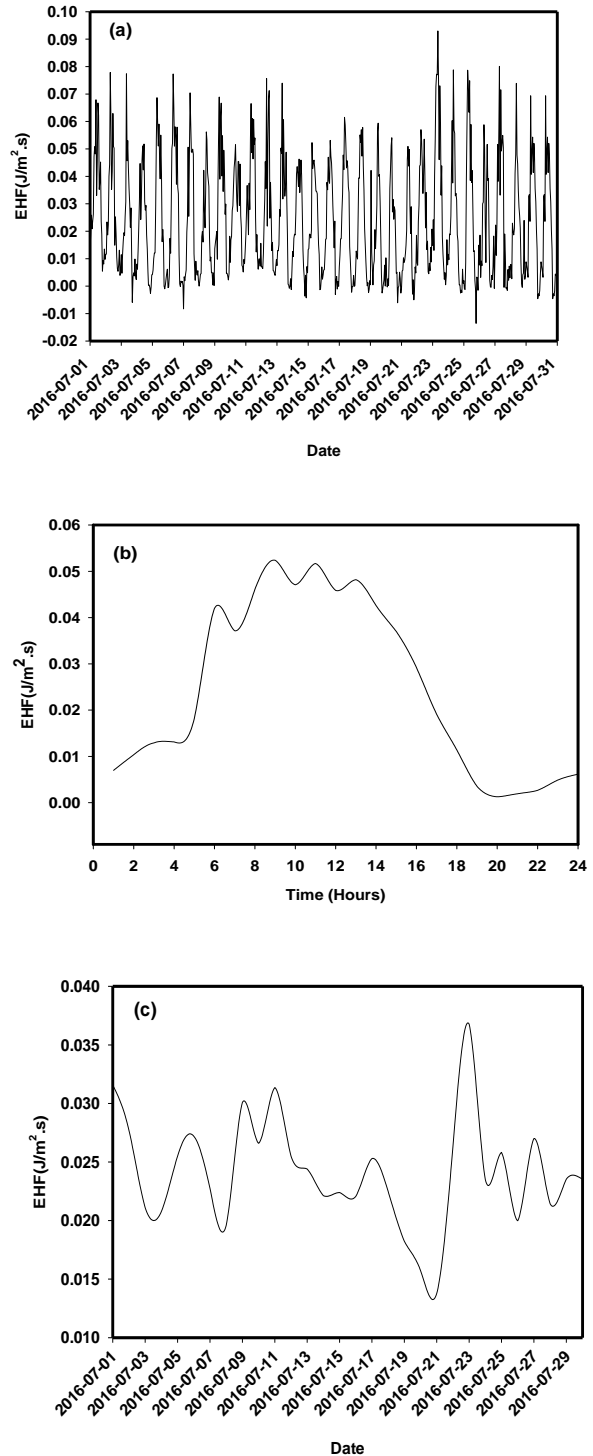


Figure 1. a: Variations of eddy heat flux. b: Hourly change of average eddy heat flux in July (2016). c: Daily change in eddy heat flux in July (2016).

Hourly change of average Eddy Heat Flux (EHF) with average air temperature(T).

Figure 2 shows the nature of the hourly change of each of the average EHF and the average air temperature for the study period. There is a clear relationship between the EHF and the temperature, as the air temperature values begin to increase gradually from 06:00 to reach their highest value at 16:00, which is in good harmony with the hourly change of EHF. It is also clear from the figure that the rates of air temperature range approximately between (37.6 - 50.18) °C while the average flux ranges approximately between (0.00127 - 0.0524) J/m².s . We note that there is a coincidence in the behavior of the temperature curves and the eddy heat flux with a lag time of 5 hours. This is because the microlayer and the beginnings of the surface layer need time for the heat flux to contribute to raising its temperature, as the heat flux begins early with the first hours of the day in the convection process, which leads to heat the bottom of the surface layer so that the temperature reaches its highest value in the day, as shown in Figure 2 within the height at which the measuring devices are located 18m. The relationship between eddy heat flux and temperatures can be seen in Figure 3.

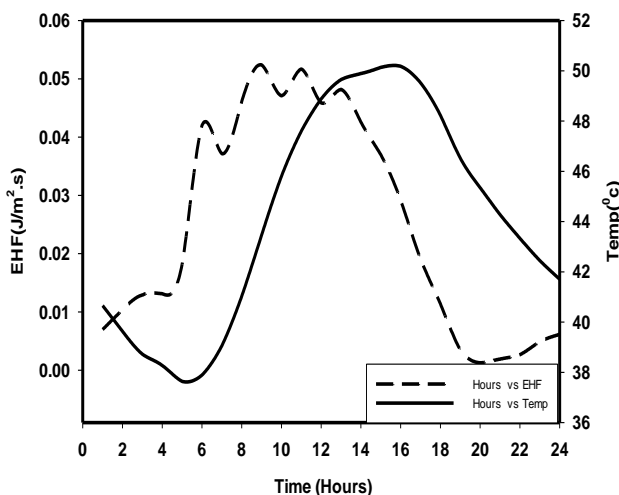


Figure 2. Hourly change of average eddy heat flux with air temperature for the period 1st to 30th July 2016.

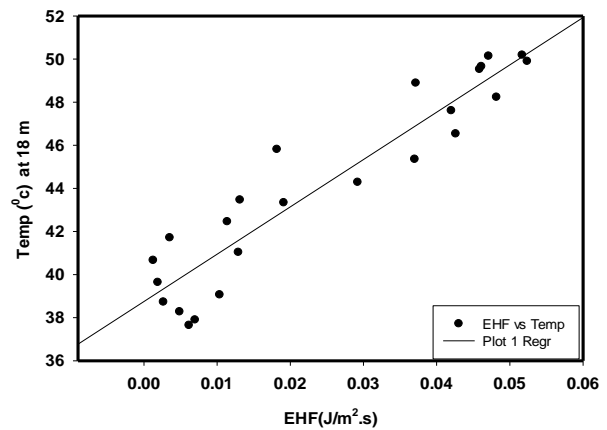


Figure 3. The relationship between EHF and air temperature with a lag time of 5 hours

Where:

Temp: Average air temperature.

EHF: Average Eddy Heat Flux.

The practical formula resulting from the linear correlation between the flux and temperatures is given in the form:

$$T = 38.747 + (219.672 * EHF) \quad (6)$$

Eq. (6) is considered a situational equation defined by the temporal and spatial conditions in which the study was conducted, and it was presented to express the pattern of the relationship between the two variables only. The correlation coefficient (r) =0.93 indicates a strong direct relationship between the two variables. This means that any increase in the eddy heat flux leads to an increase in air temperature.

Hourly change of the average Eddy Heat Flux (EHF) with the average Turbulent Kinetic Energy (TKE)

The Turbulent Kinetic Energy (TKE) values were calculated during the study period using the Eq. (5). Figure 4 shows the nature of the hourly change of each of the average Eddy Heat Flux (EHF) and the average turbulent kinetic energy (TKE) for the study period. There is a clear relationship between the EHF and the turbulent kinetic energy, as the TKE values begin to increase gradually from 05:00 to reach their highest value at 13:00, which is in good

harmony with the hourly change of EHF. It is also clear from the figure that the rates of TKE range approximately between (1.122 - 3.355) m²/s² while the average flux range is approximately between (0.00127 - 0.0524) J/m².s.

Figure 4 highlights that there is a correspondence between the curves of turbulent kinetic energy and the thermal flux with lag time of 4 hours between (9:00 and 13:00) because the production of TKE is based on mechanical and thermal turbulence, so we notice during the day that the highest value of TKE is due to the availability of the two sources of turbulence, the increases in flux (which are related to thermal convection, which represents the highest percentage of the production of TKE(TKE increases, but at night it depends only on mechanical turbulence, and therefore the value of TKE decreases.

The relationship between eddy heat flux and Turbulent Kinetic Energy can be seen in Figure 5.

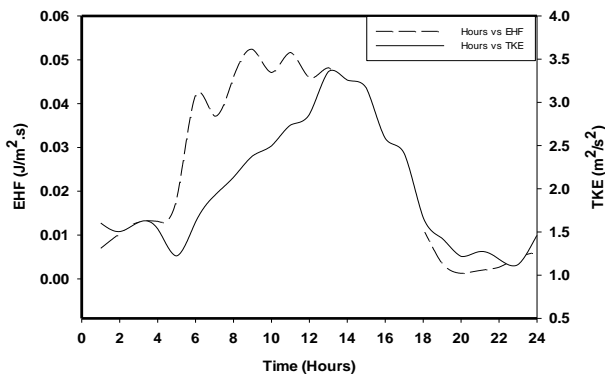


Figure 4. Hourly change of average eddy heat flux with average Turbulent Kinetic Energy for the period 1st to 30th July 2016.

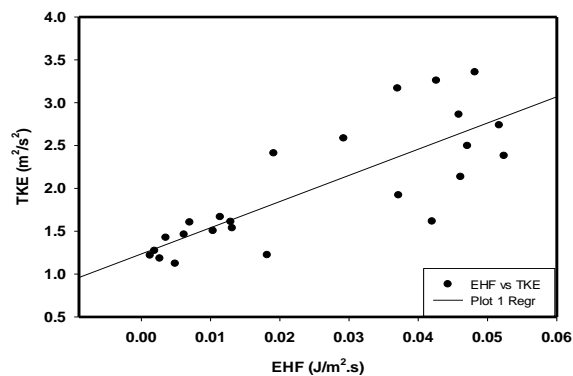


Figure 5. The relationship between EHF and TKE.

Where:

TKE: Average Turbulent Kinetic Energy.

EHF: Average Eddy Heat Flux.

The practical formula resulting from the linear correlation between the flux and TKE is given in the form:

$$TKE = 1.236 + (30.565 * EHF) \quad (7)$$

Eq. (7) is considered a situational equation defined by the temporal and spatial conditions in which the study was conducted, and it was presented to express the pattern of the relationship between the two variables only.

The correlation coefficient (r)=0.8, and indicates a strong direct relationship between the two variables. This means that any increase in the eddy heat flux leads to an increase in Turbulent Kinetic Energy. This is self-evident because an increase in the eddy heat flux leads to an increase in buoyancy and, thus, an increase in turbulence resulting from buoyancy.

CONCLUSIONS

The maximum value of the eddy heat flux equals 0.092 J/(m².s) at 10:00 on 23rd July 2016, and its minimum value equals -0.013 J/(m².s) at 21:00 on 25th July 2016.

The average turbulent kinetic energy ranges from 1.122 to 3.355 m²/s², and the average air temperature ranges from approximately 37.6 - 50.18 °C.

There is a correlation between EHF and T, where the correlation coefficient (r)=0.93. This indicates that there is a strong correlation between the two variables and that a positive formula was reached between the two variables during the study period.

There is a correlation between EHF and TKE, with a correlation coefficient (r) = 0.8. This indicates that there is a strong correlation between the two variables and that a positive formula was reached between the two variables during the study period.

Disclosure and Conflict of Interest: The authors declare that they have no conflicts of interest.

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