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Mixing height and Cloud Convection in the Canadian Prairies

by

Olga Ivanovna Stachowiak

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Examining Committee

Gerhard W Reuter, Earth and Atmospheric Sciences

John D Wilson, Earth and Atmospheric Sciences

Thian Gan, Civil and Environmental Engineering

Abstract

The Mixing Height (MH), Convective Condensation Level (CCL), and Convective Available Potential Energy (CAPE) are computed with different methods and we examined whether these parameters can help to discriminate between weak and strong convection. The observational data set contains soundings released from Stony Plain in Alberta and The Pas in Manitoba for the summers of 2006 and 2007. The major findings were:

1) The Mixing Height values computed with the Heffter method were reliable provided the critical inversion criterion was adjusted for Prairie conditions.

2) The Mixing Height values computed with the Moist Mixed layer method were in good agreement with Mixing Heights computed with the Heffter method.

3) The Mixing Height values computed with the Holzworth parcel method were less useful in that often the potential temperature did not decrease with height above the ground.

4) Observed convective cloud base heights tended to be lower than the CCL computed using the surface parcel method, the 50 mb mixed parcel method, and the moist mixed parcel method.

5) The MH, the sounding-based CCL, and the CAPE did not differentiate between weak and strong convection.

6) We derived a new parameter: the difference between the convective cloud base and the Moist Air Mixing Height. This parameter did discriminate between the likely occurrence of strong and weak convection.

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1. Introduction

This thesis is focused on estimating the depth of the atmospheric boundary layer based on synoptic sounding data as well as investigating the relationship between boundary layer mixing and cloud convection. We compare different methods of estimating the mixing heights and verify them against observations of convective cloud base heights. We then explore whether the Mixing Height (MH) and Convective Condensation Level (CCL) provide useful information about the likelihood of weak or strong convection. Our investigation is focused on summer conditions for the Canadian Prairie Provinces. In order to formulate the specific thesis objectives, we need to summarize some background material on mixing depth and convection.

1.1 Atmospheric boundary layer

The atmospheric boundary layer (ABL) is defined as the part of the troposphere that is directly influenced (on a time scale of order 10 - 100 min) by the presence of the earth's surface through the vertical exchange of heat, moisture and momentum (Stull 1988). When there is a strong upward heat flux, the air above the ground gets mixed in the vertical and the depth of the mixed layer (or Mixing Height) tends to reach the height at which the potential temperature returns to the stable stratification of the free atmosphere; in other words the Mixing Height (MH) is determined by the height of the elevated capping inversion. If the atmosphere is convectively unstable over a deep layer and deep convective clouds are formed, the MH is poorly defined and may include the entire troposphere. If convective cloud development is limited, the MH tends to coincide with the cloud base. If there is no cloud formation and the surface wind is strong, the MH agrees with the height at which the Ekman spiral gives way to the geostrophic wind above the atmospheric boundary layer (Angle and Sakiyama, 1991).

The Mixing Height depends on the season, time of the day, the synoptic weather situation and local conditions, such as orography, land use and surface roughness (Stull, 1997). There is a diurnal evolution in the depth of the atmospheric boundary layer. From sunset to sunrise there is usually a downward heat flux. The nocturnal boundary layer is often characterized by a stable layer (or even thermal inversion layer) that suppresses vertical motion. The nocturnal boundary layer thus shows little vertical mixing. After sunrise, solar heating occurs causing thermal plumes to rise, transporting moisture and heat upward and eroding or lifting the inversion layer. These convective plumes rise and expand adiabatically until a thermodynamic equilibrium is reached at the top of the atmospheric boundary layer. As the sun continues to heat the surface the convective thermals become more energetic, generating intense turbulent mixing. This tends to generate well-mixed layers, which have potential temperature and mixing ratio nearly constant with height. A well-mixed layer is often capped by a thermal inversion, which acts as a lid to any vertical motion. There is an entrainment zone between the top of the mixed layer and the bottom of the elevated inversion layer, where drier air from the free atmosphere penetrates down, replacing rising air parcels. Processes within this layer affect the variability of the mixing heights as well as the solar heating and the moisture content near the surface. Therefore, the depth through which horizontal momentum, heat and moisture are blended in the lower atmosphere determines the Mixing Height (Seibert et al., 2000). A number of complicating factors may modify the classical diurnal evolution of the boundary layer. For instance there may be elevated inversions, as a result of subsidence or passing fronts. Elevated inversions have a capping effect on mixing (Myrick et al., 1994).

In temperate continental climates convective mixing is generally confined to daylight hours and primarily to the warm season when solar insolation heats the surface intensely enough to generate buoyant thermals. The depth of the mixing layer grows while the sensible heat flux is directed upward and it often reaches 1 to 3 km in depth. The depth of the afternoon mixing layers depends on the magnitude of the net radiation and how it is partitioned into sensible and latent convective heat flux (Raddatz and Noonan, 2004). With the activation of transpiration by vegetation, the change in energy partitioning may, in some regions, result in a decrease in afternoon mixing layer depths from their spring maximum (Freedman et al., 2001).

The mixing layers can be also mechanically generated due to vertical wind shear and roughness of the surface. This mechanical turbulence is confined to a shallow layer near the ground, thus the depth of the mixing layer is typically a few hundred meters or less (Raddatz and Noonan, 2004).

1.2 Historic overview

Regular measurements of the meteorological conditions above the surface began around 1940 when the radiosondes came into use. The radiosonde, carried aloft by a helium-filled balloon, contains instruments that record temperature, humidity and pressure. The radiosonde also has a lightweight radio transmitter that emits a continuous signal. The temperature and humidity measuring elements control the frequency and amplitude of the audio output of the radio signal. An aneroid barometer cell, moving a contact arm across a series of metal strips, alternately connects temperature and humidity into the circuit. By setting consecutive contacts for known pressure intervals, temperature and humidity are recorded as a function of pressure. The altitude is then computed, based on the vertical distribution of temperature, humidity and pressure using the hypsometric equation.

A pioneering study of estimating the mixed layer depth using radiosonde observations was done by Holzworth (1964). He assumed that the Mixed Height (MH) agreed with the depth of the adiabatic layer using an unsaturated parcel lifted adiabatically from the ground. Holzworth's parcel method was subsequently refined by Garret (1981), Stull (1991) and Wotawa et al. (1996). The refinements were based on adding an excess temperature to the surface temperature to allow for advection and measurement uncertainties.

A different approach to estimating the Mixed Height (MH) was suggested by Heffter (1980). He argued that the MH could best be identified by finding the critical inversion above the adiabatic mixed layer. Seibert et al. (1998) compared Heffter's method with different parcel methods. They found that parcel methods are more reliable in cases of convective overturning. A newest method of estimating the MH based solely on the humidity profile was advocated by Lyra et al. (1992). They equated the MH with the height at which the water vapor had a significant reduction.

Only a few studies on mixing layers have been carried out for western Canada and the focus of these studies was on estimating the plume heights of pollutant dispersion released from ground sources. Portelli (1977) computed mean seasonal and annual mixing heights for radiosonde stations in western Canada from 1965 to 1969 based on the Holzworth parcel method. He presented maps showing the spatial distribution of MH. Raddatz et al. (2004) presented similar spatial distribution of monthly mixing layer depths for Manitoba, Saskatchewan and Alberta based on afternoon soundings from 1997 to 2001. Their computations of MH were also based on the Holzworth parcel method. An investigation of mixed layers was done using data sampled by minisondes released from Edmonton (Alberta Environment, 1991). Sakiyama et al. (1991) computed mixing heights using the Holzworth and the Heffter (capping inversion) methods.

1.3 Methods to compute Mixing Height

a) Holzworth (1964) parcel method: Holzworth estimated the Mixing Height (MH) using a parcel method without entrainment. He assumed that during day time, absorption of solar radiation by the ground and heat conduction to the air in contact with the warm ground result in slightly superadiabatic lapse rates causing vertical overturning (mixing) that ultimately produce a mixed dry adiabatic layer. Neglecting the modifying effects of advection and subsidence (that could change the vertical temperature profile between its time of observation and that of reaching the peak in surface temperature), Holzworth assumed that the MH depends upon the vertical structure and the surface maximum temperature. We note that the profile of water vapor is neglected in the Holzworth method. The basic idea of the Holzworth parcel method is to follow the dry adiabat starting at the surface with the measured or expected temperature up to its intersection with the temperature profile from the most recent radiosounding. It determines the MH as the equilibrium level of a hypothetical rising parcel of air representing a thermal. Seibert et al. (1999) indicated that there can be a high uncertainty in the estimated MH value in conditions without a pronounced inversion at the convective boundary layer top.

b) Heffter (1980) temperature inversion method: Heffter developed a method to estimate the MH based on finding the critical inversion in the observed potential temperature profile. In the Heffter method, the critical inversion identifies the

MH. The underlying assumption here is that turbulent mixing caused by convective and mechanical turbulence extends to the base of the elevated inversion. The inversion puts a cap on the vertical extent of mixing in the boundary layer thereby forming the mixing layer. The critical inversion was defined as the lowest inversion layer where potential temperature increased at a rate equal to or larger than 5 K km^{-1} and the temperature difference between inversion base and inversion top must exceed 2 K. The height of the mixed layer is that point in the inversion layer at which the temperature is 2 K above the temperature at the inversion base. Marsik et al. (1995) discuss the possible over-estimation of MH within a surface-based nocturnal inversion where the degree of mixing is likely to be quite shallow.

c) Lyra humidity lapse rate method: A third method to estimate the MH is based on the notion that the mixing can be identified in the humidity profile. A significant reduction in humidity with height (humidity "jump") marks the top of the mixed layer (Lyra et al., 1992). They estimated the MH by identifying a water vapor mixing ratio lapse rate of 10 g kg^{-1} km^{-1} or more. Higher water vapor mixing ratio increases the buoyancy of the air, leading to increased thermal turbulence and a greater mixing depth (Berman et al., 1995).

1.4 Convective Condensation Level

Vertical mixing within a column of air above the ground often occurs as a consequence of solar heating of the surface. Heat is transferred by conduction from the surface to the air layer in contact with it. This causes a strong lapse rate in temperature in the lowest layer of air. When the lapse rate becomes superadiabatic, any small disturbance will lead to updrafts (and compensating downdrafts) in elements of air in the layer, causing general mixing and overturning. The temperature profile in the mixing layer will tend toward the dry adiabatic and the water vapor mixing ratio will approach its average value. Thus, in the mixed layer the potential temperature and the water vapor mixing ratio are conserved and height independent, except in the lowest layer (10 - 100m) where proximity to ground reduces the efficiency of mixing.

If strong heating at the surface continues, this heat will be convected upwards, raising the potential temperature of the air throughout the layer. Additional heating raises the potential temperature and increases the thickness of the mixed layer. Eventually, the mixed layer might reach a height where condensation occurs, which is called the Convective Condensation Level (CCL). The bases of cumulus clouds are found to occur at the CCL. If the air is conditionally unstable above the CCL, ascent of a rising parcel would continue with temperature decreasing at the pseudo-adiabatic lapse rate (Rogers and Yau, 1989; Iribarne and Godson, 1981; Djuric, 1994).

Related to the CCL is the lifting condensation level (LCL), which is defined as the level where a parcel of air just reaches saturation if it is lifted dry adiabatically from the surface. In conditions under which cumulus clouds are observed to form due to surface heating, the LCL and CCL often agree closely with one another because the air below the cloud base is usually well mixed. In convective conditions, the LCL has long been used to estimate boundary layer cloud heights (Stackpole, 1967).

Stull and Eloranta (1985) used a ground-based lidar system to measure cumulus cloud bases. They found that the LCL and CCL based on surface temperature and water vapor mixing ratio were in close agreement with observed cloud bases. There are different methods used to estimate the LCL and CCL (Doswell and Rasmussen, 1994) based on different assumptions about the mixing that might occur during the lifting of parcel air.

Crum et al. (1987) and Wilde et al. (1985) found that some surface air remains undiluted in the core of thermals rising through the mixed layers. Bunkers et al. (2002), however, showed the importance of entrainment as it affects the triggering and intensity of the convection. Doswell and Rasmussen (1994) advocate the use of the most unstable parcel by showing some cases where surface-based parcels underestimated the potential for convection. Craven et al. (2002) recommend using a mean-layer parcel using a mixing depth of 100 mb to estimate convective stability parameters.

1.5 Thesis objectives

Previous research in this field in Canada was concentrated mainly on the climatology of mixing layers and spatial patterns of Mixing Height (MH). The focus of our work is to determine a practical and reliable way of calculating MH and related quantities and find how they are related to the occurrence and intensity of cloud convection. The four main objectives of this thesis are:

1) To find the best method to estimate the Mixing Height (MH) for summertime conditions over the Canadian Prairies;

2) To determine the variability of the summertime MH over the Canadian Prairies;

3) To find the best method to estimate the Convective Condensation Level (CCL) and Convective Available Potential Energy (CAPE) for summertime conditions;

4) To find whether there is dependence between the Mixing Height (MH), convective initiation and convective intensity.

In order to address these four major objectives we analyze the thermodynamic profiles sampled by radiosondes over Stony Plain (Alberta) and The Pas (Manitoba). These are the only upper air stations over the Canadian Prairies. Our analysis of MH will be compared with observed cloud base heights for days with convective clouds. The ultimate goal of our investigation is to assist operational forecasters in improved interpretation of sounding observations and to improve the assessment of potential for convective storms.

2. Data base and methodology

2.1 Data base for upper air soundings

The intensity and organization of convective storms depend largely on the vertical stratification of temperature, humidity and wind. To assess the vertical profile of the atmosphere, meteorologists rely mainly on balloon-sounding data. Radiosondes are released at designated World Meteorological Organization (WMO) stations throughout the world twice daily at 0000 UTC (Coordinated Universal Time) and 1200 UTC. There are two upper-air stations in the Canadian Prairie provinces: Stony Plain in central Alberta and The Pas in western Manitoba.

The Stony Plain upper station (WSE) and The Pas (YQD) are located at (53.55°N, 114.10°W) and (53.58°N, 101.06°W), respectively (Figure.2.1). We note that they have similar latitudes. The elevations of WSE and YQD are 766 m ASL and 271 m ASL, respectively. The surrounding landscape of Stony Plain consists of cultivated, agricultural land (Transitional Grassland eco-climate zone), while the surrounding area of The Pas consists mostly of forest and agricultural land (Mid-Boreal zone.)

In our study of mixed layers and convection we are interested in the Mixing Height (MH) of the summertime afternoon conditions when convective triggering is most common. Since the 1200 UTC rawinsonde soundings at WSE and YQD sampled early morning atmospheric profiles, they are not representative for estimating the afternoon MH conditions. Instead, we have used the 0000 UTC soundings that measure the atmospheric profiles at 6 pm Mountain Daylight Time (MDT) for WSE, and 7 pm Central Daylight Time (CDT) for YQD. Convection is most common during the summer months, and accordingly the radiosonde dataset covered the period 1 June to 31 August 2006 and 1 June to 31 August 2007. The sounding data were taken from the Plymouth State Weather Center Archive. It consists of temperature, humidity, and wind speed and wind direction for constant pressure levels. For both WSE and YQD a total of 184 soundings were included in the data set.

2.2 Data base for convective cloud observations

Our interest in estimating the Mixing Height (MH) of the atmospheric boundary layer was mostly concerned as the mixing above ground relates to the formation of convective clouds and possible development of thunderstorms. In order to relate the atmospheric profiles to convection, we need to have observations of the type and amount of cloud as well as the height of the convective cloud bases.

Initially we used only human observations of cloud type, cloud amount and cloud base height as estimated by human observations located at Stony Plain (WSE). The data were taken from the Pacific Weather Center archive. However, the human observations at Stony Plain were rather sparse and there are significant gaps in the cloud observations. To make up for the shortage of cloud observations at WSE, we also used cloud observations recorded at Edmonton International Airport (YEG) located at (53.18 °N , 113.34 °W) about 30 km southeast of WSE.

A difficult question in our study was choosing time and space proximity for the sounding. Darkow (1969), for example, required pre storm soundings to be within 80 km of a storm and released within the time frame from 45 minutes before to 60 minutes after the event. On the other hand, Rasmussen and Blanchard (1998) allowed the sounding to be released within 400 km of a storm and in a time frame of three hours before to six hours after the event.

In this study the time window for the surface-based observations of cloud type and convective cloud base heights were taken within ± 2 hours of the sounding time (i.e. from 2200 UTC to 0200 UTC). Smaller temporal constraints might provide slightly better proximity soundings for cloud convection, at the expense of a smaller dataset of soundings with convective clouds.

Another reason why we have adopted the cloud observations taken above Edmonton International Airport (YEG) is that this station is equipped with ceilometer that records cloud base heights continuously, whereas at Stony Plain (WSE) cloud bases were estimated by human observers. Human observations of cloud heights tend to be rather coarse and inaccurate based on the degree of experience of the human observer.

The ceilometer at YEG consists of a vertically pointing laser device that emits short duration pulses upwards. The duration of these laser pulses is on the order of nanoseconds. The laser pulses penetrate into the atmosphere until they are partially reflected by cloud droplets. The size of the scattering cloud particles are similar to the wavelength of the laser resulting in Mie scattering. A small fraction of the emitted laser energy pulse is scattered back to the receiver at the ground. The precise timing between the emitted laser pulse and the backscattered reflected pulse can be recorded. The accuracy of the laser ceilometer of cloud base heights is good if the cloud base is flat and distinct.

At The Pas (YQD) the cloud base observations were done only by human observers. The cloud base heights were estimated by releasing a ceiling balloon and tracking it with the human eye. A ceiling balloon is filled with a specific amount of helium. The free flight speed is approximately constant for a ceiling balloon at about 460 feet/min or 140 meter/min. The human observer records the time of the release of the ceiling balloon and when it enters into the cloud. Based on the uniform flight speed, the time interval is then converted to a cloud base height. Often it is difficult for the human eye to detect exactly when the ceiling balloon enters the cloud base. Often, the time when the ceiling balloon changes its color or starts to fade is taken as the entrance time into the cloud. Weather conditions adversely affect the accuracy of ceiling balloon cloud base estimates. In the presence of strong winds the vertical component of the flight speed is affected. Typically, strong winds result in underestimation of the cloud base height, particularly in poor visibility conditions. The large horizontal movement of the ceiling balloon in flight makes it appear that the balloon entered the cloud before it actually did. Also, breaks in the cloud layer result in inaccurate heights unless the balloon is carefully watched to see whether it enters the base of the cloud layer or goes through a break.

Based on these discussions of different ways of estimating the cloud base heights we make the following conclusions:

1) The cloud base observations at Edmonton International Airport (YEG) are reliable for convective clouds in the afternoon and early evenings unless it precipitates at the time of cloud observations. The cloud observations at Stony Plain (WSE) are less complete and likely less accurate than those sampled at YEG by laser ceilometer.

2) Cloud base observations at The Pas (YQD) are likely less accurate than at YEG due to the shortcomings of the ceiling balloon technique. We expect that the cloud height observations are reliable for low cloud bases in calm conditions, but less so for high cloud base conditions.

Table 2.1 lists all the days in our data set on which convective clouds were recorded at YEG. In most cases, the cloud observations at YEG and WSE agreed (Table 4.1). If there was discrepancy, the WSE data was adopted due to its proximity. The table shows the recorded cloud base heights (in units of kilo feet) and the type and amount of cloud and weather. The cloud observations for The Pas are listed in Table 2.2.

2.3. Comparison between the summers of 2006 and 2007

Tables 2.3 and 2.4 contain the monthly number of convective days for two summers at YEG/WSE and YQD. The total number of convective days includes the number of days when any amount of convective cloud (from FEW to OVERCAST) was observed in the required time frame. The column with number of days with convective weather includes the number of days when the convective clouds produce any weather such as thunder or thunderstorm, rain or showers.

Table 2.3 shows that the number of convective events differed significantly between the summers of 2006 and 2007 at YEG. In the summer of 2006, there were 33 convective days (with observations of a cumulonimbus (CB) and/or towering cumulus (TCU)), whereas in 2007 there were 46. The most convective month at this location was June 2007 and the least convective month was June 2006. The number of events indicates that the summer of 2007 was much more convectively active than the summer of 2006. The severe weather event database (SWED) of Environment Canada also indicates a larger number of Severe Weather Events for Alberta in 2007 compared to 2006 (Table 2.5). This database is designed to collect public reports on severe weather events in Canada. The database provides information on location, type and severity of the event.

Figures 2.2 and 2.3 compare lightning activity between the summers of 2006 and 2007. The maps show the number of cloud to ground lighting flashes per square kilometer based on a resolution of 20 km x 20 km grid boxes. Over Stony Plain the lightning flash density was 0.63 flashes per km^2 for 2006, and 1.29 flashes per km^2 for 2007 (personal correspondence with Dr. W. Burrows, Environment Canada). Thus there were about twice the number of lightning flashes in the summer of 2007 compared to the summer of 2006.

Some differences in initial soil moisture depth were found on Alberta Environment soil moisture maps estimated as of 14 May, 2006 and 7 May, 2007. In May of 2007 there was more moisture available in the ground than in May of 2006. These soil moisture data were modeled for spring wheat on medium textured soils using Modified Versatile Soil Moisture Budget V-1.0 model (Figure 2.4 and 2.5). The model was initialized with field soil moisture data collected during April of 2006 and April –May of 2007.

Additional information could be found on Government of Alberta website: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag6302.

To the contrary, the number of convective events at YQD for the same time frame did not show significant variation. There were 21 convective days in the summer of 2006 and 20 in 2007 (Table 2.4). The lightning data at YQD was also found to be different from WSE. The lightning flash density for The Pas was 0.33 flashes per km^2 for 2006 and only 0.16 flashes per km^2 for 2007. Thus, The Pas received fewer lightning strokes in 2007.

In the subsequent chapters we will often refer back to the differences in convective activity between the two summers.

2.4 Methods used to compute Mixing Height

a) HZMH - Holzworth Mixing Height

To analyze thermodynamic profiles for atmospheric stability and mixing it is convenient to analyze the observations in terms of potential temperature θ, defined

$$\theta = T\,(p_0 / p)^{k}$$

where T is the temperature (° K), p is the pressure (mb), p_0 = 1000mb , and k = 0.286 (Rogers and Yau, 1989).

The HZMH method uses the measured or expected potential temperature at the surface and assumes that vertical mixing will establish a constant θ value. In his original paper, Holzworth used the morning temperature sounding (0700 EST). Horizontal advection of temperature and humidity were neglected. The HZMH value is found by lifting a surface parcel adiabatically until it intersects with the observed θ curve.

In our analysis we have adopted the Holzworth technique with minor modifications. We used the 0000 UTC sounding with the surface temperature measured at 0000 UTC.

The Mixing Height was estimated by using the following:

1) for super-adiabatic profiles (θ decreases with height): $\theta_{MHtop} = \theta_{sfc}$

2) for adiabatic profiles (θ uniform with height): $\theta_{MHtop} = \theta_{sfc}$

3) for quasi-adiabatic profiles (θ varies only slightly with height):

$$\theta_{MHtop} = \theta_{sfc} + 0.5K$$

4) for stable profiles (θ increases with height): MH is undefined.

Modification # 3 was based on instrumentation error of about 0.3°C of the temperature probe, according to results from the WMO Radiosonde Comparison results (Nash, 2004). If the sounding was stable the Holzworth method is not applicable and the MH remains undefined. In our analysis we have set MH = 0 m in such cases. Figure 2.6 shows an example of how to use the Holzworth method for an observed potential temperature sounding.

b) HFMH - Heffter Mixing Height

For the estimation of the MH using the Heffter (1980) method the potential temperature profile is analyzed to find the critical inversion layer. Heffter defined the critical inversion as the lowest inversion layer where potential temperature lapse rate is equal or larger than 5 K km^{-1} and the temperature difference between inversion base and inversion top must exceed 2 K. The MH is the height in the critical inversion layer at which the temperature is 2 K above the temperature at the inversion base:

$$\Delta\theta/\Delta z \geq 5 \text{ K/km} \quad \text{and} \quad \theta_{top} - \theta_{base} \geq 2 \text{ K},$$

where $\Delta\theta/\Delta z$ is the potential temperature lapse rate in the inversion layer and θ_{top} and θ_{base} refer to the potential temperature at the top and bottom of the critical inversion layer.

Initially we calculated MH using the original Heffter criteria. The values of HFMH were then compared against the values reported by Raddatz et al. (2004) for central Alberta and Manitoba. The comparisons suggested that the Heffter criteria were likely not applicable for summertime conditions in western Canada. We have adjusted the Heffter criteria as follows:

1. A critical inversion θ *lapse* rate of 3 K km^{-1} was used instead of 5 K km^{-1}.

2. The second criterion of the Heffter technique, associated with temperature difference between the inversion base and top was used partially, just for assurance, that the inversion is strong enough in order to prevent the mixing.

The mixing layer top in this case is assumed to be at the inflection point, where the critical inversion lapse rate of 3 K km^{-1} begins.

3. The atmospheric conditions with shallow mixed layers (≤300 m) near the surface and strong inversion ($\Delta\theta/\Delta z \geq 3\ K\ km^{-1}$) above would be reported as days when MH was undefined.

4. Atmospheric conditions with the ground based inversion would be reported as days when this method was not applicable and MH was undefined. In this study the ground based inversion is defined by an inversion lapse rate of $\Delta\theta/\Delta z \geq 3$ K km^{-1} and an inversion depth of at least 300 m.

Figure 2.7 shows an example of using the Heffter method for an observed potential temperature sounding.

c) MAMH - Moist Air Mixing Height

The density of moist air is less than the density of dry air. Thus the presence of water vapor increases the buoyancy of a moist air parcel. Large amounts of water vapor can enhance the thermal turbulence causing a deeper mixed layer. The water vapor mixing ratio profile was neglected in the Heffter and Holzworth techniques. The use of virtual potential temperature (instead of dry potential temperature) could be adopted for moist conditions.

Lyra et al. (1992) used a humidity lapse rate of more than 10 g kg^{-1} km^{-1} as an indicator of the Mixing Height. They developed the method to examine the boundary layer in a marine tropical region. They found that the cloud layer corresponds to the layer with a large gradient of moisture between the mean water vapor mixing ratio value inside the boundary layer (about 15 to 20 g kg^{-1}) and in the free atmosphere (about 5 to 8 g kg^{-1}) (Lyra et al., 1992). Soundings taken at Stony Plain and The Pas typically have smaller differences in humidity values. The typical water vapor mixing ratio ranged from 5 to 10 g kg^{-1} near the surface and is about 1 g kg^{-1} in the free atmosphere.

We have modified the method for use in the Prairies as follows: The decrease of vapor mixing ratio of equal or greater than 1.5 g kg^{-1} km^{-1} ($\Delta w/\Delta z \geq 1.5$ g kg^{-1} km^{-1}) indicated the top of moist mixing layer (Figure 2.8). The humidity profile was often quite variable for Stony Plain therefore we adopted the following assumptions:

1. For soundings with $\Delta w/\Delta z \geq 1.5$ g kg^{-1} km^{-1} in the lowest layer greater than 600 m in depth the MH was reported as undefined (Figure 2.9).

2. For soundings with $\Delta w/\Delta z \geq 1.5$ g kg^{-1} km^{-1} within the lowest 600 m layer and on upper levels exhibiting strong moisture mixing the MH was calculated neglecting the lowest dry layer (Figure 2.10).

2.5 Methods used to compute Cloud Condensation Level (CCL)

This section describes the methods we used to compute CCL for days on which convection occurred. Specifically, a day was included in the dataset if the observational records indicated the presence of a towering cumulus (TCu) and/or cumulonimbus (Cb). The major assumption is that the atmospheric profile sampled over Stony Plain is representative of the vertical structure of the atmosphere in the circular area with radius of 50 km which covers the recorded cloud observations. Furthermore, it is assumed that the 0000 UTC sounding is representative for the period from 2200 UTC to 0200 UTC, the 4 hour time window for the convective cloud observations.

There are several methods to quantify the amount of energy that could be released during convective overturning (Doswell and Rasmussen, 1994). In this thesis, we will use three methods differing in their assumption of mixing in the layer above the ground (Figure 2.11).

1. Adiabatic lifting from the surface (SB): in this method we assume that an air parcel with the temperature, water vapor mixing ratio, and pressure of the surface air, is lifted adiabatically without mixing until its level of condensation.

2. Adiabatic lifting from the 50 mb mixed layer (ML): in this method we assume that the air is mixed in the lowest 50 mb (roughly 500 m) above the ground in

terms of temperature and water vapor mixing ratio. An air parcel with the mixed properties is lifted adiabatically until it reaches its level of condensation.

3. Adiabatic lifting from the top of the Moist Mixed Layer (MM): in this method we first determine the Moist Mixed Layer and then lift an air parcel with the temperature and water vapor mixing ratio of the top of the Moist Mixed Layer. The motivation for using the Moist Mixed Layer for assessing the potential of convection is that the moisture content is such a crucial ingredient for convective development.

The CCL(SB) by the SB method is determined on a tephigram as follows (Figure 2.11). The temperature changes follow the dry adiabatic line (i.e. constant potential temperature line) that passes through the surface. The water vapor mixing ratio remains constant at the surface value, i.e. dew point changes by following the constant mixing line passing through the surface value. Once the lifting condensation level is reached, temperature follows the moist adiabat (pseudo-adiabat) on the tephigram. The level of condensation marks the CCL(SB) value. The CCL(ML) by the ML method is determined similarly (Figure 2.11). We first mix the lowest 50 mb of air and then find the level of condensation by adiabatically lifting. The CCL(MM) is found by adiabatic lifting the parcel from the top of the Moist Air Mixing Height (MAMH). In our dataset there were three days with observed convection where there was no Moist Mixed layer and the MAMH value was undefined. On these three days we decided to replace

CCL(MM) by CCL(ML) i.e. to accept 50 mb layer where moisture could possibly to be mixed.

3. Computation of Mixing Height using different methods

3.1. HFMH - Heffter Mixing Height

The HFMH values for the period from 1 June to 31 August 2006 and 2007 are listed for Stony Plain (WSE) in Table 3.1 and 3.2, respectively. All HFMH were computed using the 0000 UTC soundings. The daily MH values for 2006 range from 0.4 km to 4.0 km, with an average value of about 2.0 km. Table 3.3 compares the monthly average values of HFMH for the six summer months. The daily MH values in 2007 range from 0.4 km to 3.0 km with an average monthly MH value about 1.4 km, suggesting that the typical mixing layer over central Alberta for this summer was shallower than in the summer of 2006. Only 20 % of all summer days in 2007 exhibited MH values greater than 2.0 km compare to 50% in 2006. Also 10% of all summer days in 2006 had MH values of 3.0 km and higher whereas none did in 2007. Only one day on 19 August 2006 had MH value greater then 4.0 km. 20% of the summer days in 2007 resulted in MH values lower than 1.0 km versus only 10% in 2006.

The HFMH values based on The Pas (YQD) soundings for summer days of 2006 and 2007 are listed in Table 3.4 and Table 3.5, respectively. The MH ranged from 0.5 km to 3.9 km in both summers. Typically, the MH was shallower over The Pas in comparison with those at Stony Plain. About 30% of the MH values were greater than 2.0 km but lower than 4.0 km. Only 10% of all days in both summers resulted in MH values below 1.0 km. The monthly MH average values at YQD show little variation between the two summers, ranging from about 1.6 km to 1.9 km (Table 3.3). There was no significant difference in the MH values between two summers at The Pas.

Portelli (1977) found a tendency for the mixing heights to decrease eastward from Rocky Mountains. His mean summer MH values were near 1.9 km over central Alberta and about 1.4 km over central Manitoba. Our calculations have shown similar results only with some variations between two summers at WSE.

3.2 HZMH - Holzworth Mixing Height

Table 3.6 and Table 3.7 list the daily Holzworth Mixing Height values computed with the Holzworth parcel method using the 0000 UTC soundings from Stony Plain (WSE). The values range from about 0.4 km to 3.0 km. The average value for the year of 2006 was about 1.9 km and about 1.4 km for 2007 (Table 3.8). 20% of all summer days for both years were found to be stable and the Holzworth method was not applicable. Only 10% of all days exhibited MH values lower than 1.0 km and 25% had MH values greater than 2.0 km. Only on 3 July 2006 the estimated MH value was slightly greater than 3.0 km. Therefore fluctuations in mixing depths, estimated by the Holzworth method were found to be smaller than those estimated by the Heffter technique. A 0.5 km difference in MH values on average was found between the summers of 2006 and 2007.

Table 3.9 and Table 3.10 list the daily Holzworth Mixing Height values computed with the parcel method using the 0000 UTC soundings from The Pas (YQD). 30% of all summer days for both years were found to be stable and Holzworth method was not applicable. The Holzworth Mixing Heights from The Pas (YQD) soundings were lower than those at WSE ranging from 0.3 km to 2.3 km, with average value near 1.3 km (Table3.8). Only 5% of all days exhibited a MH value greater than 2.0 km and 20% of the days had the MH value lower than 1.0 km. The variations in MH values between the two summers were not significant.

3.3 MAMH - Moist Air Mixing Height

In the assessment of Mixing Heights using the Moist Air method, the water vapor mixing ratio profiles did not always exhibit a clear mixing moist layer zone, despite the fact that the other two methods clearly indicated a mixing layer. Our analysis showed that mixing of moist air at low levels did not occur in 18% of the 0000 UTC soundings at Stony Plain for the summer of 2006 and 2007. Table 3.11 and Table 3.12 list the computed MAMH values for the summers of 2006 and 2007 at Stony Plain (WSE), respectively. The MAMH values ranged from 0.4 km to 3.2 km at Stony Plain (WSE) in both summers. The monthly average values were found to be lower at Stony Plain during the summer of 2007 and range on average near 1.3 km versus average values for 2006 fluctuating from 1.6 km to

2.0 km (Table 3.13). The highest MAMH value was computed for 18 July 2006 at 3.2 km.

Table 3.14 and Table 3.15 list the MAMH values for the summers of 2006 and 2007 at The Pas (YQD). The MAMH values ranged from 0.4 km to 3.4 km with an average monthly value near 1.4 km in 2006 and 1.6 km in 2007 (Table 3.13). The mixing of moist air at The Pas did not occur in 12% of all the summer days for both years.

3.4 Inter-comparison of the three Mixing Height methods techniques

An overall discrepancy in the mixing heights calculated using the simple parcel, critical inversion and moist air methods are obvious at the outset. A critical inversion mixing height (HFMH) was detected in 91% and 95% of all observations at Stony Plain and The Pas, respectively. A simple parcel method (HZMH) was developed for unstable conditions. We have added to this group neutral and near neutral conditions. In this case the HZMH was detected in 80% and 70% of all observations at Stony Plain and The Pas, respectively. The MAMH was detected in 82% and 88% of all observations at Stony Plain and The Pas, respectively.

The correlation between mixing heights determined by the different methods are presented in form of a scatter diagram on Figures 3.1- 3.6.

The Holzworth technique is based on a dry adiabat drawn from the surface temperature. This suggests that for days with strong convective mixing, the Holzworth method would tend to overestimate the actual mixing layer height. In convectively dominated mixing layers, a superadiabatic lapse rate exists in the lower part of the layer, thus a dry adiabat drawn from the surface temperature will intersect the actual mixing layer temperature profile at a point higher than where the critical inversion layer actually begins. These overestimated HZMH's are evident at Stony Plain (Figure 3.1). The Pas region does not exhibit the same tendency for HZMH's and most likely because it is a less active convective region (See Figure 3.4). In fact in almost 30% of all observations, the Holzworth technique at this region was not applicable due to more stable atmospheric conditions.

MAMH distribution exhibited in most cases lower values versus HZMH at Stony Plain (Figure 3.3) and good correlation with HFMH at both locations (See Figure 3.2 and Figure 3.6).

3.5 Comments about the "skin" layer in humidity profiles

Closer examination of the sounding data sampled over Stony Plain revealed that usually the atmosphere consists of four layers: the skin layer, the moist mixed layer, the dry mixed layer and the free atmosphere layer (Figure 3.7). The skin layer in the 0000 UTC soundings at Stony Plain was found in about 70 % of the 2006 summer soundings and about 50 % of the 2007 summer soundings. The typical depth of the skin layer was about 50 to 100 m. It typically exhibited a large moisture gradient between the bottom and the top of the layer (about 2 to 5 g kg^{-1}).

There are two possibilities that might contribute towards establishing the large low level water vapor “discontinuity”. One possibility would be strong evapo-transpiration from the local vegetation near Stony Plain. The alternative would be that there was strong low level advection of humidity.

The Pas soundings also showed the four layers profile: the skin layer, the moist mixed layer, the dry mixed layer and the free atmosphere. Skin layers with large humidity gradients, extended higher at The Pas ranging from 300 to 500m. The skin layer was found in 60% of The Pas soundings. The water vapor mixing difference between the bottom and the top of the skin layer varied from 2 to 5 g kg^{-1}, similar to that at Stony Plain.

3.6 Summary on Mixing Heights in Canadian Prairies

Almost 360 soundings were analyzed manually for the summers of 2006 and 2007 at two locations: Stony Plain and The Pas. The data were analyzed to obtain the mixing heights using three different techniques: simple parcel (Holzworth), critical inversion (Heffter) and moist air (Lyra). The major findings were:

1. All three techniques required some adjustment to estimate the Mixing Heights for summer conditions at Stony Plain and The Pas. The adjustments used were as follows:

- The HFMH method (critical inversion method) used the new criteria for critical inversion lapse rate: $\Delta\theta/\Delta z \geq 3$ Kkm^{-1}.
- The HZMH method (parcel method) allowed for neutral and near neutral condition where potential temperature was allowed to fluctuate with height ±0.5 K near the surface value within the mixed layer.
- The MAMH method used the new criteria for mixing ratio lapse rate when $\Delta w/\Delta z \geq 1.5$ g kg^{-1} km^{-1}.

2. There was fair agreement in terms of the Mixing Height computed using the HFMH (Heffter) method and the MAMH (Moist Air) method. This agreement was found for both WSE and YQD.

3. The scatter diagrams suggest that the HZMH method tends to overestimate the Mixing Height at WSE and underestimate them at YQD. Another, disadvantage in using the Holzworth method is that the parcel technique was not feasible for almost 30% and 20% of the soundings at YQD and WSE respectively, during the two summers.

4. Convective Condensation Level (CCL)

4.1 Comparison of observed and estimated CCL values at Stony Plain (WSE)

a) Observed convective cloud base heights

In section 2.2 we described the methodologies of estimating the convective cloud base heights based on ceilometer measurements and estimates of following ceiling balloons by human observers. The section had discussion of the complications and uncertainties inherent in measuring cloud base heights. The convective cloud base heights measured at YEG for the summer of 2006 were listed in Table 2.1. Table 4.1 compares the cloud base heights for YEG and WSE. Only 20% of cloud base observation exhibited substantial differences (greater than 0.3 km) between cloud base observed at YEG and WSE. The observed CCL heights were found to fluctuate from 0.8 km to 2.6 km in 2006 and from 0.5 km to 2.6 km in 2007 (Table 4.1). The number of days with low convective cloud base (1.5 km and below) was found to be greater in 2007 versus 2006. An average value for the summer of 2006 was 1.8 km and 1.3 km for the summer of 2007 (Table 4.2).

b) Comparisons of CCL (observed) and CCL(MM)

Both the estimated CCL(MM) and the observed cloud base had lower convective cloud base heights during the summer of 2007 compared to the summer of 2006.

The estimated CCL(MM) based on previously calculated moist air mixing heights (MAMH) resulted in mostly higher values than the CCL observed at the weather station with only a few exceptions (Figures 4.1 and 4.2). The observed cloud base was found to be higher than the estimated CCL(MM) in cases when the moist mixing height (MAMH) was below 700 m or no moisture mixing occurred. Low mixing heights near 600 m were estimated on 26 July 2006, 23 June 2007 and 22 August 2007. No moist mixing layer was determined on 19 July 2007 and 5 August 2007. Small differences between the estimated cloud base and its observed value were found when the estimated clouds were found to be below or near a 2000 m cloud deck. This difference mostly fluctuated within 500 m. Only 2 exceptions were found in this group on 31 July 2006 and 30 July 2007, when this difference was near 1.0 km. Greater than 1.0 km differences between the estimated and the observed cloud base were found when the estimated cloud deck was found to be above 2000 m. For example, on 17 June 2007 the difference between observed and estimated cloud base was found to be near 1.5 km with estimated cloud base near 2.5 km. Based on our observations and calculations we found that even though estimated cloud bases would be always higher than the moist mixing layer top, relatively shallow mixing layers could produce high cloud bases as well. For example on 6 July 2006 low moist mixing heights near 600m have produced relatively high cloud bases greater than 2.0 km.

Histograms of the average estimated and observed monthly CCL values confirm our findings that the CCL estimates based on the sounding were on average, higher than the observed cloud base, and that the differences in values between the estimated and the observed values tended to be smaller for the lower estimated CCL (Figure 4.3). When the cloud base was 1.5 km or less the CCL values were often in good agreement. The difference between observed and estimated CCL values were less than 0.5 km in about 40% of all convective days. Another 30% fell into the 0.5 km to 1.0 km range, and 30% exhibited difference of 1km and greater up to 2 km. In general, the lower the cloud bases, the smaller the difference between the observed and sounding-estimated value.

c) Comparison of CCL (observed) and sounding estimated values CCL(SB), CCL(ML), CCL(MM)

As described in Chapter 2, we estimated CCL values based on three different methods for all the summer days of 2007 that had observed convection. Figures 4.4, 4.5 and 4.6 represent plots of CCL estimated by three different methods. Here, CCL heights are plotted in descending order as determined by values of CCL(MM). The observed CCL is also plotted on these graphs in the same order of dates as the CCL(SB) and CCL(ML). These plots are constructed in this fashion to contrast the differences between the low cloud base and high cloud base cases.

The best comparison between estimated CCL and the observed CCL was found when the parcel was lifted from the surface CCL(SB) in June 2007 and July 2007.

The difference between these values was fluctuating from 0.1 km to 0.7 km. For August 2007, the best agreement was found when a parcel was lifted using the 50 mb mixed layer CCL(ML). This difference varied from 0 to 1.0 km. The estimated CCL(MM) based on lifting a parcel from the top of a moist mixed layer was found to be higher than the observed CCL and the other estimated values of CCL as well. The difference between the CCL(MM) and the observed CCL varied from 0 to 1.5 km with an average value of 0.5 km (Tables 4.3, 4.4, 4.5).
The Figure 4.4 shows the comparison for June 2007. At this time the CCL(SB) and actual observed value are almost identical with only few days when the difference between two values was 160 m on average. The Figure 4.5 shows the comparison for July 2007. For this period the difference between the estimated and actual cloud base value was found to be near 300 m on average with big difference near 700 m on 20 July and 29 July 2007.

Figure 4.6 shows the comparison for August 2007. During this period it seems that lifting of 50 mb mixed layer parcel would be the best way to estimate a convective cloud base as the CCL(ML) values had the best agreement with the actual cloud base. Again, a lower estimated cloud base tended to improve the agreement between the three methods and the observed CCL. Any of the methods to estimate the CCL values can cause a significant deviation from the observed CCL value when the estimates of a cloud base height exceeded 2 km.

4.2 Comparison of observed and estimated CCL values at The Pas (YQD)

41 convective days were analyzed using data from The Pas (Table 2.2). The observed cloud base heights at The Pas was found to be fairly coarse, due to the fact that the observer-estimated cloud base heights were rounded to 500's of feet. In addition, the natural variability of observed cloud base heights was fairly low. For the summers of 2006 and 2007 the records contain only seven different height categories of the convective cloud base. It varied from 0.8 km to 1.8 km in 2006 and from 0.5 km to 1.8 km in 2007. An average observed value for the summer of 2006 was found to be 1.2 km and 1.1 km for the summer of 2007 (Table 4.6). This difference in average observed cloud bases between two summers was 0.1 km versus to 0.5 km at YEG.

The cloud base value CCL(MM) was estimated using the previously calculated moist air mixing height (MAMH). The estimated value was found to be higher than the observed value (Figure 4.7) with the exception of two cases on 20 June 2006 and 12 August 2006. During the two summers period an estimated cloud base ranged from 0.7 km to 3.6 km.

The sounding-estimated CLL and the observed CCL values were in better agreement when the estimated cloud base was 2.0 km or lower. When the estimated cloud deck level was higher than 2.0 km, the gap between those two values was large reaching 2km in some instances, such as on 7 July 2007 and 21

August 2006. Figure 4.8 shows a histogram of cloud base heights. The estimated cloud base on average varied from summer to summer within 0.3 km comparing to almost 1 km at Stony Plain (Figure 4.8). Average estimated cloud heights were found to be just slightly higher in summer 2007 by about 0.3 km.

4.3. Summary and discussion

The main data set for this chapter consisted of 75 soundings from Stony Plain and 41 soundings from The Pas that had convective clouds in the observation records.

We estimated CCL values for these soundings using three different methods:
(1) lifting a surface parcel (SB); (2) lifting a 50 mb mixed layer parcel (ML);
(3) lifting a moist mixed layer parcel (MM).

The calculated cloud bases CCL(MM) for both summers were compared to the observed cloud bases CCL(obs) as well as average values. The differences between the observed and estimated CCL values were smaller when the height of estimated CCL was below 2.0 km. All three methods for calculation of the cloud base were compared to the observed cloud base for the summer of 2007. 75% of all the observed convective cloud cases had the best agreement with the observed CCL values when we used the method of lifting the surface parcel. 15% of the cases had a better agreement with observed CCL values when we used the method of lifting a 50 mb mixed layer parcel. Based on these results we might suggest that a 25 mb mixed layer parcel should be used for convective assessment for the central Alberta region. At The Pas the cloud base height observations were coarse and thus the findings were less certain. Our analysis shows better agreement between estimated and observed cloud bases when the heights of sounding estimated cloud base were found below 2.0 km above the ground.

The major finding for central Alberta was that sounding-based CCL(MM) estimates can be used for forecasting convective cloud base height when the convective cloud level is 2.0 km or lower above the ground. This has great implications in that prognostic soundings can be obtained from numerical weather prediction model output. Thus if we have a 24 hour model forecast, we have a 24 hour prognostic sounding which can be used to estimate the CCL valid in 24 h.

5. Moist Mixing Heights and Convective Intensity

5.1. Introduction

The operational forecaster often has to make an assessment of the likelihood of developing severe convection in a particular area. One of the reasons for distinguishing between strong and weak convection is that it helps to determine whether a severe weather watch (or warning) should be issued. To make a refined assessment of the likelihood of the occurrence of deep convection, forecasters often imply an ingredients-based approach which examines various physical parameters related to convective storms. These storm parameters usually include the amount of vertical shear in the ambient wind, storm-relative helicity, Convective Available Potential Energy (CAPE), Precipitable Water (PW), and others (Dupilka and Reuter, 2006).

There have been suggestions that Mixing Height (MH) might be a physical parameter that can help to distinguish between the outbreak of weak convection and strong convection. Mahrt (1977) suggested that Mixing Height might be a useful discriminator between convective storms that develop hail versus convective storms without hail. His analysis of Mixing Heights indicated that the mixed layer was usually thin and moist on days when hail occurred; while days with high Mixing Heights tended to have no hail occurrence. His findings were based on radiosondes released during the National Hail Research Experiment (NHRE) in Colorado.

McCaul and Cohen (2002) used a three dimensional numerical cloud model to quantify the relationship between storm intensity and various sounding parameters. They found that the storm convective overturning efficiency was maximized for moist layer depth of at least 1.5 - 2.0 km, with the tendency for outflow dominance being enhanced when mixed layer depths are high, but suppressed when they are low. As for convective cloud base, in previous studies this parameter was associated and related to LCL, the level where parcel becomes saturated. Rasmussen and Blanchard (1998) found that for storms producing large hail only, without tornado cases, the LCL heights were significantly higher than for ordinary thunderstorms and tornadic thunderstorms had lower LCL's. On the other hand some other studies on climatology of severe thunderstorms (Bluestein and Parks, 1983; Bluestein and Jain, 1985; Rasmussen and Straka, 1998; Rasmussen and Blanchard, 1998) found that mean LFC heights in severe storm events are generally near 2 km and typical LCL heights roughly near 1.5 km. The lower LCL in these cases is beneficial in reducing the tendency for storms to become outflow-dominated. It is hypothesized that relatively low values of boundary layer relative humidity support more low-level cooling through the evaporation of rain, leading to stronger outflow.

The amount of available moisture and mixing depth can significantly influence the initiation of moist convection and the lifted condensation level is sensitive to small changes in moisture. A parcel in a weakly developed updraft originating from near the surface which likely undergoes substantial entrainment as it rises through the deep vigorous convectively mixed layer, will upon reaching the mixed layer top be characterized by significantly lower moisture content than predicted by surface moisture values alone. Under such conditions, the elevation (above ground) of the updraft origin and the ability of the updraft to protect itself against entrainment (strong vertical motion, large diameter) become particularly important (Mahrt, 1976).

The focus of this chapter is to explore how Moist Mixing Height and convective intensity are related. In addition, we are searching for other physical parameters (related to MH) that might help to distinguish between the formations of strong versus weak convection.

5.2. Weak convection versus strong convection

In order to compare cases with strong and weak convection, we had to build a dataset for each of the two categories. In Chapter 2 we described the entire dataset of days with observed cloud convection at Stony Plain and Edmonton International Airport that span the period 1 June 2006 - 31 August 2006 and 1 June 2007 - 31 August 2007. We separated these soundings into one of two categories labeled as *weak convection* and *strong convection*, respectively. Weak convective cases were those with reports of convective clouds, convective showers or virga recorded between 2200 UTC and 0200 UTC. Strong convective cases were those with reports of thunderstorms between 2200 UTC and 0200 UTC. We should mention that none of the strong convective cases had a large hail or a tornado. Thus our data set did not include severe convection.

We constructed scatter diagrams and height distribution graphs to search for any correlation between the strong convection and mixing depth (MAMH) or convective cloud height CCL(MM) based on the moist mixed air method.

We also derive another convective parameter, which could be useful in future convective assessments. This parameter [CCL(MM)-MH] evaluates the difference in height between estimated convective cloud base and moist mixing depth, i.e., it evaluates the closeness of the moist mixed layer to the cloud base (Figure 5.1). It could be important for the storm intensity, because this parameter reflects not only depth of moisture but also the level of instability of the temperature curve. The distance between the convective cloud base height and the Mixing Height becomes smaller when the temperature lapse rate becomes steeper. We constructed scatter plots and histograms for this new parameter as well.

5.3 Mixing Heights (MH) and convective intensity

Figure 5.2 depicts the distribution of Mixing Height MH) for the two intensity categories: weak convection (top) and strong convection (bottom). The comparison suggests that the two distributions are quite similar without systematic differences; the strong convection and the weak convection have similar MH values. The strong convection maintains a relatively high percentage of occurrences with higher moist mixing heights ranging from 0 to 2.5 km, and then it decreases. It seems that the growth of the mixed layer causes a dilution of humidity due to entrainment of the overlying free atmosphere into the mixed layer. Since the entrained free flow is much drier than the mixed layer air, the drying by entrainment often overrides the effects of surface evaporation and humidity advection (Mahrt, 1976).

5.4 Convective Condensation Level (CCL) and convective intensity

Figure 5.3 compares the observed CCL distribution for strong and weak convection. The frequency distributions are very similar indicating that the observed convective cloud base height offers little insight in distinguishing between strong or weak convection if used in isolation from other cloud parameters. A similar finding occurs when comparing the CCL estimated from the sounding data. Figure 5.4 shows the comparison when the CCL distribution was based on the Moist Mixing (MM) method.

It is interesting to compare our findings with those reported in the literature. Rasmussen and Blanchard (1998) and Craven and Brooks (2004) suggested that tornadic storms were often associated with lower cloud bases. Often, hailstorms had higher cloud bases than short-lived airmass thunderstorms. They also found that the median value of the cloud bases for supercells were around 1.2 km above the ground, which was a couple hundred meters higher than cloud base heights for ordinary airmass thunderstorms. Our study does not contain severe convective storms producing tornadoes, hail or strong winds.

5.5 [CCL-MH] and convective intensity

In this section we analyze the usefulness of the difference between the Mixing Height and the computed CCL height as a possible parameter that might help to distinguish between weak and strong convection. As far as we know, there were no previous studies that investigated this parameter as a possible discriminator between categories of convective intensity. [CCL-MH] can be obtained from the sounding data. In a sense it combines information about the moisture profile (moist mixed layer) with information about the thermal stratification. We note that [CCL-MH] is smaller when either the mixing height is higher or when the temperature stratification is more (conditionally) unstable. Figure 5.5 compares the frequency distribution of the [CCL-MH] for weak and strong convection. The majority of the strong convection cases occurred when [CCL-MH] was less than

1.0 km. Only two strong convective cases had higher [CCL-MH] values. In both of them the humidity profile did not show a mixed layer. The air sounding on 6 June 2007 at 0000 UTC depicted a capping lid, yet the surface observations at YEG included thunderstorms with broken CBs at 4.0 kft (kilofeet) (Figure 5.6). The sounding and surface observation offered different value of the cloud base on this day. The CCL on the sounding curves could be found at 2.6 km while the observed value was near 1.2 km. At the same time we can derive convective cloud base based on the 50 mb mixed layer parcel and observed temperature, if the cap is broken. It could be estimated to be 1.6 km. Therefore the difference between cloud base and mixing layer top could be found to be close to 1.0 km if there is some mixing still occurring. The second case, when the humidity profile did not indicate a clear mixed layer occurred on 8 August 2007 (Figure 5.7). We could assume that in some low layers the moisture mixing had been occurred and the difference between the mixing top and the cloud base could be substantially lower.

Figure 5.8 shows the scatter diagram on which MH is plotted against [CCL-MH]. The strong convective cases are labeled with a solid dot, while weak convection is labeled with a plus sign. The scatter diagram shows that strong convection is confined to the left side of the diagram when [CCL-MH] is 1.0 km or less. Based on the histograms and scatter plot we conclude that [CCL-MH] (i.e. the thickness of the layer between the moist mixed layer top and convective cloud base) might be useful to distinguish between the likelihood of strong versus weak convection.

Figure 5.9 shows the scatter diagram of water vapor mixing ratio at the surface versus [CCL-MH] for weak and strong convection. The mixing ratio parameter is based on the 0000 UTC sounding data released from Stony Plain. The scatter diagram shows that strong convection tends to occur for low [CCL-MH] values and high water mixing ratio values.

5.6 Summary and discussion

In this chapter we determined whether the Mixing Height and related parameters might assist in distinguishing between weak and strong convective days. In our dataset we did not have severe storms producing tornadoes or large hail. Moist air mixing depth (MAMH) was considered to be the most reasonable from all three mixing heights (HFMH, HZMH, and MAMH) estimated in Chapter 3. We analyzed 43 convective days of 2007, based on Stony Plain soundings taken at 0000 UTC. We were also trying to find an agreement between convective cloud base (observed CCL(obs) and estimated CCL(MM)) and convective intensity. We derived a new parameter based on mixing heights and cloud bases as another possible differentiator between strong and weak convective days.

Our analysis shows that MH does not differentiate between weak and strong convection. We also found that both convective cloud bases estimated and observed did not show any difference between strong and weak convection. For example, the sounding estimated cloud bases CCL(MM) have shown 0% of occurrence for strong convective days with cloud height range from 0.5 to 1.0 km and 12 % of occurrence for weak convective days for the same cloud height range. The observed cloud bases offered similar results and could not differentiate between weak and strong convection. 19% and 20% of occurrence for weak and strong convection respectively have shown cloud height range from 0.5 to 1.0 km.

We investigated the difference in heights between mixing layer and convective cloud base [CCL(MM)-MH]. This parameter showed some strength in differentiating between week and strong convection. 90% of all strong convective soundings had a [CCL(MM)-MH] value within 1.0 km compared to 60% of weak convective soundings.

6. Convective Available Potential Energy (CAPE)

6.1 Introduction

The maximum energy available to an ascending air parcel is called Convective Available Potential Energy (CAPE). It is proportional to that area enclosed by the two curves delineating the temperature of the parcel and of the environment, respectively. Thus CAPE can be computed from

$$CAPE = R \int_{LFC}^{EL} (T_p - T_a) \, d \ln p$$

where (T_p-T_a) is the difference between the parcel temperature and the ambient temperature of the environment, p is the pressure, and R is the specific gas constant for dry air (Rogers and Yau, 1998). The integration is done from the *Level of Free Convection (LFC)* to the *Equilibrium Level (EL)*. The integration is performed over the positive area under the pseudoabatic curve on a tephigram (Figure 2.11). Smith and Yau (1993) found that that severe convection in Alberta is often associated with large CAPE values.

Doswell and Rasmussen (1994) compare different methods to assess CAPE. Essentially, the amount of energy depends on which parcel is selected, and there are different choices. Another alternative would be to lift the particular parcel that would result in the largest CAPE value. This is termed the Most Unstable CAPE (MUCAPE).

The choice of a surface-based parcel has significant implications for assessing the likelihood and intensity of the convection (Bunkers et al., 2002). Lifting a parcel from the surface neglects the effects of entrainment of air into the plume during the ascent. It is not known how much entrainment affects the thermal core, but Crum et al. (1987) and Wilde et al. (1985) found that some surface air remained undiluted in the core of a thermal rising through the mixed layer.

The use of a parcel having properties of some well-mixed layer requires a choice of what layer depth to use. Craven et al. (2002) recommended using a mean-layer parcel using a mixing depth of 100 mb for estimating CAPE. However, they found that the choice of a 100 mb mixed layer parcel was not appropriate for all cases. Choosing the most unstable parcel has the advantage of being applicable when surface–based parcel or layers are clearly inappropriate, as in elevated convection (Doswell and Rasmussen, 1994).

The main objective of this chapter is to compare different methods to quantify CAPE appropriate for Canadian Prairies summer conditions. A secondary objective is to determine whether CAPE can provide useful information that can distinguish between the likelihood of strong convection versus weak convection.

6.2 CAPE and convective intensity for Stony Plain

In this chapter we use two different methods to compute CAPE from sounding data. The first method, identified by CAPE(SB), assumes that a surface parcel is lifted adiabatically without mixing until it reaches saturation from which point it follows a pseudo adiabatic ascent (Figure 2.11). Our second method, assumes that there is complete mixing within the lowest 50 mb, and that a parcel of this mixed air is lifted. We will identify this method by CAPE(ML).

The values of CAPE calculated from Stony Plain soundings are listed in Table 6.1 (for 2006) and Table 6.2 (for 2007). The graphs of CAPE values for the surface parcel and 50 mb parcel for 2007 are shown in (Figure 6.1-6.3). July 2007 had relatively large CAPE values with a maximum of about 4000 J/kg and average CAPE value of 1400 J/kg. June 2007 had relatively small CAPE value, never exceeding 1500 J/kg. Nevertheless, June 2007 was the most convectively active month of all six months analyzed in this project. The result shows that high CAPE value does not always result in intense convection. For example, on 20 July 2007 and 28 July 2007 both the CAPE (SB) and the CAPE (ML) values were close to 2000 J/kg. These large CAPE values were associated only with TCU's (towering cumulus) at 3.5 and 6.0 kft.

The CAPE(ML) values were found to be substantially lower than the CAPE(SB) values in 80 % of all convective cases. 15% of CAPE(ML) values were close to zero. We also note that for both CAPE(SB) and CAPE(ML) values for the summer of 2006 were lower than those for 2007 (Table 6.1, Table 6.2).

We now turn our attention of investigating whether the CAPE value provided useful information about the likelihood of the occurrence of strong convection versus weak convection. Figure 6.4 shows the scatter diagram of CAPE(SB) value plotted against [CCL-MH]. The parameter [CCL-MH] introduced in section 5.5 denotes the depth between the CCL value and the MH. Both of these parameters were computed, based on the Moist Air technique. To distinguish the scatter diagram between weak and strong convection, we used the markers of solid dots (strong) and pluses (weak). Strong convection was found when [CCL-MH] was less than about 1.0 km. The value of CAPE(SB) offered little information about the likelihood of strong convection.

6.3 CAPE and convective intensity for The Pas

Similar analysis on CAPE(SB) and CAPE(ML) values were done for the 00Z The Pas (YQD) soundings. The results for the summer of 2007 are shown in Table 6.3 and Figure 6.5- 6.7. This site had 41 convective days with 37% of all of them yielded in strong convection.

Daily CAPE values for the surface parcel at YQD are found to range from 20 to near 4000 J/kg and on average just slightly lower than the CAPE values at WSE for the same period of time. The difference between CAPE(SB) and CAPE(ML) were found to be on average smaller at YQD compared to WSE. We speculate that this might be related to the fact that the boundary layer is better mixed at YQD compared to WSE. July 2007 displayed a wide range of CAPE values from the highest near 4000 J/kg to the lowest near 20 J/kg. We have found that strong convective days exhibited both low CAPE value (24 June 2007) and high CAPE value (5 August 2007). The estimated value of CAPE offers little guidance to distinguish between the likelihood of strong versus weak convection. This holds for both The Pas and Stony Plain.

6.4 Summary and discussion

In this chapter we examine the calculation for CAPE and its possible use in distinguishing weak and strong convection. As expected, our calculations show that a large variability in daily CAPE values, ranging from 10 to 4000 J/kg. In August at Stony Plain we have found the smallest average CAPE value and in July the largest. At the same time the month of July was not found as the most convectively intense. In fact the month of June of 2007 with CAPE values below 1500 J/kg was found to be the most intense convectively, when 50% of all convective days ended all convective with convective weather (thunderstorms or thundershowers) observed at Edmonton International or Stony Plain. The month of July of 2007 at The Pas region showed the greatest CAPE value and yet it did not produce too many strong convective days compared to the other months. Also we could find a small difference in intensity of convection between the summer months at this region.

7. Conclusions and discussion

7.1 Conclusions

The mandate of an operational weather forecasting office is to provide forecasts of weather conditions to the public, aviation, and other customers. Particularly important is forecasting of the weather features that have a high impact on the well-being of the public and the safety of aviation. One weather feature that is crucial for the Canadian Prairies during the summer months is the occurrence of strong convection that can lead to the formation of hail, tornadoes, lightning, and flash flooding. The other weather feature that requires focused attention for aviation is the prediction of the heights of low-level cloud bases, particularly, if the low level cloud is of convective nature. This thesis addresses the estimation of convective cloud base heights based on sounding data and examines parameters estimated from sounding data that assist to distinguish between strong and week convection. The major significance of our thesis work lies in the fact that numerical weather prediction models are improving over the years and that prognostic model soundings are becoming more and more reliable. All the computations of parameters using an observed balloon sounding can be done with prognostic model soundings that can be predicted several days in advance of the occurrence of convective storm.

In this thesis we compared three different methods to estimate Mixing Height based on the balloon sounding observations taken at 0000 UTC at Stony Plain

(WSE) and The Pas (YQD). The dataset contains nearly 180 soundings taken from 1 June to 31 August 2006 and 1 June to 31 August 2007. The three methods used to estimate the Mixing Height were the Heffter Mixing Height (HFMH) method, the Holzworth Mixing Height (HZMH) method, and the Moist Air Mixing Height (MAMH) method. All three methods required a refinement to be useful for the Canadian Prairies. The major refinements were:

- The HFMH method used new criteria for the critical inversion lapse rate: $\Delta\theta/\Delta z \geq 3$ K km^{-1}.
- The HZMH method allowed for neutral and near neutral condition where potential temperature was allowed to fluctuate with height ±0.5 K near the surface value within the mixed layer.
- The MAMH method used the new criteria for the water vapor mixing ratio lapse rate: $\Delta w/\Delta z \geq 1.5$ g kg^{-1} km^{-1}.

Fairly good agreement was found for both stations WSE and YQD in terms of the Mixing Height computed using the HFMH and MAMH methods. These methods can be useful to derive mixing layer depth in Canadian Prairies.

We investigated the usefulness of the mixed layer depth to estimate the Convective Condensation Level (CCL). The CCL coincides with the convective cloud base height. High CCL height is a crucial element for allowing landings at airports, particularly for smaller airplanes. To validate the estimations of the CCL values based on sounding data, we compared them with independently observed convective cloud base heights. We used surface based observations of the convective cloud base, including only TCU's and CB's and also the type of weather including convective showers, thunderstorms and thundershowers. The surface observations were taken within 2 hours prior to the sounding time (0000 UTC) and 2 hours after the sounding time. The surface observations were collected from Stony Plain (WSE), Edmonton International (YEG) and The Pas (YQD) weather stations.

We estimated the CCL value based on the soundings using three different methods: (1) lifting a surface parcel (SB); (2) lifting a 50 mb mixed layer parcel (ML); and (3) lifting a moist mixed layer parcel (MM) and three different cloud bases were calculated by these methods respectively: the CCL(SB), CCL(ML), CCL(MM). Comparison of these three different cloud bases with the actual cloud base revealed two things:

- The differences between the observed and all three estimated CCL values were lower when the height of estimated CCL was below 2.0 km. For these days the Moist Air Mixing Height (MAMH) could be easier to use to estimate the convective cloud base and derive the convective parameters for the day.
- The best agreement between the estimated cloud base and the observed cloud height (75% of all cases) was found when lifting a surface parcel. Therefore we could suggest that lifting a 25 mb mixed layer parcel would be practical choice to estimate sounding parameters for upcoming convective events.

The Mixing Heights (MAMH) and convective cloud bases (CCL) were compared in order to distinguish between weak convective days (producing only convective cloud or convective cloud and showers) and strong convective days (producing thunderstorms). The mixing height (MAMH), observed convective cloud base CCL(obs) and the estimated convective cloud base CCL(MM) parameters did not offer any differentiation between the weak convection and strong convection.

We derived a new parameter: the difference between the convective cloud base and the Moist Air Mixing Height [CCL(MM)-MH]. This could be a possible discriminator between strong and weak convection. The comparison of this parameter for weak and strong convective days revealed that almost all the strong convective days displayed the [CCL(MM)-MH] value fluctuating within 1.0 km, whereas weak convective days displayed this value fluctuating within 2.5 km.

The findings of our study on mixed layers could be used in assessing the potential for convection and the forecasting of convective cloud base heights required for aviation meteorology. Also, our findings of computing the Mixing Height have implications for dispersion meteorology dealing with the transport and turbulent diffusion of air pollutants. The intensity of convection is extremely important to forecast prior the convective event, therefore a possible discriminator between weak and strong convection could be very useful to find.

7.2 Suggestions for further research

We conclude our thesis by offering a few suggestions of what additional research should be done to compliment our work. One suggestion is to enlarge the data set. We recommend using a 10-year dataset of soundings from several stations with cloud base observations. This would allow a more comprehensive evaluation about the strength and weaknesses of different methods to compute the Mixing Height. This might confirm our new criteria for the Heffter Mixing Height Method and the Moist Air Mixing Height method, or allow fine-tuning of the threshold values if necessary.

A larger data set would also allow for a refined comparison of different methods used to estimate the Convective Condensation Level (CCL) and verification against convective cloud base observations. A larger dataset may provide possibilities of changing the time window and spatial proximity of sounding and observed convective clouds. For example, the 4 hour time frame for convective weather observation could be changed to 0000 UTC - 0400 UTC instead of 2200 UTC - 0200 UTC. This way we could cut off the observed convective weather prior to the sounding time, because those soundings would be already affected or modified by convection. We can improve proximity of location as well by extending the area of observation to 100 km in diameter. While doing this we could possibly use satellite data combined with lightning. Presence of lightning in the area could be used to identify strong convection as well.

A second suggestion for extending our research would be to include days with severe convection including storms that produce large hail and tornadoes. It would be revealing to see whether the MH and CCL can assist in discriminating between the likely severity of the convection. The difference between cloud base and moist mixing heights [CCL-MH] in future could be replaced by difference between Lifting Condensation Level (LCL) and moist mixing height [LCL -MH], because LCL is simpler to compute. This may make it easier to differentiate between weak and strong convection.

References

Angle R.P., S.K. Sakiyama. 1991: Plume Dispersion in Alberta. Standards and Approvals Division. Alberta Environment, Edmonton, Alberta, 428 pp

Anthes, R.A., 1984: Enhancement of Convective Precipitation by Mesoscale Variations in Vegetative Covering in Semiarid Regions. *J. Appl. Meteor.*, 23, 541-554

Batchvarova, E., S. E. Gryning, 1991: Applied model for the growth of the daytime mixed layer. *Boundary-Layer Meteor.*, 56, 261-274

Basara, J. B., K. C. Crawford, 2002: Linear relationships between root-zone soil moisture and atmospheric processes in the planetary boundary layer. *J.Geophys. Res.*, 107(D15), 2-18

Benkley, C.W., L.L. Schulman, 1979: Estimating Hourly Mixing Depths from Historical Meteorological Data. *J. Appl. Meteor.*, 18, 772-780

Berman S., J. Ku, S. Trivikrama Rao, 1999: Spatial and temporal variation in the mixing depth over the northeastern United States during the summer of 1995. *J. Appl. Meteor.*, 38, 1661-1673

Bluestein H. B., C. R. Parks, 1983: A synoptic and photographic climatology of low-precipitation severe thunderstorms in the southern plains. *Mon. Wea.Rev.*, 111**,** 2034–2046

Bluestein, H. B., M. H. Jain, 1985: Formation of mesoscale lines of precipitation: Severe squall lines in Oklahoma during the spring. *J. Atmos. Sci.,* 42, 1711-1732

Brooks, H.E., 2009: Proximity soundings for severe convection for Europe and the United States from reanalysis data. *Atmospheric Research*, 93, 546-553

Brooks, H.E., J. W. Lee, J.P. Craven, 2003: The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data. *Atmospheric Research*, 67-68, 73-94

Bullas, J. M., Ed., 2001: The climate of the Prairie Provinces (1961–1990): A review. Rep. AHSD-S2000-01, Environment Canada, Prairie and North Region, 130 pp

Bunkers, M.J., B.A. Klimowski, J.W. Zeitler, 2002: The importance of parcel choice and the measure of vertical wind shear in evaluating the convective environment. Preprints*, 21st Conf. on Severe Local Storms*, *Amer. Meteor. Soc*., 379-382

Carson D.J., 1973: The development of a dry inversion-capped convectively unstable boundary layer. *Quart. J. R. Met. Soc.*, *99,* 450-467

Craven, J.P., H.E. Brooks, J.A. Hart, 2002: Baseline climatology of sounding derived parameters associated with deep, moist convection. Preprints, *21st Conf. on Severe Local Storms,* San Antonio, *Amer. Meteor. Soc.,* 643-646

Craven, J.P., R.E. Jewell, H.E. Brooks, 2002: Comparison between observed convective cloud-base heights and lifting condensation level for two different lifted parcels. *Wea. Forecasting,* 17, 885-890

Crook, N.A., 1996: Sensitivity of moist convection forced by boundary layer processes to low-level thermodynamic fields. *Mon. Wea. Rev*., 124, 1767-1785

Crum, T.D., and R.B. Stull, 1987: Field Measurements of the Amount of Surface Layer Air versus Height in the Entrainment Zone. *J. Atmos. Sci.*, 44, 2743-2753

Darkow, G. L., 1969: An analysis of over sixty tornado proximity soundings. Preprints, 6th Conf. Severe Local Storms (Chicago, IL), Amer. Met. Soc, 218-222

Darkow, G. L., S. F. Tansey, 1982: Subsynoptic fields of boundary layer heat and moisture estimated from hourly surface data. Preprints, *12th Conf. on Severe Local Storms,* San Antonio, TX, Amer. Meteor. Soc., 79-83

Deardorff, J., 1979: Prediction of Convective Mixed-Layer Entrainment for Realistic Capping Inversion Structure. *J. Atmos. Sci.*, 36, 424-436

Deardorff, J. W., Willis, G. E., 1967: The free-convection temperature profile. *Quart. J. R. Met. Soc.*, 93, 166-175

Djuric, D., 1994: Weather Analysis. *Prentice-Hall Inc*., 304

Doswell, C.A., E.N.Rasmussen, 1994: The Effect of neglecting the Virtual Temperature Correction on CAPE Calculations. *Wea. Forecasting*, 9, 625-629

Driedonks, A.G.M., 1982: Models and observations of the growth of the atmospheric boundary layer. *Boundary-Layer Meteor*., 23, 283-306

Dupilka, M.L., G.W. Reuter, 2006: Forecasting tornadic thunderstorms in Alberta using environmental sounding data. *Wea. Forecasting,* 21, 325-346

Freedman J. M., D. R. Fitzjarrald, K. E. Moore, R. K. Sakai, 2001: Boundary layer clouds and vegetation–atmosphere feedbacks. *J. Climate*, 14, 180–197

Galway, J.G. 1956: The lifted index as a predictor of latent instability. *Bull. Amer. Meteor. Soc.,* 37, 528–52

Garrat, J.R., 1992: The atmospheric boundary layer. Cambridge University Press, Cambridge, UK, pp 320

Garret, A.J., 1981: Comparison of observed mixed layer depth to model estimates using observed temperature and winds and MOS forecasts. *J. Appl. Meteor.,* 1277-1283

Grossman, R. L., 1992: Convective Boundary Layer Budgets of Moisture and Sensible Heat over an Unstressed Prairie. *J. Geophys. Res.* 97, 18, 425- 438

Grossman, R. L., N.Gamage, 1995: Moisture Flux and Mixing Processes in the Daytime Continental Convective Boundary Layer. *J. Geophys. Res.* 100, 665-674

Hanna, S.R., 1967: The thickness of the planetary boundary layer. *Atmospheric Environment , 3,* 519-536

Hanesiak, J.M., R.L. Raddatz, S. Lobban, 2003: Local initiation of deep Convection on the Canadian Prairie Provinces. *Boundary-Layer Meteor.*, 110, 455-470

Heffter, J.L., 1980: Transport Layer Depth Calculations. *In Proceedings 2nd Joint Conference on Applications of Air Pollution Modelling. AMS*, pp. 787-791

Holzworth, G.C., 1964: Estimates of mean maximum mixing depths in the contiguous United States. *Mon. Wea. Rev.*, 92, 235-242

Iribarne,J.V., W.L.Godson,1981: Atmospheric Thermodynamics. Second Edition. *D. Reidet Publishing Company*, Dordrecht, Holland, 1981, 259 pp

Jeannet P., C. Bower, B. Calpini, 2005: Global Criteria for Tracing the Improvements of Radiosondes over the Last Two Decades. *Report for item 6.2 of the CIMO/OPAG-UPPER-AIR/ET-UASI-2/IOC-2/ 28-30*

LeMone, M.A., R.L.Grossman, 2000: Mesoscale and Diurnal Variability of 2-m Temperature and Mixing Ratio in CASES-9. *Proceedings of the 14th Symposium on Boundary Layer and Turbulence*, Aspen, 7-11 August, pp. 5-8

Lyra , R., A. Druilhet, B. Benech, C. Bouka Biona,1992: Dynamics above a dense equatorial rain forest from the surface boundary layer to the free atmosphere. *Geophys. Res.*, 97, 12953-12965

Mahrt, L., 1977: Influence of Low-Level Environment on Severity of High-Plains Moist Convection. *Mon. Wea. Rev.*, 105, 1315-1329

Mahrt, L., 1976: Mixed Layer Moisture structure. *Mon.. Wea. Rev.*, 104, 1403-1407

Mahrt, L., D. H. Lenschow, 1976: Growth dynamics of the convectively mixed layer. *J. Atmos. Sci.,* 33, 41-51

Marsik, F.J., K.W. Fischer, T.D. McDonald, P.J. Samson, 1995: Comparison of Methods for estimating mixing height used during the 1992 Atlanta Field Intensive. *J. Appl. Meteorol., 34,* 1802-1814

McCaul, E. W., Jr., C. Cohen, 2002 The impact of simulated storm structure and intensity on variations in the mixed layer and moist layer depths. *Mon. Weather Rev.* 130 (2002), pp. 802-824

Melgarejo, J., J. Deardorff, 1974: Stability Functions for the Boundary-Layer Resistance Laws Based upon Observed Boundary-Layer Heights. *J. Atmos. Sci.*, 31, 1324-1333

Myrick, R.H., S.K. Sakiyama, R.P. Angle, H.S. Sandhu, 1994: Seasonal mixing heights and inversions at Edmonton, Alberta. *Atmos. Environ*., 28, 723-729

Nash, J., 2004: Introduction to Performance of Modern Radiosondes Based on WMO Radiosonde Comparison Results, Temperature. *Joint Meeting CIMO Expert Team on Upper-Air Systems Intercomparisons, First Session,* CIMO/OPAG-UPPER-AIR /ET-UASI-1/IOC-1/Doc. 3.1(1)

Pino, D., J.Vilà-Guerau de Arellano, S.W. Kim, 2006: Representing Sheared Convective Boundary Layer by Zeroth- and First-Order-Jump Mixed-Layer Models: Large-Eddy Simulation Verification. *J. Appl. Meteor. Climatol.*, 45, 1224-243

Piringer, M., K. Baumann, M. Langer M, 1998: Summertime mixing heights at Vienna, Austria, estimated from vertical soundings and by a numerical model. *Boundary-Layer Meteor.,* 89, 25-45

Piringer, M., S. Joffre, A. Baklanov, A. Christen , M. Deserti, K. De Ridder , S. Emeis, P. Mestayer, M. Tombrou, D. Middleton, K. Baumann-Stanzer, A. Dandou, A.Karppinen, J. Burzynski, 2007: The surface energy balance and \ the mixing height in urban areas— activities and recommendations of COST-Action 715. *Boundary- Layer Meteor.,* 124, 3-24

Portelli, R.V., 1977: Mixing heights, wind speeds and ventilation coefficient for

Canada. *Downsview, Ont., Atmos. Environ*., 31

Raddatz, R.L., J.D.Cummine, 2003: Inter-Annual Variability of Moisture Flux from the Prairie Agro-Ecosystem: Impact of Crop Phenology on the Seasonal Pattern of Tornado Days. *Boundary-Layer Meteorol.,* 106, 283-295

Raddatz, R.L., M. Noonan, 2004: Monthly mean afternoon mixing-layer depths "tuned" to the eco-climatic zones of the Canadian Prairie Provinces. *Environmental Modeling and Assessment,* 9, 147-158

Rasmussen, E.N., D.O. Blanchard, 1998: A Baseline Climatology of Sounding-Derived Supercell andTornado Forecast Parameters. *Wea. Forecasting*, 13, 1148-1164

Rasmussen, E.N., J. M. Straka, 1998: Variations in supercell morphology: Part I. Observations of the role of upper-level storm-relative flow. *Mon. Wea. Rev.* 126**,** 2406-2421

Rogers, R. R., M. K. Yau, 1989: A Short Course in Cloud Physics. Third edition, *Butterworth-Heinemann Publishing Company*, 293 pp

Sakiyama, S.K., R.H. Myrick, R.P. Angle, H.S. Sandhu, 1991: Mixing heights and inversions from minisonde ascents at Edmonton/Ellerslie. Alberta Envoronment, 57 pp

Schaefer, J.T., 1976: Moisture features of the convective boundary layer in Oklahoma . *Quart.J.Roy.Meteor.Soc.,102*,447-450

Seibert, P., F. Beyrich, S. Gryning, S. Joffre, A. Rasmussen, P. Tercier, 2000: Review and intercomparison of operational methods for determination of the Mixing height. *Atmos. Environ*. 34, 1001-1027

Smith, S. B., G.W. Reuter, M.K. Yau, 1998: The episodic occurrence of hail in Central Alberta and the Highveld of South Africa. *Atmos.-Ocean*, 36, 169-178

Smith, S. B., M. K. Yau, 1993: The causes of severe convective outbreaks in Alberta. *Mon. Wea. Rev.,* 121, 1099-1133

Stackpole, J.D., 1967: Numerical analysis of atmospheric sounding. *J.Appl Meteor*., 6, 464-467

Stull, R.B., 1997: An Introduction to Boundary Layer Meteorology. *Dordrecht-Boston- London: Kluwer Academic Publishers*, 670 pp

Taylor, N.D., Sills, J. Hanesiak, J. Milbrant, 2007: UNSTABLE (The

Understanding Severe Thunderstorms and Alberta Boundary Layer Experiment). Scientific Overview, Environment Canada

Troen, I.B., L. Mahrt., 1986: A simple model of the atmospheric boundary layer; sensitivity to surface evaporation. *Boundary-Layer Meteor., 37,* 129-148

Taylor, C.M., T. Lebel, 1998: Observational Evidence of Persistent Convective-Scale Rainfall Patterns. *Mon. Wea. Rev.*, 126, 1597-1607

Wyngaard, J., W. Pennell, D. Lenschow, M. LeMone, 1978: The Temperature-Humidity Covariance Budget in the Convective Boundary Layer. *J. Atmos. Sci.*, 35, 47-58

Wang, J., L. Zhang, 2008: Systematic Errors in Global Radiosonde Precipitable Water Data from Comparisons with Ground-Based GPS Measurements. *J. Climate*, 21, 2218-2238

Wilde, N.P., R.B. Stull, E.W. Eloranta, 1985: The LCL Zone and Cumulus Onset. *J. Appl. Meteor.*, 24, 640-657

Zilitinkevich, S. S., 1975: Comments on "A model for the dynamics of the inversion above a convective boundary layer." *J.Atmos. Sci.,* 32, 991-992

Zipser, E. J., R.H. Johnson : 1998, Systematic Errors in Radiosonde Humidities: A Global Problem. *Proceedings 10th Symposium on Measurements, Observations, and Instrumentation*, Phoenix, AZ, American Meteorological Society, pp. 72-73

Table 2.1.Weather reports with Convective Cloud Coverage/ Type/ Height/ Weather at Edmonton International (YEG) during summer of 2006 and 2007, observed between 22:00 and 02:00 UTC. Convective cloud height (base) is observed in hundreds of feet above the ground level.

Date	Convective Cloud Coverage/ Type/ Height/ Weather	Date	Convective Cloud Coverage/ Type/ Height/ Weather
June 3, 2006	Few / TCU/ 070	June 3, 2007	Bkn/ CB / 08/ TSRA
June 6, 2006	Bkn / TCU/ 070 / TSRA	June 6, 2007	Ovc / CB/ 040/ TSRA
June 21, 2006	Few / TCU/ 045	June 10, 2007	Bkn / CB/ 050/ TSRA
June 23, 2006	Few /TCU/ 050/ VCSH	June 11, 2007	Few/ TCU/ 030/ TSRA
		June 12, 2007	Few / CB/ 020/ TS
July 1, 2006	Few / TCU/ 070	June 13, 2007	Sct / TCU/ 025/ SHRA
July 3, 2006	Sct / TCU/ 075	June 14, 2007	Bkn /TCU/ 075/ SHRA
July 4, 2006	Few/ TCU/ 045	June 15, 2007	Sct / CB 060/ TSRA
July 6, 2006	Few/ TCU/ 070	June 16, 2007	Sct/ TCU/ 065/ SHRA
July 8, 2006	Sct/ TCU/ 065/ TSRA	June 17, 2007	Few /TCU/040/ TSRA
July 10, 2006	Few/ TCU/ 045	June 18, 2007	Sct/ TCU/045/ SHRA
July 11, 2006	Few/ CB/ 030	June 19, 2007	Sct / CB/ 045/ TSRA
July 14, 2006	Few/ TCU/ 060/ TSRA	June 20, 2007	Few / CB/ 045/ TSRA
July 15, 2006	Few/ TCU/ 055	June 22, 2007	Few / TCU/ 040
July 16, 2006	Few/ TCU/ 060	June 23, 2007	Few / CB/ 035 / SHRA
July 18, 2006	Bkn/ TCU/ 070/ TSRA	June 24, 2007	Sct / TCU/ 040
July 19, 2006	Sct/ CB/ 060/ TSRA	June 25, 2007	Few/ TCU/ 046/ TS
July 24, 2006	Few/ TCU/ 080		
July 25, 2006	Few/ TCU/ 055	July 1, 2007	Few/ TCU/ 045/ SHRA
July 26, 2006	Few/ CB/ 060	July 3, 2007	Few/ CB/ 055
July 31, 2006	Few / CB/ 027/ TSRA	July 4, 2007	Few /TCU/ 050/ VIRGA
		July 9, 2007	Sct/ TCU/ 052/ SHRA
August 1, 2006	Few/ CB/ 040/ VIRGA	July 10, 2007	Bkn/ TCU/ 025/ VCSH
August 2, 2006	Few/ CB/ 060/ SHRA	July 12, 2007	Few/ TCU/ 055
August 3, 2006	Few/ TCU/ 070/ VIRGA	July 17, 2007	Few / CB/ 050/ VIRGA
August 4, 2006	Few/ CB/ 060/ SHRA	July 19, 2007	Sct/ CB/ 040
August 5, 2006	Few/ TCU/ 020	July 20, 2007	Few/ TCU/ 035/
August 13, 2006	Few/ CB/ 058/ SHRA	July 24, 2007	Few/ TCU/ 070/ VIRGA
August 15, 2006	Few/ TCU/ 085/	July 25, 2007	Few/ TCU/ 050/ VIRGA
August 16, 2006	Few/ TCU/ 055/	July 27, 2007	Few/ CB/ 070
August 17, 2006	Few/ TCU/ 045/	July 28, 2007	Few/ CB/ 060
August 19, 2006	Few/ CB/ 069/	July 29, 2007	Few / CB/ 045
August 20, 2006	Few/ TCU/ 060/ SHRA	July 30, 2007	Few / CB/ 043/ TS
August 24, 2006	Few/ TCU/ 035/ SHRA	July 31, 2007	Sct/ TCU/ 035/ TSRA
August 25, 2006	Few/ TCU/ 070		
		August 1, 2007	Few/ CB/ 045/ SHRA
		August 4, 2007	Few/ TCU/ 030/ SHRA
		August 5, 2007	Bkn/ TCU/ 017/ SHRA
		August 6, 2007	Bkn / CB/ 050/ TSRA
		August 7, 2007	Few / TCU/ 050
		August 8, 2007	Bkn/ CB/ 086/ TSRA
		August 10, 2007	Few / TCU/ 025
		August 15, 2007	Few / TCU/ 060
		August 22, 2007	Bkn / TCU/ 050/ SHRA
		August 24, 2007	Few/ TCU/ 040
		August 26, 2007	Sct / CB/ 038/ SHRA
		August 27, 2007	Sct/ TCU/ 032/ SHRA
		August 28, 2007	Few/ TCU/ 035

Table 2.2. Weather reports with Convective Cloud Coverage/ Type/ Height/ Weather at The Pas (YQD) during summer of 2006 and 2007, observed between 22:00 and 02:00 UTC. Convective cloud height (base) is observed in hundreds of feet above the ground level.

Date	Convective Cloud Coverage/ Type/ Height/ Weather	Date	Convective Cloud Coverage/ Type/ Height/ Weather
June 4, 2006	Few/ TCU/ 050/ RA	June 13, 2007	Few/ TCU/ 050
June 6, 2006	Few/ TCU/ 025/	June 20, 2007	Bkn/ CB/ 020/ TSRA
June 17, 2006	Bkn/ CB/ 025/ TSRA	June 24, 2007	Bkn/ CB/ 020/ TSRA
June 19, 2006	Few/ TCU/ 050		
June 20, 2006	Few/ TCU/ 050	July 3, 2007	Few/ TCU/ 040/ TS
June 26, 2006	Few/ TCU/ 040	July 4, 2007	Few/ TCU/ 040/ TS
June 30, 2006	Few/ TCU/ 050	July 7, 2007	Bkn / TCU/ 020/ TS
		July 10, 2007	Few/ TCU/ 040
July 2, 2006	Few/ TCU/ 030	July 11, 2007	Few/ TCU/ 040
July 3, 2006	Bkn/ CB/ 050/ TS	July 13, 2007	Bkn/ CB/ 040
July 8, 2006	Sct/ CB/ 030/ TSRA	July 14, 2007	Bkn/ TCU/ 040/ SHRA
July 12, 2006	Few/ TCU/ 030	July 25, 2007	Few/ TCU/ 060/ SHRA
July 15, 2006	Few/ TCU/ 050	July 28, 2007	Few / TCU/ 050/
July 20, 2006	Few/ CB/ 025/ TS		
July 22, 2006	Sct/ CB/ 050/ TSRA	August 2, 2007	Sct/ TCU/ 060/ SHRA
July 25, 2006	Bkn/ CB/ 030/ TSRA	August 5, 2007	Few/ CB/ 020/ TS
		August 7, 2007	Few/ CB/ 030/ TSRA
August 7, 2006	Few/ TCU/ 030	August 9, 2007	Few/ TCU/ 040
August 11, 2006	Few/ TCU/ 035/ TS	August 12, 2007	Few/ TCU/ 020
August 12, 2006	Bkn/ CB/ 055/ TSRA	August 14, 2007	Bkn/ TCU/ 015
August 16, 2006	Few/ TCU/ 060/	August 15, 2007	Bkn/ CB/ 040
August 21, 2006	Bkn/ TCU/ 030/ SHRA	August 16, 2007	Few/ CB/ 030
August 26, 2006	Bkn/ TCU/ 050/ SHRA		

Table 2.3. Total number of convective days with convective weather and/or convective cloud (CB,TCU) and number of days only with convective weather - thunderstorms (TS,TSRA) or/and rain showers, showers in vicinity ,virga (RA,SHRA,VCSH,VIRGA) at Edmonton International (YEG) and at Stony Plain (WSE) during summer of 2006 and 2007,observed between 22:00 and 02:00 UTC.

		Total number of convective days (CB, TCU, TSRA, RA, TS, VCSH)	**Number of days with convective weather (TSRA, RA, TS, VCSH)**
June	2006	4	2
July	2006	16	5
August	2006	13	7
June	2007	17	15
July	2007	16	9
August	2007	13	8

Table 2.4. Total number of convective days with convective weather and/or convective cloud (CB,TCU) and number of days only with convective weather - thunderstorms (TS,TSRA) or/and rain showers, showers in vicinity ,virga, (RA,SHRA,VCSH,VIRGA) at The Pas (YQD)during summer of 2006 and 2007,observed between 22:00 and 02:00 UTC.

		Total number of convective days (CB, TCU, TSRA, RA, TS, VCSH)	**Number of days with convective weather (TSRA, RA, TS, VCSH)**
June	2006	7	2
July	2006	8	5
August	2006	6	4
June	2007	3	2
July	2007	9	5
August	2007	8	3

Table 2.5. Annual Alberta Severe Weather events. This table includes only reports on convective events (hail, tornado, heavy showers etc.)

YEAR	TOTAL NUMBER OF REPORTS
1991	92
1992	69
1993	55
1994	79
1995	71
1996	117
1997	49
1998	65
1999	46
2000	81
2001	60
2002	20
2003	104
2004	90
2005	87
2006	106
2007	146

Table 3.1. The Heffter Mixing Heights (HFMH) for summer 2006 at 0000 UTC at Stony Plain (Alberta). The heights are given in meters above the ground level. Blank space indicates that this method was not applicable for the sounding.

Date	June (m)	July (m)	August (m)
1	2161	2349	2764
2	1763	2379	2308
3	1841	2387	
4	2237	3468	1639
5	2888	3555	2054
6		625	1956
7	2317	1808	2806
8	2573	3017	2429
9		1357	3256
10	444	516	1391
11	1505		2257
12		1771	687
13	1993	1236	3018
14	1147	1752	1955
15	613	2292	1780
16		1835	1759
17		1935	1790
18	2195	3002	2166
19	2567	2313	4029
20	2298	1669	1478
21	2134	2653	1678
22	1993	1303	637
23	2087	1136	
24	2137	2392	
25	2617	2334	3220
26	1815	2802	2156
27	3134	2011	2578
28	3325	1802	1678
39	1409	1623	1823
30	1142	841	1758
31			

Table 3.2. The Heffter Mixing heights (HFMH) for summer 2007 at 0000 UTC at Stony Plain (Alberta). The heights are given in meters above the ground level. Blank space indicates that this method was not applicable for the sounding.

Date	June (m)	July (m)	August (m)
1	1493	2806	1204
2	2085	2582	1503
3	2271	1504	1110
4	1869	2623	672
5	1993	1566	479
6		1860	1311
7	1512	1456	2119
8	2227	2141	2486
9	1233		705
10		770	1584
11	626	1553	1377
12	571	2248	896
13	484	1780	934
14	1864	1233	1794
15	1157	516	1846
16	1478		1011
17	2023	412	1862
18	416	1178	1192
19	2998	720	1661
20	1316	373	650
21	1296	2125	2679
22	518	2982	486
23	745	2475	1709
24	484	712	1503
25	1004	1080	1737
26	2311	1894	
27	1914	600	1091
28	1803	708	733
39	603	702	2323
30	390	734	612
31		1356	1812

Table 3.3. Average MH for Stony Plain (Alberta) and The Pas (Manitoba) diagnosed from radiosoundings of summers 2006 and 2007 at 0000 UTC using the Heffter technique.

	WSE	**YQD**
June 2006	2013	1778
July 2006	2006	1763
August 2006	2113	1621
June 2007	1382	1819
July 2007	1472	1905
August 2007	1369	1654

Table 3.4. The Heffter Mixing Heights (HFMH) for summer 2006 at 0000 UTC at The Pas (Manitoba). The heights are given in meters above the ground level. Blank space indicates that this method was not applicable for the sounding.

Date	June (m)	July (m)	August (m)
1	1844	2249	1098
2	3206	2338	2742
3	3700	1238	2005
4	2885	2820	2116
5	3082	2198	2756
6		1447	637
7	1036	3599	2603
8	1464	1510	991
9	1305	900	1357
10	1421	1269	1504
11	1686	564	1010
12	1398	2314	
13	1035	2248	1289
14	2300	404	862
15	1081	2683	2560
16	681	3025	1192
17		2236	1094
18	462	2755	1271
19	1710	446	2909
20	1580	433	2862
21	316	3050	2483
22	1448	2206	1471
23	1972	1850	1235
24	2317	1786	916
25	2709		1156
26		1638	1354
27	1860	520	1543
28	2270	617	1403
39	1364	2040	970
30	1882	1506	
31		1000	

Table 3.5. The Heffter Mixing Heights (HFMH) for summer 2007 at 0000 UTC at The Pas (Manitoba). The heights are given in meters above the ground level. Blank space indicates that this method was not applicable for the sounding.

Date	June (m)	July (m)	August (m)
1	1661	882	1121
2	1653	509	2767
3	2594	2644	1561
4	1930	3860	1911
5	1796	2432	339
6	1920	1940	1983
7	1892	532	2005
8	3389	2723	1700
9	2587	1408	2706
10	1828	2170	1402
11	1167	1803	1423
12	529	1722	998
13	2808	2922	2472
14	2532	1490	1894
15	2200	3203	2647
16	1579	2003	1809
17	1834	1941	2093
18	2331	2375	2012
19	1068	1686	1172
20	2674	1409	1063
21	3154	512	407
22	1247		
23	903	3267	1316
24	501	2813	1361
25	1617	1030	1722
26	1226	1745	1149
27	1787	2169	1773
28	1241	2881	2201
39	2040	1666	1562
30	886	970	2213
31		436	844

Table 3.6. The Holzworth Mixing Heights (HZMH) for summer 2006 at 0000 UTC at Stony Plain (Alberta). The heights are given in meters above the ground level. Blank space indicates that this method was not applicable for the sounding.

Date	**June (m)**	**July (m)**	**August (m)**
1	2584	2134	1284
2	2234	2484	2384
3	1919	3034	
4	2984	1669	1734
5	2984	1634	869
6		1234	1956
7	2134	1234	1534
8		2234	734
9		1834	1434
10	534	534	1434
11	2134		
12		2184	
13	773	1334	2234
14			2453
15	613	2418	2134
16		1835	1987
17		1935	2134
18	2308		2544
19	2313	2313	
20	1834	2357	
21		2653	1678
22	2334	1634	734
23	2187	1834	
24	2634	2834	
25	2432	2034	2877
26	1884	534	2234
27	1934	2034	2878
28		2034	2034
39	1634		1034
30	1534		1334
31			

Table 3.7. The Holzworth Mixing heights (HZMH) for summer 2007 at 0000 UTC at Stony Plain (Alberta). The heights are given in meters above the ground level. Blank space indicates that this method was not applicable for the sounding.

Date	June (m)	July (m)	August (m)
1	1734	1206	1688
2	2571	2305	1634
3	3034	2332	1471
4	2034	1237	1000
5	2134	1804	479
6		1034	
7	1512	1534	1800
8	2284	2310	
9	1834		705
10		1234	743
11	834	1734	
12	734	1834	1042
13	734	2034	934
14	2234	1434	978
15	1634	730	1846
16	2284		1348
17		412	760
18	463	1334	1192
19	1934	1034	
20	1634	373	650
21	1334	2125	1435
22	1134	1834	678
23	745		1709
24	676		1183
25	1434	1434	1737
26	634	2034	
27	2001	740	589
28	1325		1034
39	603	1190	2323
30	434	675	1018
31		1534	

Table 3.8. Average MH for Stony Plain (Alberta) and The Pas (Manitoba) diagnosed from radiosoundings of summers 2006 and 2007 at 0000 UTC using the Holzworth technique.

	WSE	**YQD**
June 2006	1996	1257
July 2006	1920	1273
August 2006	1811	1298
June 2007	1479	1395
July 2007	1442	1179
August 2007	1199	1243

Table 3.9. The Holzworth Mixing Heights (HZMH) for summer 2006 at 0000 UTC at The Pas (Manitoba). The heights are given in meters above the ground level. Blank space indicates that this method was not applicable for the sounding.

Date	June (m)	July (m)	August (m)
1	1844	2329	1229
2	2229	1163	1651
3	500	1238	
4			1829
5	1120	2198	1617
6		1529	
7	1180		1229
8	1260		
9	1220	458	
10	1421	1516	1729
11	1686	729	
12		1729	
13	1035	829	1289
14	1317		862
15	1429	2729	2253
16	729	2529	729
17		429	1329
18	629	1848	1529
19	1178	729	929
20	541	433	495
21		314	
22	729	729	1729
23	1729		629
24		1786	929
25	1766		
26		1638	
27	1860	629	1543
28	2270	617	1403
39	510	2040	1029
30	729	1029	
31		629	

Table 3.10. The Holzworth Mixing Heights (HZMH) for summer 2007 at 0000 UTC at The Pas (Manitoba). The heights are given in meters above the ground level. Blank space indicates that this method was not applicable for the sounding.

Date	June (m)	July (m)	August (m)
1	1761	882	1120
2	1029	679	1605
3		1129	1561
4		1721	1230
5	1796		
6	929		1630
7	1892		560
8	2054		1700
9	2029		
10	1829	1188	429
11	1253	512	1423
12	529	721	1029
13	1210		1266
14	1539		503
15			1554
16	729	2003	1129
17	1834		1237
18	1472		729
19		1564	1229
20		821	
21	1844	721	
22	1247		
23	729	1029	
24		894	1129
25			1186
26	774	1797	
27		2169	1773
28	1241	1500	2201
39	2040	1666	
30	929	970	1799
31		436	560

Table 3.11. The Moist Air Mixing Heights (MAMH) for summer 2006 at 0000 UTC at Stony Plain (Alberta). The heights are given in meters above the ground level. Blank space indicates that this method was not applicable for the sounding.

Date	**June (m)**	**July (m)**	**August (m)**
1	2161	1507	2237
2	2631	2379	2308
3	1841	2387	
4	2237	1189	1639
5	2888	1182	
6		625	1956
7	2317	713	2806
8	2573	2340	2347
9		2824	
10	444	516	1975
11	1621		1035
12		1771	
13	1993	667	3018
14	1147	1752	1955
15	1682	2292	1780
16		1835	1536
17		1935	1376
18	2195	3212	2166
19	2567	1576	2609
20	1487	1669	2552
21	2511	2340	1827
22	1993	826	
23	2187	1136	
24	2137	2380	
25	1874	709	1563
26	1869	686	2100
27	1432		2578
28	701	1802	1678
39	1409		1823
30	1142		1758
31			

Table 3.12. The Moist Air Mixing Heights (MAMH) for summer 2007 at 0000 UTC at Stony Plain (Alberta). The heights are given in meters above the ground level. Blank space indicates that this method was not applicable for the sounding.

Date	June (m)	July (m)	August (m)
1	1240	1206	1204
2	2085	1094	1503
3	2271	2004	1110
4	1869		603
5	1993	1566	
6		2275	
7	1512	1456	1284
8	1894	1627	
9	661		604
10	1735	606	402
11	626	1553	
12	571	1219	738
13	682	1780	717
14	703	553	782
15	1157		1846
16	1478	637	1011
17	2023		1862
18		1178	1192
19	1527	720	1771
20	2853	0	
21	1296	1755	2225
22	518	1241	486
23	686	2369	1709
24	484	712	1503
25	944	1080	1737
26	2210	1894	
27	1603		1091
28	1325	708	800
29	782		2323
30		665	
31		1356	1812

Table 3.13 Average MH for Stony Plain (Alberta) and The Pas (Manitoba) diagnosed from radiosoundings of summers 2006 and 2007 at 0000 UTC using the Moist Air technique.

	WSE	**YQD**
June 2006	1882	1401
July 2006	1625	1489
August 2006	2027	1407
June 2007	1379	1787
July 2007	1223	1500
August 2007	1253	1595

Table 3.14. The Moist Air Mixing Heights (MAMH) for summer 2006 at 0000 UTC at The Pas (Manitoba). The heights are given in meters above the ground level. Blank space indicates that this method was not applicable for the sounding.

Date	June (m)	July (m)	August (m)
1	1844	2250	1195
2	1914	1046	2742
3	1226	1645	2005
4		2820	2116
5	2308	1778	1216
6		1447	
7			1031
8	2378	1510	991
9	1220	1574	1357
10	1288	1230	1504
11	1235	1604	1010
12		1160	
13	555	2248	1934
14	1317	856	1645
15	1277	2184	1301
16	1517	2247	2102
17	400		1094
18		1050	1271
19	1710	1364	2909
20	671	433	
21		1757	2483
22	1745	671	1471
23	1972	1850	522
24	530	1786	1363
25	1303	967	1205
26		1638	1354
27	1860	520	1207
28	2270	1915	1403
39	1234	1834	970
30	448	692	
31		1108	

Table 3.15. The Moist Air Mixing Heights (MAMH) for summer 2007 at 0000 UTC at The Pas (Manitoba). The heights are given in meters above the ground level. Blank space indicates that this method was not applicable for the sounding.

Date	June (m)	July (m)	August (m)
1	1899	1694	1121
2	1202	426	1605
3	2594	876	1561
4	1930	2834	974
5	1696	2432	1131
6	668	1940	1181
7	1892	1180	2005
8	3389	443	1700
9	2587	1408	1395
10	1828	1159	2134
11	1634	1216	1423
12	1229	2074	998
13	1780	1180	2472
14	2532	1199	503
15		2203	1395
16	1579	1950	1809
17	1834	1941	2093
18	2331	2375	2012
19		1574	1974
20	1108	553	1063
21	2402	484	1376
22	3096		
23	1401	917	1099
24	1148	2173	1528
25	1617	1030	1722
26	774	1745	1149
27		2169	2512
28	882	1700	2201
39	1787	1666	2539
30	1427	970	1799
31			1367

Table 4.1. Observed Convective cloud base at YEG and WSE converted in meters, reported between 22:00 and 02:00 UTC.

Date	CCL obs (m) at CYEG	Date	CCL obs (m) at CYEG and at CWSE in brockets
June 2006		**June 2007**	
3	2134	3	2651
6	2134	6	1219
21	1372	10	1524
23	1524	11	914
July 2006		12	610 (915)
1	2134	13	762
3	2286	14	2286 (1372)
4	1372	15	1829 (1220)
6	2134	16	1981 (1524)
8	1981	17	1219 (915)
10	1372	18	1372 (1067)
11	914	19	1372 (1524)
14	1829	20	1372
15	1676	22	1219
16	1829	23	1066
18	2134	24	1219
19	1829	25	1402 (1067)
24	2438	**July 2007**	
25	1676	1	1372 (1341)
26	1829	3	1677
31	823	4	(1524)
August 2006		9	1585 (1220)
1	1219	10	762 (762)
2	1828	12	1677
4	1828	17	1524
5	610	19	1220
13	1768	20	1067 (914)
15	2590	24	2134 (1585)
16	1676	25	1524 (1372)
17	1372	27	2134
19	2103	28	1829 (1372)
20	1828	29	(1372)
24	1067	30	1310 (1220)
25	2133	31	1067(1220)
		August 2007	
		1	1372
		4	915
		5	518
		6	1524 (1524)
		7	(1524)
		8	2621 (1524)
		10	(762)
		15	1829
		22	1524
		24	(1220)
		26	1158 (457)
		27	975 (914)
		28	1067(1220)

Table 4.2. Monthly average estimated and observed convective cloud heights at Stony Plain (WSE) for summer 2006 and 2007. CCL(MM) is estimated, based on Moist Air Mixing Height.

Month	Estimated CCL (MM) Average (m)	Observed CCL Average (m)
June, 2006	2659	1791
July, 2006	2468	1766
August, 2006	2667	1669
June, 2007	1613	1154
July, 2007	1954	1394
August, 2007	1446	1177

Table 4.3. Monthly variability of [CCL(SB)-CCL(obs)] at Stony Plain (WSE) during summer 2007.

Month	**Variability in [CCL(SB)-CCL(obs)]**		
	Max	**Min**	**Average**
June	493	35	165
July	726	13	290
August	1093	37	376

Table 4.4. Monthly variability of [CCL(ML)-CCL(obs)] at Stony Plain (WSE) during summer 2007.

Month	**Variability in [CCL(ML)- CCL(obs)]**		
	Max	**Min**	**Average**
June	579	63	318
July	1162	44	457
August	993	2	261

Table 4.5. Monthly variability of [CCL(MM)-CCL(obs)] at Stony Plain (WSE) during summer 2007.

Month	**Variability in [CCL(MM)-CCL(obs)]**		
	Max	**Min**	**Average**
June	1519	63	507
July	1384	44	627
August	1149	1	420

Table 4.6.Monthly average estimated and observed convective cloud heights at The Pas (YQD) for summer 2006 and 2007. CCL(MM) is estimated, based on Moist Air Mixing Height.

Month	Estimated CCL (MM) Average (m)	Observed CCL Average (m)
June, 2006	1903	1277
July, 2006	1956	1124
August, 2006	1878	1320
June, 2007	2257	915
July, 2007	2293	1236
August, 2007	1841	881

Table 6.1.CAPE values, based on surface and 50 mb mixed layer parcel at Stony Plain for 0000 UTC sounding profile for the summer period of 2006.

Date CYEG	CAPE(SB) (J/kg)	CAPE(ML) (J/kg)
June,2006		
21	135	6
3	600	98
6	475	37
23	469	16
July,2006		
3	1333	93
18	384	54
11	256	0
1	577	0
6	1238	382
15	420	215
4	1437	386
24	1856	505
16	180	35
8	701	191
14	296	83
19	1068	59
25	1219	201
31	0	0
10	641	18
26	1096	396
August, 2006		
13	502	53
19	682	486
15	116	10
1	861	437
25	80	36
4	150	109
16	106	21
20	100	0
2	884	97
5	231	0
24	0	0
17	785	77

Table 6.2.CAPE values, based on surface and 50 mb mixed layer parcel at Stony Plain for 0000 UTC sounding profile for the summer period of 2007.

Date CYEG	CAPE(SB) (J/kg)	CAPE(ML) (J/kg)
June,2007		
11	246	41
12	719	565
13	104	68
14	921	515
15	610	223
16	1280	561
17	101	51
18	549	240
19	1153	614
20	209	9
22	1314	540
23	93	93
24	233	51
25	857	380
July,2007		
1	979	334
3	478	203
4	622	321
10	518	118
12	135	124
17	1892	1434
19	3018	2472
20	2482	1996
24	1097	55
25	153	97
27	901	378
28	2121	1895
29	1662	1206
30	4157	3064
31	939	253
August, 2007		
1	1212	464
4	1252	920
5	631	212
6	1080	815
7	475	206
10	42	21
8	1000	291
15	61	27
22	235	138
24	600	217
26	6	0
27	131	33
28	89	67

Table 6.3. CAPE values, based on surface and 50 mb mixed layer parcel at The Pas for 0000 UTC sounding profile for the summer period of 2007.

Date CYQD	CAPE(SB) (J/kg)	CAPE(ML) (J/kg)
June,2007		
13	213	95
20	0	0
24	18	8
July,2007		
3	750	750
4	893	609
7	954	681
10	287	203
11	487	214
13	22	7
14	318	215
25	3813	3024
28	709	492
August, 2007		
2	306	75
5	1953	1635
7	916	575
9	1573	506
12	976	613
14	443	294
15	201	22
16	339	193

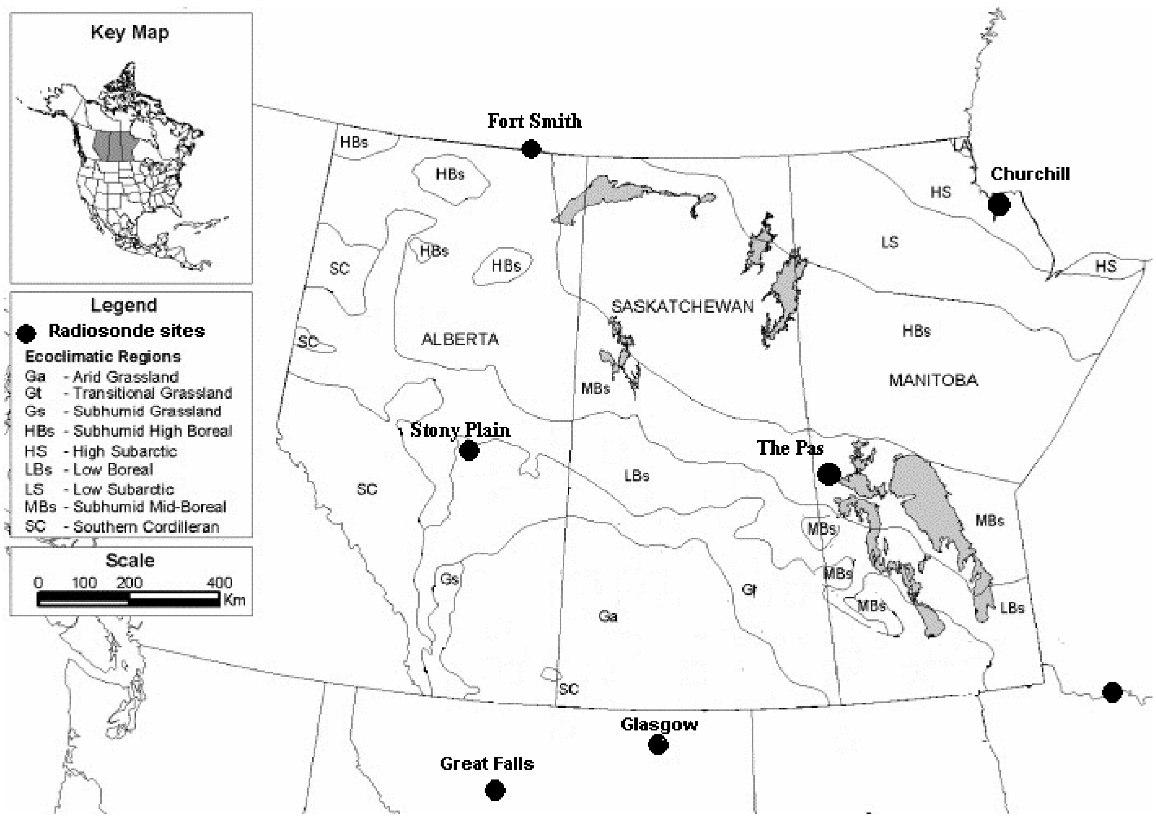

Figure 2.1. Eco-climatic regions of the Canadian Prairie Provinces, showing the upper air radiosonde sites: Stony Plain, Fort Smith, The Pas, Churchill, International Falls, Glasgow, and Great Falls. Adapted from Raddatz and Noonan (2004).

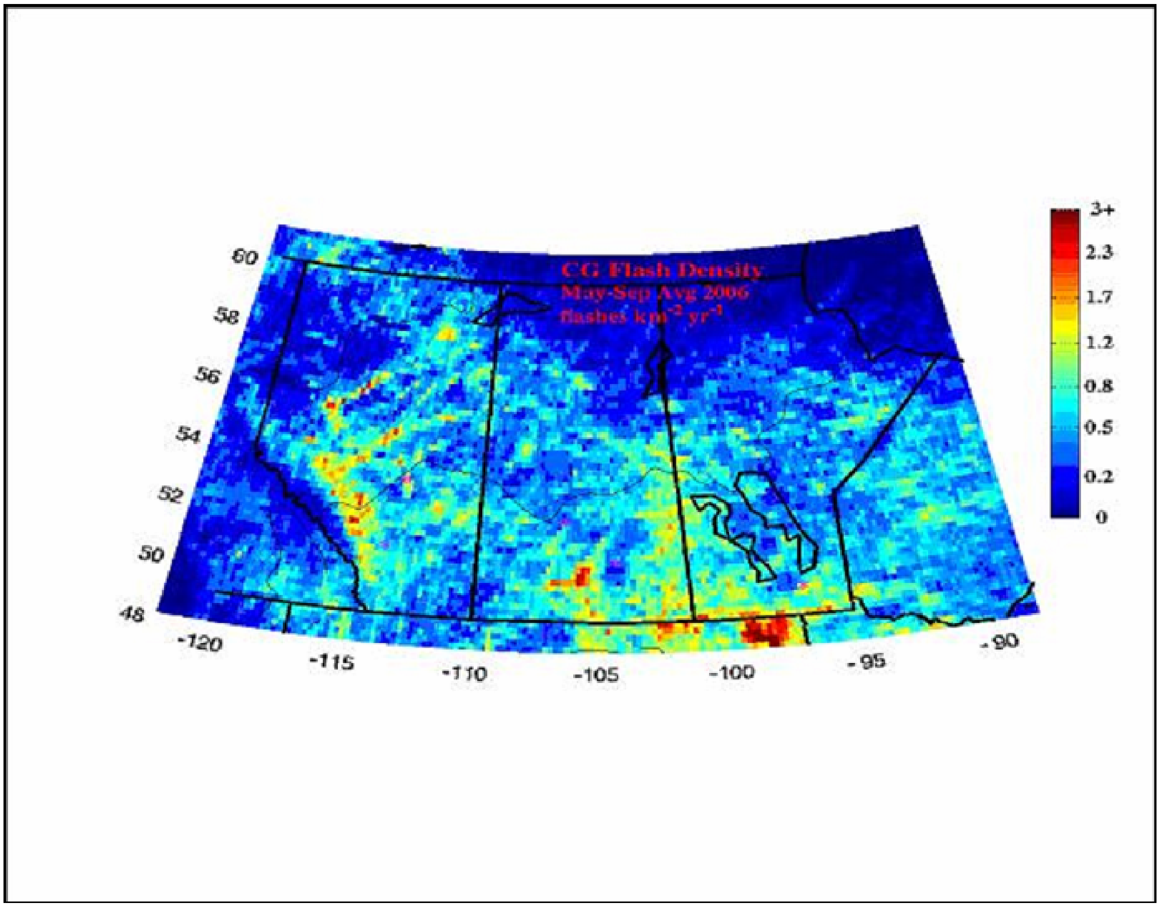

Figure 2.2. Cumulative cloud to ground flash density (number of flashes per km^2) for the summer of 2006.

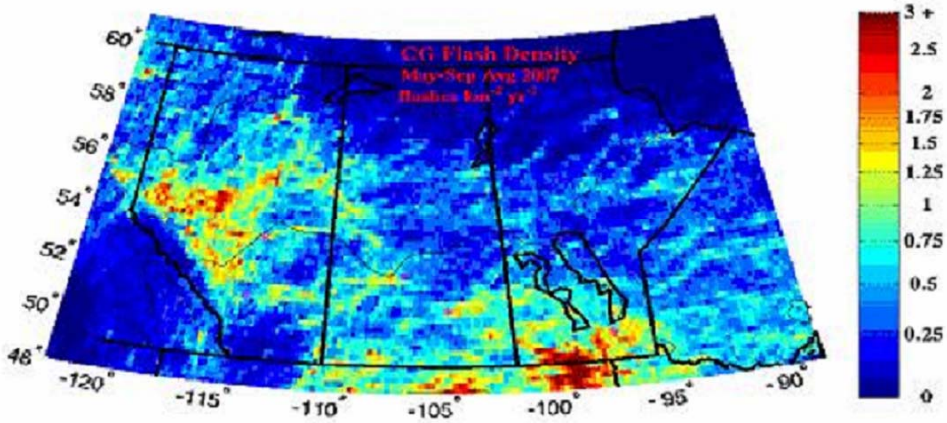

Figure 2.3. Cumulative cloud to ground flash density (number of flashes per km^2) for the summer of 2007.

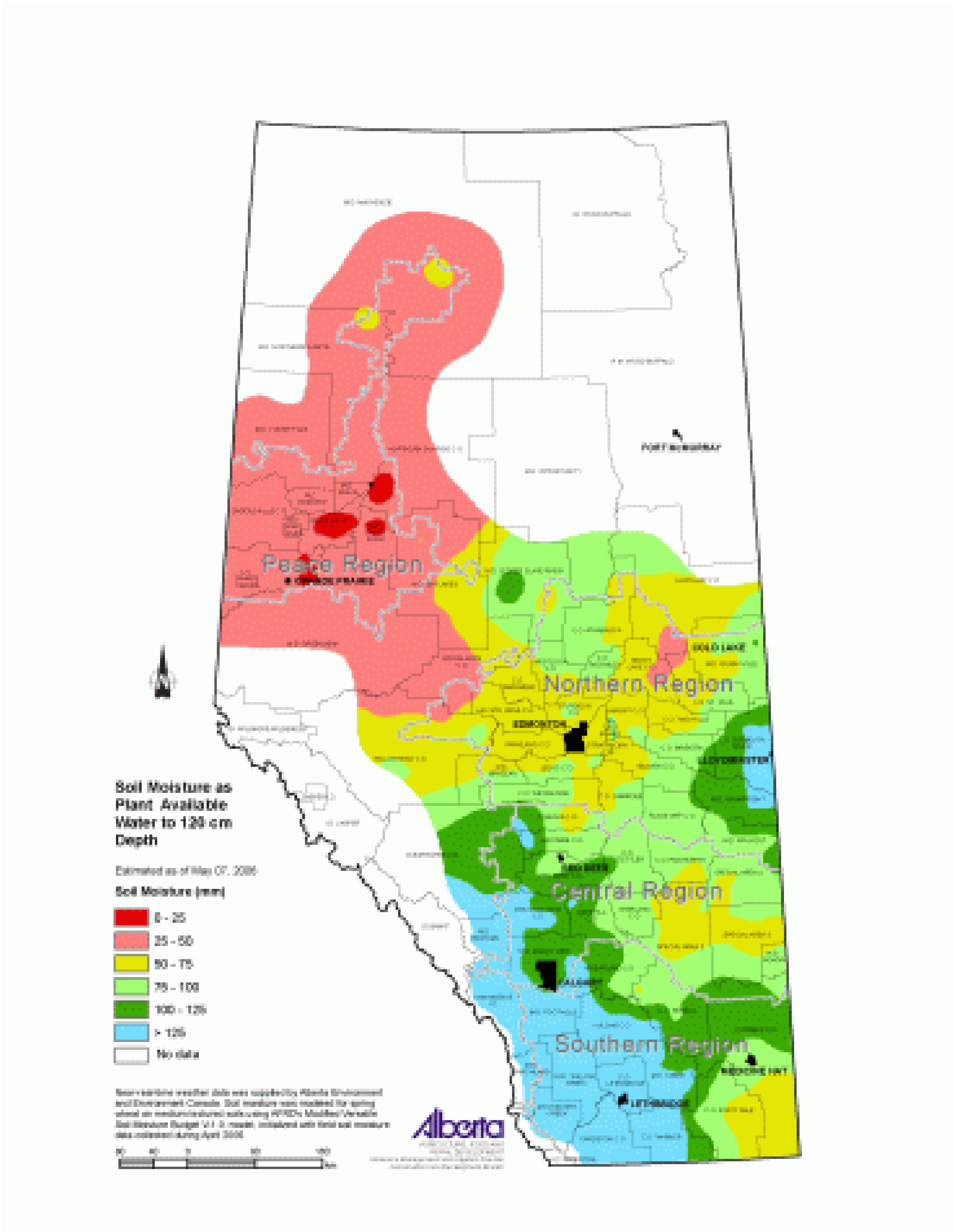

Figure 2.4. Soil Moisture Depth (mm), estimated as of May 7, 2006.

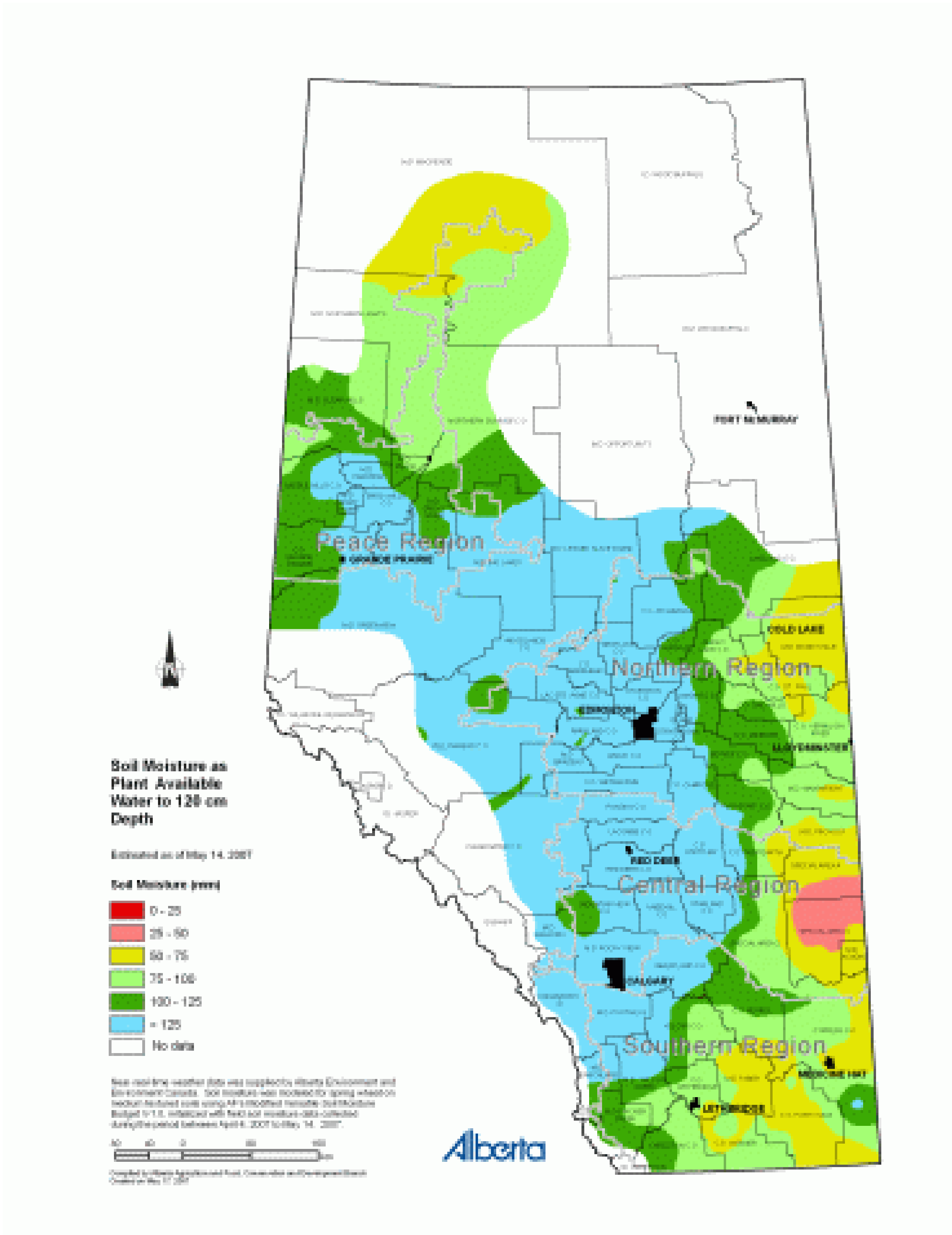

Figure 2.5. Soil Moisture Depth (mm), estimated as of May 14, 2007.

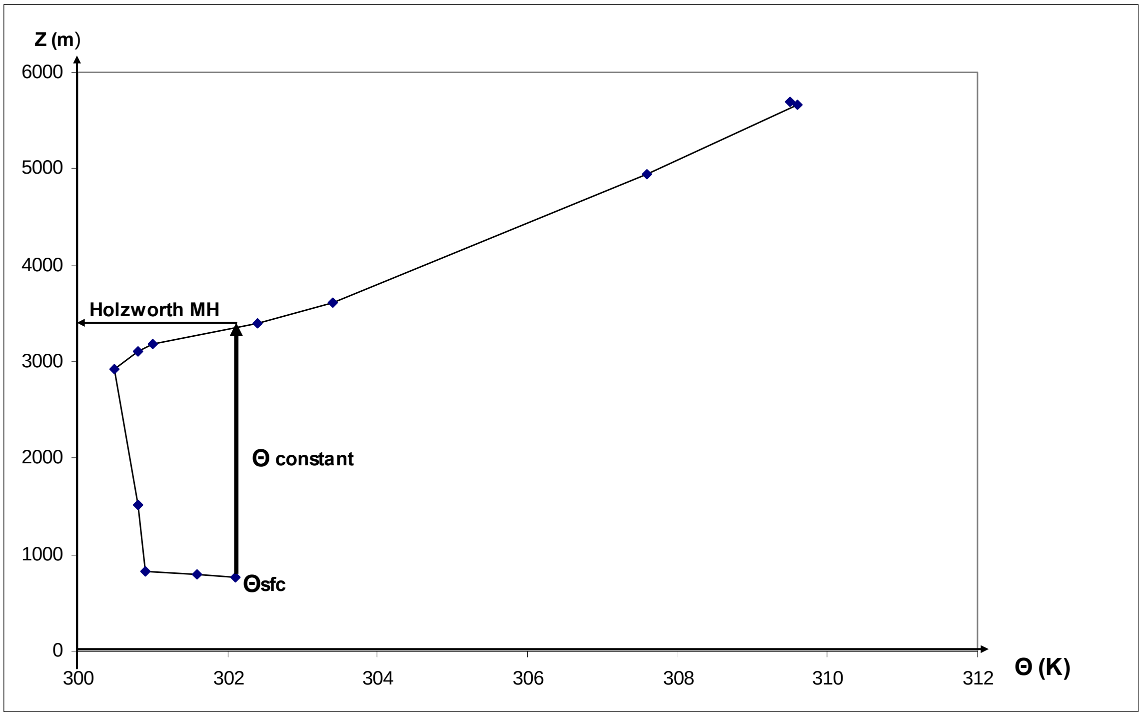

Figure 2.6. Illustration of the Holzworth method to estimate Mixing Height (MH) for the potential temperature (θ) sounding observed at 0000 UTC 1 June 2006 over Stony Plain (WSE).

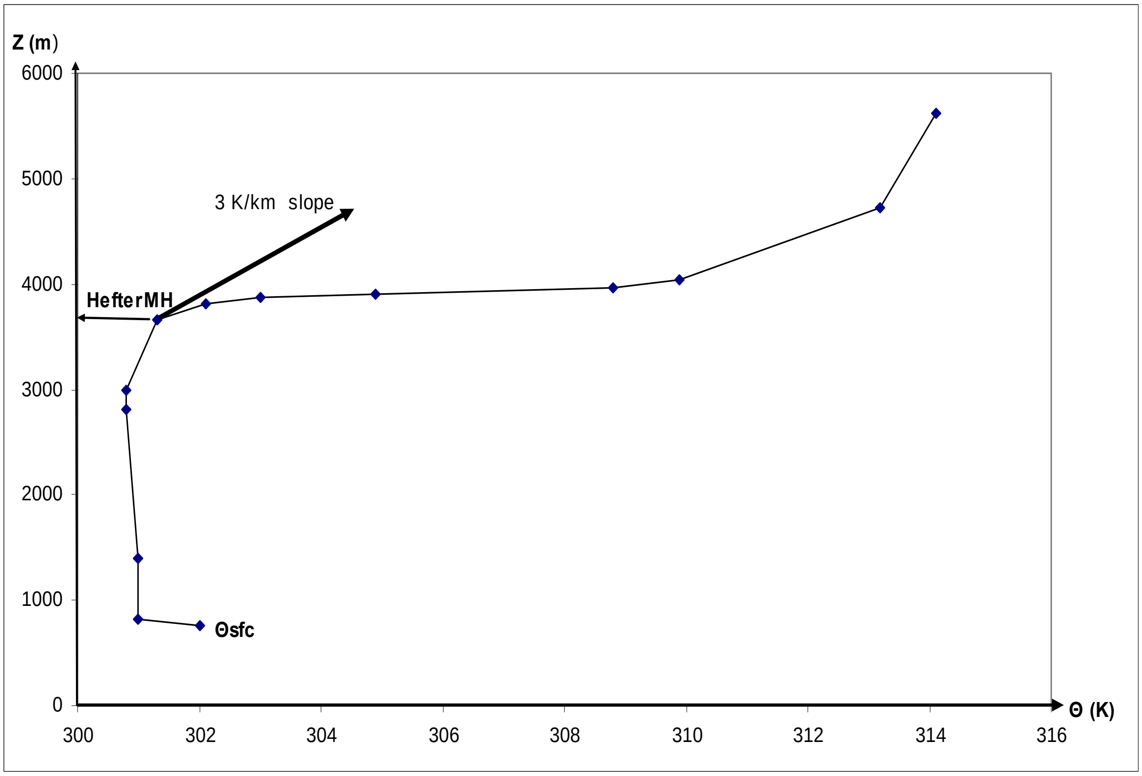

Figure 2.7. Illustration of the Heffter method to estimate Mixing Height (MH) for the potential temperature (θ) sounding observed at 0000 UTC 5 June 2006 over Stony Plain (WSE).

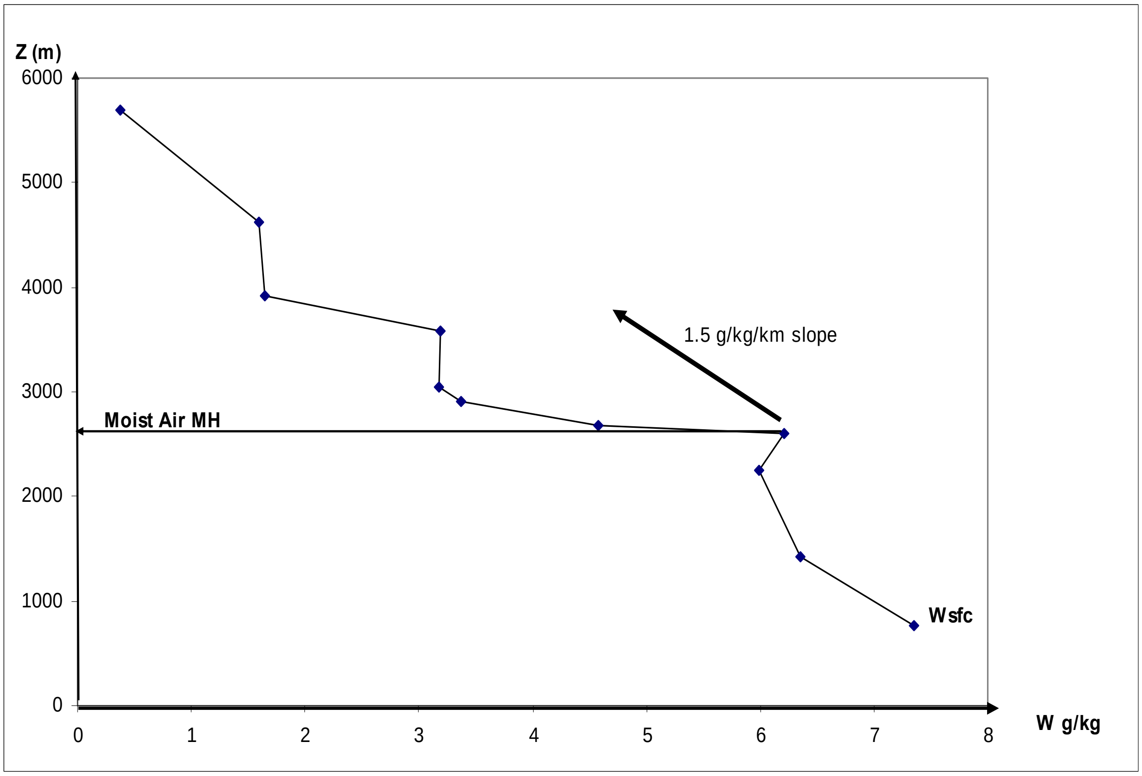

Figure 2.8. Illustration of the Moist Air method to estimate Mixing Height (MH) based on the water vapor mixing ratio (W) profile observed at 0000 UTC 3 June 2006 over Stony Plain (WSE).

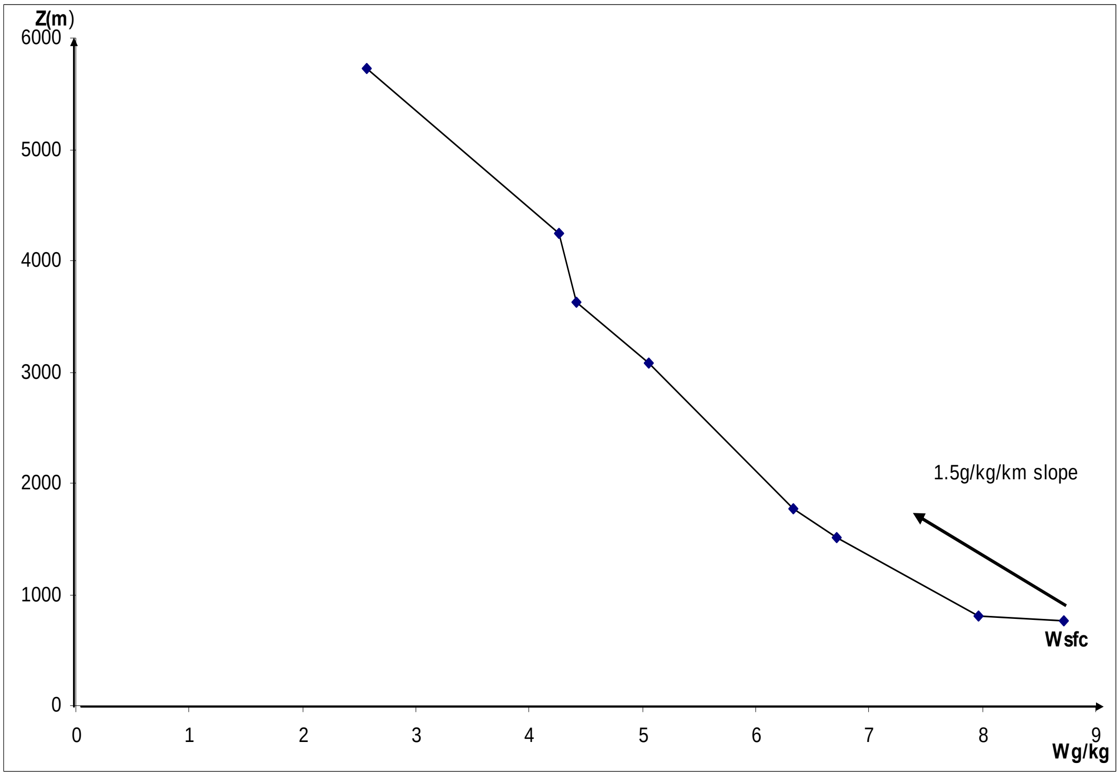

Figure 2.9. Illustration of assumption #1 in the Moist Air method to estimate MH based on the water vapor mixing ratio (w) profile observed at 0000 UTC 9 June 2006 over Stony Plain (WSE).

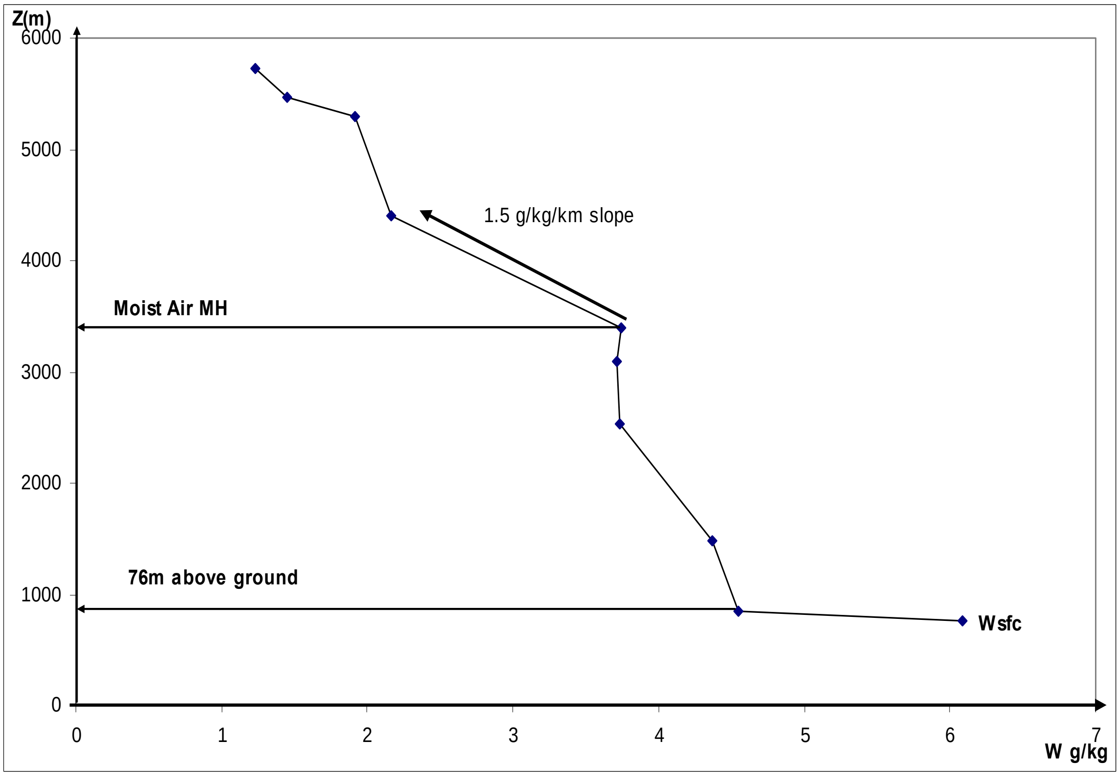

Figure 2.10. Illustration of assumption #2 in the Moist Air method to estimate MH based on the water vapor mixing ratio (w) profile observed at 0000 UTC 2 June 2006 over Stony Plain (WSE).

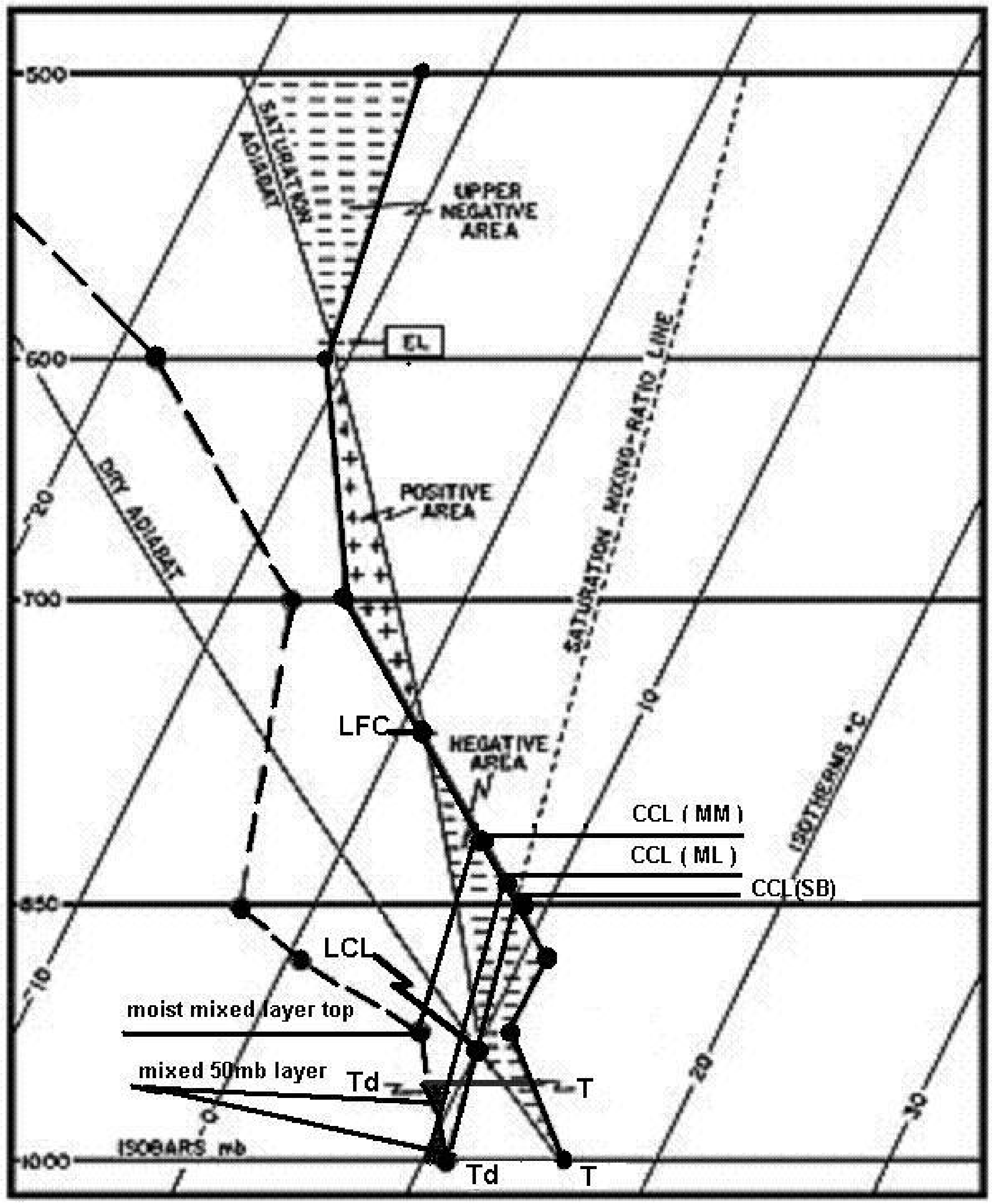

Figure 2.11.Skew T - log p diagram showing the soundings of temperature (solid) and dew point temperature (dashed). The diagram shows skewed isotherms, horizontal isobars, and the dry adiabat and the saturated adiabat passing through the Lifted Condensation Level (LCL). Further explanation is given in the text.

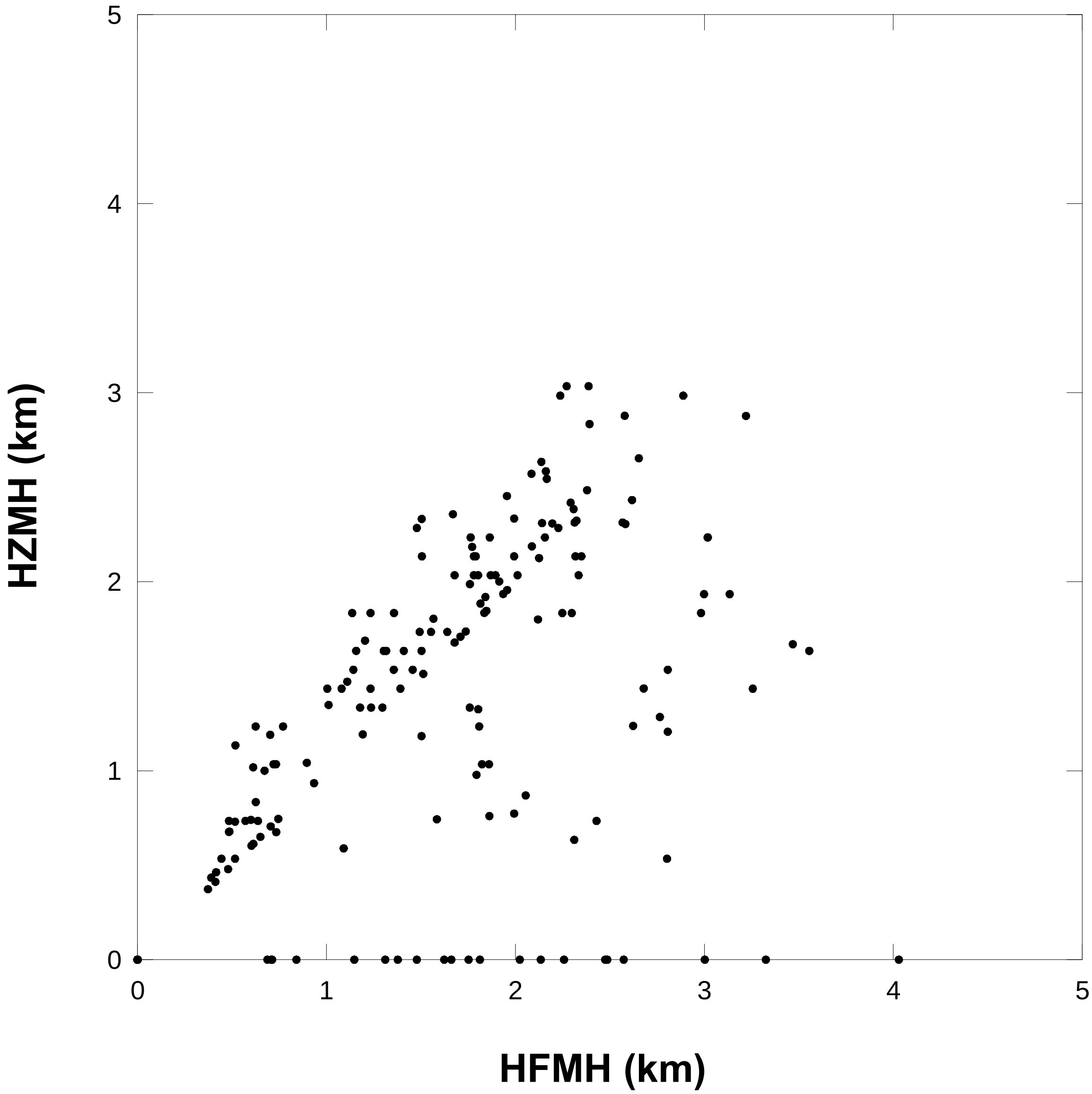

Figure 3.1. Scatter diagram of Holzworth Mixing Height (HZMH) versus Heffter Mixing Height (HFMH) for the summers of 2006 and 2007 at Stony Plain (WSE). Each data point represents a sounding. The data points on the axis line represent undefined MH.

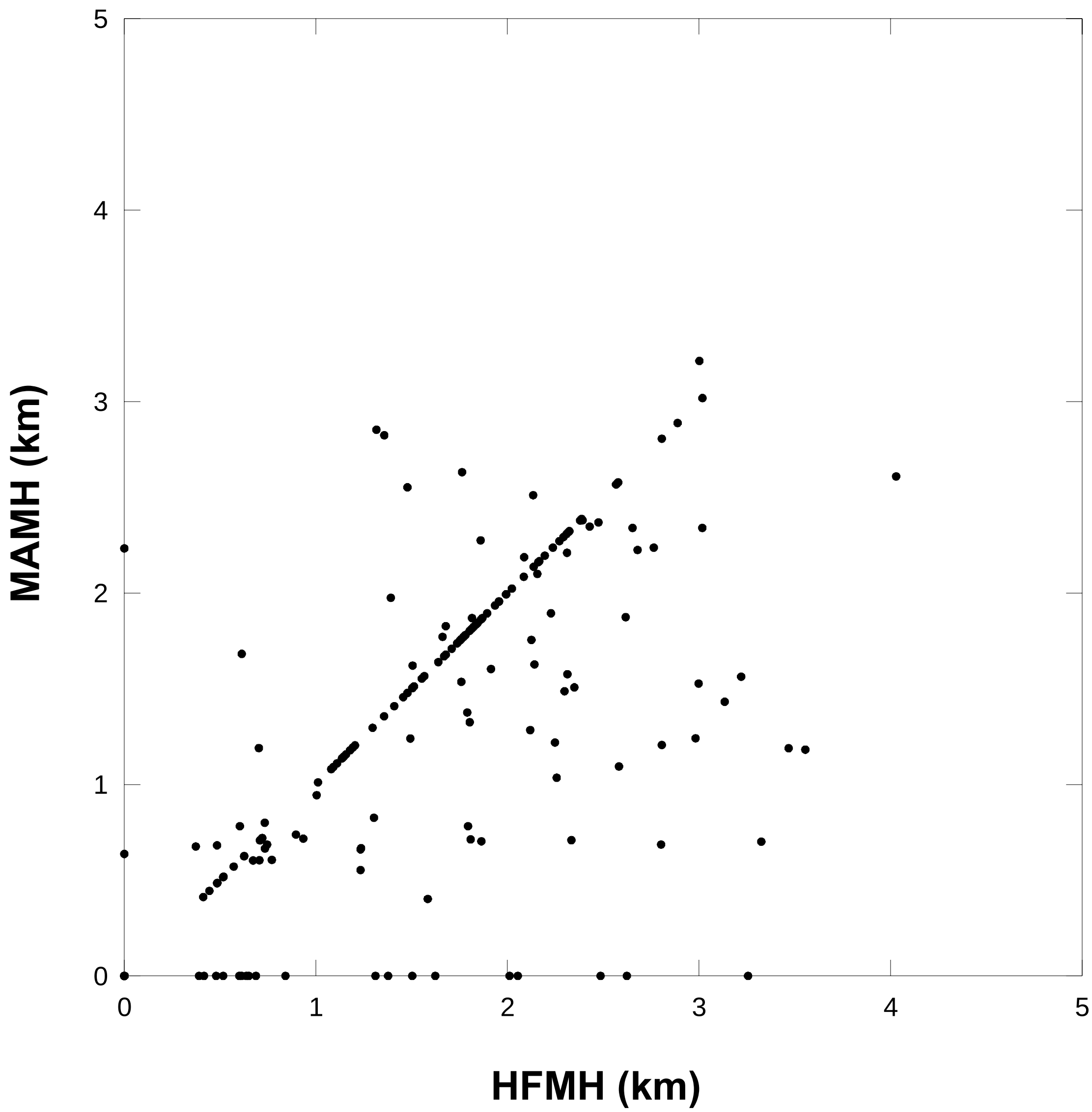

Figure 3.2. Scatter diagram of Moist Air Mixing Height (MAMH) versus Heffter Mixing Height (HZMH) for the summers of 2006 and 2007 at Stony Plain (WSE). Each data point represents a sounding. The data points on the axis line represent undefined MH.

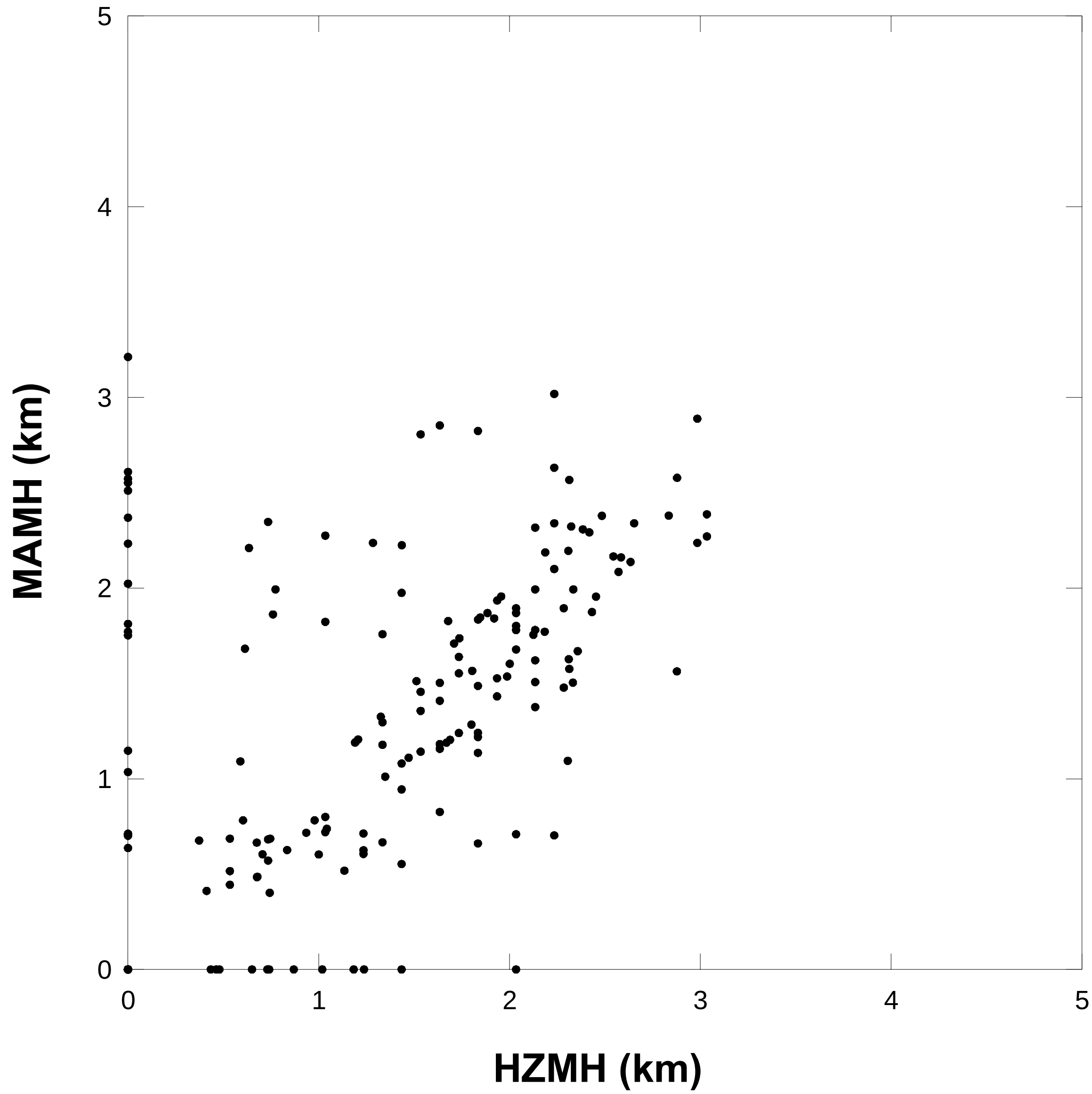

Figure 3.3. Scatter diagram of Moist Air Mixing Height (MAMH) versus Holzworth Mixing Height (HZMH) for the summers of 2006 and 2007 at Stony Plain (WSE). Each data point represents a sounding. The data points on the axis line represent undefined MH.

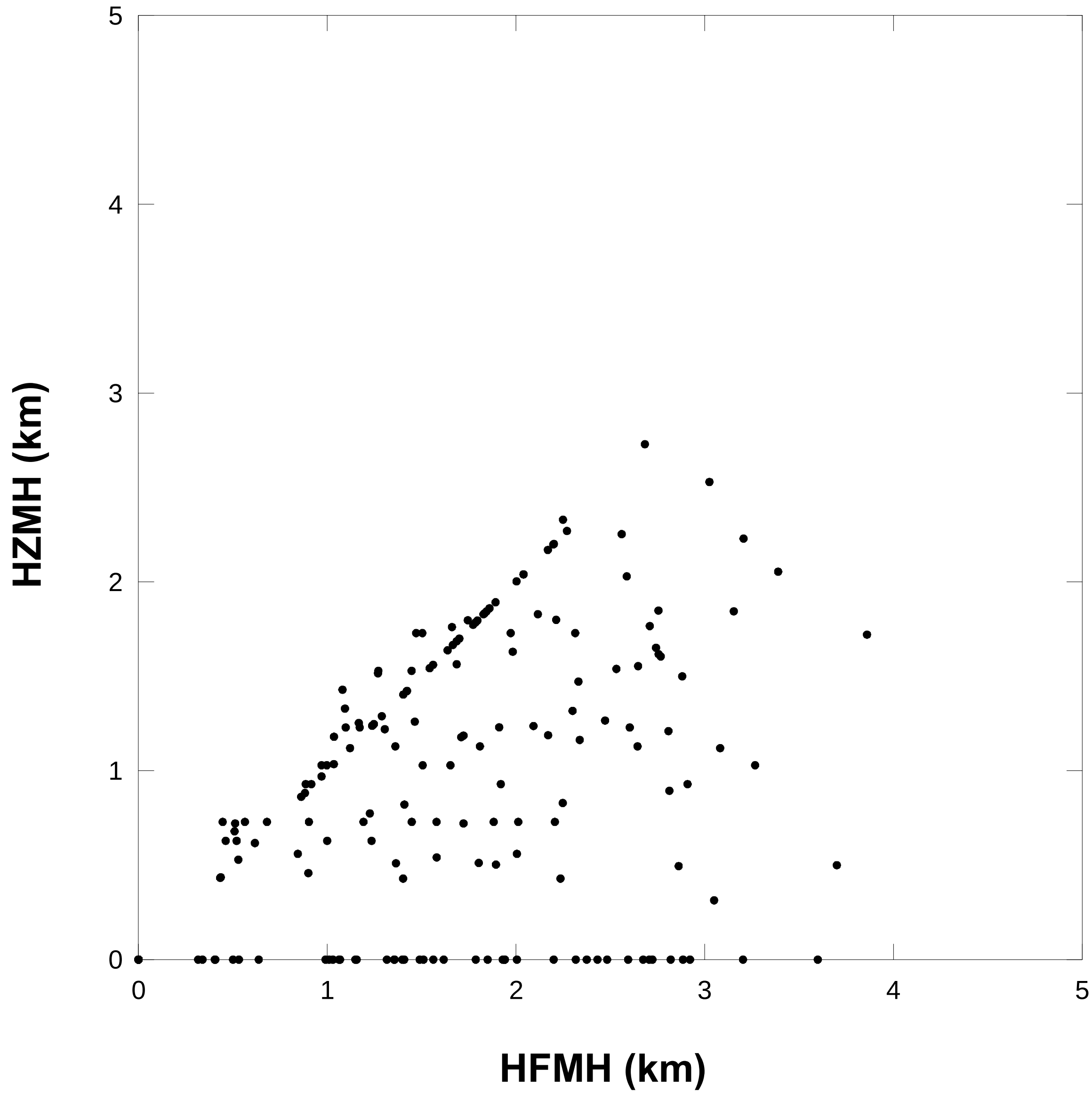

Figure 3.4. Scatter diagram of Holzworth Mixing Height (HZMH) versus Heffter Mixing Height (HFMH) for the summers of 2006 and 2007 at The Pas (YQD). Each data point represents a sounding. The data points on the axis line represent undefined MH.

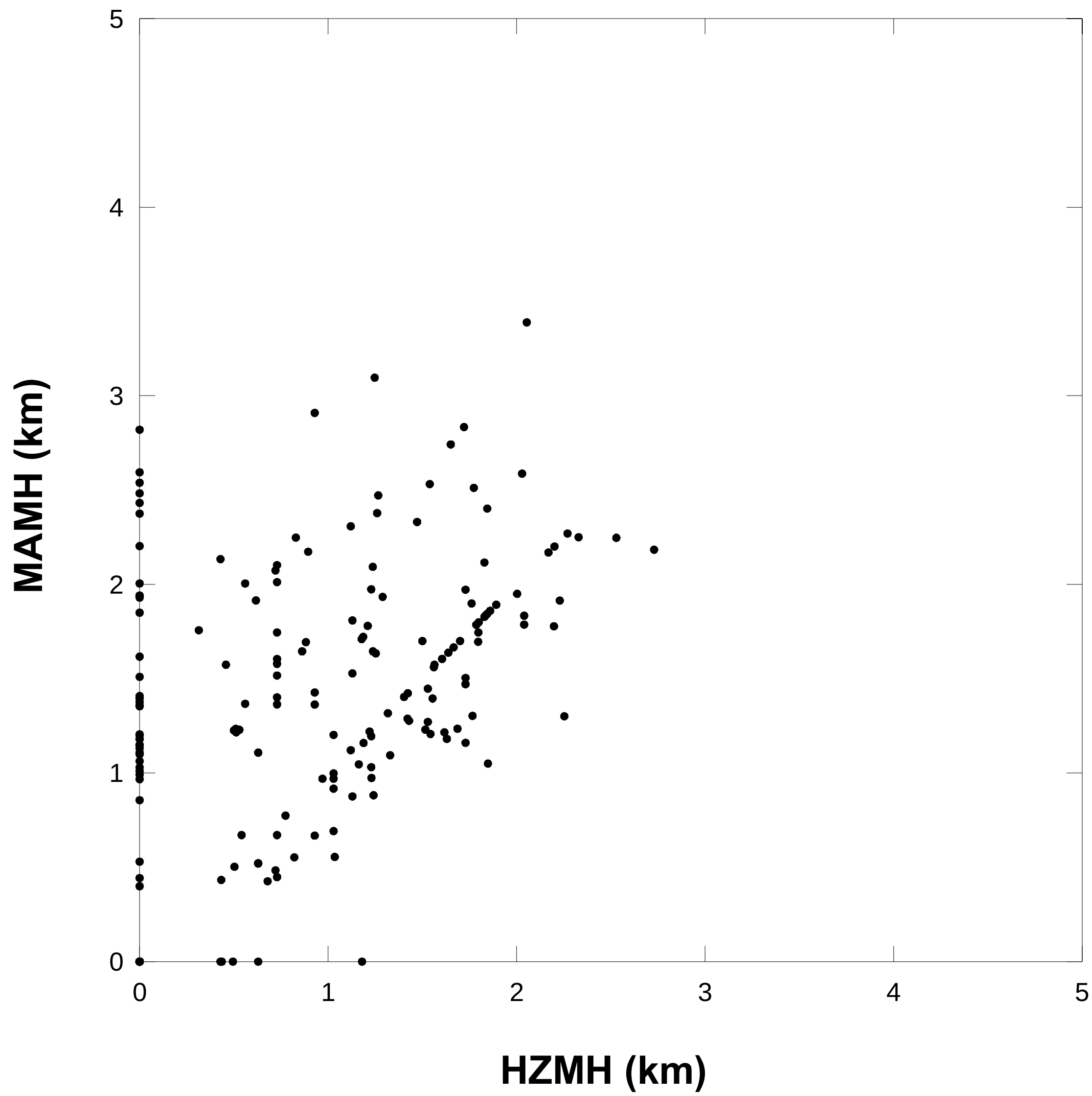

Figure 3.5. Scatter diagram of Moist Air Mixing Height (MAMH) versus Holzworth Mixing Height (HZMH) for the summers of 2006 and 2007 at The Pas (YQD). Each data point represents a sounding. The data points on the axis line represent undefined MH.

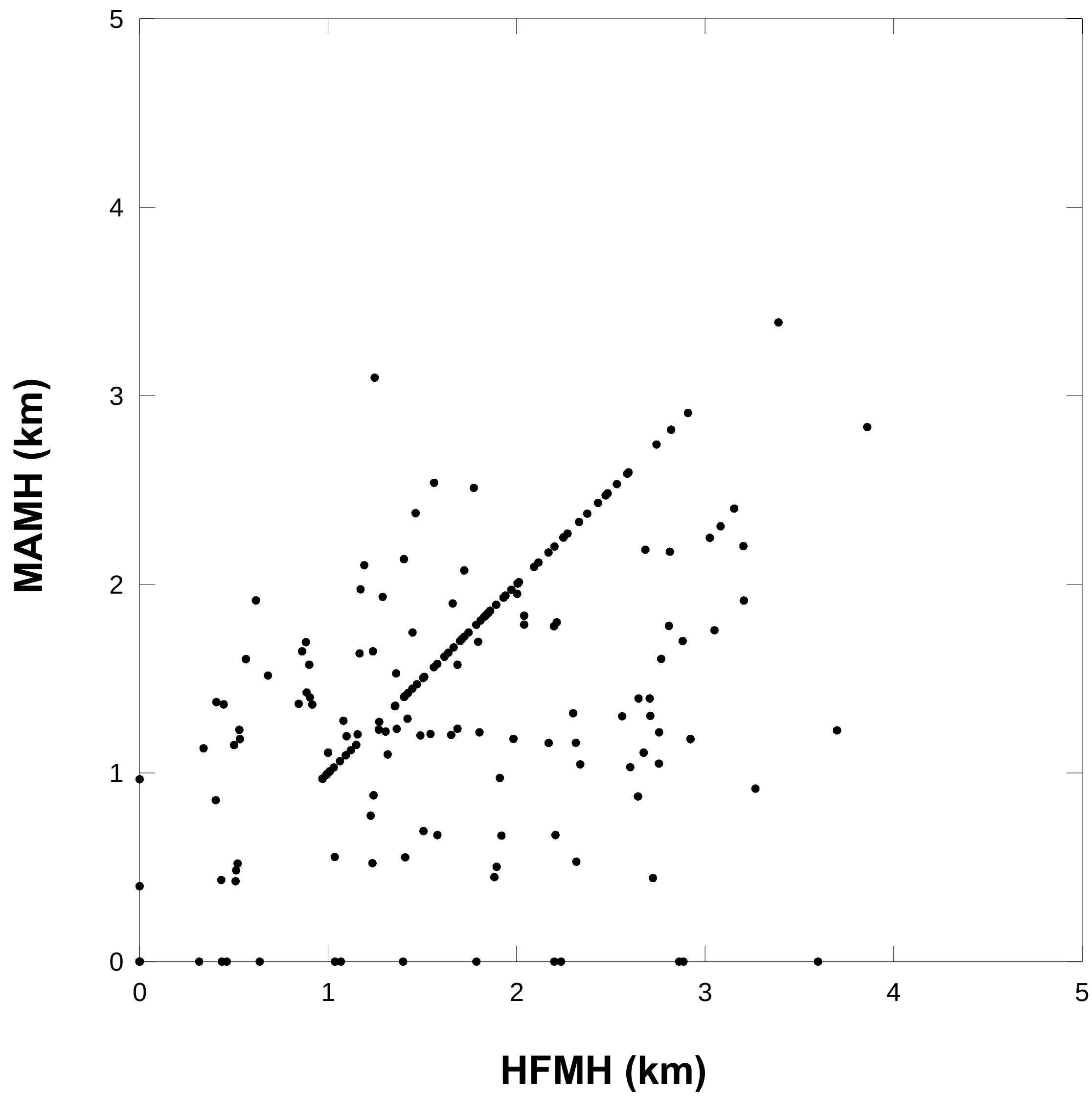

Figure 3.6. Scatter diagram of Moist Air Mixing Height (MAMH) versus Heffter Mixing Height (HFMH) for the summers of 2006 and 2007 at The Pas (YQD). Each data point represents a sounding. The data points on the axis line represent undefined MH.

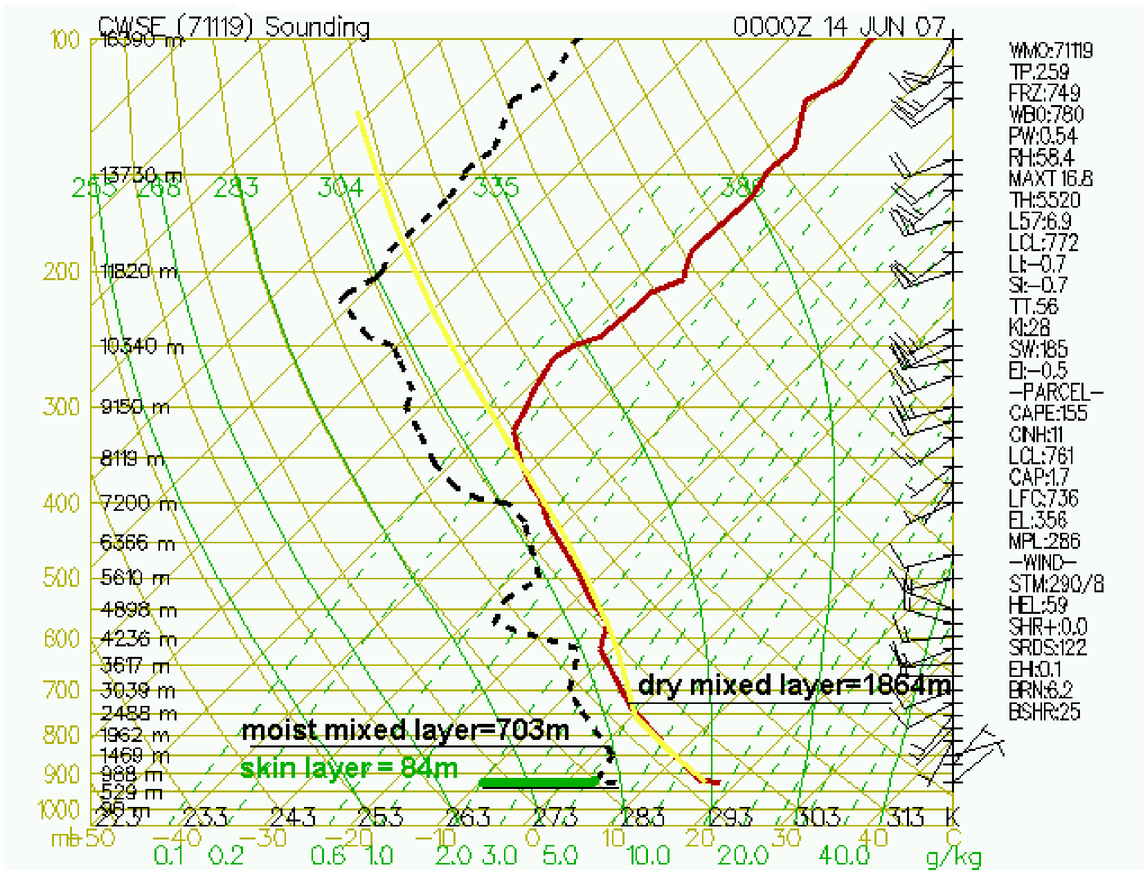

Figure 3.7. Skew T – log p diagram showing the skin layer, the moist mixed layer, the dry mixed layer and the free atmosphere associated with the sounding observed at 0000 UTC 14 June 2007 over Stony Plain (WSE).

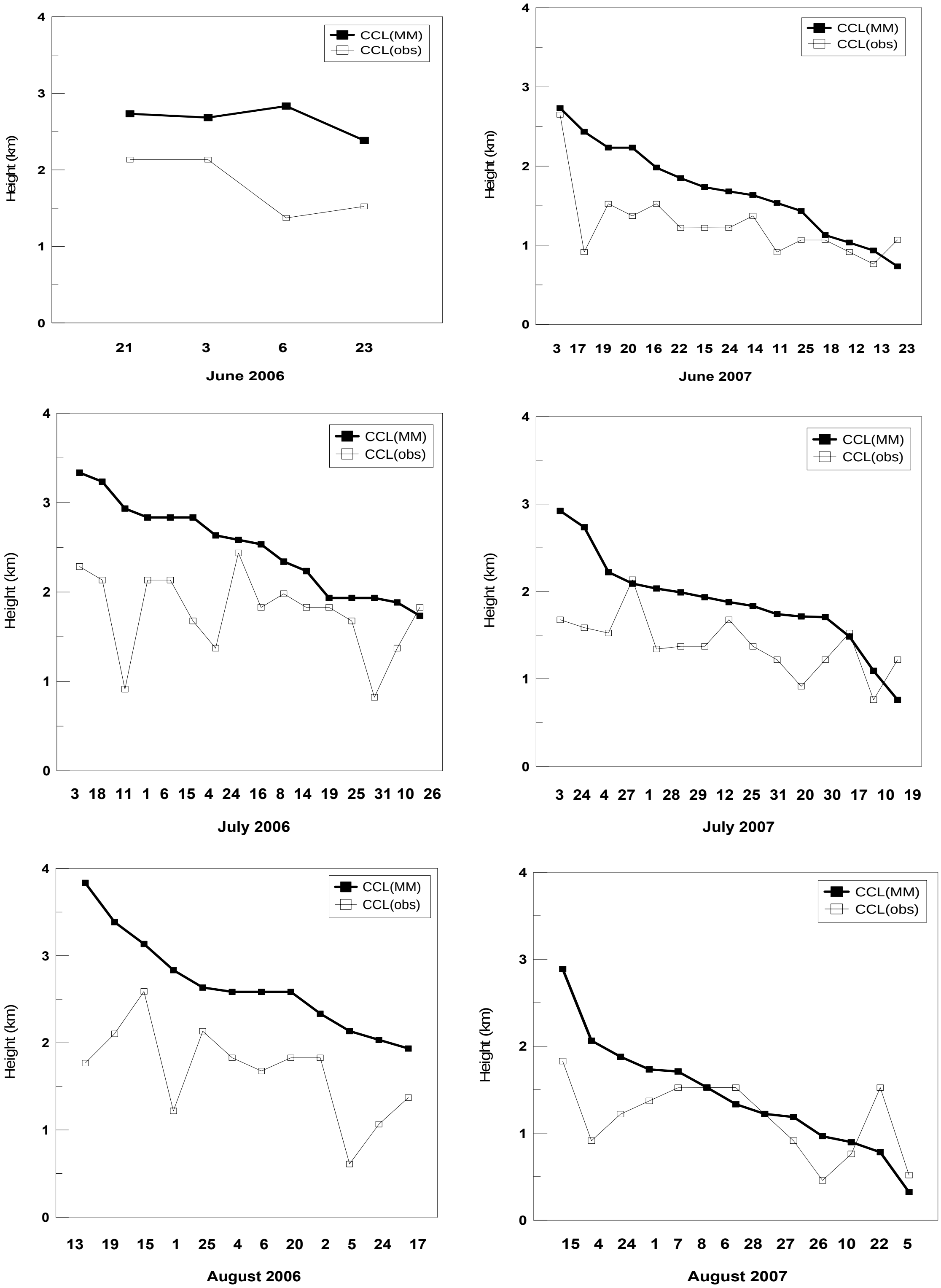

Figure 4.1 Comparison of Cloud Condensation Level (CCL) using the MAMH method with observed CCL for the summer of 2006 and 2007 at Stony Plain (WSE).

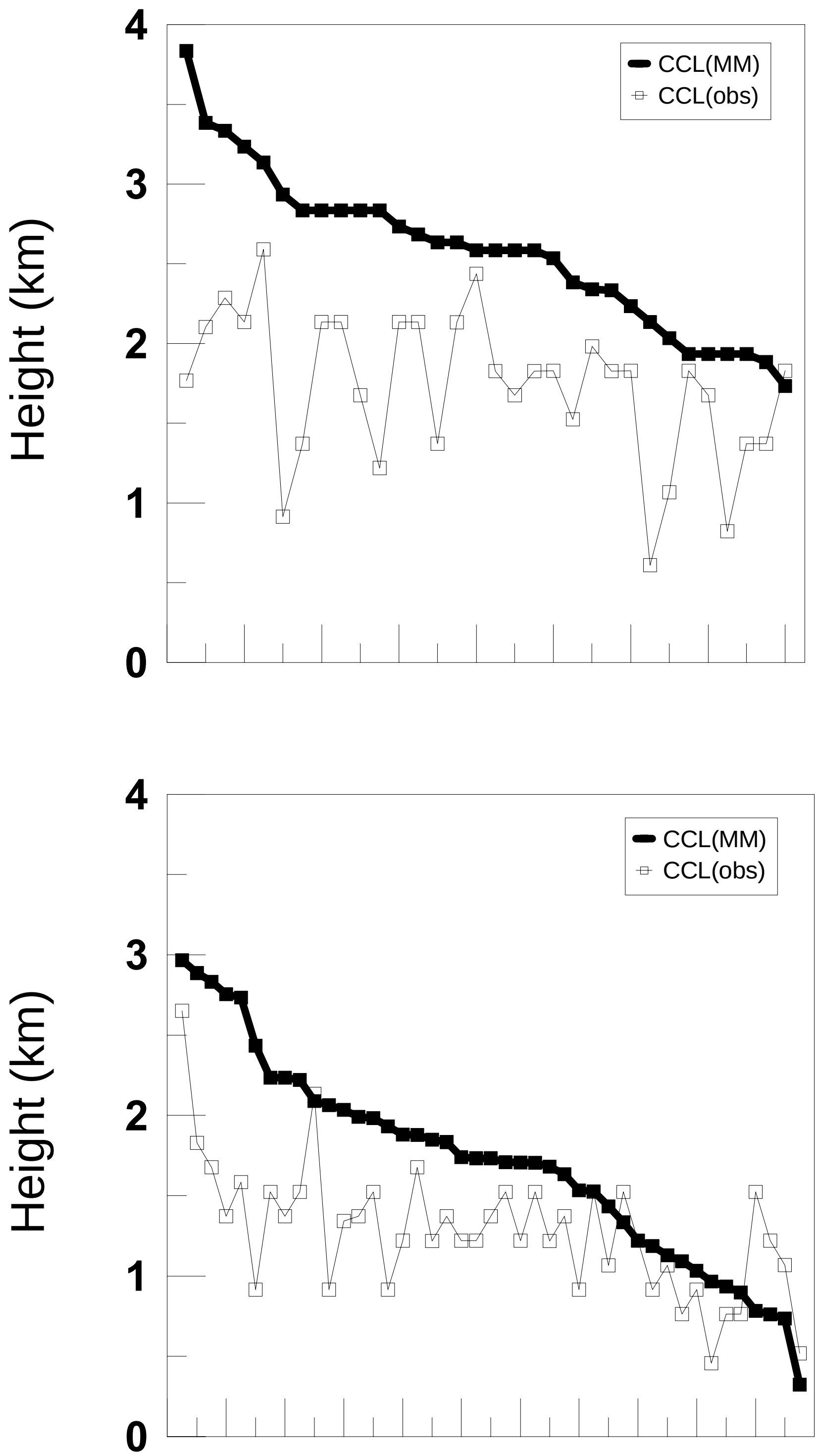

Figure 4.2. Comparison of Convective Condensation Level (CCL) estimated with the Moist Mixed (MM) method and observed CCL for the summer of 2006 (top) and summer of 2007 (bottom) at Stony Plain (WSE).

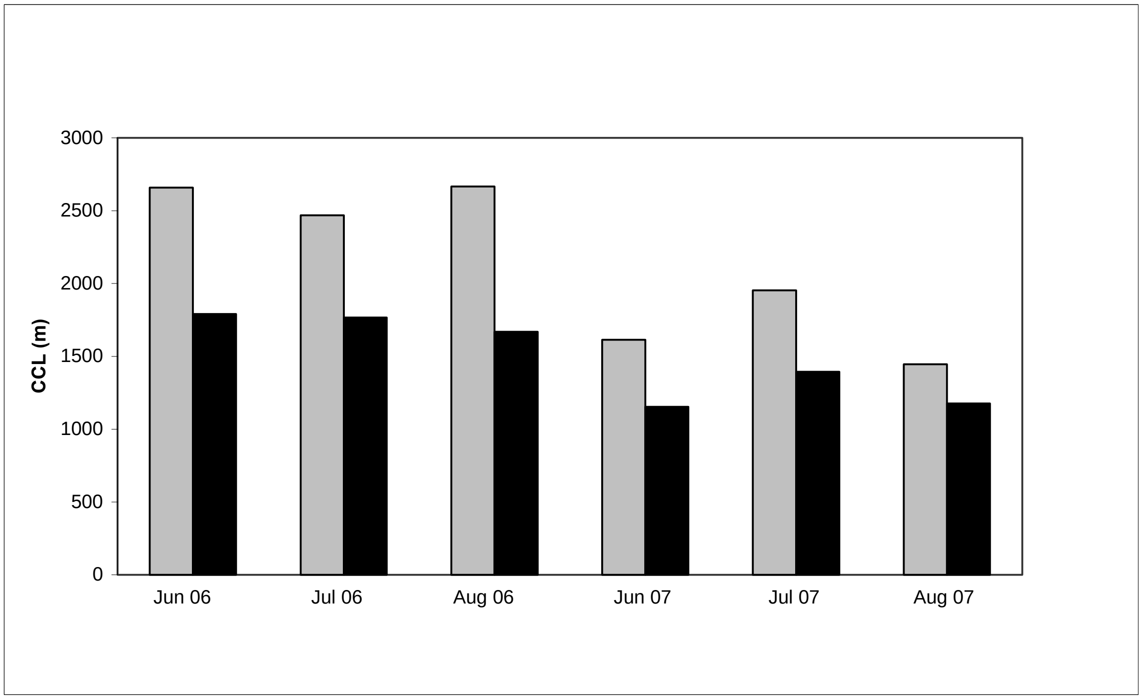

Figure 4.3. Average Convective Condensation Level (CCL) using the Moist Mixed (MM) method (grey) and the observed CCL (black) for the six summer months of 2006 and 2007 at Stony Plain (WSE).

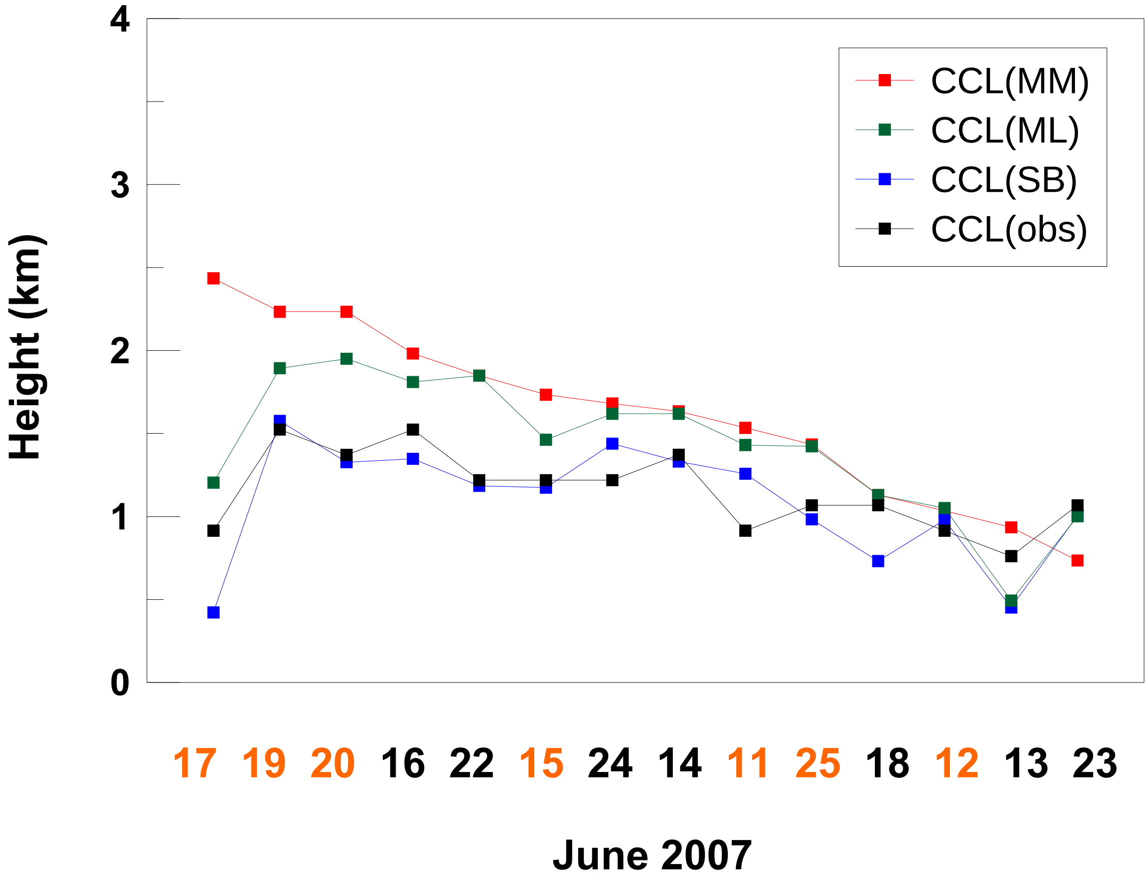

Figure 4. 4. Comparison of CCL using the MM, ML and SB methods with observed CCL for June 2007 at Stony Plain (WSE). Days with observed thunderstorms are labeled in orange color.

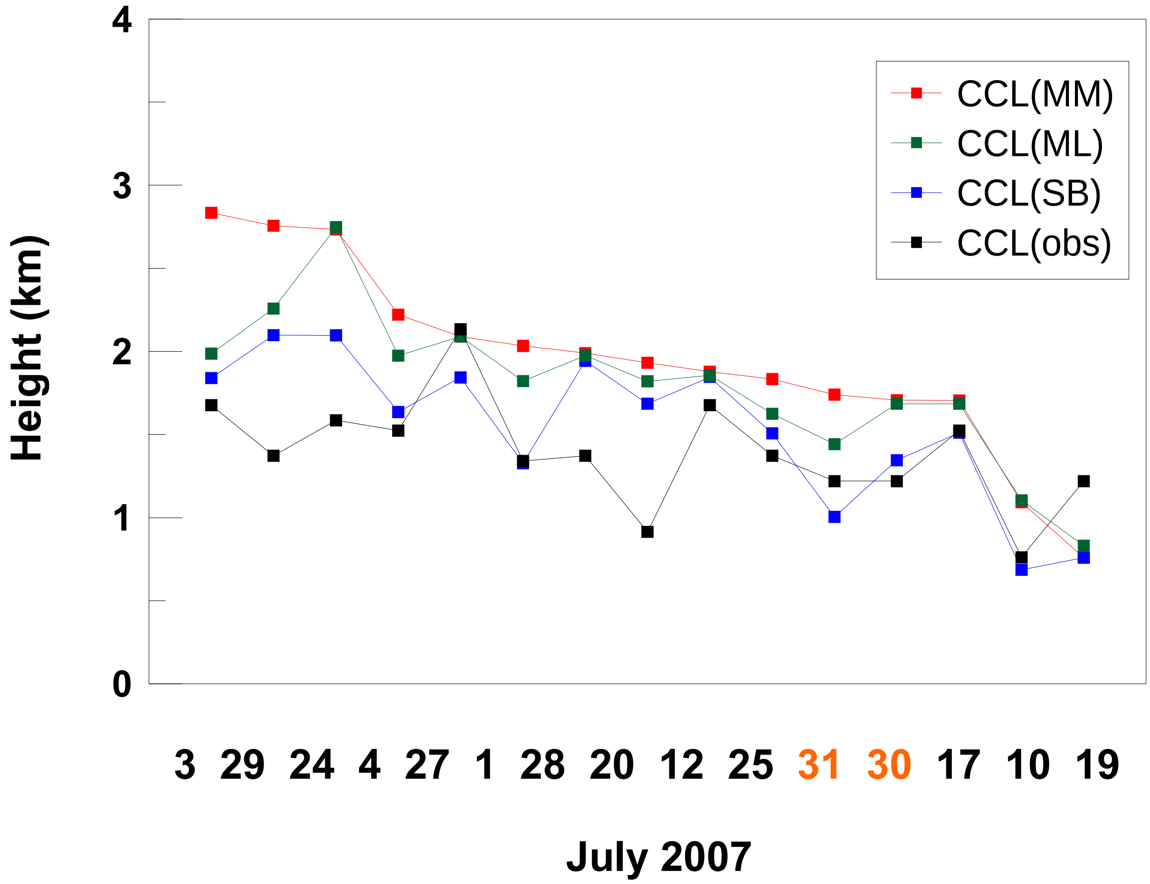

Figure 4. 5. Comparison of CCL using the MM, ML and SB methods with observed CCL for July 2007 at Stony Plain (WSE). Days with observed thunderstorms are labeled in orange color.

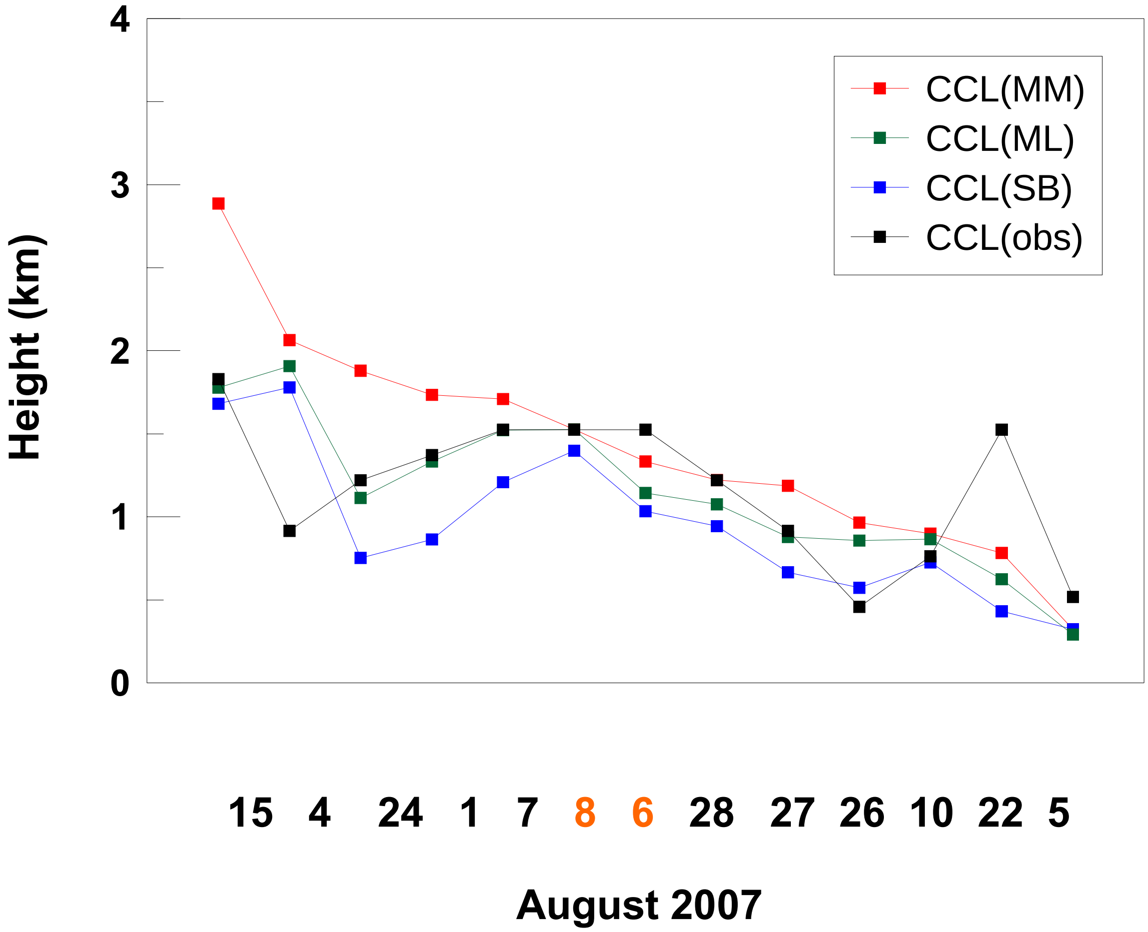

Figure 4.6. Comparison of CCL using the MM, ML and SB methods with observed CCL for August 2007 at Stony Plain (WSE). Days with observed thunderstorms are labeled in orange color.

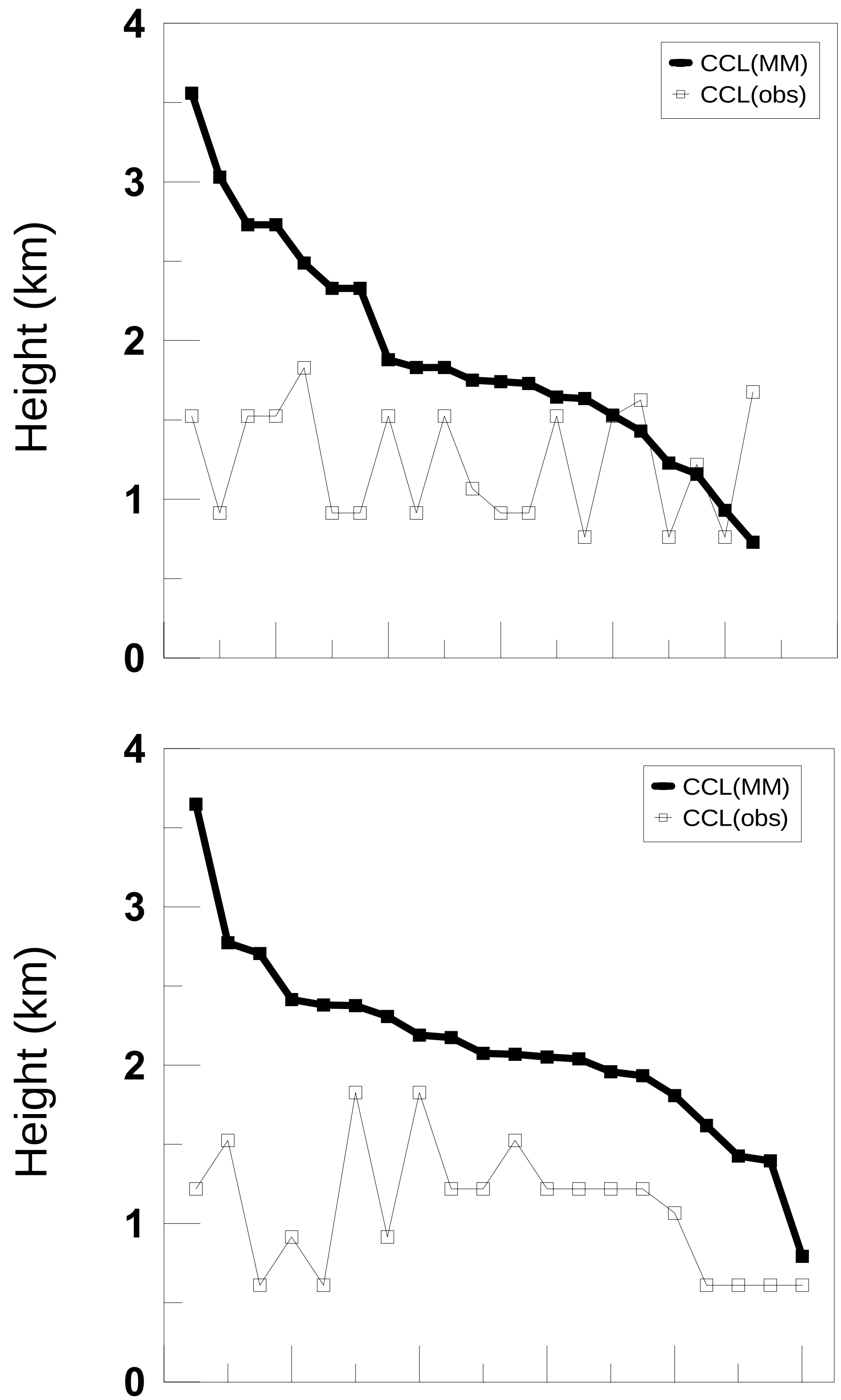

Figure 4.7. Comparison of Convective Condensation Level (CCL) estimated with the Moist Mixed (MM) method and observed CCL for the summer of 2006 (top) and summer of 2007 (bottom) at The Pas (YQD).

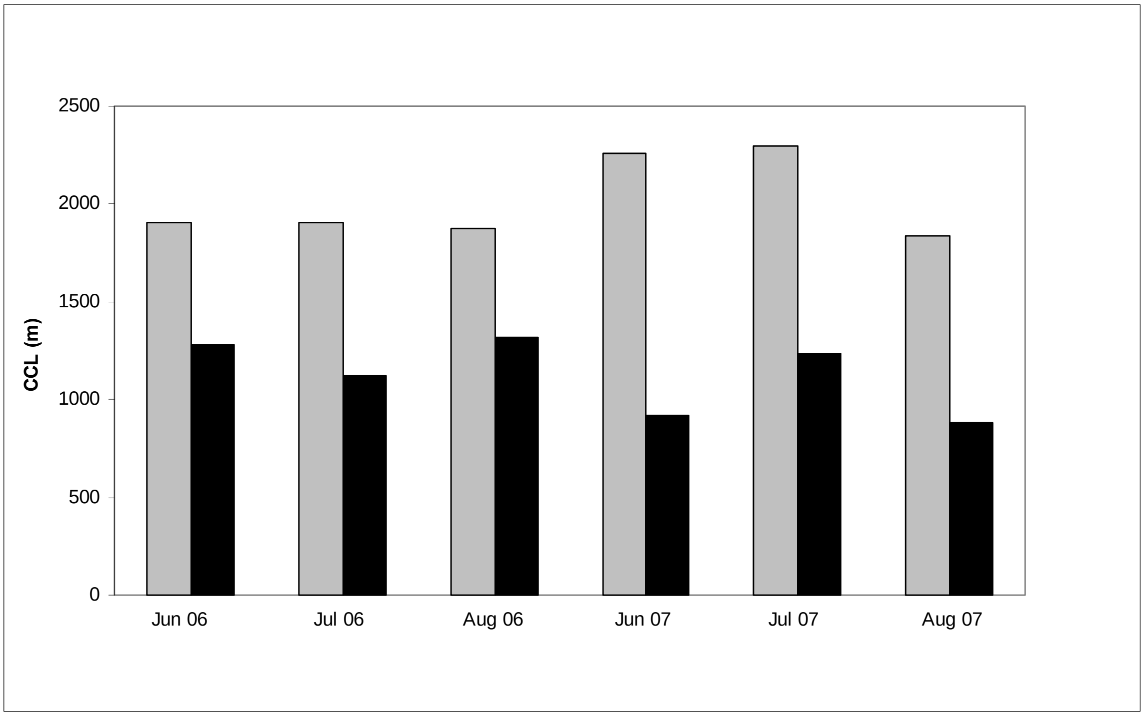

Figure 4.8 Average Convective Condensation Level (CCL) using the Moist Mixed (MM) method (grey) and the observed CCL (black) for the six summer months of 2006 and 2007 at The Pas (YQD).

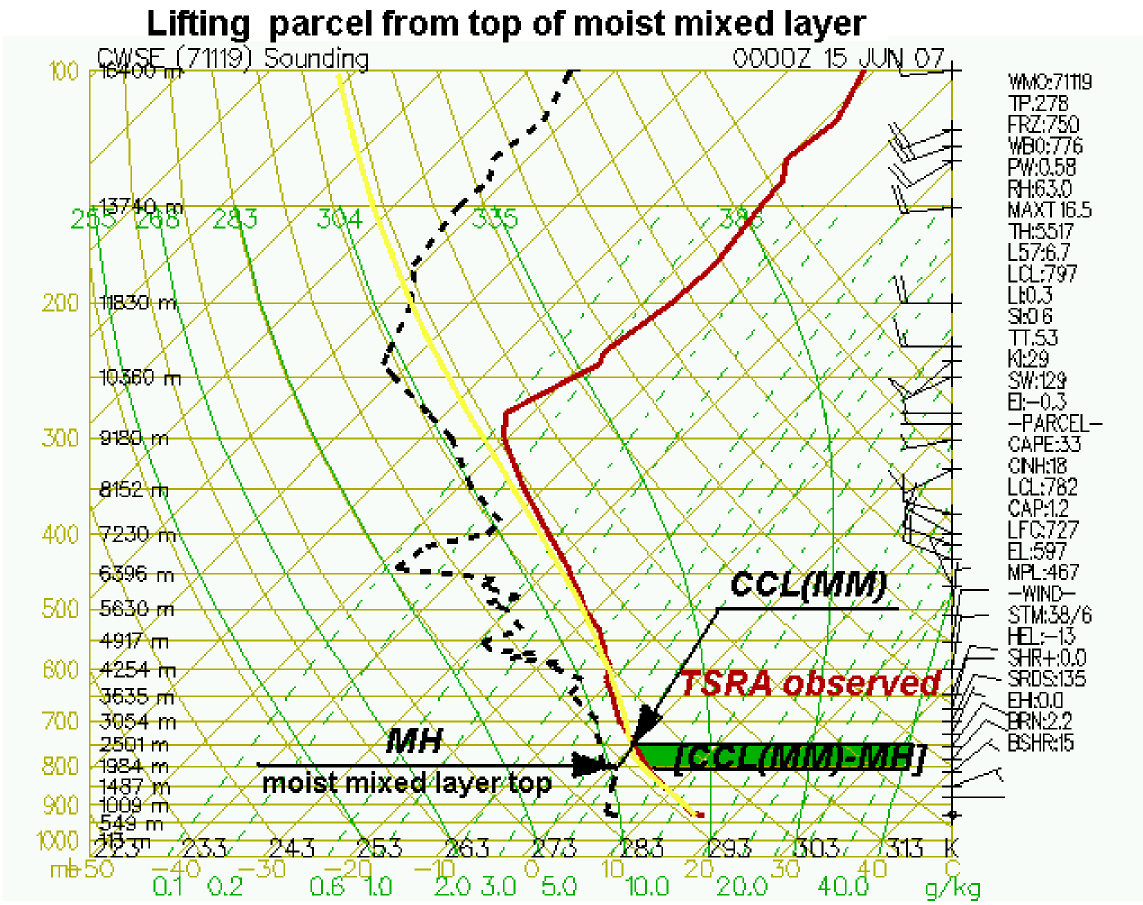

Figure 5.1. Skew T – log p diagram showing the thermodynamic properties of an air parcel lifted adiabatically from the top of moist mixed layer. The figure also shows the [CCL(MM)-MH] parameter. The sounding was observed at 0000 UTC 15 June 2007 over Stony Plain (WSE).

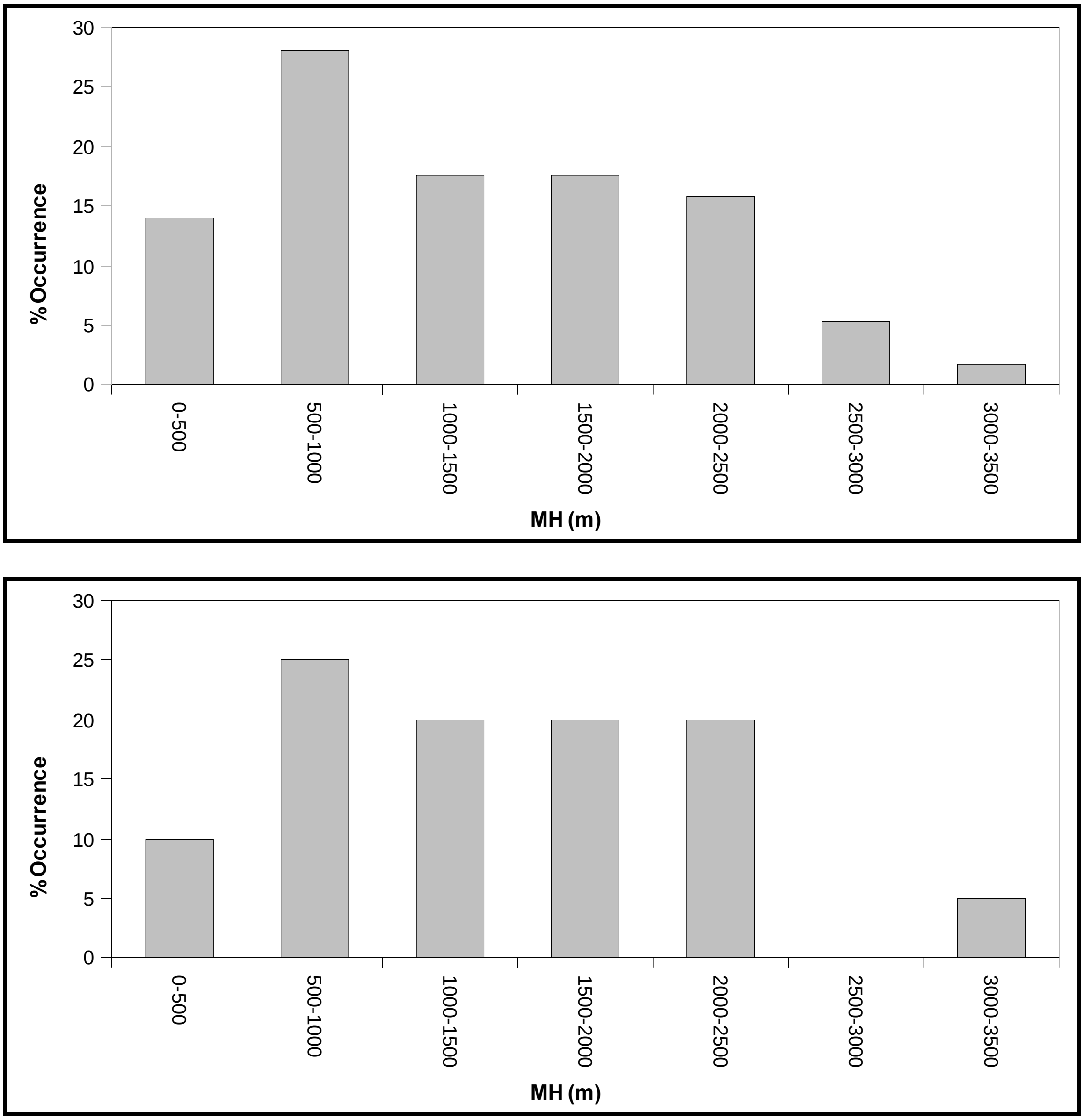

Figure 5.2. Comparison of the frequency distributions of Mixing Heights (MH) for weak convective cases (top) and strong convective cases (bottom) at Stony Plain (WSE).

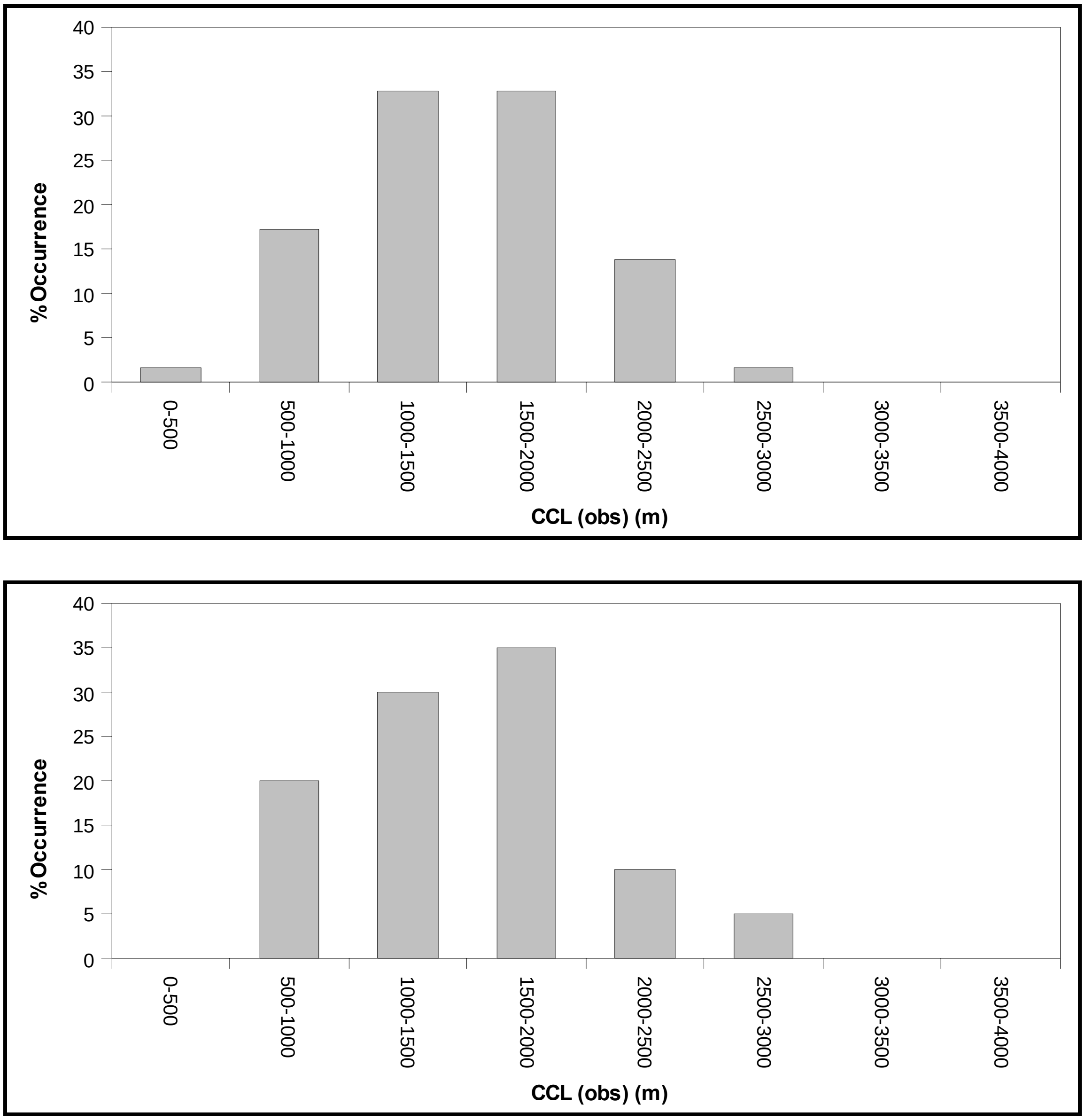

Figure 5.3. Comparison of the frequency distributions of observed Cloud Condensation Level (CCL) for weak convective cases (top) and strong convective cases (bottom) at Stony Plain (WSE).

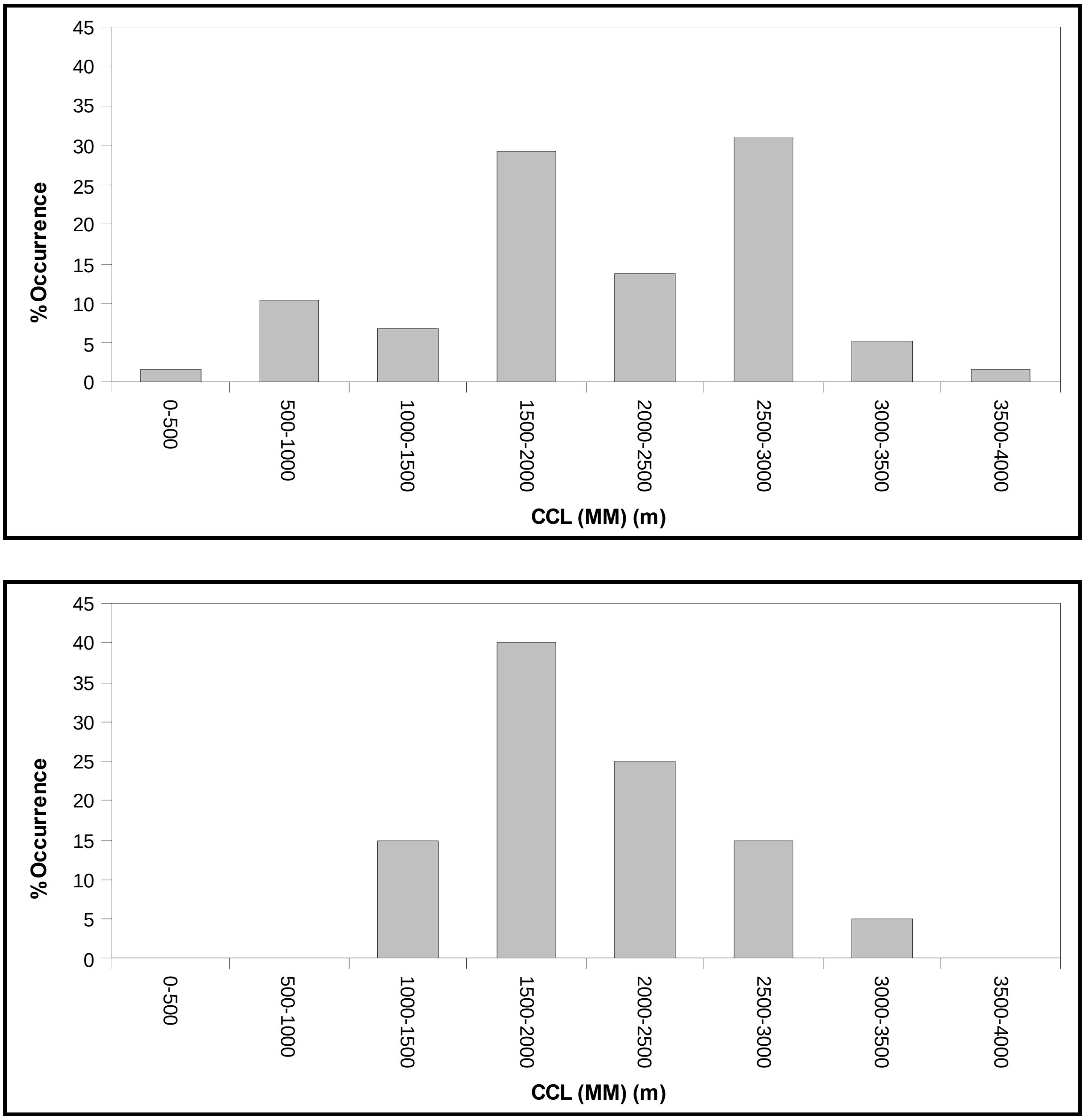

Figure 5.4. Comparison of the frequency distributions of Cloud Condensation Level (CCL) using the Moist Mixing method (MM) for weak convective cases (top) and strong convective cases (bottom) at Stony Plain (WSE).

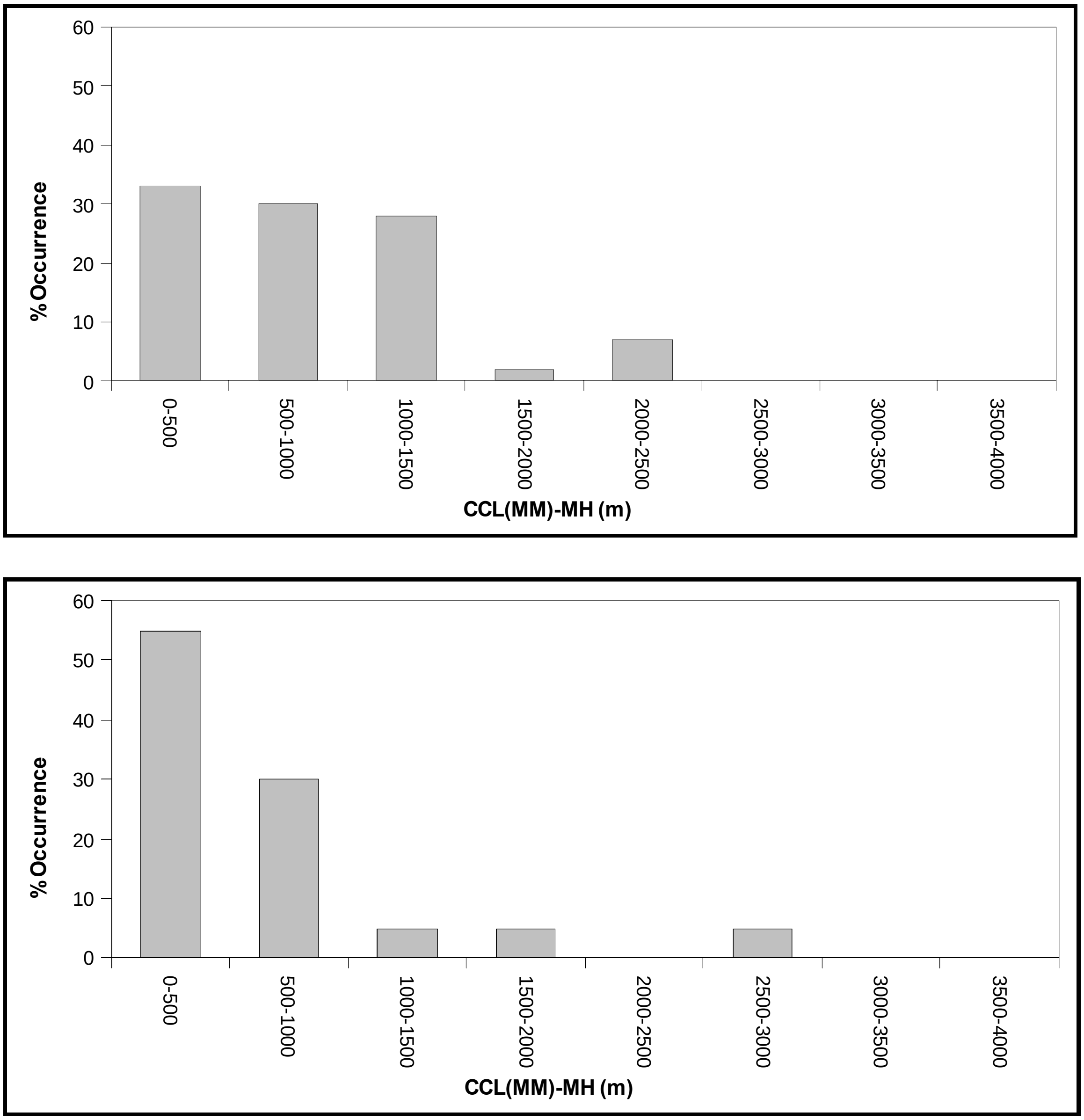

Figure 5.5. Comparison of the frequency distributions of difference between CCL(MM) and observed mixing height (MH) for weak convective cases (top) and strong convective cases (bottom) at Stony Plain (WSE).

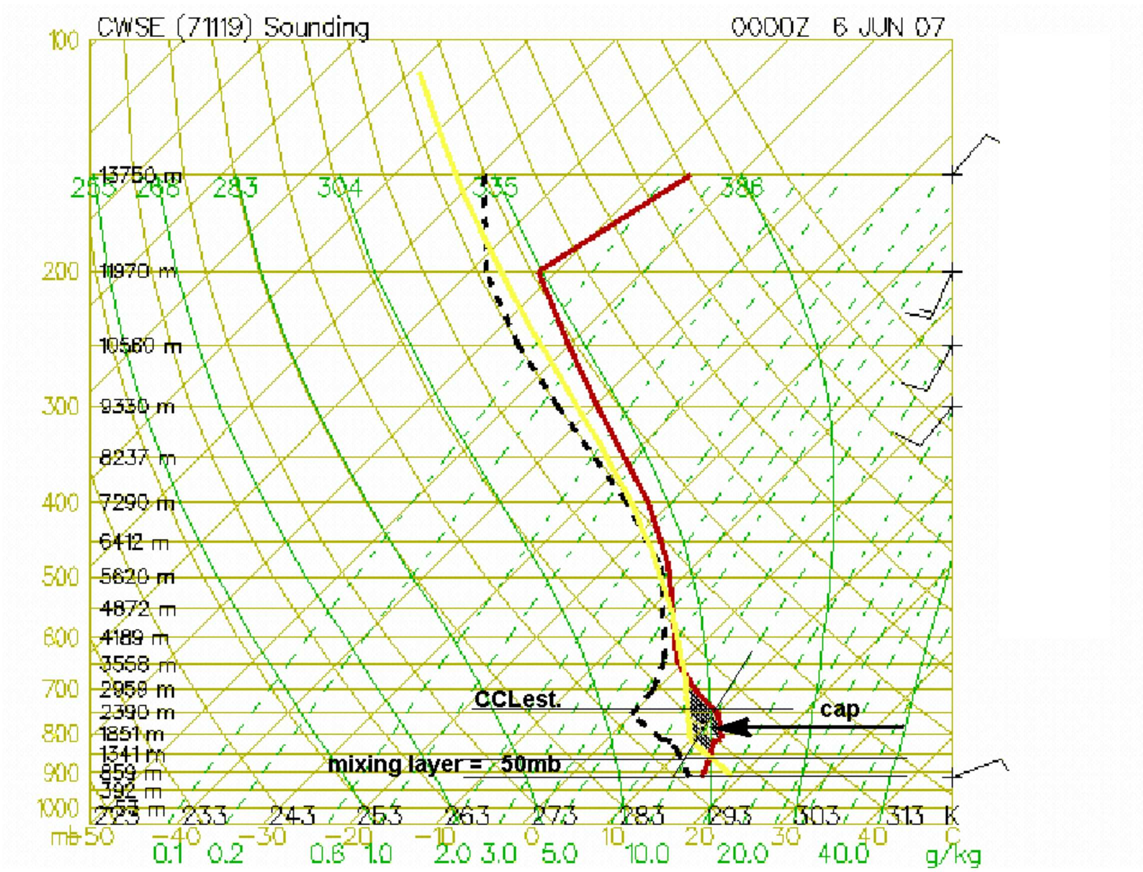

Figure 5.6. Skew T – log p diagram showing the convective conditions associated with the sounding observed at 0000 UTC 6 June 2007 over Stony Plain (WSE).

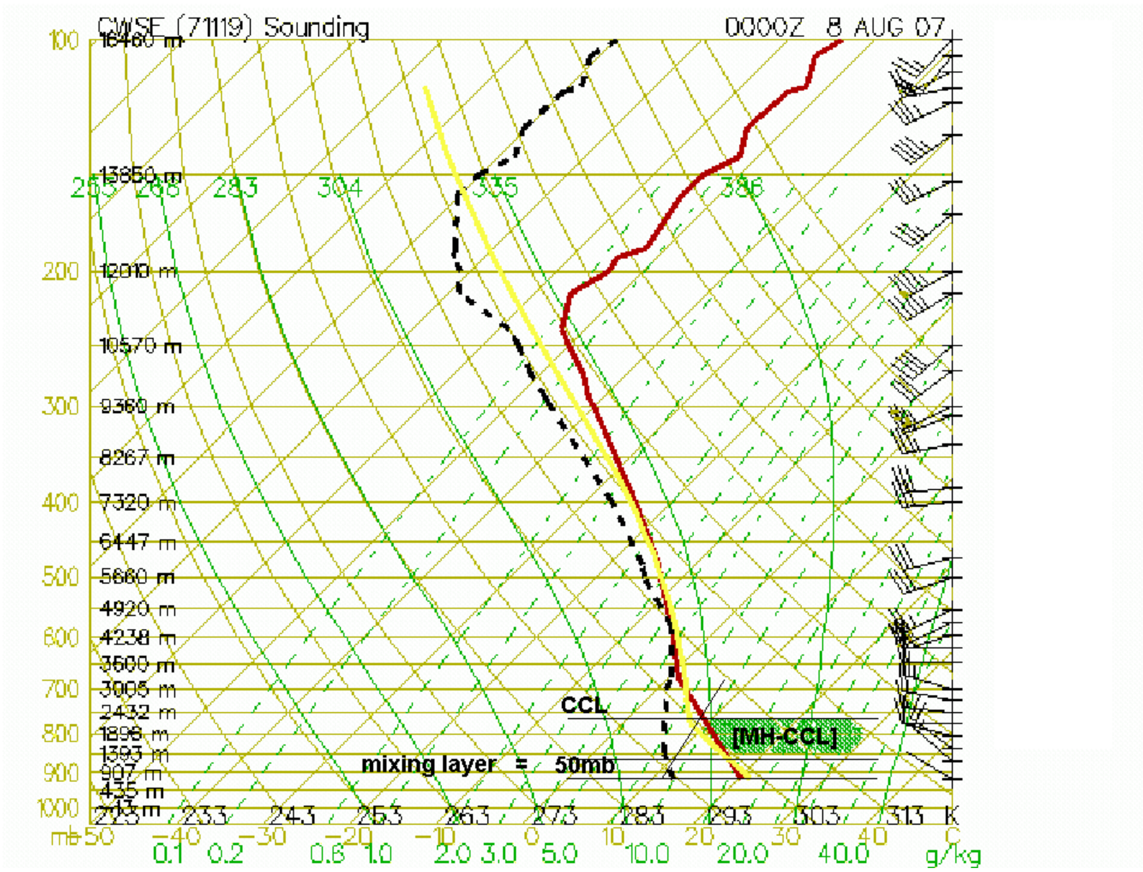

Figure 5.7. Skew T – log p diagram showing the convective conditions associated with the sounding observed at 0000 UTC 8 August 2007 over Stony Plain (WSE).

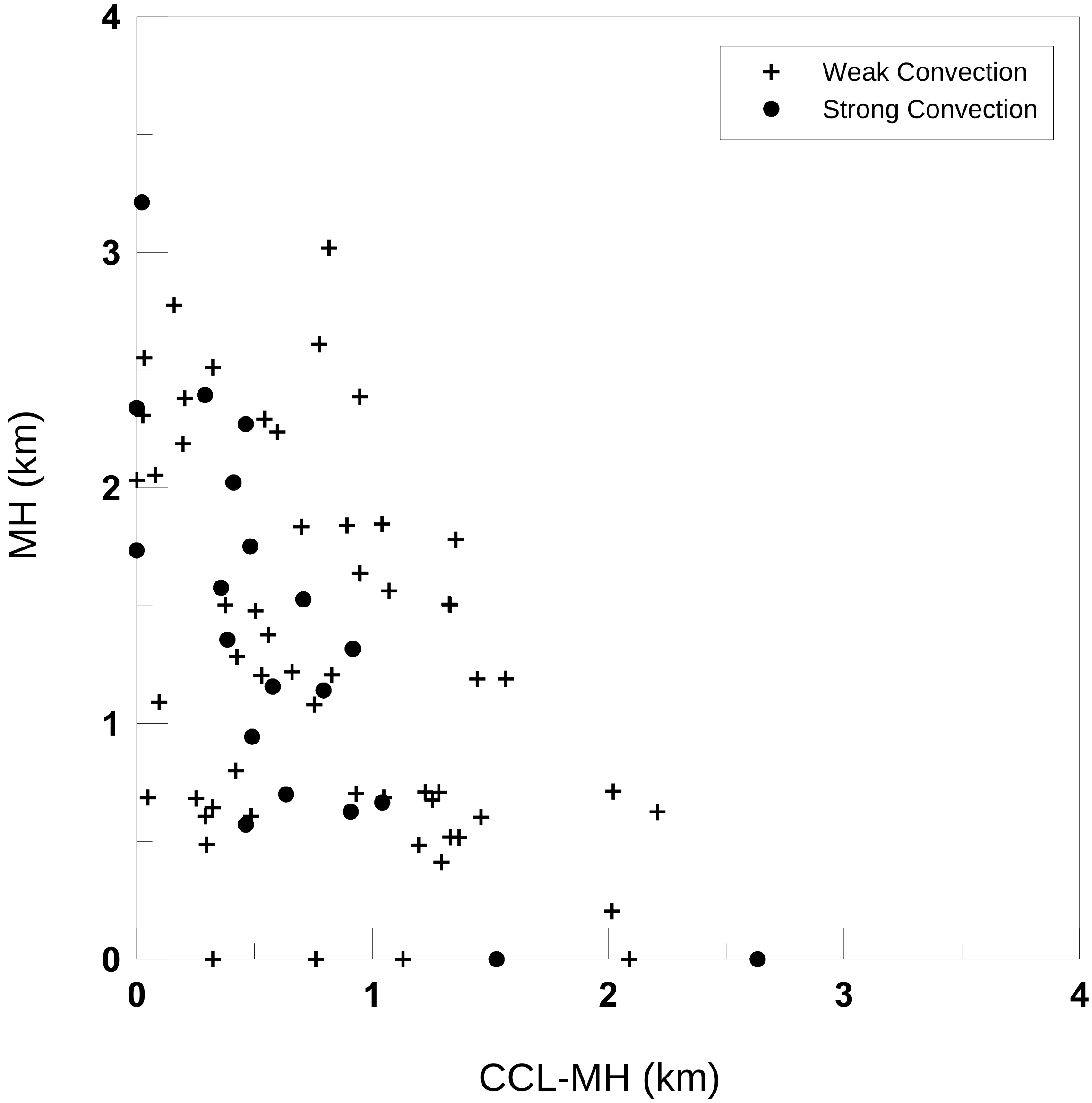

Figure 5.8. Scatter diagram of Mixing Height (MH) versus CCL minus MH (CCL-MH) for the summers of 2006 and 2007 at Stony Plain (WSE). A “plus” indicates a weak convective day, while a bullet indicates a strong convective case.

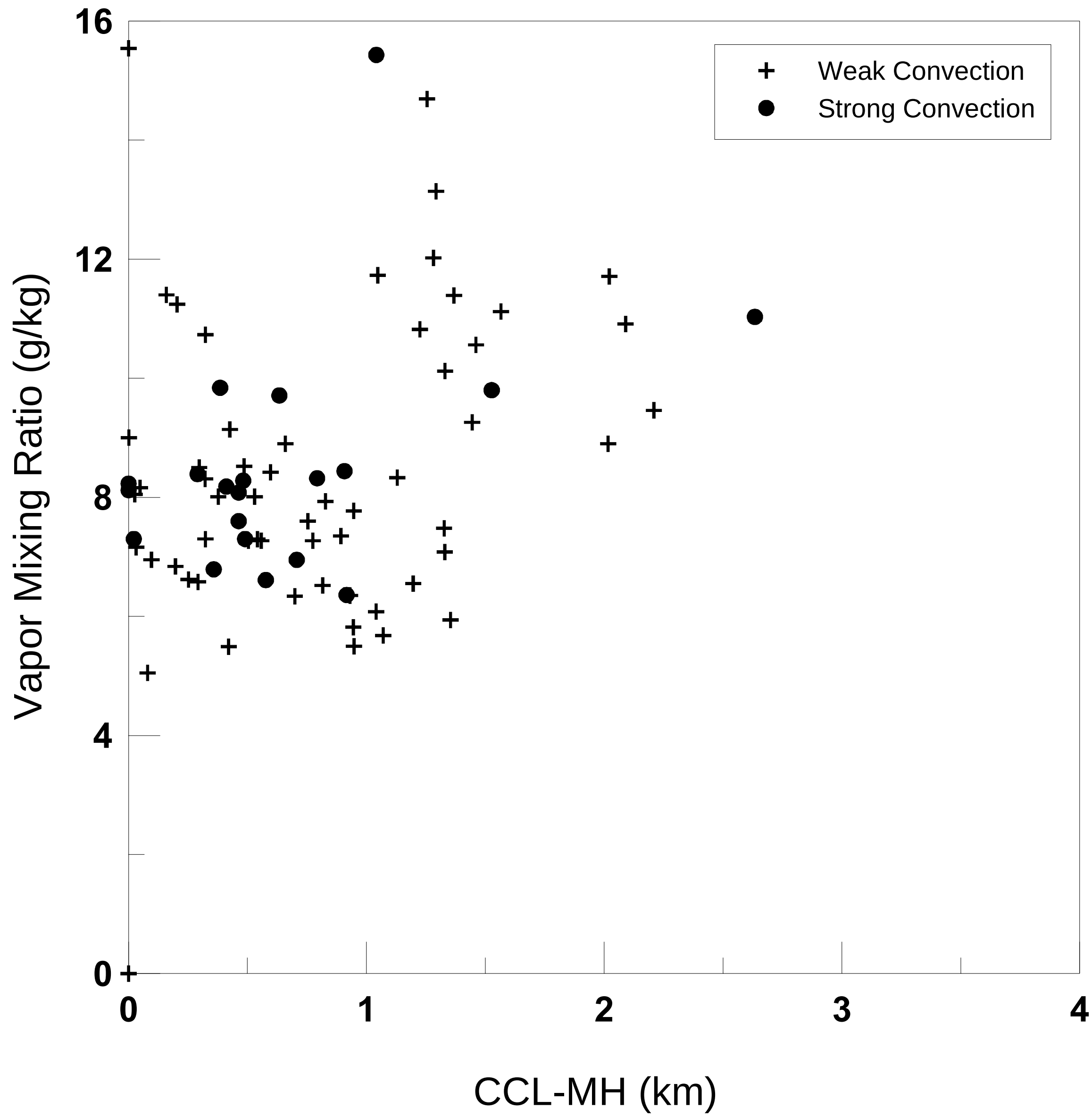

Figure 5.9. Scatter diagram of surface vapor mixing ration in g/kg versus CCL minus MH (CCL-MH) for the summers of 2006 and 2007 at Stony Plain (WSE). A “plus” indicates a weak convective day, while a bullet indicates a strong convective case.

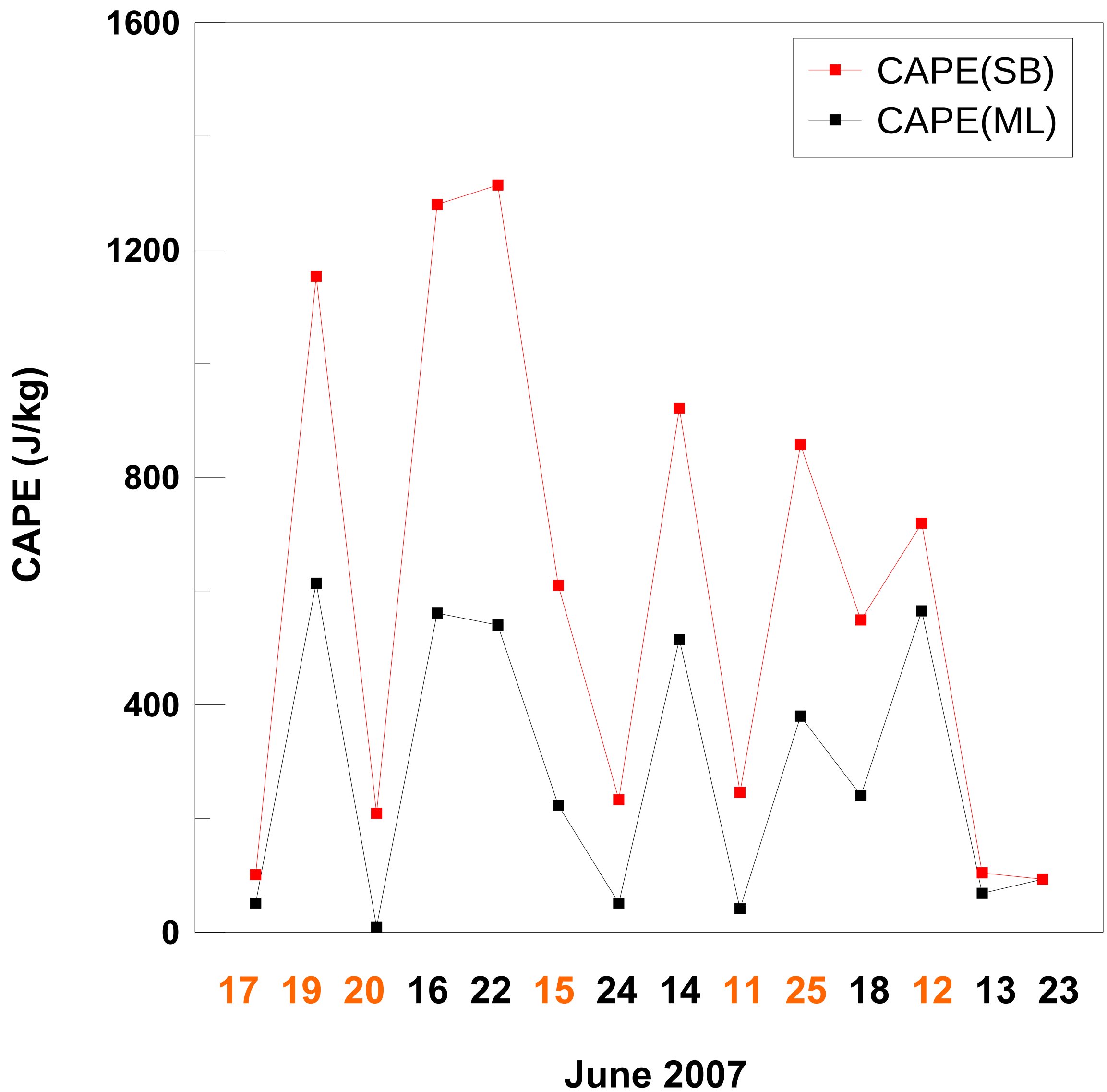

Figure 6.1. Comparison of Convective Available Potential Energy (CAPE) using the Surface Based (SB) method and the 50 mb Mixed Lifted (ML) method for June 2007 at Stony Plain (WSE). The days with observed thunderstorms are labeled in orange color.

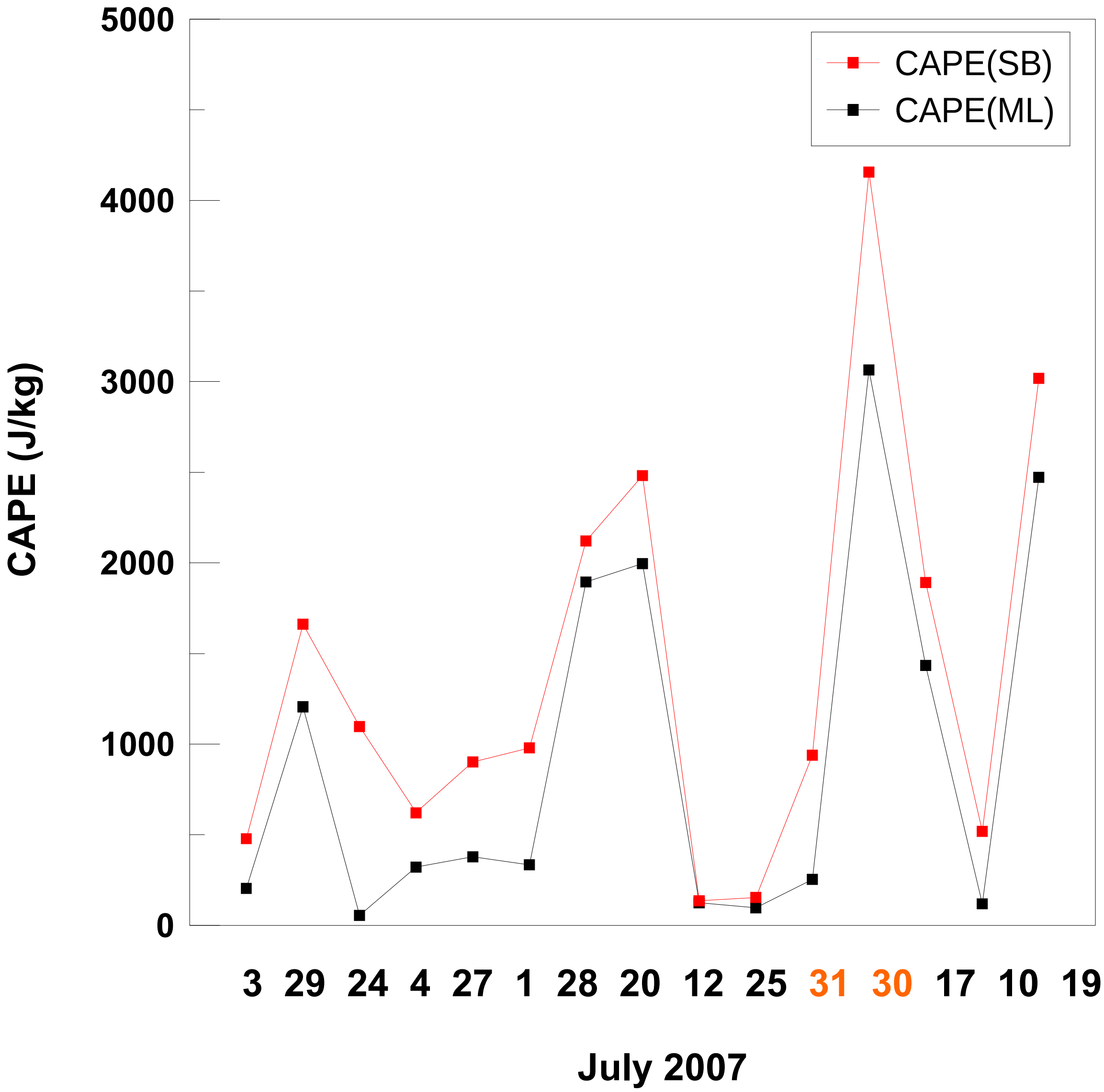

Figure 6.2. Comparison of Convective Available Potential Energy (CAPE) using the Surface Based (SB) method and the 50 mb Mixed Lifted (ML) method for July 2007 at Stony Plain (WSE). The days with observed thunderstorms are labeled in orange color.

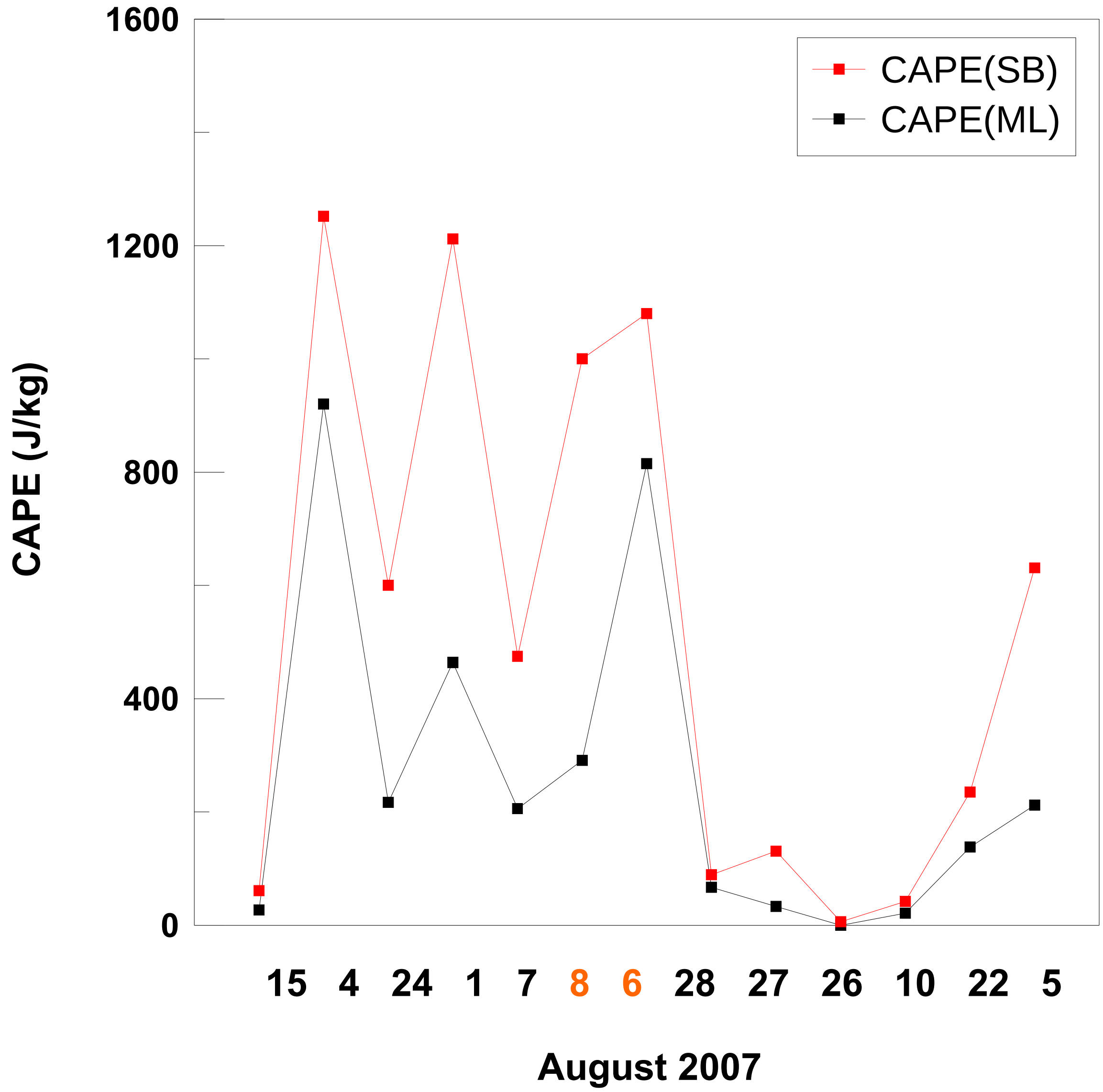

Figure 6.3. Comparison of Convective Available Potential Energy (CAPE) using the Surface Based (SB) method and the 50 mb Mixed Lifted (ML) method for August 2007 at Stony Plain (WSE). The days with observed thunderstorms are labeled in orange color.

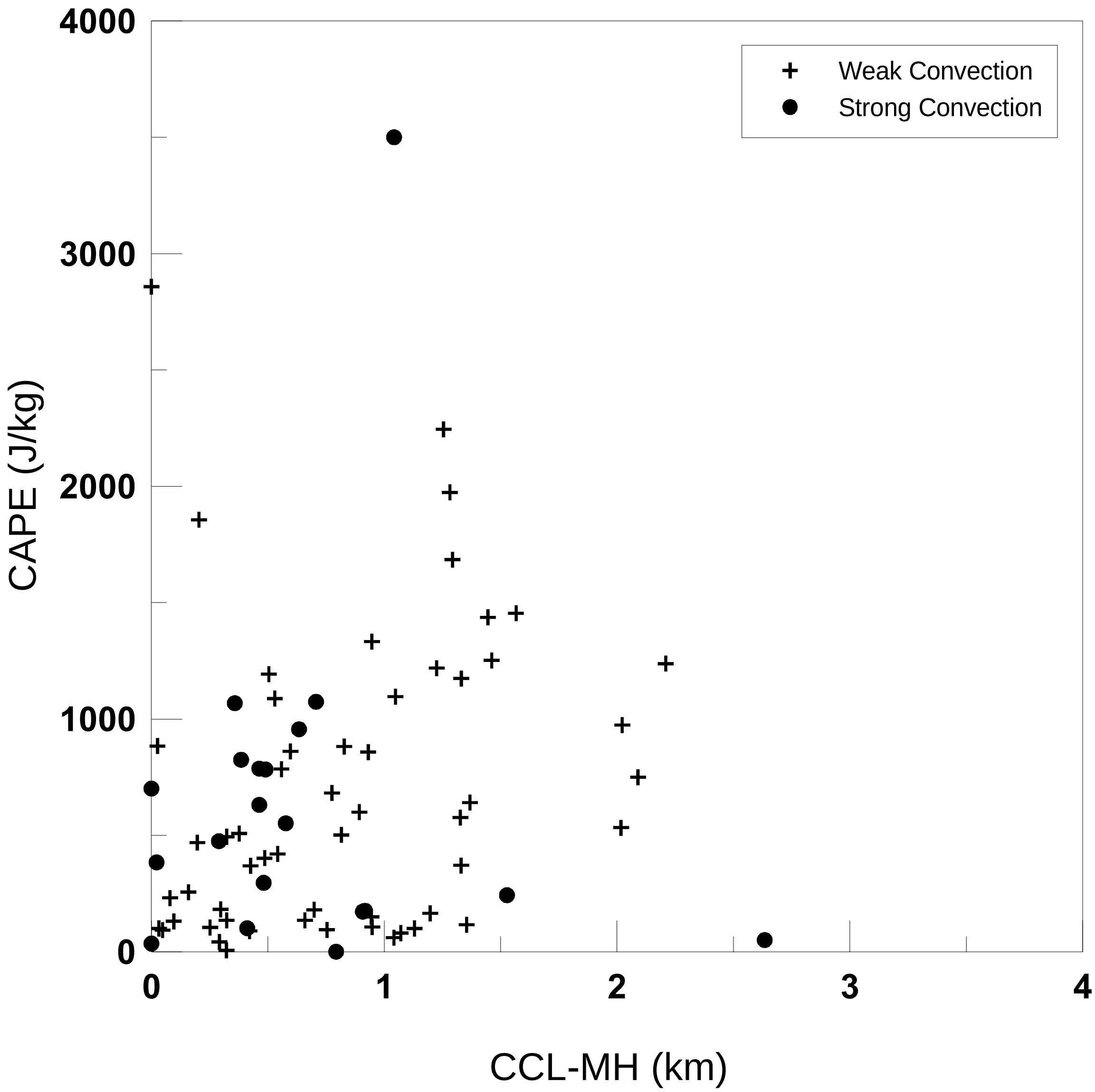

Figure 6.4. Scatter diagram of Convective Available Potential Energy (CAPE) versus CCL minus MH (CCL-MH) for the summers of 2006 and 2007 at Stony Plain (WSE). A "plus" indicates a weak convective day, while a bullet indicates a strong convective case.

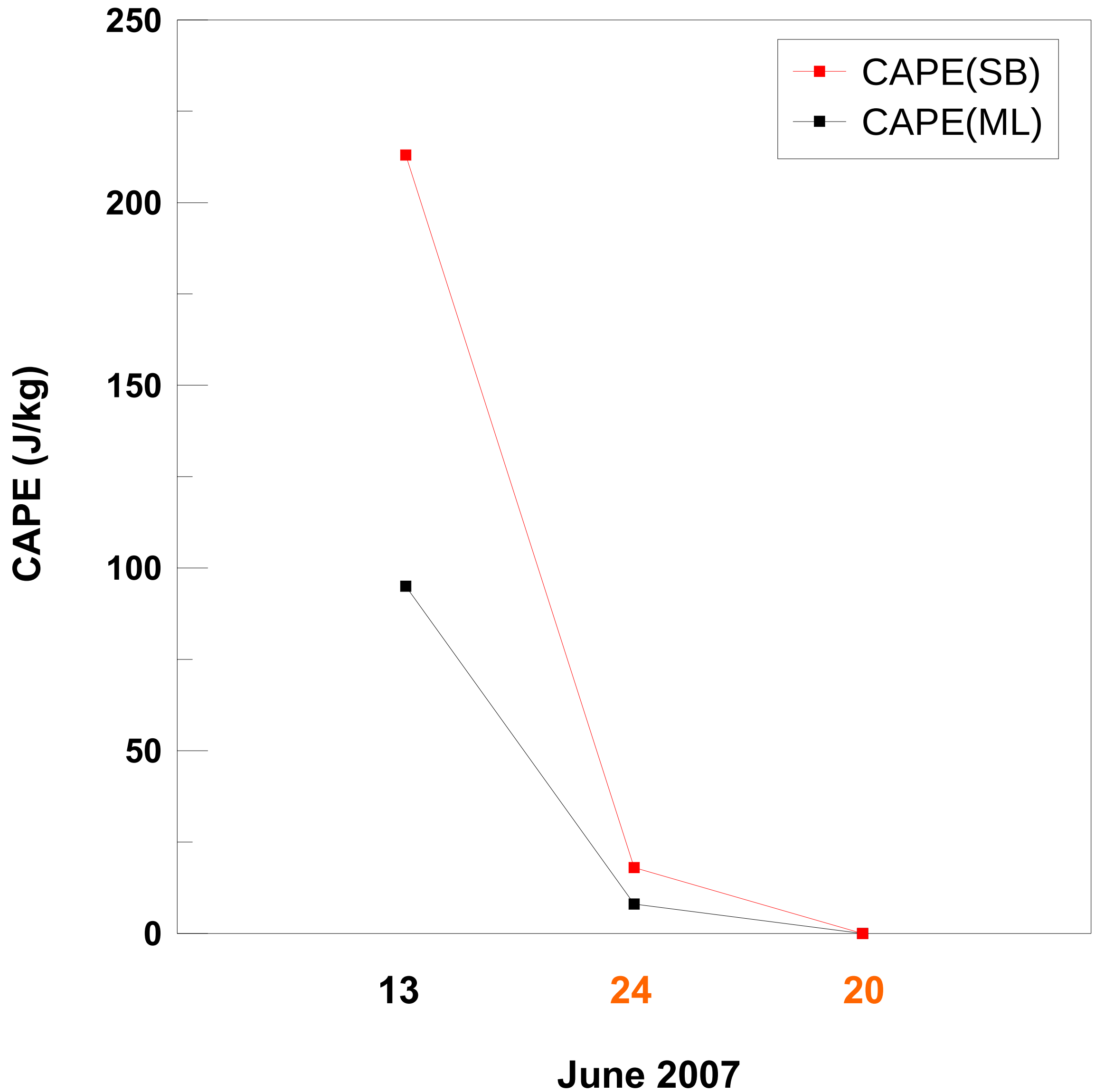

Figure 6.5. Comparison of Convective Available Potential Energy (CAPE) using the Surface Based (SB) method and the 50 mb Mixed Lifted (ML) method for June 2007 at The Pas (YQD). The days with observed thunderstorms are labeled in orange color.

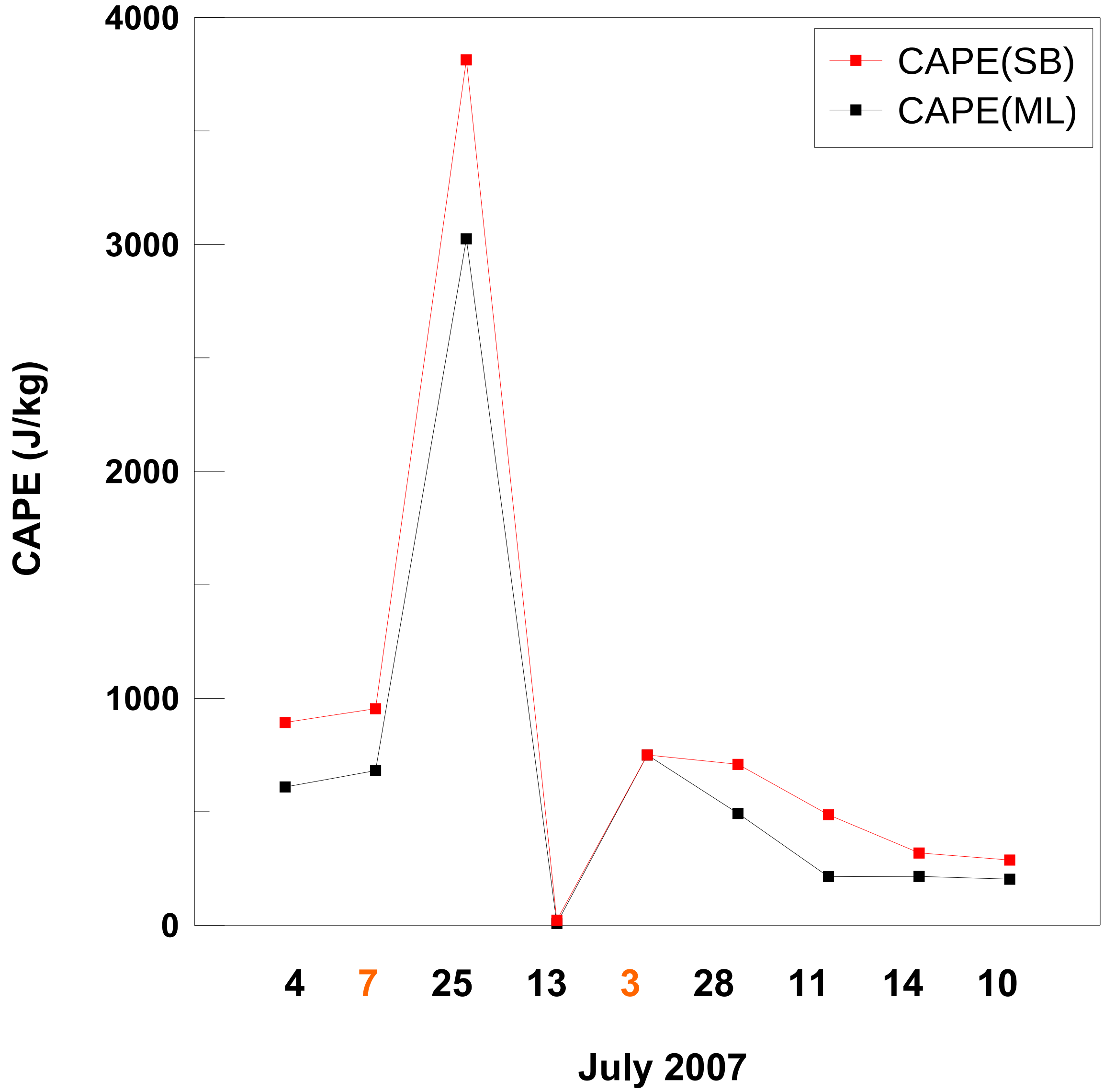

Figure 6.6. Comparison of Convective Available Potential Energy (CAPE) using the Surface Based (SB) method and the 50 mb Mixed Lifted (ML) method for July 2007 at The Pas (YQD). The days with observed thunderstorms are labeled in orange color.

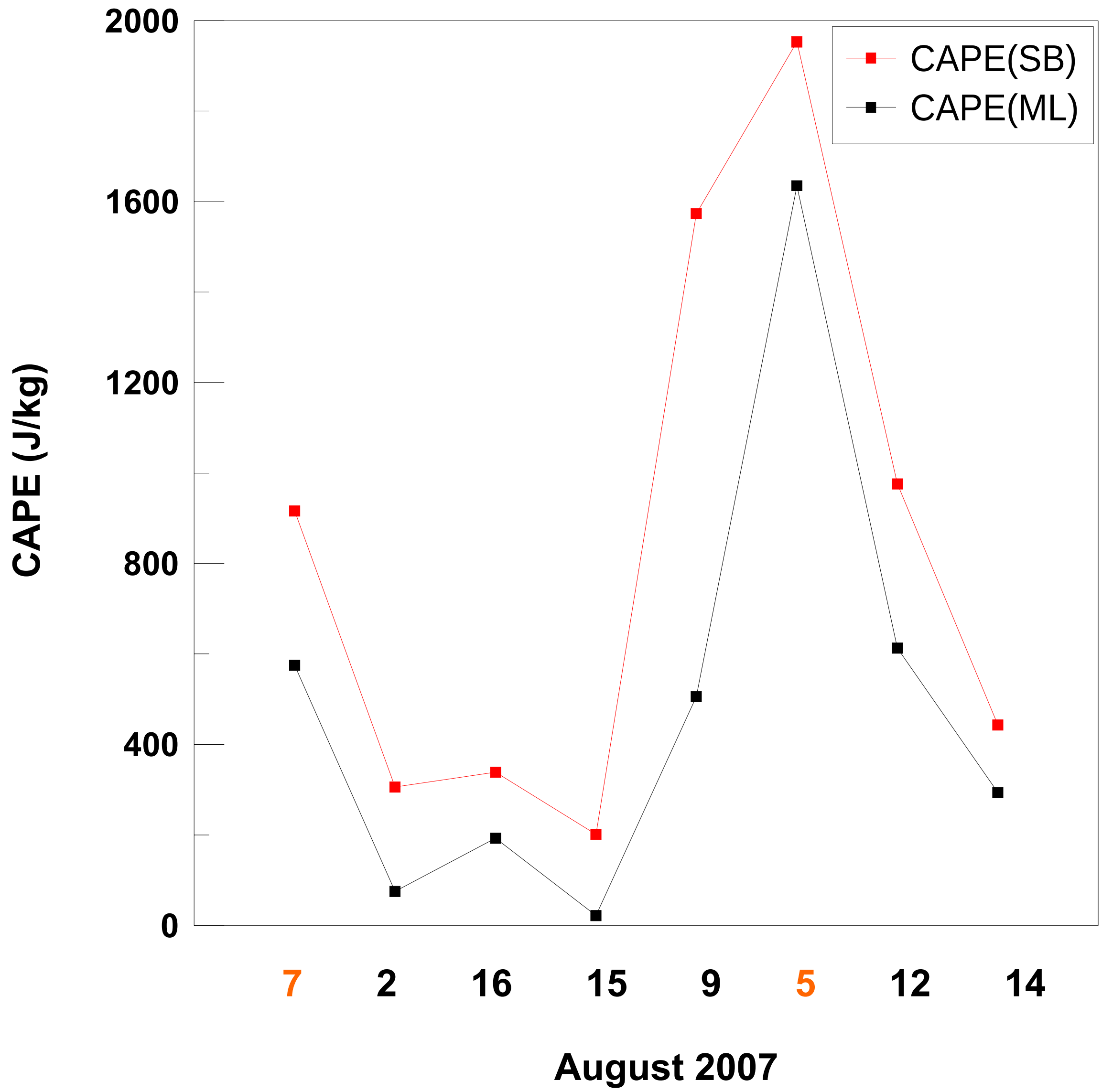

Figure 6.7. Comparison of Convective Available Potential Energy (CAPE) using the Surface Based (SB) method and the 50 mb Mixed Lifted (ML) method for August 2007 at The Pas (YQD). The days with observed thunderstorms are labeled in orange color.