Diurnal Cycle of the Thermal Structure and a Mesoscale Wind on the West Slope of the Colorado Rockies

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ABSTRACT

DIURNAL CYCLE OF THE THERMAL STRUCTURE AND A MESOSCALE WIND ON THE WEST SLOPE OF THE COLORADO ROCKIES

The west slope of the Colorado Rockies has topographical features consisting of mesas in the western portion and high mountainous terrain in the eastern portion. Observations from this region show the existence of an intermediate layer exhibiting diurnal variations in both wind and thermal structure. This intermediate layer is a vertical layer above mesa top height and below mountain top height, 2.5 km to 3.5 km above sea level. As the night progresses, the intermediate layer's westerly flow of the late afternoon changes to winds increasing in velocity and rotating in a clockwise direction with increasing height.

The first of two physical mechanisms which can explain the existence of this diurnal variation in the wind structure observed in the intermediate layer is the development of an east to west thermal gradient. In an evening with clear, dry conditions, the air within the intermediate layer nearer to the high terrain will cool more relative to the air farther away. Because of this cooling process, the intermediate layer should develop a pressure gradient on a constant height surface with the higher pressure in the east near the mountains. A thermally driven circulation initiated with this cooling pattern will support the diurnal variation of the winds observed in the intermediate layer.

Deep stability growth during the night leads to a second physical mechanism explaining the existence of the wind structure's diurnal variation observed in the intermediate layer. During days with a neutral or weakly stable convective boundary layer, westerly winds have little difficulty lifting over the mountainous terrain in the eastern portion of the region. Evening stability grows well above the flat mesas adjacent to the high terrain up to approximately 3.5 km above sea level. Because of this stability, the westerly flow will have less potential to lift over the mountain barrier thus a blocking of the wind can occur. An excess of mass will develop a higher pressure near the mountains, which creates a pressure gradient within the intermediate layer. A pressure gradient of this kind, like the thermal gradient, will support the winds observed in the intermediate layer.

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CHAPTER I

INTRODUCTION

Thermal structure and wind flow regions of complex terrain have been studied for many years with particular interest in the diurnal cycle of in-valley flow characteristics. For example, in the summer of 1989, The Journal of Applied Meteorology (JAM) devoted two issues to the subject of complex terrain behavior. Many new theories and findings emerged from these two editions concerning atmospheric phenomena in complex terrain. McKee and O'Neal (1989) developed an interesting theory explaining how the geometrical structure of a valley will cause it to pool or drain during the night and cause up-valley flow during the day. Neff and King (1989) studied the possibility of Brush Creek valley, located in western Colorado, influencing its own drainage by having its drainage pool into a basin south of the valley mouth.

The possibility of external winds contributing to the in-valley flow was also considered. Barr and Orgill (1989) were able to describe changes in the depth of drainage and volume flux in terms of ambient wind characteristics. In complex terrain, like western Colorado, external winds reaching into the valley may have characteristics different than the synoptic flow. Reiter and Tang (1984) studied winds over, and in the vicinity of, the Great Basin. In their large scale study, they showed that wind observations reveal the development of a nocturnal high and a daytime low in the Rockies. Parish (1982) studied the possibility of barrier winds along the Sierra Nevada Mountains. He showed how cold air damming at the upwind side of a mountain barrier can create a low level jet parallel to the mountain barrier. The cold air damming will result in a pressure increase near the mountain barrier thus creating a pressure gradient capable of supporting a low level jet.

A. Objective

The west slope of the Colorado Rockies has had very little industrial development. Western Colorado has a great deal of potential for large industrial development, in particular, the development of an oil industry based on oil shale. This development can indeed lead to pollution, which, in turn, is transported within the region.

The west slope of the Colorado Rockies is a location of complex terrain. To the east is high mountainous terrain of the rockies, and to the west are lower elevations of the mesas and valleys. Bader et al. (1987) found, from limited wind data, a thin layer of winds present above a valley on the west slope. It was determined the winds were not synoptically induced, but, perhaps, topographically induced. Barr and Clements (1981) obtained data in western Colorado in August 1980. They observed an east wind in a layer above 2.5 km Above Sea Level (ASL) during the night hours on two consecutive days. The east wind was not the focal point of their study, therefore they had no explanation for what they observed.

The Department of Energy's Atmospheric Studies in Complex Terrain (ASCOT) had an intense field project in northwest Colorado in September of 1984 (ASCOT '84). The primary purpose of this study was to study valley nocturnal drainage winds. The experiment included a set of deep sounding sites to provide observations of the diurnal behavior in the atmosphere above the valleys in the region. The purpose of this study is to define the diurnal evolution of an atmospheric layer from mesa top height upward into the free atmosphere. Observations will be used to establish the identity of an intermediate layer (IL) above the mesas. Finally, a conceptual model will be presented to illustrate the layer's diurnal evolution and to identify some physical processes contributing to this layer.

B. Description of the Region

To better understand studies of wind and thermal structure in western Colorado, a regional description is necessary. The region is west of the Continental Divide, and figure 1.1 from Clements et al. (1989) shows its location with respect to Colorado. The upper air sounding sites located within the region of study are at the towns of Rangely, Meeker, and Rifle and the valley of Brush Creek. The western portion of the region is near the Colorado-Utah border. The region consists of mostly mesa-flattops with numerous valleys of various widths and depths cut into them by small streams and creeks. The White River flows east to west through the northern portions of the region, and the Colorado River flows east to west through the southern portions. The terrain gradually slopes upward from west to east over the mesa flattops. The east portion is very similar to the west, and the only significant difference is that high mountainous terrain of the Rockies lie adjacent to the east portion. To better understand the elevations of the region, figures 1.2 (a-d) shows four different

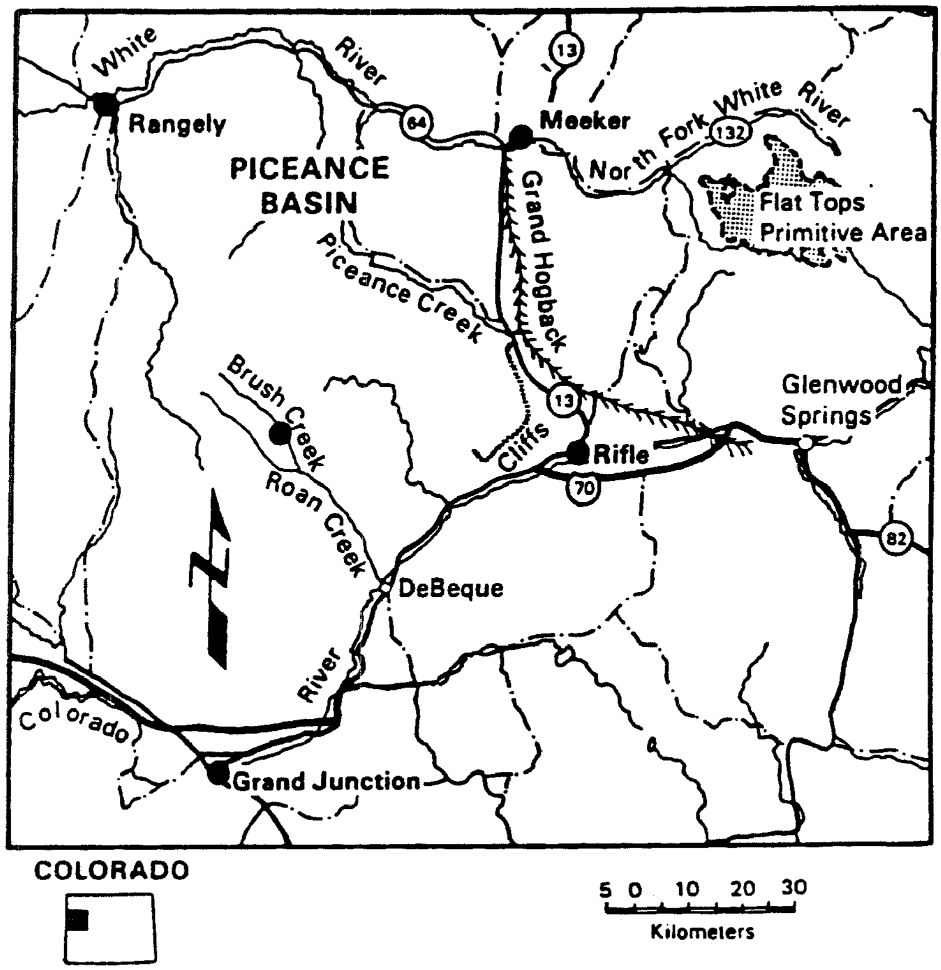

Fig. 1.1. Map of Northwest Colorado showing region of ASCOT '84 field work. From Clements et al. (1989)

elevation contours of the region. Figure 1.2a shows elevations greater than 2.0 km ASL, and the valleys are very well defined. Figure 1.2b shows elevations greater than 2.5 km ASL. The valleys become less distinct, because much of the region lies below 2.5 km ASL. This allows the Rockies to the east to show up very well. In figure 1.2c only the eastern portion of the region is greater than 3.0 km ASL, and figure 1.2d shows only the higher Rocky Mountains.

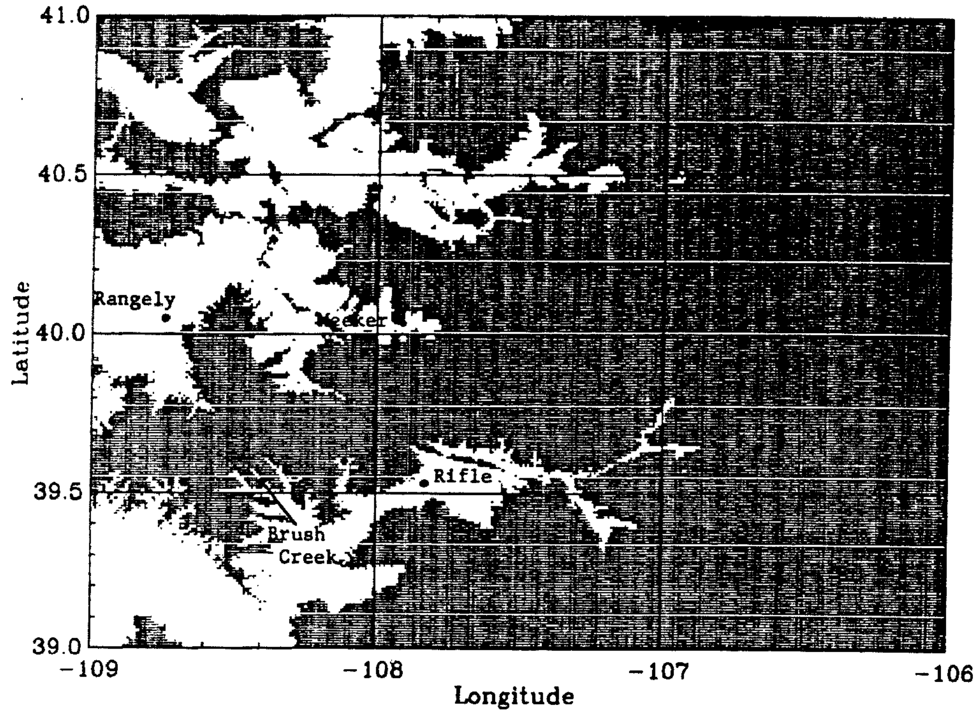

Fig. 1.2a. ASCOT '84 upper air sounding sites. Shaded region represents elevations greater than 2000 m Above Sea Level(ASL).

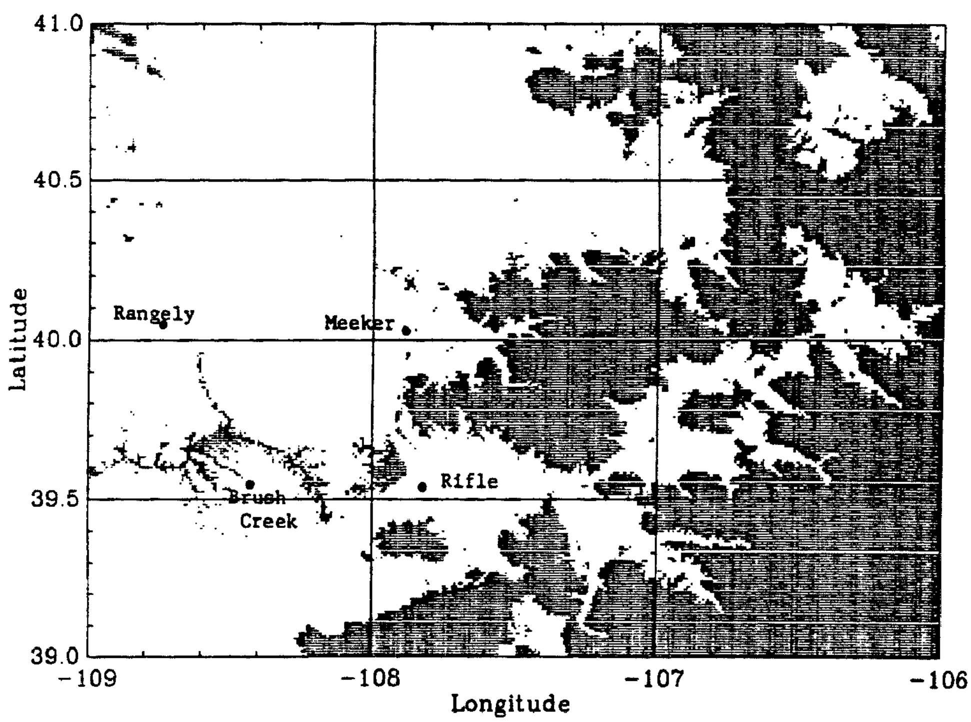

Fig. 1.2b. Same as figure 1.2a except the shaded region represents elevations greater than 2500 m ASL.

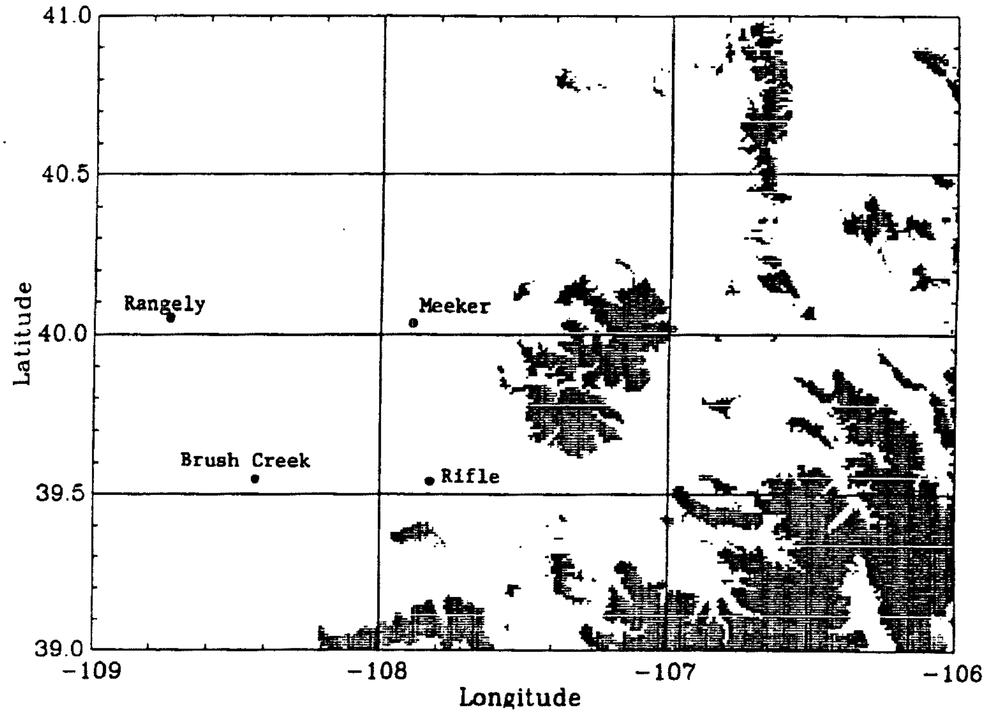

Fig. 1.2c. Same as figure 1.2a except the shaded region represents elevations greater than 3000 m ASL.

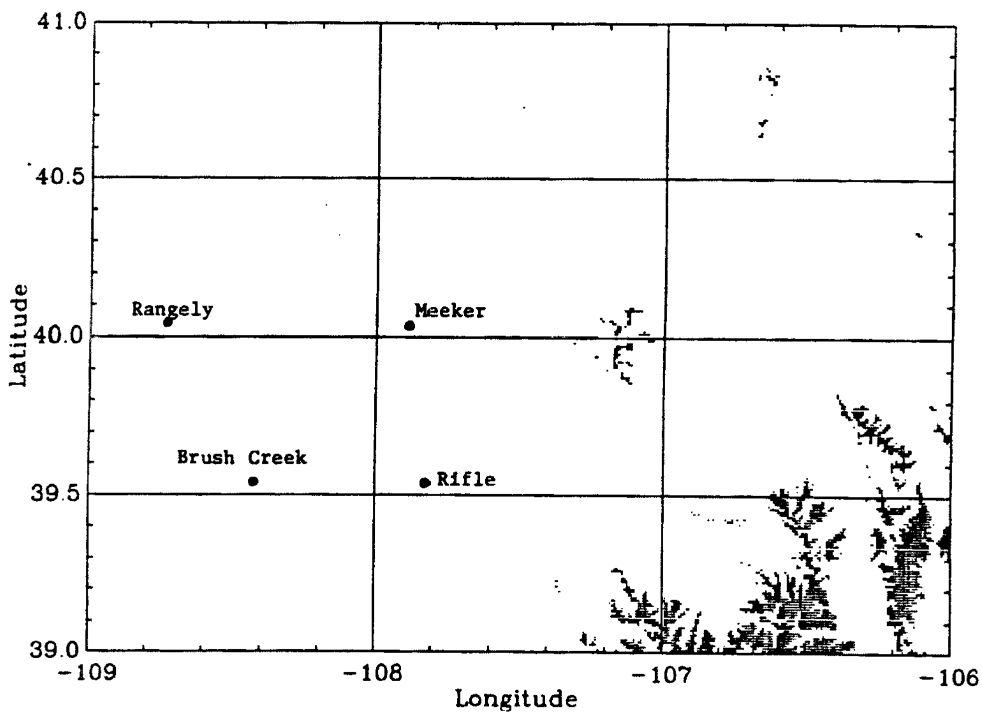

Fig. 1.2d. Same as figure 1.2a except the shaded region represents elevations greater than 3500 m ASL.

CHAPTER II

DATA

A. Collection of Data

The focal point of the ASCOT '84 experiment was the valley of Brush Creek, in which a series of tethersondes were placed along the valley floor. Within the valley and on its ridgetops are not only tethersondes, but a wide range of instrumentation from acoustic sounders to a doppler lidar to tracers. For a better description of data collection in Brush Creek, the reader is referred to Clements et al. (1989). All instrumentation and data collection was done in an effort to understand valley drainage winds better than ever before. In an attempt to understand how air flow above the valley will affect flow characteristics in valleys, a four corner network of upper air soundings was also established.

The four corner network included an upper air station at Meeker, Rifle, and Rangely and in the valley of Brush Creek. Table 2.1a gives detailed locations and elevations of each site and table 2.1b the sunset and sunrise in Mountain Standard Time (MST). The upper air observations were designed to span a twenty one hour period encompassing each experimental night. Three hourly soundings began at 16:00 MST and ended at 13:00 MST the following day. The ASCOT '84 field experiments attempted to choose clear sky and undisturbed conditions with little temperature advection. Dry conditions reduce

Table 2.1a.

Exact locations and elevations of each upper air sounding site participating in the ASCOT '84 field project.

SITE	LATTITUDE	LONGITUDE	ELEV(m)
Meeker	40.06	107.9	1947.7
Rifle	39.53	107.8	1692.2
Rangely	40.06	108.78	1607.5
Brush Creek	39.56	108.43	1856.8

Table 2.1b.

Listing of sunsets and sunrises at each site during the ASCOT '84 field project. All times are in Mountain Standard Time (MST).

	Meeker		Rifle		Rangely		Brush Creek	
Date	sets	rises	sets	rises	sets	rises	sets	rises
17–18	18:19	6:00	18:19	6:00	18:22	6:04	18:21	6:03
19–20	18:16	6:03	18:16	6:03	18:19	6:07	18:18	6:06
25–26	18:02	6:05	18:02	6:05	18:06	6:09	18:05	6:08
27–28	17:59	6:07	17:59	6:07	18:03	6:11	18:02	6:10
29–30	17:56	6:09	17:56	6:09	17:59	6:13	17:58	6:12

the role of moisture, and small advection keeps observed temperature and wind changes a result of local phenomena.

B. Weather Conditions

During the experimental period, conditions were considered adequate for the project. After studying the wind and thermal observations, four nights were considered appropriate for data analysis of the atmosphere above the valleys for this study. The 27th-28th showed large temperature advection in the upper atmosphere between the late afternoon and the late night hours and was eliminated for the purpose of this study. The nights considered appropriate for data analysis are the nights of the 17th-18th, 19th-20th, 25th-26th, and 29th-30th.

Surface weather conditions are consistent from one experimental day to the next with light winds and dry conditions, however, the synoptic conditions were changing. Scattered light showers did persist along and west of the Continental Divide during the experimental period, but no precipitation fell at the experimental sites (McKee, 1984). Four weather maps, if available, are presented for each night. The 00Z and 12Z maps contain height and temperature contours for 500 mb and 700 mb. These maps presented in appendix A, are used in the following discussion of weather conditions present on the nights of the experimental period.

The experimental period began with the 17th-18th. Very good weather conditions are present with little advection. The high pressure at 700 mb over northern Utah moved into western Colorado and centered over the experimental region by the end of the sounding period on the 18th, and 500 mb had the same pattern. High pressure was over the region at 500 mb with little advection and light winds, less than 10 m/s.

On the 19th-20th, the charts show very little pressure gradient through the region at 700 mb with only the slightest thermal advection present. At 500 mb there is little pressure gradient and light winds for this height, 4 m/s, and little advection.

Following a week of unsettled weather, the 25th-26th has better conditions. A southerly flow at 500 mb starts the sounding period and it becomes westerly by the end of the period. According to the charts, there is little advection and little pressure gradient. The upper level charts have little temperature advection or pressure gradient, but the flow is strong with winds from the west at 15-20 m/s.

A small pressure gradient with light winds existed at 700 mb on the 29th-30th. Light winds and a small temperature gradient prevent large advection. The winds at 500 mb are moderate from the west with little indication of temperature advection.

C. Data Quality

1. Temperature measurements

Sondes are excellent devices for retrieving information from all levels of the troposphere, however, they are not perfect. Recent calibrations of sondes (AIR, ADAS, Intellisondes, CLASS) were done in an attempt to gather information on the accuracy of the temperature sensors. Calibrations were not done for the ASCOT '84 field experiment. These calibrations were intended to give some indication about the accuracy of the sondes used in the ASCOT '84 field work.

Water was the material used to calibrate the sondes and thermocouples. One temperature measurement was done in room temperature water and a second in ice water. The temperature of the sondes are then compared to the temperature of the thermocouples. The sondes had temperature differentials of +0.4C to -0.4C from one sonde to the next.

Differences such as these may seem rather insignificant, but they are not. When it becomes necessary to use the temperature measurements from one sounding to the next, these differentials can become increasingly important. With these errors involved, calibrating sondes prior to launching is highly recommended.

2. Wind measurements

During ASCOT '84, Rifle, Meeker, and Rangely were rawinsonde stations which used an auto tracking radiotheodolite, data acquisition system, and a 1680 MHz radiosonde package. Winds were calculated from the tracking data using a 30 s averaging interval in the lowest layers and a 60 s interval through the mid layers (Clements et al., 1989).

An optical theodolite was used to get wind data at the CSU site in Brush Creek. Obtaining data with an optical theodolite requires time. The pressure received from the airsonde is used to calculate the height of the balloon, and the optical theodolite is used to measure azimuth and elevation angles. Wind velocity and direction are calculated from these three variables. The tracker needs time to get these measurements with the theodolite. In general, thirty seconds is the length of time involved, however, a time interval of thirty seconds is not required. When everything is going well, the time interval may be smaller, or if there are problems the time interval may be longer.

Wind measurement resolution may not be very good sometimes, but the lack of resolution does not mean wind errors.

These sites use different instrumentation, but data is collected every thirty seconds. A rise rate of 5 m/s results in a data point every 150 meters, therefore, wind resolution is a very important factor to consider. In particular, to find a transition between one layer of winds and another becomes very difficult.

CHAPTER III

OBSERVATIONS

A. Wind Structure

1. Introduction to wind structure

Above the valleys of western Colorado is an Intermediate Layer (IL), which has a diurnal evolution different from that of the valleys, however, the characteristics of this layer are not well defined.

The wind observations from ASCOT '84 will be used to define the IL. These observations will provide the thickness, depth and wind flow structure of the IL. Observations analyzed here are obtained from Meeker, Rifle, and Rangely on the night of the 19th-20th. Figures 3.1 (a-c) are the observations from these three sites in a time series starting in the late afternoon. Remaining wind observations, from these sites on the 17th-18th, 25th-26th, and 29th-30th can be seen in appendix B.

2. Wind observations

The sounding at 16:00 Mountain Standard Time (MST) starts the evening of the 19th-20th. A westerly component to the wind starts the late afternoon at all sites and all levels except within the valleys. Individual in-valley topographical features are producing wind unique to each site below mesa top height, 2.5 km Above Sea Level (ASL).

At approximately one hour beyond sunset, the 19:00 MST set of soundings has interesting changes different to each site. These

Fig. 3.1a. Wind time series for Rifle on 19-20 September 1984. Height is in kilometers Above Sea Level (ASL), and Rifle is 1692 m ASL. Horizontal axis represents sounding times in Mountain Standard Time (MST) with sunset and sunrise at 18:16 MST and 6:03 MST, respectively. Vectors point in the direction air is going, and north is the top of the graph. Lines A and B represent mesa top and mountain top heights, respectively.

Fig. 3.1b. Same as figure 3.1a except it is for Meeker, which has an elevation of 1947 m ASL.

Fig. 3.1c. Same as figure 3.1a except it is for Rangely, which has an elevation of 1607 m ASL, and sunset is at 18:19 MST and sunrise at 6:07 MST

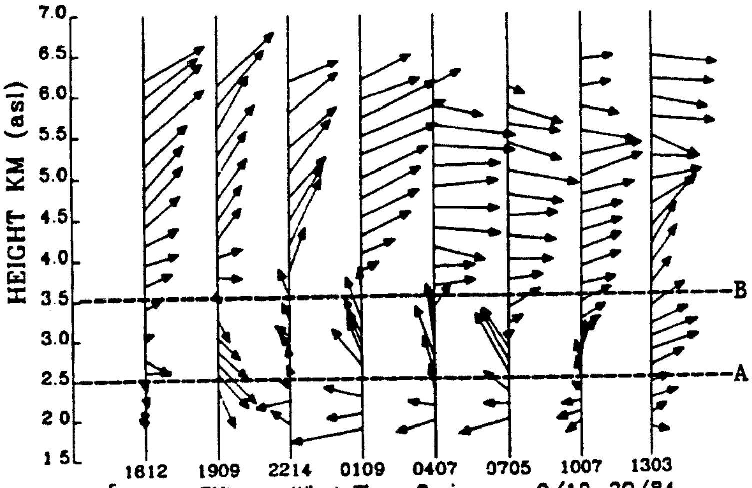

Fig. 3.1a. Rifle: Wind Time Series 9/19-20/84

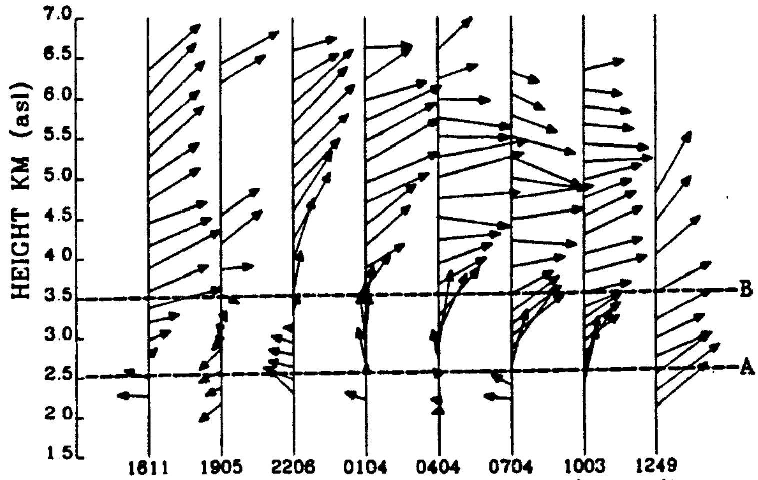

Fig. 3.1b. Meeker: Wind Time Series 9/19-20/84

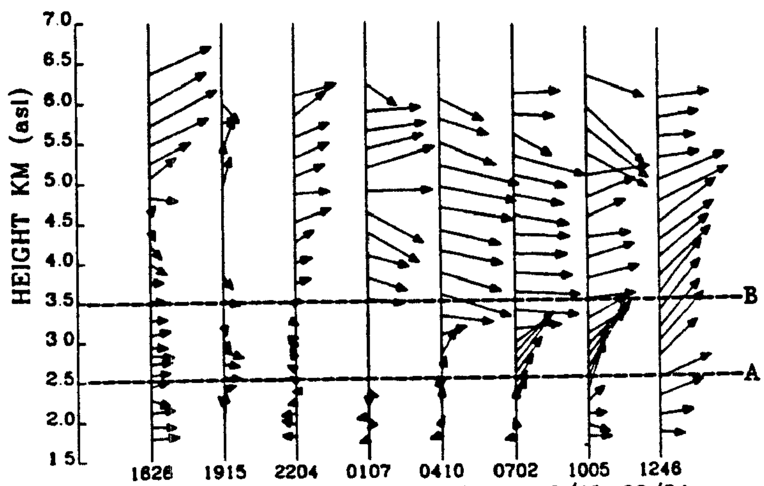

Fig. 3.1c. Rangely: Wind Time Series 9/19-20/84

changes do not occur in the upper levels, but rather below mountain top height, 3.5 km ASL.

Rifle has some very distinct changes take place in the night hours above mesa tops and below mountain top height (see figure 3.1a). At 19:09 MST, a strong northwesterly flow is present below mesa tops up to mountain top height, and near mountain top height is a noticeable shear in wind velocity. By 22:14 MST, this flow has been replaced by two layers. A valley drainage has replaced the flow below mesa top, and a southeasterly wind has replaced the flow between mesa top and mountain top height. This flow is a distinct part of the IL wind structure. At mountain top height is a shear of velocity and direction creating a natural boundary between the IL wind and the free atmosphere. At night the IL winds feature,

$$\frac{dV}{dZ} > 0 \qquad (3.1)$$

and

$$\frac{d\phi}{dZ} > 0 \qquad (3.2)$$

where V is wind velocity, Z is height, and ϕ is angle of direction the wind is going with $\phi = 0$ being north. The IL - free atmosphere boundary lowers progressively in elevation through the night.

Velocity profiles at Meeker are much different than those at Rifle at 19:00 MST (see figure 3.1b). Rifle has a northwesterly flow between mesa top height and mountain top height, but Meeker has a northeasterly flow in the same regime, however, like Rifle, Meeker has a speed shear at mountain top height. At 22:06 MST, a northeasterly flow is present up to 3.0 km ASL. Above this winds are southwesterly from just above mountain top height. Later in the night, Meeker has the IL wind characteristics like those observed at Rifle. Meeker's IL - free atmosphere boundary is lowering in elevation through the night.

Rangely doesn't have nighttime IL characteristics much different than Meeker and Rifle (see figure 3.1c). To start the night, at 19:15 MST, Rangely has a westerly component still present up to 3.0 km ASL and a northwesterly flow up to mountain top height. At 22:04 MST, a southeasterly flow has appeared below 3.0 km ASL, and a mountain height speed shear distinguishes the IL from the free atmosphere above. Late in the night, Rangely has an IL characteristics similar to Meeker and Rifle. These characteristics are an increase in velocity and direction with increasing height, and the IL - free atmosphere boundary decreases in height through the night.

Four hours after sunrise, at 10:00 MST, valley drainage at Rifle and Rangely have noticeable changes. Missing data from Meeker in the lowest in-valley layer makes it difficult to determine the result of solar heating on its drainage. Above 3.0 km ASL, all sites observe a westerly flow. Rangely, Meeker, and Rifle have the same IL characteristics observed during the night except the layer is much thinner.

By early afternoon all sites observe a westerly component to the wind, and a consistent velocity at all heights.

3. Summary of wind structure

Three atmospheric layers, common to the experimental period, are very apparent. One layer is the well known drainage wind present below mesa tops. A second layer present is the free atmosphere above 3.5 km ASL, which has no apparent diurnal phase shift. The third layer is one not so well known. It is the IL found above valley drainage and below the free atmosphere. The IL is characterized by an initial west

wind in the late afternoon which changes to southerly component flow by several hours after sunset. The nocturnal IL has a clockwise turning of the winds with increasing height, and a velocity shear at the IL - free atmosphere boundary. After becoming well established a few hours after sunset this boundary progressively lowers in elevation through the night.

All nights of the observation period do not have the same IL - free atmosphere boundary height. However, the boundary does not exceed mountain top height, and the lowest boundary of the IL does not go below mesa top height.

B. Thermal Structure

1. Introduction to thermal structure

Wind observations from Meeker, Rifle, and Rangely describe the depth and thickness of the IL, however, a full understanding of the IL cannot be obtained from the wind observations done. Wind is not independent of the thermal structure. Evolution of the thermal structure is shown in Figure 3.2. Data is presented as potential temperature since it does not change with vertical motion under adiabatic conditions. In Figure 3.2 is an overview of the evolution for September 19-20 given with three soundings at approximately 16:00 MST, 22:00 MST, and 4:00 MST.

The late afternoon begins with a nearly neutral convective boundary layer (CBL). At Rangely the CBL extends 2.5 to 3.0 km above the ground which is 0.5 to 1.0 km above the mountains to the east. The potential temperature is about 314 K to 315 K. The sounding at Rifle is slightly stable with a 2 K increase in a 2.5 km layer and the potential

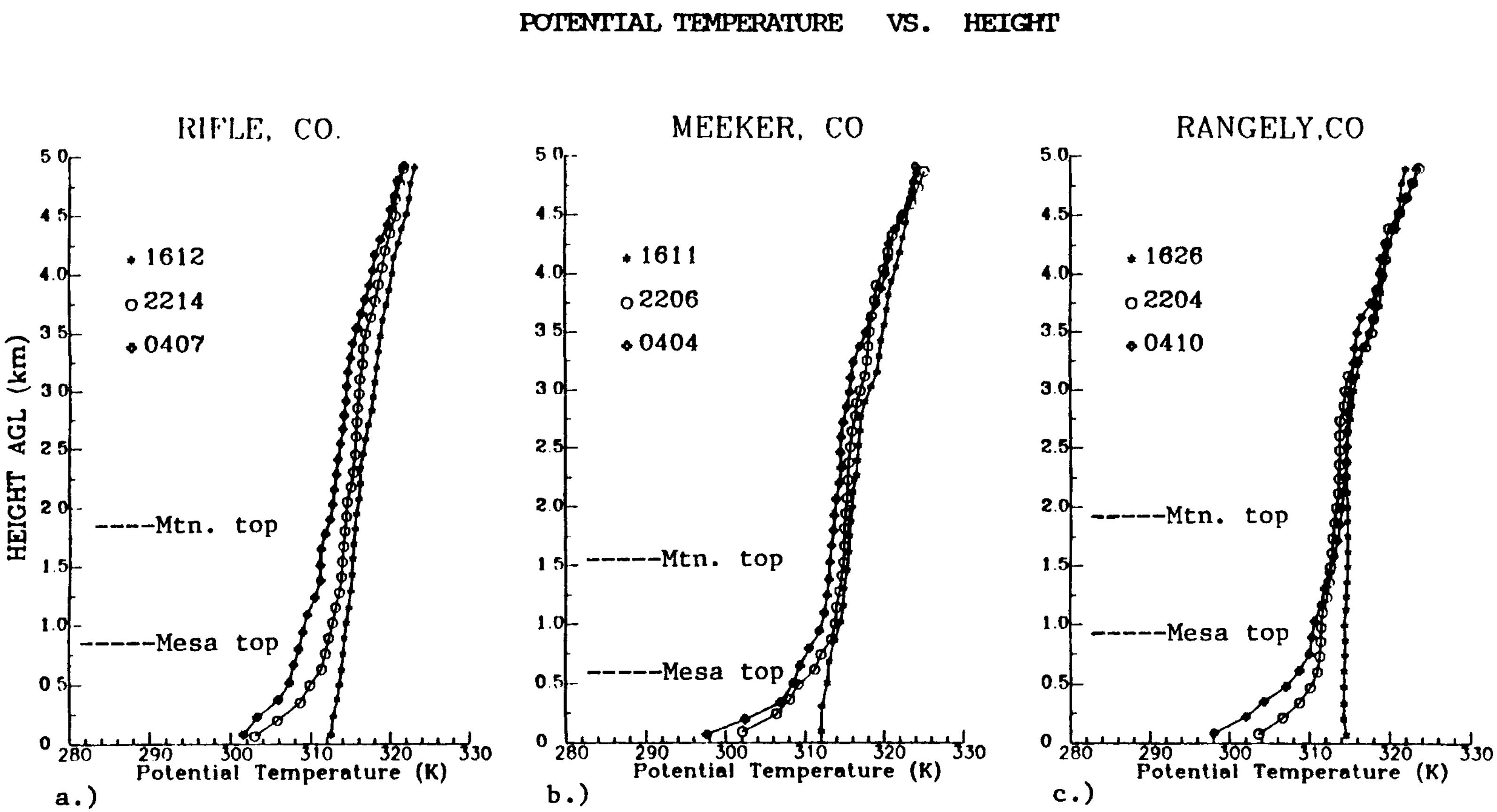

Fig. 3.2. Potential temperatures on the 19-20 September 1984 for the 16:00 MST, 22:00 MST, and 4:00 MST soundings at a)Rifle with an elevation of 1692 m ASL, b)Meeker with an elevation of 1947 m ASL, and c) Rangely with an elevation of 1607 m ASL. Approximate sunset and sunrise is 18:10 and 6:10 MST, respectively.

temperature above mountain top height are nearly the same. Meeker also is slightly stable but potential temperatures above mountain top height is similar to Rangely and Rifle. As the night progresses the potential temperatures cool 10 K or more at the surface and the cooling extends above the mesa tops to near the height of the mountains. Detailed intercomparisons from one sounding to another are not easily accomplished due to unknown error magnitudes. The discussion of accuracy in chapter 2 indicated errors of +/- 0.4 C are possible. Temperature advection was judged to be small above mountain top but can not be assumed to be zero. Changes in potential temperature during the night just above mountain top is small (1.0 K - 2.0 K) at Rangely, a little larger at Meeker (2.0 K - 3.0 K), and larger yet at Rifle (3.0 K - 4.0 K).

Data presented in Figure 3.3, 3.4, and 3.5 allow a closer examination of the diurnal evolution at each site. The nocturnal cooling can be described as a cooling and also as a change in stability. Cooling appears at Rangely early in the evening and extends nearly 1 km above the surrounding mesas. Rifle and Meeker also have the cooling to mountain top height. Each site also has the remnants of the CBL from the previous day seen as a neutral layer above mountain top height. The IL identified in the wind analyses is seen in the thermal structure also as a layer extending from the mesas up to mountain top height. Possible errors in temperature observations limit the analysis of sonde to sonde comparisons, but they do not limit an analysis of atmospheric stability.

POTENTIAL TEMPERATURE VS. HEIGHT
RANGELY: 9/19-20/84

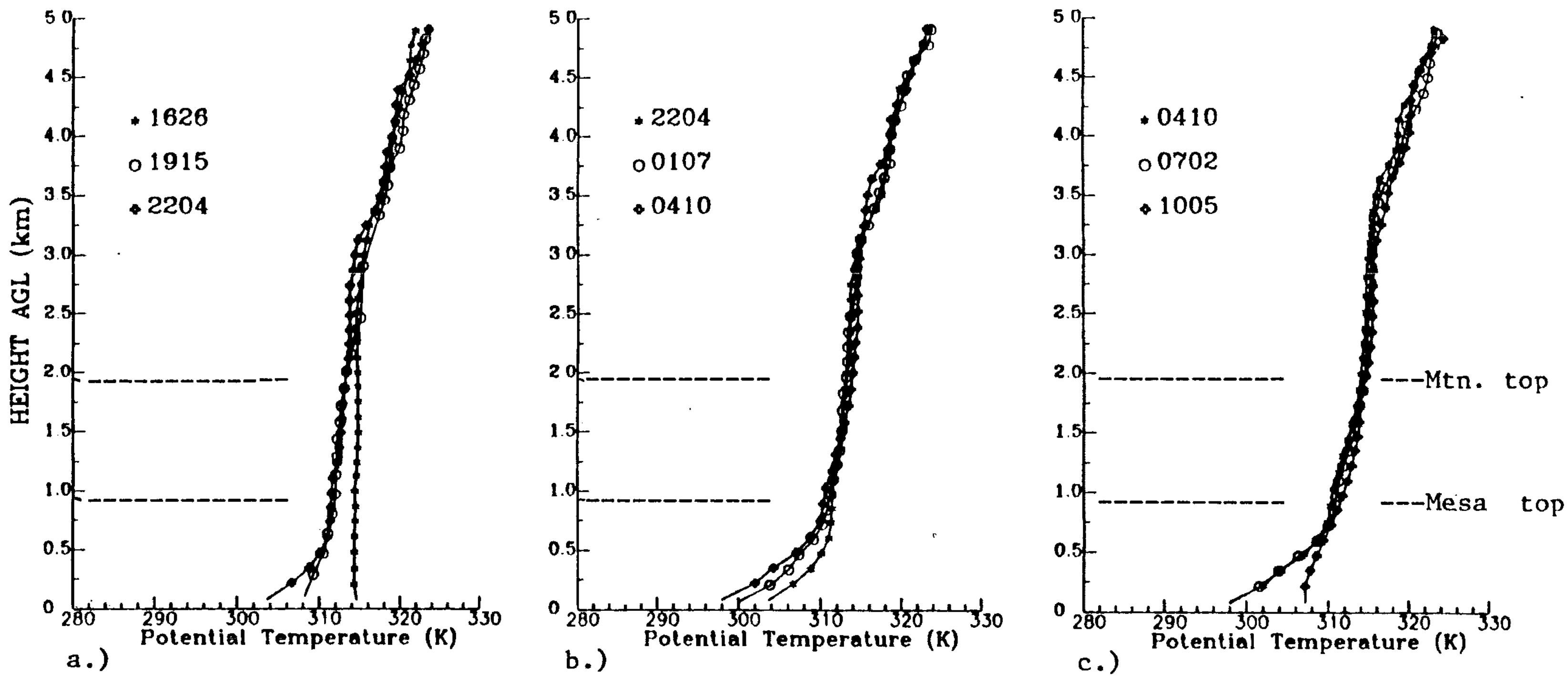

Fig. 3.3(a-c). Potential temperature plots on 19-20 September 1984 for Rangley with an elevation of 1607 m ASL. Sunset and sunrise are at 18:19 and 6:07 MST, respectively. All soundings are in MST.

POTENTIAL TEMPERATURE VS. HEIGHT
MEEKER: 9/19-20/84

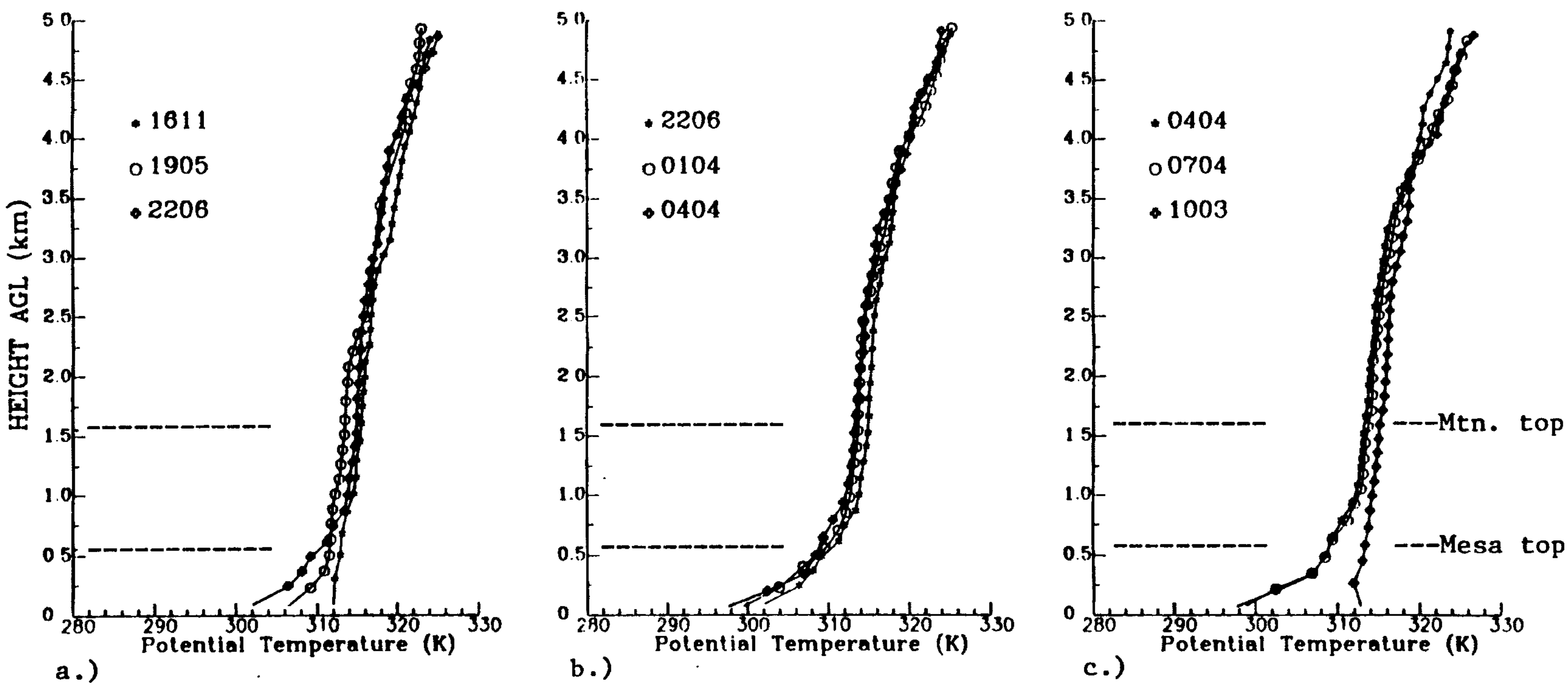

Fig. 3.4(a-c). Potential temperatures on 19-20 September 1984 for Meeker. Meeker has an elevation of 1947 m ASL, with sunset and sunrise at 18:16 and 6:03 MST, respectively. All soundings are in MST.

POTENTIAL TEMPERATURE VS. HEIGHT
RIFLE: 9/19-20/84

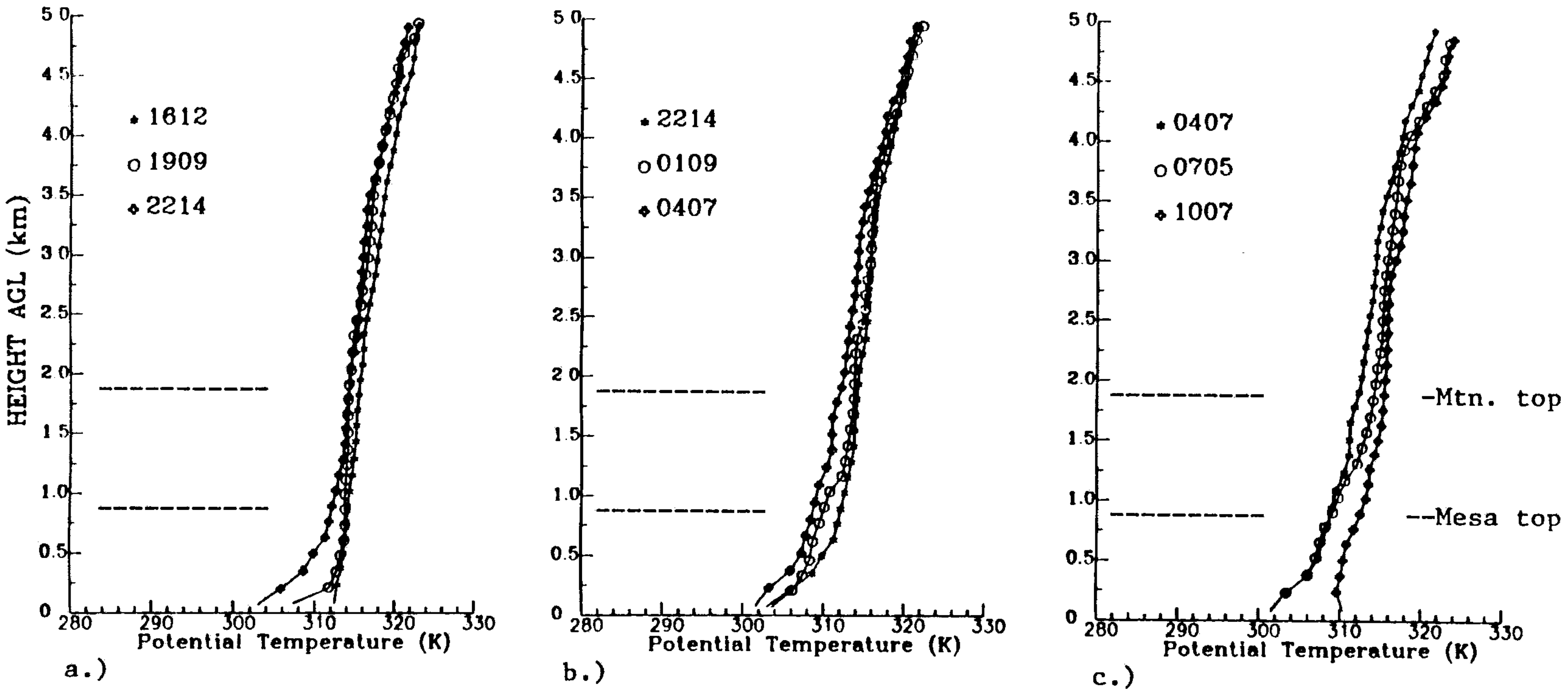

Fig. 3.5(a-c). Potential temperatures on 19-20 September 1984 for Rifle. Rifle has an elevation of 1692 m ASL, with sunset and sunrise at 18:16 and 6:03 MST, respectively. All soundings are in MST.

2. Atmospheric stability

a. stability criteria for a dry atmosphere

During the day, a clear, dry atmosphere will allow a great deal of surface heating by the sun. As heating continues through the day, a Convective Boundary Layer (CBL) will form as a result of surface heating. As long as there is solar insolation on the surface, this CBL will continue to grow. Several minutes prior to sunset, the atmosphere near the surface will cool, and stability will become noticed in the lower layers of the boundary layer.

Stability is defined here as the change of potential temperature, θ, with height, Z; stability criteria commonly used for a dry atmosphere are (Holten, 1979):

$$\frac{d\theta}{dZ} > 0, \quad \text{Stable} \qquad (3.4)$$

$$\frac{d\theta}{dZ} < 0, \quad \text{Unstable} \qquad (3.5)$$

$$\frac{d\theta}{dZ} > 0, \quad \text{Neutral (well mixed).} \qquad (3.6)$$

A vertical displacement of a parcel in an environment having a positive potential temperature lapse rate will result in the parcel oscillating about its initial position at a frequency equivalent to the Brunt-Väisällä frequency,

$$N^2 = \frac{g}{\theta}\frac{d\theta}{dZ} \qquad (3.7)$$

where g is gravitational acceleration. An environment having $d\theta/dz > 0$ will have a lapse rate greater than the dry adiabatic lapse of -9.8 K/km (eg. $dT/dz = -8.0$ K/km, T = absolute temperature). If the parcel is forced vertically dry adiabatically, it expands and cools.

The cooling results in a cooler temperature than the environment it enters. In return, the parcel is more dense than the environment and, therefore, returns to its initial level.

A vertically displaced parcel in an environment decreasing in potential temperature with height will not oscillate about its initial level. Rather, if the parcel is forced vertically dry adiabatically by any means, it will continue to rise. This environment has a lapse rate less than the dry adiabatic lapse rate (eg. dT/dz = -10.0 K/km). A parcel lifted dry adiabatically will expand and cool, but the final temperature will be greater than the environment. As a result of its initial displacement in the vertical, the parcel will continue to rise.

A parcel in an environment having no change of potential temperature with height will not accelerate upward or be returned to its initial level. After its initial displacement in the vertical, it will rise dry adiabatically. Since the environment is adiabatic, the parcel will retain the same temperature as the environment. As a result, the parcel remains where it has risen.

b. mean atmospheric stability

When discussing the stability of a region with the complexity of western Colorado, it becomes helpful to understand how the stability over this complex terrain differs from stability growth over flat terrain. Under clear, dry, conditions, regions of flat terrain have typical nocturnal stable boundary layer (NSBL) depths of 0.2 - 0.4 km Above Ground Level (AGL) (Stull, 1988), with little change in depth over many horizontal kilometers. However, over complex terrain the NSBL will acquire variable depths over a few kilometers and will be much deeper than NSBLs over typical flat terrain. Even though the

atmospheric conditions may be the same above both types of terrain, the NSBL will be deeper over the complex terrain. Sensible heat flux in valleys act on a smaller volume of air. Furthermore, greater turbulence can exist in regions of complex terrain and cause greater mixing of cold air near the surface into higher layers (Bader et al., 1987).

A similar discussion can be made when considering the comparison of the CBL over flat and complex terrain. Again, the CBL will generally be deeper over regions of complex terrain, because valleys help to heat the smaller volume of air like they did to stabilize a smaller volume of air. Figure 3.6 from Stull (1988) gives an excellent illustration of the typical atmospheric cycle. It shows the depth of a CBL, and the growth of stability over flat terrain as the night progresses.

c. stability calculations from observations

Observations were made on four nights, and each night had its own distinct evolution. Similarities do exist from night to night, and analyzing one night will be sufficient to describe the characteristics of each night. Data chosen for analysis are on the night of the 19th and 20th. Figures 3.7 (a-c) will be used as a reference for the analyses of the Rifle, Meeker, and Rangely soundings on the night of the 19th-20th. Stability plots of the 17th-18th, 25th-26th and 29th-30th are found in appendix D.

Starting the 19th-20th is the 16:00 MST sounding on the afternoon of the 19th. Solar heating is very strong at this hour, and Rangely has the most neutral CBL of the three sites, while Meeker and Rifle have a boundary layer of very weak stability. The depths of these boundary layers are not significantly different from site to site, with the heights varying from 4.0 km ASL over both Rangely and Rifle to 4.5

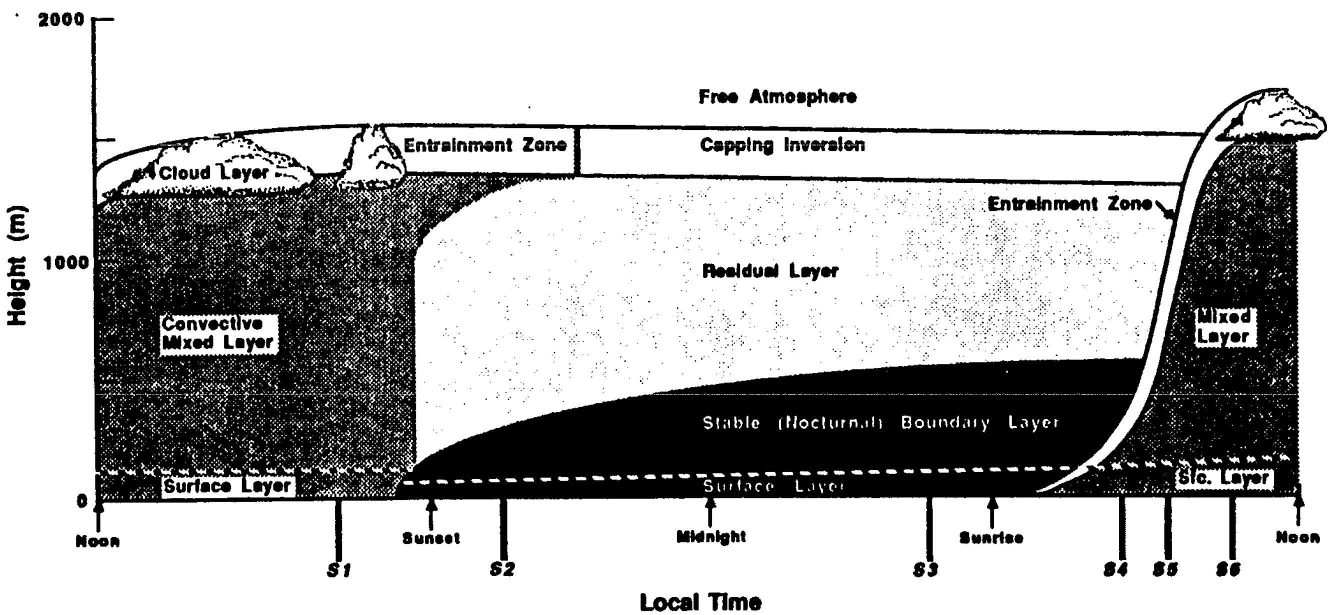

Fig. 3.6. Schematic diagram of the typical atmospheric cycle. From Stull (1988).

Fig. 3.7a. Change of potential temperature with height for Rifle on 19-20 September 1984. Height is in kilometers Above Sea Level (ASL) with Rifle at 1692 m ASL. Horizontal axis represents soundings in MST and stability. Rifle has sunset and sunrise at 18:16 MST and 6:03 MST, respectively. Lines A and B represent mesa top and mountain top heights, respectively.

Fig. 3.7b. Same as figure 3.7a except for Meeker, which has an elevation at 1947 m ASL.

Fig. 3.7c. Same as figure 3.7a except for Rangely, which has an elevation of 1607 m ASL. Sunset and sunrise are at 18:19 and 6:07 MST, respectively.

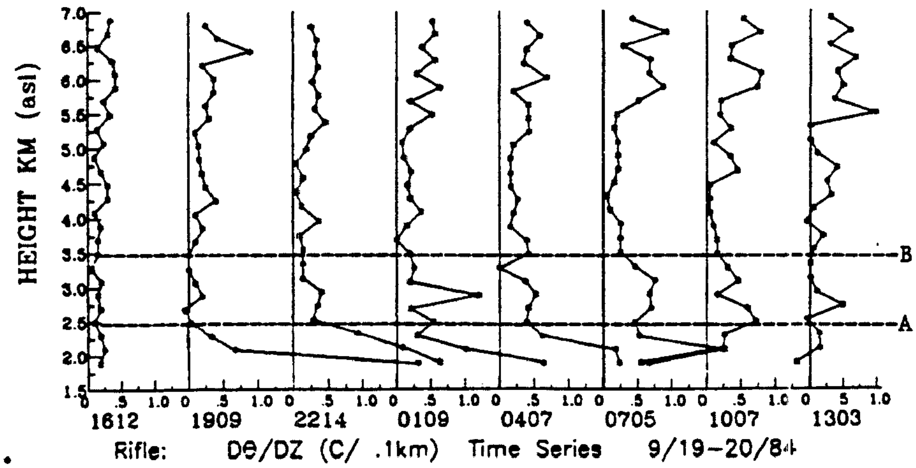

Fig. 3.7a.

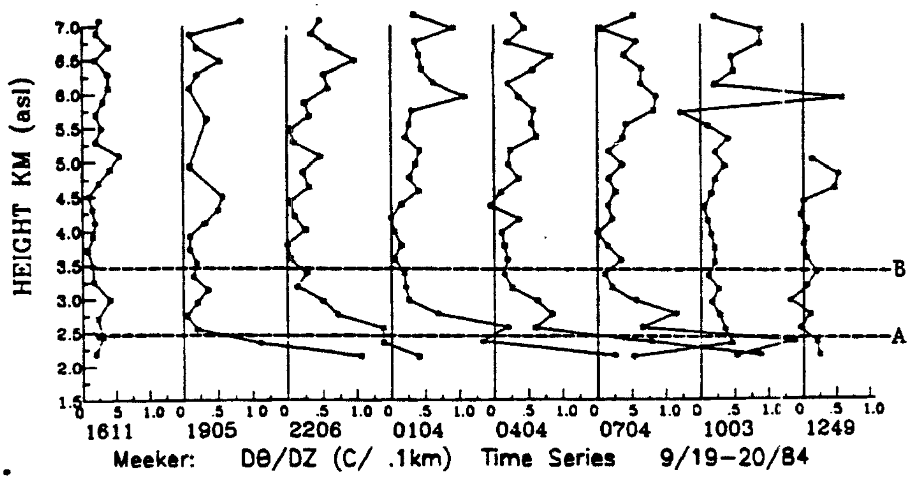

Fig. 3.7b.

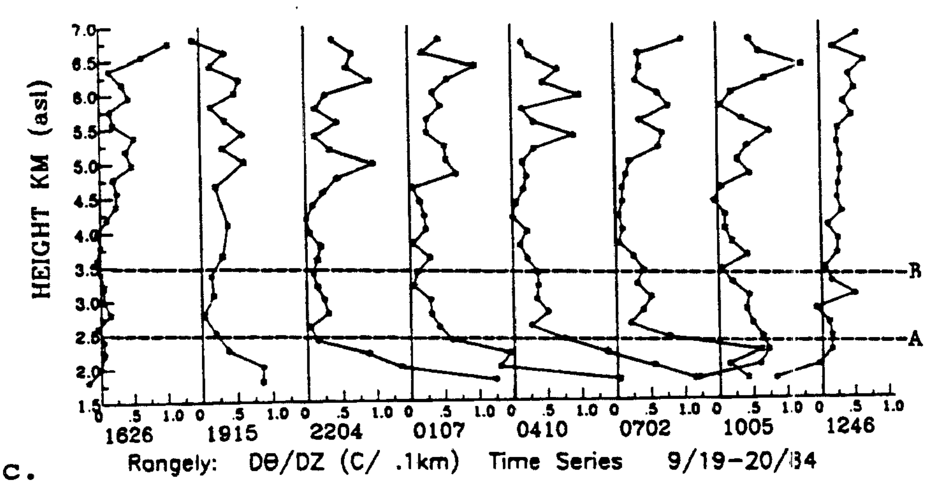

Fig. 3.7c.

km ASL over Meeker. Stability is present above these boundary layers, with $d\Theta/dz$ = 3-5 K/km at each site.

At 22:00 MST, the sun has been down for almost four hours. Stability is still shallow over Rangely, with a depth of 2.4 km ASL. Strong stability greater than 5 K/km is below 2.25 km ASL (see figure 3.7c). A similar stability is over Rifle, but it is deeper, with 5 K/km at 2.5 km ASL and weak stability reaching up to 3.0 km ASL (see figure 3.7a). Stability over Meeker is similar to that over Rifle, but strong stability of 5 K/km extends slightly higher, and weak stability is up to 3.0 km ASL (see figure 3.7b). Above these stable layers are remnants of the boundary layer observed prior to sunset extending to heights originally observed.

Ten hours after sunset, at 4:00 MST, stability depths are reaching maximum heights. Stability over Rangely has characteristics observed throughout the experimental period; strong stability is present to 2.5 km ASL and weak stability extends an additional one kilometer above this. Rifle has increasing stability strength up to 3.5 km ASL, and strongest stability is less than 2.8 km ASL. Strong stability to 3.0 km ASL is over Meeker with very little stability above this. The remnants of the afternoon boundary layer are still present at each site, but the depth and clarity of the remnants are diminishing with time.

Between the 4:00 MST and 7:00 MST soundings, stability changes little in depth or strength at each site. Surface heating is noticed approximately four hours after sunrise, and a neutral atmosphere is present over each site up to 2.0 km ASL. Remnants of the prior evening's stability are still present, but it is not as strong or deep as it was in the 4:00 MST or 7:00 MST soundings.

Solar heating is once again a dominant force at 13:00 MST. A weak, stable boundary layer, not as deep as the previous day, is noticed over each site.

3. Thermal gradient in the IL

Figure 3.8(a-d) represents the cooling process observed over Rangely, Rifle, and Meeker. These are plots of the change in temperature, ΔT, with time taking place after 16:00 MST on the night of the 19th-20th. Four layers are presented; a) the layer below mesa tops, less than 2.5 km ASL, b) 2.5-3.0 km ASL, c) 3.0 - 3.5 km ASL, and d) 3.5-4.0 km ASL. The average temperature is obtained for each of the layers, at each of the sites, for each sounding. After the average temperature is obtained, the average of all four nights is calculated for each layer and each site and each sounding. An average of four nights should alleviate any problems associated with sonde temperature errors. It was decided, after examining stability, that it would be advantageous to divide the IL into two layers.

Cooling in the valley is large but different for all three sites. The differences in the valley are not considered a factor to the IL, because valley cooling will be associated with the structure of the valley. Between 2.5 km and 3.0 km ASL, Rifle cools the greatest during the night hours. At this elevation, Meeker and Rangely are cooling very much the same. Above 3.0 km ASL, Rifle and Meeker are showing a greater magnitude of cooling. The magnitude of cooling becomes very similar at all sights in the layer above the mountains.

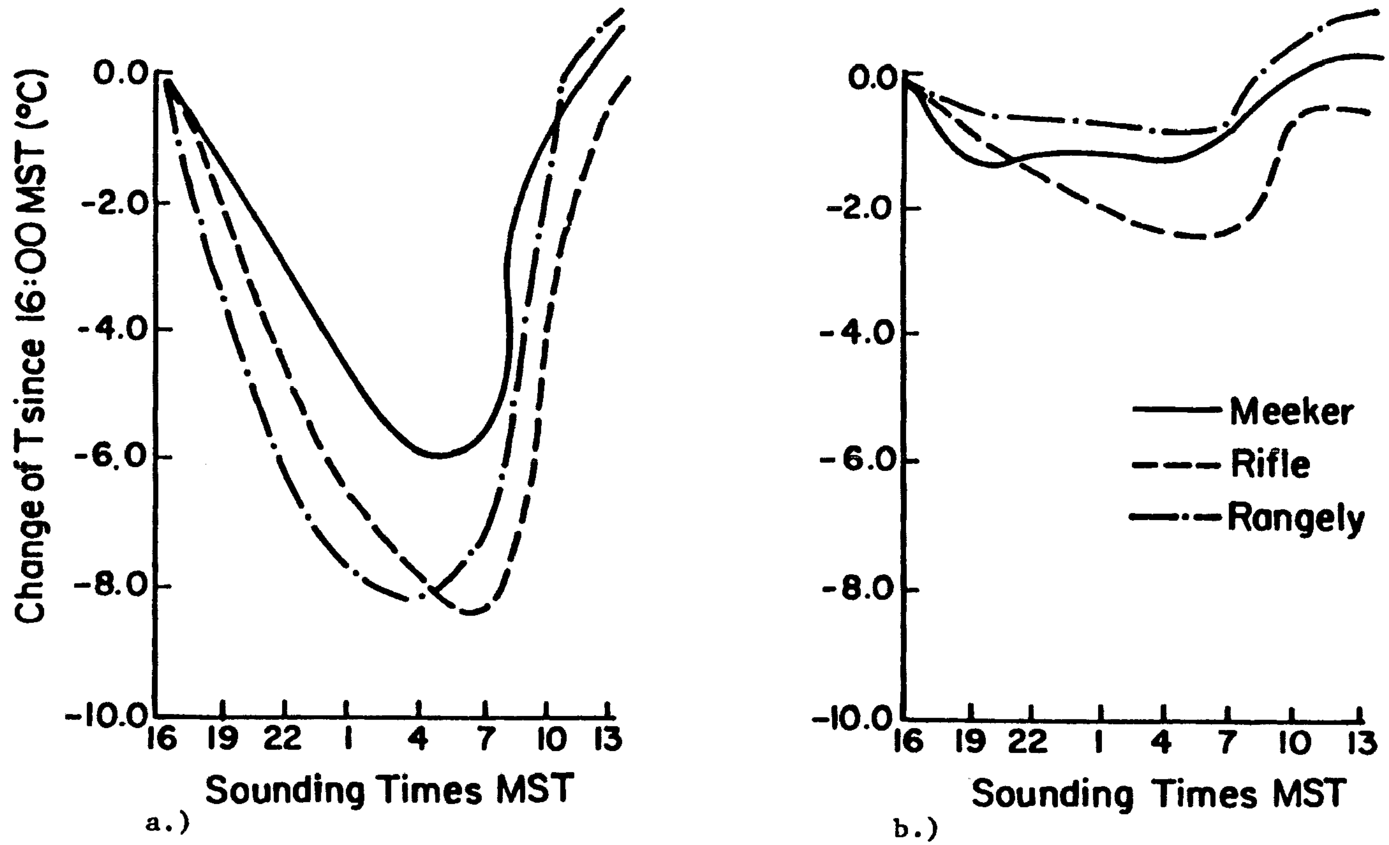

Fig. 3.8(a-b). Cooling comparison among the sites within the region of western Colorado. The cooling since 16:00 MST is an average of four nights for the layers a) less than 2500 m ASL and b) 2500-3000 m ASL. Sunset and sunrise are approximately 18:00 and 6:00 MST, respectively.

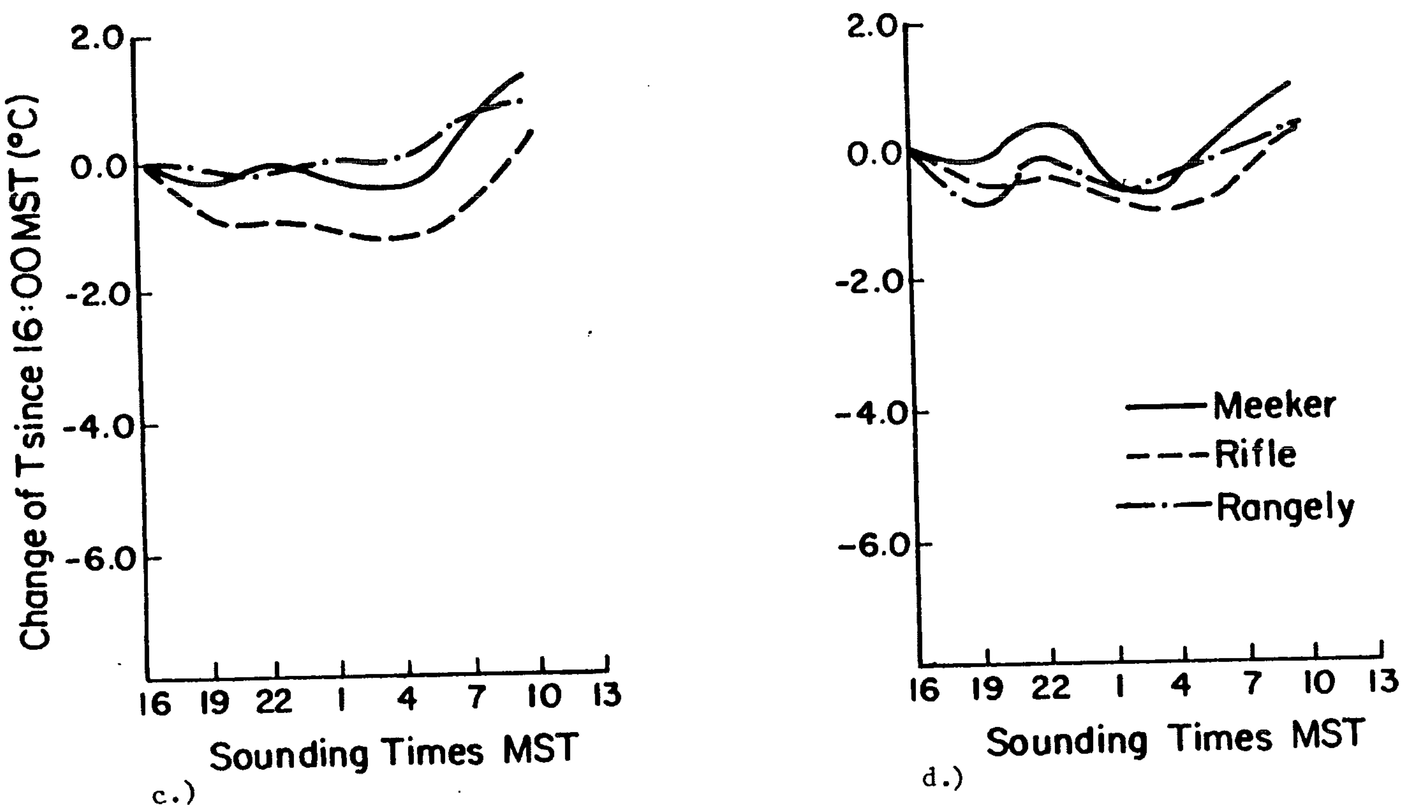

Fig. 3.8(c-d). Cooling comparison among the sites within the region of western Colorado. The cooling since 16:00 MST is an average of four nights for the layers c) 3000-3500 m ASL and d) 3500-4000 m ASL. Sunset and sunrise are approximately 18:00 and 6:00 MST, respectively.

Using a program referred to in Cox and Griffith (1979), the amount of radiative cooling in the rather dry atmosphere is calculated to be approximately a degree celsius throughout the night. Therefore, the radiative cooling cannot be neglected, but it is not considered a very important factor in the observations. It does, perhaps, explain the cooling well above mountain tops.

It is apparent, from averaging the temperature data, IL cooling of a greater magnitude takes place near the mountains. Rifle cools more than either Meeker or Rangely, and Meeker more than Rangely.

4. Energy loss within the IL

Cooling comparisons among the sites within our experimental region of Colorado does show the presence of more cooling within the IL near the mountains than farther away. However, the cooling may be a result of mixing the air cooled by the mesa top into the IL. Calculations of the energy loss will help determine whether mesa top cooling can be the sole source of the cooling.

According to Whiteman et al. (1989), the mesa top sensible heat loss at night is approximately 20 W/m^2. This measurement was for the night of the 25th-26th of the ASCOT '84 project, however, the sensible heat loss from night to night should not vary greatly if the weather conditions and sky cover are very much the same. Much of the air cooled by the sensible heat loss will drain into adjacent valleys. Gudiksen and Shearer (1989) studied the dispersion of tracers in the valley of Brush Creek during the ASCOT '84 project. They found that perflurocarbon released from the mesa tops drain into the valley and get caught up in the valley drainage, which is in the lowest three hundred meters of the valley. Also from the ASCOT project, the SRL site, located on the ridgetop (see Clements et al., 1989), took tethersonde soundings. They observed an inversion approximately 50 meters deep over the mesa top and a very light drainage of 2-3 m/s flowing off the mesas into the valley.

A measure of the energy loss in the atmosphere above the mesas within the IL can be done. The change in potential temperature from one time to another is converted into an energy loss. This is done with the use of the total derivative of the energy equation (ie. the first law of thermosdynamics).

$$\frac{dq}{dt} = C_v \frac{dT}{dt} + P \frac{d\alpha}{dt} \qquad (3.8)$$

where α is the specific volume, $1/\rho$, C_v is the specific heat at constant volume, and dq/dt in the first law is the rate of heating per unit mass due to radiation, conduction and latent heat release. We will neglect latent heat release because of dry conditions and the lack of clouds. Combine equation (3.8) and the total derivative of the equation of state,

$$\alpha \frac{dp}{dt} + P \frac{d\alpha}{dt} = R \frac{dT}{dt} \qquad (3.9)$$

to get

$$T C_p \frac{d\ln T}{dt} - T R \frac{d\ln P}{dt} = \frac{dq}{dt} \qquad (3.10)$$

where $C_p = C_v + R$, 1004 J/k/kg. Then substitute the total derivative of the logarithm of the potential temperature

$$C_p \frac{d\ln\theta}{dt} = C_p \frac{d\ln T}{dt} - R \frac{d\ln P}{dt} \qquad (3.11)$$

into equation (3.10) to get

$$\frac{dq}{dt} = T\, C_p \frac{d\ln\theta}{dt} \qquad (3.12)$$

which is the final relationship between the change of potential temperature with time and the change of energy in the atmosphere with time.

Equation (3.12) is used to find the amount of energy loss that has taken place in the atmosphere at each site above mesa top, 2.5 km ASL, up to mountain top height, 3.5 km ASL. Rifle had approximately 30 W/m^2 cooling within the IL, Meeker approximately 15 W/m^2 cooling, and Rangely approximately 7 W/m^2. The value at Rifle is larger than the the value of the sensible heat loss Whiteman et al. (1989) observed, which indicates that the cooling at Rifle is probably more than just a function of mesa top cooling. The 15 W/m^2 at Meeker is more than half of the value given by Whiteman et al. (1989), which indicates that the value of 15 W/m^2 observed leads to a reasonable probability that a cooling source in addition to mesa tops is needed. At Rangley, 7 W/m^2 can be caused by mixing upward the air cooled by the mesa tops, even though much of the cooled air may drain into the valley.

Calculations of energy loss within the IL cannot completely verify another source of cooling other than the mesas, but it does give some indication that there is more. The sites close to the mountains cool more than the site far from the mountains, and cooling near the mountains may be more than mesa top cooling. It may be caused by the mountains cooling the air around them and advecting that cool air into the IL close to them.

CHAPTER IV

CONCEPTUAL MODEL

A. Conceptual Introduction

Above the valleys of western Colorado is an Intermediate Layer (IL) capable of supporting a diurnal evolution in wind and thermal structure. Observations of both structures identify these diurnal evolutions, which are separate from the atmosphere within the valleys and the free atmosphere above mountain top height.

The wind structure behaves in a manner conceptually illustrated in figure 4.1. In the conceptual model is an imaginary valley existing on the west slope of Colorado. The daytime westerlies are present throughout the atmosphere including the valley. This is a behavior unique to this valley, because the valley has an east to west orientation which is associated with a daytime flow from west to east and a nocturnal drainage from east to west.

During the day, a neutral atmosphere is within and above the valley. As the night progresses, stability will begin to grow from the surface of the valley to elevations at approximately mountain top height. This stability will enable the mountains to block the westerly flow. Blocking will cause an east-west pressure gradient, and initiate the winds seen during the night hours in the conceptual model; a southerly component wind increasing in velocity and direction with increasing height will be present in the IL.

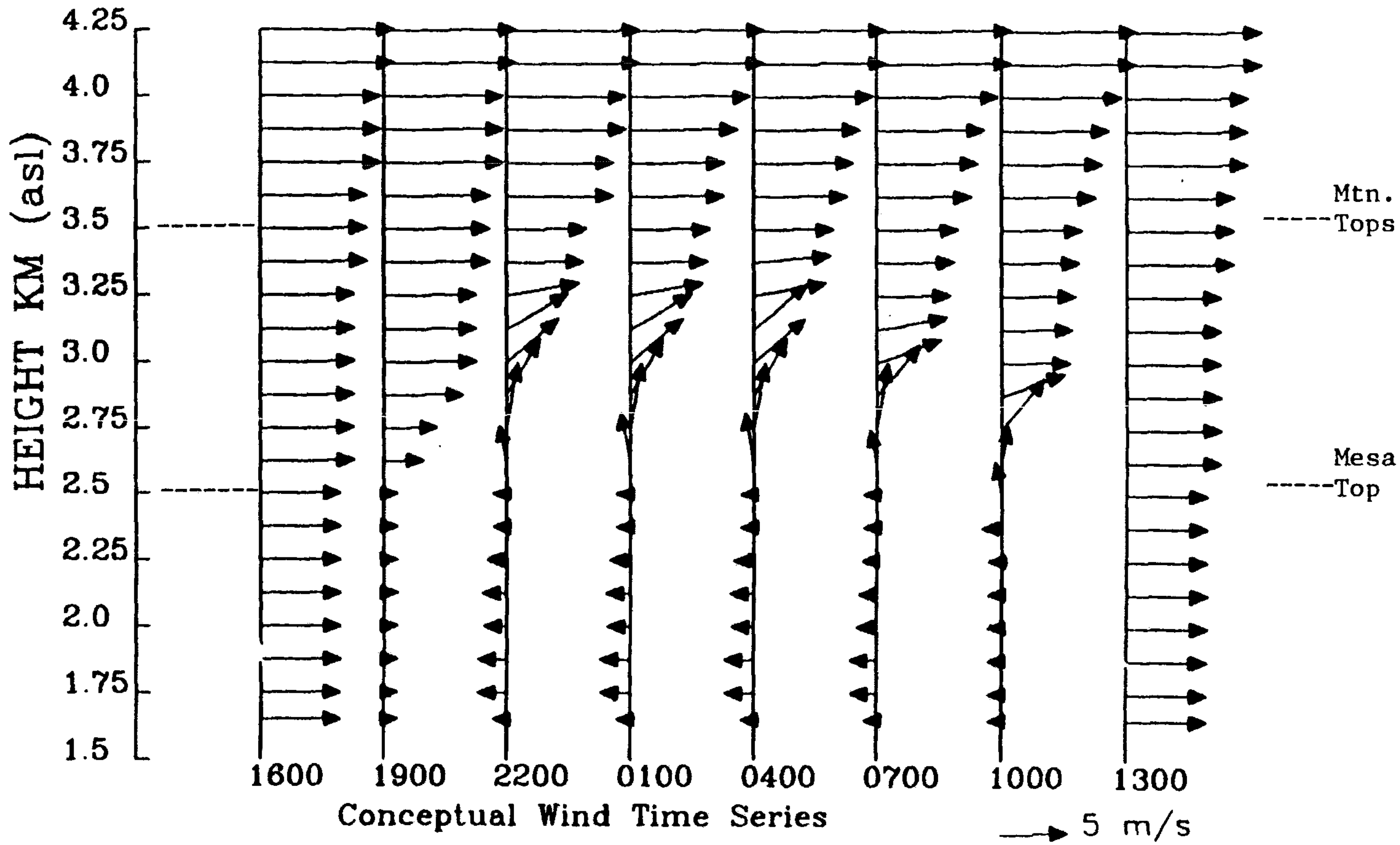

Fig. 4.1. Conceptual model of the winds for an imaginary valley of northwest Colorado. Height is in kilometers Above Sea Level(ASL). Horizontal axis represents times in MST. This assumes a sunset at 18:00 MST and sunrise at 6:00 MST. Vectors point in the direction wind is going with north being the top of graph.

In addition to mountain blocking, diverse cooling takes place throughout the region on the west slope. The mountains will cool the atmosphere around them and advect the cool air into the IL atmosphere above the adjacent mesas. This advection from the mountains will cause a more rapid cooling in the atmosphere close to the mountains than the atmosphere farther from the mountains. An east-west thermal gradient will be in the region, which will result in a pressure gradient across the region. This, like the mountain blocking, will initiate the IL winds in the night hours.

In the later hours the IL wind and free atmosphere boundary lowers progressively in elevation until the next morning. The stability and thermal gradient both become eliminated by the heating of the day, and the IL becomes dominated by the westerlies.

B. Physical Mechanisms

1. Thermal gradient

a. thermal gradient model

In the observations, a thermal gradient was found within the region of western Colorado. Figure 4.2 is a conceptual model of the thermal gradient on the west slope. The cooling shown is a conceptual view of IL cooling taking place close to and far from the mountains since 16:00 Mountain Standard Time (MST).

From the model analyses, cooling is more dominant close to the mountains (see figure 4.2). Having more cooling close to the mountains will create an east-west pressure gradient on a constant height surface. The higher pressure will be present in the east, because of more cooling. More cooling in an open environment creates a higher pressure. The air becomes more dense as it cools, and in return more

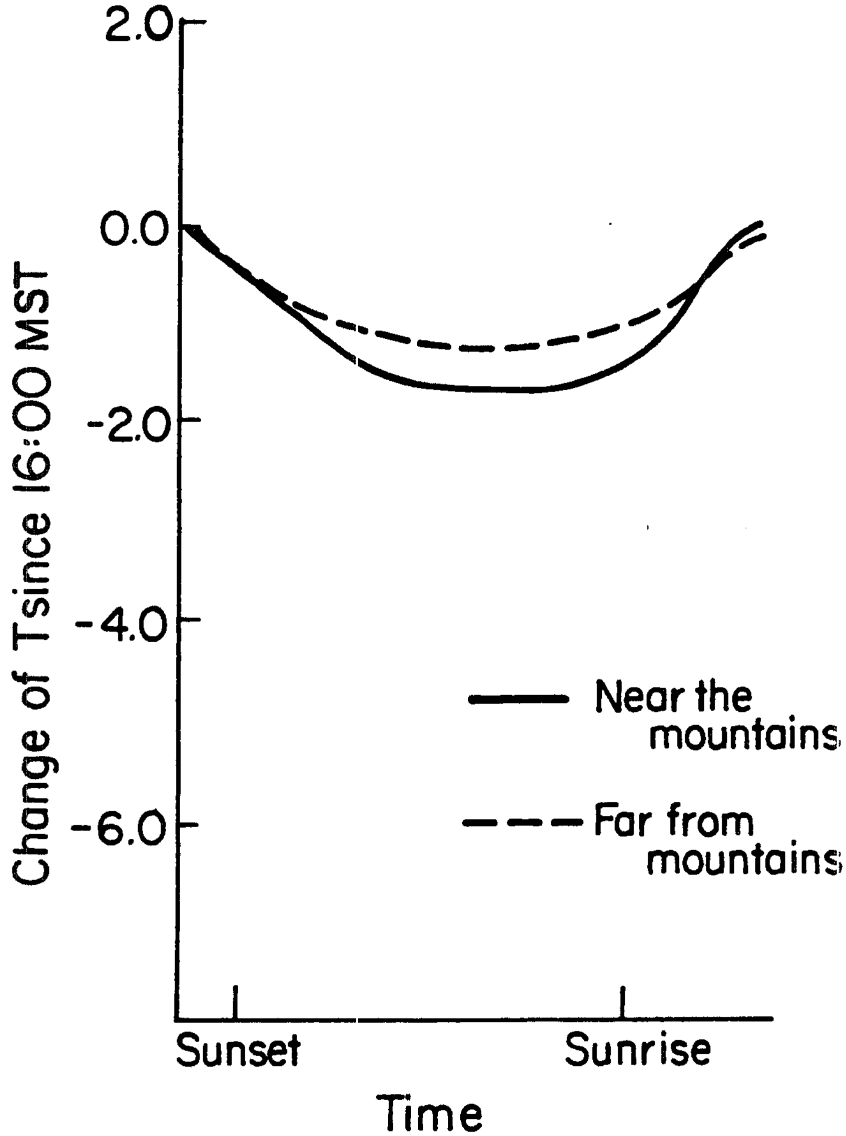

Fig. 4.2. Conceptual model of the nocturnal cooling comparison in the IL between near the mountains and far from the mountains. The horizontal axis is Local Time.

mass can be contained in the same volume, which creates a higher pressure.

b. results of thermal gradient

Take for example a hypothetical region that allows air to move freely in and out of it. Initially, the absolute temperature is uniform and the air is calm. Now we suppose more cooling in the east develops a higher pressure in the east. If the east has a higher pressure on a constant height surface, the air will begin to flow from the higher pressure to the lower pressure. Of course, the time for air to flow from the higher pressure to the lower pressure will decide if the coriolis parameter is an influence. If the time scale is large enough, the flow will become parallel to the isobars. If the region has a source to replace the mass leaving the east, the wind will continue to blow from east to west, or eventually from south to north if coriolis is a factor.

However, the conceptual wind model presented in the previous section did not have calm winds, but there is a moderate westerly wind in the late afternoon. In figure 4.3a the wind and corresponding pressure gradient is illustrated. The synoptic, regional westerlies are created by a higher pressure to the south and a lower pressure to the north.

Cooling near the mountains creates a higher pressure to the east and a lower pressure to the west, and ΔP in figure 4.3b is the increase in pressure near the mountains. The increase in pressure near the mountains will cause the highest pressure in the region to be in the southeast and the lowest pressure in the northwest.

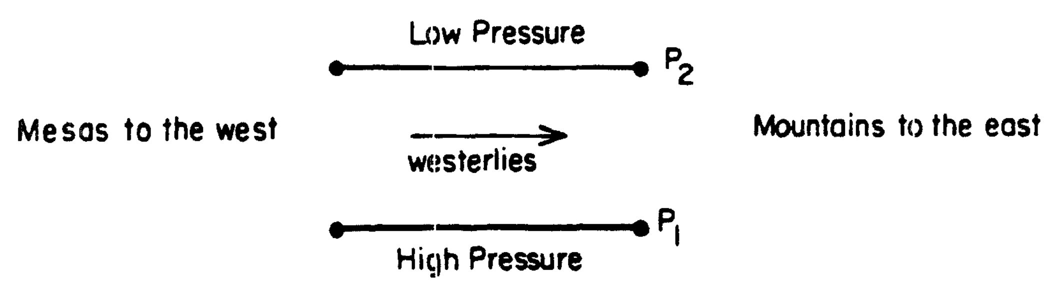

Fig. 4.3a. Pressure field corresponding to the geostrophic westerlies. $P_1 > P_2$. Mountains and Mesas are assumed to run infinitely north to south.

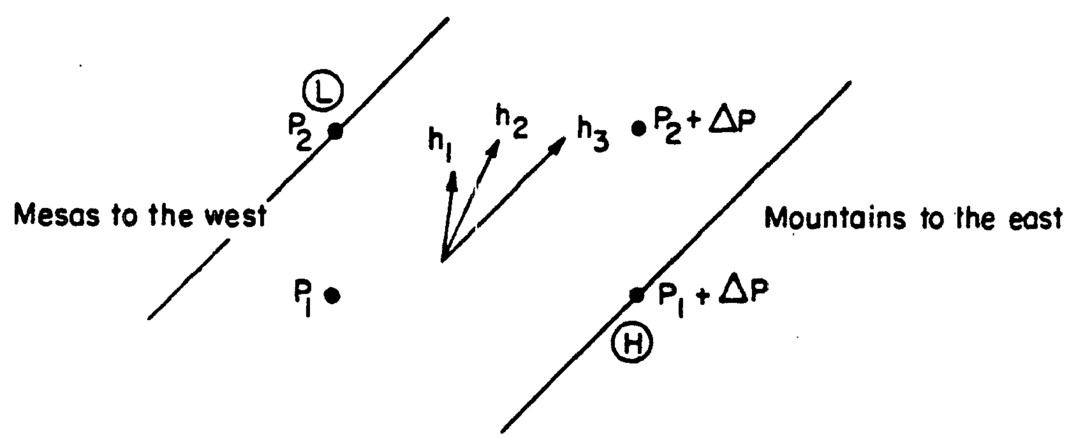

Fig. 4.3b. Pressure field following the nocturnal cooling near the mountains. $\Delta P > 0$, and $P_1 > P_2$. Arrow h_3 represents geostrophic northwest wind at height h_3 with $h_3 > h_2 > h_1$.

This southeast to northwest pressure gradient will create a geostrophic southwest flow. The influence of coriolis is verified with calculations of the Rossby number

$$Ro = \frac{U}{fL} \tag{4.1}$$

where U is the velocity scale, L the distance scale, and f the coriolis parameter taken to be 10^{-4}/s in mid latitudes. The following calculation of the Rossby number is an estimation. If U is assumed to be approximately 5 m/s and L is taken to be 100 km , then the Rossby number is approximately 0.5. The smallness of the Rossby number indicates the coriolis influence is important for the present problem.

Since the coriolis parameter is now considered an influence, it is of interest to understand in detail how a slight temperature gradient will lead to a substantial geostrophic wind. It is first necessary to put pressure in terms of temperature. We first start with the hydrostatic equation

$$dP = - \rho g \, dZ \tag{4.2}$$

where P is pressure, Z is height, g is gravitational acceleration, and ρ is the atmospheric density which is a function of pressure and temperature. Therefore, we will substitute for density in equation (4.2) by using the equation of state

$$\rho = \frac{P}{R\,T} \tag{4.3}$$

where T is the absolute temperature in kelvin, and R is the universal gas constant, 287 J/k/kg. This substitution will result in

$$\frac{dP}{P} = - \frac{g}{R\,T} \, dZ \tag{4.4}$$

which can be integrated vertically. Integrate the right side from Z_1 to Z_2 where $Z_2 > Z_1$, and integrate the left side from the pressure at Z_1, $P(Z_1)$, to the pressure at Z_2, $P(Z_2)$ to get

$$\ln \frac{P(Z_2)}{P(Z_1)} = -\frac{g}{R\,T'}\,(Z_2 - Z_1) \qquad (4.5)$$

where T' is the average temperature in the integrated layer, $\Delta Z = Z_2 - Z_1$. We will assume from here on that $P(Z_2)$ = constant, therefore, we solve for $P(Z_1)$ to get

$$P(Z_1) = P(Z_2)\,\exp(\frac{g}{R\,T'}\,\Delta Z) \;. \qquad (4.6)$$

With this equation in mind we will now establish two sites X_A and X_B separated by 50 km. In the free atmosphere above these sites is a layer, ΔZ = 1 km. Both sites have the same pressure at Z_2,

$$P_A(Z_2) = P_B(Z_2) = 700 \text{ mb}$$

where the subscripts A and B represent sites X_A and X_B, respectively. Initially we will assume both sites to have the same average temperature within the layer ΔZ (eg. $T'_A = T'_B = 273$ K). Using equation (4.6) we find that the pressure at both sites at height Z_1 is 793.26 mb.

Using the geostrophic wind equation in the y-component

$$v_g = \frac{1}{\rho f}\;\frac{\partial P}{\partial x} \qquad (4.7)$$

we find that with no pressure gradient there is no geostrophic wind (assuming that there is no x-component wind).

Now some cooling has taken place at site X_B so that T'_B = 272.5 K. Using equation 4.6 and assuming that Z and $P(Z_2)$ remain unchanged

$$P_B(Z_1) = P_B(Z_1)\,\exp(\frac{g}{R\,T'_B}\;\Delta Z)$$

which is

$$P_B(Z_1) = 793.44 \text{ mb} .$$

Because of this cooling within the layer there has been a pressure increase at site X_B at height Z_1. Now returning to the geostrophic wind in the y-component at height Z_1 between sites X_A and X_B

$$v_g = \frac{1}{\rho f} \frac{P_A(Z_1) - P_B(Z_2)}{50 \text{ km}}$$

to get a geostrophic wind

$$v_g = 3.6 \text{ m/s} .$$

In summary, a temperature gradient of 0.5 K will result in a geostrophic wind of 3.6 m/s.

c. summary of thermal gradient

A thermal gradient across the region of western Colorado will be an instigator of winds similar to the winds observed in the IL. From the thermal observations, a thermal gradient was shown to exist in the IL, as a result of the thermal gradient, a northwest to southeast pressure gradient is created on a constant height surface.

2. Mountain blocking

a. explanation of blocking

Mountain blocking is a function of wind and stability. In the afternoon, stability is considered very weak or even neutral. It was explained earlier how a parcel in a neutral environment will behave; the parcel forced vertically will not return to its initial level. In this environment, the potential for the wind flow in the IL to lift over the mountains is very large. The flow will lift very easily over the mountains, because there is no restoring force to return the flow to its initial level.

The stability of the atmosphere increases throughout the night. A parcel lifted vertically in a stable environment will return to its initial level (see chapter 3). In this environment, the air will need more kinetic energy to lift itself over the mountains. Therefore, the potential for a parcel to lift over the mountains in a stable environment is very small.

b. stability model

Most clear, dry days of western Colorado begin with a weakly stable or sometimes neutral Convective Boundary Layer (CBL). As the night progresses, atmospheric stability grows from the valley floor upward to heights well above valley top. Figure 4.4 is a conceptual model of stability for our imaginary valley in the region of western Colorado.

The afternoon has a neutral layer over 3.5 km Above Sea Level (ASL) (see figure 4.4). At about an hour past sunset, a shallow stable layer has formed in the valley, and the CBL is still present above the stable layer. Several hours after sunset, stability grows to 0.5 km above the valley top, but it is very weak above the valley. Seven hours after sunset, stability is present up to mountain top height. At valley top, stability is 5-10 k/km and weakens with increasing elevation. At ten hours after sunset, stability has not increased in elevation any more, but stability has strengthened.

Bader et al. (1987) explains the large effects shear has on the depth of stability. Without the shear induced turbulence, the stability was very strong but shallow, therefore, the addition of turbulence increases the depth of stability but weakens it. As the nocturnal drainage winds form in valleys beneath and the wind changes direction in the IL, the speed and direction shear relative to the

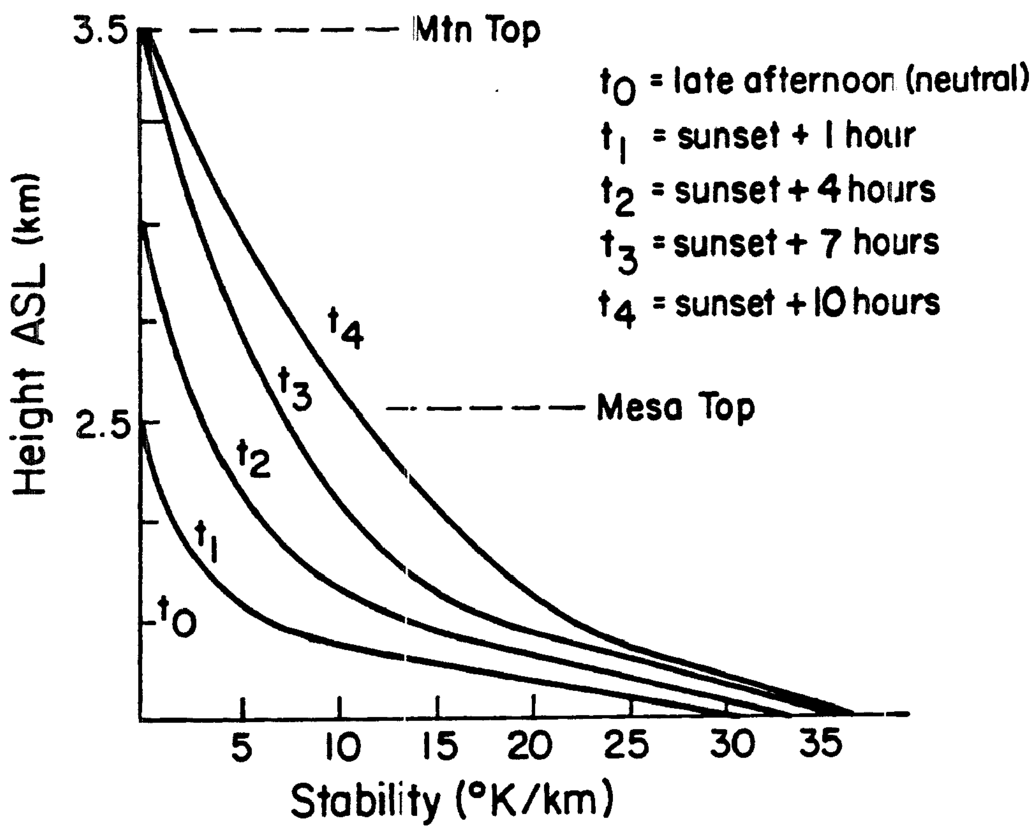

Fig. 4.4. Conceptual model of stability growth. Horizontal axis represents stability in K/km.

westerlies above provide a mechanism to increase turbulent mixing and to effectively mix cold air upward from the valleys and mesa tops into the IL. The increase of stability above the mesa tops will also increase the tendency for air west of the mountains to be blocked by the mountains.

c. evidence of blocking (Froude Number)

The amount of blocking in a region is a function of wind velocity, stability, and the height of the barrier. A representation of a barrier's capability to block is the Froude number,

$$Fr = \frac{V}{NZ} . \tag{4.9}$$

The Froude number is a ratio of kinetic energy to potential energy. This basically shows whether the wind flow has sufficient kinetic energy to compensate for the work represented by lifting the parcel a distance, ΔZ, in an environment with stability, $d\theta/dz$. The larger the Froude number, the less blocking. A small Froude number means the wind's velocity is not capable of overtaking the potential energy necessary to overcome the stability (ie. blocking). Generally a Froude number less than 0.4 means that some blocking is present. A Froude number less than 0.1 means that significant blocking is present. A Froude number greater than 0.4 means that the flow is capable of lifting over the barrier (Stull, 1988).

Calculations of the Froude number do require some initial assumptions. The layer of calculations (in this case the IL) is assumed to have a uniform wind velocity. Wind velocity is chosen carefully for IL calculations on the night of the 19th-20th.

Froude numbers for three times are given in table 4.1. The values at 16:00 MST indicate essentially no blocking for the conditions at

Table 4.1

Froude numbers on September 19-20, 1984.
Times shown are MST.

Site	16:00	22:00	1:00
Meeker	0.31	0.23	0.25
Rifle	0.39	0.30	0.23
Rangely	1.40	0.33	0.31

Rangely but some blocking is indicated at Meeker and Rifle. The Froude numbers for data times reflect the changes in wind direction which yield a smaller speed perpendicular to the mountains. Changes in the wind occur in less time than the three hours between soundings. A diurnal increase in blocking is suggested by the values (particularly at Rangely) but can not be proven with this data.

c. effects of blocking

The existence of blocking is now apparent. How does it affect the IL over western Colorado? Figure 4.5a and 4.5b are illustrations of the air flow in the afternoon and night, respectively. The air will lift over the mountain in an afternoon with a neutral environment, and nighttime stability will enhance mountain blocking.

At night, the air flowing toward the mountain becomes blocked, the air has few escapes and will continue to pile up against the mountains. This means more mass will go into the region than out. The air piling near the mountain will increase the pressure near the mountians. As a result, an east-west pressure gradient will form on a constant height surface, with higher pressure in the east. If the westerlies found in the conceptual model are present then a southeast to northwest pressure

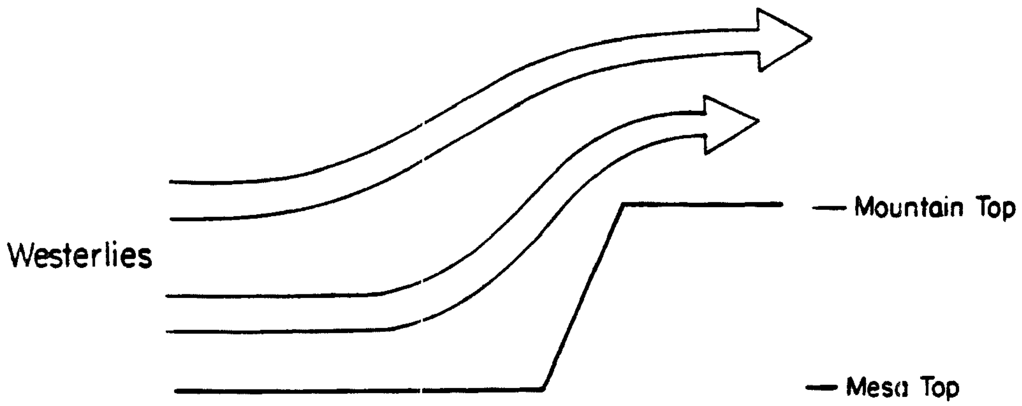

Fig. 4.5a. Schematic diagram of the wind flow lifting over the mountains in a neutral atmosphere, $d\theta/dz = 0$.

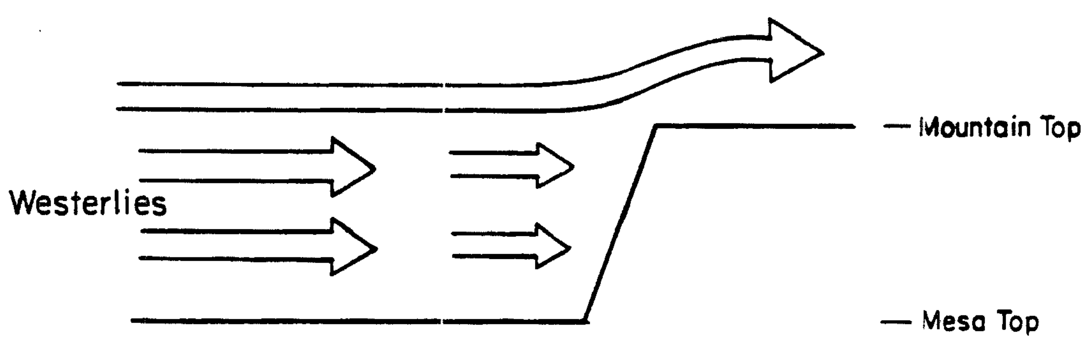

Fig. 4.5b. Schematic diagram of mountain blocking during the night when stability is present up to mountain top.

gradient will develop with the higher pressure in the southeast (see figure 4.3b). A pressure gradient of this kind, like the thermal gradient, will initiate and support the IL winds observed on the west slope of the Colorado Rockies.

3. Vertical Momentum Exchange

Meeker, Rifle, and Rangely each have a valley drainage with an easterly component, and have daytime, up-valley flows in the afternoon. During the day, no noticeable effect of wind direction is present because the westerlies will simply enhance the up-valley flow as in the conceptual model. At night, the valley drainage and westerlies have momentum in the opposite direction, and the result is an increased vertical shear of the wind. The increased shear should lead to an increased vertical mixing of the air. The result would be to mix cold air formed near the mesa tops upward to form a deeper layer of increased stability. The effect of momentum exchange on wind direction are not as obvious. Each valley shows a rapid transition of nighttime winds parallel to the valley axis at night to a southerly wind immediately above the valley.

A fourth valley which demonstrates this trait of wind direction is Brush Creek. In figure 4.6 is a wind profile from the CSU site in Brush Creek on the night of the 19th-20th. Brush Creek has a ridgetop at approximately 0.6 km Above Ground Level (AGL), and drains from the northwest to the southeast. The CSU site is located near the middle of the valley, and has an elevation approximately 1.9 km ASL. The figure shows a valley drainage up to 0.3 km AGL, 2.2 km ASL, and the air is calm up to 0.6 km AGL (2.5 km ASL). At 1:05 MST, the air above 2.5 km ASL is from the south, which is the same direction observed at Meeker,

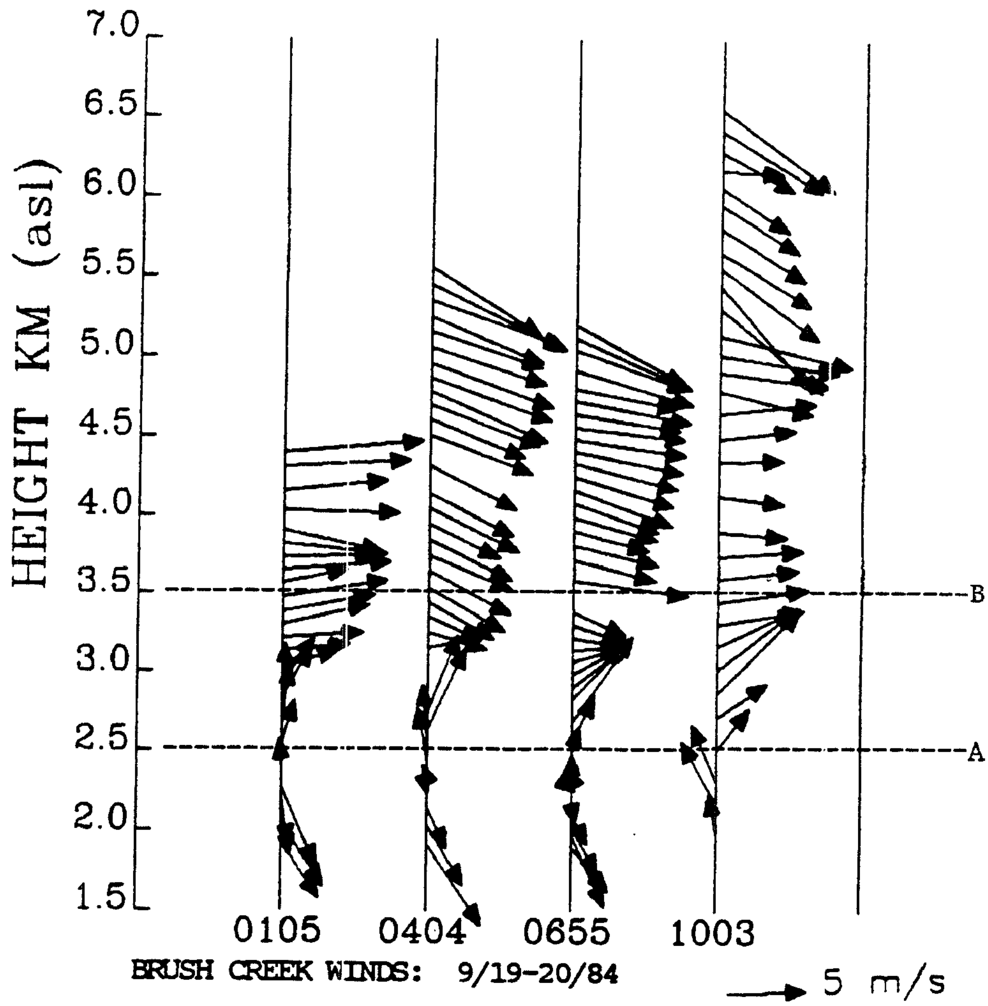

Fig. 4.6. Wind time series from the CSU site at Brush Creek on 19-20 September 1984. Brush creek has an elevation of 1850m ASL. Sunset is at 18:18 MST and sunrise at 6:06 MST. Horizontal axis represents sounding times in MST. Wind vectors point in the direction the wind is going with north being the top of the graph. Line A and B represent mesa top and mountain top heights, respectively.

Rifle, and Rangely. The valley is draining in a direction that should enhance the westerlies.

Using Brush Creek as an example along with the other sites, the wind direction observed in the IL is not consistent with a vertical momentum exchange.

CHAPTER V

CONCLUSIONS

The west slope of the Colorado Rockies has topographical features consisting of mesas in the western portion and high mountainous terrain in the eastern portion. Observations from this region show the existence of an intermediate layer exhibiting diurnal variations in both wind and thermal structure. This intermediate layer is a vertical layer above mesa top height and below mountain top height, 2.5 km to 3.5 km above sea level. As the night progresses, the intermediate layer's westerly flow of the late afternoon changes to winds increasing in velocity and rotating in a clockwise direction with increasing height.

The first of two physical mechanisms which can explain the existence of this diurnal variation in the wind structure observed in the intermediate layer is the development of an east to west thermal gradient. In an evening with clear, dry conditions, the air within the intermediate layer nearer to the high terrain will cool more relative to the air farther away. Because of this cooling process, the intermediate layer should develop a pressure gradient on a constant height surface with the higher pressure in the east near the mountains. A thermally driven circulation initiated with this cooling pattern will support the diurnal variation of the winds observed in the intermediate layer.

Deep stability growth during the night leads to a second physical mechanism explaining the existence of the wind structure's diurnal variation observed in the intermediate layer. During days with a neutral or weakly stable convective boundary layer, westerly winds have little difficulty lifting over the mountainous terrain in the eastern portion of the region. Evening stability grows well above the flat mesas adjacent to the high terrain up to approximately 3.5 km above sea level. Because of this stability, the westerly flow will have less potential to lift over the mountain barrier thus a blocking of the wind can occur. An excess of mass will develop a higher pressure near the mountains, which creates a pressure gradient within the intermediate layer. A pressure gradient of this kind, like the thermal gradient, will support the winds observed in the intermediate layer.

CHAPTER VI

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APPENDIX A

NATIONAL WEATHER SERVICE MAPS FOR ASCOT '84

This appendix contains weather maps for the the ASCOT September 1984 field experiment. Contained in the appendix are 00Z and 12Z maps for 700 mb and 500 mb. Lines of constant temperature are represent by the dashed lines at an interval of 5 C. Lines of constant thickness are represented by the solid lines at an interval of 30 m for 700 mb and 60 m for 500 mb.

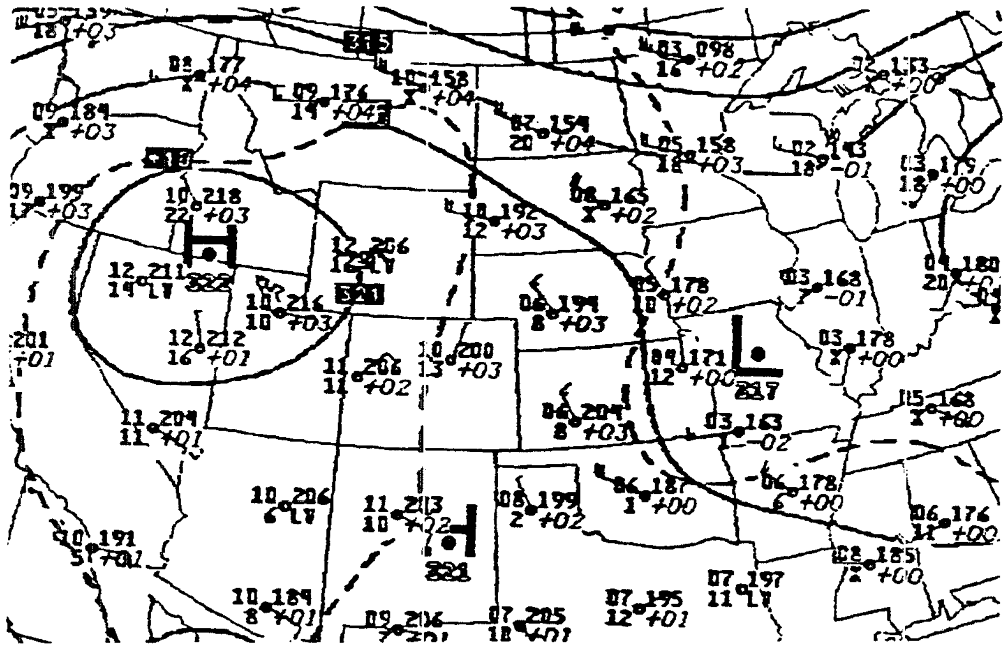

Fig. A.1. The 00Z, 700 mb NWS map for 18 September 1984.

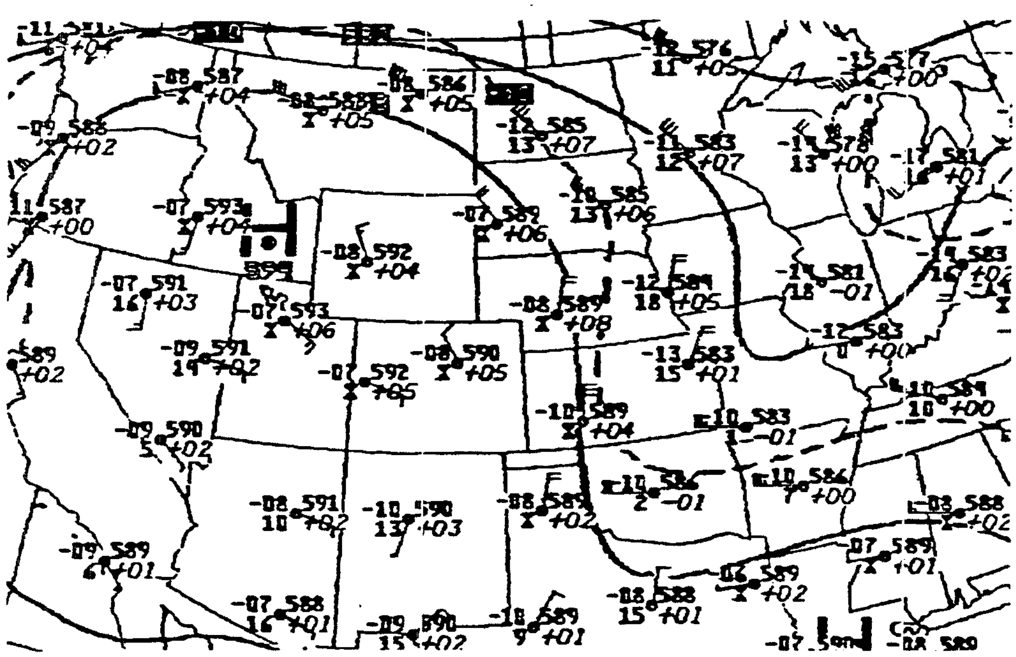

Fig. A.2. The 00Z, 500 mb NWS map for 18 September 1984.

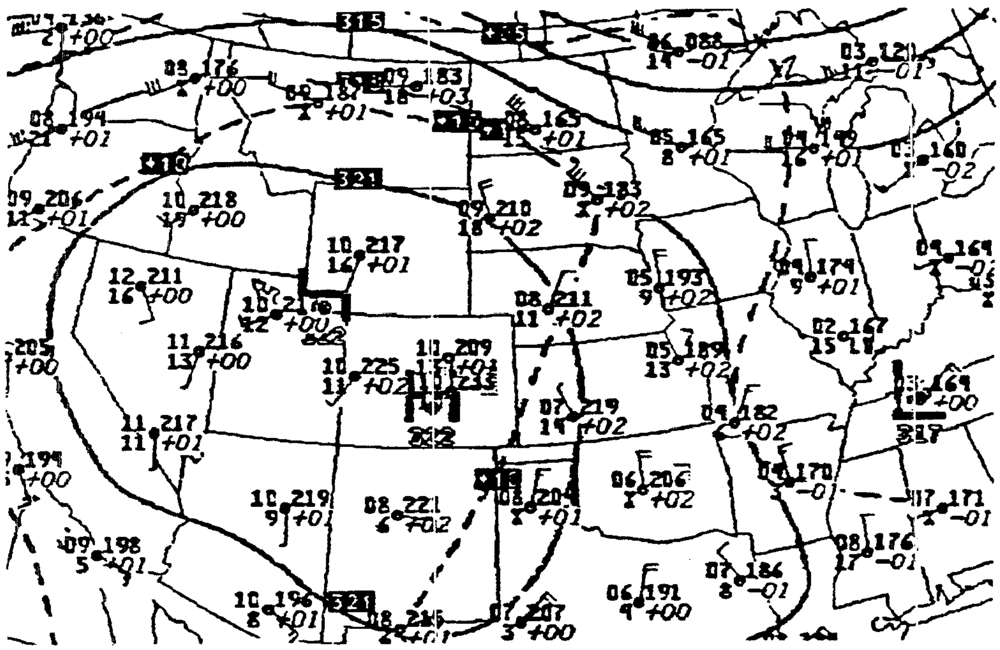

Fig. A.3. The 12Z, 700 mb NWS map for 18 September 1984.

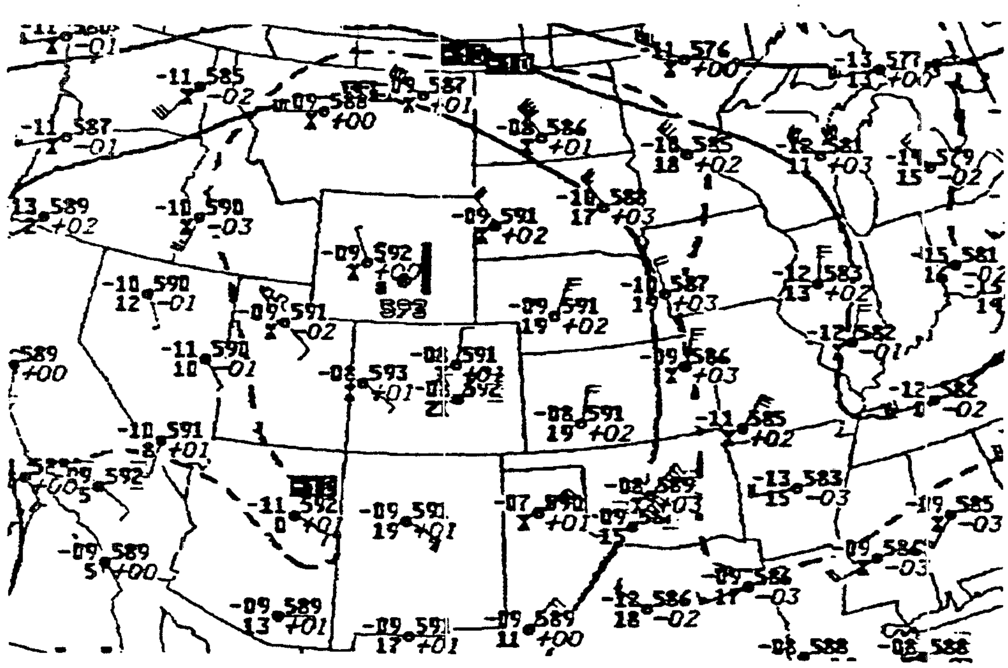

Fig. A.4. The 12Z, 500 mb NWS map for 18 September 1984.

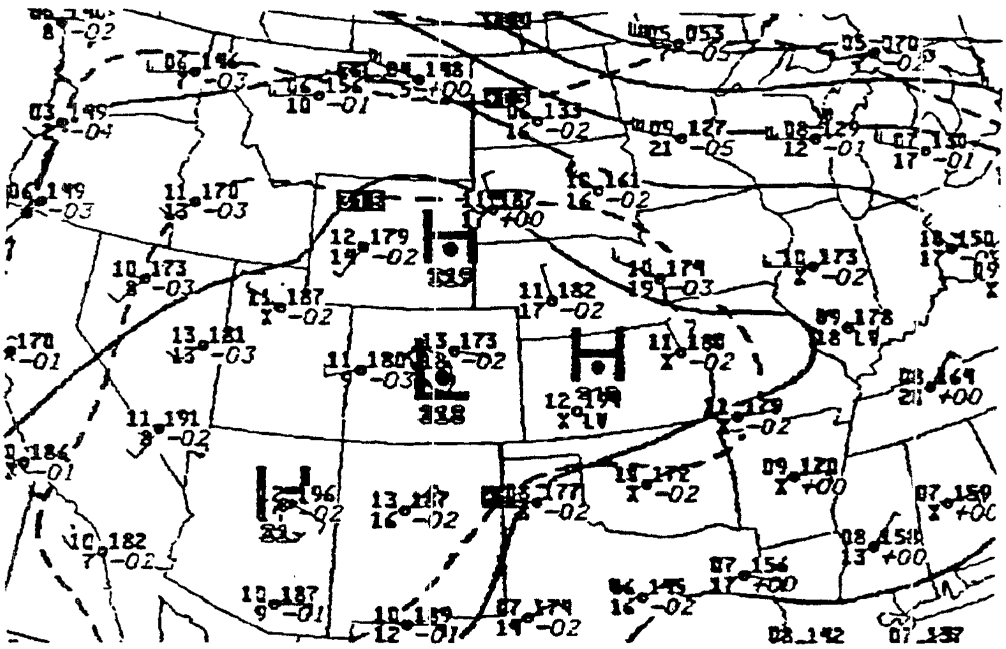

Fig. A.5. The 00Z, 700 mb NWS map for 20 September 1984.

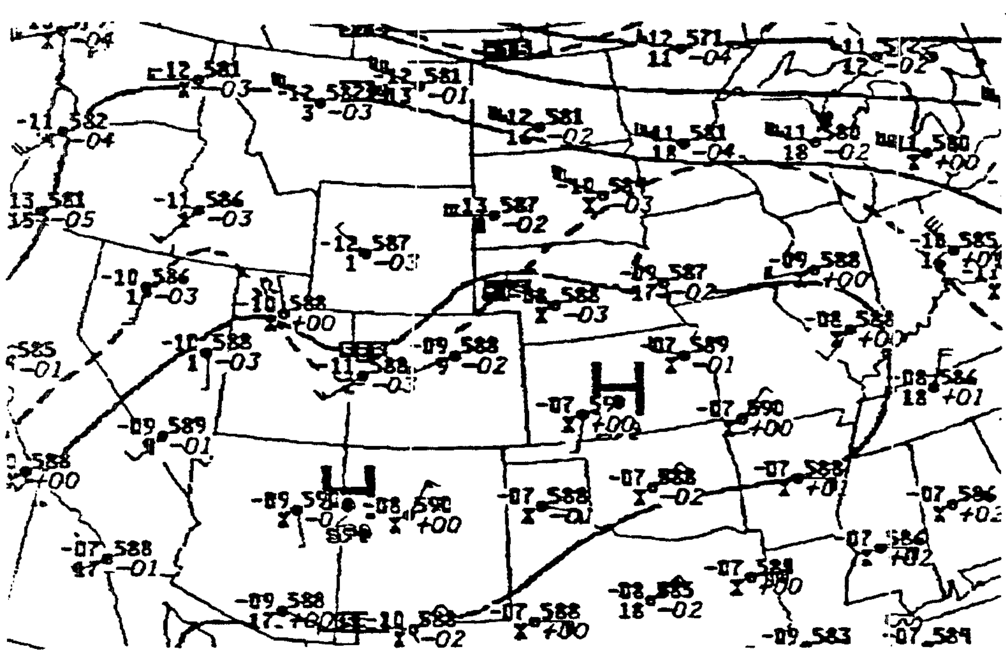

Fig. A.6. The 00Z, 500 mb NWS map for 20 September 1984.

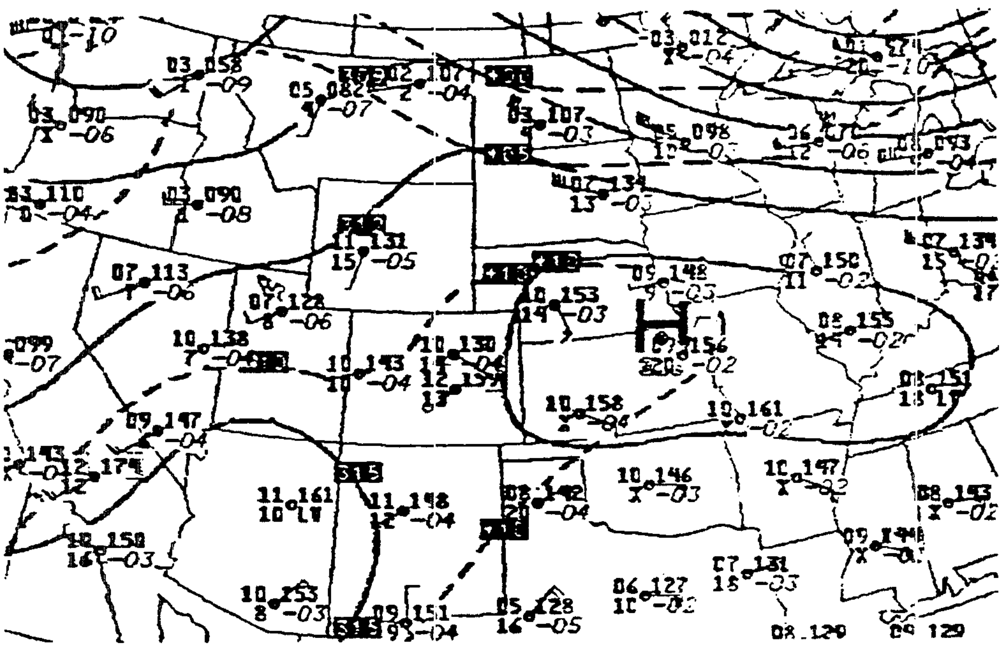

Fig. A.7. The 12Z, 700 mb NWS map for 20 September 1984.

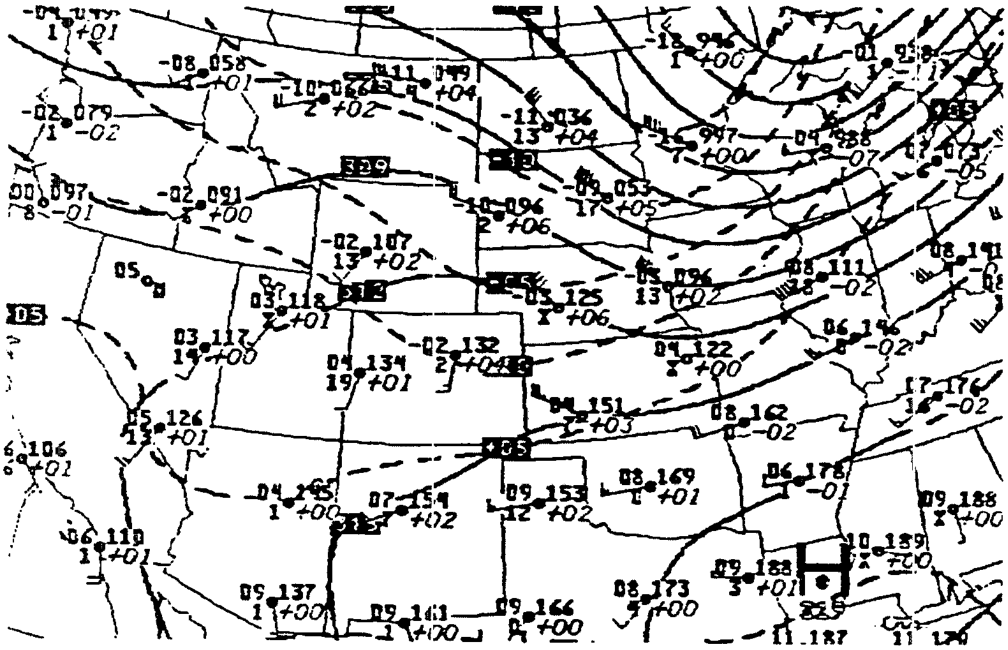

Fig. A.8. The 00Z, 700 mb NWS map for 26 September 1984.

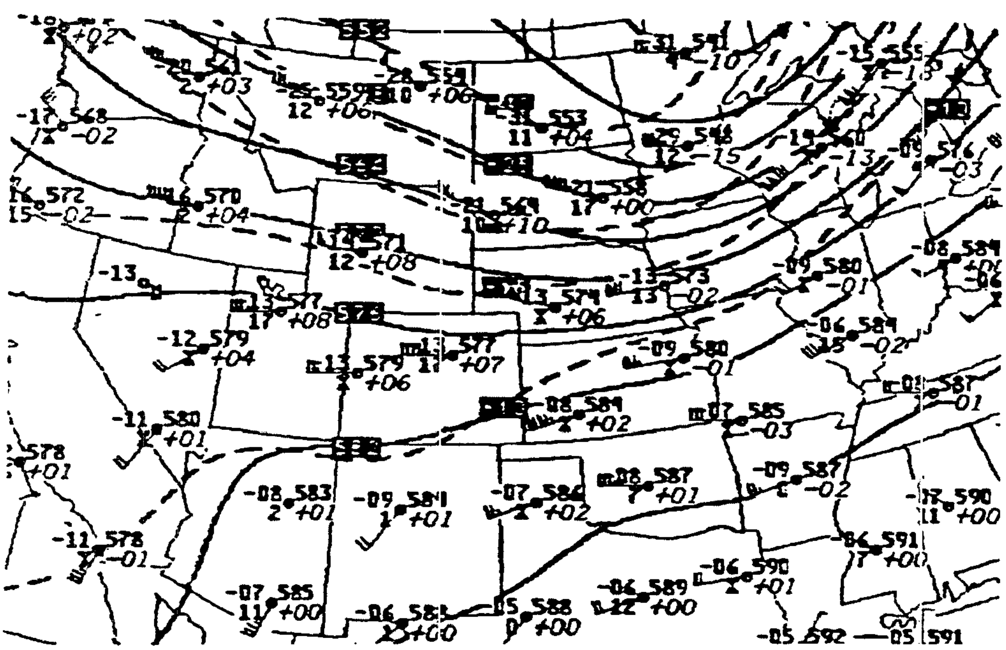

Fig. A.9. The 00Z, 500 mb NWS map for 26 September 1984.

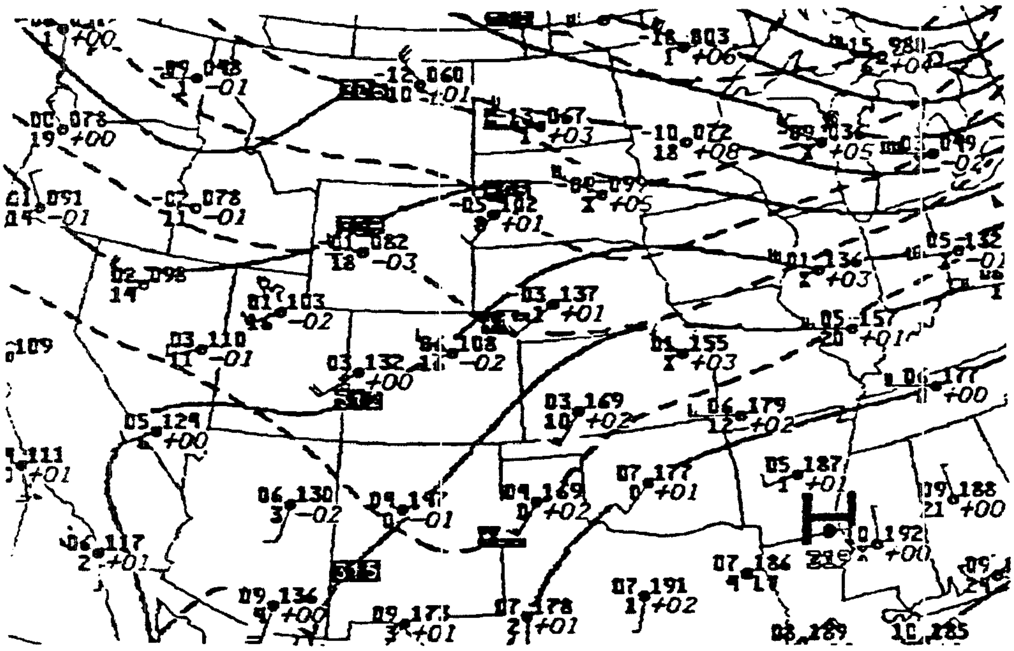

Fig. A.10. The 12Z, 700 mb NWS map for 26 September 1984.

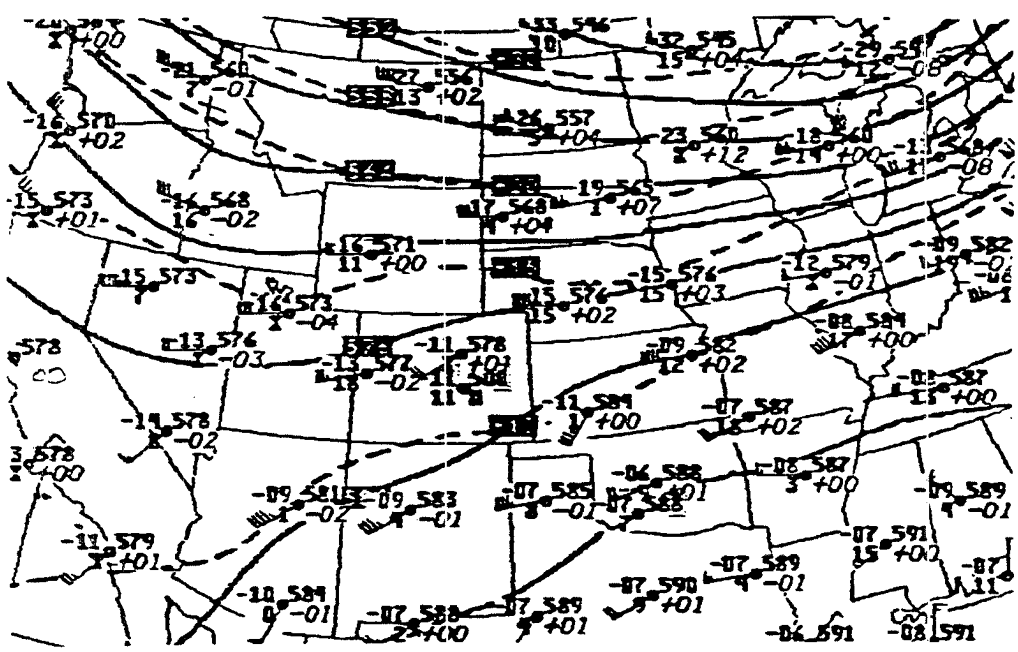

Fig. A.11. The 12Z, 500 mb NWS map for 26 September 1984.

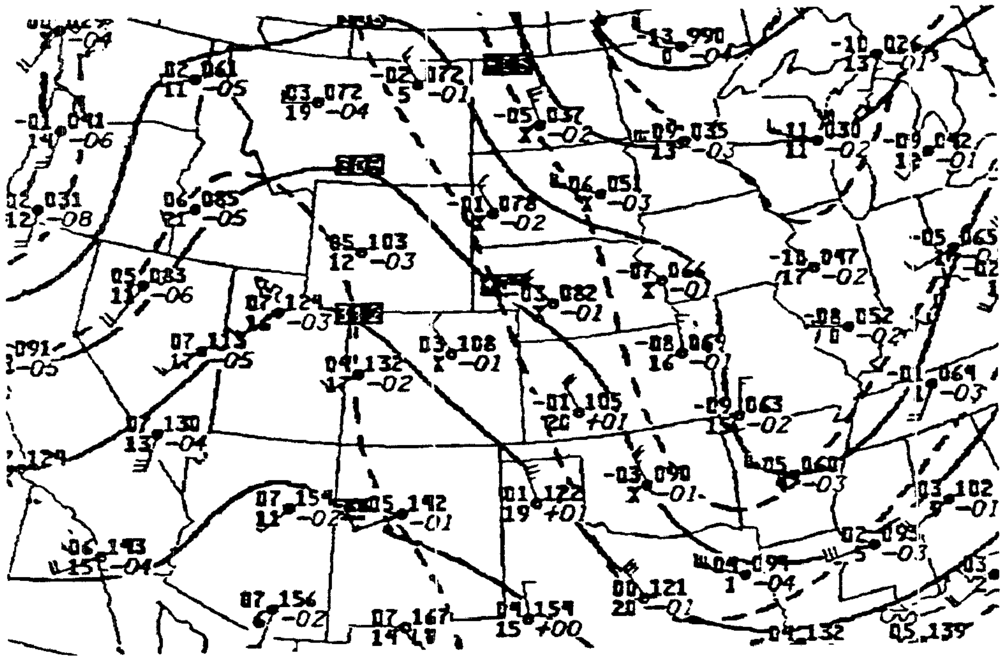

Fig. A.12. The 12Z, 700 mb NWS map for 30 September 1984.

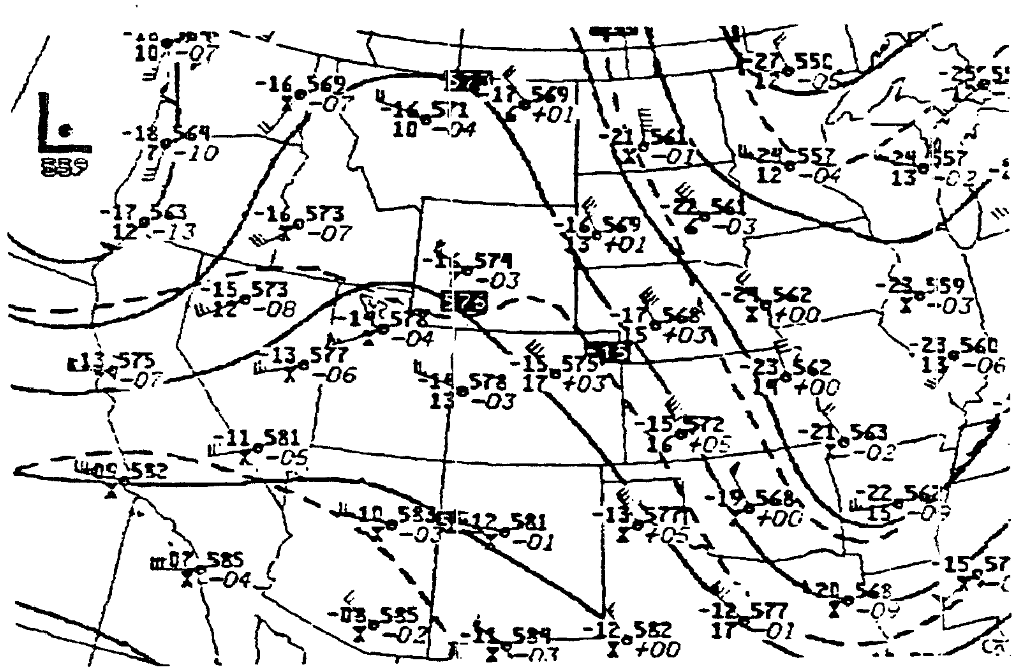

Fig. A.13. The 12Z, 500 mb NWS map for 30 September 1984.

APPENDIX B

WIND OBSERVATIONS FROM ASCOT '84 SEPTEMBER

These are wind observations taken from the upper air sounding sites during the ASCOT September 1984 field experiment. The observations are from Rifle, Meeker, and Rangely on 17-18, 25-26, 29-30 September 1984.

Fig. B.1a. Wind time series for Rifle on 17-18 September 1984. Height is in kilometers Above Sea Level (ASL), and Rifle is 1692 m ASL. Horizontal axis represents sounding times in Mountain Standard Time (MST) with sunset and sunrise at 18:19 MST and 6:00 MST, respectively. Vectors point in the direction air is going, and north is the top of the graph. Lines A and B represent mesa top and mountain top heights, respectively.

Fig. B.1b. Same as figure B.1a except it is for Meeker, which has an elevation of 1947 m ASL.

Fig. B.1c. Same as figure B.1a except it is for Rangely, which has an elevation of 1607 m ASL, and sunset is at 18:22 MST and sunrise at 6:04 MST

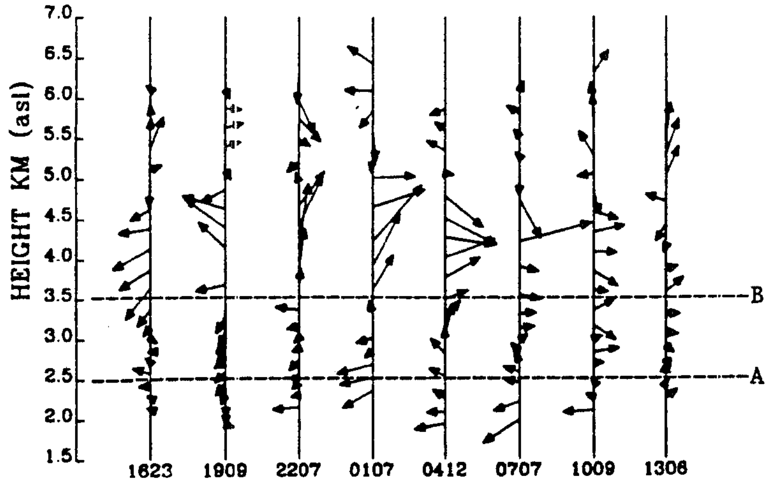

Fig. B.1a. → 5 m/s RIFLE: WIND TIME SERIES 9/17-18/84

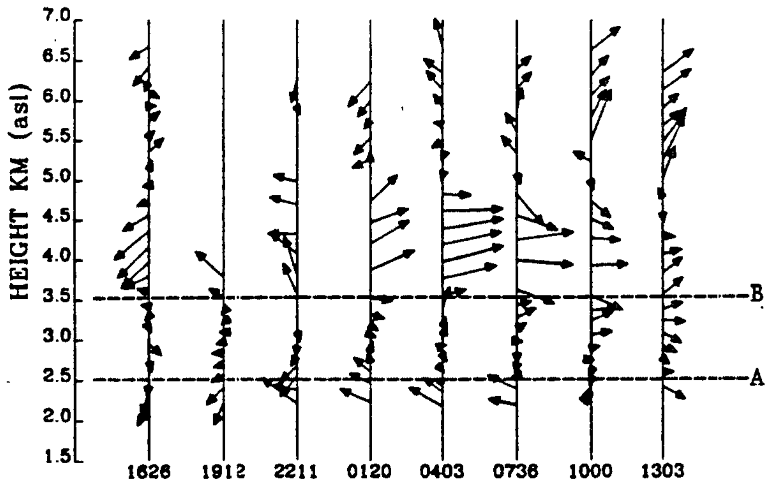

Fig. B.1b. → 5 m/s MEEKER: WIND TIME SERIES 9/17-18/84

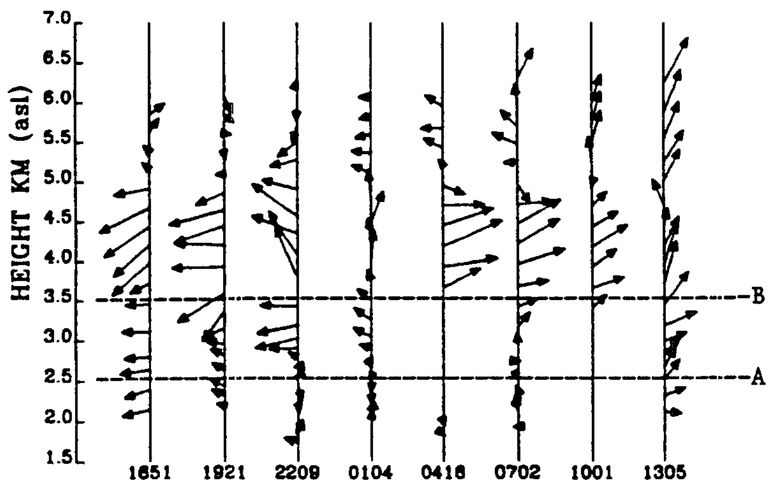

Fig. B.1c. → 5 m/s RANGELY: WIND TIME SERIES 9/17-18/84

Fig. B.2a. Wind time series for Rifle on 25-26 September 1984. Height is in kilometers Above Sea Level (ASL), and Rifle is 1692 m ASL. Horizontal axis represents sounding times in Mountain Standard Time (MST) with sunset and sunrise at 18:02 MST and 6:05 MST, respectively. Vectors point in the direction air is going, and north is the top of the graph. Lines A and B represent mesa top and mountain top heights, respectively.

Fig. B.2b. Same as figure B.2a except it is for Meeker, which has an elevation of 1947 m ASL.

Fig. B.2c. Same as figure B.2a except it is for Rangely, which has an elevation of 1607 m ASL, and sunset is at 18:06 MST and sunrise at 6:09 MST

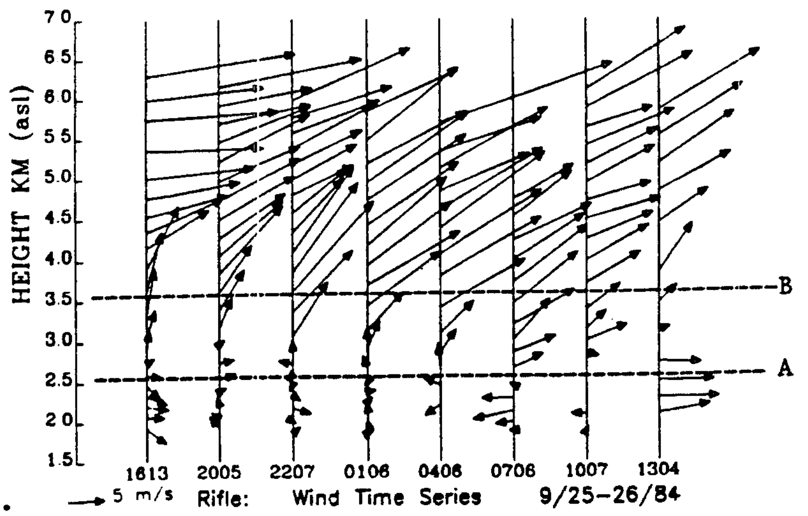

Fig. B.2a.

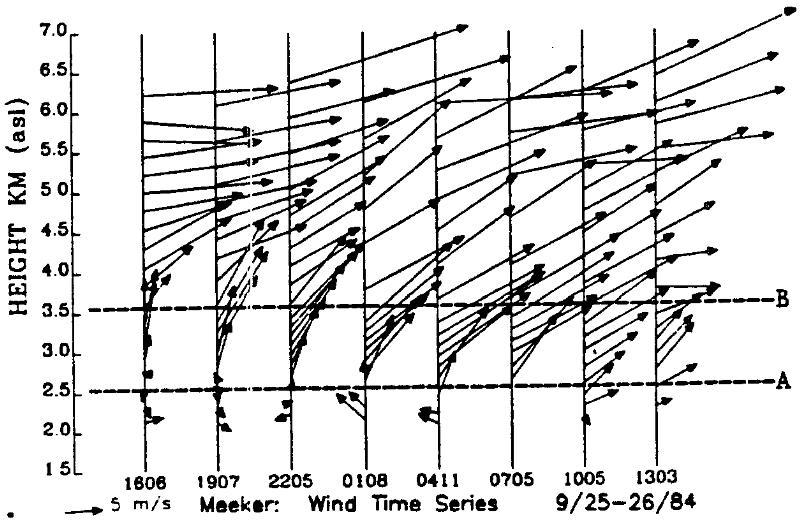

Fig. B.2b.

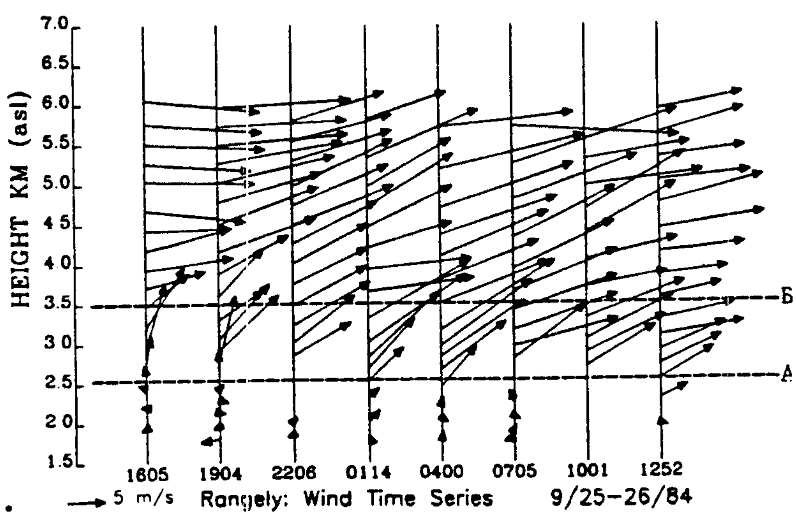

Fig. B.2c.

Fig. B.3a. Wind time series for Rifle on 29-30 September 1984. Height is in kilometers Above Sea Level (ASL), and Rifle is 1692 m ASL. Horizontal axis represents sounding times in Mountain Standard Time (MST) with sunset and sunrise at 17:56 MST and 6:09 MST, respectively. Vectors point in the direction air is going, and north is the top of the graph. Lines A and B represent mesa top and mountain top heights, respectively.

Fig. B.3b. Same as figure B.3a except it is for Meeker, which has an elevation of 1947 m ASL.

Fig. B.3c. Same as figure B.3a except it is for Rangely, which has an elevation of 1607 m ASL, and sunset is at 17:59 MST and sunrise at 6:13 MST

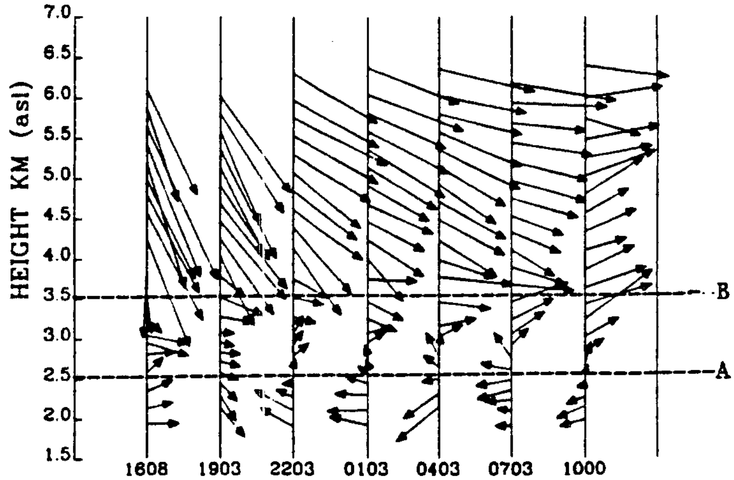

Fig. B.3a. Rifle: Wind Time Series 9/29-30/84

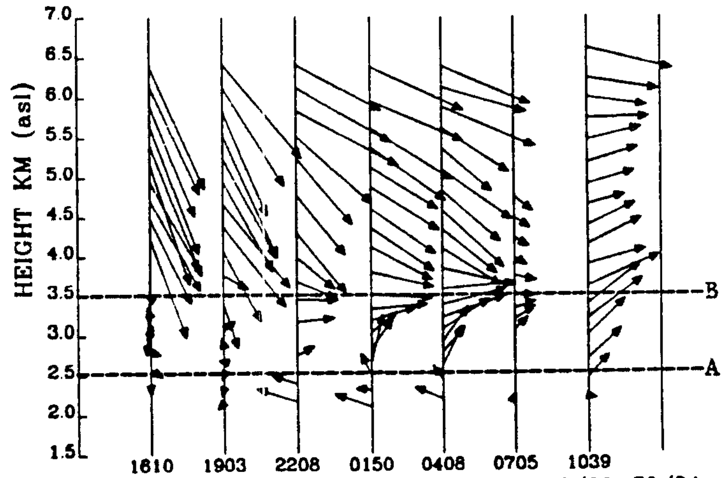

Fig. B.3b. Meeker: Wind Time Series 9/29-30/84

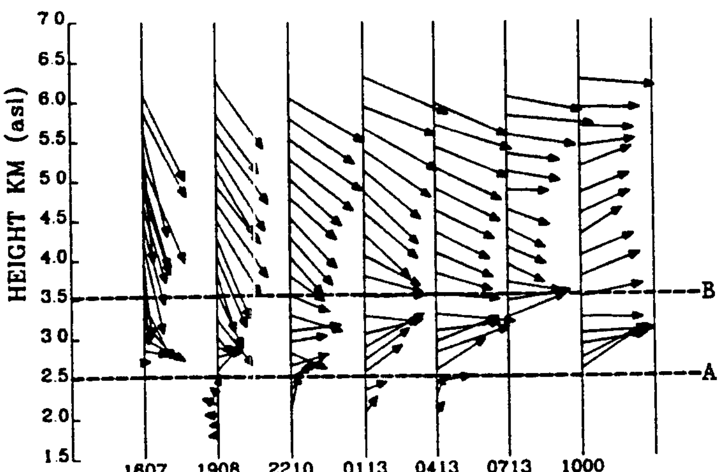

Fig. B.3c. Rangely: Wind Time Series 9/29-30/84

APPENDIX C

POTENTIAL TEMPERATURE PLOTS FROM ASCOT '84

These are potential temperature plots from the upper air sounding sites during the ASCOT September 1984 field experiment. The observations are from Rifle, Meeker, and Rangely on 17-18, 25-26, 29-30 September 1984. Each night has three separate graphs from each site. Each graph contains only three soundings in order to alleviate sloppiness.

POTENTIAL TEMPERATURE VS. HEIGHT
RANGELY: 9/17-18/84

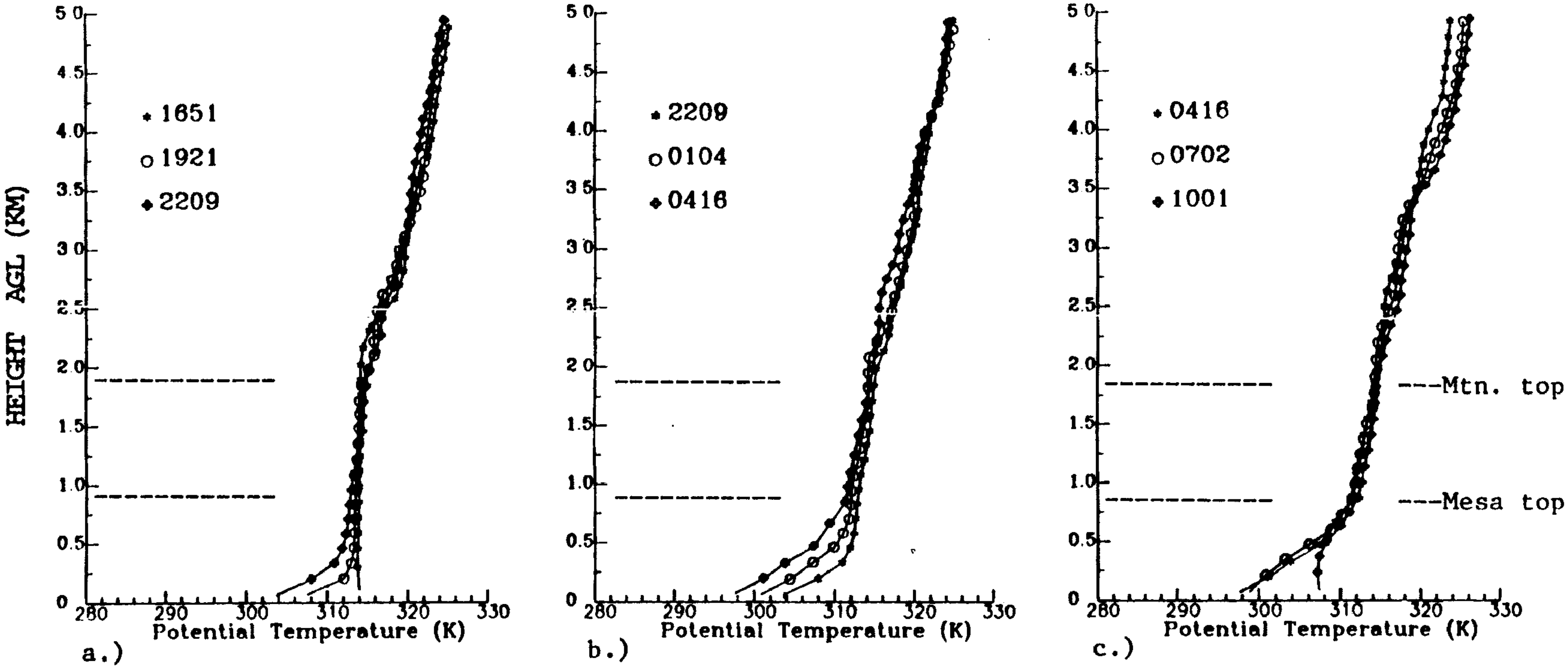

Fig. C.1(a-c). Potential temperature plots on 17-18 September 1984 for Rangley with an elevation of 1607 m ASL. Sunset and sunrise are at 18:22 and 6:04 MST, respectively. All soundings are in MST.

POTENTIAL TEMPERATURE VS. HEIGHT
MEEKER: 9/17-18/84

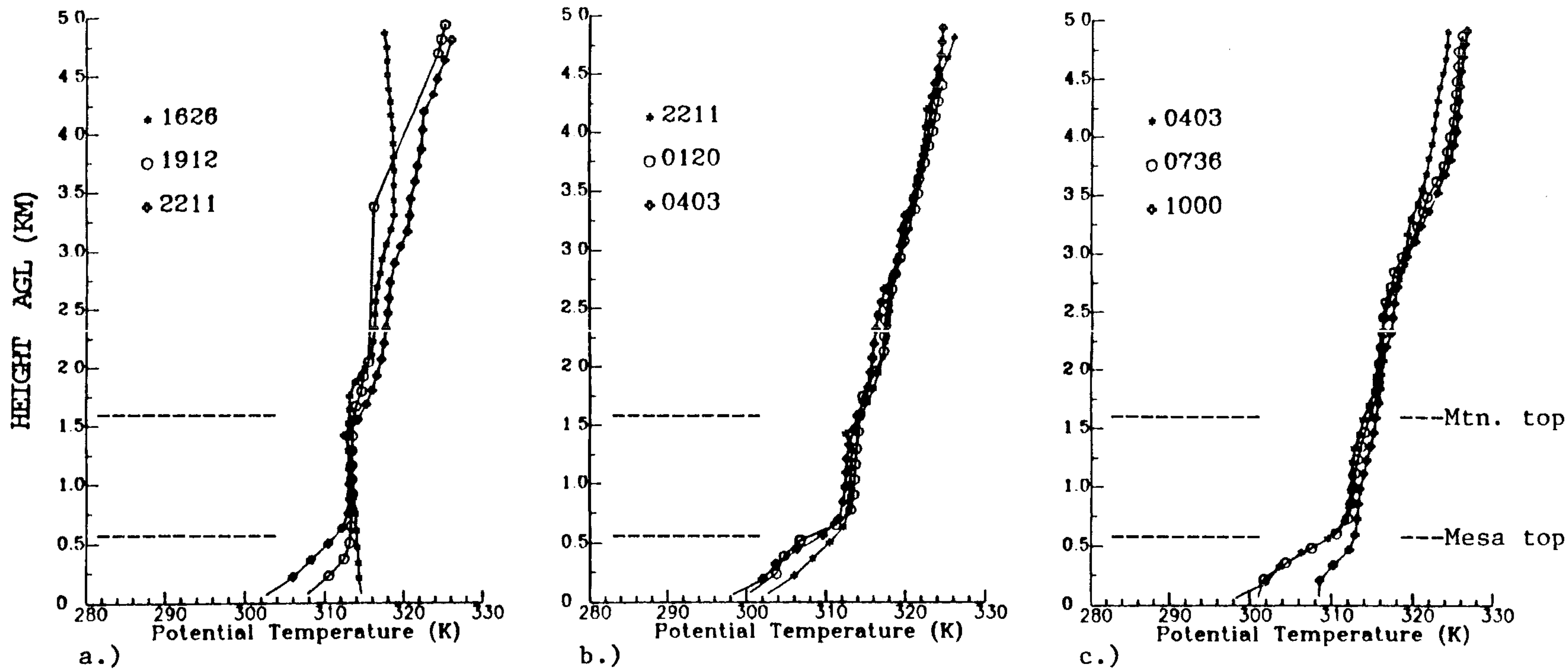

Fig. C.2(a-c). Potential temperatures on 17-18 September 1984 for Meeker. Meeker has an elevation of 1947 m ASL, with sunset and sunrise at 18:19 and 6:00 MST, respectively. All soundings are in MST.

POTENTIAL TEMPERATURE VS. HEIGHT
RIFLE: 9/17-18/84

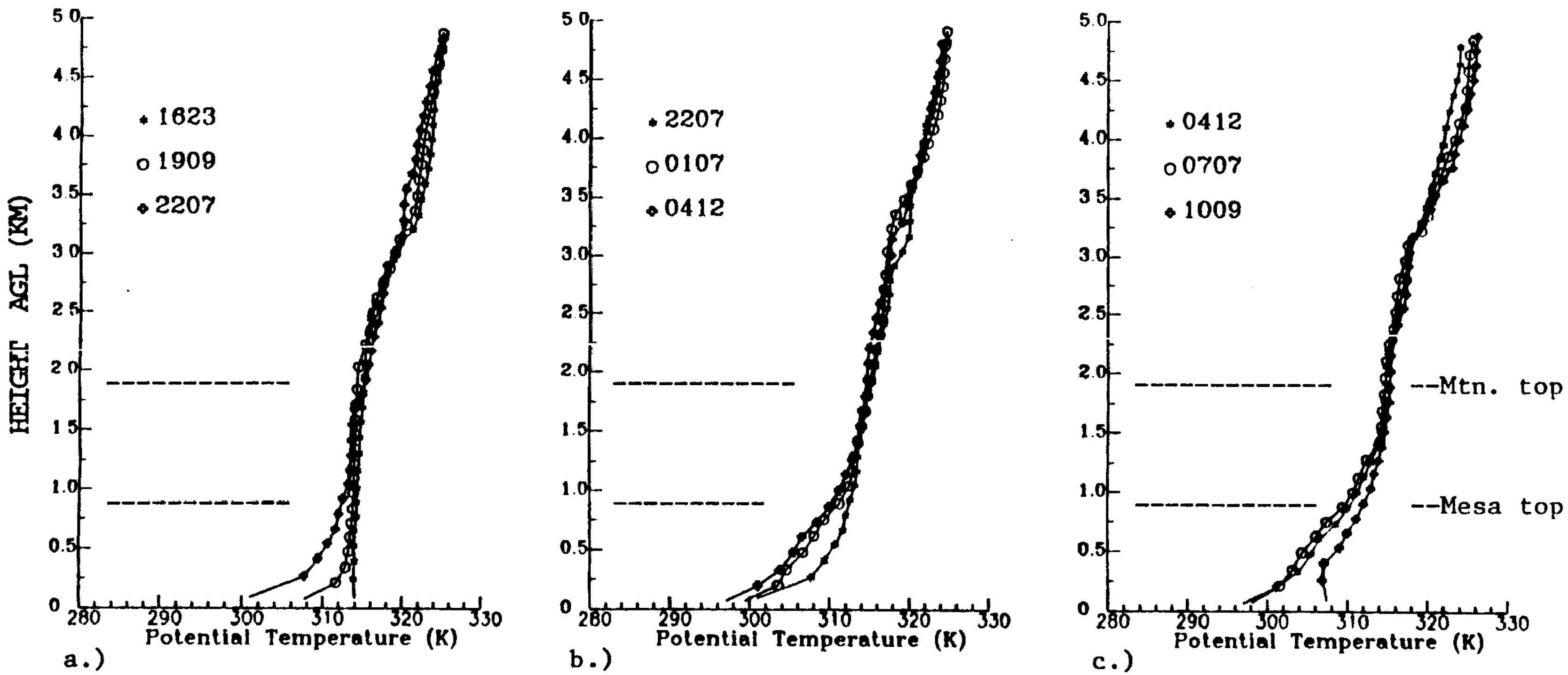

Fig. C.3(a-c). Potential temperatures on 17-18 September 1984 for Rifle. Rifle has an elevation of 1692 m ASL, with sunset and sunrise at 18:19 and 6:00 MST, respectively. All soundings are in MST.

POTENTIAL TEMPERATURE VS. HEIGHT
RANGELY: 9/25-26/84

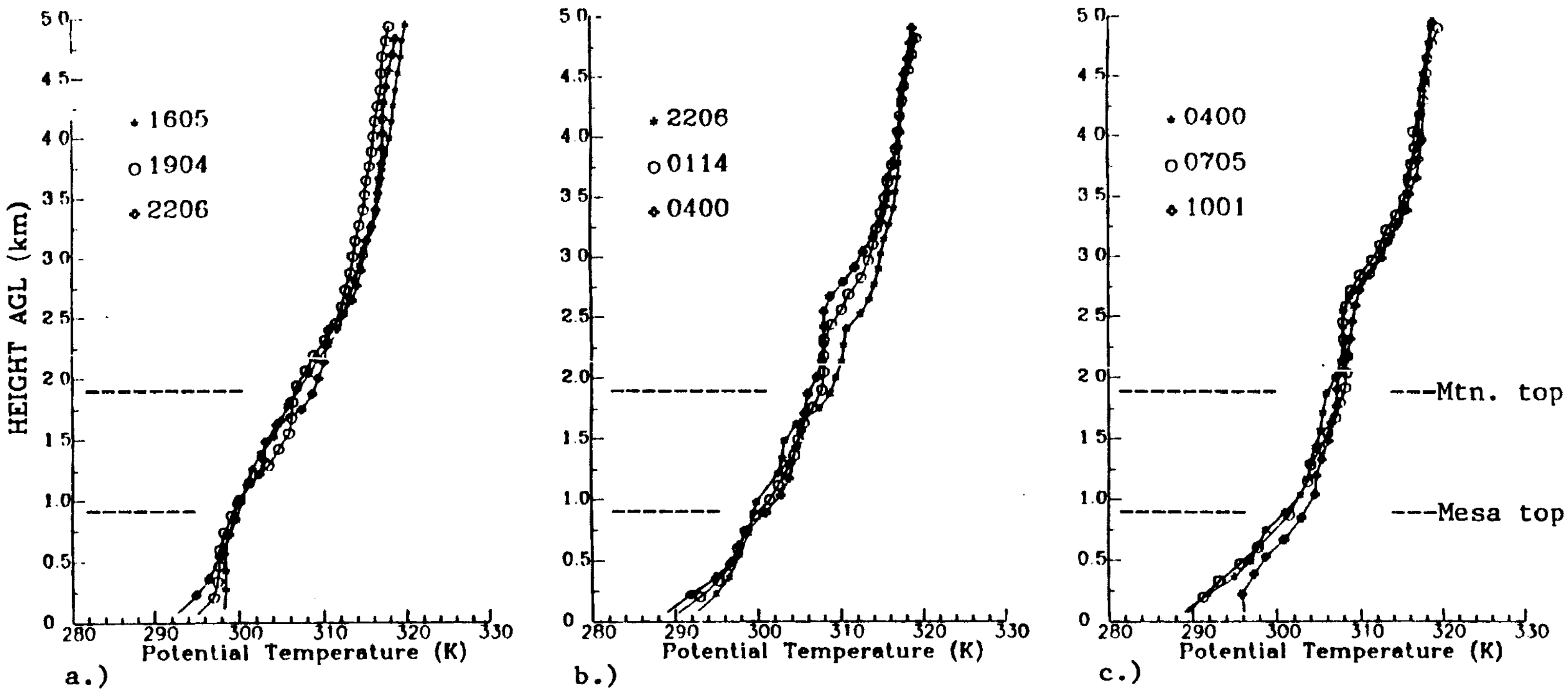

Fig. C.4(a-c). Potential temperature plots on 25-26 September 1984 for Rangley with an elevation of 1607 m ASL. Sunset and sunrise are at 18:06 and 6:09 MST, respectively. All soundings are in MST.

POTENTIAL TEMPERATURE VS. HEIGHT
MEEKER: 9/25-26/84

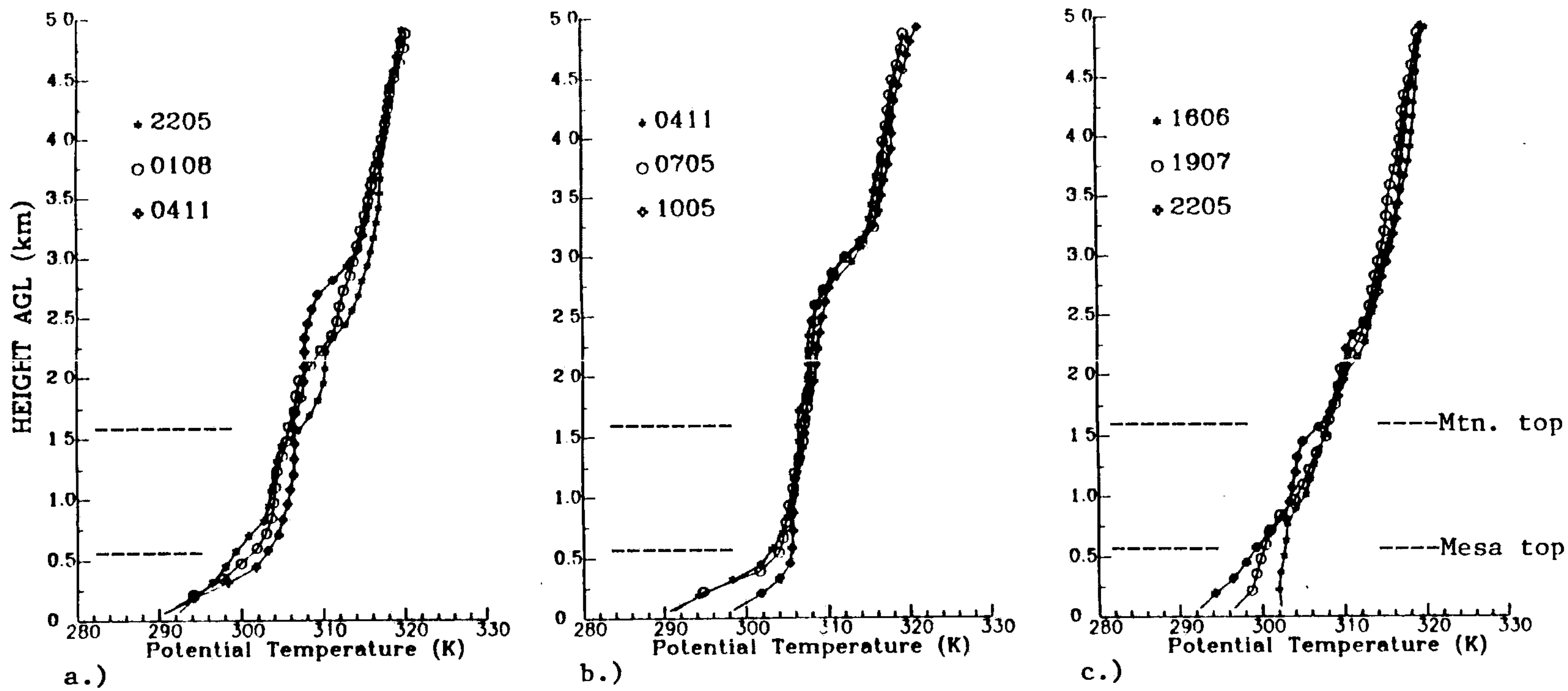

Fig. C.5(a-c). Potential temperatures on 25-26 September 1984 for Meeker. Meeker has an elevation of 1947 m ASL, with sunset and sunrise at 19:02 and 6:05 MST, respectively. All soundings are in MST.

POTENTIAL TEMPERATURE VS. HEIGHT
RIFLE: 9/25-26/84

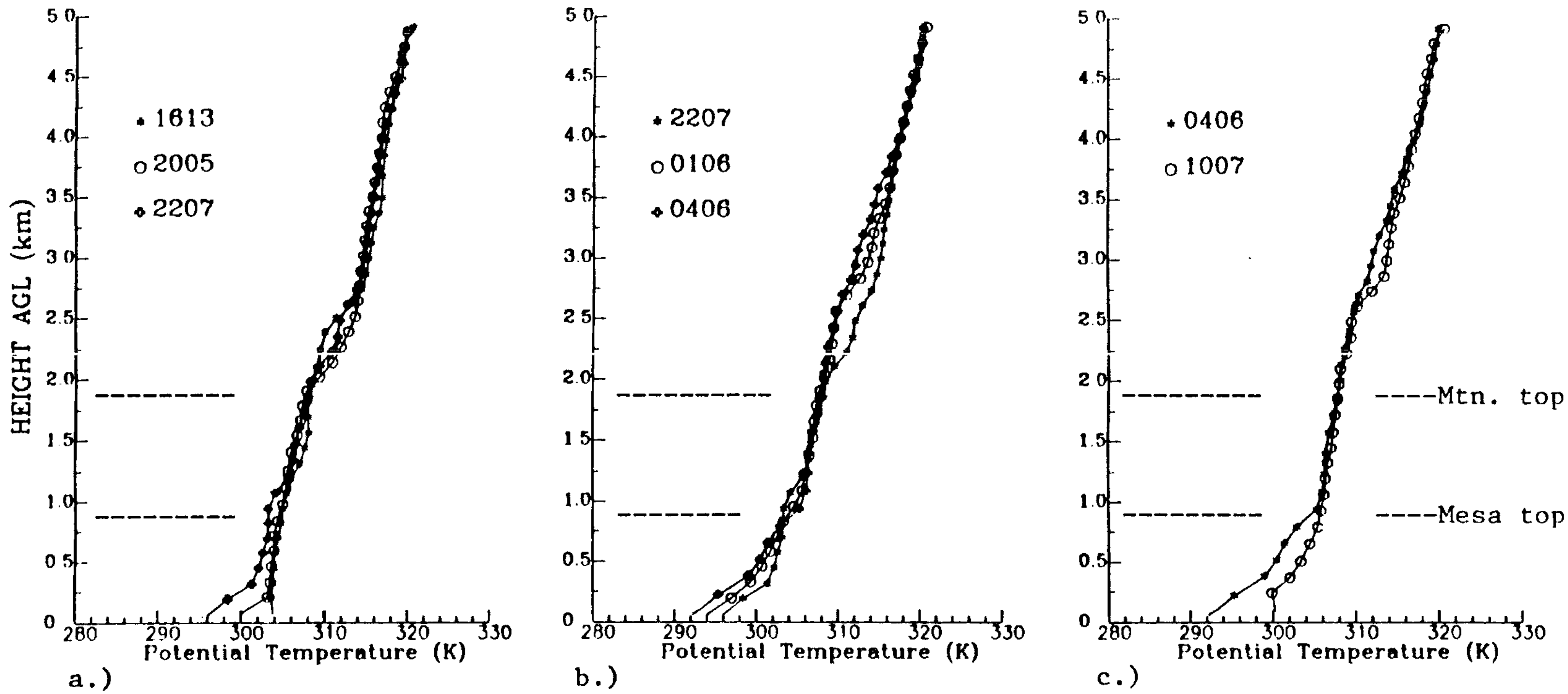

Fig. C.6(a-c). Potential temperatures on 25-26 September 1984 for Rifle. Rifle has an elevation of 1692 m ASL, with sunset and sunrise at 18:02 and 6:05 MST, respectively. All soundings are in MST.

POTENTIAL TEMPERATURE VS. HEIGHT
RANGELY: 9/29-30/84

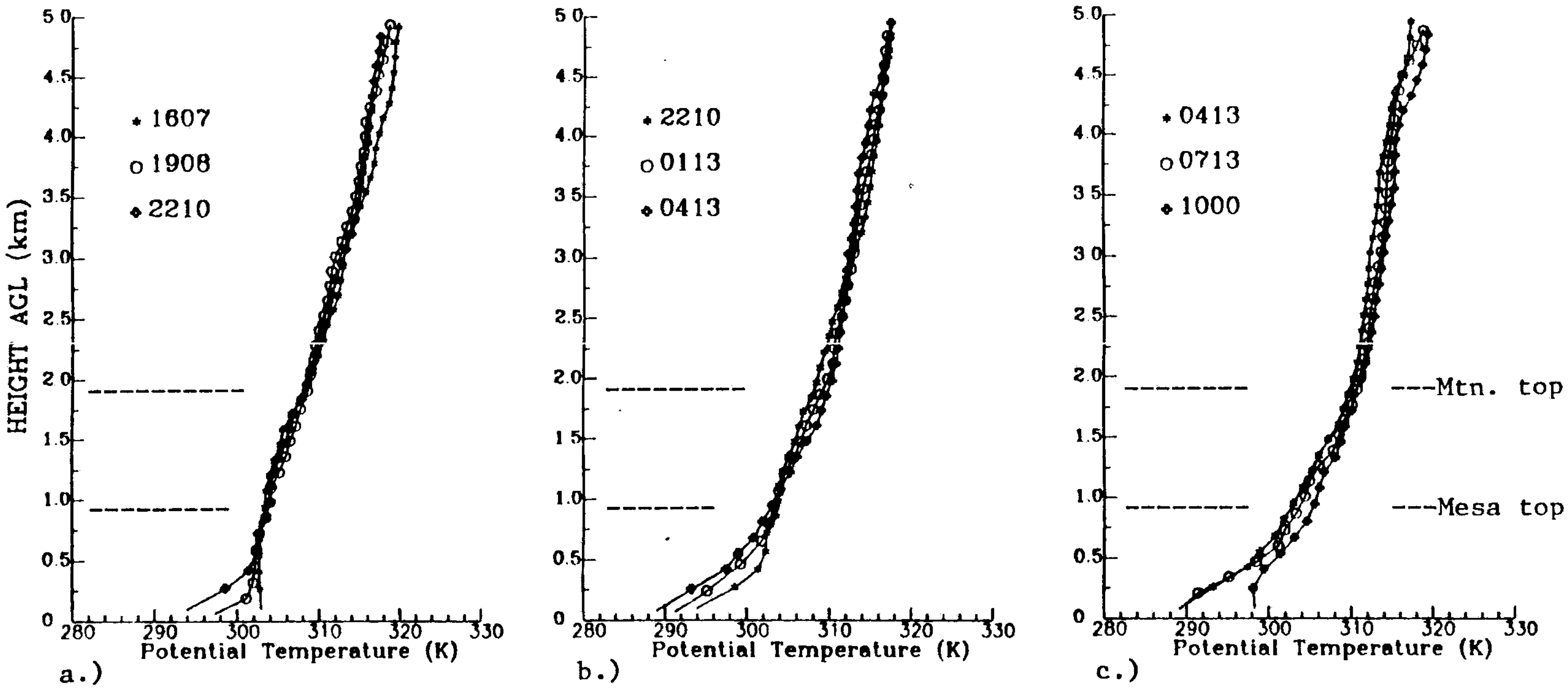

Fig. C.7(a-c). Potential temperature plots on 29-30 September 1984 for Rangley with an elevation of 1607 m ASL. Sunset and sunrise are at 17:59 and 6:13 MST, respectively. All soundings are in MST.

POTENTIAL TEMPERATURE VS. HEIGHT
MEEKER: 9/29-30/84

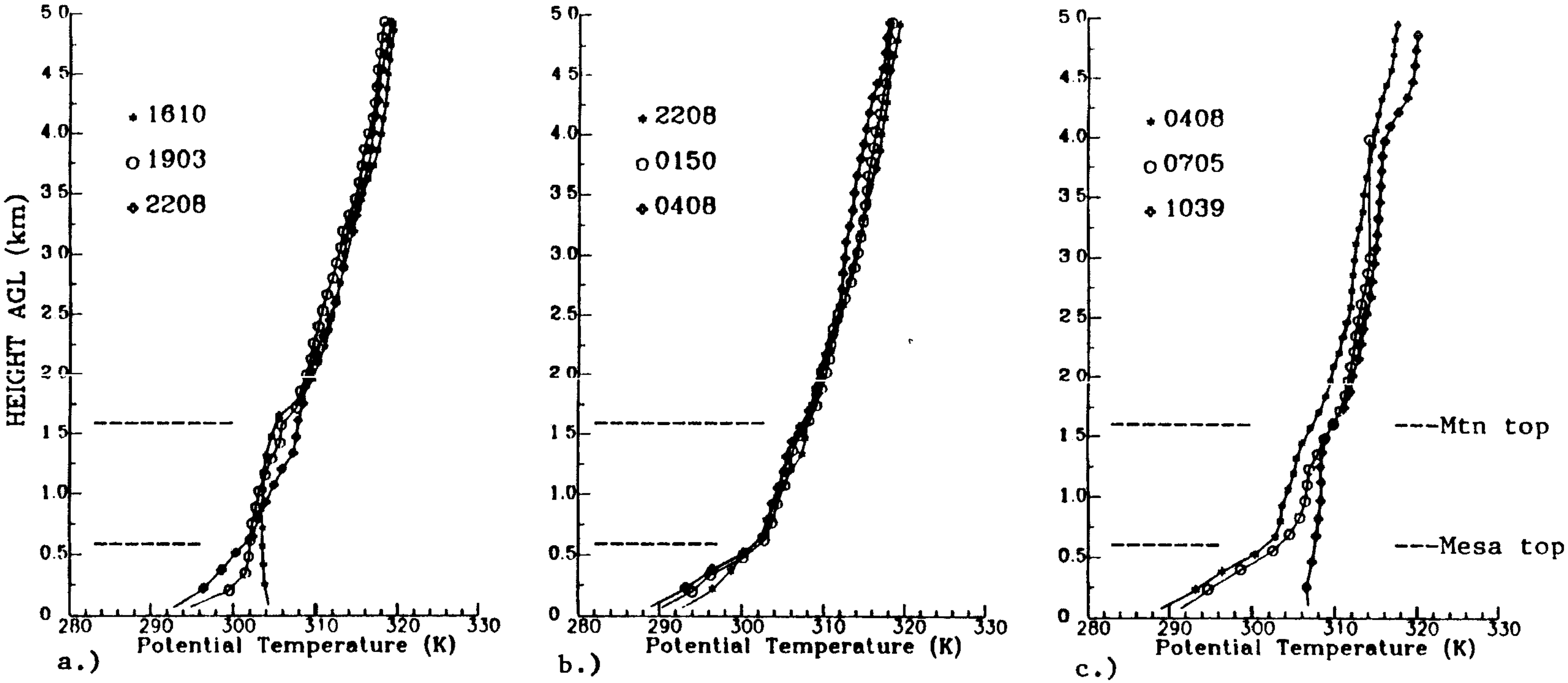

Fig. C.8(a-c). Potential temperatures on 29-30 September 1984 for Meeker. Meeker has an elevation of 1947 m ASL, with sunset and sunrise at 17:56 and 6:09 MST, respectively. All soundings are in MST.

POTENTIAL TEMPERATURE VS. HEIGHT
RIFLE: 9/29-30/84

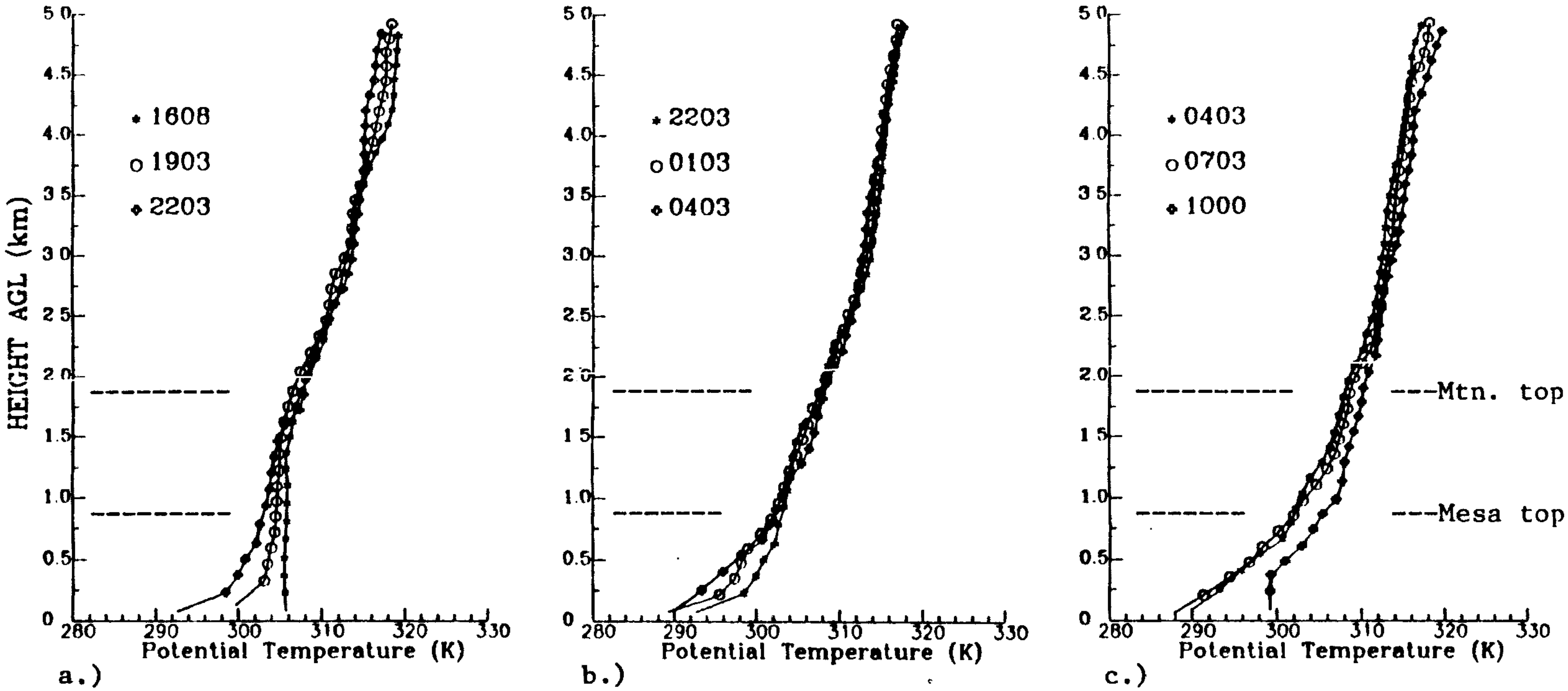

Fig. C.9(a-c). Potential temperatures on 29-30 September 1984 for Rifle. Rifle has an elevation of 1692 m ASL, with sunset and sunrise at 17:56 and 6:09 MST, respectively. All soundings are in MST.

APPENDIX D

STABILITY PLOTS FROM ASCOT '84

These are stability plots from the upper air sounding sites during the ASCOT September 1984 field experiment. The observations are from Rifle, Meeker, and Rangley, on 17-18, 25-26, 29-30 September 1984.

Fig. D.1a. Change of potential temperature with height for Rifle on 19-20 September 1984. Height is in kilometers Above Sea Level (ASL) with Rifle at 1692 m ASL. Horizontal axis represents soundings in MST and stability. Rifle has sunset and sunrise at 18:19 MST and 6:09 MST, respectively. Lines A and B represent mesa top and mountain top heights, respectively.

Fig. D.1b. Same as figure D.1a except for Meeker, which has an elevation at 1947 m ASL.

Fig. D.1c. Same as figure D.1a except for Rangely, which has an elevation of 1607 m ASL. Sunset and sunrise are at 18:22 and 6:04 MST, respectively.

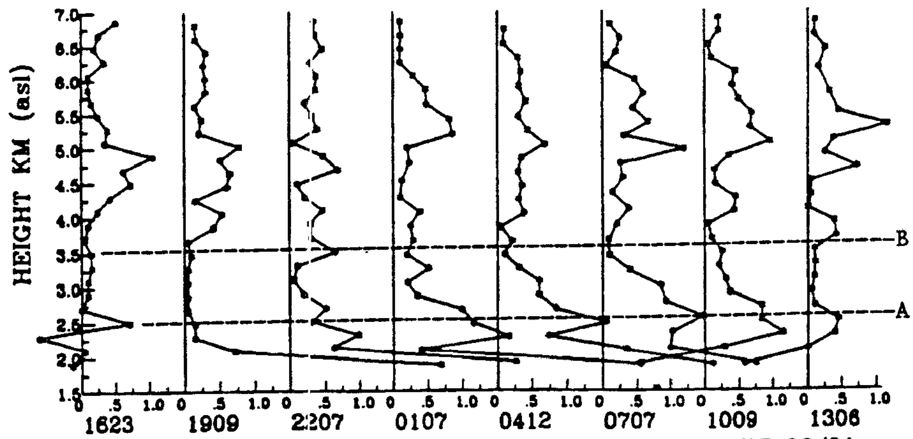

Fig. D.1a. RIFLE: Dθ/DZ (C/ 0.1KM) TIME SERIES 9/17-18/84

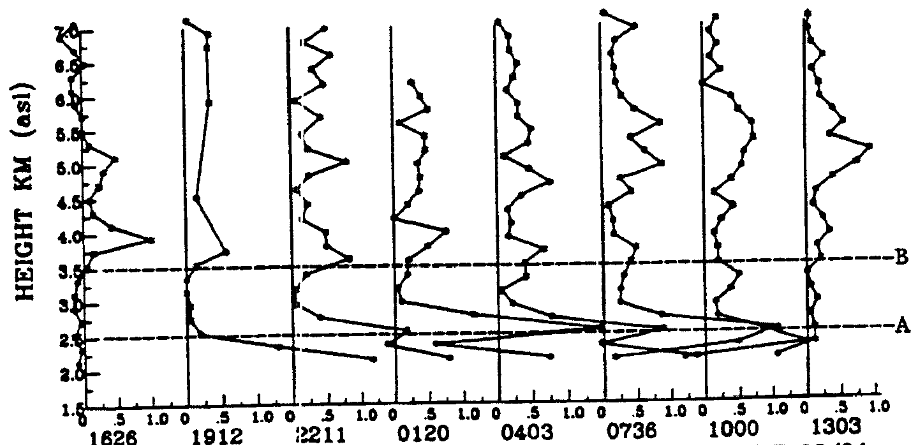

Fig. D.1b. MEEKER: Dθ/DZ (C/ 0.1KM) TIME SERIES 9/17-18/84

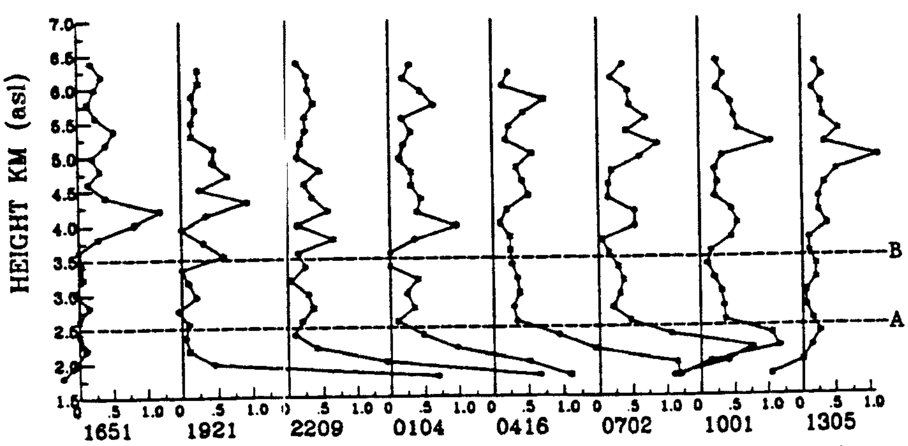

Fig. D.1c. RANGELY: Dθ/DZ (C/ 0.1KM) TIME SERIES 9/17-18/84

Fig. D.2a. Change of potential temperature with height for Rifle on 25-26 September 1984. Height is in kilometers Above Sea Level (ASL) with Rifle at 1692 m ASL. Horizontal axis represents soundings in MST and stability. Rifle has sunset and sunrise at 18:02 MST and 6:05 MST, respectively. Lines A and B represent mesa top and mountain top heights, respectively.

Fig. D.2b. Same as figure D.2a except for Meeker, which has an elevation at 1947 m ASL.

Fig. D.2c. Same as figure D.1a except for Rangely, which has an elevation of 1607 m ASL. Sunset and sunrise are at 18:06 and 6:09 MST, respectively.

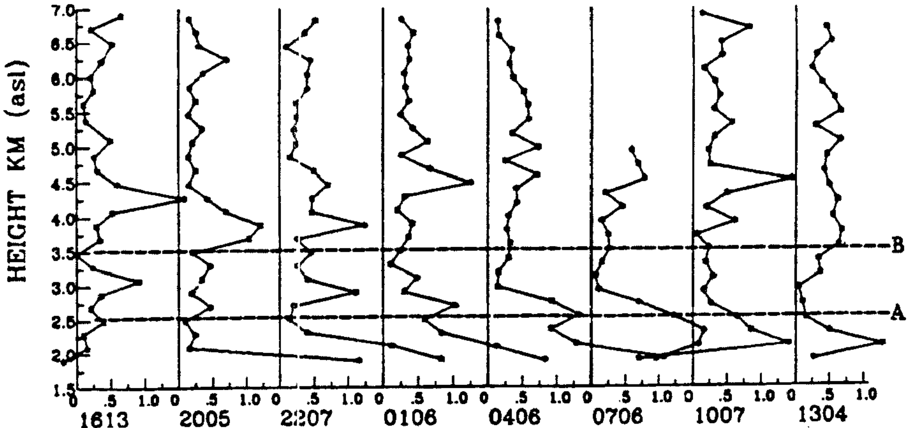

Fig. D.2a. Rifle: DΘ/DZ (C/ .1km) Time Series 9/25-26/84

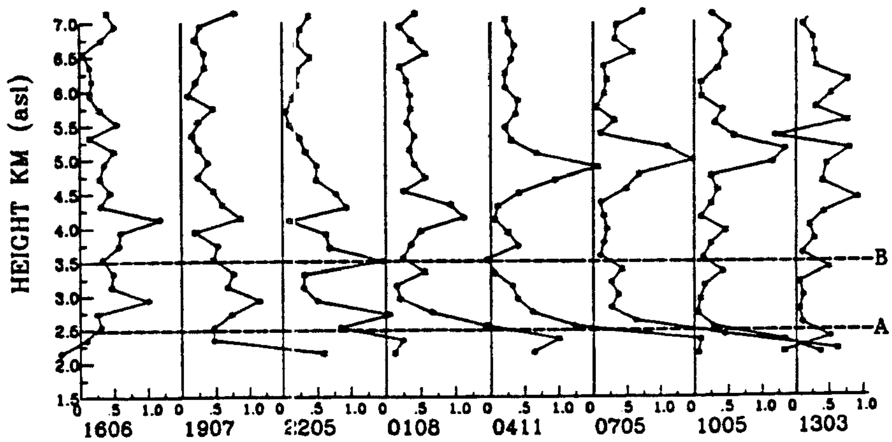

Fig. D.2b. Meeker: DΘ/DZ (C/ .1km) Time Series 9/25-26/84

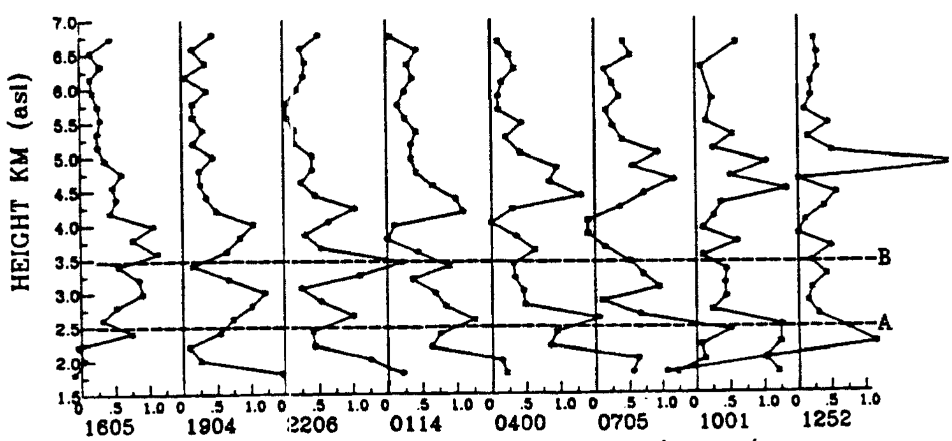

Fig. D.2c. Rangely: DΘ/DZ (C/ .1km) Time Series 9/25-26/84

Fig. D.3a. Change of potential temperature with height for Rifle on 29-30 September 1984. Height is in kilometers Above Sea Level (ASL) with Rifle at 1692 m ASL. Horizontal axis represents soundings in MST and stability. Rifle has sunset and sunrise at 17:56 MST and 6:09 MST, respectively. Lines A and B represent mesa top and mountain top heights, respectively.

Fig. D.3b. Same as figure D.3a except for Meeker, which has an elevation at 1947 m ASL.

Fig. D.3c. Same as figure D.3a except for Rangely, which has an elevation of 1607 m ASL. Sunset and sunrise are at 17:59 and 6:13 MST, respectively.

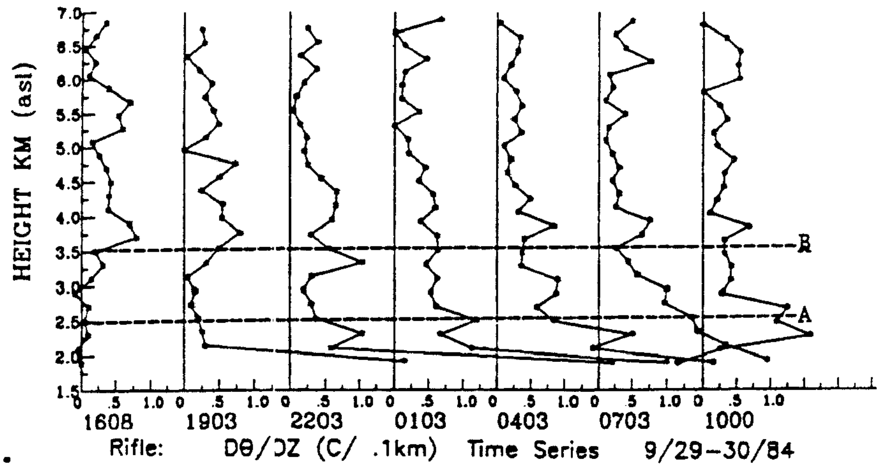

Fig. D.3a.

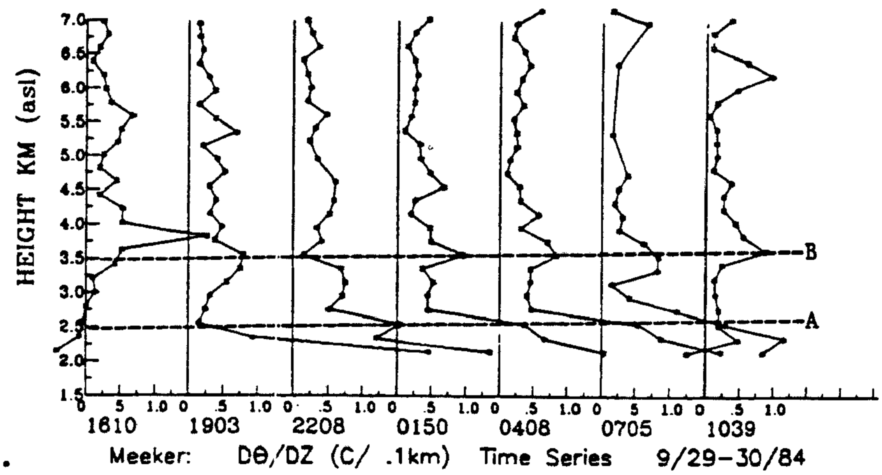

Fig. D.3b.

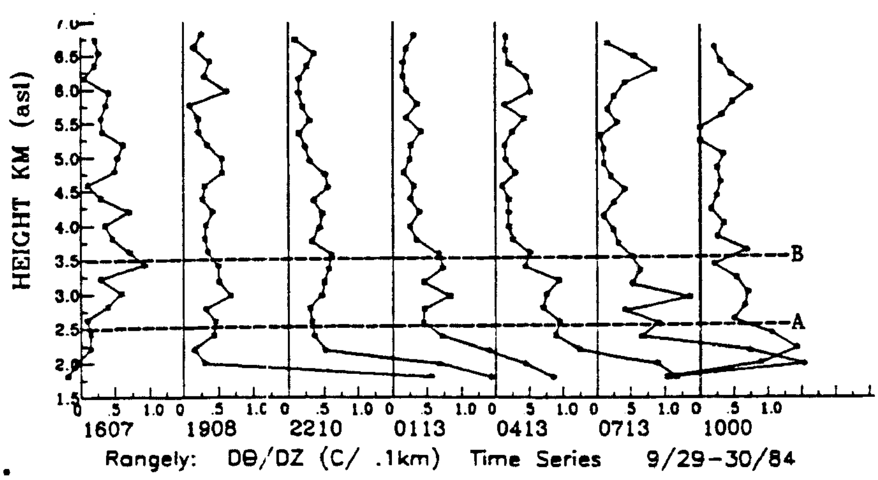

Fig. D.3c.