CHAPTER VIII

SUMMARY AND CONCLUSIONS, RECOMMENDATIONS, AND FURTHER RESEARCH

8.1 SUMMARY AND CONCLUSIONS

The state of the atmospheric boundary layer (ABL) changes continuously during the course of a day due to the transfer of energy between the surface and the large-scale atmospheric flow. Therefore, its height, temperature, humidity, and momentum are all functions of time. As the ABL is a major link in global biogeochemical cycles, it is of primary importance to be able to understand, measure, parameterise, simulate, and predict its structure and behaviour.

Measurements, parameterisations, and predictions of the height of the ABL have many theoretical and practical applications, such as the prediction of pollutant concentrations and of surface temperature, the scaling of turbulence measurements, or the treatment of the ABL in numerical weather prediction and climate models. These measurements and parameterisations of the time-dependence of the structure and behaviour of the ABL have been accomplished in previous studies. However, although those models were developed to simulate the evolution of the ABL, their development and validation were focused on the conditions in the mid-latitude regions. The problem
for the models is that the mid-latitude boundary layer is, in many respects, physically quite different from that of the tropical boundary layer. In the tropics, the Coriolis parameter $f$ is small or zero; conditions with calm winds are frequent; and the role of moisture plays a greater role in controlling the atmospheric stability and the surface energy balance. As a result of these differences, and the relative lack of observations, the tropical ABL is incorrectly represented in models, and also in various applications use the ABL mid-latitude representation (for example, air pollution dispersion models). Therefore, the prediction of the structure and behaviour of the TABL is of great importance to improve the accuracy and usefulness of such models and applications. In this thesis, the aim has been to develop and understand the formation, structure, and evolutionary dynamics of the atmospheric boundary layer in the near-equatorial tropics. This aim has been achieved by using observational data to constrain the structure of the ABL, and by using numerical models to examine the effects of the main mechanisms (mechanical and thermal) in the growth of the ABL. As such, this work contributes to micrometeorological research by increasing knowledge and understanding of the formation, structure, and behaviour of the ABL as developed over the tropics.

The important findings presented in this thesis can be separated into two categories. One is the presentation and analysis of the observed ABL in a near-equatorial area of the tropics. Data consisted of radiosondings and the surface fluxes of momentum, heat, and moisture (Chapters IV & V). The second related to the modelling of the mixing layer height, which were then compared to the observed data. A sensitivity analysis of the models was also performed in Chapters VI & VII.
8.1.1 Conclusions from Observational Data

The Tropical Boundary Layer Experiments (TBLEs) conducted during the Northeast (NE) and the Southwest (SW) monsoons were designed to collect data on the evolution of the tropical ABL. The NE-TBLE was executed from January 24\textsuperscript{th} to 30\textsuperscript{th}, 2000, while the SW-TBLE was performed from September 11\textsuperscript{th} to 14\textsuperscript{th}, 2000. Both field experiments took place at the University Malaya campus using slow-rise radiosonde ascents of about 3 m/sec, at every 2 or 4 hours. Observations were analysed using the radiosonde measurements, to characterise both the diurnal and nocturnal evolutions of the tropical ABL. Data on the tropical surface energy and momentum fluxes are necessary in understanding and processes taking place in the boundary layer. These were measured, and used to prescribe the input of energy to the convective boundary layer model and to initiate the boundary layer growth models. Hourly values of surface fluxes were obtained from an eddy-correlation method (described in Chapter V). From the TBLEs, the following conclusions can be drawn:

1. Observations of the sensible heat, latent heat and momentum fluxes have shown a significantly larger latent heat flux than sensible heat flux. In the tropics, most of the surface energy is used for evaporation. Therefore, moisture plays an important role in the surface energy balance and therefore moisture processes should be included in models of the growth of the tropical boundary layer. Observed heat flux showed a maximum value of 173 W/m\textsuperscript{2} at 13 (LT), whereas the latent heat flux maximum value was 240 W/m\textsuperscript{2} at the same time.
2. Most of the meteorological pre-processors in the air pollution dispersion models used parameterisation for the fluxes based on regularly collected surface data. They were validated using data from the midlatitude region. Comparison of model estimated fluxes using the surface data in the tropics have been compared with observed fluxes. Model-estimated fluxes did not show the observed partition of energy as measured in the tropics (with latent heat flux higher than sensible heat flux). Contrary to the observed trend, estimated sensible heat flux has higher values than the latent heat flux.

3. In studying the evolution of the convective and nocturnal boundary layers in the humid tropical area, some insights can be gained from analysing and comparing the structures for the NE-TBLE and the SW-TBLE.

- Mixed layer mean temperature is slightly warmer with higher heating rates in clear conditions. The influence of surface sensible heat flux is important but is not the only significant heat flux; the influence of entrainment in maintaining the mixed layer’s temperature and in contributing to the development of the CBL height in the afternoon is also important and was demonstrated.

- The heating rate becomes stationary in the afternoon. In spite of the reduced surface heating in the late afternoon, the layer is still warmed by the entrainment flux of hot and dry air from above the CBL. This
behaviour is similar that previously reported for the Amazon convective boundary layer (Fisch et al., 1996).

- The growth of the CBL was slightly more strongly during the NE-TBLE. The final mixing layer is 150 m deeper compared to the observed layer of the SW-TBLE. This can be attributed to a higher growth rate in the morning during the NE-TBLE (375 m/h between 8:00 and 12:00 LT) compared to 225 m/h during the SW-TBLE. During both experiments, the heating rate in the afternoon was less than 0.5 K/h. In the case of the tropical nocturnal boundary layer it is shallower during the NE monsoon in comparison to the SW monsoon period. The nocturnal boundary layer during the SW monsoon were similar to the observed over the forest in the Amazon experiments. due to the calm conditions at night (NE-TBLE case) or similar to those observed over the forest (SW-TBLE case).

- Due to the calm wind at night, the nocturnal boundary layer in the tropics is shallow. This reduces the influence of mechanical turbulence and hence vertical diffusion cannot deepen the nocturnal layer. The greater depth of the nocturnal boundary layer during the SW-TBLE may be due to the influence of the mechanical turbulence. Wind speeds during the SW-TBLE were higher compared to those during the NE-TBLE, which can deepen the nocturnal layer.
4. With respect to the gradient of the virtual potential temperature above the convective boundary layer ($\gamma$), previous authors have considered the temperature gradient above the convective boundary layer as being time-invariant (e.g. Tennekes, 1973, Driedonks 1982). However in this study, this slope has a small dependence, slowly increasing with time: from 4.3 K Km$^{-1}$ (at 8:00 LT) it increases to 5.3 K Km$^{-1}$ (at 16:00 LT) during the NE-TBLE and from 4.01 K Km$^{-1}$ (at 8:00 LT) to 4.17 K Km$^{-1}$ (at 16:00 LT). $\gamma$ increases with time during the course of the daytime. These values are slightly higher compared to those observed in the Amazon boundary layer over the forest as reported by Nobre et al. (1996). They reported a slow increase from 1.8 K Km$^{-1}$ to 3.3 K Km$^{-1}$. Also of interest is that the clear-day data set in this study shows temporal variation in the gradient of virtual potential temperature above the CBL from 3.8 K Km$^{-1}$ to 7.6 K Km$^{-1}$. These values are similar to the values observed over the pasture site in Amazon (3.6 K Km$^{-1}$ to 8.0 K Km$^{-1}$, RBLE-II, Nobre et al., 1996).

5. The CBL and NBL heights in the tropics generally grow higher than its mid-latitude counterpart. Using data on the evolution of the daytime boundary layer at Cabauw, the Netherlands, Driedonks (1982) observed a mixing height between 900-1350 m for the CBL.

6. In comparison to the Amazonian mixing layer, the CBL heights measured at the TBLE site are similar to those observed over the Amazonian pasture areas (RBLE-II, Nobre et al., 1996). In both sites, the CBL height typically reaches a
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height in the afternoon of greater than 2 km. The CBL grows deeper over the TBLE site when compared to the boundary layer over an equatorial rain forest. The ABLE 2A experiment was concerned with the structure and growth of the atmospheric mixed layer over an equatorial (central Amazon) rain forest during the "dry" season (Martin et al. 1988). In that experiment, the maximum depth of the mean mixed layer reached a height of 1200 m at 13:00 LT. However, the CBL heights measured in this study are less than those observed during the Land Surface Processes Experiment (LASPEX-97) conducted at a semi-arid station (Anand) over Sabarmati basin of Gujarat state in western India. In that study, the CBL developed to a height of 3.2-3.6 km under hot weather conditions (Nagar et al., 2001).

7. Preliminary analysis of the wind-profiles indicated the importance of land and sea breeze circulation in influencing the evolution of the tropical boundary layer. The interaction of the thermodynamics and dynamics of the atmosphere needs further investigation.

8.1.2 Conclusions from Models

It is necessary to examine the validity and the performance of the slab models in the simulation of the tropical atmospheric boundary layer. This was only possible with the simultaneous observations of the mixing layer growth and of the surface energy processes. These observations are needed for the verification and validation of the slab models. In conclusion, it was found that:
1. In their current formulation and with the generally recommended parameterisation constants for the mid-latitudes, the models are unable to reproduce the characteristics of the convective boundary layer observed during the TBLs. There are discrepancies in both the CBL height and the virtual potential temperature profiles. A rather poor agreement with the observations is found, especially in the mid-morning. Several processes that take place at this time of the day could conceivably influence the degree of turbulence, thereby leading to a more rapid growth of the CBL. This led to the necessity of making further investigations concerning the model formulation, and the values used of empirical constants (representing the mechanical and thermal contributions to the entrainment flux).

2. A sensitivity analysis on the models showed that the encroachment model is inappropriate for the tropics situation. The growth of the mixing layer in this model is controlled completely by convection, while in the tropics it is controlled by entrainment at the top of the CBL, and by convective and mechanical turbulence.

3. The above findings suggested a need for a closer inspection of the basic assumptions of the slab model. One of the jump conditions at the top of the mixing layer indicates that entrainment of warmer air from the stable environment aloft into the cooler boundary layer requires a downward heat flux at the inversion base. The values of the entrainment coefficients that could the best fit to observations are higher than the generally recommended values.
Previously, simple entrainment has been used in situations when more complex parameterisation is required; this study shows that the tropical boundary layer likely represents such a complex situation. However, the slab model can still be used (e.g., the Gryning and Batchvarova (1991) model as used in chapter VI) by increasing the entrainment coefficients. But in this case, the actual physics of the entrainment processes described should be investigated.

4. The Gryning and Batchvarova (1991) model presented in Chapter VI is a good fit to the observed data in the lowest range of heights, but there are possibly other processes (not captured in the model) that contribute to the overall entrainment processes. Possible candidates are contribution of moisture to the growth (neglected in the model), wind shear at the inversion base, or breaking gravity waves in the entrainment zone. Another quite different possibility is the existence of an extra source of energy that may explain the observed rapid growth in the mixing layer height in the mid-morning hours. Anthropogenic heating from cars, mainly limited to rush hours, probably contributes to levels of surface layer sensible heat and the mixing layer height over the city and its surroundings. Observations must be undertaken to verify such possibility.

5. The inclusion of moisture in the mixing layer growth resulted in a 10 % increase in the mixing layer height compared to the dry case. This result is similar to results reported from studies of the mid-latitude region due to the higher values of the Bowen Ratio.
6. A combined two-layer model for the mixing layer and the entrainment zone was used to model the growth of the CBL during the TBLEs. The model was used with the inclusion of the effect of moisture on the growth as described by Driedonks. In the NE-TBLE simulation, the model still suffers from poor representation of the rapid growth in the mid-morning hours. The model predictions fit the SW-TBLE observed mixing layer height better, both in the morning and in the afternoon. This good agreement between observations and simulations is due to the use of the actual forcings required for the model, as fluxes were measured for August and represent the SW monsoon season in the tropics being simulated by the model.

7. A sensitivity analysis with different entrainment processes to better understand the growth mechanisms was also performed. The analysis shows clearly that a model with increased entrainment from the inversion layer better fits the observed values. This means that in the TBLE site where convection dominates the observed mixing layer, the influence of convection and entrainment (associated with $A = 0.5$) is much more important than friction (associated with $B = 5.0$). This is due to the calm wind conditions in the tropics compared to the mid-latitudes. Therefore, when using a slab model, for example the models of GB (1991) or BG (1994), the use of a greater entrainment parameter due to convection processes is recommended when simulating a tropical boundary layer (the use of a value of 0.5 instead of the widely used 0.2).
8. A sensitivity analysis showed that convection has a greater contribution in any tropical slab model entrainment equation compared to the mid-latitude convection processes. It plays a more important role in entrainment at the top of the mixing layer in the tropics than was previously believed, leading to a recommended value of 0.5 for the $A$ parameter in comparison with generally recommended values of 0.2.

9. The uncertainty in the estimate of the observed mixing height is rather large, and more frequent radiosondings are recommended to better follow the development of the mixing height in the tropics in any future experiments. Also, the structure of the entrainment zone should be considered when estimating the mixing layer height from the measurements. A suitable measurement system would collect the half-hourly or hourly averaged surface fluxes (sensible heat, latent heat, and ground heat) and the standard hourly meteorological parameters during radiosondings. More definitive results will require more detailed and frequent radiosondings, combined with turbulence measurements at the ground.

8.2 RECOMMENDATIONS AND FURTHER RESEARCH

- The boundary layer parameterisations and meteorological pre-processors for applied dispersion modelling should be modified to correctly estimate the surface fluxes of heat, moisture, and momentum in the tropics.
• Generally, there is a need for better representation of the tropical atmospheric boundary layer in all the models and applications used in predicting the atmospheric boundary layer structure.

• When applying the dispersion models in the tropics, the following points should be noted:

  1. Convective turbulence from the heated surface in the tropics contributes more to entrainment compared to the mid-latitude situation.

  2. Moisture processes do contribute to the growth of the tropical atmospheric boundary layer, and the influence of moisture should be included in the simulation and explanation of ABL dynamics in the tropics.

  3. The entrainment zone must be considered in any slab model. The assumed idealised ABL structure used in the models is inappropriate to simulate the vertical profiles of the tropical mixing layer. The vertical profiles in the mixing layer deviate from this schematic picture in the tropics.

• It is recommended that the constants and parameters specific to particular climatic regions should be clearly documented in any meteorological pre-processors and users should have the possibility to change them. These include, for example, entertainment constants, absolute maxima or minima of the mixing height, or criteria to find convective lids.
• The tropical nocturnal boundary layer (TNBL) is still an open challenge for researchers. Besides the TNBL structure, other areas of investigation could be explored with the available data set. One could be an attempt to model the TNBL in order to obtain better understanding of the processes that contribute to the growth of the TNBL. Wind speed is higher in the mid-latitudes, this brings about a higher contribution of mechanical turbulence to the growth of the ABL. Therefore, an interesting comparison could be done with the growth of the NBL under calm conditions as in the tropics.

• The dynamics of the tropical boundary layer should be further analysed. As sea breeze circulation is also responsible for the transfer of heat energy from the earth’s surface to the free atmosphere, its role in the region should further investigated. This would require the use of a two-dimensional or three-dimensional mesoscale models for better enhance the understanding of the circulation and its influence to the evolution.