CHAPTER V

REGIONAL BOUNDARY-LAYER PARAMETERISATION FOR DISPERSION MODELLING: FLUXES OVER A TROPICAL AREA

5.1 INTRODUCTION

The atmospheric boundary layer (ABL) is the lowest layer of the atmosphere, and is characterised by the divergence of the vertical fluxes of momentum, heat, and water vapour. The ABL is directly and indirectly a product of the interaction between the atmosphere and the surface. The fluxes determine to a great extent the state of the atmospheric boundary layer. As such, these fluxes are the principal boundary components for numerical weather prediction models, air pollution dispersion models, and general climate models.

The boundary layer is more difficult to treat in a numerical model than the free troposphere, because turbulence is stronger and reflects the underlying surface processes and their changes, which impact on the boundary layer. Parameters important for modelling the boundary layer include turbulent fluxes of momentum, sensible and latent heat, eddy diffusion coefficients, surface roughness length, surface temperatures, and the availability of water either on the surface for evaporation or in plants for transpiration.
Parameterisations that describe the boundary layer are discussed in this study. Therefore, turbulent fluxes have to be parameterised for the study area.

The surface fluxes of momentum, heat, and moisture determine to an important extent the state of the atmosphere. The direct interaction between the atmosphere and the surface takes place in the surface boundary layer which is characterised by constant fluxes. It comprises roughly 10% of the boundary layer depth. The surface fluxes are of crucial importance, not only because they influence the state of the atmosphere, but also because they are used to parameterise the mean profiles of wind and temperature and their variances on the surface and in the ABL (Holtslag & Nieuwstadt, 1986; Beljaars & Holtslag, 1991).

Understanding the dynamics, formation, and evolution of the convective boundary layer (CBL) is very important. The layer acts as a lid for the vertical dispersion of pollutants emitted near the ground. Its state reflects the underlying fluxes from the surfaces that are efficiently mixed within the layer. It is generally the case that heat released from the surface is so effectively mixed by atmospheric turbulence and that the atmosphere is able to maintain a near-constant profile of potential temperature within the layer. On the other hand, the layer is not passive in response to this turbulence. It also displays interaction mechanisms with the overlying free atmosphere, by the entrainment of warm and dry air from the free atmosphere into the CBL, which in turn modifies the layer deficit of temperature and humidity, thus altering the sensible and latent fluxes of the surface (Fisch, 1996).
Many applied dispersion models require knowledge of boundary layer parameters. The quality of those dispersion models depends on the quality of the meteorological input, which in turn depends on the quality of the parameterisation of the structure of the ABL. As modelling the mixing height in the tropics is one of the main objectives of this work, a complementary data set is needed to simulate the CBL growth during the experiments (from Chapter IV). Heat turbulent flux (heat and latent heat), momentum flux (friction velocity), and temperature must all be known as a function of time, and the potential temperature and its gradient as a function of height.

In principle the fluxes can be measured. However, such measurements are not usually available, and in forecast models the fluxes have to be parameterised in terms of variables predicted by the model. So, in general, there is a need to relate the surface fluxes to weather variables, either measured routinely or predicted by forecast models (Holtslag & Van Ulden, 1983).

The study of boundary layer processes in the tropics is of importance in order to better understand the influence of the fluxes on the growth of the boundary layer. Therefore, this chapter is concerned primarily with the surface fluxes of momentum, heat, and latent heat under humid tropical conditions. Further, the estimated fluxes will be compared to observations for verification purposes.
5.2 METHODOLOGY

Many methods for estimating the boundary layer parameters have appeared in the literature (Holtslag & Nieuwstadt, 1986; Gryning et al., 1987; Irwin & Paumier, 1990). Some of these methods have been used in applied dispersion models (e.g., Berkowicz et al., 1985; Hanna & Paine, 1989). However, it is not widely recognised that these parameterisations are based on limited field observations taken during relatively ideal conditions (Hanna & Chang, 1992).

Two of the available methods for calculating the boundary layer parameters are considered in this study: the model-parameterisation method suggested by Hanna & Chang (1992); and a method based on measurements of turbulent fluctuations, the so-called Eddy-Correlation method. The degree of turbulence can be quantified with the turbulent flux term. Mean kinematic turbulent fluxes in the surface layer can be obtained from observation or parameterised by a model. The energy, water vapour, and momentum fluxes obtained from observation using the Eddy-Correlation method and the model-parameterised fluxes are discussed in section 5.3.

5.2.1 Model-Parameterised Method

5.2.1.1 Experimental Data

Hanna & Chang (1992) suggested formulae for calculating sensible and latent heat fluxes over a wide variety of types of ground surface, based on simple observations of
wind speed near the ground, fractional cloud cover, and on the specification of constants such as roughness length, albedo, and soil moisture availability. The formulas developed by Hanna & Chang will be used in the estimation of the fluxes for the TBLE site. The estimated fluxes will also be compared with observations.

The Malaysian Meteorological Service (MMS) provided the standard meteorological data for the periods over which the TBLEs took place. Using the hourly values of temperature, wind speed, wind direction, and cloud cover from the MMS, values of $Q^*$ (the net radiative flux, being the sum of the net incoming short wave (solar radiation) and long-wave radiation), $Q_H$ (sensible heat flux), $Q_L$ (latent heat flux), $Q_G$ (heat flux to the ground), and $u^*$ (friction velocity) were estimated following the approach of Hanna & Chang.

5.2.1.2 Model Formulae

In order to derive the surface fluxes of $Q_H$ and $Q_E$, it is necessary to establish some relation between the latent heat flux, $Q_E$, and the sensible heat flux, $Q_H$. Some models define a constant value for the Bowen Ratio, $BR=Q_H/Q_E$, but an increasing amount of observational evidence suggests that this ratio can be highly variable over time and space.

An alternative method is to derive the total available energy, which then can be partitioned into sensible and latent fluxes of heat. In the model of Hanna & Chang (1992) the energy balance at the surface is derived. First, we consider the incoming short
wave radiation $Q_{sw}$. If short wave radiation, $Q_{sw}$, is not observed, it can be parameterised by a formula proposed by Holtslag & van Ulden (1983):

$$Q_{sw} = (790 \text{ W/m}^2) \sin \nu - 30 \text{ W/m}^2(1 - b_1N^{b_2})$$

(5.1)

where $\nu$ is the solar elevation angle, that can be calculated as suggested by Nyren & Gryning (1999). The empirical constants $b_1$ and $b_2$ are assumed to be equal to 0.75 and 3.4, respectively, although they may be expected to vary with cloud type and ceiling height.

The net radiation flux, $Q^*$, is the sum of the net short wave and long wave radiation. It is sometimes directly observed as part of routine measurement programs, but in general is a difficult parameter to measure because it includes the long wave component of the radiation. Typically, only the solar (short wave) heat flux, $Q_{sw}$, may be observed. In this latter case, Holtslag & van Ulden (1983) recommended the following parameterisation for $Q^*$, based on knowledge of the albedo, $A$, the air temperature near the surface, $T$, and the fractional cover, $N$:

$$Q^* = (1 - A)Q_{sw} + c_1 T^6 - \sigma T^4 + c_2 N/(1 + c_3)$$

(5.2)

where the first term on the right hand side represents the net short wave radiation (incoming minus reflected); the second term represents incoming long wave radiation to the surface from the air; the third term represents the outgoing long wave radiation from
the surface; and the fourth term represents long wave radiation from clouds. In the
equation, \( \sigma \) is the Stefan-Boltzmann constant \( \sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4 \), and the constants \( c_1 = 5.31 \times 10^{-13} \text{ W/m}^2\text{K}^6 \) and \( c_2 = 60 \text{ W/m}^2 \).

The parameter \( c_3 \) is given by the formula

\[
c_3 = 0.38 \frac{(1 - \alpha)(S + 1)}{(S + 1)}
\]

(5.3)

where \( \alpha \) and \( S \) are as defined above. Guidance on choice of albedo, \( A \), for various types of land usage is given by Hanna & Chang (1991).

The net radiation flux, \( Q^* \), is partitioned into ground heat flux, and sensible and latent heat fluxes to the atmosphere. The surface moisture availability factor, \( \alpha \), suggested in the method developed by Penman-Monteith and recommended by Holtslag & van Ulden (1983), is a robust parameter for describing the relation between \( Q_H \) and \( Q_E \). Based on information presented by Beljaars & Holtslag (1989, 1991), Hanna & Chang proposed the following range of values for \( \alpha \):

\[
\alpha = 0.0 - 0.2 \text{ (dry desert with no rain for months)}
\]

\[
\alpha = 0.2 - 0.4 \text{ (arid rural area)}
\]

\[
\alpha = 0.4 - 0.6 \text{ (crops and fields, mid summer during periods when rain has not fallen for several days)}
\]

\[
\alpha = 0.5 - 1.0 \text{ (urban environment, some parks)}
\]
\[ \alpha = 0.8 - 1.2 \text{ (crops, fields, or forests with sufficient soil moisture)} \]

\[ \alpha = 1.2 - 1.4 \text{ (large lake or ocean with land more than 10 km distant)} \]

Given \( \alpha \), \( Q_H \) and \( Q_E \) can be parameterised during daytime periods using equations 5.4 and 5.5, respectively:

\[
Q_H = \left[ \frac{(1-\alpha)^+ + S}{1+S} \right] (Q^* + Q_A - Q_G) - \alpha \beta' \tag{5.4}
\]

\[
Q_E = \left[ \frac{\alpha}{1+S} \right] (Q^* + Q_A - Q_G) + \alpha \beta' \tag{5.5}
\]

where \( \beta' \) is a constant, assumed equal to 20 W/m\(^2\), that accounts for the observation that \( Q_H \) becomes negative before sunset; \( Q_A \) is the anthropogenic heat flux and is traditionally neglected and therefore not considered in this study; \( Q_G \) is the ground heat flux which is taken as 0.1\( Q^* \); and the parameter \( S \) is defined as \( (c_p/L_e dq_s/dT) \), where \( L_e \) is the latent heat and \( dq_s/dT \) is the slope of the saturation specific humidity curve (the Clausius-Clapeyron relation). \( S \) varies with temperature as shown below:

<table>
<thead>
<tr>
<th>T(°C)</th>
<th>-5</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>2.01</td>
<td>1.44</td>
<td>1.05</td>
<td>0.79</td>
<td>0.60</td>
<td>0.45</td>
<td>0.35</td>
<td>0.27</td>
<td>0.21</td>
</tr>
</tbody>
</table>

In practice, Hanna & Paine (1989) found that the calculations of the fluxes using the equations 5.4 and 5.5 are relatively insensitive to whether the observed or calculated
net or solar heat fluxes are employed. This method will be further investigated and compared with observations to verify its applicability in the tropics.

5.2.2 Eddy-Correlation Method

5.2.2.1 Experimental

The eddy correlation technique is employed in this study to estimate the fluxes of sensible heat, latent heat and momentum using data obtained from the sonic anemometer and krypton hygrometer installed at a height of 3 m on a micrometeorological tower. The experiment is a part of the Tropical Atmospheric Boundary Layer Experiments (TBLEs) conducted at the University of Malaya, Malaysia.

The measurements were taken at the Subang meteorological station (latitude: 03° 07'; longitude: 101° 33'). The site is about 20 km from the campus of the University of Malaya where the TBLEs took place. An instrumented tower (3 m high) was erected in the field, which is covered homogeneously with short grass with a mean height of 2 cm.

The tower was fitted with a sonic anemometer USA-1 (METEK), a krypton hygrometer (Campbell Scientific, Inc.), and a CNR 1 Net-Radiometer (Kipp & Zonen), at 3 m height. The instruments were mounted on a rotatable boom attached to a one-metre-long support arm connected to the tower. The instruments used were factory calibrated.
Data were recorded at a one-second sampling interval, continuously for 24 hours per day from the 19th to 26th of August 2001. Parameters measured during the SW monsoon period were wind speed components (u, v, w), temperature (T), water vapour (q), and net radiation (Q* it is the net solar radiation (only short-wave, Qsh)).

5.2.2.2 Eddy-Correlation Formulae

Energy in the surface layer is transferred vertically by mechanical and convective turbulence arising from wind shear and buoyancy. The vertical turbulent sensible heat flux (W/m²) due to wind shear and buoyancy is given in equation 5.6. Water vapour is also transferred vertically from the surface by mechanical and convective turbulence (equation 5.7). The friction velocity (equation 5.8), a scaling variable, gives a measure of the vertical kinematic turbulent flux of horizontal momentum in the surface layer.

The data measured at the Subang meteorological station were used in the calculation of the surface fluxes using the Eddy-Correlation technique. Fluxes of sensible heat (H), latent heat (LE), and the momentum flux represented by the friction velocity (u*) were determined from the relations:

\[ H = \rho c_p \overline{w'T'} \quad (5.6) \]

\[ LE = L_v \left( \overline{w'q'} / q^* x K_w \right) \quad (5.7) \]
\[ u_* = \left[ \left( \overline{w'w'} \right)^2 + \left( \overline{w'v'} \right)^2 \right]^{1/4} \] (5.8)

where \( c_p \) is the specific heat of air under constant pressure (1010 J/kg·°C); \( \rho \) is the air density (1.225 kg·m⁻³); \( w', T', \) and \( q' \) are the turbulent fluctuations of vertical wind, temperature, and water vapour specific humidity, respectively; the product \( \overline{w'T'} \) is the vertical transfer of sensible heat flux in the surface layer; \( L_v \) is the latent heat of vaporisation (2.43 \times 10^6 J/Kg); \( xK_w \) is the KH20- calibration; and the product \( \overline{w'q'} \) is the vertical kinematic moisture flux in the surface layer.

5.3 RESULTS AND DISCUSSION

5.3.1 Model Estimated Fluxes

To summarise, the hourly values of the surface wind speed near the ground, wind direction, temperature, and fractional cloud cover, and the specification of constants such as roughness length, albedo, and soil moisture, were used to estimate the fluxes for the site. The Malaysian Meteorological Service provided the hourly data set. The surface heat flux \( (Q_H) \), latent heat flux \( (Q_L) \), and friction velocity \( (u*) \) were estimated using the scheme suggested by Hanna & Chang (1992). Two sets of data, obtained during the NE-TBLE and the SW-TBLE, were used in this estimation.

Tables 5.1a and 5.1b report the hourly variation of the estimated net radiation \( (Q*) \), heat flux, latent heat flux, and friction velocity during the NE-TBLE and the SW-
TBLE, respectively. Figures 5.1a and 5.1b show the diurnal course of \( Q^* \), \( Q_H \), and \( Q_L \) during the experiments. The friction velocity was estimated to be 20 % of the hourly wind speed and is presented in Figure 5.2 (Gryning, personal communication).

Figures 5.1a,b show that all the estimated parameters have maxima around midday LT. The maximum values of \( Q^* \), \( Q_H \), and \( Q_L \) were 468 W/m\(^2\), 253 W/m\(^2\), and 193 W/m\(^2\) respectively during the NE-TBLE whereas the maximum values were 538 W.m\(^{-2}\), 274 W.m\(^{-2}\), and 210 W/m\(^2\) respectively during the SW-TBLE. The estimated friction velocity followed the diurnal cycle of the estimated fluxes, i.e., increasing until midday and decreasing through the afternoon. Generally, higher values were estimated during the SW monsoon (maximum of 0.7 m/s) compared to values below 0.3 m/s estimated during the NE monsoon.

**Table 5.1:** Model-estimated values of net radiation \( (Q^*) \), sensible heat flux \( (Q_H) \), latent heat flux \( (Q_L) \), and friction velocity \( (u^*) \) during the NE-TBLE (a) and during the SW-TBLE (b).

<table>
<thead>
<tr>
<th>Time (LT)</th>
<th>( Q_H ) (NE-TBLE)</th>
<th>( Q_L ) (NE-TBLE)</th>
<th>( Q^* ) (NE-TBLE)</th>
<th>( u^* ) (NE-TBLE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>17.4</td>
<td>27.5</td>
<td>44.2</td>
<td>0.029</td>
</tr>
<tr>
<td>9</td>
<td>93.1</td>
<td>76.9</td>
<td>188.3</td>
<td>0.169</td>
</tr>
<tr>
<td>10</td>
<td>159.5</td>
<td>120.1</td>
<td>309.8</td>
<td>0.271</td>
</tr>
<tr>
<td>11</td>
<td>209.1</td>
<td>156.3</td>
<td>404.9</td>
<td>0.211</td>
</tr>
<tr>
<td>12</td>
<td>241.9</td>
<td>180.5</td>
<td>468.4</td>
<td>0.249</td>
</tr>
<tr>
<td>13</td>
<td>253.6</td>
<td>193.2</td>
<td>444.4</td>
<td>0.274</td>
</tr>
<tr>
<td>14</td>
<td>249.9</td>
<td>188.2</td>
<td>435.6</td>
<td>0.274</td>
</tr>
<tr>
<td>15</td>
<td>225.8</td>
<td>169.5</td>
<td>438.2</td>
<td>0.274</td>
</tr>
<tr>
<td>16</td>
<td>181.7</td>
<td>139.7</td>
<td>356.5</td>
<td>0.24</td>
</tr>
<tr>
<td>17</td>
<td>106.6</td>
<td>89.4</td>
<td>221.5</td>
<td>0.217</td>
</tr>
<tr>
<td>18</td>
<td>45.4</td>
<td>47.1</td>
<td>92.3</td>
<td>0.166</td>
</tr>
</tbody>
</table>
### Table

<table>
<thead>
<tr>
<th>Time (LT)</th>
<th>Q\textsubscript{H} (SW-TBLE)</th>
<th>Q\textsubscript{L} (SW-TBLE)</th>
<th>Q\textsuperscript{*} (SW-TBLE)</th>
<th>u\textsuperscript{*} (SW-TBLE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>28.6</td>
<td>35.1</td>
<td>70.7</td>
<td>0.1</td>
</tr>
<tr>
<td>9</td>
<td>107.1</td>
<td>87.6</td>
<td>216.3</td>
<td>0.165</td>
</tr>
<tr>
<td>10</td>
<td>170.9</td>
<td>137.4</td>
<td>342.5</td>
<td>0.34</td>
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<tr>
<td>11</td>
<td>223.9</td>
<td>174.7</td>
<td>442.9</td>
<td>0.435</td>
</tr>
<tr>
<td>12</td>
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<td>199.4</td>
<td>509.3</td>
<td>0.545</td>
</tr>
<tr>
<td>13</td>
<td>274.3</td>
<td>210.2</td>
<td>538.4</td>
<td>0.52</td>
</tr>
<tr>
<td>14</td>
<td>268.9</td>
<td>206.4</td>
<td>528.1</td>
<td>0.515</td>
</tr>
<tr>
<td>15</td>
<td>242.6</td>
<td>187.9</td>
<td>478.3</td>
<td>0.675</td>
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<tr>
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<td>393.3</td>
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<td>112.2</td>
<td>278.2</td>
<td>0.34</td>
</tr>
<tr>
<td>18</td>
<td>64.9</td>
<td>61.8</td>
<td>140.8</td>
<td>0.31</td>
</tr>
</tbody>
</table>

### Figure 5.1a

Figure 5.1a: Daytime course of model-estimated fluxes during the NE-TBLE, showing net radiation (Q\textsuperscript{*}), sensible heat flux (Q\textsubscript{H}), and latent heat flux (Q\textsubscript{L}).
Figure 5.1b: Daytime course of model-estimated fluxes during the SW-TBLE, showing net radiation ($Q^*$), sensible heat flux ($Q_H$), and latent heat flux ($Q_L$).

Figure 5.2: Daytime course of estimated friction velocity during the NE-TBLE and the SW-TBLE.
5.3.2 Observed Fluxes

The diurnal cycles of the net radiation ($Q^*$), sensible flux ($Q_h$), and latent heat flux ($Q_l$) are presented in Table 5.2 and shown graphically in Figure 5.3. The sensible heat flux reached its maximum value at 13:00 LT, with an intensity of 173 W/m$^2$. At the same time, the latent heat flux had its maximum value of 240 W/m$^2$. Both of the fluxes were observed to follow the characteristic behaviour of the net radiation flux. The results show that in the humid tropics, most of the solar energy is used to evaporate water. Nober et al. (1996) showed a similar partition with most of the energy going into evaporation in the Amazonian tropics.

The observed fluxes (Figure 5.3) are similar to the values observed over pasture in the Amazon region (Fisch et al., 1996). Values over the forest site in that

| Table 5.2: Observed values of net radiation ($Q^*$), sensible heat flux ($Q_h$), latent heat flux ($Q_l$), and friction velocity ($u_*$) during the daytime at Subang during 19-26 August 2001. |
|---------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Time (LT)                      | 8:00     | 9:00     | 10:00     | 11:00     | 12:00     | 13:00     | 14:00     | 15:00     | 16:00     | 17:00     |
| $Q^*$ (W/m$^2$)                | 30.1     | 138.6    | 309.9     | 467.2     | 524.9     | 598.5     | 508.3     | 506.4     | 459.5     | 325.      |
| $Q_h$ (W/m$^2$)                | 6.60     | 18.80    | 59.59     | 102.1     | 121.76    | 173.66    | 83.62     | 78.39     | 80.99     | 72.0      |
| LE (W/m$^2$)                   | 23.37    | 6.47     | 57.12     | 101.81    | 214.74    | 240.14    | 196.79    | 143.98    | 135.10    | 70.1      |
| $u_*$ (m/s)                    | 0.118    | 0.153    | 0.191     | 0.293     | 0.329     | 0.337     | 0.340     | 0.319     | 0.348     | 0.32      |
| $B_o$                          | -0.28    | 2.9      | 1.04      | 1.0       | 0.57      | 0.72      | 0.42      | 0.54      | 0.59      | 1         |
Figure 5.3: Daytime course of observed fluxes during August 2001 at Subang station, showing net radiation ($Q^*$), sensible heat flux ($QH$), and latent heat flux ($QL$).

Figure 5.4: Daytime course of observed friction velocity in August 2001, at Subang station, showing $u^*$ as measured at 3 m height.
study were slightly higher in the afternoon with a maximum value of 0.43 m/s (at 14:00). Observations over a semi-arid region (Anand, India) showed two peaks around 8:30 and 11:30 (Indian LT) of 0.24 m/s and 0.25 m/s respectively, with values decreasing throughout the evening (Nagar et al., 2001).

Figure 5.4 shows the variations of the observed friction velocity $u_\tau$. It starts with a value of 0.12 (m/s) in the morning and increases till the midday (0.34 m/s, maximum at 12:00 LT). The friction velocity values were maintained throughout the evening hours.

The observed fluxes (Figure 5.3) are similar to the values observed over the pasture in the Amazon region (Fisch et al., 1996). Values over the forest site are slightly higher in the afternoon with maximum value of 0.43 m/s (at 14:00). Observations over a semi-arid region (Anand, India) show two peaks around 8:30 and 11:30 (Indian Local Time). The values were 0.24 m/s and 0.25 m/s, respectively. Values then decreased throughout the evening (Nagar et al., 2001).

## 5.4 CONCLUSIONS

A study on the land surface processes in the boundary layer over a humid tropical area has resulted in the following conclusions.
1. Model-estimated fluxes did not show the observed partition of energy as was observed over the tropics (observed latent heat flux was greater than sensible heat flux).

2. Contrary to the observed trend, the modelled sensible heat flux was estimated to have higher values compared to the latent heat flux. The latent heat flux in the humid tropics is significantly greater than those of the sensible heat flux. This can be deduced from the values of the Bowen ratio (the ratio of sensible to latent heat fluxes at the surface). Values as small as 0.4 were observed (at 14:00 LT) and represent a moist surface where most of the energy goes into evaporation. These values are typical of those observed over grassland and forests (Stull, 1988).

3. Since moisture plays an important role in the surface energy balance, moisture-related processes should be included in modelling the growth of the tropical boundary layer.