Vertical Structure and the Convective Characteristics of the Tropical Atmosphere

by

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(1982)

Submitted to the Department of Earth, Atmospheric, and Planetary Science in Partial Fulfillment of the Requirements for the Degree of Master of Science at the Massachusetts Institute of Technology

May 1987

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Abstract

This paper examines the vertical structure and the variability of thermodynamic parameters such as the (saturated) equivalent potential temperature $(\theta^*_e)$, the buoyancy and the "dilution ratio" using the summer soundings of Truk, Koror, and Majuro stations from 1965 to 1980. By postulating that clouds are nearly in buoyant equilibrium with their environment, dilution ratios are defined to measure the degree of mixing necessary to make the clouds neutrally buoyant. One of the dilution ratios is defined as a weighting function so that $\theta^*_e$ of the ambient environment is the weighted average of the ambient $\theta_e$ and the cloud $\theta^*_c$ calculated from undiluted parcel ascent from the boundary layer. The other is defined as a weighting function so that the virtual temperature of the ambient environment is the weighted average of the cloud virtual temperature with condensate loading and the minimum virtual temperature due to mixing between the ambient and cloudy air. The difference between the two definitions is whether to ignore or include water loading effects. The minimum temperature is obtained after three processes, (1) moist adiabatic ascent, (2) mixing with that ambient air which produces the smallest minimum temperature, and (3) dry-adiabatic descent to the level considered. This mixing process differs from the cloud-top mixing or lateral mixing of previous studies in the original level of the entrained parcel and the mixing procedure.

Suppose that cloud parcels are lifted adiabatically from the $\theta_{c_{max}}$ level in the planetary boundary layer (PBL). The mean structures of dilution ratio from the first definition are very distinctive for different subsets categorized according to the location of the level of free convection (LFC). This is shown to be a good way of classifying the thermodynamic soundings in the tropics. Subsets with lower LFC's usually have a small dilution ratio, large buoyancy and high moisture content at any level, compared with those with higher LFC's and lower levels of neutral buoyancy (LNB). If cloud parcels are assumed to be lifted from the top of the PBL whose thickness is determined by the absolute gradient of the virtual potential temperature, significantly smaller buoyancy at high levels, a larger dilution ratio at any level, a secondary maximum of buoyancy and a maximum amount of mixing at 850 mb are shown for convective atmospheres with lower LFC's, compared with those using the $\theta_{c_{max}}$ level in the PBL as the origin of cloud parcels.
When water loading effects are included to define the dilution ratio, the vertical profile of amount of mixing differs from that ignoring water loading effects in the following aspects. The amount of mixing does not vary much with height above the LFC. There is a region of maximum mixing in the lower troposphere around 850 mb for almost all types of convective atmospheres, which is especially obviously shown for those with the same LCL’s. Another maximum mixing region always appears around 600 mb for all types of convective atmospheres with different LFC’s. This is associated with the relative large buoyant acceleration of the updraft in that region. It is also shown that including water loading effects result in a small difference of the dilution ratio between soundings with low LFC’s and high LFC’s, compared with that neglecting water loading effects.

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Acknowledgment

I am grateful to Professor Kerry A. Emanuel who gave me an opportunity to study at M.I.T. Also, I would appreciate Professor Emanuel for suggesting the topics and giving numerous conversations which make this work to be completed. I also want to express my gratitude to my friends and classmates at M.I.T. for their help and friendship during my stay at M.I.T., especially to my officemate, Mark Handel, and to Y.Y. Lu of Math Department at M.I.T.

Finally, I want to thank my girlfriend, Yongping, for her love, encourage, and patience. And I also want to thank Jane McNabb for numerous help during my years at M.I.T.
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Chapter 1

Introduction

The purpose of this study is to investigate the vertical structure and the variability of the tropical atmosphere associated with various types of cumulus convection. In the tropics, the moisture content at the surface is as high as 20 g/kg and the ocean is a water vapor source for the atmosphere. For these reasons cumulus convection occurs frequently there, while the middle-latitude atmosphere typically has a much lower moisture content and most clouds are associated with synoptic systems. In contrast, cumulus towers in the tropics occur, develop, and dissipate in most regions, even when not associated with synoptic systems. Although the importance of cumulus clouds for the weather in the tropics has been recognized for decades, properties of convective atmospheres associated with various cumulus clouds at an individual station are rarely studied from observational data. These properties are our major concern in this paper.

It is well-known that a cloud is formed because water vapor is condensed as a moist air parcel is lifted. The amount of buoyancy energy, not including condensate loading, can be easily seen from a tephigram, which shows the amount of buoyancy energy by the area between the environmental sounding and the temperature of a surface air parcel lifted adiabatically. As shown in Section 2.2, the more accurate estimation of buoyancy should include the effects of condensate loading. The mean
buoyancy from this estimation is very close to zero. This is due probably to the fact that a cloud is not an isolated element which does not mix with the surrounding air. The mixing between clouds and surrounding air is known as an entrainment or detrainment process. Entrainment means that environmental air mixes with and becomes part of the cloud, while detrainment causes cloud air parcels to mix with and become part of the surroundings. Calculation from Stommel's (1947, 1951) results suggests that cumulus clouds have a maximum entrainment near the cloud base and a maximum detrainment at the cloud top, respectively. Several studies (e.g., Paluch, 1979) have quantified the degree of mixing in clouds. What we want to do is to deduce the amount of mixing from environmental soundings by postulating that clouds are nearly in buoyant equilibrium with their environment and calculating what degree of mixing is necessary to make the clouds neutrally buoyant. It is the premise of this paper that the "dilution ratio" (to be defined in Chapter 2) is the best parameter to describe the degree of mixing between the environment and cloud air parcels.

Another major concern is the variability in the thermodynamic parameters of the tropical atmosphere for a single station. It is well recognized that the thermal variability of the tropical atmosphere is very small, compared with that of the middle-latitude atmosphere. But the variability of water vapor is not always small and such variability may vary with height. For instance, the standard deviation of the temperature from the mean at Truk (7.3 °N, 152 °E) from 1965 to 1980 for the period July 1-September 30 is less than 1 °C for most levels except 1000 mb where the standard deviation is 1.2 °C (Fig. 1a). The smallest standard deviation of the relative humidity for the same station is 7.7% which appears at 1000 mb, but the largest standard deviation of the relative humidity (RH) is 25% at 500 mb although the mean RH at the same level is only about 55% (Fig. 1b). These clearly indicate that the variability of moisture content in the tropical atmosphere is not small at all. Related thermodynamic parameters such as the buoyancy and the equivalent
Figure 1.1: The mean (solid line) and the standard deviation (dashed line) of temperature (a) and relative humidity (b) for Truk station from 1965 to 1980 for period from July 1-September 30. The scale for the standard deviation of temperature is from $-3$ to $+3^\circ C$ which is labeled at the bottom of (a).
potential temperature may also have large variability. Furthermore, the magnitude of variability might be used as an indication of the uniformity of subsets which may correspond to different types of convective atmospheres.

Specifically, this paper studies the mean structures and standard deviations of equivalent potential temperature, saturated equivalent potential temperature, buoyancy and dilution ratios, as well as temperature and mixing ratio differences from the whole dataset for convective atmospheres associated with different types of cumulus convection, using the radiosonde soundings of Truk (7.3°N, 152°E), Majuro (7.3°N, 172°E), and Koror (7.5°N, 135°E) stations from 1965 to 1980 for the period July 1-September 30. Since temperature and mixing ratio are widely used, temperature and mixing ratio differences from the whole data may give a better picture of differences between convective atmospheres associated with various types of cumulus convection.

Two kinds of undiluted cloud parcels will be treated in this study, one neglecting water loading effects, the other including water loading effects. But, both types of cloud parcels conserve their equivalent potential temperature as they are lifted adiabatically. In this study, it is assumed that the cloud parcel is lifted from the level of the maximum equivalent potential temperature (1000 mb or 950 mb) in the planetary boundary layer (PBL), which makes it possible to study dilution characteristics of convective atmospheres not including (Chapter 3) and including (Chapter 5) water loading effects. The origin of such cloud parcels is referred to as an idealized level, for convenience. The origin of these cloud parcels is difficult to determine due to coarse resolution of the data. Even if high resolution data is available, the originating level of cloud parcels can only be approximately estimated because some physical processes in the PBL are not well understood (Sarachik, 1974).

Although it is difficult to know the originating level of a cloud parcel, it is still possible to approximately estimate the level, based on our current understanding of
the PBL. A previous study shows that the PBL is well mixed in the virtual potential temperature (Betts, 1976). The difference of the virtual potential temperature between 1000 mb and 950 mb ($\Delta\theta_v$) may reflect whether or not the PBL extends upward to or above 950 mb, and, in consequence, could be used to estimate the originating level of a cloud parcel more realistically if a cloud parcel is assumed to be lifted from the top of the PBL. However, a fixed originating level of a cloud parcel (e.g., 980 mb) was frequently used in some studies where higher-resolution datasets were available (Albrecht, 1987; Kloesol, 1987). In this study, the originating level, which is estimated based on the magnitude of $\Delta\theta_v$, will be referred to as a realistic one, compared with the idealized one at the $\theta_e$ maximum discussed above.

With all the above in mind, the approach taken here will be as follows.

1. Categorize the dataset into subsets which may represent different types of convective atmospheres.

2. Compute the means and standard deviations of thermodynamic parameters associated with lifting undiluted cloud parcels from an idealized level and compare various types of convective atmospheres without including water loading effects.

3. Take the undiluted cloud parcel from a realistic level to see what additional characteristics are obtained and consider what other unrealistic features may be due to using an undiluted cloud parcel neglecting water loading effects.

4. Use undiluted cloud parcels but including water loading effects to repeat step 2 to find the additional characteristics associated with such types of convective atmospheres.

Following the guidelines above, Chapter 2 provides a brief background about the structure of the tropical atmosphere and the maintenance of this structure with various types of cumulus clouds, and presents the methodology adopted in this
study. Specifically, dilution ratios are defined both including and ignoring water loading effects. Categorization using the level of free convection (LFC) and the dataset are described in detail. In addition, analysis procedures using mixing ratio coordinates are provided in Section 2.5.

Chapter 3 investigates the characteristics of convective atmospheres, ignoring water loading effects in mixing process. The cloud parcel is assumed to be lifted from an idealized level. These characteristics are studied in pressure coordinates and in mixing ratio coordinates. Classifying convective atmospheres are examined. In addition, the necessity for studying more realistic cloud parcels is pointed out.

Chapter 4 addresses the problem of choosing a level for the origin of the cloud parcel. The study for an undiluted cloud parcel lifted from a more realistic origin shows more clearly that maximum mixing exists at 850 mb where the mean buoyancy has a secondary maximum. Furthermore, the magnitude of convective instability between 1000 mb and 950 mb is shown to have a very large effect upon the characteristics of various types of convective atmosphere.

It is also necessary to consider water loading effects in mixing processes. Chapter 5 is devoted to examining some aspects of convective atmospheres including water loading effects during mixing with an undiluted cloud parcel lifted from an idealized level, using three measures for dividing the dataset. There are two extraordinary features noted in this chapter, one being that the large vertical variations of the dilution ratio are much smaller when including virtual effects, the other being that large mixing is found around 600 mb where the buoyant acceleration of the updraft is the strongest.

Though it is necessary to study the convective atmosphere by including water loading effects in mixing process for parcels lifted from a realistic originating level, the indications shown in Chapters 4 and 5 may be enough to characterize the convective atmospheres associated with the most realistic clouds. Chapter 6 summarizes the results of the previous three chapters.
Chapter 2

Background and Methods of Analysis

From knowledge of the structure of the tropical atmosphere, it is generally recognized that the equivalent potential temperature and the mixing ratio do not change much with height within the PBL (Arakawa and Schubert, 1974). An undiluted air parcel lifted adiabatically from the PBL will conserve its equivalent potential temperature until reaching the level of neutral buoyancy (LNB). However, due to entrainment and/or detrainment, the equivalent potential temperature is not conserved so that the LNB of actual clouds is lower than that of the undiluted clouds (Fig. 2.1). The dilution of clouds will be the major concern in this chapter.

The schematic diagram of Fig. 2.1 gives a detailed description of the structure of the tropical atmosphere. The cloud base is usually coincident with the lifting condensation level (LCL), which is near the top of the PBL for an air parcel lifted within the PBL (Sarachik, 1974), while the level of free convection (LFC) is further above the LCL. Above the LFC, the buoyancy of clouds is positive until the parcel reaches the LNB. In the present study, one of the fundamental assumptions is that the cloud parcel is lifted adiabatically from the PBL, not from other higher levels. Dilution ratios are calculated with respect to clouds so formed.
Figure 2.1: Schematic diagram of the structure of the tropical atmosphere. The relative location of the lifting condensation level (LCL), the level of free convection (LFC), the level of neutral buoyancy for an undiluted cloud parcel (LNB) and for a diluted cloud parcel (LNBDC) is illustrated. The curves intercepting A, B, C, and D are $\theta_e$, $\theta^*_e$, $\theta_{eb}$ of diluted cloud parcels and $\theta_{eb}$ of undiluted cloud parcels, respectively.
Due to the coarse resolution of the data used here, the treatment of the PBL must be crude. Since only data at the standard pressure levels (every 50 mb) are available, the actual thickness of the PBL is largely unknown. Therefore, we study in Chapters 3 and 5 the characteristics of convective atmospheres with a cloud parcel lifted from an idealized level. These clouds have the maximum possible buoyancy available. But, in Chapter 4, the cloud air parcel does not originate at an idealized level, but at a more realistic level. The virtual potential temperature difference between 950 mb and 1000 mb is used to determine the originating level of cloud parcels using the fact that the virtual potential temperature is well-mixed within the PBL (Betts, 1976).

The importance of cumulus convection in the tropics has been recognized for a long time (Riehl and Malkus, 1958; Sarachik, 1974, 1985). And the physical processes operating in the tropical atmosphere have been discussed by many investigators. Riehl and Malkus (1958) showed the importance of cumulus convection in the heat balance of the tropical atmosphere. Sarachik (1974, 1985) discussed the maintenance of the vertical structure of the tropical atmosphere in the presence of various types of cumulus convection.

According to the theory of Sarachik (1974, 1985), the role of cumulus convection may be described as follows. The surface sensible and latent heat fluxes are the main source for cumulus convection and maintain the PBL about 600 m in thickness through penetrative convection from the PBL inversion. Condensation due to the surface latent heat flux creates the trade cumulus clouds between the PBL inversion and the trade inversion. Breaking of the trade inversion allows deep convection to occur in the whole troposphere. Meanwhile, subsidence due to the deep clouds maintains the trade inversion and the PBL inversion (Sarachik, 1985).

On the other hand, the structure of the tropical atmosphere at any given time is quite different from the mean structure as described, for example, by Jordan (1958). For instance, the level of the minimum equivalent potential temperature
may be at any level between 300 mb and 900 mb, but the mean level of it is around 650 mb. Moreover, the thickness of the PBL varies from several meters to a thousand meters. These temporal variations are associated with the complexity of the tropical motion which, in consequence, changes the vertical structure of thermodynamic variables. Any attempt to model the tropical atmosphere would fail without considering the causes of these temporal variations. In the present study, the complicated structures are treated differently according to some measures which may describe the properties of different types of convective atmospheres, especially, the PBL structure and the LFC. Therefore, we introduce some new thermodynamic parameters in this chapter in order to study the structure of the tropical atmosphere associated with various types of cumulus convection.

2.1 The Dilution Ratio Ignoring Water Loading Effects

A quantity (σ) measures the degree of mixing between the ambient environment and clouds without reference to water loading effects by postulating that clouds are nearly in buoyant equilibrium with their environment. This is defined such that

\[ \ln \theta_e^* = \sigma \ln \theta_{eb} + (1 - \sigma) \ln \theta_e \]

(2.1)

where \( \theta_{eb} \) is the equivalent potential temperature in the PBL. Under the assumption that cloud air parcels originate within the PBL, \( \theta_{eb} \) is taken as the saturated equivalent potential temperature of undiluted cloud parcels.

The physical interpretation is that \( \sigma \) is treated as a weighting function of the two equivalent potential temperatures mentioned above. If the buoyancy in the cloud is very small, the equivalent potential temperature of cloudy air may be taken approximately as the saturated potential temperature of the ambient air in which case \( \sigma = 1 \). Then we may define a weighting function so that the saturated potential
temperature is the weighted average of the equivalent potential temperature of the
ambient air and that of undiluted cloudy air. The weighting is such that the mixture
of cloud and environment produces a neutral mixture, neglecting water loading
effects.

The formula for computing the equivalent potential temperature given by Bolton
(1980) for pseudo-adiabatic processes is employed in the calculations. This formula
is largely empirical and is easily evaluated. The accuracy of Bolton's formula, better
than 0.02 °C, is impressive. The expression for \( \theta_e \) is as follows:

\[
\theta_e = \theta_{DL} \exp \left[ \left( \frac{3.036}{T_L} - 0.00178 \right) q \right]
\]

(2.2)

where \( \theta_{DL} \) is the potential temperature at the LCL. This can be defined as \( \theta_{DL} =
T \left( \frac{1000}{p_{-e}} \right)^{0.2854} \left( \frac{T}{T_L} \right)^{0.00028q} \), where \( T_L \) is the temperature which the air would obtain if
lifted adiabatically to its condensation level (formula (21) or (22) in Bolton), \( q \) the
mixing ratio in g/kg, and \( e \) the vapor pressure in millibars.

Since the definition of dilution ratio including water loading effects is associated
with the virtual temperature of clouds with condensate loading, we must discuss
the definition of virtual temperature of cloudy air first.

### 2.2 The Buoyancy

The buoyancy defined in this study is the difference between the virtual temperature
of cloudy air with condensate loading and the virtual temperature of the ambient
air. The motivation for this definition is to see the difference between the convective
energy associated with a pseudo-adiabatic process and a reversible moist adiabatic
process which includes condensate loading. The buoyancy obtained for the pseudo-
adiabatic process is very large, especially, in the middle and upper troposphere, but
the result from the present definition is much smaller (Fig. 2.2).

The buoyancy without condensate loading is larger than that with condensate
loading by 4.3 °C at 300 mb and by 2.2 °C at 600 mb where the buoyancy has
Figure 2.2: The mean buoyancy with condensate loading (a) and without condensate loading (b) at Truk station for the period from July 1-September 30, 1979. The buoyancy is plotted in log $p$ coordinates. The curve with D is the standard deviation from the mean buoyancy (curve with +).
its maximum for clouds with condensate loading (Fig. 2.2). Observations may not support that clouds are warmer than the ambient air, on average, by almost 5 °C above 600 mb. The implication is that most buoyant parcels within clouds have approximately their adiabatic liquid water content (Betts, 1982) or have mixed extensively with their environment.

For a given \( \theta_s \) of the parcel lifted adiabatically from the PBL, the temperature of the cloud parcel \( T_\text{p} \) may be estimated from the conservation of the saturated equivalent potential temperature, which requires about 3 iterations. Then, the virtual temperature of cloudy air is defined by

\[
T_v \equiv T_\text{p} \frac{1 + q_s(T_\text{p})/622}{1 + Q_T/1000}
\]  

(2.3)

where \( Q_T \) is the total water content of clouds, which is taken to be the same as the mixing ratio within the PBL, and \( q_s \) the saturation mixing ratio. Since the liquid water content is kept in clouds, the density of cloudy air is expected to be larger than the density of cloudy air without liquid water content, especially at high levels, and consequently, the virtual temperature of clouds is lower.

In contrast, the virtual temperature of the ambient air is defined by

\[
T_v \equiv T_a \frac{1 + q/622}{1 + q/1000}
\]  

(2.4)

where \( T_a \) and \( q \) are the temperature and the mixing ratio of the ambient air, respectively.

### 2.3 The Dilution Ratio Including Water Loading Effects

The mixing of cloudy and ambient air is the main process which reduces the density difference between the cloudy air and the ambient air. During a mixing process lower temperatures can be reached due to evaporation of cloud water into unsaturated
environmental air. The minimum temperature usually corresponds to the saturation state of the mixture at constant pressure. In this study, a minimum temperature is obtained in three steps: 1) moist adiabatically lifting of PBL air, 2) mixing with all possible ambient parcels, and 3) dry-adiabatic descent to the level in question to get the minimum temperature. The details of the mixing process will be discussed in Chapter 5.

It might be expected that the minimum temperature will be achieved by mixing the cloud parcel with ambient air at the level of the minimum $\theta_e$. But this is not the case since the dry adiabatic process may warm the mixture dramatically when it falls to the level considered. Computations show that the minimum temperature is achieved by mixing air 50 mb or 100 mb above the level considered provided this is below the level of the minimum $\theta_e$, and at the same level as considered if this is above the level of the minimum $\theta_e$.

The definition of the dilution ratio including water loading effects is straightforward. We define the dilution ratio such that the ambient virtual temperature is a weighting average of the virtual temperature of undiluted cloud air and the minimum virtual temperature that can be achieved by mixing, i.e., $T_{va} = \sigma T_{vc} + (1 - \sigma) T_{v\min}$, from which it follows that

$$\sigma \equiv \frac{T_{va} - T_{v\min}}{T_{vc} - T_{v\min}}$$

(2.5)

So the smaller the dilution ratio is, the larger the mixing in the clouds. If the dilution ratio is zero, the ambient virtual temperature is totally determined by the mixing processes. The difference from the first definition is that water loading effects and evaporational cooling are included during mixing between the ambient and cloudy air.
2.4 Data and Subsets

Before proceeding further, we delete those soundings with any missing thermodynamic data at the standard pressure levels. The data set for this study includes three stations from 1965 to 1980 for the period July 1-September 30. The three stations are Truk, Koror, and Majuro which are located in the central and western equatorial Pacific. About 3% of the data is deleted, including all soundings without observations at all standard pressure levels.

Since we are interested in the convective characteristics of troposphere, the data set only includes 15 pressure levels at 50 mb increments, from 1000 mb to 300 mb. Because the tropopause is far above 300 mb (≈ 150 mb), the present study does not cover the troposphere. Data above 300 mb was not available to us.

In order to deal with different types of convective atmospheres, it is convenient to divide the whole data set into several subsets according to the level of free convection (LFC), as described in Section 3.3. The LFC can roughly be estimated as the level where the saturated equivalent potential temperature of the ambient atmosphere is the same as the equivalent potential temperature of cloudy air from the PBL. However, due to the coarse resolution of the data, we divide the data set into subsets according to 50 mb intervals.

There are six subsets in this study. Subset F has the LFC within the PBL. Subset F2 is chosen by the criterion that $\theta_e$ within the PBL is smaller than $\theta_e^*$ at 950 mb, but larger than $\theta_e^*$ at 900 mb. Subset F3 is determined by the same criterion as that of Subset F2 except that the interval where the LFC is located is raised by 50 mb. The remaining subsets, F4, F5, and F6 are chosen according to similar criteria.

In Chapter 4, we divide the dataset according to a different criterion which considers cloud parcels lifted adiabatically from the top of the PBL. The absolute difference of the virtual potential temperature between 1000 mb and 950 mb ($|\Delta \theta_v|$) is used as a criterion, based on the fact that $\theta_v$ is well-mixed within the PBL. When
the mixed layer (PBL) extends upward to or above 950 mb, $|\Delta \theta_e|$ should be small. Otherwise, the top of the PBL must be lower than 950 mb since $\theta_e$ increases rapidly with height above the PBL. In the first case, the cloud parcel is assumed to originate at 950 mb. Otherwise, the cloud parcel is assumed to originate from a lower level, e.g., 975 mb or 1000 mb (see Chapter 4). The data at 975 mb are obtained from the average of those at 950 mb and 1000 mb.

In practice, when $|\Delta \theta_e| < 0.5^\circ C$, the cloud parcel is assumed to be lifted from 950 mb. If $0.5^\circ C < |\Delta \theta_e| < 1.0^\circ C$, 975 mb is taken to be the top of the PBL, and the cloud parcel is lifted from 1000 mb when $|\Delta \theta_e| > 1.0^\circ C$. The subsets so divided have an almost equal percentage of data and the mean buoyancy for these three subsets have nearly equal magnitude and similar vertical distributions (see Section 4.2). We think that these results are not accidental. These results may imply that cumulus clouds are sensitive to the characteristics of air at the top of the PBL. On the other hand, they indirectly prove the suitability of dividing the data by these criteria. Finally, the datasets with various types of more realistic PBL characteristics are divided into subsets according to the location of the LFC to compare with results in Chapter 3.

2.5 Analyses in Mixing Ratio Coordinates

There are a variety of analyses on conserved variable diagrams from high resolution data (e.g., Betts and Albrecht, 1986). Mixing does not result in change in mixing ratio and equivalent potential temperature. The analyses in mixing ratio coordinates in this study is to detect the structures due to vigorous mixing between various levels associated with various types of convection, using coarse resolution data and a different averaging method.

When computing the mean, standard deviation and correlation coefficients at constant mixing ratio ($q$), we must interpolate data on constant pressure surface to some specified standard mixing ratio levels. But this method suffers from the multi-
valued nature of the equivalent potential temperature and the saturated equivalent potential temperature with respect to the mixing ratio. That is to say, the mixing ratio at 300 mb may be the same as that at 500 mb, but their respective \( \theta_e \) and \( \theta^*_e \) may be not the same. The interpolation may not produce unique results.

Therefore, we try an alternative to cope with the multivalued nature of the equivalent potential temperatures. For small intervals of the now independent variable \( q \), averages of the dependent variables \( \theta_e \), \( \theta^*_e \), and \( \sigma \) are calculated providing a set of single valued functions, \( \bar{\theta}_e(q) \), \( \bar{\theta}^*_e(q) \), and \( \bar{\sigma}(q) \). Standard deviations and correlation coefficients between the independent variables are calculated within the same intervals of \( q \). Because the equivalent potential temperature and the saturated equivalent potential temperature are single valued functions of the mixing ratio at relatively large mixing ratio, the intervals chosen may be larger than the intervals chosen at smaller mixing ratio. We, therefore, choose intervals of 1 g/kg for the mixing ratios larger than 10 g/kg and 0.5 g/kg for the rest of the range. The small standard deviation of the equivalent potential temperature for \( q \) larger than 10 g/kg affirms that the intervals so divided are not unreasonable since the mixing ratio has a larger correlation with the equivalent potential temperature, compared with the correlation with the saturated equivalent potential temperature.

2.6 Summary

In this chapter, some new thermodynamic parameters and methods dividing dataset are discussed. Dilution ratios are defined both including and ignoring water loading effects. The virtual temperature of clouds is defined to include the effects of condensate loading. This is shown to produce more systematic results than those obtained without considering condensate loading.
Chapter 3

Convective Atmospheres Ignoring Water Loading Effects (A)

In this chapter, we try to answer the question of whether or not convective characteristics can be sensibly classified according to the location of the LFC defined from the maximum $\theta_e$ in the PBL. If the answer is yes, what controls the characteristics of various convective atmospheres? More specifically, we deal with environmental characteristics with a view toward providing a basis for cumulus parameterization, such as the scheme developed by Betts (1986).

Dividing the data into subsets according to the location of the LFC has been discussed in Section 2.4. In this chapter, the subsets are divided according to different structures of the dilution ratio ignoring water loading effects. If the dilution ratio is greater than unity, the cloud parcel may be either located below the LFC or above the LNB. That is to say, the air parcel is not buoyant in either location. If the dilution ratio is negative, the parcel is far above the LNB. Therefore, we should ignore the data at this level and levels above it. The mean structure is obtained as the average of the soundings with dilution ratios less than unity, except for levels just below the LFC for Subsets F2, F3, F4, F5, and F6. Details concerning the criteria for choosing subsets and percentage of data of subsets from the whole
dataset are summarized in Table 3.1.

In this chapter, various results are presented in the following order. Section 3.1 shows the mean, the standard deviation, and the correlation coefficients of dilution ratio, equivalent potential temperature, saturated equivalent potential temperature, and buoyancy all in constant pressure coordinates. The buoyancy presented in this chapter represents the maximum possible value available for various types of undiluted clouds since the parcel lifted from 1000 mb is invariably the warmest one. More realistic buoyancy profiles will be presented in Chapter 4. Although the different vertical structures of various types of convective atmospheres can be seen from the mean structure of $\theta_e$ and $\theta_e^*$, we obtain a clearer picture if the temperature and the mixing ratio differences of the subsets from the whole data set are given, which will be discussed in Section 3.1.4 for various types of convective atmospheres.

Section 3.2, on the other hand, uses the mixing ratio and $\theta_e$ as coordinates to present the mean, the standard deviation and the correlation coefficients of the dilution ratio, $\theta_e$, and $\theta_e^*$. The goal is to detect structures that might result from vigorous mixing between various levels in the convective layer.

In Section 3.3 we discuss the classification of the dataset. The requirement for the suitability of dividing data is whether the subset represents a uniform type of convective atmosphere or not. We define a potential thickness from 1000 mb to 300 mb which is the thickness that would result if the ambient atmosphere has the same virtual temperature as that of a reversibly produced cloud. The correlation coefficients between the actual thickness and the potential thickness are computed for various classifications as a means of assessing their validity.

Lastly, Section 3.4 will summarize the results of this chapter.
Table 3.1: The criteria for choosing subsets and percentages of data in each subset for Truk, Majuro, and Koror. Cloud parcels are lifted from an idealized level in the PBL. In the table, $\sigma$ represents the dilution ratio ignoring water loading effects.
3.1 Vertical Structure in Pressure Coordinates

3.1.1 Equivalent Potential Temperatures

Figure 3.1 shows the means and the standard deviations of $\theta_e$ and $\theta_e^*$ at Truk for the whole data set (Set T) and the subsets (Subsets F, F2, F3, F4, F5, and F6) from 1965 to 1980. The structures at Majuro and Koror are similar to that of Truk although the specific values may differ from each other. The first obvious feature is that the standard deviations of $\theta_e$ and $\theta_e^*$ do not show obvious differences from subset to subset. Overall, the standard deviation of $\theta_e$ is larger than that of $\theta_e^*$ by 1-3 °C except at 1000 mb. Its magnitude is around 4.5 °C below 600 mb and decreases with height above 600 mb. The standard deviations of $\theta_e$ and $\theta_e^*$ coincide in the upper troposphere due to the small moisture content. The standard deviation of $\theta_e^*$ at 1000 mb is about 7 °C, which is associated with large deviations of temperature (Fig. 1.1a).

The means of $\theta_e$ and $\theta_e^*$ in the subsets are different from Set T below the level of the minimum $\theta_e$ which is located between 750 mb and 550 mb (Fig. 3.1). The conditional instability exists only if $\frac{\partial^2 z}{\partial z^2} < 0$, i.e., the region below the level of the minimum $\theta_e^*$ for most of the cases, which indicates a possibility for convection to occur. On the other hand, the convective instability can happen in the region where $\frac{\partial^2 z}{\partial z^2}$ is negative. Some of obvious features in the whole data set (Set T) are as follows:

1. The value of $\theta_e$ decreases with increase of height, reaching a minimum at 600 mb. From 600 mb to 300 mb the gradient of $\theta_e$ is very weak.

2. The difference of $\theta_e$ between 1000 mb and 950 mb is 3.3 °C for Koror, 1.9 °C for Truk, and 1.4 °C for Majuro. However, due to restrictions on $\sigma$ in calculating the means of $\theta_e$, the numbers of soundings at 950 mb are relatively few. These are largely soundings with $\theta_e$ at 950 mb being larger than that at 1000 mb, or few soundings with $\sigma$ being less than unity. If all soundings are included to
Figure 3.1: The mean and the standard deviation of $\theta_e$ and $\theta_e^*$ for the whole data set (Set T) and all the subsets of Truk station. The right two curves in each plot are for the means of $\theta_e$ (solid) and of $\theta_e^*$ (longest dashed) which have the scale on the top of a plot, while the standard deviations of $\theta_e$ (short dashed) and $\theta_e^*$ (long dashed) are shown on the left in each plot.
calculate $\theta_e$ without restricting $\sigma$, the difference of $\theta_e$ between 1000 mb and 950 mb is about 5 °C (see Section 4.1).

The subsets differ from Set T in three aspects: the PBL structure, the moisture content, and the height of inversion layer. The surface $\theta_e$ varies from 358 °K to 349°K as the LFC varies from 1000 mb to 700 mb. Subsets F and F2 do not have a well-mixed layer between 1000 mb and 950 mb. However, the rest of subsets have a relatively well-mixed layer, as does Set T.

The mean relative humidity (RH) in various subsets may be seen from the difference between $\theta_e^*$ and $\theta_e$. The reasons are that temperature in the tropical atmosphere rarely changes and that $\theta_e$ is very sensitive to the change of the moisture content. The mean RH, in general, decreases as the LFC increases. Subset F is characterized by the highest RH. It also shows the smallest difference between $\theta_e$ and $\theta_e^*$ near the surface levels. Subset F2 does not have many differences from those of Set T, but the rest of the subsets are drier than Set T. The higher the LFC is, the higher the low RH layer extends.

There is a conditionally stable layer in Subsets F4, F5, and F6. The base of this layer is always located at 900 mb, but the top of it reaches a higher level as the LFC is lifted. This stable layer looks like the trade cumulus layer as seen later in the analysis of mean buoyancy. However, the amount of data in Subsets F4, F5, and F6 is very small, around or less than 10 % (Table 3.1).

### 3.1.2 Dilution Ratio Ignoring Water Loading Effects

Although the calculation of the dilution ratio ($\sigma$) is restricted to levels where it is between 0 and 1, results with $\sigma$ over unity are kept at the level just below the LFC's for Subsets F2, F3, F4, F5, and F6 because no data remains just below the LFC (Table 3.1).

The mean $\sigma$ for Set T decreases slowly with height except in three regions, i.e., 1000-900 mb, 750-600 mb, and above 400 mb. The standard deviation of it decreases
Figure 3.2: The mean (solid) and the standard deviation (dashed) of dilution ratio ignoring water loading effects for the whole data set (Set T) and all the subsets at Truk, Koror, and Majuro. The cloud parcel is assumed to be lifted adiabatically from an idealized level.
Fig. 3.2 (continued)
Fig. 3. (continued)
with height much more slowly and its maximum appears at 950 mb (Fig. 3.2). The value of $\sigma$ at each level in Subset F is smaller than all other subsets and Set T as it has the highest $\theta_e$ at 1000 mb among the subsets, and $\sigma$ decreases with height from the surface to 900 mb by a factor of 2 (Fig. 3.2).

Subset F2 is almost the same as that of Set T except at 950 mb where the mean and the standard deviation of $\sigma$ exceeds unity, because Set T is mainly contributed to by Subset F2. Subset F3 has a region of linear variation of $\sigma$ in the lower troposphere, compared with Subset F2. The remaining subsets have the similar profiles to Subset F3 except larger $\sigma$ in the middle and upper troposphere as the LFC gets higher.

Another feature is that $\sigma$ in the upper troposphere in Subsets F5 and F6 is almost twice that of Subset F, which indicates that the deep clouds with a lower LFC are much more diluted than clouds with a higher LFC for mixing process ignoring water loading effects. Notes that the amount of mixing necessary to make clouds neutrally buoyant is very large above 600 mb, when ignoring water loading effects.

One more feature about $\sigma$ is that the surface properties may change the magnitude of $\sigma$, but not its vertical distribution. The sea surface temperature decreases eastward (i.e., from Koror, Truk, to Majuro) and hence the air parcel from the surface is warmer in Koror than the other two stations. Therefore, the value of $\sigma$ increases eastward (Fig. 3.2).

3.1.3 Buoyancy

As defined in Section 2.2, the buoyancy is the difference between the virtual temperature of clouds with condensate loading and the virtual temperature of the ambient air. In this chapter and Chapter 4, water loading effects are ignored when defining the dilution ratio, but condensate loading is included in buoyancy since the buoyancy from this definition is more realistic. The uniform distribution of the
Figure 3.3: The mean (solid curve) and the standard deviation (dashed curve) of the buoyancy for the whole data set (Set T) and all the subsets at Truk, Koror, and Majuro.
Fig. (continued)
fig. 3 (continued)

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standard deviation of the buoyancy among the subsets (Fig. 3.3) may affirm the reasonability of dividing data according to locations of the LFC, and may further be affirmed by the correlation analysis between the 1000-300 mb potential thickness and the ambient thickness in Section 3.3.

The vertical profile of the standard deviation of buoyancy is very similar to that of the maximum instrumental errors of radiosonde observations. Suppose that the temperature error is increased linearly from 0.2 °C at 1000 mb to 0.6 °C at 300 mb and that the relative humidity error is increased linearly from 1 % to 5% in the same region (WMO, 1971), the maximum error for the buoyancy would be increased from 0.6 °C at 1000 mb to 1.4 °C at 300 mb (not shown). So the clouds with mean buoyancy of less than 1.0 °C are observationally indistinguishable from neutral ones.

As discussed in Section 3.1.2, the calculation of dilution ratio is restricted to levels where \( \sigma \) is between 0 and 1. That is, \( \theta^* \) of cloud parcels must be greater than that of the ambient air at each level. From this, we know that the temperature of cloud parcels is higher than that of the ambient air, but the buoyancy including condensate loading may be negative, especially in the upper troposphere. Therefore, the mean buoyancy is negative at higher levels in some subsets.

It is not surprising that the subset with the largest buoyancy is Subset F which has buoyancy over 2 °C above 875 mb for Koror where the surface parcel is the warmest among the three stations, above 750 mb for Truk, and just around 550 mb for Majuro due to the low \( \theta^* \) at 1000 mb. The mean buoyancy for Set T is much smaller than that of Subset F since Set T includes soundings with a large range of LFC's.

Subset F2 has the similar profile of buoyancy as that of Set T except for the negative buoyancy at 950 mb, due to including the data with \( \sigma \) greater than unity, and has a larger buoyancy above 800 mb. Moreover, the standard deviation of buoyancy for Subset F2 is smaller than that of Set T by 0.4 °C at all the levels
which indicates that the clouds represented by Subset F2 are more uniform than those of Set T.

Subset F3 differs from Set T mainly in the lowest 100 mb level where the buoyancy is negative and standard deviation of it is larger. Also the magnitude of the buoyancy at each level is smaller which implies a lower mean cloud top compared with that of Set T. In the remaining three subsets, some common features are that there is a layer of small positive buoyancy between 930 mb and the level just below LFC, and that there is a thin layer of negative buoyancy right below the LFC which probably corresponds to the trade inversion. The buoyancy above the LFC is very small for these three subsets and the cloud top heights decrease as the LFC increases. Moreover, the cloud top heights are determined by $\theta_e$ at 1000 mb. Therefore, those of Koror are the highest ones among the three stations.

However, we must realize that the buoyancy shown above is the maximum one possible for various clouds since some clouds may have a higher base. If a more realistic PBL is considered, the buoyancy may be smaller and some clouds may have neutral buoyancy at most levels. However, the maximum buoyancy gives some indication of the characteristics of various types of convective atmospheres with different LFC's.

3.1.4 Temperature and Mixing Ratio of Mean Soundings

In order to look further at the difference among the subsets, we subtract the temperature and the mixing ratio derived from the mean structure of $\theta_e$ and $\theta_e^*$ of the subsets (Fig. 3.1) from those of the Set T. They are referred to as $\delta T$ and $\delta q$, respectively. The results are shown in Fig. 3.4 for all three stations.

Subset F is characterized by a large positive $\delta q$ at all levels. At 1000 mb $\delta q$ is over 1 g/kg at all stations (1.7 g/kg at Koror). The temperature difference from Set T is within 0.2 °C at all levels except 1000 mb where Majuro has a $-0.4$ °C difference. The high $\delta q$ at 1000 mb may explain why the buoyancy of Subset F is so large, especially at Koror (Fig. 3.3).
Figure 3.4: The temperature (solid line) and the mixing ratio (dashed line) differences from Set T for all subsets at Truk, Koror, and Majuro. From left to right, the upper panel is for Subsets F, F2, and F3, while the lower panel for Subsets F4, F5, and F6. The scales are from $-1.5 \, ^\circ C$ (g/kg) to $1.5 \, ^\circ C$ (g/kg).
Fig. 3.4: (Continued)
Fig. 3.4: (Continued)
Subsets F2 and F3 show neither a temperature nor a mixing ratio difference in all levels above 800 mb. Below 800 mb, all three stations show large positive $\delta T$ and negative $\delta q$ near the LFC's, but the negative $\delta q$ at 950 mb is the smallest one in this region (Fig. 3.4).

In the remaining three subsets, the vertical distributions are more complicated. Above the LFC's, the magnitude of $\delta q$ and $\delta T$ is larger than that of Subsets F2 and F3. Subset F4 shows a positive $\delta T$ and a negative $\delta q$ above the LFC, and Subset F5 has a large positive $\delta q$ and very small negative $\delta T$ above 650 mb for Koror (while Majuro has the opposite, and Truk shows negative $\delta T$ only), while Subset F6 shows both negative $\delta T$ and $\delta q$ for Truk and Majuro and both negative $\delta T$ and positive $\delta q$ for Koror above the LFC's.

More interestingly, very large positive $\delta T$ and negative $\delta q$ appears just around the LFC's in these subsets, similar to the subsets with lower LFC's. These layers may be treated as the top of the trade cumulus clouds. In the trade cumulus layer, drier and cooler ambient environments are associated with positive buoyancy in this layer (Fig. 3.4). In general, for the last three subsets, drier ambient air is accompanied with warm ambient air above a cool layer.

3.1.5 Correlation Coefficients

The correlation coefficients between $\sigma$, $\theta$, $\theta^*$, and the buoyancy are not shown here for all data sets and stations. But the main features are 1) positive correlation coefficients between $\theta^*$ and $\sigma$, 2) negative correlation coefficients between $\theta$ and $\sigma$ with some exception near and below the LFC's, and 3) positive correlation coefficients between $\theta$ and $\theta^*$ for most levels with minimum around 550 mb (negative value for subsets with a high LFC) and 4) the maximum negative correlation coefficients between the buoyancy and $\theta$ are associated with zero buoyancy.
3.1.6 Dilution Ratio for Saturated Parcels from 950 mb

Suppose that the PBL air will not convect unless its $\theta_e$ exceeds $\theta_e^*$ at 950 mb. What are the differences of the dilution ratio for these types of clouds? As indicated in Table 3.1, there are only 12-20 % of data which have $\theta_e$ within the PBL exceeded $\theta_e^*$ at 950 mb. We would expect that $\sigma$ is smaller than those previously calculated since the cloud parcel is warmer for most soundings, compared with those studied in Section 3.1.2.

The dilution ratio has a similar vertical profile as that of Set T shown in Fig. 3.2 except that it is smaller by 0.1 at all levels and the standard deviation is less by 0.05 (not shown), due to a smaller variation of $\theta_e^*$ at 950 mb compared with that of $\theta_e$ at 1000 mb. Note that the standard deviation of the dilution ratio is closely related to the properties of the surface cloud parcel.

3.2 Structure in $\theta_e - Q$ Coordinates

This section addresses the question of what the different characteristics are associated with different types of convective atmospheres using conserved variable diagrams. The goal is to detect structures of a variety of convective atmospheres that might result from vigorous mixing between various levels in the convective layers. The data set and its classification are exactly the same as in the section above. The methods of analysis have been discussed in Section 2.5. The methods differ from those of Kloesol (1987) because the resolution of the current dataset is not as high as his. For the sake of brevity, the results are only shown for station of Truk.
3.2.1 Equivalent Potential Temperatures

Unlike the means of θ_e and θ_e* in pressure coordinates, those in mixing ratio coordinates vary very smoothly with the mixing ratio (Fig. 3.5). At levels above where the mixing ratio is less than 6.0 g/kg, θ_e* does not vary with q much, slightly decrease with increasing q. However, in the subsets with the LFC higher than 875 mb, the smooth variation of θ_e is disturbed by a convectively stable layer where θ_e does not increase or even decreases with increasing q around 16.5 g/kg for Subset F3, around 15.5 g/kg for Subset F4, around 15.0 g/kg for Subset F5, and around 14.5 g/kg for Subset F6. These feature are similar to those found using high-resolution ratio (Betts and Albrecht, 1987).

However, for subsets with very low LFC’s, the mixing line structure is not very obvious. The magnitude of \( \frac{d\theta_e}{dq} \) is large at large q. The mixing line can be broken into two at 17.5 g/kg in Set T, at 15 g/kg in Subset F, and at 14 g/kg in Subset F2. In these datasets, we do not see any discontinuity in neither θ_e nor θ_e* curve, which differs from the subsets with higher LFC’s. Because the data have a coarse resolution, we can not obtain very fine structure of kink-like in the θ_e - Q diagrams. But more indication will be shown later in correlation analysis of θ_e and θ_e*.

3.2.2 Dilution Ratio

The mean σ in mixing ratio coordinates is generally larger than in pressure coordinates and so is its standard deviation since the small σ usually corresponds to a very small mixing ratio (Fig. 3.6). Majuro is a case at this point, larger by 0.1 at most levels (not shown). For Set T, σ has a relative minimum around 14 g/kg, which is probably associated with the entrainment layer, but Subsets F, F2,F3,and F4 do not have this maximum entrainment layer. Subsets F5 and F6 have a very obvious minimum dilution ratio below the LFC (at 13 g/kg), which is associated with the top of the trade cumulus layer.
Figure 3.5: Same as Fig. 3.1 except using mixing ratio coordinates.
The region with relatively small dilution ratio may be treated as the origin of
tense mixing between the ambient and cloudy air. For the whole data set, this
region is around 14 g/kg. There are two such region in Set F, one being around 14
g/kg, the other around 6 g/kg. But the top of clouds is always such a region in any
subset. The subsets with LFC higher than 850 mb have another region just below
LFC's, which corresponds to the trade inversion.

3.2.3 Correlation Coefficients

The correlation coefficients, $R(\sigma, \theta_e)$, $R(\sigma, \theta^*_e)$, and $R(\theta_e, \theta^*_e)$, in mixing ratio co-
ordinates are shown in Fig. 3.7. As mentioned in section 3.1.5, the correlation
coefficient between $\theta_e$ and $\theta^*_e$ is slightly negative around 550 mb. But in the mid-
dle range of $q$ for Set T and all the subsets the absolute value of this correlation
coefficient is larger than those in pressure coordinates. The level of the maximum
absolute value of this correlation coefficient differs from subset to subset, but the
area occupied by this negative correlation and zero correlation line increases as the
LFC gets higher. The large negative correlation coefficient appears at 6 g/kg for
Set T which corresponds to the kink structure shown in Kloesol (1987).

The shallow convective atmospheres has a larger negative correlation between
$\theta_e$ and $\theta^*_e$, compared with that of deep convection, however, this evidence is not
obviously shown in pressure coordinates (Fig. 3.7). The reason for the more obvi-
ous evidence in mixing ratio coordinates is probably that there are more kink-like
structures in the shallow convective atmospheres than in the deep convective atmo-
spheres. The kink-like structure indicates that a small $\theta_e$ is usually associated with
a large $\theta^*_e$ and a large $\theta_e$ is associated with a small $\theta^*_e$, which can be seen clearly
from $q - \theta_e$ and $q - \theta^*_e$ plots for individual soundings. But the physical explanation
for this structure is not very clear (Kloesol, 1987, Betts and Albrecht, 1987).

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Figure 3.6: Same as Fig. 3.2 except using mixing ratio coordinates for Truk.
Figure 3.7: The correlation coefficients between $\theta_*$ and $\theta_*^*$ (long-dashed line), between $\sigma$ and $\theta_*$ (solid line) and between $\sigma$ and $\theta_*^*$ (short-dashed line) for Set T and all the subsets at Truk in mixing ratio coordinates.
3.3 The Potential Thickness and Classification of Dataset

In this section, we answer a question relevant to the classification of the data. Can the types of convective atmospheres be determined by the mixing ratio or the virtual temperature at 1000 mb where a cloud air parcel is lifted? In other words, suppose that the surface thermodynamic properties are known, which types of cumulus convection are more likely to occur?

For a given measure, for example, the mixing ratio at 1000 mb, the convective atmospheres described by this measure are supposed to be uniform. The uniformity of clouds may be described by the correlation coefficient between the potential thickness and the ambient thickness from 1000 mb to 300 mb. The potential thickness is the thickness that the atmosphere would have if it had the same virtual temperature as an undiluted cloud. Therefore, the larger the correlation coefficient is, the more true it is that $\theta_e$ and $q$ at 1000 mb determines the bulk density of the free atmosphere. We consider four different classifications with which we determine the correlation coefficients between the ambient thickness and the potential thickness.

First of all, we consider the mixing ratio at 1000 mb as a means of classifying convective atmospheres. Within small intervals of the mixing ratio, we calculate the correlation coefficient between the ambient thickness and the potential thickness from 1000 mb to 300 mb. Figure 3.8a shows correlation coefficients for Truk for various mixing ratios at 1000 mb in intervals of 0.25 g/kg. The correlation coefficient is shown by the solid curve and the number of soundings in an interval by the dashed line. For mixing ratios less than 21.0 g/kg, the correlation coefficients are less than 0.4, while the correlation coefficients are less than 0.3 for mixing ratio intervals with the largest number of soundings. The correlation coefficient approaches 0.8 as $q$ goes to 22.5 g/kg, but the numbers of soundings around this mixing ratio are quite few.
Figure 3.8: The correlation coefficient between the potential thickness and the ambient thickness (solid curve) for the surface mixing ratio of Truk (a) and the surface virtual temperature [(b) for Truk, (c) for Koror, and (d) for Majuro] as the measures to classify the thermodynamic soundings with intervals 0.25 g/kg (°C). And the dashed line is the relative size of soundings in an interval.
Secondly, the virtual temperature at 1000 mb is used as a means of classifying convective atmospheres using an interval of 0.25 °C. The solid curve in Fig. 3.8b, c, and d shows the correlation coefficients whose distribution is very irregular as a function of the virtual temperature at 1000 mb for Majuro and Koror (Fig. 3.8c and d). For example, the correlation coefficient for Majuro is around 0.0 for the intervals with the largest numbers of soundings. The correlation coefficient for Koror is less than 0.3 for most of the intervals, but that for Truk is little bit larger. For Truk, the correlation coefficient reaches 0.6 around 301 °K and around 306 °K. However, that for Koror and Majuro reaches very large values (over 0.8) only around 306 °K. But the corresponding numbers of soundings are less than 10 % of the largest one in an interval.

The third measure used for dividing the types of convective atmosphere is the LFC. We calculate the correlation coefficients for the whole data set and all the subsets described in Section 2.4. Table 3.2 shows that the correlation coefficients are much larger than those shown in Fig 3.8. For the whole data set, the correlation coefficients for Koror, Majuro, and Truk are 0.428, 0.383, and 0.454, respectively. However, the correlation coefficients for subsets are much larger than those of Set T by 0.2 except Subset F which has the largest buoyancy at all levels. For Truk, the correlation coefficients for all subsets are 0.412, 0.508, 0.576, 0.616, 0.678, and 0.622, respectively.

So far, the best measure for describing the types of convective atmospheres is the one that we have used throughout this paper, i.e., the location of the LFC. Also, we can see that the correlation coefficients for Subsets F5 and F6 are relatively high, presumably due to the very small temperature difference between clouds and the ambient environment. Moreover, the whole dataset shows a small correlation coefficient.

Lastly, one might suppose that the lifting condensation level would be a better measure because the LCL is more closely associated with the cloud base. Table 3.3
shows the correlation coefficients for subsets with the LCL ranging from 915 mb to 985 mb. The interval of pressure for each subset is 10 mb. The subsets which have a larger correlation coefficient than Set T is one for Truk, four for Koror, and six for Majuro. But there is only one subset with correlation coefficient larger than that of Subset F2 which is the largest subset (Tables 3.1, 3.2 and 3.3). From the comparison between Tables 3.2 and 3.3, it can be seen that the measure using the LFC is much more consistent than that using the LCL.

3.4 Summary

This chapter has examined the vertical structure and the variability associated with a variety of convective atmospheres using undiluted cloud parcels which are lifted from the level of the maximum $\theta_e$ in the PBL. The characteristics of the dilution ratio are used to divide the dataset into several subsets whose LFC's are located at intervals of 50 mb. This is shown in Section 3.5 to be a good way of classifying the datasets. Each subset represents a type convective atmosphere. The deep convection with a lower LFC shows a smaller dilution ratio, a larger buoyancy, and a higher moisture content at all levels, compared with shallow convection which has a higher LFC and a lower level of neutral buoyancy (LNB). For all types of convective atmospheres, the maximum buoyancy usually appears at 600 mb, which coincides with the mean level of the minimum $\theta_e$. The study using mixing ratio coordinates affirms some results obtained from high-resolution data (e.g., Betts and Albrecht, 1987).

In the following chapters we extend these results by considering a more realistic originating level for cloud parcels and including water loading effects during mixing between cloud parcels and the ambient parcels.
Table 3.2: The correlation coefficients between the potential thickness and the ambient thickness for subsets categorized according to the level of free convection for Truk, Koror, and Majuro.

<table>
<thead>
<tr>
<th>P (LCL) (mb)</th>
<th>915</th>
<th>925</th>
<th>935</th>
<th>945</th>
<th>955</th>
<th>965</th>
<th>975</th>
<th>985</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truk</td>
<td>0.33</td>
<td>0.40</td>
<td>0.40</td>
<td>0.50</td>
<td>0.41</td>
<td>0.40</td>
<td>0.37</td>
<td>0.47</td>
</tr>
<tr>
<td>Koror</td>
<td>0.46</td>
<td>0.37</td>
<td>0.50</td>
<td>0.44</td>
<td>0.55</td>
<td>0.39</td>
<td>0.40</td>
<td>0.36</td>
</tr>
<tr>
<td>Majuro</td>
<td>0.46</td>
<td>0.53</td>
<td>0.54</td>
<td>0.41</td>
<td>0.37</td>
<td>0.44</td>
<td>0.45</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Table 3.3: The correlation coefficients between the potential thickness and the ambient thickness for subsets categorized according to the lifting condensation level. The pressure of the mean LCL is used to label the subsets.
Chapter 4

Convective Atmospheres Ignoring Water Loading Effects (B)

In this chapter, we attempt to use various PBL characteristics to estimate originating levels of cloud parcels in order to obtain more realistic vertical profiles of buoyancy and other thermodynamic parameters. Recall that in Chapter 3, the cloud air parcel is assumed to originate at 1000 mb or 950 mb, depending on the relative magnitude of $\theta_e$ at these two levels. The cloud air parcel was chosen to have the maximum $\theta_e$ of two levels so that the buoyancy obtained is the maximum possible one.

As mentioned before, PBL is characterized by uniform $\theta_v$, although the mixing ratio and equivalent potential temperature may individually vary. The data set used here cannot give us an accurate estimate of the thickness of the PBL because of the coarse resolution. Moreover, difference in $\theta_e$ between 950 mb and 1000 mb ($\Delta \theta_e = \theta_e(1000\ mb) - \theta_e(950\ mb)$), on average, is about 5 °C (cf. Set ML, Table 4.1), which further suggests either that the average top of the PBL is below 950 mb or that $\theta_e$ is not well-mixed in the PBL.

The purpose of this chapter is to use $\theta_v$ at the lowest two levels to distinguish between various convective atmospheres associated with different PBL’s. The dif-
ference in $\theta_e$ between 1000 mb and 950 mb is used to assess the influence of the strength of convective instability in the lowest 50 mb on the dilution characteristics of convective atmospheres.

### 4.1 Classification of the PBL

Betts (1976) suggested that the virtual potential temperature may be the best conserved quantity to characterize the well-mixed layer. Above the well-mixed layer, the virtual potential temperature increases rapidly with height. Hence, if the PBL extended above 950 mb, the absolute difference in the virtual potential temperature between 1000 mb and 950 mb would be very small. If it is large, the PBL top is probably below 950 mb. We will define a critical value of $|\Delta \theta_v|$ to distinguish various PBL’s.

First of all, we will try some experiments to define the critical value of $|\Delta \theta_v|$. Set ML includes all the soundings with $|\Delta \theta_v| < 0.25^\circ C$, which make up about 20% of the total soundings. Set ML1 has the same restriction as Set ML except adding that the $\theta_e$ difference between 1000 mb and 950 mb be less than 5 $^\circ C$, which is the average value of $\Delta \theta_e$. This is so that the soundings obtained by Set ML1 have relatively well-mixed $\theta_e$. Set ML2 has the same restrictions as those of Set ML1 except doubling the critical value of $|\Delta \theta_v|$. Set ML3 differs from Set ML2 by halving the criterion for $\Delta \theta_v$. Details concerning the criteria, the numbers of soundings, and the averages of $\Delta \theta_v$ ($= \theta_v(1000mb) - \theta_v(950mb)$) and of $\Delta \theta_e$ are summarized in Table 4.1. Clearly, $\overline{\Delta \theta_v}$ is almost zero for the first two sets.

Next, we calculate the mean and the standard deviation of the buoyancy for all sets at all three stations with the cloud parcels lifted adiabatically from 950 mb, which is presumed to be near the PBL top. When there is no restriction on $\Delta \theta_v$, the mean buoyancy is smaller and the level of zero buoyancy is lower than those sets with a restriction on $\Delta \theta_v$. Clearly, the restriction on $\Delta \theta_v$ not only increases
<table>
<thead>
<tr>
<th>SET ML</th>
<th>Soundings (%)</th>
<th>Truk</th>
<th>Koror</th>
<th>Majuro</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML</td>
<td>21</td>
<td>18</td>
<td>19</td>
<td></td>
<td>(</td>
</tr>
<tr>
<td></td>
<td>(\Delta \theta_v)</td>
<td>-0.016</td>
<td>-0.021</td>
<td>-0.003</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\Delta \theta_e)</td>
<td>4.82</td>
<td>5.81</td>
<td>4.15</td>
<td></td>
</tr>
<tr>
<td>ML1</td>
<td>12</td>
<td>8</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\Delta \theta_v)</td>
<td>-0.039</td>
<td>-0.043</td>
<td>-0.016</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\Delta \theta_e)</td>
<td>2.93</td>
<td>3.55</td>
<td>2.42</td>
<td></td>
</tr>
<tr>
<td>ML2</td>
<td>21</td>
<td>15</td>
<td>24</td>
<td></td>
<td>(</td>
</tr>
<tr>
<td></td>
<td>(\Delta \theta_v)</td>
<td>-0.103</td>
<td>-0.123</td>
<td>-0.091</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\Delta \theta_e)</td>
<td>2.89</td>
<td>3.26</td>
<td>2.29</td>
<td></td>
</tr>
<tr>
<td>ML3</td>
<td>8</td>
<td>3</td>
<td>12</td>
<td></td>
<td>(</td>
</tr>
<tr>
<td></td>
<td>(\Delta \theta_v)</td>
<td>-0.188</td>
<td>-0.229</td>
<td>-0.138</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\Delta \theta_e)</td>
<td>1.29</td>
<td>1.40</td>
<td>0.91</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: The criteria for choosing the Sets ML, ML1, ML2, and ML3, and number of soundings in each subset and the average of \(\Delta \theta_v\) (\(\theta_v(1000mb) - \theta_v(950mb)\)) and \(\Delta \theta_e\) (\(\theta_e(1000mb) - \theta_e(950mb)\)) for each subset and all three stations.
the mean buoyancy, but also reduces the standard deviation of the buoyancy by about 0.5 °C (Fig. 4.1). When the criterion for \(|\Delta \theta_v|\) is doubled (see Sets ML1 and ML2), the mean and the standard deviation of the buoyancy do not show very large differences. However, the mean \(\Delta \theta_v\) increases by about 3 times for Koror and Truk, and by 5 times for Majuro. The slight difference between Sets ML1 and ML2 indicates that the criterion for \(|\Delta \theta_v|\) is too small in Set ML1 to fully represent the type of convective atmospheres where cloud air parcels originate near 950 mb. The number of soundings in Set ML2 is almost twice as large as that in Set ML1.

Close examination shows that the buoyancy at 900 mb is not negative at Koror except in Set ML and that the negative buoyancy at the same level in other stations is very small, which implies that less external forcing is needed to initiate cumulus convection in these subsets. This is the case when cloud air parcels originate at 950 mb, when the PBL is relatively deep (Fig. 4.1). The reason is that the cloud air originated at 950 mb is moister than that at 1000 mb (Fig. 1). Although \(\theta_e\) at 1000 mb is mostly larger than that at 950 mb, the drier air lifted adiabatically would reach a lower temperature at 950 mb with reference to the ambient environment and moisture air lifted adiabatically from 950 mb may reach a higher temperature at 900 mb with reference to the ambient environment. Furthermore, the mean buoyancy is close to zero for Majuro and around 1 °C for other two stations. This suggests that the convective atmosphere is much closer to a neutral one for cloudy air originating at 950 mb, in instance in which the PBL is deeper than 950 mb.

From the comparison between Sets ML2 and ML3, we note that the smaller critical value of \(\Delta \theta_e\) (Set ML3) does not reduce the standard deviation of the buoyancy, but does increase the mean buoyancy in the middle and upper troposphere, which implies that classification of convective atmospheres should not be based on the magnitude of convective instability in the lowest 50 mb. Therefore, the criteria used for Set ML3 are not suitable for generating a subset with uniform properties. The criterion for \(|\Delta \theta_v|\) for Sets ML and ML1 is too small to fully describe the sound-
Figure 4.1: The mean (solid line) and the standard deviation (dashed line) of the buoyancy for Sets ML, M1, ML2, and ML3 at Truk, Koror, and Majuro in log $p$ coordinates. See text for definitions of the sets.
Fig. 4.1: (continued)
Fig. 4.1: (continued)
ings where the top of the PBL is at or above 950 mb. Based on the experiments above, we choose 0.5 °C as the criterion for $|\Delta \theta_v|$ to describe various PBL’s. When $|\Delta \theta_v| < 0.5^\circ C$, the PBL extends above 950 mb and the cloud parcel is assumed to originate at 950 mb. If $0.5^\circ C < |\Delta \theta_v| < 1.0^\circ C$, the PBL might be below 950 mb and the cloud parcel is assumed to be lifted from 975 mb where the properties of the parcel are taken to be the average of those at 1000 mb and at 950 mb. For the rest of soundings, i.e., $|\Delta \theta_v| > 1^\circ C$, the PBL is assumed very thin and the cloud parcel is assumed to have its origin at 1000 mb. So there are three different subsets which are based on three different assumptions on cloud parcels’ origins. In order to see the influence of the magnitude of convective instability between 1000 mb and 950 mb on dilution characteristics and other thermodynamic variables, another series of subsets are generated from the three subsets discussed above by using the criterion of $\Delta \theta_v < 5.0^\circ C$.

4.2 Vertical Structure for Various PBL’s

The vertical structures of the dilution ratio ignoring water loading effects (see Section 2.1 for the definition), buoyancy, temperature and mixing ratio for three different types of the PBL’s are shown in Figs. 4.2, 4.3 and 4.4. Set ML4 includes the soundings with $|\Delta \theta_v| < 0.5^\circ C$ where cloud parcels are assumed to originate at 950 mb. Set ML5 describes the soundings with $0.5^\circ C < |\Delta \theta_v| < 1.0^\circ C$ where cloud parcels are assumed to originate at 950 mb, too. But since the mean buoyancy for Set ML5 is smaller than that of Set ML4 (Fig. 4.2), it may be more proper to assume the cloud parcels originate at 975 mb so that the mean buoyancy is compatible with that of Set ML4. This new set is described by Set ML6. And in Set ML7 it is assumed that cloud air parcels originate at 1000 mb for the soundings with $|\Delta \theta_v| > 1.0^\circ C$. Subsets ML4, ML5 ML6, ML7 are generated from the corresponding sets, using the criterion, $\Delta \theta_v < 5.0^\circ C$, so that the convective instability
Figure 4.2: Same as Fig. 4.1 except for Sets ML4, ML5, ML6, and ML7 (right panel) and their subsets (left panel) at Truk, Koror, and Majuro. See text for definitions of different datasets.
KOROR Station

Fig. 4.2: (continued)
between 1000 mb and 950 mb is smaller than for the corresponding sets.

4.2.1 Temperature and Mixing Ratio ($\delta T$, $\delta q$)

The computation of temperature and mixing ratio differences of subsets from the whole data set (Set T) has been discussed in Section 3.1.4. Although the mean structures of temperature and mixing ratio are very different from station to station, the structure of the temperature and mixing ratio differences ($\delta T$, $\delta q$) are found to be very similar in all datasets discussed in this section. So only those of Truk station are shown in Fig. 4.3. Some obvious features are summarized as follows:

1. A very large negative $\delta q$ appears at 950 mb for all datasets (Fig. 4.3). Its absolute value in the subsets is smaller than that of the sets. This is because the $\theta_e$ difference between 1000 mb and 950 mb in the present datasets is larger than that of Set T (not shown).

2. Sets ML4, ML5 and ML6 differ from Set T mainly below 600 mb, i.e., (a) a large positive $\delta q$ and a small negative $\delta T$ between 910 mb and 600 mb. (b) the minimum negative $\delta T$ is above the maximum $\delta q$ between 910 mb and 600 mb. (c) a maximum $\delta T$ appears at 950 mb, as do Subset ML4, ML5, and ML6.

3. The mean soundings in Set and Subset ML7 are drier and cooler in the lowest layers than those in Set T. But the soundings in Subset ML7 have a large moisture content.

Overall, the subsets differ from their sets mostly in the moisture content, and not as much in the temperature distribution. This is consistent with the restriction of $\Delta \theta_e$ on the subsets. The magnitudes of $\delta T$ and $\delta q$ increase as the top of the PBL decreases. The relatively cool ambient air below 910 mb in Sets ML7 and Subset ML7 are associated with a thinner PBL than occurs in the other set.
Figure 4.3: Temperature and mixing ratio differences from Set T for Sets ML4, ML5, ML6, and ML7 (left panel) and their subsets (right panel) for Truk.
4.2.2 Dilution Ratio

Since the cloud parcel is here lifted from a higher level than that studied in Chapter 3, the dilution ratio not including water loading effects should increase by definition. We wish to know by what amount it increases. Therefore, the dilution ratio differences from Set T of Chapter 3 are calculated for comparison (Fig. 4.4).

The dilution ratio increases as the top of the PBL increases. The largest increase is about 0.1 at most levels in the datasets in which cloud parcels originate at 950 mb. The dilution ratio shows the smallest difference from Set T in Chapter 3 in the region around 850 mb, which implies that degree of mixing at this level is stronger than at the other levels using more realistic cloud air parcels’ origins.

The subsets differ from their respective sets in reduced mean and standard deviation of $\sigma$ as the soundings in these subsets have a higher mixing ratio when compared with their sets (Fig. 4.3). Note especially that the dilution ratio decreases most in Subset ML7 where the moisture content is about 1 g/kg larger than that of Set T (Fig. 4.3). The larger standard deviation in the upper troposphere may be due to smaller $\theta^*_c$ of cloud parcels than found in Chapter 3 (Fig. 4.4). Koror shows the largest increase in the standard deviation of $\sigma$ (not shown) as the mean $\Delta\theta_c$ is the largest among the stations (Table 4.1).

We note that the positive $\sigma$ difference around 950 mb in Sets and Subsets ML4, ML5 and ML6 results because the origins of cloud air parcels are higher than those of Set T. But the large negative $\sigma$ difference in Set and Subset ML7 is interesting because this indicates that the degree of mixing is large in convective atmospheres represented by these subsets.

4.2.3 Buoyancy

The magnitude of the buoyancy is different from station to station, but overall their distributions are similar (Fig. 4.2). Figure 4.2 shows the mean and the standard deviation of the buoyancy at all three stations. The maximum mean buoyancy
Figure 4.4: Same as Fig. 4.3 except for dilution ratio difference with more realistic cloud parcels' origins from that of Set T for which undiluted cloud parcels originate at an idealized level.
varies from 0.7 to 1.7 °C in the sets. These values are about about 0.5 C smaller than in Set T. In addition, the following common features are found:

1. The level of neutral buoyancy in the subsets is higher than in their respective sets, except in Subset ML7, as Subset ML7 has a higher moisture content than that of Set ML7 (Fig. 4.3).

2. There is a secondary maximum in buoyancy at 850 mb for most sets, which is not seen in Chapter 3. Obviously, the mean structures of temperature and mixing ratio do not explain this (Fig. 4.3). In the next section, the same feature appears even when the data sets are divided according to the LFC.

3. The negative mean buoyancy at 950 mb for Sets ML6 and Subset ML6 is probably due to errors in assuming that the temperature and relative humidity at 975 mb is a linear average of the values available at 1000 mb and 950 mb.

4. The standard deviation of the buoyancy in the subsets is smaller than that found in their respective sets (Fig. 4.2). Set and Subset ML7 show the largest standard deviation of buoyancy. This is because the cloud air parcels have a large $\theta_e$ variation at 1000 mb.

### 4.3 Vertical Structure for Various LFC’s

As discussed in Section 3.3, the LFC is the best measure that we examined in dividing the data into subsets. It is worth comparing the results found here with those studied in Chapter 3. What are the distributions of $\sigma$ and the buoyancy when parcels are lifted from the top of the PBL? What are the specific characteristics that we did not find in Chapter 3 using undiluted parcels originating at an idealized level? Here, we divide the data into subsets according to the LFC which is defined from $\theta_e$ at the tops of various PBL’s, instead of from the maximum $\theta_e$ as studied in Chapter 3.
First of all, the mean structures of $\theta_e$ and $\theta'_e$ are shown in Fig. 4.5 for Set T and Subsets F, F2, F3, F4, F5, and F6 (hereafter, the first series of datasets) and their subsets generated by adding an additional restriction that $\Delta \theta_e < 5.0^\circ C$. The subsets so generated are associated with a smaller magnitude of convective instability between 1000 mb and 950 mb. They will be designated as Set ST, Subsets SF, SF2, SF3, SF4, SF5, and SF6 (hereafter, the second series of datasets).

In this section, we do not repeat features which are similar to those found in Chapter 3. The differences from those of Chapter 3 will be discussed in the next section. Here we emphasize some differences found between the two series of datasets mentioned above, which are summarized as follows:

1. Increased $\theta_e$ and relative humidity in the second series of datasets due to the restriction of $\Delta \theta_e < 5^\circ C$. This is especially true for Subset SF2 (Fig. 4.5).

2. A more well-mixed $\theta_e$ in the lowest 50 mb for the second series of datasets. $\theta'_e$s at 1000 mb are a little higher for the first series of datasets. But $\theta'_e$s at 975 mb or 950 mb are not, except for Subset SF (Fig. 4.5).

3. The dilution ratio for cloud parcels which originate near the PBL top has a secondary minimum in Subsets F and SF, indicating that the degree of mixing is larger than at adjacent levels (Fig. 4.6). This corresponds to a secondary maximum of buoyancy (Fig. 4.7). The interpretation is that neutral buoyancy is achieved when the buoyancy is reduced through large mixing of cloud air parcels with the ambient environment.

4. Magnitudes of mean buoyancy are larger in the second series of datasets except in Subsets SF and SF2 where higher relative humidity or lower $\theta_e$ in the PBL may play a role. It will be shown that in Subset SF the latter factor is important but in Subset SF2 higher relative humidity is important.

5. The standard deviations of dilution ratio around LFC’s in the second series of
Figure 4.5: The means and standard deviations of $\theta_e$ and $\theta^*$ at Truk for Set T and Subsets F, F2, F3, F4, F5, and F6 and their subsets, Set ST and Subsets SF, SF2, SF3, SF4, SF5, and SF6. The cloud parcels originate at various PBL tops in these datasets. See Fig. 3.1 for more illustration.
Figure 4.6: Same as Fig. 4.5 except for the mean (solid curve) and standard deviation (dashed curve) of dilution ratio.
datasets are smaller, but no significant differences appear in those of buoyancy, $\theta_v$ and $\theta'_v$.

### 4.4 Difference from Idealized Origins of Cloud Parcels

By lifting cloud parcels near the top of the PBL, what features have we obtained which are different from those studied in Chapter 3 where cloud parcels originate at idealized levels? In order to discuss them quantitatively, we compute the differences of the dilution ratio (ignoring water loading effects), buoyancy, temperature and mixing ratio, as well as the differences of the standard deviations of the dilution ratio and the buoyancy, from the corresponding quantities studied in Chapter 3.

#### 4.4.1 Dilution Ratio Difference

The characteristic of the maximum entrainment at 850 mb is more clearly shown for undiluted cloud parcels originating at realistic levels, especially for Subsets F, F2, and F5 (Figs. 3.5, 4.6 and 4.8) and for data sets with the same originating levels of cloud parcels (Fig. 4.4). The magnitude of the mean and the standard deviation of dilution ratio increases substantially for Set T and Subset F with the minimum increase appearing at 850 mb. The magnitude of dilution ratio decreases substantially for Subset SF2. This probably due to high relative humidity.

For the remaining subsets, there are some obvious variations in the magnitude of the mean and the standard deviation of the dilution ratio at the lowest levels. The increase in the mean dilution ratio may indicate that shallow convection has a small degree of mixing at the cloud base, compared with deep convection. The standard deviation of dilution ratio for the same originating levels of undiluted cloud parcels increases with height (Fig. 4.4). For convective atmospheres divided according to
Figure 4.7: Same as Fig. 4.5 except for the mean (solid line) and the standard deviation (dashed line) of buoyancy.
the location of the LFC this is not true, except Subset F, which further suggests the uniformity of clouds in this classification (Fig. 4.8).

Lastly, it can be seen that the profiles of $\sigma$ differences in Subsets F2 and SF2 are very similar to those for cloud parcels originating at 1000 mb (Figs. 4.4 and 4.8). This may suggest that most cloud parcels in these subsets originate at 1000 mb.

4.4.2 Temperature and Mixing Ratio Difference

Figure 4.9 shows the temperature and mixing ratio difference between these two series of datasets and those found in Chapter 3 where cloud parcels originate at an idealized level. Is there any difference in temperature and moisture content due to the use of more realistic origins of cloud parcels?

From Fig. 4.9, we see it is generally true that an increase/decrease of mixing ratio is associated with a decrease/increase in temperature in the lower troposphere. The magnitude of moisture increase is larger for the datasets with a restriction on $\Delta \theta_e$ than for those without it, except for Subset SF. Overall, the magnitude of the temperature difference is very small for all sets except Subset F2 which has a very large negative temperature difference near the surface. The large negative temperature difference at the surface for Subset F2 and the large negative mixing ratio difference at the surface for Subset SF may explain why the mean buoyancy is reduced substantially for these subsets. The large negative temperature difference for Subset SF2 below 600 mb has the opposite effect on the mean buoyancy.

4.4.3 Buoyancy Difference

As discussed in the beginning of this chapter, the mean buoyancy studied in Chapter 3 is the maximum value available in clouds as the cloud parcels are lifted from the level of the maximum $\theta_e$. In order to examine differences between buoyancy so defined and the buoyancy of air lifted from near the top of the PBL, the mean and the standard deviation of the buoyancy (Fig. 4.7) are subtracted from those of
Figure 4.8: Same as Fig. 4.5 except for the mean (solid line) and the standard deviation (dashed line) of the dilution ratio differences from those with cloud parcels originating at idealized levels in Fig. 3.2.
Figure 4.9: Same as Fig. 4.5 except for temperature (solid line) and mixing ratio (dashed line) differences from those of convective atmospheres with idealized cloud origins.
Chapter 3 (Fig. 3.3). The results are shown in Fig. 4.10 for Truk. The differences are summarized as follows:

1. For the subsets with the same depths of PBL's, the buoyancy is positive except in the case where the cloud parcel is lifted from 975 mb (Fig. 4.2). The buoyancy at 850 mb has a secondary maximum (Fig. 4.2) which is not seen in Chapter 3. The buoyancy reduction around 850 mb is a secondary maximum for most subsets shown in Fig. 4.10.

2. Negative buoyancy around the cloud base is very small. This indicates that less external forcing is needed to form these clouds (Figs. 4.2 and 4.7).

3. The magnitude of convective instability between 1000 mb and 950 mb does influence the magnitude of the buoyancy. For a cloud parcel originating from 950 mb or 975 mb, the larger the convective instability is, the smaller the buoyancy and the lower the mean tops of clouds are. For a cloud parcel lifted from 1000 mb, the opposite is true (Fig. 4.2).

4. The standard deviation of the buoyancy is reduced for all subsets except for Subset F2. The reduction is the largest at 950 mb for all sets and at 300 mb for Subsets F and Set T. The increase in the standard deviation of the buoyancy and the large reduction in the mean buoyancy found in Subsets SF2 and F2 are not understood. Most cloud parcels in these subsets probably originate at 1000 mb where the standard deviation of $\theta_e$ is large and $\theta_e$ is low at 1000 mb. The latter may cause large reductions in the mean buoyancy.

5. The reduction in the mean buoyancy is most obvious for subsets where the LFC is lower than 850 mb. The remaining sets show a large reduction at some levels, especially around 600 mb and just below the LFC.
Figure 4.10: Same as Fig. 4.5 except for the mean (solid line) and the standard deviation (dashed line) differences of the buoyancy from those with idealized cloud origins.
4.5 Summary

This chapter uses undiluted cloud parcels originating at the PBL tops to study certain thermodynamic parameters. The main findings is that the convective atmosphere is more neutrally buoyant to air from the PBL tops. The presumed degree of mixing is generally less than one would infer using parcels lifted from \( \theta_{\text{ref}} \) level. Specifically, a substantial increase in the dilution ratio occurs in Set T and in all subsets except Subset F2. A substantial reduction in buoyancy occurs in all data sets. The maximum mixing at 850 mb is a special feature deduced by using cloud parcels from the PBL top and is associated with the secondary maximum in mean buoyancy at the same level for deep convective atmospheres and for those with same originating levels, respectively.

The subsets with smaller magnitudes of convective instability between 1000 mb and 950 mb show larger moisture content in the lower troposphere and less increase in dilution ratio for all types of convective atmospheres. They also show a larger reduction in buoyancy except in Set T. But the uniformity of convective atmospheres is not influenced very much by the magnitude of convective instability. The dilution ratio increases as the top of the PBL increases, and so does the moisture content.
Chapter 5

Convective Atmospheres Including Water Loading Effects

In the last two chapters, the effects of water substance on buoyancy were neglected in defining the dilution ratio. However, in real clouds, condensate loading is not a negligible factor and the mixing between cloud parcels and the ambient air is not well understood. In this chapter, we assume that the cloud parcel has its adiabatic water content. Mixing between such cloud parcels and the ambient air is here used to define a new dilution ratio.

In Section 5.1, the mixing processes including water loading effects are discussed in detail. These differ from some earlier theory in the choice of origin of the entrained parcel and in the measure of the degree of mixing between the ambient and cloudy air. For a review of cumulus entrainment studies, see Reuter (1986). All studies performed in this chapter are for cloud parcels originating at the level of the maximum $\theta_e$ in the PBL, i.e., the idealized level.

Section 5.2 deals with convective atmospheres with the same lifting condensation level (LCL) which is defined from the maximum $\theta_e$ in the PBL. The goal is to estimate the degree of mixing necessary to produce neutral buoyancy in subsets defined by including water loading effects for soundings with the same LCL’s.
In Section 5.3 we will consider whether the level of minimum $\theta_e$ has any influence on the mixing process, i.e., if the strength of the convective instability has anything to do with the mixing between cloudy and the ambient air.

Section 5.4 is devoted to revealing properties of convective atmospheres having the same LFC and comparing them with convective atmospheres ignoring water loading effects studied in Chapter 3. A summary and comparison with results of previous chapters will be presented in Section 5.5.

5.1 The Mixing Processes

To begin with, let us suppose that a rising parcel carries all condensed moisture with it. Then, an intercepting aircraft should record the adiabatic liquid water content. Recent aircraft measurements show that the peak liquid water content in trade cumulus clouds is generally close to the value of adiabatic liquid water content (Jensen, pers. commun., 1987).

As early as 1947, Stommel was aware that mixing between the ascending plumes and their surroundings must occur because the mean lapse rate and temperature of clouds are closely approximated by those of the environmental atmosphere. He worked out the rate of mixing or "entrainment" on the basis of conservation of mass and energy, assuming lateral entrainment. However, if the outside air enters (is entrained into) the rising top directly, a rapid decrease of buoyancy may occur and the cloud may not continue to grow. Here, we hypothesize that the virtual temperature of the free atmosphere represents a weighted mean of the virtual temperature of undiluted cloud parcels and the minimum virtual temperature that can be produced by mixing.

The mixing process is defined as follows. First, the cloud parcel is lifted adiabatically to a level which we are considering and then is mixed with enough ambient air to obtain the minimum possible virtual temperature. Second, the cloud parcel is lifted adiabatically to a higher level (higher by 50 mb in the present study) than the
one considered, and then is mixed with the ambient air at this level. The mixture is lowered dry-adiabatically to the level that we are considering to obtain another virtual temperature of the mixture. This new virtual temperature is compared with the previous one resulting from mixing at the lower pressure level. This process is repeated each time mixing the air at higher level until a minimum virtual temperature is obtained. As determined from this process, the original level of the ambient parcel that is entrained into a cloud to produce the mixture of minimum virtual temperature is not at the cloud top in most circumstances. In fact, the ambient air that, when mixed with undiluted cloudy air, achieves the minimum virtual temperature usually originates 50 mb or 100 mb above the level considered provided this is below the level of the minimum $\theta_s$, and at the same level as considered if this is above the level of the minimum $\theta_s$.

In summary, the minimum virtual temperature is obtained after three processes: (1) moist adiabatic ascent from the top of the PBL, (2) mixing with all potentially colder ambient parcels, and (3) dry-adiabatic descent to the level considered to get the minimum virtual temperature.

As discussed in Section 2.3, the dilution ratio including water loading effects ($\sigma$) is defined such that the virtual temperature of the ambient air is a weighted average of the virtual temperature of clouds and the minimum virtual temperature that is achieved by mixing between the ambient and cloudy air, i.e.

$$T_{va} = \sigma T_{vc} + (1 - \sigma) T_{va}$$ (5.1)

This can also be expressed

$$\frac{1 - \sigma}{\sigma} = \frac{T_{vc} - T_{va}}{T_{va} - T_{v_{min}}}$$ (5.2)

Equation (5.2) shows that the ratio of the buoyant acceleration of the updraft to that of the downdraft is related to dilution ratio including water loading effects. In order to achieve neutrally buoyant clouds, a larger degree of mixing is required for more buoyant clouds. The hypothetical clouds are formed from a reversible moist adiabatic process with water loading effects.
Finally, it should be mentioned that the calculations in the following are performed with those soundings at levels where \(0 < \sigma < 1\). Since the ambient temperature is higher than the minimum virtual temperature that is achieved by mixing between the ambient and cloudy air, the buoyancy must be positive for any level where \(0 < \sigma < 1\). Therefore, the buoyancy calculated in the following sections has a smaller standard deviation than those in the previous chapters. The larger standard deviation of buoyancy in the previous chapter results from including some soundings with negative buoyancy at high levels where \(0 < \sigma < 1\), due to different definitions of dilution ratios. (see Section 3.1.3 for details.)

5.2 Structure with the Same LCL

When a parcel is lifted adiabatically, it becomes saturated at the lifting condensation level (LCL). The measured cloud base is a little higher than the LCL of surface parcels (Betts, 1976). As shown in Section 3.3 (Table 3.3), the LCL is not the best measure to classify the thermodynamic soundings in the tropics. We divide the dataset according to the location of the LCL to study the mean and the variability of dilution ratio and buoyancy of such types of convective atmospheres. The pressure of the LCL can be easily calculated using the conservation of potential temperature. The interval is 10 mb for each subset. The mean values of the LCL for subsets are from 915 mb to 985 mb.

5.2.1 Dilution Ratio

Figures 5.1, 5.2 and 5.3 show the mean and the standard deviation of the dilution ratio for Truk, Koror, and Majuro stations, respectively. Although there are some differences between stations, the common features are obvious.

The means of the dilution ratio decrease as the LCL decreases. This is probably caused by the high relative humidity of the surface cloud parcels when the LCL is
Figure 5.1: The mean (solid line) and the standard deviation (dashed line) of dilution ratio including water loading effects for Truk, using the LCL as the measure to classify the thermodynamic soundings. The datasets are labeled with their mean LCL.
Figure 5.2: Same as Fig. 5.1 except for Koror.
Figure 5.3: Same as Fig. 5.1 except for Majuro.
low. High RH of cloud parcels at originating levels increases the virtual temperature of cloud parcels at all levels. Therefore, the RH of cloud parcels at originating levels influences the magnitude of the degree of mixing at high levels.

The most important point is that convective atmospheres with a higher LCL have a uniform degree of mixing with hypothetical clouds above 850 mb. But the degree of mixing is small in such convective atmospheres as the higher LCL, the less the buoyancy of hypothetical clouds. For instance, the mean dilution ratio is around 0.7 for convective atmospheres with a mean LCL of 915 mb. The corresponding value varies with height from 0.3 to 0.7 for convective atmospheres with a mean LCL of 985 mb. Meanwhile, the maximum standard deviation of dilution ratio increases as the LCL decreases, from 0.17 to 0.3 for datasets with the mean LCL from 915 mb to 985 mb. From the vertical profiles of the standard deviations of dilution ratio, it can been seen that the categorization using the LCL may be not as good as the one using the LFC, as discussed in Section 3.3.

Next, the minima of the dilution ratio are more clearly shown around 850 mb and 600 mb as the LCL decreases, especially for Majuro station. The minimum dilution ratio at 850 mb corresponds to the maximum mixing at the cloud base. There is almost no indication of the maximum mixing at the cloud base for the undiluted cloud parcel studied in Chapter 3. In Chapter 3 dilution ratio at 850 mb does not show to be a minimum at any subset. However, the indication of the minimum dilution ratio is not very obvious in all subsets of Koror (Fig. 5.2) and in some subsets of Truk. This may imply that the cloud parcel should originate at a higher level (cf., Chapter 4) in order to see whether there is a maximum mixing at the cloud base for cloud parcels originating at the PBL top.

The minimum dilution ratio around 600 mb appears since the mean $\theta^*_e$ is a minimum, corresponding to the maximum buoyancy level. The reason for relatively large mixing in middle levels of cumulus clouds has been discussed in Section 5.1, and is not suggested by the classical model (Stommel, 1947) dealing with the entrainment
in trade cumulus clouds. After calculating the entrainment rate from Stommel's results, one may infer that the classical model proposes a maximum entrainment at the cloud base, a maximum detrainment at the cloud top, and no entrainment at middle levels of clouds.

Furthermore, the mean dilution ratio above 400 mb seem to decrease with height very fast. This rate of decrease is larger for convective atmospheres with a higher LCL. There are some differences between stations. Koror shows the smallest dilution ratio for most of the subsets and also shows the largest difference of the dilution ratio at levels above 600 mb and at levels below 600 mb. Moreover, the dilution ratio in the lowest 100 mb decreases faster than for the other stations.

5.2.2 Buoyancy

In the end of Section 5.1, we have discussed that the soundings with negative buoyancy are ignored in this chapter. But such kinds of soundings may be kept in calculation in the previous chapters because of the definition definitions of the dilution ratio (see Section 3.1.3).

The mean and the standard deviation of buoyancy are shown in Figs. 5.4, 5.5, and 5.6 for Truk, Koror, and Majuro stations, respectively. Both increase as the LCL decreases. The mean buoyancy is about 1.2 °C for the subset with a mean LCL of 915 mb. That for the subset with a mean LCL of 975 mb is close to 3.0 °C in the middle and upper troposphere. The buoyancy difference between subsets is probably due to $\theta_e$ at 1000 mb because $\theta_d$ in the subset with mean LCL of 975 mb is 6-7 °C larger than the subset with the LCL of 915 mb. If there is not such a large difference in $\theta_e$ at 1000 mb, high RH at various levels causes an opposite effect on the buoyancy profiles. For example, the subset with a mean LCL of 985 mb has much higher RH but not a higher $\theta_e$ at 1000 mb than those of the subset with a mean LCL of 975 mb. The mean buoyancy in the former subset is smaller.

The second feature, which differs from those in Chapters 3 and 4, is that the mean buoyancy does not decrease with height above 600 mb as fast as those shown
Figure 5.4: Same as Fig. 5.1 except for the mean (solid curve) and the standard deviation (dashed curve) of buoyancy in log $p$ coordinates at Truk.
Figure 5.5: Same as Fig. 5.4 except for Koror.
Figure 5.6: Same as Fig. 5.4 except for Majuro.
in Chapters 3 and 4. The different definitions of dilution ratios are the main cause. Specifically, when the dilution ratio ignoring water loading is less than unity near the top of clouds, the buoyancy may be negative, due to ignoring the condensate loading. But the buoyancy is definitely positive for the same circumstances when water loading effects are included in the definition of dilution ratio (see Section 3.1.3).

Moreover, the standard deviation of buoyancy is smaller than those in Chapters 3 and 4 because the data with negative buoyancy is eliminated in calculating the mean buoyancy in this chapter. However, the mean and the standard deviation below 600 mb do not show large differences. This implies that the water loading effects have more influence at higher levels. Furthermore, a secondary minimum in the buoyancy profiles appears around 400 mb for some subsets, which may be associated with the larger dilution ratio at that level.

The mean buoyancy increases rapidly near the cloud base levels. The buoyancy does not increase with height between 850 mb and 600 mb as fast as that near the cloud base. When the buoyancy between 850 mb and 700 mb is almost a constant, the dilution ratio has a minimum at 850 mb. Otherwise, the dilution ratio does not have a minimum at 850 mb. The physical reason for this relationship is not yet known.

5.3 Structure with the Same \( \Theta_{min} \) Level

In this section, the level of the minimum \( \Theta_e \) (hereafter, \( \Theta_{min} \) level) is used as a criterion to classify the soundings into subsets. The aim is to explain the influence of the \( \Theta_{min} \) level on the degree of mixing in convective atmospheres. The potentially coldest ambient air appears at the \( \Theta_{min} \) level. Another aim is to see whether or not there are any different structures associated with such atmospheres with different \( \Theta_{min} \) levels. The results are shown in Figs. 5.7 to 5.12 for subsets with the \( \Theta_{min} \) level from 800 mb to 450 mb. The pressure difference between the \( \Theta_{min} \) levels is 50 mb for two adjacent subsets.
5.3.1 Dilution Ratio

Figures 5.7, 5.8 and 5.9 show the mean and the standard deviation of dilution ratios for Truk, Koror, and Majuro stations, respectively. One of the fundamental characteristics is that a larger mean and a slightly smaller standard deviation of dilution ratio appear 50 mb higher than the $\theta_{e_{\text{min}}}$ level. This characteristic is mainly due to the relatively warm ambient air at these levels compared to that at the $\theta_{e_{\text{min}}}$ level.

Another feature is that the minimum dilution ratio at 850 mb appears to be less obvious for subsets with a higher $\theta_{e_{\text{min}}}$ level for Majuro. Truk and Koror stations do not show a minimum dilution ratio at 850 mb except for subsets with the $\theta_{e_{\text{min}}}$ at 450 mb and 800 mb for Koror and at 450 mb for Truk. The minimum dilution ratio at 800 mb is only shown at Truk for the subset with the $\theta_{e_{\text{min}}}$ at 800 mb.

In the previous section, it was shown that there is a minimum dilution ratio around 600 mb for convective atmospheres with the same LCL. However, this minimum is shifted to a level 50 mb higher and the magnitudes of the minimum seem smaller for subsets with the $\theta_{e_{\text{min}}}$ at 450, 500, 600, and 650 mb. The rest of the subsets have a minimum dilution ratio at 600 mb. The location of this minimum is associated with the level of the minimum $\theta^*_e$, instead of that of the minimum $\theta_e$. The magnitude of the largest degree of mixing around 600 mb is associated with the convective instability. That is, the smaller magnitude of convective instability, the larger the degree of mixing at middle levels. Overall, the soundings with very large amounts of convective instability show smaller amounts of mixing with the ambient air in the middle troposphere.

The standard deviation of dilution ratios exceeds 0.2. Its maximum appears around 850 mb for most of the datasets with the same $\theta_{e_{\text{min}}}$ levels. This is larger than that appearing in the other classifications. However, the standard deviations of $\theta_e$ and $\theta^*_e$ are smaller for this classification using the $\theta_{e_{\text{min}}}$ level (not shown). The only possibility is that the standard deviation of $\theta_{ob}$ of cloud parcels is large in this
Figure 5.7: Same as Fig. 5.1 except using the $\theta_{c_{\text{min}}}$ level as the measure to classify thermodynamic soundings at Truk. The datasets are labeled with the pressures at the $\theta_{c_{\text{min}}}$ levels.
Figure 5.8: Same as Fig 5.7 except for Koror.
Figure 5.9: Same as Fig. 5.7 except for Majuro.
classification.

5.3.2 Buoyancy

The mean and the standard deviation of the buoyancy for subsets with the same level of the minimum $\theta_e$ are shown in Figs. 5.10, 5.11, and 5.12 for Truk, Koror, and Majuro stations, respectively. The levels of maximum buoyancy are at 600 mb or above it. The level of the minimum $\theta_e$, in some circumstances, is associated with a secondary maximum buoyancy, e.g., the subsets with the $\theta_{e_{\text{min}}}$ at 800 mb for Truk, and Majuro. The relative humidity is usually low at the $\theta_{e_{\text{min}}}$ levels. The minimum $\theta_e^*$ is located at levels above or below the $\theta_{e_{\text{min}}}$ level, depending on various subsets. In other words, the minimum $\theta_e^*$ is around 600 mb for most of subsets, which is the most important factor in determining the location of the maximum buoyancy.

The magnitude of the buoyancy does vary slightly from subset to subset, increasing with increase in the $\theta_{e_{\text{min}}}$ level. The largest means are around 2°C for Truk, 1.7°C for Majuro and 2.5°C for Koror. The magnitude seems not determined by the $\theta_{e_{\text{min}}}$ level. Furthermore, the standard deviation does not show a large difference between subsets, either. The larger the mean buoyancy is, the larger the standard deviation is.

5.4 Structure with the Same LFC

In this section, the data set is divided into subsets according to the characteristics of the dilution ratio including water loading effects, or the location of the LFC. The description of the subsets has been presented in Chapter 3. Sections 5.2 and 5.3 have shown some special features of various convective atmospheres according to different classifications, but they can not be compared with the results found in Chapters 3 and 4 closely. This section is aimed at that purpose, i.e., we wish to know the differences between the degree of mixing necessary to produce neutrally buoyant
Figure 5.10: Same as Fig. 5.7 except for the mean (solid curve) and the standard deviation (dashed curve) of buoyancy in log $p$ coordinates at Truk.
Figure 5.11: Same as Fig. 5.10 except for Koror.
Figure 5.12: Same as Fig. 5.10 except for Majuro.
clouds by ignoring and including water loading effects during mixing between the ambient and cloudy air. Figures 5.13, 5.14 and 5.15 show the vertical distribution and the variability of dilution ratio, and Figs. 5.16, 5.17, and 5.18 show those of buoyancy for Truk, Koror, and Majuro stations, respectively.

5.4.1 Dilution Ratio

The magnitude of the dilution ratio differs from station to station. The magnitude is dependent on $\theta_v$ at 1000 mb (Figs 5.13 to 5.15). Subsets with larger $\theta_v$ at 1000 mb show a smaller dilution ratio, i.e., larger degree of mixing associated with deep convective atmospheres. The dilution ratios at Koror are less than those of Majuro by 0.1-0.15 at various levels (Figs. 5.14 and 5.15). Moreover, the dilution ratio including water loading effects is larger above 600 mb than that ignoring water loading effects (Figs. 5.13, 4.6 and 3.2). But below 600 mb it is smaller than that ignoring water loading effects when the cloud parcel originates near the PBL top. (Figs. 4.6 and 5.14). The most interesting feature is that the vertical variation of dilution ratio is very small above the LFC. This uniform structure is interrupted by a minimum around 600 mb.

The maximum mixing around 850 mb is also related to the magnitude of $\theta_v$ at 1000 mb. As discussed in the previous two sections, Koror does not show a maximum degree of mixing around 850 mb (Fig. 5.14). Majuro indicates a very large amount of mixing around 850 mb compared with the adjacent levels, although the signal is not very strong compared with the variability. As indicated in Chapter 4 (Figs. 4.3 and 4.9), the characteristics of the maximum degree of mixing around 850 mb may be better estimated when realistic originating levels of clouds parcels are used in calculating the dilution ratio including water loading effects.

Two other maximum mixing regions are revealed as indicated in the previous two sections, i.e., around 600 mb and above 350 mb. Subsets F3, F4, F5, and F6 show a very large amount of mixing around 600 mb. But Subsets F and F2
Figure 5.13: Same as Fig. 5.1 except using the LFC as the measure to classify thermodynamic soundings for Set T, Subsets F, F2, F3, F4, F5, F6, and F7 at Truk.
Figure 5.14: Same as Fig. 5.13 except for Koror
Figure 5.15: Same as Fig. 5.13 except for Majuro.
have very uniform profiles of dilution ratio above 600 mb, and between 850 mb and 650 mb, respectively. This indicates that convective atmospheres with a low LFC are more uniform with height and require a larger amount of mixing to make neutrally buoyant clouds at levels above 850 mb.

The difference of the mean dilution ratio between subsets is not as large as that shown in Chapter 3 (Figs. 3.2 and 5.13-15). That is to say, the degree of mixing for convective atmospheres with a lower LFC is large when water loading effects are included.

Lastly, the standard deviation in the vertical is very uniform, around 0.2. There is almost no difference between subsets. When comparing the standard deviations of various subsets with those in the previous two sections, we may conclude that the convective atmospheres classified by the LFC are more uniform, at least, in dilution ratios.

5.4.2 Buoyancy

For the subsets, the standard deviation of buoyancy rarely exceeds $1 \, ^\circ C$ except Subsets F and F2 (Figs. 5.16-18). The mean buoyancy for all subsets except subsets F and F2 is around $1 \, ^\circ C$ or slightly exceeds $1 \, ^\circ C$ and does not vary much with height above 700 mb. The mean buoyancy exceeds $2 \, ^\circ C$ at most of levels (close to $3 \, ^\circ C$ for Koror) for subsets F and F2, and the standard deviations in the middle and upper troposphere for these two subsets are much larger than those of the rest of the subsets. It seems that deep convective atmospheres are more inhomogeneous in buoyancy distribution.

In the previous chapter, we discussed the magnitude of negative buoyancy at the cloud base. There is a fundamental difference from those without including water loading effects in Chapter 3, i.e., the positive buoyancy at 950 mb for all subsets in the present calculation except subset F2 which has the LFC at 975 mb. The magnitude of the negative buoyancy just below LFC’s shown in Figs. 5.16-18 rarely
Figure 5.16: Same as Fig. 5.13 except for the mean (solid curve) and the standard deviation (dashed curve) of buoyancy at Truk.
Figure 5.17: Same as Fig. 5.16 except for Koror.
Figure 5.18: Same as Fig. 5.16 except for Majuro.
exceeds $0.5 \, ^\circ C$ for all subsets, implying that the external forcing needed to form clouds is small. The second difference from that in Chapter 3 is that the magnitude of the buoyancy below the LFC is usually less than $0.6 \, ^\circ C$, half of that above the LFC. The shallow convective atmospheres seem more uniform and closer to neutral buoyancy with reference to cloud parcels including water loading during mixing with the ambient environment.

### 5.5 Summary

This chapter examined the mean structure and the variability of buoyancy and dilution ratio including water loading effects. The cloud parcels are assumed to originate at the level of the maximum $\theta_v$ in the PBL and are lifted adiabatically. The results can be compared with those found in the previous two chapters. In those chapters, water loading effects are ignored during mixing between the ambient and cloudy air.

Two extraordinary features are found in the data analyses of this chapter which were not found ignoring water loading effects in Chapter 3. One is that the maximum amount of mixing are found in various types of convective atmospheres categorized with the location of the LFC, the location of the LCL, and the level of the minimum $\theta_v$. The other is that a minimum dilution ratio around 600 mb appears in almost all subsets of these three categorizations.

There is some indication that a more consistent vertical structure may be obtained by lifting parcels from the top of the PBL. The vertical variation of the dilution ratio including water loading effects is smaller than that ignoring water loading effects.
Chapter 6

Summary and Concluding Remarks

In this paper, it is assumed that the actual atmosphere represents a convectively adjusted state. We have calculated the vertical profiles of the degree of mixing that is necessary to make the clouds neutrally buoyant. Thermodynamic variables of convective atmospheres associated with various types of cumulus convection in the tropics were examined. The hypothetical clouds are formed from a reversible moist adiabatic process which includes condensate loading. The mixing between the ambient and cloudy air has been performed for two extreme cases, one ignoring water loading effects (Chapter 3 and 4), the other including adiabatic liquid water content (Chapter 5).

Since we are interested in the macro-structure of convective atmospheres, we have attempted to find a good way of classifying the thermodynamic soundings in the tropics. It is found that the uniformity of convective atmospheres is dependent on (1) the assumed originating levels of cloud parcels and (2) the level of free convection; but not on the thermodynamic characteristics of the surface air such as the mixing ratio, the virtual temperature and the lifting condensation level.

Assuming that cloud parcels originate at an idealized level (the \( \theta_{\text{e,ms}} \) level) in
the PBL, we have found that the two types of mixing processes are distinctive in the following aspects:

1. The minimum virtual temperature achieved by mixing involves air from 50 to 100 mb above the reference level provided this is below the \( \theta_{\text{min}} \) level.

2. A smaller amount of mixing is necessary to achieve neutral buoyancy at high levels when water loading effects are accounted for in defining the dilution ratio.

3. A large amount of mixing appears at the maximum buoyancy level (about 600 mb) when including water loading effects, which is not suggested by the classical theory of entrainment (Stommel, 1947).

4. The differences between convective atmospheres associated with high LFC's and with low LFC's are smaller when including water loading effects.

We have found that the results are sensible to the assumed level of origin of the cloud parcel. The virtual potential temperature difference between 1000 mb and 950 mb has been used to characterize various PBL's in Chapter 4. We have compared cloud parcels lifted adiabatically from the top of the PBL with those lifted from an idealized level. The following properties are found:

1. The amount of mixing necessary to achieve neutral buoyancy is reduced at all levels when air is assumed to originate at the PBL top. The smallest reduction appears at 850 mb. The maximum dilution exists at 850 mb in convective atmospheres assuming that cloud parcels originate near the PBL top.

2. The buoyancy of the hypothetical clouds is closer to neutral when cloudy air is taken to originate at the PBL top. This explains why less mixing is necessary to achieve neutral buoyancy, compared with using idealized origins of cloud parcels.
3. The standard deviation of dilution ratio is not reduced, but that of buoyancy is when cloudy air is assumed to originate from the PBL top. The results may imply that the uniformity of dilution ratio may not only be influenced by the originating level of cloud parcels, but also determined by the uniformity of moisture content at higher levels (above 700 mb) because the standard deviation of dilution ratios are not reduced above 700 mb where the standard deviations of RH are higher than those below 700 mb.

4. The maximum dilution is around 850 mb and is closely associated with a secondary maximum in the mean buoyancy. This feature also appears when water loading effects are included in the mixing process.

Future work should be aimed at understanding the classification of convective atmospheres associated with a variety of cumulus convection. Cumulus parameterization will be aided by knowledge of the properties of such convective atmospheres. The present study suggests the following line of research:

1. To use high resolution data to better estimate the originating levels of clouds parcels, and to better classify thermodynamic soundings.

2. More general mixing processes should be studied in order to properly determine the degree of mixing necessary to make clouds neutrally buoyant.
REFERENCES


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