Comparison of Heat Flux Observation at Three Different Locations around Bandung, West Java

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Abstract. We observed heat flux profiles at three different locations around Bandung, West Java. Heat flux values were calculated using the covariance method with the vertical flow and potential air temperature fluctuation parameters. Observations have shown diurnal patterns in the three observation locations. Increasing heat flux during morning time flux on all three location shows similar pattern, but decreasing heat flux on the afternoon varies between locations. Urban residential area of Dago shows the most distinct pattern, with a rapid decrease in the afternoon and also after midnight. We also compared observed heat flux data with estimate values using the Bulk Parameterization method. We found that the estimated heat flux was not able to produce values in accordance with the observation data. Wind shear factor and inadequate implementation of the Bulk Parameterization method were thought to causing poor estimation of surface heat flux in Bandung. Improvements in this method, especially on the bulk transfer coefficient and surface skin temperature, are necessary to get better estimation result.

Keywords : heat flux, temperature, bulk transfer, surface skin temperature.

1. Introduction
Atmospheric boundary layer is part of the atmospheric layer that receives direct influence from activities on the earth's surface [1]. Changes in physical parameters of the earth's surface also change the transfer of surface heat and moisture, which in turn affect the structure of the atmospheric boundary layer. An important parameter that most influences changes in the structure of the atmospheric boundary layer are the phenomenon of air mass exchange, which is represented in the energy equilibrium equation, and turbulence parameters [1]. Therefore, the phenomenon of energy transfer represented through surface flux parameters is one of the important things in the study of atmospheric boundary layers.

Surface observation data from observation stations, such as wind; air temperature; etc., used as initial input in parameterization for flux calculations using various numerical weather prediction (NWP) models. There are various types of parameterization of heat fluxes used by NWP, one of which is Bulk Parameterization. This parameterization method has been widely used in various types of NWP and is usually combined with other parameters, such as the Penman-Monteith approach and the multi-source approach [2].

Because of the lack of availability of data on heat flux observations used as the main reference, research on the characteristic of heat flux in tropical regions are still very limited. Therefore, it is necessary to study heat flux in the tropics and their response to differences in surface characteristics in each observation area. This study aims to analyze heat fluxes at three different points in Bandung, West
This research was conducted on June 16, 2016, until July 21, 2016. In addition, we also estimate heat fluxes using Bulk Parameterization and compared it with the observed data.

2. Data and methods

Data used in this study are weather observation data from three different locations in Bandung. The first point located in the Dago area, with coordinates 6° 52' 17.3" S, 107° 37' 8.9" E and an altitude of 837 m.a.s.l. (figure 1). This location considered as a representation of the urban residential area of Bandung with dense settlements and little vegetation (figure 2a). The second location is at Sulaiman Air Force Base (Lanud Sulaiman or Lanud) with coordinates 6° 58' 53.1" S, 107° 34' 25.49" E and an altitude of 688 m.a.s.l (figure 1). The second location was chosen because of flat and wide surface characteristics, with a homogeneous surface cover in the form of grass (figure 2b). The third location is in Manoko plantation with coordinates 6° 48' 25.02" S, 107° 36' 46.62" E and height of 1312 m.a.s.l. (figure 1). This location was chosen because of the hill characteristics that represent the morphology of the North Bandung region (figure 2c).

Figure 1. Altitude (left) and map (right) of observation locations, namely Dago, Lanud Sulaiman and Manoko

Figure 2. The appearance of the observation locations in a) Dago, b) Lanud Sulaiman and c) Manoko
There are three types of instruments used in the observation, namely Young Model 81000 Ultrasonic Anemometer, Davis Vantage Vue Automatic Weather Station (AWS), and Davis Vantage Pro Automatic Weather Station (AWS). Data obtained from the ultrasonic anemometer measurements are vertical wind velocity data \( w \) and virtual air temperature \( T_v \). To remove the effect of different pressure altitude, \( T_v \) should be converted into a virtual potential air temperature \( \theta_v \) [1]. This could be done using Poisson’s equation (1), by changing \( T \) with \( T_v \), thus resulting in \( \theta_v \) instead of \( \theta \). \( P_0 \) is the reference pressure, which usually is set to 1000 hPa, and \( P \) is station pressure which we take from the AWS measurement. Apart from \( P \), we also obtain other parameters from AWS measurement, including air temperature \( T \), relative humidity \( R_h \), and horizontal wind velocity \( (u, v) \). In order to compare result from ultrasonic anemometer and AWS equally, we also convert the temperature measurement of AWS into virtual potential air temperature \( \theta_v \). The conversion was done by calculating potential temperature \( \theta \) using equation (1), and then convert the result into virtual potential air temperature \( \theta_v \) using equation (2) [1]. \( r \) on equation (2) is the unsaturated mixing ratio which could be calculated from \( R_h, T, \) and \( P \) using formulas that could be found in [3], in the Annex 4 part.

\[
\theta = T \left( \frac{P_0}{P} \right)^{0.286} \quad (1)
\]

\[
\theta_v = \theta (1 + 0.61r) \quad (2)
\]

For each site, the AWSs were installed on two different height. The Vantage Pro AWS was installed at two meters above the ground and the Vantage Vue AWS was placed at 10 meters above the ground. This configuration is needed because the Bulk Parameterization estimation method requires air temperature data at two different heights. Installation configuration of these instruments in this study can be seen in figure 3.

![Figure 3. Instruments configuration used in observation activities. a) RM Young 81000 Ultrasonic Anemometer. b) Davis Vantage Vue AWS. c) Davis Vantage Pro AWS.](image)

The first step to calculate sensible heat fluxes are to obtain vertical flow fluctuation \( w' \) and air temperature fluctuation \( T' \) [1]. However, to remove the influence of altitude on air temperature, the air temperature parameter \( T' \) is replaced by potential air temperature \( \theta \), so the fluctuation parameter
used is the potential air temperature fluctuation ($\theta'$). The values of $w'$ and $\theta'$ can be calculated using equations (3) and (4). The overbar on these equation denotes the time average over a certain time window. In this study, we choose 30 minutes time window for averaging, just like [4], to account for most of turbulent eddies spectrum [1].

$$ w' = w - \bar{w} \quad (3) $$

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

After obtaining the fluctuation value of the two parameters, the heat flux can be calculated using a covariance method, as shown in equation (5), where $C_p$ is the air heat capacity at constant pressure and $\rho$ is the dry air density [1].

$$ Qh = C_p \rho \overline{w'\theta'} \quad (5) $$

However, in this study, the parameters of heat flux used are kinematic sensible heat flux, where the heat capacity and the air density are removed from the calculation [1]. Since in this experiment we do not have any fast response temperature sensor (e.g. thermocouple), we use the air temperature recorded by the ultrasonic anemometer instead. As previously explained, the ultrasonic temperature measurement is actually a virtual temperature, or more precisely an acoustic virtual air temperature, which highly affected by moisture in the air. Although slightly different, but these acoustic virtual temperature could be considered as virtual temperature as the ultrasonic anemometer (i.e. RM Young 81000) has already corrected for crosswind velocity contamination [5]. Thus equation (5) was modified into equation (6), where $\theta$ is replaced by $\theta_{v}$, and the heat capacity and air density was removed. Conversion from virtual temperature into virtual potential temperature could be done using equation (1) as previously explained.

$$ Qh_{kv} = w' \theta_{v}' \quad (6) $$

The usage of virtual temperature (or ultrasonic temperature) to measure heat flux may yield an over or underestimate results, compared with using actual or absolute temperature. As pointed out by [6], a correction is necessary to get a good heat flux measurement from ultrasonic anemometer. This will require a fast response hygrometer or an H2O gas analyzer to estimate the Bowen Ratio; or a net radiation observation to completing the energy balance equation [6]. However, research by [4] found that for horizontal wind speed that was less than 8 m/s, heat flux measurement using ultrasonic temperature have a good agreement with measurement using thermocouple, with variation less than 30 W/m-2 or less than 0.02 K.m.s$^{-1}$ in kinematic form. Our observation show that the horizontal wind speed on all sites were less than 8 m/s, thus we consider that the heat flux measurement was quite accurate to represent the heat flux exchange over the study area.

$$ \langle w'\theta' \rangle_{est} = -C_H \overline{U(z)}[\bar{\theta}(z) - \theta_0] \quad (7) $$

$$ \langle w'\theta_{v}' \rangle_{est} = -C_H \overline{U(z)}[\bar{\theta}_v(z) - \theta_{v0}] \quad (8) $$

To estimate surface heat flux using Bulk Parameterization method, we used formulation defined in equation (7), adapted from [1] and [2]. All data to calculate these estimates comes from AWS, both on 2 m (Vantage Pro) and 10 m (Vantage Vue). Since we used virtual potential temperature for measurement of heat flux, the equation (7) was modified into equation (8). $\bar{\theta}_v(z)$ is the virtual potential temperature on 10 m height, while is the virtual potential temperature on 2 m height. $\overline{U(z)}$ is the average horizontal velocity at an altitude of 10 meters from the ground. We use 30 minutes averaging for all averaged variables to match the heat flux measurement from ultrasonic anemometer. CH on the equation
is called bulk transfer coefficient or sometimes called Stanton number. The value of $C_H$ used in this study is $1.5 \times 10^{-2}$ based on trial and error to get a comparable value of heat flux estimation.

During observation, several rain event took place on the observation site. Since rain could induce large scale error on ultrasonic anemometer measurement, we discard all data during the rain event. Thus, we focus this study on clear non-rainy days.

3. Results and discussion

3.1. Diurnal pattern analysis

We process and display wind data from observations of an ultrasonic anemometer, Vantage Pro AWS, and Vantage Vue AWS in the form of wind rose graphs for general wind conditions. The wind rose graphs produced from the data of the three instruments did not show significant differences, so we will only display the wind data obtained through ultrasonic anemometer measurements (figure 4). The wind rose graph plot shows that in the Dago observation area, the wind blows from the west, east and south directions (figure 4a). This shows that there is no dominant wind in the Dago observation area. The maximum wind speed in Dago ranges from 2 - 2.5 m/s. Meanwhile, the dominant wind that flows over Lanud Sulaiman came from the northeast with a tendency towards east with a maximum speed of 7 m/s (figure 4b). Whereas over Manoko the dominant wind blew from the southeast with a maximum value range between 3 - 3.5 m/s (figure 4c).

![Wind rose graphs in (a) Dago, (b) Lanud Sulaiman, and (c) Manoko which were obtained from observations of ultrasonic anemometers.](image)

Figure 4. Wind rose graphs in (a) Dago, (b) Lanud Sulaiman, and (c) Manoko which were obtained from observations of ultrasonic anemometers.

Wind over Dago site was highly affected by numerous building surrounding the observation site. Those buildings causing distortion to the wind field and decreasing the wind speed. In Manoko, wind flows more freely than in Dago, so there is no significant change in direction. However, the condition of the observation area in Manoko, which is a plantation with many vegetation covers and hilly contour characteristics, also influences the wind speed in the observation area. Sulaiman observation area is a very wide open space. The flowing wind does not get many obstacles, so the wind speed in this region was greater than the other two observation locations.

Figure 5 shows the values of $u'$, $v'$, $w'$, and $\theta'$ in Lanud Sulaiman. We chose to display the observations in this observation area because the characteristics of the location were in accordance with the criteria for the area of observation of heat flux, namely the location of the observation with an open state and without many obstacles, and homogeneous surface conditions. From these data, it can be seen that the fluctuations of the four variables above are influenced by diurnal patterns. During the daytime, the fluctuations of the four parameters are very high (shown in a red circle), while at night the fluctuations are relatively lower than during the daytime (indicated by a black circle).
Figure 5. $u'$, $v'$, $w'$, and $\theta'$ data which were observed by the ultrasonic anemometer on Lanud Sulaiman. The red circle shows fluctuations during the day, while the dark circles show fluctuations at night.

In figure 6 we show the histogram of frequency of occurrence of $w'$, $\theta'$, and $w'\theta'$ in all three observation locations. The frequency occurrence of $w'$ in all sites tend to be balance between positive and negative. The same thing also happen for the frequency occurrence of $\theta'$. However, the frequency occurrence of $w'\theta'$ Dago, Lanud Sulaiman, and Manoko tends to be more positive. This indicated a more active occurrence of heat flux transfer from ground to the atmosphere above it [1]. It was an expected result as positive heat flux was highly supported by sun radiation during the day, while negative heat flux was just depend on surface temperature, which may not have big discrepancies with the air above it.

All days composite value of kinematic sensible heat flux over three locations in Bandung was presented in figure 7. Comparing this results with [7], we found that our observation was comparable with their results. The kinematic sensible heat flux observation in Bandung ranges from -0.025 to 0.15 K.m.s$^{-1}$, while the range of kinematic sensible heat flux from [7] varies between -0.02 to 0.2 K.m.s$^{-1}$. The diurnal pattern shown in figure 7 also shows similarities with the diurnal pattern observed in [7]. So it can be concluded that the measurement of the heat flux that we are conducting in Bandung was in accordance with the theory that we referred.

Figure 7 also shows a clear distinction in the diurnal pattern of heat flux on the three locations. Manoko exhibits more rapid decrease of heat flux on the afternoon, while on Dago and Lanud Sulaiman the decreasing rate were much slower. In the morning, all sites show an increase of heat flux in a comparable rate among sites. In the night, all sites also exhibit negative values which comparable one to another, although Dago site shows slightly lower value. This means that during nighttime, in Dago, the surface took a little bit more heat from the atmosphere, compared to the other two places. Nevertheless, all site shown to have similar diurnal pattern of heat flux.
Figure 6. Histograms of $w'$, $\theta'$, and $w'\theta'$ for a) Dago, b) Lanud Sulaiman and c) Manoko.
3.2. Comparison of the heat flux values in the three observation locations.

Figure 8 shows the results of the measurement of heat flux on a sunny day in the three observation locations. It appears that the heat flux in Dago (which is marked by a red line) has the fastest increase in value compared to the other two observation locations. Heat fluxes at Manoko (green line) and Lanud Sulaiman (blue line) reach their peak faster than Dago. The peak already reached around 10:30 AM in Manoko and around 11 AM in Lanud Sulaiman, but in Dago the peak was reached after 12 AM. The heat flux in Manoko and Sulaiman experienced a relatively slow decline after reaching its peak and experienced an increase again after 3 PM. By 5 PM, the value of the heat flux in Manoko and Sulaiman changed to negative. While in Dago, the pattern was completely different. After it reaches the peak, the heat flux was decreasing rapidly and reach negative value just after 3 PM.

Based on observational data on the two observation locations, it can be concluded that heat flux during the clear night is more inclined to have a negative value (figure 9). The heat flux in Sulaiman has a lower value compared to Dago at 6 PM until 9 PM. Around 10 PM, there was a fluctuation in the value of heat flux in both observation locations. After midnight, the heat flux in Dago experienced a very significant decline, this condition continued until it reached a positive value at 6 AM. The lowest value of heat flux during the clear night in Dago is -0.023 K.m.s\(^{-1}\), while the lowest value in Sulaiman is -0.0117 K.m.s\(^{-1}\).
Figure 9. Heat flux values during the clear night over Dago and Lanud Sulaiman. Data over Manoko was not used due to long rainfall over the site during night time.

3.3. Comparison of heat flux observation and estimation results

Observed heat flux values are shown by the red line and the estimation results are shown by the green line in figure 10. It can be seen in figure 10a, that the estimation results in Dago are in line with the observations, but tend to take place in different time frames. At 9 AM to 1 PM the estimated heat flux results tend to stagnate at 0.1 K.m.s\(^{-1}\). Observation results showed that the heat flux in Dago reached its peak around 12 PM, while the peak of estimation occurred around 2 PM. These show the time lag between the results of the observation and the estimation results until the heat flux reaches its peak. After reaching the peak point, both heat flux values decrease rapidly.

Comparison of the two heat flux values in Lanud Sulaiman (figure 10b) shows a different pattern when compared to the pattern in Dago. The heat flux from the estimation results is very slow to increase its value when compared to the observational flux. The estimated heat flux is still negative until 2 PM, then it experiences a very rapid increase until it reaches its peak, and it returns down very quickly. Comparison of heat flux estimation and observation results in Manoko (figure 10c) produced a better pattern compared to the pattern in Lanud Sulaiman. The heat flux estimation results in Manoko show a pattern that is in line with the observations. The estimated heat flux tends to fluctuate around the value of 0.5 K.m.s\(^{-1}\) until 1:30 PM, while the observations show a continuous increase until it reaches its peak at 11 AM. The estimated heat flux reaches its peak at 3 PM.

Figure 10. Comparison of the daytime observed (red line) and estimated (green line) heat flux values in (a) Dago, (b) Lanud Sulaiman, and (c) Manoko.
Compatibility of the comparison results in three observation locations is thought to be influenced by the heat flux formation mechanism. The observation location that has a buoyancy formed mechanism as in Dago generally has a greater alignment between the estimation results and the results of its observations. Wind shear factors also affect the accuracy of the heat flux estimation. Wind shear is the wind velocity difference at two and 10 meters above the ground at each observation location. It can be seen in figure 11, that the wind shear in Sulaiman is very high with a maximum value at noon reaching 2.46 m.s\(^{-1}\), while the wind shear value in Dago is much smaller. So it can be concluded that wind shear is inversely proportional to the estimation results accuracy.

![Figure 11. Wind shear charts in three observation locations.](image)

Figure 12 shows the heat flux plots in the three observation locations at night. Observed heat flux values are shown by the red line and the estimation results are shown by the green line. There are differences in the pattern of heat flux results from estimations and observations in the Dago region. The estimated heat flux tends to have a value of 0 K.m.s\(^{-1}\), only at 02:30 and 05.30 there is a slight change in values to -0.01 and 0.012 K.m.s\(^{-1}\), throughout the observation period. This is different from the results of observations that show negative values throughout the observation period. At Sulaiman, the heat flux from the estimation is positive from 6 to 9 PM., while the observation data shows the opposite. After 9 PM, the estimated heat flux shows a value of 0 K.m.s\(^{-1}\), but the observation data shows a negative value. The estimation results of heat flux in Manoko showed a significant difference compared to the observation data. This large difference is seen in terms of its magnitude, the value of the observed heat flux ranges in the range of 0 to -0.005 K.m.s\(^{-1}\), while the estimated value can even reach -0.19 K.m.s\(^{-1}\). The positive heat flux at the beginning of the night in Dago and Sulaiman occurs because of the effect of the time lag from heat flux during the day. As mentioned earlier, the ability of estimation results to approach the observation pattern is influenced by the well-mixed mechanism. At night, there is no buoyant production in the process of heat flux formation, so the comparison between the observation results and the estimation results is much different. It seems clear that there is an inability of the estimation results to approach observation results, especially during night time. The absolute correlation between estimated value and the observed value was less than 0.3, indicating a very weak relation between them.

Based on our results, the Bulk Parameterization method seem unable to produce good estimate of sensible heat flux over Bandung, either during day time nor night time. However, further investigation has found out that our implementation of the method seems inadequate. According to [2], the bulk transfer coefficient (C\(_H\)) need to be carefully calculated using roughness lengths for momentum and heat. The surface skin temperature (\(\theta_0\)) also need to be measured or estimated correctly and could not simply be estimated using air temperature [1]. By implementing these improvements, further research could be conducted to give a better estimation on the surface sensible heat flux over Bandung.
4. Conclusion
Surface sensible heat flux observation over three locations around Bandung has shown a diurnal pattern that match the pattern from other research. In the morning, the heat flux over all location were increasing in relatively same rate. However, the decreasing rate of heat flux during afternoon shows varying results among three locations, with urban residential area (Dago) show most rapid decrease. In the night time, all location shows mostly negative value of heat flux. Dago area also shows more rapid decrease in flux value, especially after midnight.

Estimation of heat flux using Bulk Parameterization method over three sites on Bandung shows a poor results. The estimated values were barely matched the observed heat flux. Wind shear over the sites was found to have a strong influence on the estimation results, but the major error may be caused by simplification of the bulk transfer coefficient and the surface skin temperature. A more careful and detailed research must be carried out to gain a better estimation of surface sensible heat flux over the study area.

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