A MODEL FOR REFINING PRECIPITATION-TYPE FORECASTS FOR WINTER WEATHER IN THE PIEDMONT REGION OF NORTH CAROLINA ON THE BASIS OF PARTIAL THICKNESS AND SYNOPTIC WEATHER PATTERNS

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A thesis submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Masters in the Department of Geography (Climatology).

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ABSTRACT

Matthew P. Cuviello: A model for refining Precipitation-Type Forecasts for Winter Weather in the Piedmont Region of North Carolina on the basis of Partial Thickness and Synoptic Weather Patterns
(Under the direction of Charles E. Konrad II)

Determining precipitation types and intensity of winter weather events in the Piedmont region of North Carolina is difficult for forecasters. Sounding and climatological data along with cyclone and anticyclone characteristics (e.g. pressure, location, and time) from microfilmed surface weather maps are examined for 237 winter weather events at Greensboro, North Carolina over a 37 year period. The data is used to explore precipitation type determination and synoptic (large scale) pattern influence on intensity. A model for predicting precipitation type (i.e. a nomogram) is developed from the sounding and climate data. The tracks of the cyclones and anticyclones are classified and used to characterize the intensity of observed snow, freezing rain and sleet in the study area.

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To all those serving their country in harms way, God bless you and keep you safe.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

1.1 Research Context

“Perhaps the most challenging winter weather forecast problem in the Southeast is the forecasting precipitation type (P-type).” (Keeter et al, 1995) This is especially true in the North Carolina Piedmont where forecasters have developed techniques that have some skill in forecasting when a winter weather event will occur. The difficult part of the forecast is to determine the precipitation or P-type (i.e. rain, snow, freezing rain, and sleet) that will fall in a region. Frozen P-types bring about unique problems for a population not accustomed to winter weather. Small amounts of frozen and freezing precipitation can have a significant economic and safety impact.

In the North Carolina Piedmont (**Fig 1.1**), P-type forecasting is especially challenging because of two general factors. First, computer generated forecast models

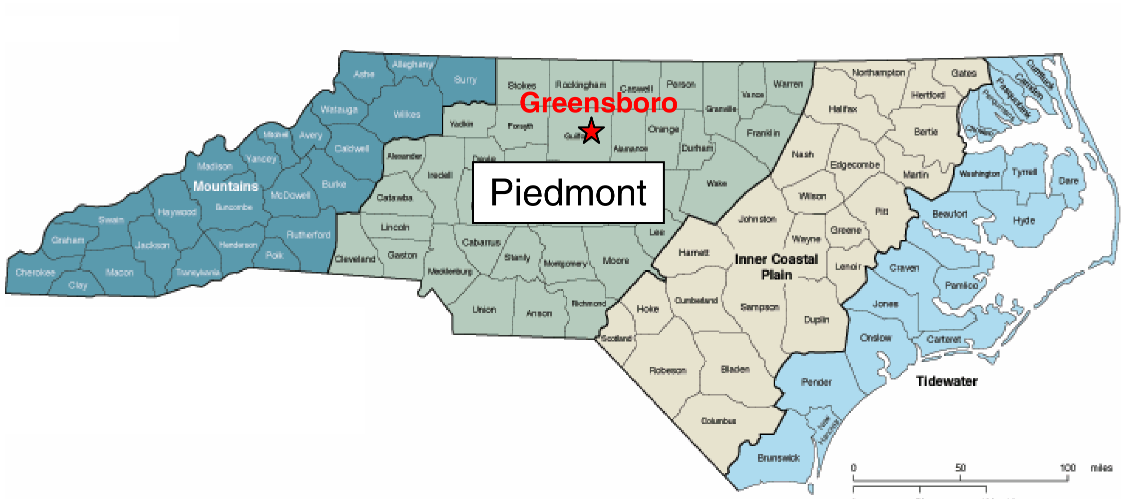


Fig 1.1. Greensboro, NC and the Carolina Piedmont, Atlas of North Carolina

fail to reproduce the fine grained details of the P-type pattern in many winter weather events (Ahrens, 2003). Second, North Carolina is positioned in a unique location between the Appalachian Mountains, the Atlantic Ocean and the Gulf of Mexico where subtle variations in the synoptic and mesoscale circulation often control P-type and the exact location of P-type transitions (Keeter et al, 1991).

In this Thesis, a dataset describing the characteristics of all winter weather events in the North Carolina Piedmont (e.g. P-type and precipitation totals) is combined with radiosonde data recorded at Greensboro, North Carolina (GSO) and surface weather analyses to identify the factors that control P-type and the intensity of the precipitation. The ultimate goal of this research is to provide a refined conceptual model that forecasters can use to more skillfully predict P-type and intensity.

1.2 Background

An analysis of P-Type determination in the North Carolina Piedmont is informed by several bodies of literature. This section provides background information on the relationships between P-type synoptic weather features and vertical thermal profiles. The section will focus on the partial thickness nomogram as method for assessing different vertical thermal structures and predicting P-types.

1.2.1 Frozen P-Type

Precipitation in winter events reaches the ground as rain, snow, freezing rain or ice pellets. Predicting the location where these forms of precipitation will occur is the challenge (Stewart, 1992). Forecasting P-Types in transition zones is an extremely difficult problem in the Piedmont (Keeter and Cline, 1991). P-types can transition quickly across types, and mixed types (e.g. snow and sleet) can be observed at a given time. Small changes in the atmosphere can have a major impact on frozen P-type determination (Lackman et al, 2002). If a region experiencing cold rain in an atmosphere immediately above freezing gets slightly colder, precipitation will turn over to snow and can potentially accumulate quickly.

The vertical temperature profile is the major determining factor as to what particular P-type or mix of P-types will occur in an event. This section will start with a description of these vertical profiles. Next it will provide a brief description of processes that influence the vertical temperature profiles conducive to producing frozen precipitation.

1.2.1a Snow

Much of the precipitation in a winter event starts as snow in the middle troposphere. Snow will reach the ground if the air throughout the atmospheric column is at or below freezing (**Fig 1.2**). At times snow can reach the surface when the temperature in the column is above freezing. For example, melting snow can provide a mechanism for cooling. Melting is a diabatic process that consumes sensible heat in the atmosphere, thus providing a cooling effect. If enough snow melts in the atmosphere, the temperature in the column will become isothermal, near 0^{o}C. This isothermal condition will allow some snow flakes to reach the ground. Evaporation can also cool the atmosphere. Snowflakes that melt will supply rain droplets that can evaporate in a dry atmosphere beneath the clouds. Evaporation converts sensible heat into latent heat that can provide enough cooling to get some snow flakes to the ground (Hux et al, 2001).

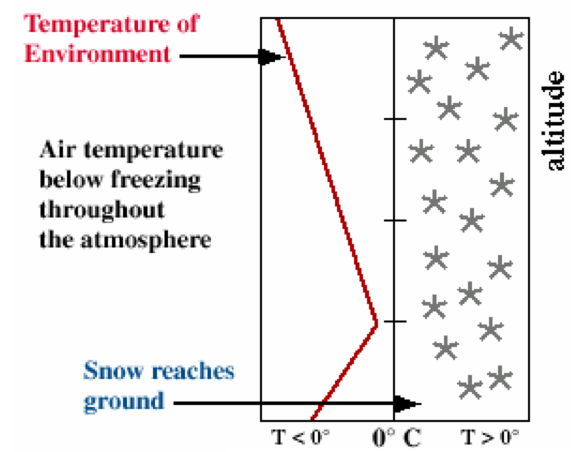


Fig 1.2 Snow Profile

1.2.1b Ice Pellets and Freezing Rain

Ice pellets, or sleet, form most typically through a melting and refreezing process (Bernstien, 2000). Snow falling in the atmosphere melts in a warm layer in the mid to lower troposphere and then refreezes near the surface in a layer that is at or below zero degrees. (Gay and Davis, 1993). The freezing process near the surface is not instantaneous therefore the cold layer above the surface must be sufficiently cold and deep to refreeze the rain droplets (**Fig 1.3**). Sleet normally occurs in conjunction with the other P-types because subtle changes in the temperature of the cold and warm layers during the event are enough to change the form of the precipitation.

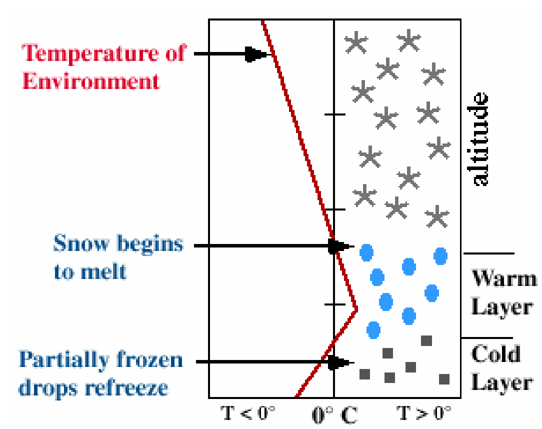


Fig 1.3 Sleet Profile

Freezing rain follows the same process as sleet. The difference is that when the snow melts in the warm layer it does not refreeze in the cold air layer near the surface

(**Fig 1.4**). The cold layer for a freezing rain event is shallower; therefore supercooled rain drops will freeze on a surface that is below the freezing point instead of in the atmosphere (Bendal and Paton, 1981). If there is not a sustained cold air source to counteract the latent heat release in the freezing of the rain droplets the temperature will rise to the freezing point and the freezing rain will transition into rain (Lackman et al, 2002).

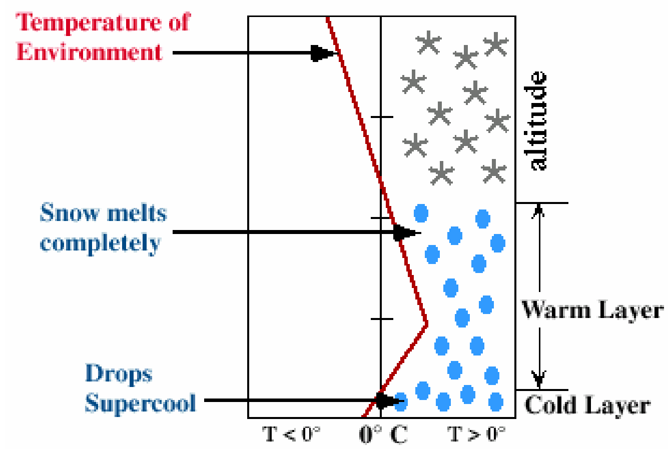


Fig 1.4 Freezing Rain Profile

The vertical profiles for the different P-types are well documented. The challenge in forecasting P-types of an event is apparent when looking at the subtleties in the atmospheric column. Small changes in the vertical temperature profile can result in P-type transitions.

1.2.1c Vertical Profiles of temperature and moisture

Adiabatic and diabatic processes play important roles that can affect the vertical temperature profile in frozen precipitation scenarios. The rising (sinking) of unsaturated air produces adiabatic cooling (adiabatic warming) as air moves into a lower (higher) pressure environment and expands (contracts). This produces a steep lapse rate when the air is unsaturated. When air becomes saturated in the column, the water vapor will start to condense. Condensation releases latent heat and creates some warming that partially off sets adiabatic cooling. Rising air will adiabatically cool the atmospheric column. This adiabatic cooling is observed in upslope flow and may cause precipitation at higher elevations on a slope to turn over to snow.

The lower troposphere can cool substantially as rain droplets evaporate below cloud base through diabatic processes. Evaporation removes heat from the atmosphere which results in a cooling effect. This can have a pronounced effect on temperatures throughout a winter weather event and can force a change in P-type (Hux et al, 2000). Melting can also provide some minimal cooling (sensible heat to latent heat) to help provide an additional cooling (NWS). Diabatic processes can cause quick transitions of P-type throughout the evolution of a winter weather event.

In addition to these diabatic processes, thermal advection can have profound impacts on the P-type. Warm (cold) air advection involves the transport of warm (cold) air by the wind from a region of higher (lower) temperatures to a region of lower (higher) temperatures. The Gulf of Mexico (primary) or the Atlantic Ocean (secondary) provides sources for warm tropical air, while continental polar or continental artic air masses provide the source for cold air advection.

1.2.2 Partial Thickness

The vertical thermal profile of temperature can be effectively conceptualized by considering the thickness of various layers within it. The thickness between two fixed pressure levels in the column is proportional to the mean temperature between these two levels (Wagner, 1957). In other words, a relatively warm or cool layer in the column is indicated by a relatively higher or lower thickness value. Warm air expands (i.e. random motion of molecules is more rapid) increasing its thickness. (Keeter and Cline, 1991).

The 1000mb – 500mb thickness layer was commonly used to help predict P-Type (Wagner, 1957) before the advancement of computer models that could project heights at multiple pressure levels. In 1975, Koolwine encouraged the use of 1000-850mb and 850-700mb partial thicknesses, citing that these two layers were a better predictor of winter P-Type (Koolwine, 1975). These layers provide the best measurable resolution of the parts of the vertical thermal structure that control P-types (Keeter and Cline, 1991). The 1000-850mb thickness provides an accurate measure of the mean temperature in the layer nearest the surface. In winter weather situations this layer is a good measure of low level cold air. A relatively lower thickness value will indicate an atmosphere capable of supporting frozen precipitation. The 850-700mb thickness provides a useful measure of the temperature higher in the atmospheric column where a warm layer is often present. A lower thickness is equated with temperatures below freezing thus enabling snow to enter the very bottom portion of the atmosphere. A relatively higher 850-700 hPa thickness coupled with a cold wedge below will support freezing rain and sleet by indicating the presence of a warm layer. This warm layer is commonly referred to as a warm nose.

The increasing partial thickness at 850 to 700mb denotes an increasing warm nose temperature due to the advection of warm air aloft. In this case snow will transition to rain. Conversely, rain will transition to snow when cold air advection at mid levels decreases the temperature and thus decreases the partial thickness (**Fig 1.5a**). Snow will also transition to rain when the increasing thickness at 1000-850mb due to warm air advection causes a warming of the lowest level of the atmosphere (**Fig 1.5b**). At some point in time snow will not be able to reach the ground or the precipitation will transition to another p-type. Cooling at the surface will occur if there is cold air advection in the low levels of the atmosphere. The cold atmosphere will support the falling snow. As the 1000 to 850mb decreases (increases) and the 850 to 700mb increases (decreases) there is a point where the transition from rain to snow (snow to rain) will occur (**Fig 1.5c**).

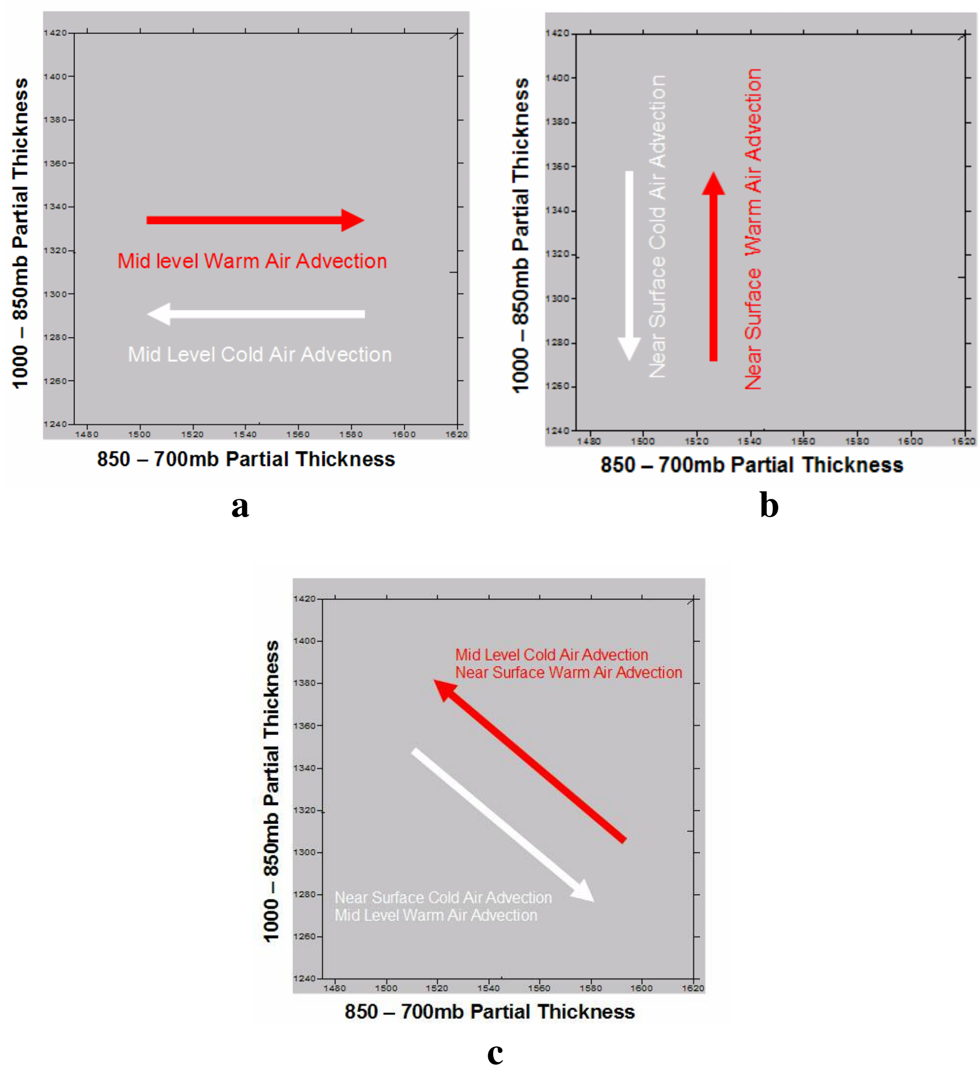


Fig 1.5 Affects of Diabatic Processes on P-Type Trajectory

The Raleigh National Weather Service has developed an algorithm called Forecasting Predominate Precipitation Type Trends (TREND). TREND is a technique for helping to predict predominant p-type in the Southeast. Because regions of the country are geographically different, the method is best suited for the region it was developed in. The TREND nomogram was developed using data from the Southeast, and therefore would not accurately predict winter weather P-types in other regions of the country or the world. Use of the TREND technique alone is not recommended for locations above 1500 ft MSL and should be used with caution in coastal regions. (Keeter and Lee, 2001) The NWS in Raleigh last publicly released a revised nomogram in October of 2001. The nomogram is constantly under review in part to new data (new events) and new research (from other parts of the country to include the Midwest).

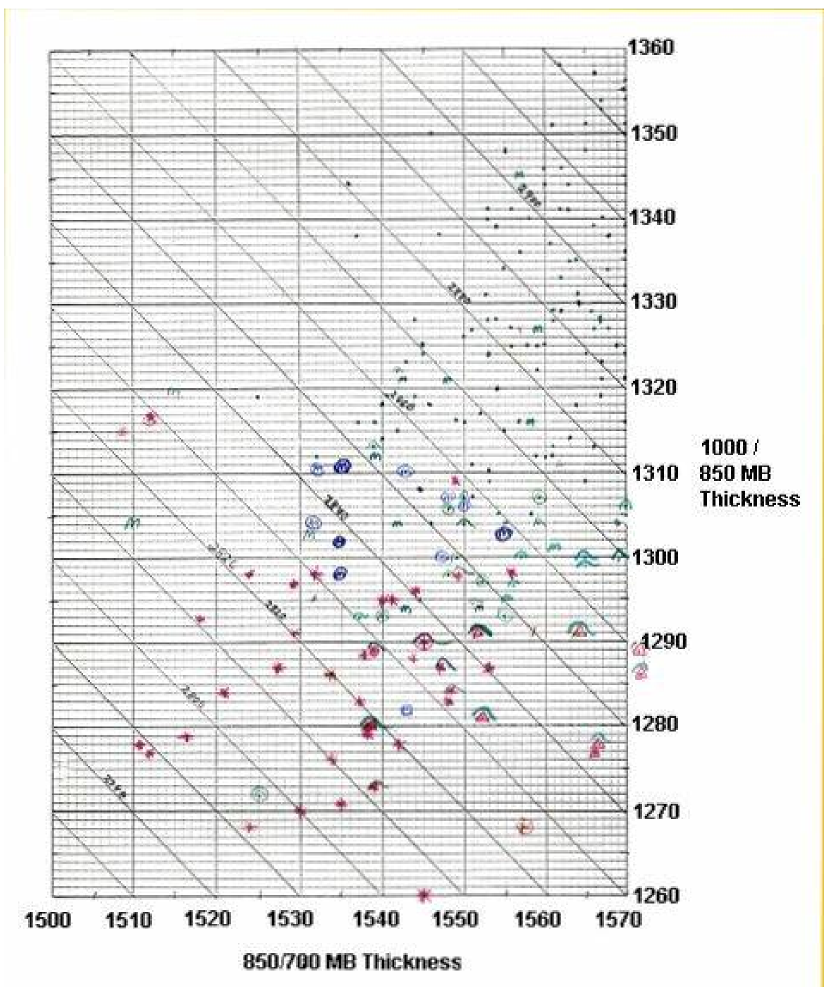


Figure 1.6 Keeter et al Empirical Database

TREND uses an empirical approach using only selected events starting with the winter of 1970-1971. Kermit et al developed the database (**Fig 1.6**) to include events with recordable frozen precipitation. They did not include trace precipitation events or nuisance sleet events. (Keeter and Lee, 2001). Keeter et al were interested in those events that had some type of impact on the community either in transportation or lifestyle disruption. They designed the method to forecast the trend (P-type predominance) of an event over six hours for the Southeast United States rather than at one point at one time interval, for example, Greensboro where the radiosondes to assess the vertical thermal profile are released. An updated database has been created by the NWS Raleigh that links plots of partial thickness of selected events (measurable) to radiosonde data. Even with this in mind, the TRENDs database is a partial database of winter weather events, not a climatology.

TRENDs uses the actual 1000-850mb and the 850-700mb thicknesses measured from radiosondes launched at Greensboro(GSO) in order to develop a universal precipitation type nomogram (**Fig 1.7**). GSO was used because of its location in the region. It falls close to the center of the Southeast region and falls in between the low coastal area and the elevated mountain region, both of which could have a major impact on p-type determination. The radiosondes at Greensboro also monitor the intrusion of cold, dry Canadian air, which plays a critical role in p-type determination (Keeter and Cline, 1991). Soundings are launched at 12 hour intervals (00Z and 12Z) and at six hours in special cases (6Z and 18Z). The nomogram can be used by either plotting model forecast data (trends) or real time radiosonde data (Nowcast). (NWS) TRENDs was

Region	Precipitation Trend
S:	All/Mostly snow
S/R:	Measurable snow with rain
R/S:	Dominate rain and some snow
R:	All/Mostly rain
ZR/IP:	Mostly freezing rain, trace sleet
IP/ZR:	Measurable sleet and freezing rain
IP/S	Mostly sleet with snow
S/IP:	More snow than freezing rain
ZR/R	Freezing rain and rain
A:	Mixed events with little predictability

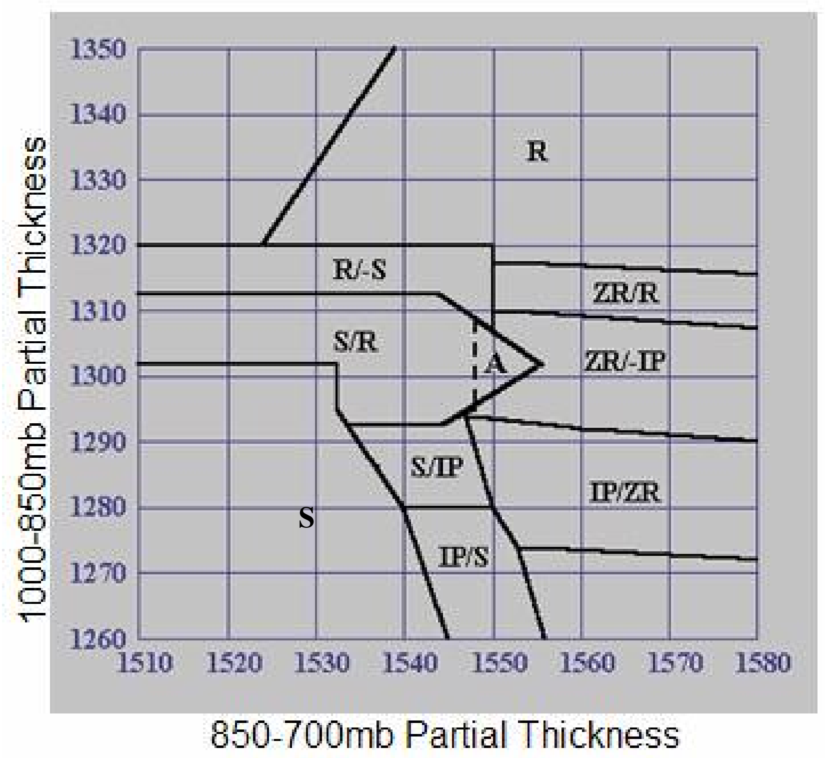


Figure 1.7 Partial Thickness Nomogram for Raleigh, NC

refined for use in the Piedmont by Keeter et al based on Koolwine's work predicating P-types over southern Ontario, Canada (Hux et al., 2000).

The universal nomogram shows the distribution of P-type trends as a function of partial thickness values. The boundaries on the nomogram separating the various p-type trend areas are based on analysis of selected events over thirty years. The mid level thickness values (850-700mb) increase from left to right along the x axis, while low level thickness values (1000-850mb) increase from bottom to top along the y-axis (NWS Raleigh).

TREND is a modified technique that associated the partial thicknesses at a point (Greensboro) and projects them over a region (the Southeast). The partial thickness nomogram was developed keeping in mind the synoptic and mesoscale patterns as well as looking at local and regional influences. (Keeter and Cline, 1991) Boundaries are drawn based on a regional understanding of the North Carolina Piedmont with a best fit in mind.

1.2.3 Synoptic Ingredients for Winter Weather in the Southeast

This section will focus on synoptic scale (1000-10,000 km^2) features that are associated with winter weather in the Carolina Piedmont. Extra- tropical cyclones and cold surface anticyclones influence the vertical temperature profile of the atmospheric column and P-type determination. They typically force the advection of warm or cold air into the Piedmont region.

1.2.3a Extra Tropical Cyclones

Extra tropical cyclones are areas of low pressure that form outside of the tropics (above 30^{o}N Lat) during all seasons. From late fall to early spring they typically form in the lee of the Rocky Mountains in Alberta, in the lee of the Rocky Mountains in Colorado, in the Gulf of Mexico and along the east coast of the US (Zishka and Smith, 1980). Those that form in the vicinity of the Gulf of Mexico and along the east coast of the US can produce winter weather in the North Carolina Piedmont (Cione, J.J., S. Raman, and L.J. Pietrafesa, 1993, Keeter et al, 1995). Cyclogenesis in these regions is most often tied to the temperature contrast of cold land and warm water (Harman, 1991). Cyclones typically track along baroclinic boundaries, lines of strong horizontal temperature gradients (e.g. 5-10°C) (Richwien, 1980).

Winter cyclones advect warm, moist air primarily from the Gulf of Mexico or the Atlantic Ocean over a cold wedge in the Piedmont and provide water vapor necessary for precipitation. (Lackman and Stanton, 2002). The cyclones set the conditions for winter events, but ultimately do not determine p-type. The p-type will be determined by the vertical temperature profile of the atmosphere.

Two primary cyclone tracks influencing the eastern US were formalized by J.E. Miller(1944): Miller A type and Miller B type. The Miller A type cyclone (**Fig 1.8**) is identified by a track of low pressure moving up the east coast of the United States, spreading precipitation in the coastal Mid-Atlantic and Northeastern states (Miller, 1944). It often forms in the Gulf of Mexico and strengthens off the coast of North Carolina due to the strong baroclinicity (Culluci, 1976). Jet streaks or short wave troughs can also strengthen the cyclone by creating more lift (Bosart, 1981).

The Miller B type cyclone (**Fig 1.9**) is identified by a primary cyclone in the Midwest and another cyclone (the secondary) that forms off the coast of the eastern United States (Miller,1944). In between these two cyclones is an area of cold air, commonly formed by damming of cold air along the eastern slopes of the Appalachian Mountains from high pressure located in the Northern United States/Canada. With the secondary cyclone often forming off the coast of North Carolina, this scenario is favorable for frozen precipitation with a dependence on sustained cold air at the surface (Bell and Bossart, 1988).

Fig 1.8 Miller Type A Cyclone

Fig 1.9 Miller Type B Cyclone

In some winter cases, the cyclone tracks too far off the coast or develops too far north to have influence on the NC Piedmont. The favored location for heavy snow is approximately 282 km (175 miles) to the northwest of a cyclone tracking to the Northeast (Goree and Younkin, 1966). A cyclone tracking along the coast near the South Carolina/North Carolina coast is in perfect position for Greensboro. If a Miller A or Miller B secondary cyclone tracks well off the coast, it may not be able to advect moisture and warm air far enough west. Likewise a Miller B secondary cyclone that forms to the north off the coast of Virginia or Maryland, may bring that area winter precipitation but leave the Piedmont of North Carolina cold and dry. In these cases the cold air over North Carolina may be present but the atmosphere lacks moisture.

The correlations of cyclone tracks to P-type in the Piedmont are not well documented. Keeter and Cline (1991) discuss methods using strong Miller A cyclones to predict the location of a narrow transition zone. They add that with weaker Miller A and Miller B type cyclones the transition zones between P-types become broader. Kocin and Uccellini (1990) state that most east coast winter storms track toward the northeast or north-northeast, MaGlaras et al (1995) discuss other studies that help explain some of the synoptic features associated with winter weather, but no study performs a climatology that specifically explores the connections between cyclone tracking and P-type determination.

1.2.3b Anticyclones

Anticyclones, areas of high pressure, in southeast Canada or the northeast United States often provide the source of cold air needed to produce frozen precipitation (**Fig 1.10**). The extent and depth of cold air in the lower troposphere help determine P-type.

Anticyclones east of Appalachian Mountains are of interest because they are associated with cold air damming (CAD) events (Colucci and Davenport, 1987). During CAD events the anticyclone advects cold air south forming a cold layer at the surface trapped by the mountain barrier. WAA aloft from the south establishes the temperature inversion (i.e. warm nose) that can cause melting (Mote et al, 1997).

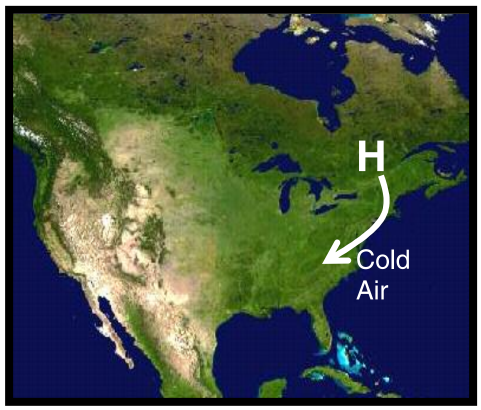


Fig 1.10 Eastern Anticyclone

The CAD processes are well documented in the literature (Richwein, 1980, Bell and Bossart, 1988, Lackman and Stanton, 2002). Little has been documented (Rauber et al, 2001, Keeter et al, 1995) regarding the connections between p-types and the location and strength of the surface anticyclone.

1.2.4 Mesoscale Ingredients for Winter Weather in the Southeast

This section will focus on mesoscale features (10 – 1000km^2) in the atmosphere that affect winter weather precipitation in the North Carolina Piedmont. The affects of cold air damming and convective banding on the determination of frozen P-type will be discussed.

1.2.4a Cold Air Damming

Cold Air Damming(CAD) in the Piedmont occurs when cold air is entrapped along the eastern slopes of the Appalachian Mountains(Bell and Bossart, Keeter et al, 1995, Riechwien, 1980). CADs are identified by a "u" shaped pressure ridge in the sea

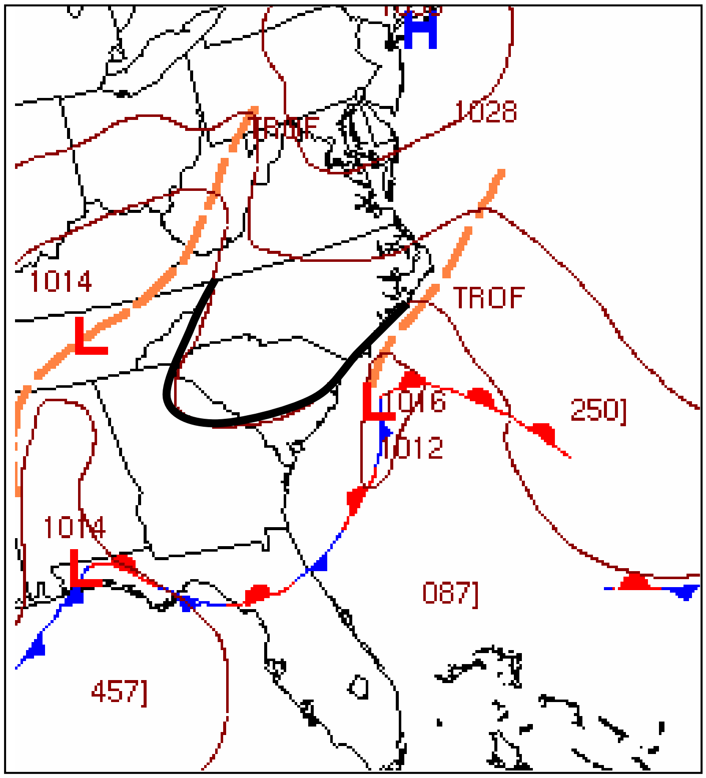


Fig 1.11 CAD Event, "U" shaped isobars

level isobar pattern as shown in **Figure 1.11**. Cold layers in the Piedmont usually average a depth of 1700m (Forbes, Anthes, Thomson, 1987). The cold air is contributed by cold air advection, orographic ascent, evaporative cooling and sheltering from insolation due to cloudiness (Lackman and Stanton, 2002).

CADs are significant contributors of all types of frozen precipitation when coupled with a moisture source. The precipitation type depends on the depth of the cold wedge and presence/absence of a warm nose. Slight alterations in the vertical temperature profile can have profound effects on P-type (Forbes, Anthes, Thomson, 1987). The cold layer at the surface (below 850mb) can be a distinguishing factor in determining whether an event will produce rain or frozen precipitation (Bell and Bossart, 1988). The source of sustained cold air in the Appalachians is usually from a cold surface anticyclone located in southern Canada or the northeast US. Another factor is the temperature and moisture in the warm nose. Ice pellets and freezing rain can not form without the presence of this warm nose.

The breakdown of a CAD is associated with a change in P-types. CAD wedges can thin out due to stronger WAA aloft in the warm nose or through the loss of sustained cold air, creating P-types transitions from snow to sleet/freezing rain to rain. If WAA weakens aloft or transitions to cold air advection, a more unstable atmosphere is created producing less cloud cover (Lackman and Stanton, 2004). Precipitation will eventually stop most likely as snow, while solar heating at the surface will help breakdown the CAD.

Low level divergence and sheer induced mixing also help breakdown the CAD (Lackman and Stanton, 2004). As the cold air source to the north weakens and eventually dies, the wedge will thin and then disappear. With the wedge thinning, P-types will transition from frozen to all rain. Shear-induced mixing (entrainment) across the top of the cold dome will decrease the gradient of the inversion and eventually erode the cold wedge. The source of the air is usually the low level jet from the southeast. In these cases P-type will transition to all rain.

There is much recorded in the literature about cold air damming at the mesoscale and its influence on P-type. The literature does not explore the relationship of the presence/absence of the northern anticyclone and its influence on P-type. No studies link the anticyclone with partial thickness. Relationships identified between the anticyclone to the north and the cold wedge may give forecasters another tool for assessing winter weather potential in the North Carolina Piedmont.

1.2.4b Summary

The bottom line is that the determination of p-type in the North Carolina Piedmont is a big challenge for forecasters. There are many different ingredients and variables that factor in to the determination of p-type and none of them is a stand alone solution. Broad assumptions have been made regarding the influence of synoptic features on P-types. Different synoptic patterns may be useful in the determination of p-type and their intensity.

1.3 Research Design

1.3.1. Research Questions

1) What are synoptic patterns associated with different types of winter weather events in the North Carolina Piedmont, and how might their identification be useful in terms of better predicting precipitation types (e.g. snow, sleet, and freezing rain) and totals?

2) What refinements (if any) of the partial thickness nomogram are needed to better predict P-types for Greensboro and the surrounding area? In particular, what are the winter weather events in which the partial thicknesses do not correspond to the expected P-type based on available tools and why does this occur?

1.3.2 Research Objectives

The research questions above will be addressed with the following objectives in mind:

a) Develop a 37-year database of winter weather events at Greensboro, NC that combines precipitation type, partial thickness measurements and synoptic variables

b) Plot the partial thicknesses associated with each winter weather event. Compare with the Kermit et al scheme and analyze events that do not correspond to the expected precipitation type.

c) Identify the strength/track of anticyclones and cyclones associated with each event Compare the strengths and tracks of different event types to see if they are predictive.

CHAPTER II
DATA AND METHODS

2.1 Introduction

This chapter describes the data and methods used to develop a synoptic climatology of winter weather events in the North Carolina Piedmont with a focus on Greensboro, North Carolina.

2.2 Study Area: The Piedmont of North Carolina

The Piedmont region (**Fig 2.1**) is located in central North Carolina. Although the Piedmont extends north into Virginia and south into South Carolina and northern Georgia (**Fig 2.2**), only the area located inside the borders of North Carolina is of concern.

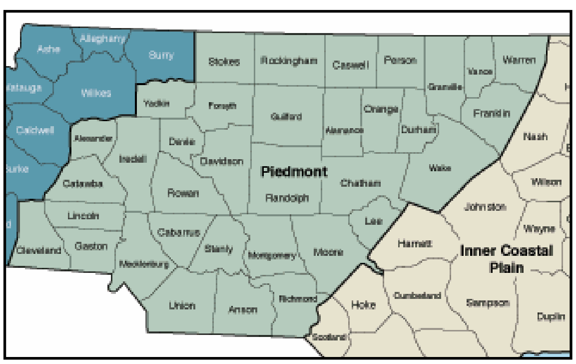


Fig 2.1 Piedmont of North Carolina

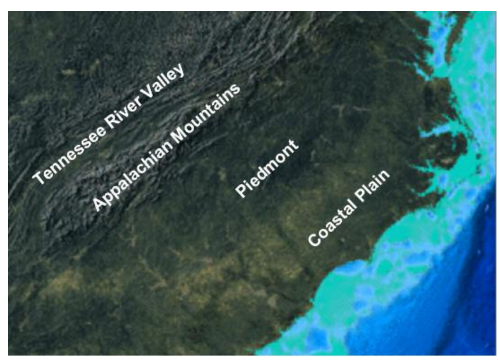


Fig 2.2 Physiographic Map of the Land Regions of the East Coast of the US

Topographically, the Piedmont forms a wide, rolling plateau between the low relief Coastal Plain, to the east, and the more rugged mountains to the west. The Appalachian Mountains to the west provide a barrier that creates an ideal location for the damming of cold air. The relatively flat coastal plain to the east provides a clear path for the advection of warm air and moisture from the east/southeast. The region contains

North Carolina's seven largest (population) municipalities (Charlotte, Raleigh, Greensboro, Durham, Winston-Salem, Fayetteville, and Cary), thus one of the major concerns for accurate forecasts in wintertime.

For this study a vertical profile of the atmosphere is essential, therefore radiosonde (sounding data) from Greensboro (GSO) was examined. It is the only station in the North Carolina Piedmont that collects this data. The radiosonde, attached to a weather balloon, contains instruments capable of measuring air temperature, humidity and pressure with height. These observed data are transmitted immediately to the ground station by a radio transmitter located within the instrument package. The ascent of a radiosonde also provides an indirect measure of the wind speed and direction at various levels throughout the troposphere.

2.3 Data Sources

2.3.1 Events Data

Winter weather events for this study are defined as any event that had observed winter precipitation (snow, sleet, and freezing rain) at Greensboro for any one hour. This is significant because the events database includes not only measurable precipitation events that other studies have used (Keeter et al, 2002, Keeter and Cline, 1991), but also includes "nuisance" or non-measurable events. By including all events in the climatology, a non-biased assessment can be made as to P-type determination.

This study uses the Konrad/Fuhrmann Southeastern Winter Weather Database to identify the start times of all frozen precipitation and snow events at Greensboro from January 1958 through December 1995. The database captures over 70 variables of winter weather events from 18 first order stations across the Southeast for a 55 year period,

Greensboro Winter Weather Events Database Variables			
Mean Temperature(24hrs, 6hrs before)	Total amount of Precipitation	Minimum Dew Point (During the event)	Maximum Cloud Cover (During the event)
Mean Temperature(During)	Total amount of Rain	Dew Point Difference (During the event)	Minimum Cloud Cover (During the event)
Mean Temperature(24hrs, 6hrs, 4 days after)	Total amount of Freezing Rain	Maximum Dew Point(6 hrs after the event)	Cloud Cover Average (6hrs after the event)
Magnitude of Coldness for all time periods	Total amount of Sleet	Minimum Dew Point (6 hrs after the event)	Maximum Cloud Cover (6 hrs after the event)
Mean Wind Chill During the Event	Total amount of Snow	Dew Point Trend (6 hrs after the event)	Minimum Cloud Cover (6 hrs after the event)
Frozen Preciptation	Maximum Temperature (in the 6hrs Prior)	Maximum Wet Buld Temperature (in the 6hrs Prior)	Average Visibility (in the 6hrs Prior)
Magnitude of Frozen Preciptation (by return interval)	Minimum Temperature(in the 6hrs Prior)	Minimum Wet Bulb Temperature (in the 6hrs Prior)	Maximum Visibility (in the 6hrs Prior)
Total amount of Frozen Precipitation (liquid equivalent)	Temperature Trend(in the 6hrs Prior)	Wet Bulb Temperature Trend (in the 6hrs Prior)	Minimum Visibility (in the 6hrs Prior)
Highest observed hourly (liquid equivalent) precipitation total during the event	Maximum Temperature (During the event)	Maximum Wet Buld Temperature (During the event)	Average Visibility (During the event)
Duration of the Event	Minimum Temperature (During the event)	Minimum Wet Bulb Temperature (During the event)	Maximum Visibility (During the event)
Total Hours of Drizzle	Temperature Difference (During the event)	Wet Bulb Temperature Difference(During the event)	Minimum Visibility (During the event)
Total Hours of Rain	Maximum Temperature (After the event)	Maximum Wet Buld Temperature (6 hrs after the event)	Average Visibility (6 hrs after the event)
Total Hours of Freezing Drizzle	Minimum Temperature (After the event)	Minimum Wet Bulb Temperature (6 hrs after the event)	Maximum Visibility (6 hrs after the event)
Total Hours of Freezing Rain	Temperature Trend (6 hrs after the event)	Wet Bulb Temperature Trend (6 hrs after the event)	Minimum Visibility (6 hrs after the event)
Total Hours of Sleet	Maximum Dew Point (in the 6hrs Prior)	Cloud Cover Average (in the 6hrs Prior)	Percentage of Rain Dominance
Total Hours of Snow	Minimum Dew Point (in the 6hrs Prior)	Maximum Cloud Cover (in the 6hrs Prior)	Percentage of Freezing Rain Dominance
Total Hours of no Observed Weather	Dew Point Difference (in the 6hrs Prior)	Minimum Cloud Cover (in the 6hrs Prior)	Percentage of Sleet Dominance
Total Hours of Precipitation	Maximum Dew Point(During the event)	Cloud Cover Average (During the event)	Percentage of Snow Dominance

Table 2.1 Greensboro Winter Weather Database Variables

beginning in 1948 and ending with the last winter event of the 2002-2003 season (**Table 2.1**). Events at Greensboro were defined by the occurrence of measurable (0.01") precipitation and one or more observations of frozen precipitation. An event was terminated if there was more than a six-hour lapse in these conditions. Events could have lapses in the requisite conditions of up to six hours (Fuhrmann and Konrad, 2005). Hourly observations from all first-order weather stations for the period of study were extracted from CD-ROM's produced by EarthInfo. Hourly Precipitation Data (HPD) was extracted from the National Climatic Data Center (NCDC) CD to get hourly precipitation amounts.

One caveat to the data is that weather reports for the period 1966 to 1971, with the exception of precipitation totals, were only made every three hours. In order to mitigate this, Furhmann and Konrad (2005) extrapolated to the intervening two hours (e.g. 1200 LST and 1400 LST reports are assumed to be the same as the 1300 LST report). The interpolation of these observations has no impact on the study.

2.3.2 Temperature Profile and Precipitation Type

Information about the atmospheric temperature profile and the observed precipitation type at GSO comes from two sources: 1) Sounding data and 2) The National Oceanic and Atmospheric Administration's (NOAA) Form A and Form B hourly surface observations. The sounding data provides atmospheric readings twice a day (at 12z [0700 EST] and 24z [1900 EST]) routinely and up to four times (6z[0100], 12z[0700], 18z[1300]. 24z[1900]) daily when significant weather events occur. The Plymouth State Weather Center and University of Wyoming Soundings websites were used to retrieve the GSO sounding data from 1958-1973 and 1973-1996, respectively. The Plymouth State website does not contain data from any supplemental soundings (0600z and 1800z), thus limiting the data in those years. **Figure 2.3** shows an example of a Skew-T sounding diagram. Pressure and height are on the y axis, temperature and mixing ratio are on the x axis. The temperature is recorded by the red line, while the

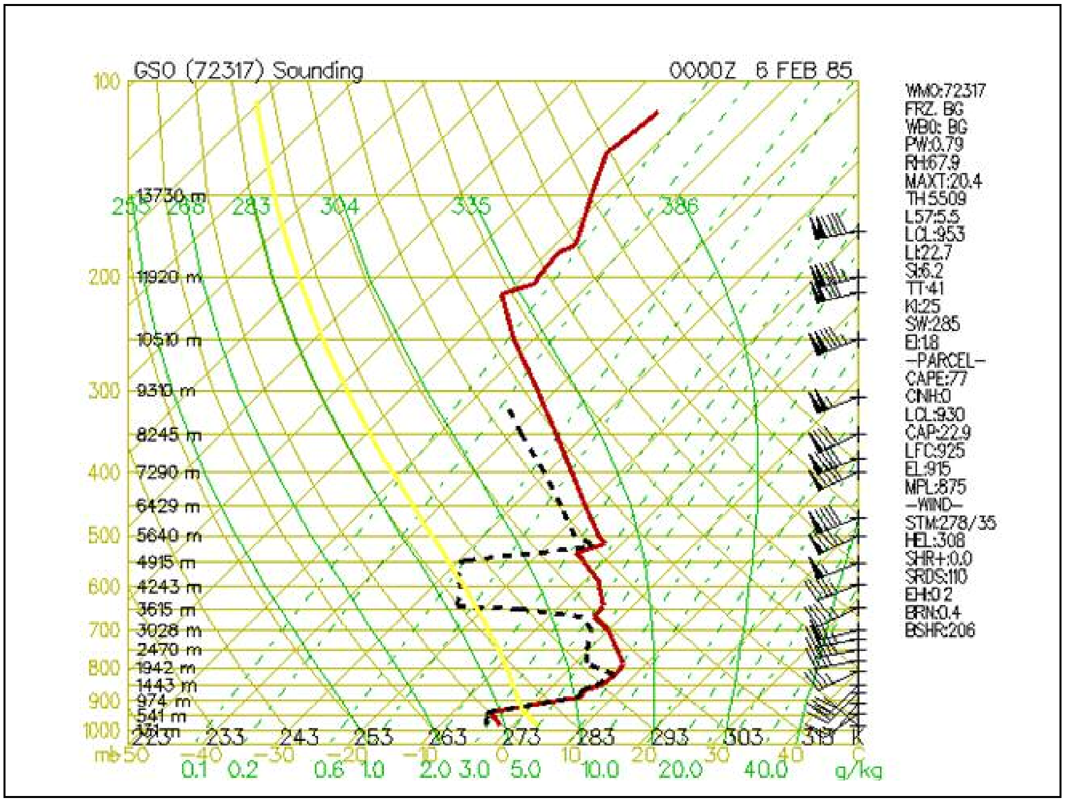


Fig 2.3 Skew-T sounding Graph at Greensboro

dotted line indicates the dew point. The wind is also noted on the right side of the diagram.

The data from the soundings were used to create a database using the identified winter weather events. Thickness values of the 1000-500mb, 1000 – 850mb and 850-700mb layers were recorded from the sounding data as well as 0^{o} C isothermal layer thickness (i.e. thickness of a continuous layer in the atmospheric column in which the temperature is between -1.5 C and 1.5 C), temperatures at 850mb and the surface, the dew point depression at -10^{o} C and -15^{o} C, the surface dew point, the minimum temperature in the cold wedge and the maximum temperature in the warm nose (see **Fig 2.4 for** a visual representation of the measurements.)

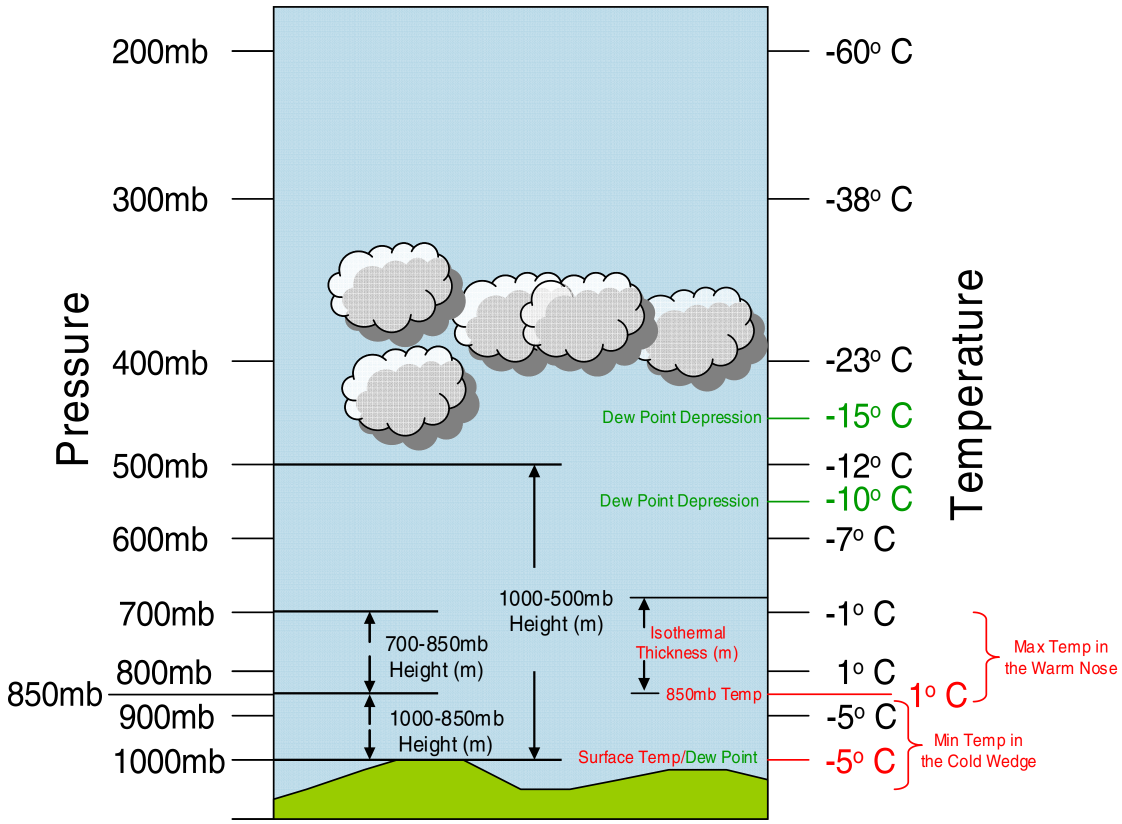


Fig 2.4 Vertical Temperature and Pressure Profile

NOAA's Surface Weather Observation data forms 10A and 10b contain hourly observations of p-type. The dominant p-type in an event was recorded for the 3 hour period surrounding and for the 6 hour period following each available sounding. Surface observations/sounding information were recorded starting with the sounding immediately prior to the onset of precipitation and ending with the first sounding after the event was over or the first sounding after the precipitation has turned over to all rain for the remainder of the event.

Although sounding data is accurate, it has certain caveats. For one, the data is recorded by a balloon whose flight can last in excess of two hours, and can drift more than 125 miles from the release point (NOAA). In many instances data is recorded over an area and not vertically at one point. The radiosonde package was replaced with a GPS tracked radiosonde in the winter of 2006/2007 at Greensboro which will aid in determining the distance of flight. There can also be transmission errors from the radiosonde package to the ground that, if not quality controlled, will record erroneous data (Marshall, 2002). The radiosonde data is the only measure of the vertical atmosphere available for analysis.

In order to maintain continuity of observations, the study uses data from 1958 through 1996. In 1958, the format for the NOAA 10A and 10B forms changed. The old format did not contain the same information as the later form. In 1996, GSO changed to the Automated Surface Observing System (ASOS) in order to define p-type. Since the ASOS uses sensors, no events after 1996 were included in order to use the same observation method. With that said, the observed data over the 37 year period was recorded by multiple individuals each with their own biases.

2.3.3 Synoptic Data

In order to relate synoptic patterns to the precipitation types in the winter weather events, the positions and strengths of surface anticyclones and cyclones were recorded from the North American Surface Charts microfilm from NCDC and the NOAA Central Library U.S. Daily Weather Map Project found on the World Wide Web. The microfilm contains surface maps at three hour intervals for every day of the year. The Daily Weather Map Project shows two daily maps prior to 1968 and only one post 1968.

Miller A type cyclones are identified by a track of low pressure moving up the East Coast of the United States, usually forming in the Gulf of Mexico and spreading precipitation in the coastal Mid-Atlantic and Northeastern states. Miller B type cyclones are identified by a primary low pressure system in the Midwest that aids cyclogenesis most often occurring off the east coast of the United States producing a secondary cyclone. Examples of a Miller A map sequence (**Fig 2.5**), a Miller B map sequence (**Fig 2.6**) and a map sequence with no cyclone track (**Fig 2.7**) are provided in order to visually identify all of the recorded values in the study. *Map a*. shows 0z hour for the events, Map b. the next 24hrs and map c. the last 24hrs. The position (Lat/Lon) and recorded pressure of extra tropical cyclones (marked as a L on the map) were manually recorded every six hours starting with 0z time. Not shown are the 6 hour microfilm maps used to record the pressures at these intervals. The circulation of the system (closed isobar on map/not closed) was also recorded. The central pressure and location of anticyclones located to the north and northwest were recorded for each map time in the study if they were present.

One caveat of the cyclone data is that between 1993 and 1995 microfilmed North American Surface Charts were not available; therefore for the 14 events in this time period, only the daily weather maps were used to record the information. Pressure readings were unavailable for these events on the daily maps for every 6 hour time period along the cyclone track (e.g. Map b of **Figure 2.5** shows the track and location [square with x symbol] of the low pressure but does not identify the pressure at that location). The daily maps, at times, do not show the intermediate locations (square with x symbol) of the cyclone. In these cases, interpolated pressures (average) and locations (average using direction and distance) were used to fill in the data. Another caveat is that when defining the track type, a subjective decision was made when cyclone tracks were not

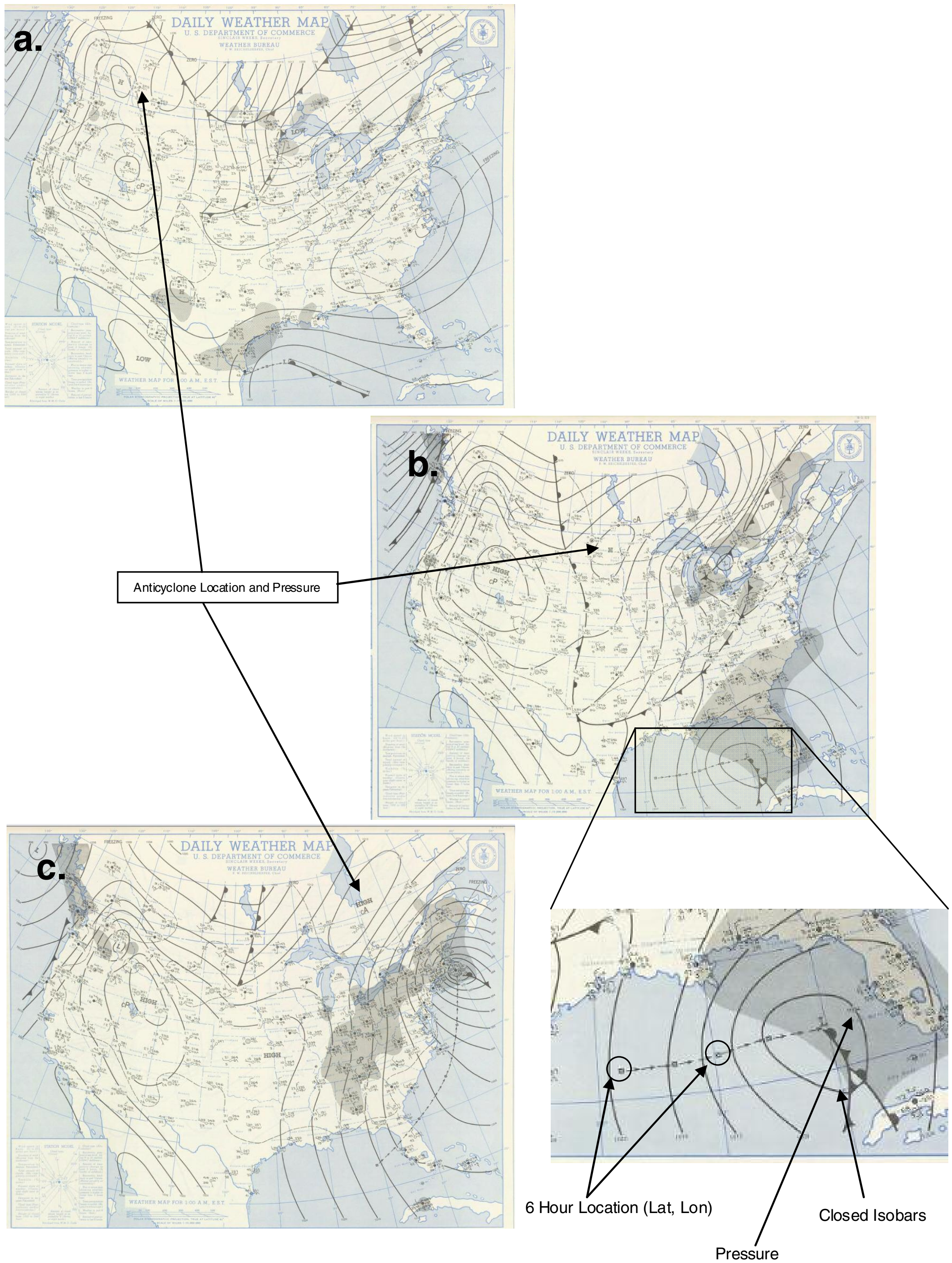


Fig 2.5 Miller A Map Example

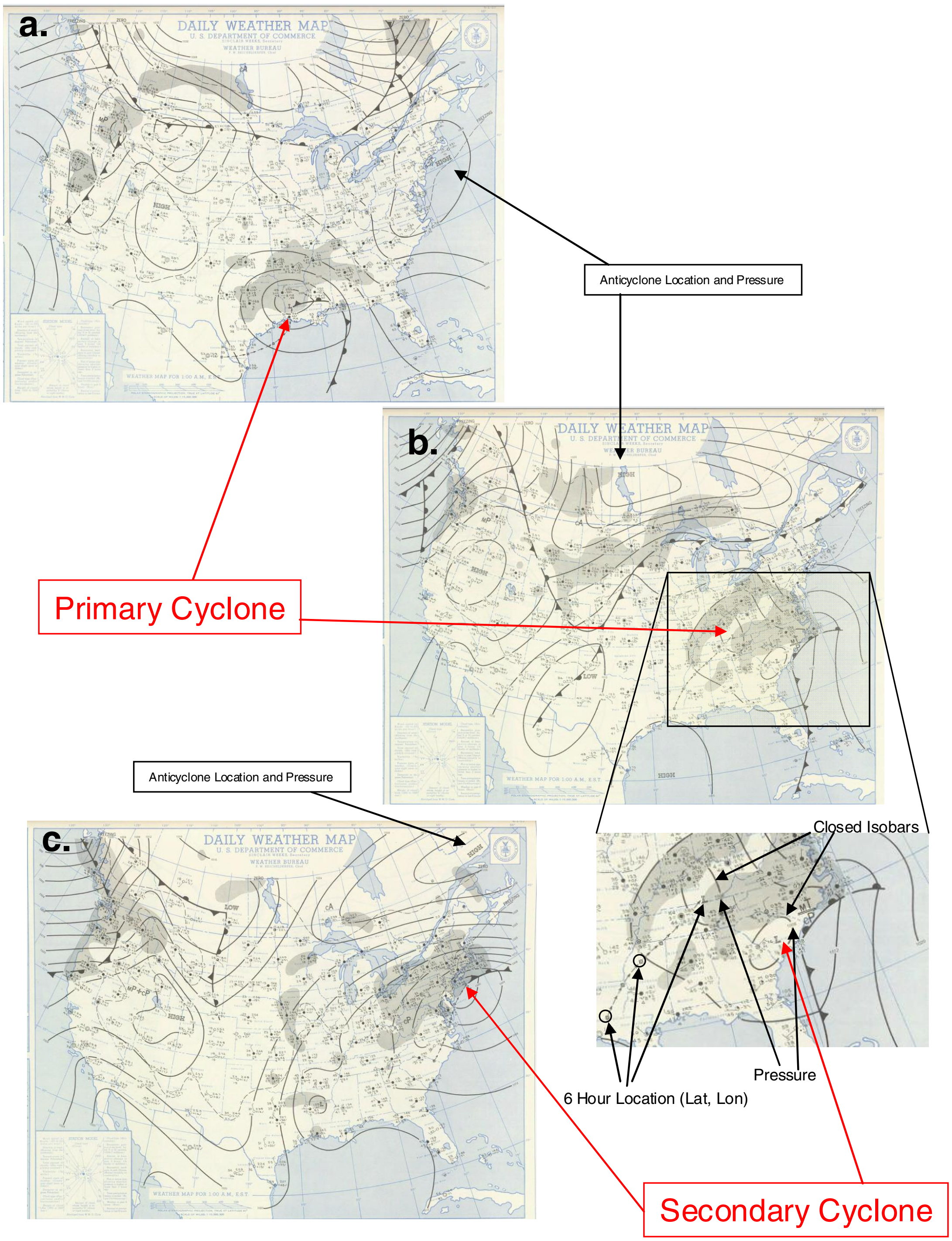


Fig 2.6 Miller B Map Example

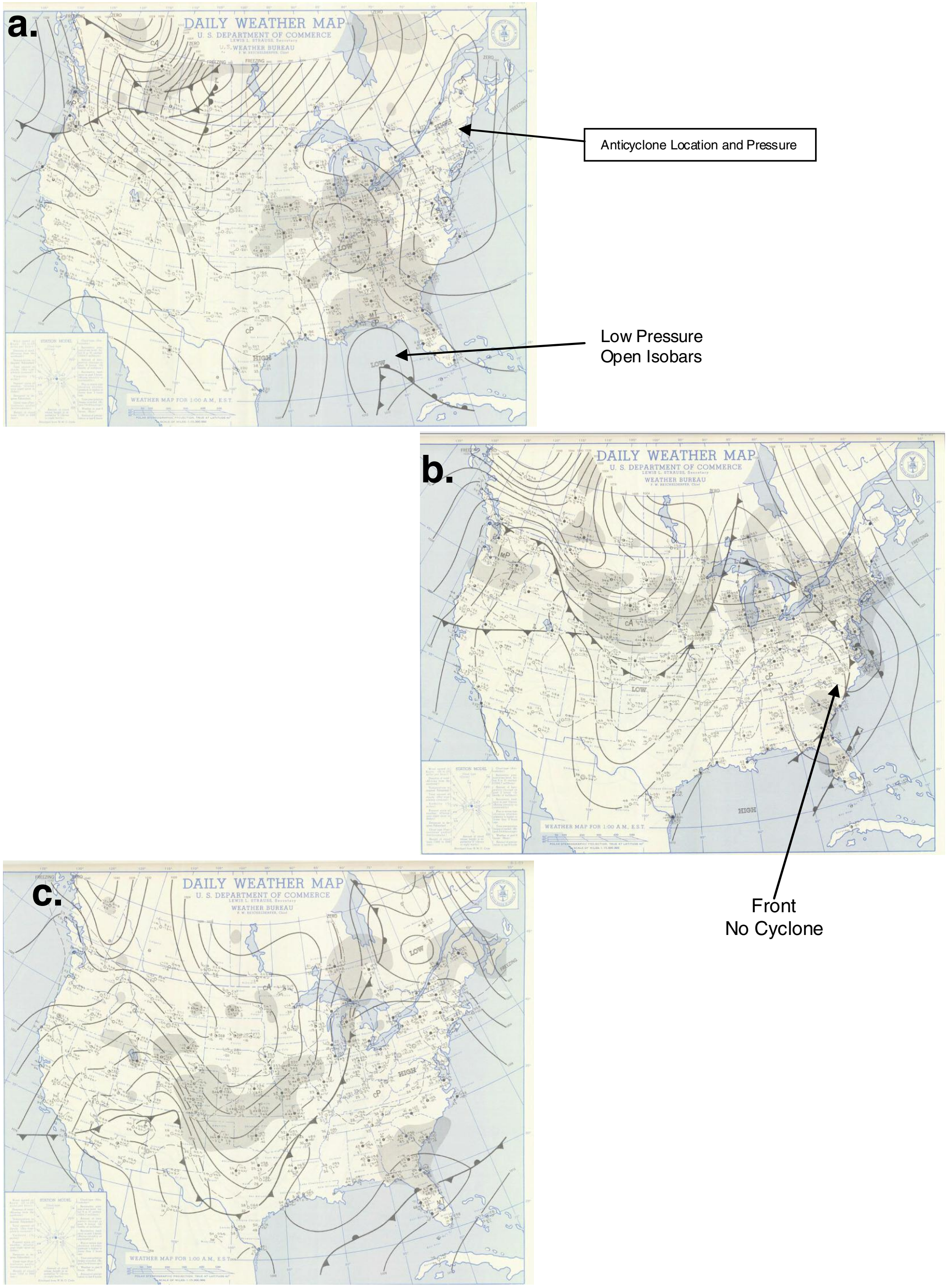


Fig 2.7 No Cyclone Track Map Example

obvious. For example, if a cyclone tracked to the east of the Appalachian Mountains and on the next map time a cyclone was off the coast, the cyclone was defined as a "Miller B." If that same cyclone continued on its path, it was defined as a "Miller A." At times this juxtaposition/no juxtaposition of the cyclone was not clear cut. A cyclone that did not have closed isobars surrounding it and "disappeared" on consecutive 6 hour maps was defined as having no track.

2.4 Methodology

2.4.1 Observed P-Type Classification

236 winter weather events were identified and analyzed during the study period. The observation of frozen p-type can occur at anytime throughout the day, most often not directly corresponding to the sounding times. Therefore to capture the evolution of the event, sounding information was collected prior to an event start, during an event, and immediately after the event. In total 870 different soundings comprise the database created for this study.

Critical to the study is defining the observed p-type. The p-type definitions center on two time frames: 3 hour period surrounding each available sounding and the 6 hour period after each sounding. The p-type is defined as the most predominate and second most predominant precipitation types observed during those time periods. If only one p-type is observed, that p-type is assigned to the event. The p-types for the remainder of this document will be categorized as follows:

Abbreviation	P-Type
XX	No Precipitation
SS	All Snow
RR	All Rain
ZR	All Freezing Rain
ZRIP	Freezing Rain/Ice Pellets
IP	All Ice Pellets
RZR	Rain/Freezing Rain
D	Drizzle
SIP	Snow/Ice Pellets
IPS	Ice Pellets/Snow
SR	Snow/Rain
RS	Rain/Snow
RIP	Rain/Ice Pellets
ZRS	Freezing Rain/Snow
ZRR	Freezing Rain/Rain
IPZR	Ice Pellets/Freezing Rain
IPR	Ice Pellets/Rain
SZR	Snow/Freezing Rain

Table 2.2 Observed P-Type

The rationale for the "six hour after" classification follows from earlier studies (Keeter and Cline, 1991, Keeter et al,, 1995). It gives forecasters an idea as to what to expect during the 6 hour period following the sounding. In contrast, the three hour period allows for identification the sounding structure contemporaneously with the p-type observation. This short time frame provides a minimally sufficient time to sample a p-type mix, and, at the same time, not to stray too far from the sounding time (i.e. maintain high temporal resolution or precision).

In both classification schemes it is important to look at the event over time (i.e. looking at the sounding prior to and after the observed p-type). This provides a broader perspective on the temporal evolution of the vertical thermal structure across the entire event. It also provides a much larger sample of pure rain observations near transition zones. Most events in the climatology start and/or end as rain and can be referenced as "cold rain." These rains can transition to freezing p-types with subtle changes in the vertical thermal structure. By capturing the sounding prior to and after the event, more of these cold rain events were included and analyzed to get a better understanding of the vertical thermal profiles associated with cold rain around winter weather events.

2.4.2 Greensboro Nomograms

Two unique partial thickness nomograms were created by follow the same methodology that Keeter et al used to develop the TRENDS universal nomogram. 1000-850mb and 850-700mb partial thicknesses are plotted on a grid and associated with the observed P-type. The Six Hour Greensboro Nomogram (**Fig 2.8)** uses the six hour P-type classification method (dominant P-type(s) six hours following the sounding) to determine what P-type is associated with the sounding (**Fig 2.10**). By combining all of the partial thickness points for each observed P-type, boundaries are drawn to form regions in the nomogram that best circumscribe events of a given type and at the same time largely exclude other event types. The Three Hour Greensboro Nomogram (**Fig 2.9)** utilizes the same method, but uses the plots of P-Types associated with the dominate P-type(s) three hours surrounding the sounding (**Fig 2.11**).

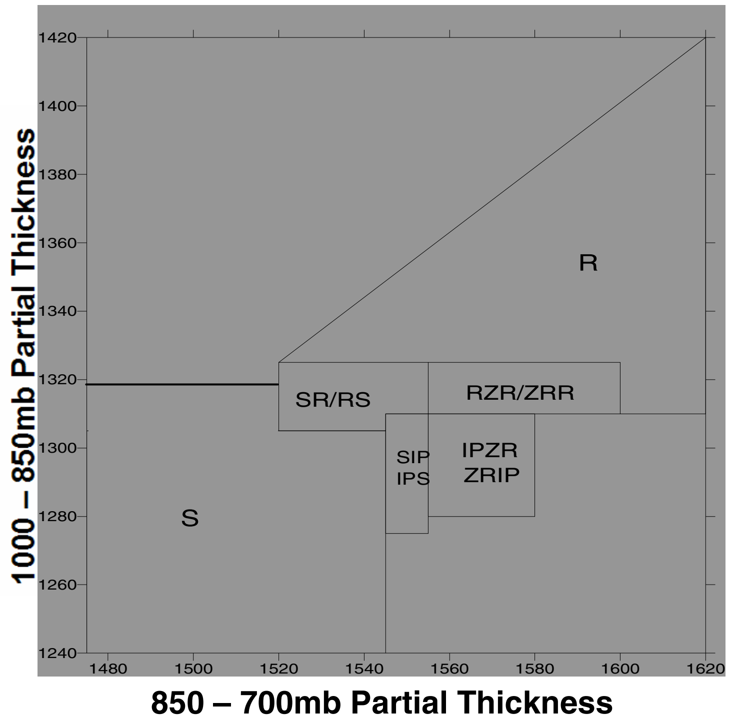


Figure 2.8 Six Hour Nomogram

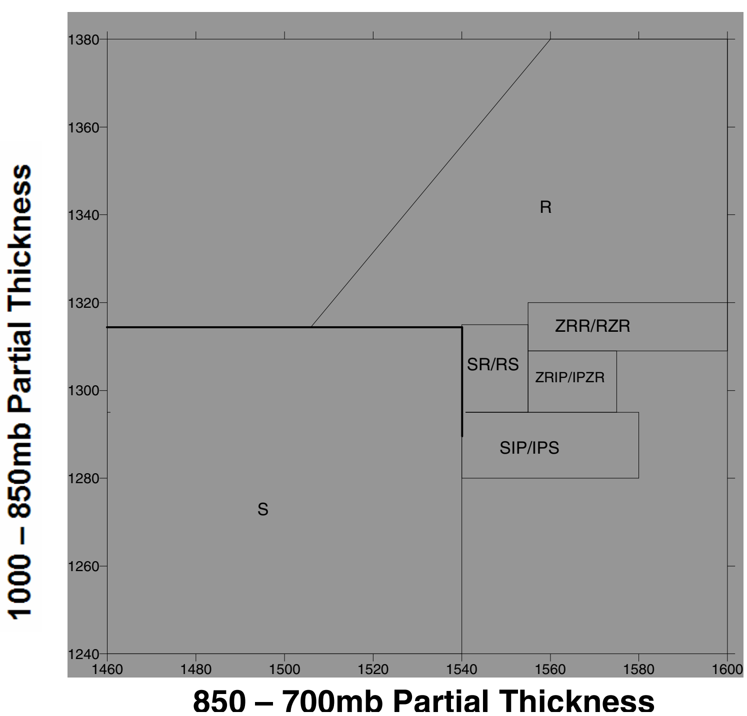
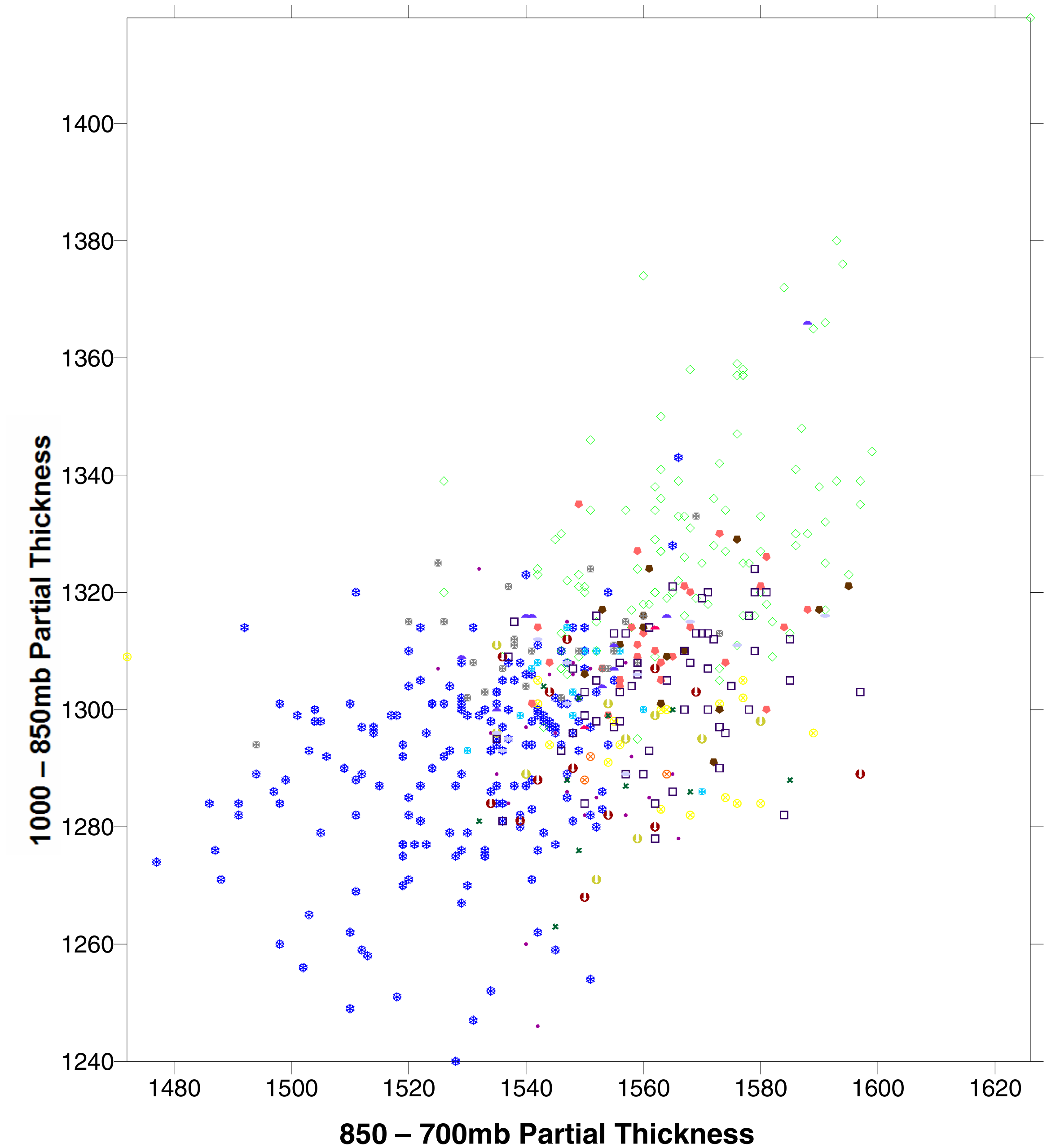


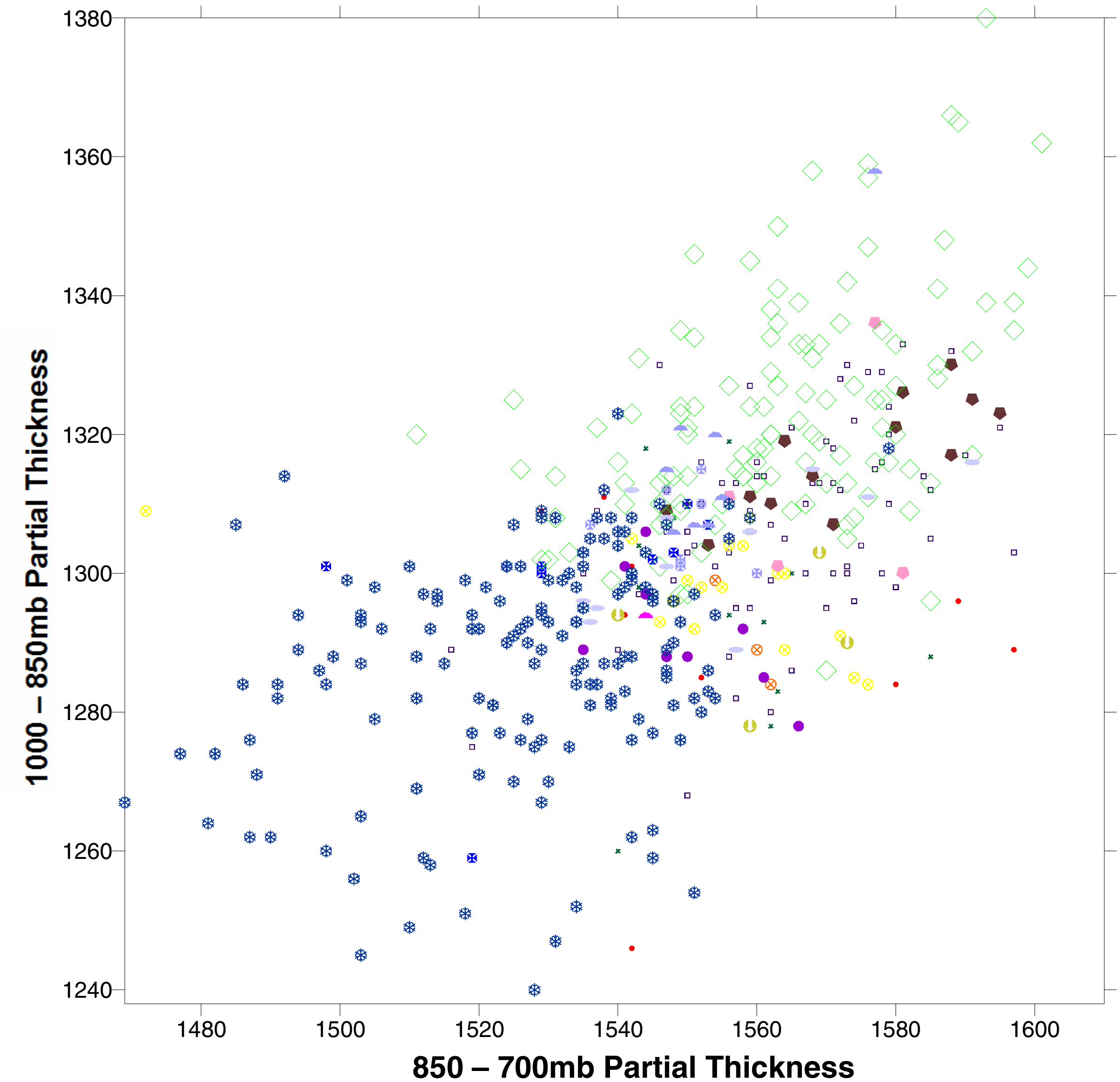
Figure 2.9 Three Hour Nomogram



Abbreviation	P-Type	Symbol
SS	All Snow	
RR	All Rain	
ZR	All Freezing Rain	
ZRIP	Freezing Rain/Ice Pellets	
IP	All Ice Pellets	
RZR	Rain/Freezing Rain	
D	Drizzle	
SIP	Snow/Ice Pellets	

Abbreviation	P-Type	Symbol
IPS	Ice Pellets/Snow	
SR	Snow/Rain	
RS	Rain/Snow	
RIP	Rain/Ice Pellets	
ZRS	Freezing Rain/Snow	
ZRR	Freezing Rain/Rain	
IPZR	Ice Pellets/Freezing Rain	
IPR	Ice Pellets/Rain	
SZR	Snow/Freezing Rain	

Figure 2.10 Six Hour Climatology



Abbreviation	P-Type	Symbol
SS	All Snow	
RR	All Rain	
ZR	All Freezing Rain	
ZRIP	Freezing Rain/Ice Pellets	
IP	All Ice Pellets	
RZR	Rain/Freezing Rain	
D	Drizzle	
SIP	Snow/Ice Pellets	

Abbreviation	P-Type	Symbol
IPS	Ice Pellets/Snow	
SR	Snow/Rain	
RS	Rain/Snow	
RIP	Rain/Ice Pellets	
ZRS	Freezing Rain/Snow	
ZRR	Freezing Rain/Rain	
IPZR	Ice Pellets/Freezing Rain	
IPR	Ice Pellets/Rain	
SZR	Snow/Freezing Rain	

Figure 2.11 Three Hour Climatology

2.5 Data Analysis

2.5.1 Nomogram Analysis

The six hour Greensboro nomogram and the three hour Greensboro nomogram were analyzed as to how well they predicted P-type of winter weather events. Soundings were plotted on the two nomograms in order to determine how many soundings were correctly classified. The two nomograms were compared to help determine what the effect the different methods have on the P-type regions on the nomograms. Each nomogram was also compared with the TRENDs nomogram.

The TRENDs nomogram was also analyzed using the sounding data in the study. The plots of the six hour and three hour classification method were plotted on the TRENDs nomogram in order to determine how many P-types were classified correctly.

2.5.2 Outlier Analysis

P-types that plot outside of the identified regions are defined as outliers. These are soundings where the nomogram fails to predict the p-type of an event. The analysis of these soundings may give a forecaster key variables to watch that influence P-type development in order to give a more accurate forecast. To obtain objectivity in finding all statistical outliers, a Euclidean z-score was calculated for each event. The Euclidian z-score is determined by taking the square root of the sum of the square of the distance between the 850-700mb and 1000-850mb partial thicknesses of each point and the centroid (average geometric point on a 2D surface) of the P-type (normalized distance).

$$Z\ score = SQRT((Normalized\ Distance_{\ 850\text{-}700})^2 + (Normalized\ Distance_{\ 850\text{-}1000})^2)$$

The z-score provides an objective measure of how much the partial thicknesses of a given sounding departs from the mean partial thicknesses associated with all observations of the given P-type. For this study, partial thickness pairs associated with a z-score that exceeds 2.0z are defined as outliers. In other words, those soundings that plot greater than 2 standard deviations from the centroid of its P-type were included as outliers.

2.5.3 Synoptic Data

Each event is classified into one of three groups according to its intensity (**Table 2.3**). The intensity categories are defined according to event return intervals as determined by Fuhrmann and Konrad. Relationships are then identified between the event intensities and the synoptic attributes (i.e. cyclone tracks and anticyclone presence/strength.)

The relationships are found by consolidating the data from the surface maps, the sounding data and the Greensboro winter weather database. Using time of the event as the linking parameter, a FORTRAN program (Konrad, 2006) was used to populate 101 different variables for each event.

P-Type	None	Light	Moderate	Heavy
Snow	0	0.1 up to 3 in	3 up to 7.8 in	7.8 in or greater
Freezing Rain	0	0.01 up to 0.24 in	0.25 up to 0.49 in	0.50 inches or greater
Sleet	0	1 to 2 hrs	3 to 4 hours	4.99 hours or greater

Table 2.3 P-Type Intensity Definitions

CHAPTER III
RESULTS AND DISCUSSION

3.1 Introduction

This chapter begins with a classification of vertical thermal structures by P-type using partial thickness nomograms at Greensboro and finishes with an analysis of synoptic patterns associated with different precipitation types (P-types). In the first section, emphasis is placed on the differences in classification methods in order to assign a P-type for each sounding. The second section focuses on the Six Hour and Three Hour Greensboro partial thickness nomograms and provides a statistical analysis for each nomogram. The section also includes a comparison with existing methods. The third section contains an analysis of the TRENDs nomogram. The fourth section explores the outliers in the partial nomogram classification by looking at each outlying event in order to determine why the event plots outside of the expected range of partial thicknesses for the given P-type. The fifth section searches for connections between cyclone tracks, P-type and their intensities at Greensboro. The fifth section examines relationships between cyclone tracking and p-type intensity. The sixth and final section of this chapter looks at the relationships between anticyclones, P-types and intensities.

3.2 Sounding Classification

Two sounding classifications (six hours following and three hours surrounding a sounding) were used to analyze P-type at Greensboro in this study. **Table 3.1** summarizes the classification of P-types for the two methods. The difference in the length of the observation has a profound effect on the outcomes of the two methods. The six hour method identifies more soundings (i.e. 6%) that are associated with precipitation and mixed precipitation types. The three hour method captures 2% more soundings associated with pure ice pellets (IP) and pure freezing rain (ZR), which indicates that the vertical profile needed for the formation of these pure P-types occurs on a shorter time scale. Using the six hour method, the vertical profile of the atmosphere is more susceptible to change due to the longer temporal scale, thus the tendency for more transitional P-types (8% greater).

Sounding Precipitation Type	3 Hours	6 Hours	Difference
No precipitation recorded	405 (47%)	356 (41%)	6%
SS - all snow	160 (18%)	168 (19%)	1%
RR - all rain	117 (13%)	103 (12%)	1%
ZR - all freezing rain	73 (8%)	58 (7%)	1%
ZRIP – Freezing rain/ice pellets	16 (2%)	18 (2%)	0
IP - all ice pellets	15 (2%)	11 (1%)	1%
RZR – rain/freezing rain	13 (1%)	27 (3%)	2%
D – drizzle	12 (1%)	12 (1%)	0
SIP – snow/ice pellets	10 (1%)	21 (2%)	1%
IPS – ice pellets/snow	10 (1%)	4 (0%)	1%
SR – snow/rain	9 (1%)	14 (2%)	1%
RS – rain/snow	9 (1%)	25 (3%)	2%
RIP – rain/ice pellets	8 (1%)	9 (1%)	0
ZRS – Freezing rain/snow	5 (1%)	10 (1%)	0
ZRR- Freezing rain/rain	4 (0%)	14 (2%)	2%
IPZR – ice pellets/freezing rain	3 (0%)	5 (1%)	1%
IPR – ice pellets/rain	1 (0%)	2 (0%)	0
SZR – snow/freezing rain	0 (0%)	13 (1%)	1%

Table 3.1 Classification of Soundings by P-Type

3.3 Nomogram Analysis

The following sections describe the 3-hour surrounding and 6-hour following classifications as well as the TRENDs 6-hour following classification. First, the six hour nomogram is analyzed by how well the plotted partial thicknesses fit in the P-type regions of the nomogram. Next, the three hour nomogram is analyzed using the same criteria. Then, a comparison of the six and three hour nomograms follows. Lastly, the partial thicknesses from this study are plotted on the TRENDs universal nomogram and compared to the six and three hour nomograms.

3.3.1 Six Hour Greensboro Nomogram

The Six hour nomogram was developed by using the plotted partial thicknesses of the assigned P-type 6 hour following the sounding to draw boundaries to best fit the data into regions that would best determine P-type outcome. Not all partial thickness plots of a certain P-type fit into a region due to the method used to assign P-type and atmospheric processes that influenced P-type change during the six hours following a sounding. The plots of the partial thicknesses were overlaid on the nomogram in order to determine how the 6 hour following classifications fit into the derived regions (**Fig 3.1**). Overall the nomogram classifies 62% of the P-types into the correct region (**Table 3.2**).

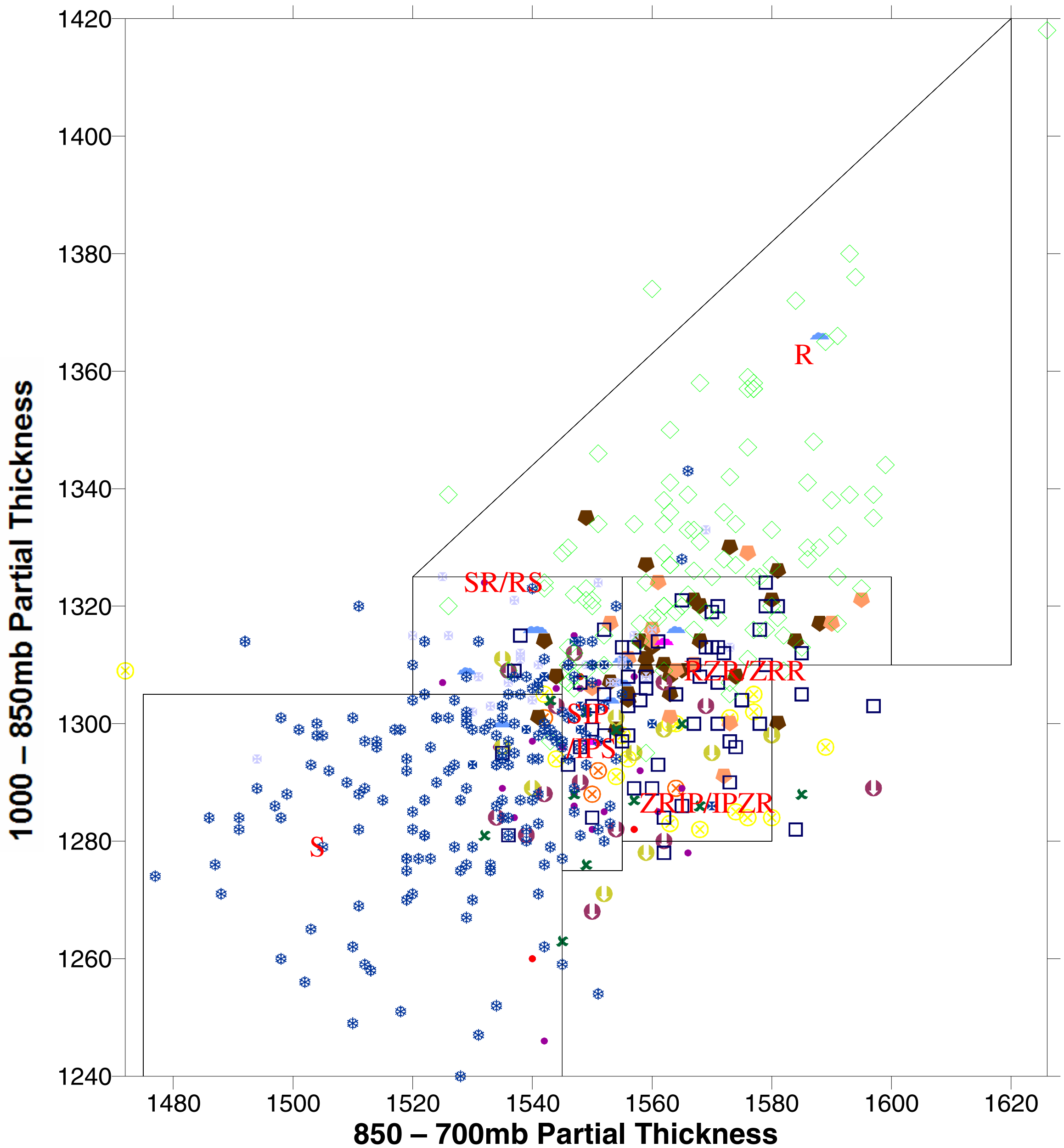
6hr P-type	P-Type Correctly Classified	Total Soundings	Percent of Sample
Snow	120	171	70%
Rain	59	104	57%
SR/RS	20	39	51%
SIP/IPS	9	25	36%
ZRIP/IPZR	14	23	61%
ZRR/RZR	21	41	51%
IP (Plotted into one of the IP regions)	7	11	64%
ZR (Plotted in one of the ZR regions)	41	58	71%
Total	291	472	62%

Table 3.2 Six hour Nomogram Statistics

The six hour classification plot identifies a crisp boundary where transitions from snow to rain or rain to snow frequently occur. As the partial thicknesses increase (decrease) the snow (rain) shows a crisp transition to rain (snow). The majority of pure rain and pure snow sounding plots that are misclassified fall into the transition regions of the nomogram where there are heavy concentrations of mixed events. Forecasters can use this line as a guideline for distinguishing snow versus rain events.

One limitation of the six hour Greensboro nomogram is that does not have separate regions for pure ice pellets (IP) and pure freezing rain (ZR). The partial thicknesses for ZR and IP plot in a large area on the nomogram grid. The six hour IP sounding classifications plot below 1310m on the 1000-850mb axis and between 1540m to 1570m on the 700 to 850mb axis. These numbers are indicative of a thick cold wedge and the presence of the warm nose. The six hour ZR sounding classifications plot in a box bounded by 1280m to 1320m on the 1000-850mb heights and 1540m to 1580m on the 700 to 850mb heights. These ranges define an atmospheric structure that has a thick warm nose and a shallow cold wedge. Drawing a separate boundary for both ZR and IP soundings would not have created a region with high predictability. The response to a forecast of IP or ZR mixed with another P-type would illicit a similar response.

A concentration of mixed p-type sounding classifications plot in what can be termed the transition zone. The SIP/IPS, ZRR/RZR, ZRIP/IPZR, SR/RS regions create a zone between the pure rain and pure snow plots. Subtle changes in the atmospheric column in short time periods can have a profound effect on the observed P-type. This is reflected by a modest 50% correct classification rate for transitional P-types.



Abbreviation	P-Type	Symbol
SS	All Snow	
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ZRIP	Freezing Rain/Ice Pellets	
IP	All Ice Pellets	
RZR	Rain/Freezing Rain	
D	Drizzle	
SIP	Snow/Ice Pellets	

Abbreviation	P-Type	Symbol
IPS	Ice Pellets/Snow	
SR	Snow/Rain	
RS	Rain/Snow	
RIP	Rain/Ice Pellets	
ZRS	Freezing Rain/Snow	
ZRR	Freezing Rain/Rain	
IPZR	Ice Pellets/Freezing Rain	
IPR	Ice Pellets/Rain	
SZR	Snow/Freezing Rain	

Figure 3.1 6hr Classification Soundings on the 6hr Greensboro Nomogram

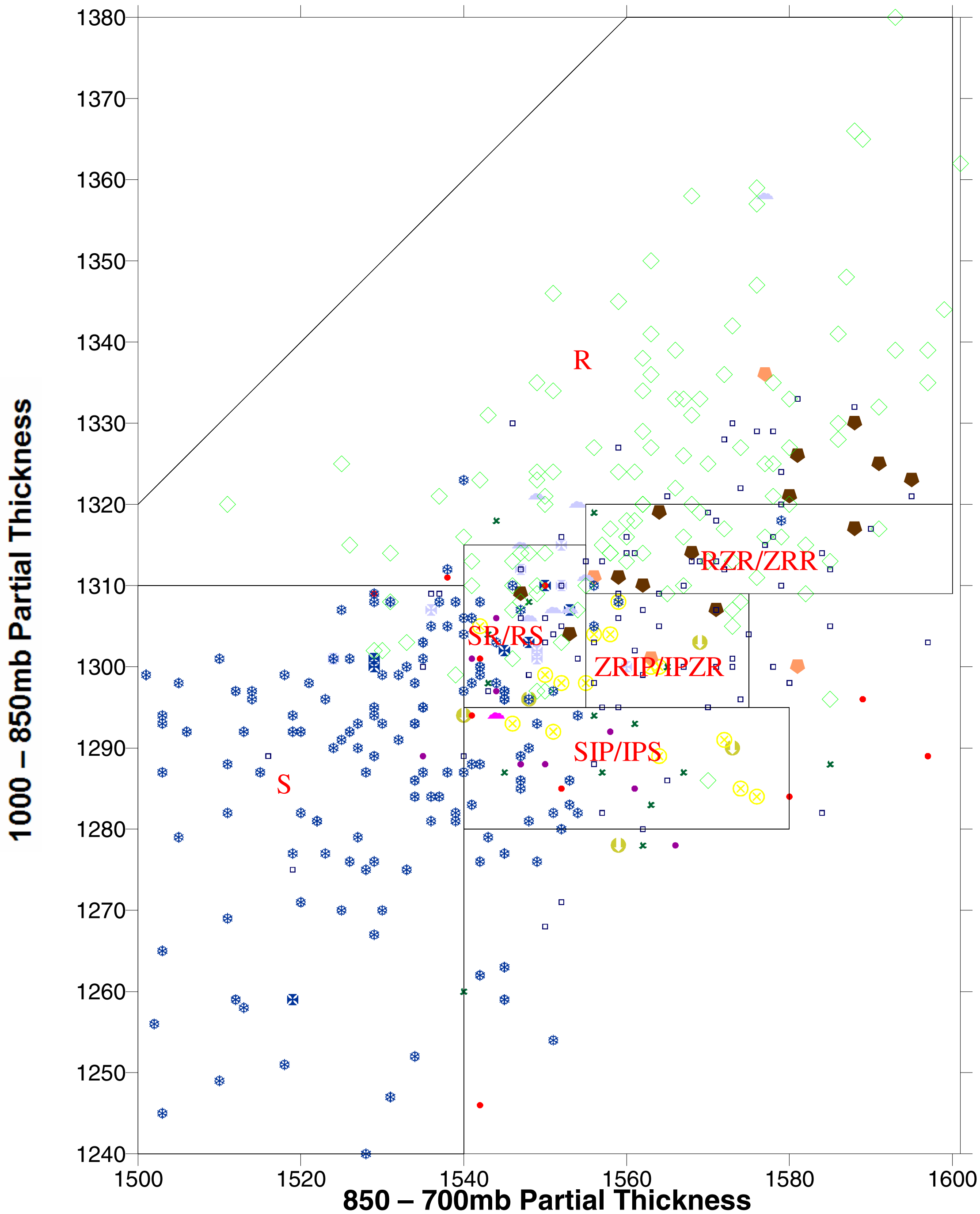
3.3.2 Three Hour Greensboro Nomogram

The three hour sounding classifications were plotted on to the Three Hour Greensboro nomogram in order to determine how the classifications fit into its derived regions (**Fig 3.2**). Overall, this classification classifies 54% of the P-types into the correct region (**Table 3.3**).

P-type	P-Type Correctly Classified	Total Soundings	Percent of Sample
Snow	107	160	67%
Rain	64	117	55%
SR/RS	9	18	50%
SIP/IPS	7	20	35%
ZRIP/IPZR	7	20	35%
ZRR/RZR	6	17	35%
IP (Plotted into one of the IP regions)	7	15	47%
ZR (Plotted in one of the ZR regions)	35	82	43%
Total	242	449	54%

Table 3.3 Three hour Nomogram Statistics

The three hour classification plot also identifies a crisp boundary where transitions from snow to rain or rain to snow frequently occur. 45% of the pure rain partial thicknesses plot in the transition zone as compared to only 23% for pure snow. Snow requires relatively low partial thicknesses (i.e. a cold atmosphere). In this case the vertical thermal profile typically lacks a warm nose thereby limiting the occurrence of ZR, IP or rain. Cold rain (supercooled water droplets) can fall in an atmosphere that is near isothermal (0^{o} C). Small changes to this vertical temperature profile (e.g. cold air advection near the surface or evaporative cooling under the cloud base) can transition cold rain into freezing rain or sleet. If there are no other forcings, pure rain will fall. Therefore, the majority of mixed P-types plot amongst the pure rain plots. All mixed P-type regions have 850-700mb partial thicknesses greater than 1540m. This confirms



Abbreviation	P-Type	Symbol
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RR	All Rain	
ZR	All Freezing Rain	
ZRIP	Freezing Rain/Ice Pellets	
IP	All Ice Pellets	
RZR	Rain/Freezing Rain	
D	Drizzle	
SIP	Snow/Ice Pellets	

Abbreviation	P-Type	Symbol
IPS	Ice Pellets/Snow	
SR	Snow/Rain	
RS	Rain/Snow	
RIP	Rain/Ice Pellets	
ZRS	Freezing Rain/Snow	
ZRR	Freezing Rain/Rain	
IPZR	Ice Pellets/Freezing Rain	
IPR	Ice Pellets/Rain	
SZR	Snow/Freezing Rain	

Figure 3.2 3hr Classification Soundings on the 3hr Greensboro Nomogram

the importance of the warm nose in the formation of ZR and IP. The three hour nomogram correctly identifies only 39% of all mixed P-types.

The three hour nomogram does not have separate regions for pure ice pellets and pure freezing rain. As with the six hour nomogram, the regions for pure IP and ZR would eliminate or reduce the area of many transitional P-types. The nomogram correctly classifies ZR soundings (plots into either ZRIP, IPZR, RZR or ZRR) 43% of the time. The three hour ZR sounding classification plots fall in wide range of thicknesses bounded by 1280m to 1330m on the 1000-850mb axis and 1540m to 1590m on the 700 to 850mb axis. ZR can be observed within this thicknesses range if the temperature at the surface is below freezing and the rain droplets are supercooled (near freezing). The three hour IP sounding classifications plot below 1320m on the 1000-850mb axis and between 1540m to 1590m on the 700 to 850mb axis. 50% of these observations plot within the SIP/IPS region.

3.3.3 Comparison of the Six Hour and Three Hour Greensboro Nomograms

The six hour nomogram offers a prediction of what P-type will be observed (based on a climatology) in the six hours following the sounding, while the three hour nomogram projects what is happening (based on a climatology) during the 3-hour period surrounding the sounding. The locations of the transition regions (mixed P-types) are where the greatest differences occur in the two nomograms (**Fig 3.3**).

The Six Hour Nomogram transition regions include a greater range of partial thicknesses especially in the 1000-850mb heights. Classifying using observations over six hours as opposed to three allows for more possible combinations of P-Types as well as for changes to occur in the atmospheric temperature profile over time. For example, the same sounding classified as rain using the three hour classification may plot as a RS event using the six hour classification.

On the Three Hour nomogram the mixed P-type regions plot where 1000-850mb heights are lower and 850-700mb heights are higher. This shifts the regions (especially SIP/IPS and SR/RS) down and to the right on the nomogram. This suggests that a more prominent temperature inversion (warm air over cold air) is associated with these P-types over a shorter time period. Much of the SR/RS region on the six hour nomogram plots as

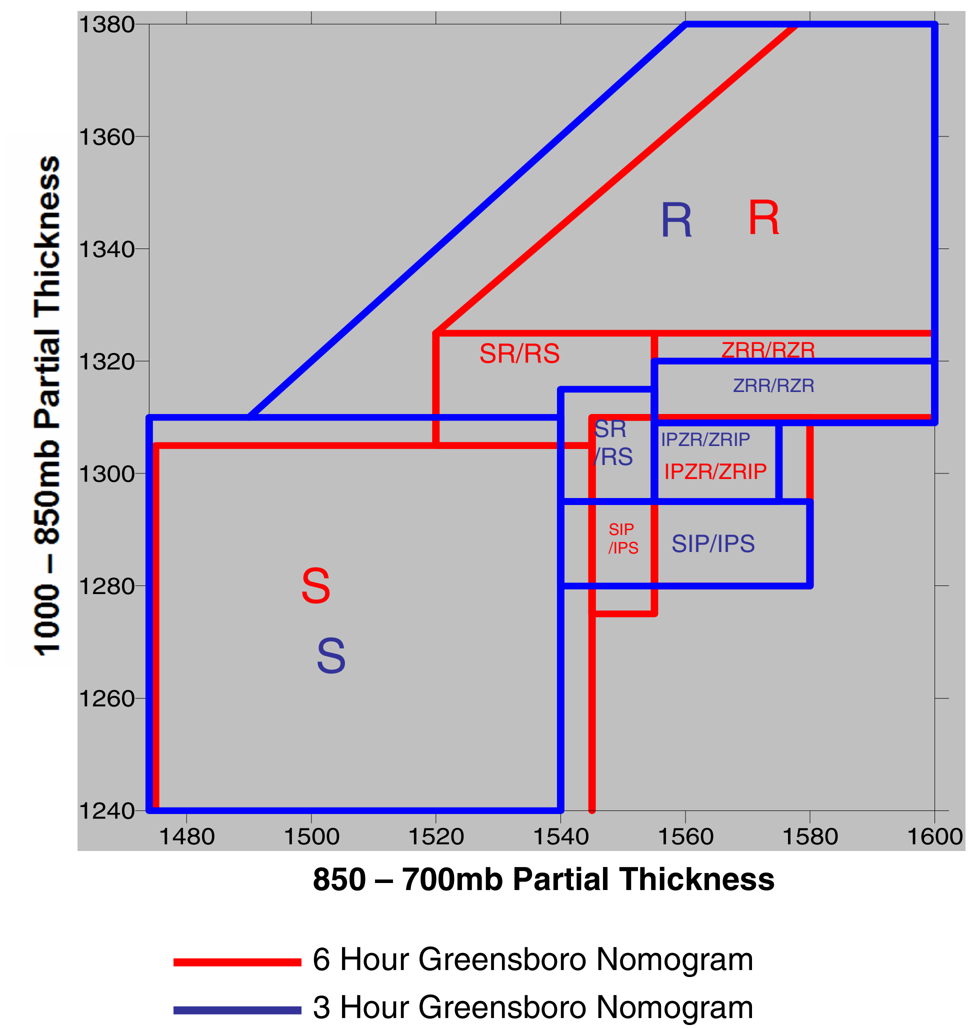


Figure 3.3 Differences in the Six and Three Hour Greensboro Nomograms

all rain or all snow on the Three Hour Nomogram, indicating that at a shorter temporal scale there is a greater likelihood of a pure rain or pure snow event to occur when the 850-700mb is below 1540.

3.3.5 Comparison to the TRENDs Universal Nomogram

The standard tool for winter weather forecasting in the Carolina Piedmont is the TRENDs Universal Nomogram. The regions on the TRENDs nomogram were developed using the six hour following classification method. The TRENDS method was developed to capture the range of P-types across the region (i.e. the North Carolina Piedmont) as opposed to at a point (i.e. Greensboro).

The display range for the TRENDS nomogram is from 1260m to 1350m on the 1000-850mb axis and 1515m to 1580m on the 850-700mb axis. The six hour and three hour nomograms expand this area to 1470m-1620m/1240m-1420m and 1460m-1600m/1240m-1380m respectively. This expansion is due to the inclusion of more data points by capturing events over a longer time period, capturing sounding before and after the occurrence of winter P-types, and by not discriminating out light or insignificant events. More soundings with a cold rain classification are included by recording the partial thicknesses of the soundings prior to a winter weather event starts. Many of these soundings plot with thicker (warmer) partial thicknesses (i.e. expands the nomograms up and to the right). The inclusion of light or insignificant snowfall soundings expands the nomograms where partial thicknesses are low (i.e. down and to the left) where very cold atmospheres produce snow.

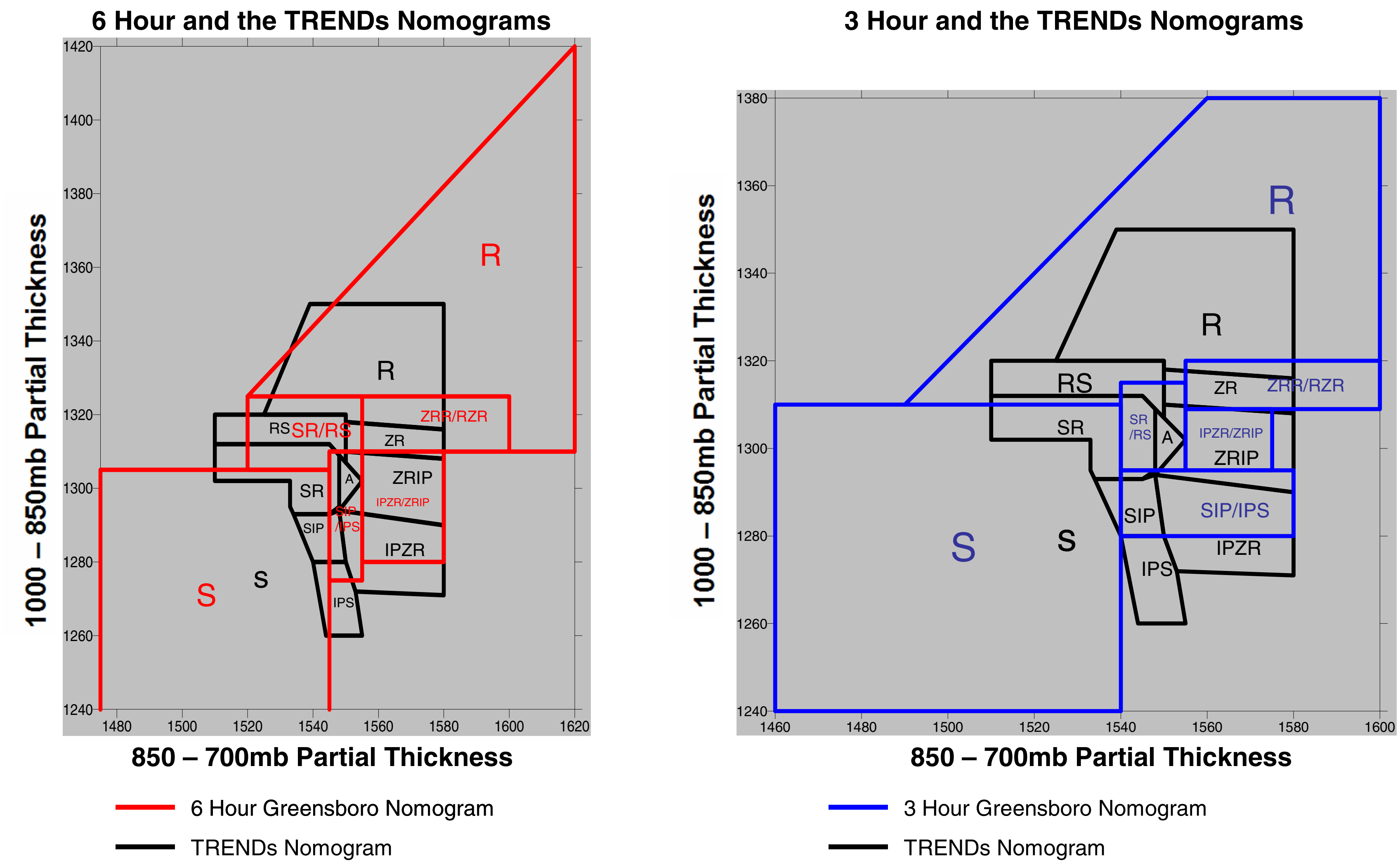


Figure 3.4 Comparison of the Six and Three Hour Greensboro Nomograms to the TRENDs Nomogram

The Six Hour Greensboro Nomogram, using the same classification method but with more events, has many similarities but differs in some areas (**Fig 3.4**). First, the TRENDs nomogram separates P-types into more regions (i.e. SIP/IPS into SIP and IPS.) The plots of the soundings of all winter weather events from 1958 to 1995 did not show any crisp separation of SIP/IPS, IPZR/ZRIP, ZRR/RZR, and SR/RS. Rather, most of these combinations of P-Types plotted intermixed in generally the same range of 1000-850mb and 850-700mb heights. Second, the boundary for the all snow region (S) on both of the six and three hour nomograms is shifted to the right on the 850-700mb axis. This suggests that all snow soundings occurred with warmer temperatures in the warm nose region at Greensboro than the TRENDs nomogram suggests for the region. Third, the Six Hour Greensboro nomogram's SIP/IPS regions are found where heights were greater on the 1000-850mb axis than on the TREND nomogram. The two nomograms are in general agreement when determining snow, rain, ZRIP/IPZR, ZR, and SR/RS.

The Three Hour Greensboro Nomogram, using the three hour classification method, has greater disparities. Many of the differences are similar to those found between the Six Hour and Three hour Greensboro Nomograms due to the classification schemes. There is the shift to the right in the 850-700mb heights but less of a shift in the 1000-850mb heights. The SIP/IPS and SR/RS regions have the most displacement. Also, the rain region on the Three Hour nomogram includes the majority of the RS region on the TRENDs nomogram. The nomograms compare similarly only in the ZR – ZRR/RZR region.

3.4 TRENDs Universal Nomogram Analysis

In the TRENDS scheme, events were selected on a subjective basis according to whether or not they had a societal impact in the Carolina Piedmont, not just at Greensboro, from 1971 to 2001. This definition limits the total amount of soundings used in the development of regions on the nomogram (eliminates light or trace precipitation events and events prior to 1971). The TRENDs nomogram performance was compared with the six hour classification sounding plots (**Fig. 3.5**) and the three hour sounding plots (**Fig 3.6**.).

The methods used for the development of the TRENDs nomogram presents some issues for comparison of sounding plots. 18% of snow soundings and 27% of rain soundings plotted outside the boundaries of the TRENDs nomogram. These snow soundings have low 1000-850mb and 850-700mb partial thickness values (i.e. plot down and to the right on the nomogram), which denotes a cold atmospheric profile that would support only snow. Likewise, the rain soundings plot in a region with high 1000-850mb and 850-700mb partial thicknesses. These heights indicate an atmosphere that would support rain. For the analysis in this section, if rain and snow plots clearly indicate snow or rain, the sounding was included in the correctly classified category. On the contrary, the 16% of mixed P-type events that fell outside of the TRENDs nomogram analysis area were not defined as correctly classified. These events did not plot in the best fit region developed by the TRENDs analysis. The boundaries for the mixed P-type regions were drawn with the data from selected events. Including any events outside of the TRENDs regions would induce subjectivity into the comparison.

When using the six hour classification data at Greensboro, the TRENDs nomogram correctly classified 54% of the winter weather soundings (**Table 3.4**), which is 8% lower than the results using the Six Hour Greensboro nomogram. The TRENDs nomogram correctly classifies only 28% of mixed events (SR, RS, IPS, SIP, IPZR, ZRIP, ZRR), but captures 64% IP and ZR soundings.

6 Hour P-type	P-Type Correctly Classified	Total Soundings	Percent of Sample
Snow	87	171	51%
Rain	76	104	73%
SR	5	14	36%
RS	4	25	16%
IPS	0	4	0%
SIP	2	21	10%
IPZR	3	5	60%
ZRIP	8	18	44%
ZRR	6	14	43%
IP (Plotted into one of the IP regions)	5	11	45%
ZR (Plotted into one of the ZR regions)	41	58	71%
Total	240	445	54%

Table 3.4 Statistics for the 6 hour P-Type Classification on the TRENDS Nomogram

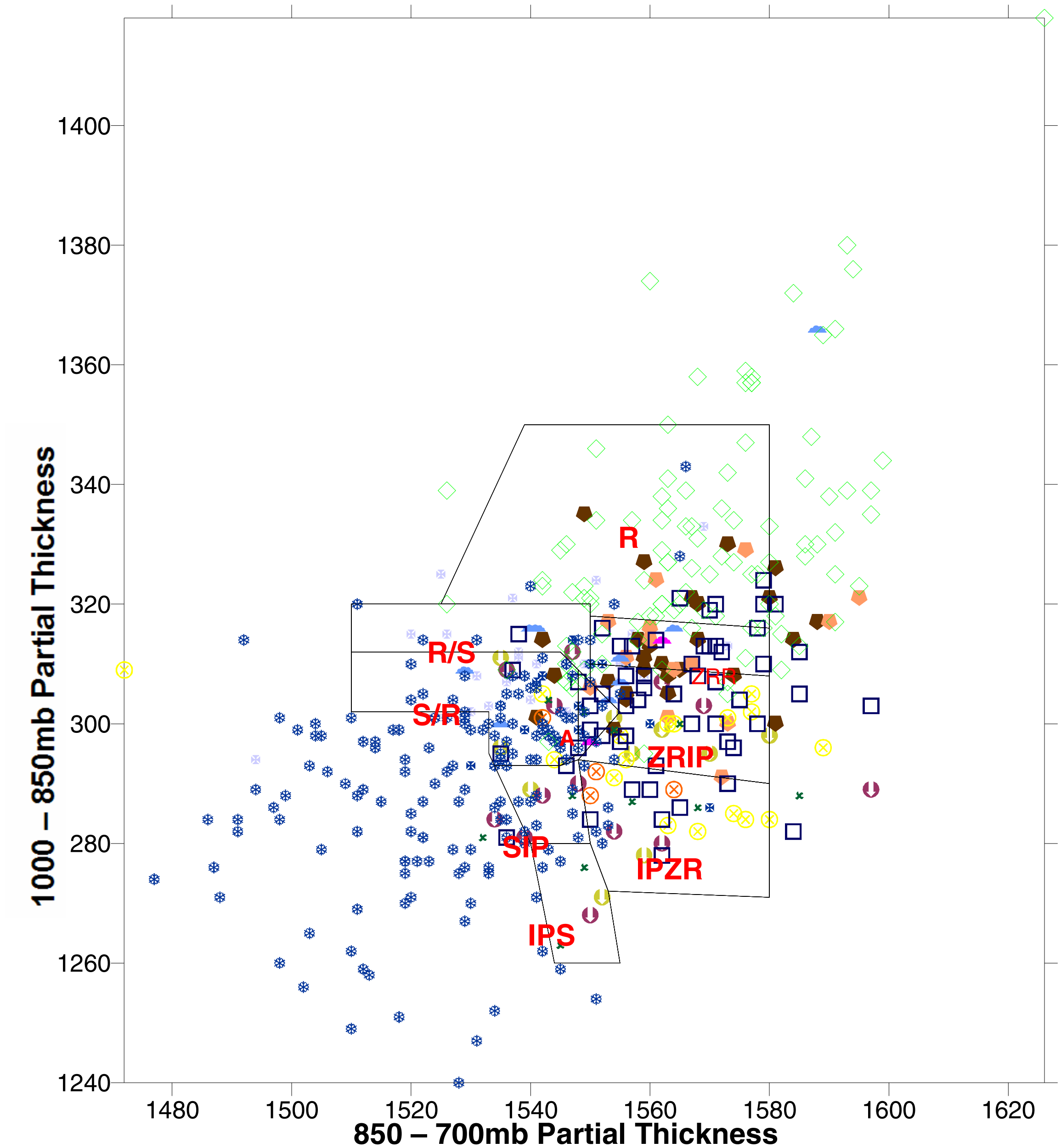
When the three hour classification method data was plotted on the TRENDs nomogram, it correctly classified 53% of all soundings (**Table 3.5**). It was expected that the TRENDs nomogram would not correctly account for as high of a percentage based on the fact that the nomogram was constructed using the 6 hour classification method. The TRENDs nomogram correctly classified 82% of the rain soundings; however the nomogram correctly classifies only 24% of mixed events, and only captures 49% IP and ZR soundings.

P-type	P-Type Correctly Classified	Total Soundings	Precent of Sample
Snow	84	171	49%
Rain	85	104	82%
SR	2	9	22%
RS	1	9	11%
IPS	0	10	0%
SIP	1	10	10%
IPZR	2	3	67%
ZRIP	8	17	47%
ZRR	1	4	25%
IP (Plotted into one of the IP regions)	1	15	7%
ZR (Plotted into one of the ZR regions)	47	82	57%
Total	232	434	53%

Table 3.5 Statistics for the 3 hour P-Type Classification on the TRENDs Nomogram

3.5 Outlier Analysis

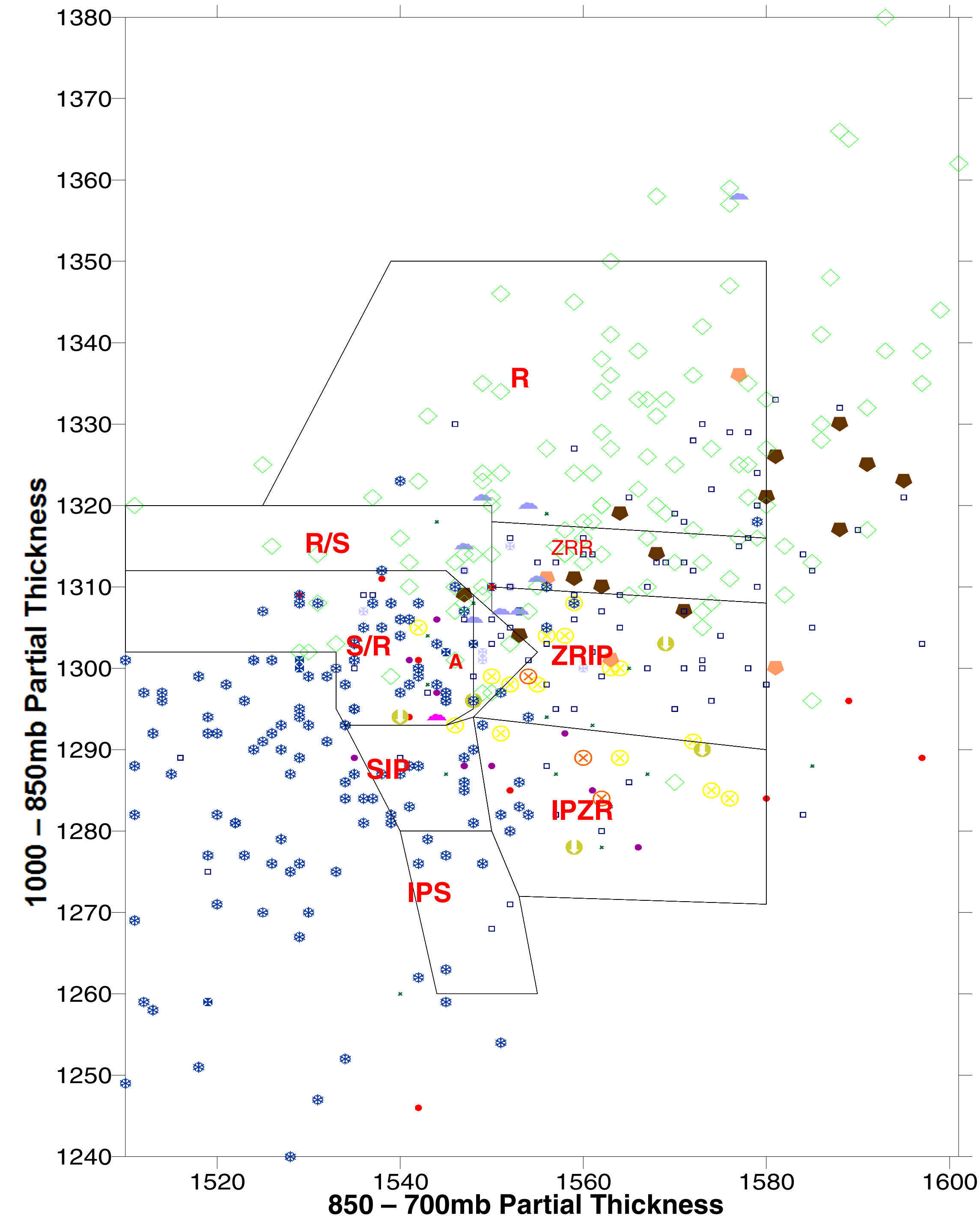
Statistical outliers, as referenced in the methodology, are soundings whose partial thickness of a particular P-type plots greater than two standard deviations from the centroid for all observations of that P-type. To be included as an outlier in this study, a sounding not only had to meet the statistical outlier definition, but it must have plotted outside of the P-type region (i.e. returned a forecast for a P-type other than the observed P-type for that sounding). An analysis of the outlier that fell outside of the nomogram region (i.e. where the tool failed) was needed in order to determine any variables the forecaster must be aware of in order to make the most accurate forecast. The study identified 45 six hour statistical outliers and as 24 three hour outliers. In the majority of the 6 hour outliers (67%) and half of the 3 hour outliers, the partial thicknesses forecast in a different P-type region on the nomogram than what was observed at Greensboro.



Abbreviation	P-Type	Symbol
SS	All Snow	
RR	All Rain	
ZR	All Freezing Rain	
ZRIP	Freezing Rain/Ice Pellets	
IP	All Ice Pellets	
RZR	Rain/Freezing Rain	
D	Drizzle	
SIP	Snow/Ice Pellets	

Abbreviation	P-Type	Symbol
IPS	Ice Pellets/Snow	
SR	Snow/Rain	
RS	Rain/Snow	
RIP	Rain/Ice Pellets	
ZRS	Freezing Rain/Snow	
ZRR	Freezing Rain/Rain	
IPZR	Ice Pellets/Freezing Rain	
IPR	Ice Pellets/Rain	
SZR	Snow/Freezing Rain	

Figure 3.5 6hr Classification Soundings on the TRENDs Universal Nomogram



Abbreviation	P-Type	Symbol
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ZR	All Freezing Rain	
ZRIP	Freezing Rain/Ice Pellets	
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SIP	Snow/Ice Pellets	

Abbreviation	P-Type	Symbol
IPS	Ice Pellets/Snow	
SR	Snow/Rain	
RS	Rain/Snow	
RIP	Rain/Ice Pellets	
ZRS	Freezing Rain/Snow	
ZRR	Freezing Rain/Rain	
IPZR	Ice Pellets/Freezing Rain	
IPR	Ice Pellets/Rain	
SZR	Snow/Freezing Rain	

Figure 3.6 3hr Classification Soundings on the TRENDs Universal Nomogram

3.5.1 Six Hour Classification Outliers

Outliers were identified for 14 different P-types using the six hour method (**Table 3.6, Fig 3.7**). The greatest numbers of statistical outliers were found in the all snow category (9). When plotted on the nomogram the majority (7 out of 9) of the cases fell in the all snow region. The partial thicknesses of these soundings record low heights in the 1000-850mb and the 850-700mb (i.e. a very cold vertical profile). The plots fall two standard deviations away from the transition region (i.e. down and right on the nomogram), forecasting the correct observed P-type.

The two statistical outliers for snow soundings that fall outside of the snow region plot in the rain region. The first snow sounding outlier, which was part of an event producing significant snow, had a surface temperature that was near freezing before (1.1^{o}C) and just below freezing (-1.7^{o}C) during the event. The atmosphere was dry at the surface (-8.3^{o}C Dew Point) and dry aloft (18^{o} dew point depression at the altitude in which the temperature and the dew point where the atmosphere is -10^{o}C) in the six hours before the event. In this case, moisture below the cloud base evaporated in the dry air cooling the atmosphere to below freezing allowing snow to reach the surface (i.e. evaporational cooling). The second snow sounding outlier, producing only light snow, was associated with a cold front. The temperatures in the column rapidly decreased as cold air wedged under the warmer air present at Greensboro. The front was responsible for the precipitation which fell as snow due to the cold air in place.

6 Hour Sounding Classification P-Type	Total Number of Soundings	Number of Statistical Outliers	Number of Outliers that plot outside of P-Type region
SS – all snow	168	9	2
ZR - all freezing rain	58	8	5
SIP – snow/ice pellets	21	4	4
RR – all rain	103	5	3
RZR – rain/freezing rain	27	3	2
SZR – snow/freezing rain	13	3	3
RS – rain/snow	25	2	2
ZRR- Freezing rain/rain	14	2	1
SR – snow/rain	14	2	0
IP - all ice pellets	11	2	2
ZRS – Freezing rain/snow	10	2	2
ZRIP – Freezing rain/ice pellets	18	1	1
RIP – rain/ice pellets	9	1	1
IPZR – ice pellets/freezing rain	5	1	1
IPR – ice pellets/rain	2	0	0
IPS – ice pellets/snow	4	0	0

Table 3.6 Outlier Statistics for the 6hr Classification

Three statistical rain outliers plotted outside the rain region on the nomogram. One outlier plotted in the snow rain/rain snow (SRRS) region recording slightly lower 1000-850mb heights (i.e. colder atmosphere) than anticipated. Warm air advection aloft was strong enough to offset decreasing 850-700mb heights that transitioned this event to snow. By next sounding in this event (+ 12hrs) recorded all snow. The other two rain outliers are a result of erroneous data for 1000-850mb heights. In the first instance, the sounding height recorded (737m) does not correspond to the sounding before (1359m) or the sounding after (1250m). In the other instance, the sounding height recorded (827m) also does not correspond to the sounding after (1278m).

Five freezing rain outliers plotted outside a region with freezing on the nomogram. The majority (80%) were associated with a cooling trend at the surface before the sounding. All of the soundings had lower 850-700mb heights than expected suggesting a weaker warm nose. In all five cases the 850 -700mb heights increased following the sounding, indicating a strengthening of the warm nose. Even though the

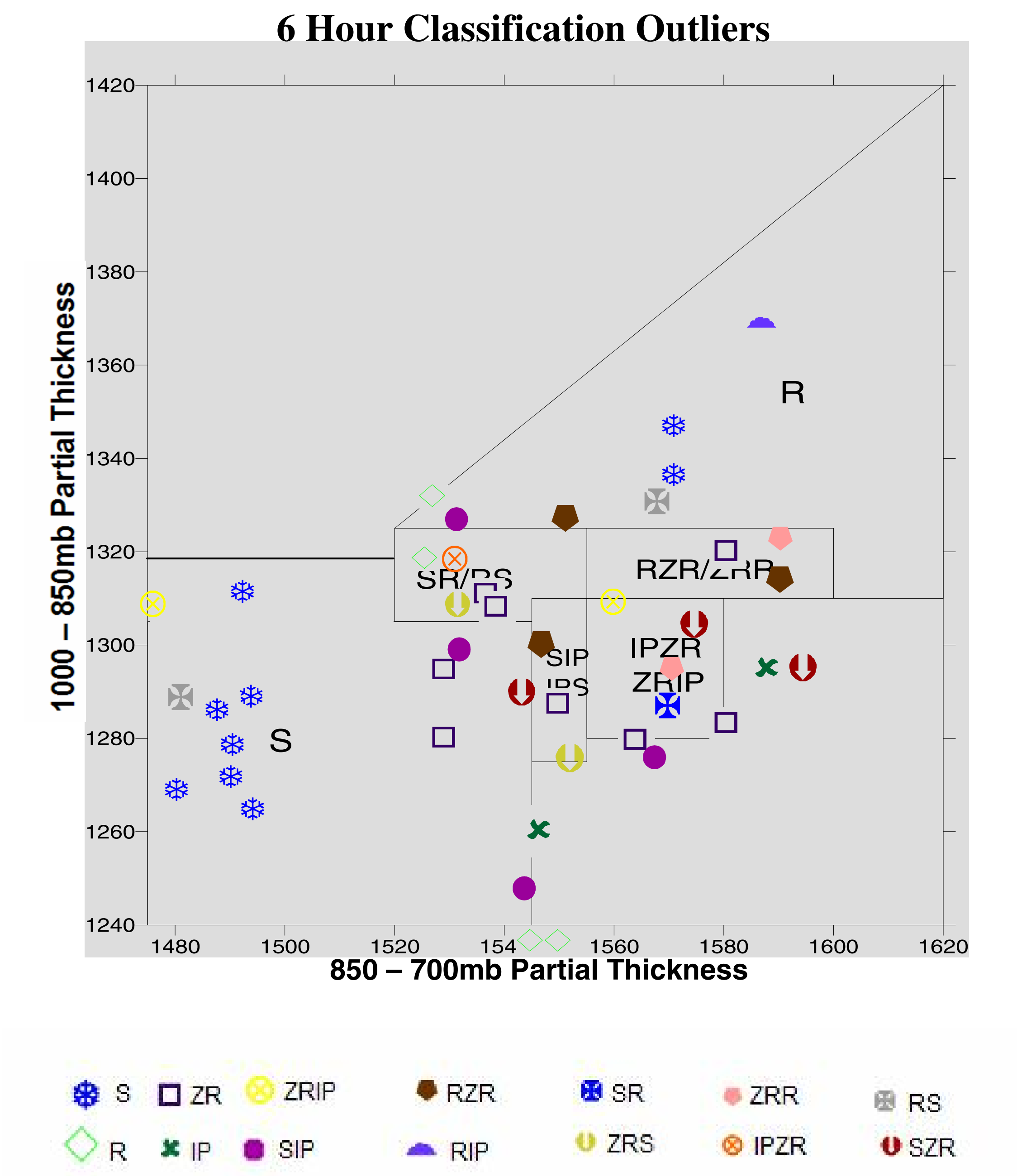

Figure 3.7 Six Hour Outliers

soundings plotted in the snow, SRRS or snow/ice pellet (SIP) regions, over the six hours following the sounding warm air advection created a warm nose that melted snow that refroze in the remaining shallow cold wedge. The two IP outliers plotted in areas on the nomogram where no P-type was defined. These areas could support IP due to the presence of a cold wedge (low 1000-850mb heights) and a warm nose (850-700mb height greater than 1545m.)

Soundings defined as mixed P-types provide a difficult area for analysis. These soundings capture the two most dominant P-types as transitions occur usually from snow to rain or from rain to snow. Atmospheric processes can help to explain some of the mixed P-type sounding outliers. For instance, of the two rain/freezing rain outliers, one is transitioning to freezing rain, the other is transitioning to rain. The first case plots in the all rain region, however a strong eastern anticyclone is advecting cold air at the surface allowing for the transition to ZR within six hours. The second case plots in the SIP region, however in the six hour following the sounding, the cold wedge erodes not allowing IP. ZR is observed for a short duration followed by rain for the majority of hours following the sounding. There are three different cases for SZR sounding outliers. In the first case, the sounding plots in the snow region, however snow is transitioning to rain. WAA aloft creates a warm nose melting the snow which refreezes at the surface in a cold wedge sustained by an eastern anticyclone. In the second case (plots in the IPZR region) snow is the dominant P-type when freezing rain transitions to snow as a passing Miller A cyclone rapidly cools the atmospheric column. In the last case (plots in IPZR), evaporative cooling aloft (high dew point depression at -10^{o}C) erodes the warm nose and allows snow to reach the cold wedge and fall to the ground.

The one SR outlier plots in the IPZR region. The partial thickness trajectory of this event (from rain to snow) goes through the IPZR region, but because of the rapid cooling of the atmosphere, neither IP nor ZR was a dominant P-type. The outliers for RS present two different cases. In the first case (plots in the all snow region), WAA from the secondary cyclone rapidly warms the atmosphere during the six hours following the sounding transitioning snow to rain. In the second case, rain is transitioning to snow as a cold front passes over Greensboro. The front passes quickly cooling the atmosphere over Greensboro allowing for a short period of snow to fall. Evaporative cooling explains the IPZR outlier that plots in the SRRS region. WAA warms the column aloft. The cold wedge is very shallow, but at the time of the sounding the air is very dry at the surface. Evaporative cooling near the surface deepens the cold wedge.

The RIP outlier that plots in the rain region may be an artifact of a bad observation. During the six hours following the sounding, the surface temperature is well above freezing (greater than 10^{o}C), thus indicating that ice cannot form. The data for the ZRIP outlier for the 850-700mb height (1472m) is not consistent with the soundings prior (1544m) and after (1553m), therefore the recordings are deemed not accurate.

3.5.2 3 Hour Classification Outliers

The three hour method produced 24 outliers over 11 different P-type classifications (**Table 3.7, Fig 3.8**). The greatest numbers of outliers were found in the all snow and all rain categories (7). Six of the statistical snow outliers (87%) plotted in the all snow region. The partial thicknesses of these soundings record low heights in the 1000-850mb and the 850-700mb. The one all snow sounding that plots in the RZR/RRZ region is part of an event that had no measurable snow and then transitioned to rain. Evaporative cooling in a dry atmosphere (10^{o}C dew point depression) allowed snow to

3 Hour Sounding Classification Precipitation Type	Total Number of Soundings	Number of Statistical Outliers	Number of Outliers that plot outside of P-Type region
SS - all snow	160	7	1
RR - all rain	117	7	2
IP - all ice pellets	15	2	2
ZR - all freezing rain	82	1	1
ZRIP – Freezing rain/ice pellets	17	1	1
RZR – rain/freezing rain	13	1	1
IPS – ice pellets/snow	10	1	1
SIP – snow/ice pellets	10	1	0
RS – rain/snow	9	1	1
SR – snow/rain	9	1	0
RIP – rain/ice pellets	8	1	0
IPR – ice pellets/rain	1	0	0
IPZR – ice pellets/freezing rain	3	0	0
SZR – snow/freezing rain	0	0	0
ZRR- Freezing rain/rain	4	0	0
ZRS – Freezing rain/snow	5	0	0

Table 3.7 Outlier Statistics for the 3hr Classification

persist in the air. The warm surface temperatures did not allow for accumulation. Only two statistical rain outliers fall outside of the all rain region on the three hour nomogram. These two soundings contained erroneous data as explained in the six hour analysis. The two IP outliers plotted in areas on the nomogram where no P-type was defined. These areas could support IP due to the presence of a cold wedge (low 1000-850mb heights) and a warm nose (850-700mb height greater than 1545m.)

The three hour method produced only a few outliers (4) that plot outside of their respective regions. The IPS sounding outlier captures the transition from IP to snow due to cold air advection aloft. The outlier plots in an unmarked region between SIP/IPS and the all snow region. The RS outlier plots in the all snow region with slightly lower 850-700mb heights than expected. In this event the surface temperature, as well as the 1000-850mb height, slightly decreases. The sounding captures rain (the hour before and during the sounding) transitioning into snow (the hour after the sounding) in a cooling atmosphere. The sounding outlier for RZR captures an event that transitions from rain to freezing rain to ice pellets. The outlier plots in the SRRS region with lower 1000-850mb and 850-700mb heights than expected. At the sounding time, the atmosphere near the surface is dry (-7.7°C dew point, -0.7°C Surface temperature). Evaporation cooled the atmosphere to the freezing point at the surface to allow for freezing rain.

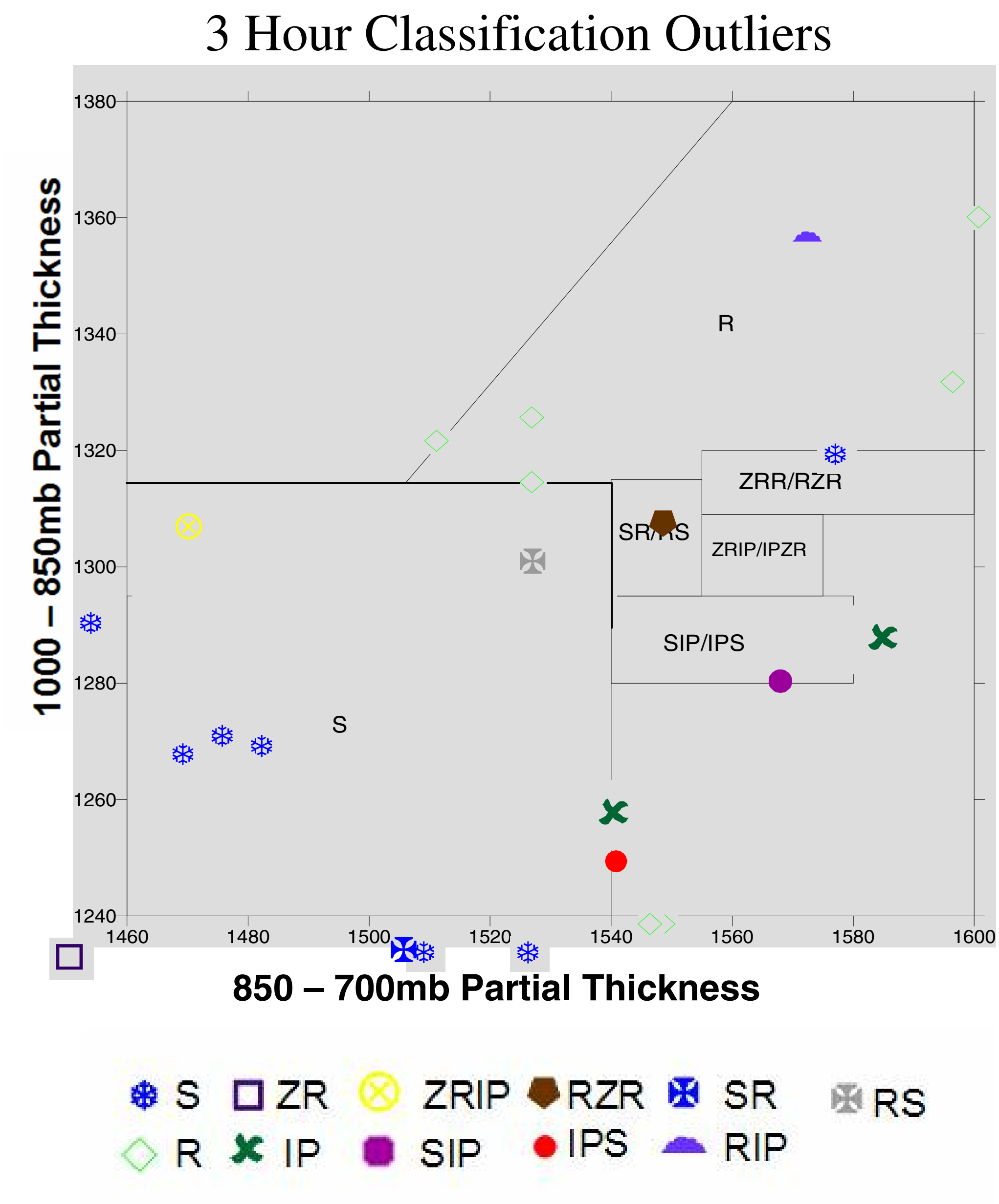

Figure 3.8 3 Hour Classification Outliers

The data for the ZRIP outlier for the 850-700mb height (1472m) was not consistent with the soundings prior (1544m) and after (1553m), therefore the recordings were deemed not accurate. Likewise the data for the ZR outlier was inconsistent in both the 1000-850mb (1276m to 1063m) and the 850-700mb (1549m to 1290m) heights with the sounding 12 hours before. The surface temperatures for this event have a warming trend. A drop from 1276m to 1063m at 1000-850mb would indicate a significant drop in surface temperature.

3.5.3 Summary of Outliers

The six hour classification identified nearly twice as many outliers as the three hour classifications. The atmospheric profile in the six hours following the sounding showed much greater changes as adiabatic and diabatic processes had a longer time to change the vertical thermal profile. The three hour classification method, showed less drastic change. Proximity of observations from the sounding are another factor of this discrepancy. The last observation used in the study was six full hours removed from the balloon launch in the six hour classification. In the three hour classification, observations are used only one hour from the balloon launch. This explains the increased accuracy for the three hour method.

The partial thickness nomograms are tools that provide guidance, but do have instances where they fail. Forecasters must be aware of the influence of diabatic and adiabatic processes on the atmosphere when using the nomogram. Evaporative cooling and advection patterns (warm and cold) were identified as the main processes that influence the P-type in outlier cases.

3.6 Cyclone Tracks

In the following sections events are analyzed by cyclone type. Maps were constructed that show the tracks of Miller A (**Fig 3.9**) and Miller B (**Fig 3.10**) cyclones, respectively stratified by P-type and intensity.

3.6.1 Miller A Tracks

No clear differences are evident in the tracks of Miller A cyclones associated with snow versus freezing rain. Much variability, however, exists in the tracking of Miller A cyclones associated with snow and freezing rain at Greensboro. This variability decreases markedly in the sample of events displaying significant amounts of snow and freezing rain. The majority of these events are tied to cyclones that track offshore southeast of the Carolina coast. Miller A cyclones associated with sleet display less track variability with most of them tracking offshore of the Carolina Coast.

3.6.1a Snow

A heavy concentration of Miller A cyclone tracks producing snow make landfall on the Florida panhandle near Panama City (30.0^{o} Lat, -85.4^{o} Lon) and hit the Atlantic Ocean near the South Carolina/Georgia border (32.0^{o} Lat, 81.0^{o} Lon). Cyclones tracking west of Panama City or north of the border did not result in heavy snowfall. Heavy snowfall cyclones exhibited a slower rate of speed (influences study area for a longer

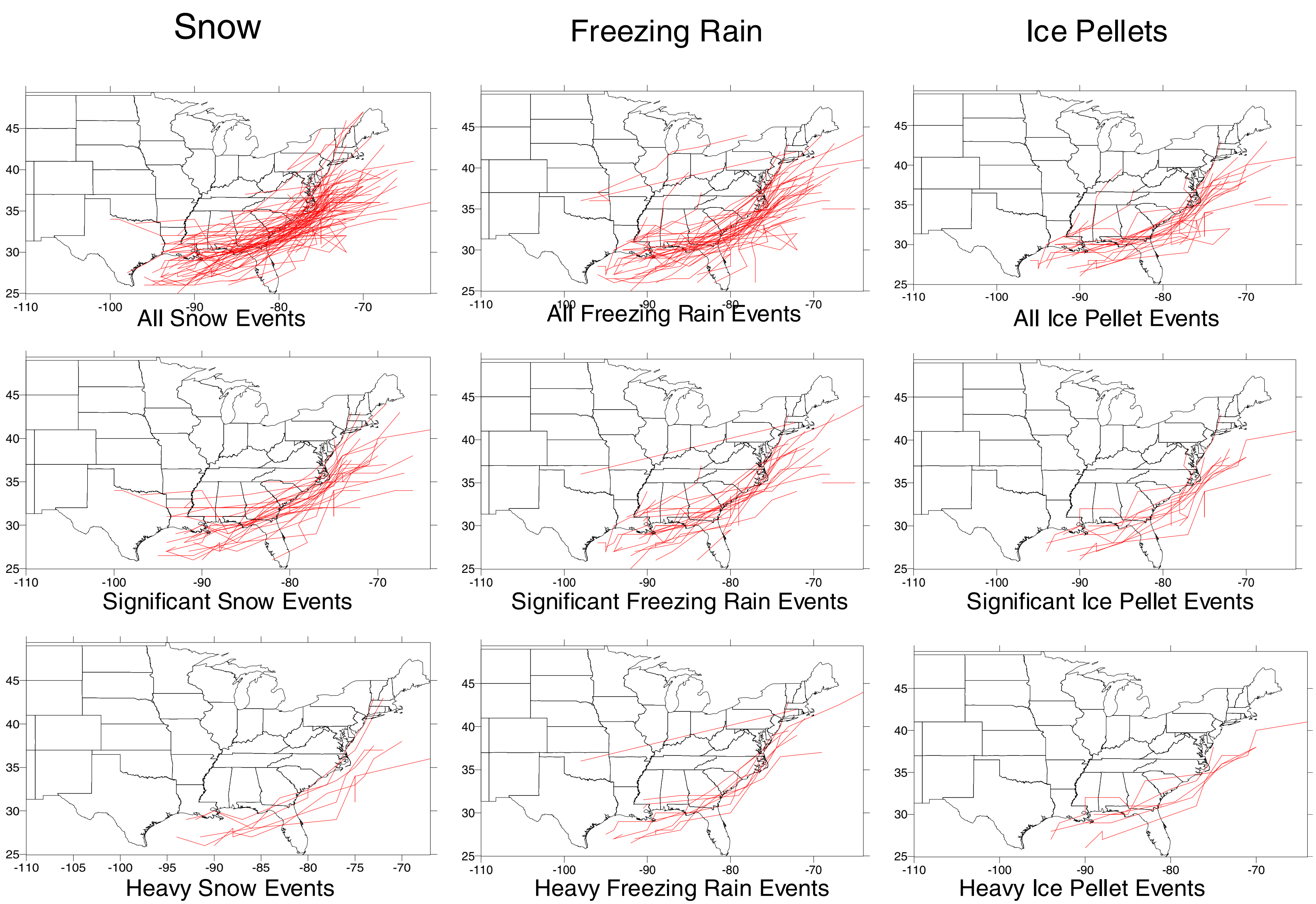

Figure 3.9 Miller A Tracks Producing Winter P-types

	Min Distance to Greensboro	Average Speed	Average Pressure	Pressure Change (from cycloenesis to 40^{o} LAT)
All Snow Events	221km	34km/hr	1003mb	3mb
Significant Snow	229km	23km/hr	1001mb	19mb
Heavy Snow	223km	20km/hr	1001mb	25mb

Table 3.8 Characteristics of Miller A Snow Producing Cyclones

duration) as well as a greater change in pressure (creates more dynamic forcing) (**Table 3.8).**

3.6.1b Freezing Rain

Miller A tracks associated with freezing rain are similar to those associated with snow, however the heaviest ZR events track closer to Greensboro (**Table 3.9**). Regions closer to the cyclone center tend to have shallower cold wedges coupled with enough warm air advection required for freezing rain.

	Min Distance to Greensboro	Average Speed	Average Pressure	Pressure Change (from cycloenesis to 40^{o} LAT)
All Freezing Rain Events	68km	27km/hr	1007mb	13mb
Significant Freezing Rain	101km	16km/hr	1007mb	11mb
Heavy Freezing Rain	119km	17km/hr	1002mb	13mb

Table 3.9 Characteristics of Miller A Freezing Rain Producing Cyclones

3.6.1c Ice Pellets

The pressure and the pressure change of a Miller a cyclone is not a factor in determining the intensity of ice pellets. Heavy ice pellet events, however, are associated with a fast moving cyclone that tracks off the Carolina coast (**Table 3.10**).

	Min Distance to Greensboro	Average Speed	Average Pressure	Pressure Change (from cycloenesis to 40^{o} LAT)
All Ice Pellet Producing Events	110km	14km/hr	1006mb	13mb
Significant Ice Pellets	155km	18km/hr	1006mb	13mb
Heavy Ice Pellets	213km	37km/hr	1007mb	13mb

Table 3.10 Characteristics of Miller A Ice Pellet Producing Cyclones

3.6.2 Miller B Tracks

No great disparities are evident in the primary or secondary tracks of Miller B cyclones associated with snow versus freezing rain versus ice pellets. Much variability exists in the primary and secondary tracks associated with all three P-types at Greensboro. IP and ZR show primary cyclone variability throughout the progression of intensities, while with the heaviest snows the variation is decreased. The majority of the secondary cyclones for snow and ZR track off the coast of the Carolinas. Secondary Miller B cyclones associated with sleet display more track variability.

3.6.2a Snow

The primary Miller B cyclones of snow producing events track east of Greensboro (greater than 397km) and travel fast (greater than 43km/hr) (**Table 3.11**). A high proportion of the tracks for significant/heavy snow pass through Tennessee. Cyclonegenesis of the secondary Miller B cyclone associated with significant and heavy snow occurs off the Carolina coast.

Primary Cyclone	Min Distance to Greensboro	Average Speed	Average Pressure	Pressure Change (from 100^o LON to no cyclone)
All Snow Producing Events	524km	56km/hr	1008mb	7mb
Significant Snow	449km	47km/hr	1007mb	7mb
Heavy Snow	397km	43km/hr	1011mb	2mb
Secondary Cyclone	Min Distance to Greensboro	Average Speed	Average Pressure	Pressure Change (from cycloenesis to 40^o LAT)
All Snow Producing Events	560km	53km/hr	1002mb	9mb
Significant Snow	514km	65km/hr	1002mb	10mb
Heavy Snow	407km	55km/hr	1002mb	13mb

Table 3.11 Characteristics of Miller B Snow Producing Cyclones

3.6.1b Freezing Rain

Two outliers exist in the primary cyclone tracks that are associated with ZR. Although the tracks pass through Iowa, Wisconsin, and Michigan of freezing, they are associated with a secondary cyclogenesis off the Carolina coast. The secondary cyclones track slightly closer to Greensboro than the snow confirming results found in Miller A events. The heaviest ZR events are associated with stronger (i.e. 992mb average) and deepening (i.e. 20mb average change) secondary cyclones (**Table 3.12**).

Primary Cyclone	Min Distance to Greensboro	Average Speed	Average Pressure	Pressure Change (from 100^o LON to no cyclone)
All Freezing Rain Producing Events	591km	93km/hr	1009	8mb
Significant Freezing Rain	663km	59km/hr	1005	10mb
Heavy Freezing Rain	586km	35km/hr	1004	11mb
Secondary Cyclone	Min Distance to Greensboro	Average Speed	Average Pressure	Pressure Change (from cycloenesis to 40^o LAT)
All Freezing Rain Producing Events	570km	51km/hr	1006mb	11mb
Significant Freezing Rain	489km	54km/hr	1005mb	11mb
Heavy Freezing	281km	52km/hr	992mb	20mb

Table 3.12 Characteristics of Miller B Freezing Rain Producing Cyclones

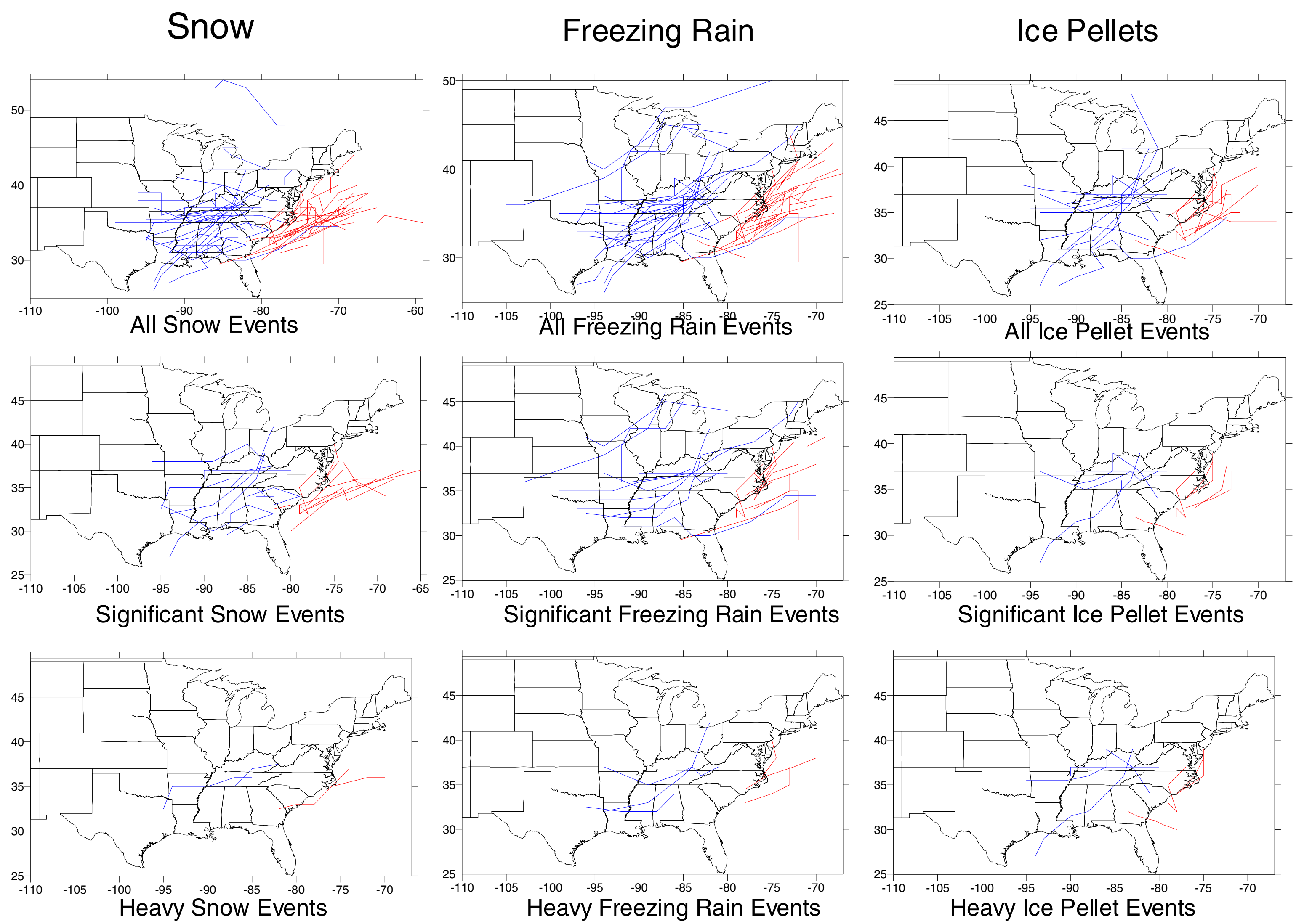

Figure 3.10 Miller B Tracks Producing Winter P-types

3.6.2c Ice Pellets

The majority of Miller B primary cyclones associated with IP weaken as they move quickly through Tennessee (**Table 3.13**). Secondary cyclogenesis occurs as far south as Georgia north to Virginia.

Primary Cyclone	Min Distance to Greensboro	Average Speed	Average Pressure	Pressure Change (from 100^o LON to no cyclone)
All Ice Pellet Producing Events	556km	58km/hr	1007mb	8mb
Significant Ice Pellets	553km	55km/hr	1010mb	8mb
Heavy Pellets	534km	66km/hr	1011mb	14mb
Secondary Cyclone	Min Distance to Greensboro	Average Speed	Average Pressure	Pressure Change (from cycloenesis to 40^o LAT)
All Ice Pellet Producing Events	453km	54km/hr	1005mb	9mb
Significant Ice Pellets	493km	50km/hr	1004mb	8mb
Heavy Ice Pellets	500km	45km/hr	1008mb	7mb

Table 3.13 Miller B Freezing Rain Producing Cyclones

3.6.3 Summary

The path an extra tropical cyclone takes does not directly correlate to the amount of snow, freezing rain or sleet an event will produce. On the contrary, similar Miller A and Miller B cyclone tracks produce light, significant and heavy snow, freezing rain and sleet.

3.7 Anticyclone Analysis

An anticyclone located in Eastern Canada or the Northeast US often acts as the source of cold air for winter weather events in the North Carolina Piedmont. In the following sections, the presence and strength of an anticyclone is associated with the intensity of different P-types by cyclone type (i.e. Miller A and B).

3.7.1 Anticyclones with Miller A Tracks

3.7.1a Snow

The majority of Miller A snow events (i.e. 85%) have an associated eastern anticyclone (**Table 3.14**). Significant snow events occur at a greater proportion with a weaker anticyclone (i.e. 21% greater than strong) as defined in the methodology. Stronger anticyclones are associated proportionally with the least amount of snow events (i.e. 64%). This may correlate with the presence of too much cold air, which hinders the moisture necessary for heavier snow.

East	Range	No Snow	Light Snow	Significant Snow
None	N/A	4 11%	8	3 9%
Weak Anticyclone	1016-1029	9 25%	24	14 56%
Strong Anticyclone	1030-1048	23 64%	15	10 35%

Table 3.14 Anticyclone Strength resulting in Snow with a Miller A Cyclone Track

3.7.1b Freezing Rain

An overwhelming majority of Miller A freezing rain events (i.e. 98%) have an associated eastern anticyclone (**Table 3.15**). A high proportion of significant ZR events (71%) are associated with strong anticyclones. Strong anticyclones in the Northeast provide a stronger, persistent, stream of cold as well as dry air, which encourages evaporational cooling.

East	Range	No ZR	Light ZR	Significant ZR
None	N/A	14 22%	0	1 5%
Weak Anticyclone	1016-1029	32 50%	10	5 24%
Strong Anticyclone	1030-1048	18 28%	15	15 71%

Table 3.15 Anticyclone Strength resulting in Freezing Rain with a Miller A Cyclone Track

3.7.1c Ice Pellets

A majority of Miller A IP events (i.e. 91%) have an associated eastern anticyclone (**Table 3.16**). Half of the significant IP events are associated with strong anticyclones. Ice pellets require a deep cold wedge above the surface in order to refreeze water droplets. A region of cold air at the surface (below freezing surface temperatures before and during the event) was in place in the region during the two events not associated with an anticyclone to the northeast.

East	Range	No IP	Light IP	Significant IP
None	N/A	13 15%	0	2 17%
Weak Anticyclone	1016-1029.4	41 47%	2	4 33%
Strong Anticyclone	1030-1048	34 38%	8	6 50%

Table 3.16 Anticyclone Strength resulting in Ice Pellets with a Miller A Cyclone Track

3.7.2 Miller B track Anticyclones

3.7.2a Snow

The majority of Miller B snow events (i.e. 91%) have an associated eastern anticyclone (**Table 3.17**). Like in Miller A events, significant snow events occur at a greater proportion with a weaker anticyclone (i.e. 19% greater than strong.) Also similar to Miller A events, stronger anticyclones are proportionally associated with the least amount of snow events (50%).

East	Range	No Snow	Light Snow	Significant Snow
None	N/A	1 3%	2	1 9%
Weak Anticyclone	1013-1028	14 47%	11	6 55%
Strong Anticyclone	1029-1044	15 50%	12	4 36%

Table 3.17 Anticyclone Strength resulting in Snow with a Miller B Cyclone Track

3.7.2b Freezing Rain

All Miller B cyclones associated with freezing rain had an associated eastern anticyclone (**Table 3.18**). A slight majority of significant events were associated with a stronger anticyclone (10% greater than a weak anticyclone).

East	Range	No ZR	Light ZR	Significant ZR
None	N/A	4 12%	0	0 0%
Weak Anticyclone	1013.33-1028	18 51%	8	5 45%
Strong Anticyclone	1029-1044	13 37%	12	6 55%

Table 3.18 Anticyclone Strength resulting in Freezing Rain with a Miller B Cyclone Track

3.7.2c Ice Pellets

All Miller B cyclones associated with ice pellet had an anticyclone positioned to the northeast (**Table 3.19**). A majority of significant ice pellet events (73%) were associated with a strong anticyclone.

East	Range	No IP	Light IP	Significant IP
None	N/A	4 8%	0	0 0%
Weak Anticyclone	1013-1028	25 48%	5	1 17%
Strong Anticyclone	1029-1044	23 44%	3	5 73%

Table 3.19 Anticyclone Strength resulting in Ice Pellets with a Miller B Cyclone Track

3.7.3 No Cyclone Track with an Anticyclone

3.7.3a Snow

A majority of snow producing events associated with no cyclone (88%) had an anticyclone located to the northeast (**Table 3.20**). Consistent with Miller A and Miller B events, a weak anticyclone was associated with a higher proportion of significant snowfalls (57%).

East	Range	No Snow	Light Snow	Significant Snow
None	N/A	1 2%	3	0 0%
Weak Anticyclone	1014-1031	17 49%	7	4 57%
Strong Anticyclone	1032-1049.8	17 49%	8	3 43%

Table 3.20 Anticyclone Strength resulting in Snow with a No Cyclone Track

3.7.3b Freezing Rain

An anticyclone was identified in all events that produced freezing rain with no defined cyclone (**Table 3.21**). Consistant with findings with the Miller A and Miller B events, the highest proportion of significant ZR events (75%) are associated with a strong anticyclone.

East	Range	No ZR	Light ZR	Significant ZR
None	N/A	4 12%	0	0 0%
Weak Anticyclone	1014-1031	18 53%	8	2 25%
Strong Anticyclone	1032-1049	12 35%	10	6 75%

Table 3.21 Anticyclone Strength resulting in Freezing Rain with a No Cyclone Track

3.7.3c Ice Pellets

Although the sample size is small, all events with no cyclone observed associated with ice pellets, an anticyclone was recognized. All significant events were associated with a strong anticyclone (**Table 3.22**).

East	Range	No IP	Light IP	Significant IP
None	N/A	4 8%	0	0 0%
Weak Anticyclone	1014-1031	21 42%	7	0 0%
Strong Anticyclone	1032-1049	25 50%	1	2 100%

Table 3.22 Anticyclone Strength resulting in Ice Pellets with a No Cyclone Track

3.7.4 Summary

An eastern anticyclone was identified in 99% of all freezing rain events, 96% of all ice pellets events and 87% of all snow events. The importance of the anticyclone in winter weather producing systems in the North Carolina Piedmont can not be understated. The majority of significant freezing rain and ice pellet events were tied to a strong anticyclone in the Northeast, while snow events were less dependent on the strength of the anticyclone.

CHAPTER IV
SUMMARY AND CONCLUSIONS

4.1 Summary

A winter weather event climatology from 1957 to 1995 that included 236 events in which snow, freezing rain or sleet was recorded was constructed for Greensboro, North Carolina. Precipitation types for each sounding of the events were determined by a three hour method (hour before, during and one hour after the sounding) and a six hour method (six hours following the sounding). Two unique partial thickness nomograms were constructed utilizing the three hour data (Three Hour Greensboro Nomogram) and the six hour data (Six Hour Greensboro Nomogram). The performance of the nomograms were analyzed as to how well they predict the p-type of an event based on 1000-850mb and 850-700mb partial thickness. Data outliers were examined to determine why certain partial thickness values did not yield predicted results. The nomograms were then compared to the current operational forecast tool for the Southeast US, the TRENDs nomogram.

Events in the climatology were also classified by synoptic pattern to include cyclone tracks (Miller A track, Miller B or no cyclone track) and the presence or absence of an anticyclone to the northeast of the study area. Next, connections were analyzed between synoptic features (cyclone, anticyclone) and precipitation intensity by P-type (no precipitation, light, medium, or heavy precipitation).

4.2 Conclusions

4.2.1 Greensboro Nomograms

Of the two nomograms that were developed in this Thesis, the Six Hour Greensboro nomogram is more accurate (62% correct classification of p-type). The method captures more transitions of events. The trends of these transitions (i.e. rain to snow or snow to rain) are important when making winter weather forecasting decisions. The value in the six hour methodology is in its ability to aid in the prediction of how the P-type will evolve in the six hours following a sounding time. This gives lead time for agencies (electrical, governmental, public service, etc) and the public (to include school systems, work force, daycares, etc.) to help mitigate some of the dangers of a winter weather event.

The Three Hour Greensboro nomogram was less accurate than the six hour (8% less accuracy), but identified over half as many outliers (more precise). The nomogram has value in refining a forecast in the present using sounding data and partial thickness model forecasts. Using the data from these sources, precise NOWCASTs can be delivered to the public and governmental agencies via television and radio.

4.2.2 Comparison to TREND

The TREND nomogram uses the data at Greensboro in order to develop a prediction tool for the Carolina Piedmont. The sounding data at Greensboro is projected over the Piedmont and adjusted in order to create a prediction tool that fits the region. This regional bias is potentially most problematic when forecasters use model forecasted partial thickness lines to prognosticate P-type transition. Although the only station in the

Piedmont that launches radiosondes, the data recorded at Greensboro is not an accurate representation at every point in the Piedmont.

The nomogram was developed with using only selected events thus limiting the sample size and creating a subjective dataset that places a broader emphasis on mixed events and less on emphasis on rain events surrounding frozen precipitation. When applied to the data at Greensboro, the TRENDs nomogram exhibited less accuracy (8% less) than the Six hour Greensboro nomogram.

4.2.3 Partial Thickness Outliers

Events associated with partial thickness outliers were examined to help forecasters key on certain processes that can lead to the miss-classification of a P-type using the developed scheme. Forecasters must look at the following variables before trusting the nomogram:

a. *Surface Dew Point* – Low surface dew points indicate a dry atmosphere near the surface at Greensboro. If the atmosphere near the surface is above freezing, evaporation of falling precipitation near the surface can cool the air and create a cold wedge. Events that plot as rain can be observed as IP, ZR or snow.

b. *Dew Point Depression at -10^{o}C* – High dew point depressions at -10^{o}C (greater than 15^{o}C) indicates a dry atmosphere aloft. Evaporation of falling precipitation can decrease the temperature of a warm nose. When there is a cold wedge in place at the surface this cooling can cause a sounding that plots as IP or ZR to be observed as snow.

c. *Anticyclone* – An anticyclone in the Northeast can provide cold air advection at the surface. A look at the surface maps will indicate if an anticyclone is present. The cold air advection can quickly provide cold air to enhance a cold wedge. A sounding plotting in the rain region could be observed as IP or ZR.

d. *Frontal passage* – A passing front can cause the temperature in the atmospheric column to change very rapidly. In the six hours following the sounding this rapid change can cause a sounding that plots in the all rain or in the transition zone to be observed as snow.

4.2.4 Influence of Cyclone Patterns

Nearly half (47%) of the winter weather events at Greensboro are associated with Miller A Cyclones. Over a quarter (28%) are associated with a Miller B cyclones and the remaining quarter are associated with no cyclone. Miller A type cyclones are associated the greatest number of winter weather events at Greensboro (74 events with snow, 22 with IP, 46 with ZR) and the most heavy events in each P-type catagory. Miller A cyclones have a proportionally higher snow occurrence than Miller B(+12%), but near equal proportionality with sleet occurrence (+1%) and with freezing rain occurrence (+5%).

The path a Miller A or Miller B cyclone travels does not directly correlate to the intensity of a winter weather event. Significant snow, IP and ZR events occurred with cyclones that passed directly over Greensboro and those that were over 500km to the east. Significant events also occurred with no cyclone in the region. However, heavy snow events occur only in cases where there was a cyclone.

4.2.5 Influence of an Eastern Anticyclone

An anticyclone is often present in the Northeast US/Eastern Canada during in winter weather events at Greensboro. In particular it is present and provides a source for cold air advection, in 99% of all freezing rain events, 96% of all ice pellet events and 87% of all snow events. Only 7% of all significant events had no identifiable anticyclone. The majority of significant ice pellet (65%) and freezing rain (68%) events were associated with a strong anticyclone. In these events the anticyclone in the Northeast provided a steady source of cold air into the cold air dam along the Appalachian Mountains needed for the formation of IP and ZR. Significant snow events occurred more often when associated with a weak anticyclone (24 events) as opposed to a strong anticyclone (17 events).

4.3 Unanswered Questions/Future Work

This Thesis has raised many more questions about winter weather in the Carolina Piedmont:

1. *How skillful is the Six Hour and Three Hour Nomograms in forecasting P-type in winter weather events beyond the period of study?* Greensboro ASOS data from 1996 to the present can be used to independently validate the classification. The addition of 11 seasons of winter weather events would provide a more robust data set that can be used to refine the two nomograms.

2. *How well do the nomograms perform when assessing only significant measurable events (i.e. those that require/elicit a public/governmental response)?* By isolating only

significant events, do the boundaries on the nomograms predict the correct P-type that will fall? Preliminary work suggests that there is not much change in the classification boundaries when only significant events are plotted.

3. *How well do the Six and Three Hour Nomograms perform over the Southeast US?* Observation data from first order stations in the Southeast can be used to determine the accuracy of nomograms in regions outside of the Carolina Piedmont. This can lead to local nomograms for each station or validate the nomograms for use over the region.

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