A Climatology of the Structure, Frequency, and Propagation of Midlatitude Cyclones that affect North Carolina

by

Linwood E. Hall

May, 2013

Director of Thesis: Rosana Nieto-Ferreira, PhD

Major Department: Deparment of Geography, Planning, and Environment

The seasonal and interannual variability of midlatitude cyclone structure, frequency, and propagation was studied based on composites of precipitation over North Carolina. This analysis showed significant changes in the structure, frequency, and propagation of midlatitude cyclones on seasonal and interannual timescales between 1998-2010. Winter was the peak season for midlatitude cyclone passages. Summer was the least frequent in terms of midlatitude cyclone passages. The region of origin of midlatitude cyclones also had a significant effect on their structure, intensity, rainfall amounts and tracks. For all seasons, the most frequent midlatitude cyclone type was the Rockies type. This midlatitude cyclone type brought the most consistent rainfall to NC. The most intense precipitation occurred during Gulf type midlatitude cyclones. The most intense midlatitude cyclones were the Hatteras type. The El Niño Southern Oscillation also played a role in midlatitude cyclone development. During El Niño events, an increase in Gulf type midlatitude cyclones occurred. During these events, intense rainfall occurred. On the other hand, during La Niña, Rockies were the dominant midlatitude cyclone type. These midlatitude cyclones brought consistent, but less intense precipitation to the SE US.

A Climatology of the Structure, Frequency, and Propagation

of Midlatitude Cyclones that affect North Carolina

A Thesis

Presented To

the Faculty of the Department of Geography

East Carolina University

In Partial Fulfillment

of the Requirements for the Degree

Master of Geography

by

Linwood Earl Hall Jr.

May 2013

A Climatology of the Structure, Frequency, and Propagation

of Midlatitude Cyclones that affect North Carolina

by

Linwood Earl Hall Jr.

APPROVED BY:

DIRECTOR OF
DISSERTATION/THESIS: ____________________

(Rosana Nieto-Ferreira, PhD)

COMMITTEE MEMBER: ____________________

(Tom Rickenbach, PhD)

COMMITTEE MEMBER: ____________________

(Dr. Scott Curtis, PhD)

CHAIR OF THE DEPARTMENT
OF (Put Department Name Here): ____________________

(Dr. Burrell Montz, PhD)

DEAN OF THE
GRADUATE SCHOOL: ____________________

Paul J. Gemperline, PhD

Acknowledgements

I would like to thank my wife Tiffany for her overwhelming support in my life as well as my studies. Next, I would like to thank my family for their support throughout my career endeavors. They have cheered me along throughout my graduate studies. I would like to thank my advisor Dr. Rosana Nieto-Ferreira who has been an outstanding mentor and friend. Her insight and encouragement during my graduate studies has aided me as a professional, as a geographer, and as an atmospheric scientist. I would like to thank Dr. Scott Curtis and Dr. Tom Rickenbach for serving on my committee and providing me with useful insight as I completed my thesis research. I would also like to thank our department chair Dr. Burrell Montz. Her perspectives in geography helped me understand the world outside of research, and how it affects people. Last but not least, a special thanks goes out to all of my fellow graduate students for sticking with me through graduate school. Everyone has been wonderful to be around, and I cannot imagine a better group of colleagues and friends.

TABLE OF CONTENTS

LIST OF TABLES vii

LIST OF FIGURES ix

1. INTRODUCTION 1

2. LITERATURE REVIEW 1

  2.1 MIDLATITUDE CYCLONES AND FRONTS 5

  2.2 MIDLATITUDE CYCLONE STRUCTURE 7

  2.3 INTERANNUAL VARIABILITY: SOUTHERN OSCILLATION EFFECT ON MIDLATITUDE WEATHER 9

3. RESEARCH QUESTION 11

4. DATA AND METHODOLOGY 12

  4.1 NCEP REANALYSIS 12

  4.2 TROPICAL RAINFALL MEASURING MISSION (TRMM) 12

  4.3 STUDY AREA 12

  4.4 MIDLATITUDE CYCLONE IDENTIFICATION 13

  4.5 SEASONAL MIDLATITUDE CYCLONE COMPOSITES 14

  4.6 MIDLATITUDE CYCLONE CLASSIFICATION 16

  4.7 SEASONAL MIDLATITUDE CYCLONE COMPOSITES BY TYPE 16

  4.8 ENSO MIDLATITUDE CYCLONE COMPOSITES 17

5. RESULTS 18

  5.1 SEASONAL MIDLATITUDE CYCLONE PATTERNS 18

  5.2 SEASONAL MIDLATITUDE CYCLONES BY TYPE 35

  5.3 ENSO INFLUENCE ON MIDLATITUDE CYCLONE STRUCTURE 54

6. DISCUSSION AND CONCLUSIONS 63

7. REFERENCES 67

8. APPENDIX A: MIDLATITUDE CYCLONE FORMATION COORDINATES 72

9. APPENDIX B: MIDLATITUDE CYCLONES BY TYPE (SPRING – FALL) 84

LIST OF FIGURES

1. NC SEASONAL CYCLE OF PRECIPITATION 3

2. JANUARY/JULY CLIMATOLOGY 4

3. TYPICAL ENSO WEATHER PATTERNS 10

4. GEOGRAPHICAL DISTRIBUTION OF MIDLATITUDE CYCLONES 15

5. OCEANIC NIÑO INDEX 17

6. 850 MB WINTER SEASONAL COMPOSITE 20

7. 200 MB WINTER SEASONAL COMPOSITE 22

8. 850 MB SPRING SEASONAL COMPOSITE 25

9. 200 MB SPRING SEASONAL COMPOSITE 26

10. 850 MB SUMMER SEASONAL COMPOSITE 29

11. 200 MB SUMMER SEASONAL COMPOSITE 30

12. 850 MB FALL SEASONAL COMPOSITE 33

13. 200 MB FALL SEASONAL COMPOSITE 34

14. ANNUAL CYCLE OF MIDLATITUDE CYCLONES BY TYPE 35

15. 850 MB WINTER ROCKIES COMPOSITE 38

16. 200 MB WINTER ROCKIES COMPOSITE 39

17. 850 MB WINTER CANADIAN COMPOSITE 41

18. 200 MB WINTER CANADIAN COMPOSITE 43

19. 850 MB WINTER GULF COMPOSITE 46

20. 200 MB WINTER GULF COMPOSITE 48

21. 850 MB WINTER HATTERAS COMPOSITE 51

22. 200 MB WINTER HATTERAS COMPOSITE 53

23.WINTER MIDLATITUDE CYCLONE COMPARISON – ENSO 55
24. 850 MB NIÑO WINTER COMPOSITE 57
25. 200 MB NIÑO WINTER COMPOSITE 59
26. 850 MB NIÑA WINTER COMPOSITE 61
27. 200 MB NIÑA WINTER COMPOSITE 62
28. 850 MB SPRING ROCKIES COMPOSITE 85
29. 200 MB SPRING ROCKIES COMPOSITE 86
30. 850 MB SPRING CANADIAN COMPOSITE 88
31. 200 MB SPRING CANADIAN COMPOSITE 89
32. 850 MB SPRING GULF COMPOSITE 91
33. 200 MB SPRING GULF COMPOSITE 92
34. 850 MB SUMMER ROCKIES COMPOSITE 95
35. 200 MB SUMMER ROCKIES COMPOSITE 96
36. 850 MB SUMMER CANADIAN COMPOSITE 99
37. 200 MB SUMMER CANADIAN COMPOSITE 100
38. 850 MB SUMMER STATIONARY COMPOSITE 103
39. 200 MB SUMMER STATIONARY COMPOSITE 104
40. 850 MB FALL ROCKIES COMPOSITE 107
41. 200 MB FALL ROCKIES COMPOSITE 108
42. 850 MB FALL CANADIAN COMPOSITE 110
43. 200 MB FALL CANADIAN COMPOSITE 111
44. 850 MB FALL HATTERAS COMPOSITE 114
45. 200 MB FALL HATTERAS COMPOSITE 115

LIST OF TABLES

1. SEASONAL DESIGNATION 14

2. ENSO CLASSIFICATION USING THE ONI 55

A Climatology of the Structure, Frequency, and Propagation of Midlatitude Cyclones that affect North Carolina

1. Introduction

Since no major rivers flow into North Carolina, precipitation is the main source of water for replenishing surface and ground water, as well as our soils. In North Carolina, water supplies are replenished by precipitation from a wide range of different precipitating systems such as midlatitude cyclones, mesoscale convective systems (MCS), isolated thunderstorms and the occasional tropical cyclone passage. Here a composite analysis is used to study the seasonal and interannual variability of the structure, frequency, and propagation of midlatitude cyclones that affect North Carolina.

Midlatitude cyclones are the most significant form of rainfall for North Carolina. This study uses a composite analysis to analyze the variability in structure, frequency, and propagation of midlatitude cyclones on seasonal and interannual timescales.

2. Literature Review

North Carolina's position in the Mid-Atlantic region of the United States is unique when considering the various types of weather systems that affect it each year. North Carolina's annual precipitation is delivered by tropical cyclones (Shepherd et al. 2007), isolated convection from sea-breeze fronts (Koch and Ray 1997), mesoscale convective systems (MCS) (Parker and Ahijevych 2007), and mid-latitude cyclones whose track depends on the position of the Bermuda High (Robinson 2006). However, the association between the seasonal climatology of precipitation systems and synoptic-scale climate regimes has not garnered much research in the past.

North Carolina’s precipitation varies climatologically throughout the state. Figure 1 shows the climatological seasonal precipitation cycles for the different regions of North Carolina. Raleigh, in the Piedmont, and Kinston and Cape Hatteras in the Coastal Plains, show summertime maxima in precipitation. On the other hand Boone, which is located in the mountainous western region of NC, has no distinct peak in the annual distribution of precipitation. So, for most of NC, a summertime maximum in precipitation is evident, however, a more even distribution of precipitation occurs in the mountains.

North Carolina’s summer rainfall is associated with mesoscale convective systems, mid-latitude cyclone passage, and the occasional tropical cyclone. Rainfall is frequently in the form of isolated afternoon thunderstorms, but can also be in the form of topography-induced mesoscale convective systems (MCS). The presence of topography-induced propagating MCS was studied in Parker and Ahijevych (2007). In these systems, storms develop near the Appalachian Mountains, and propagate eastward until reaching the Outer Banks and into the Atlantic Ocean (Parker and Ahijevych 2007).

Transitioning into the late-summer and fall months, another source of precipitation are tropical cyclones. North Carolina, on average, is impacted by a tropical cyclone about once a year and is in a prime position for tropical cyclone activity. The Coastal Plains region, or eastern third of NC, juts out into the Atlantic Ocean, increasing the chance of being hit by a tropical cyclone. Shepherd et al. (2007) determined that on average, about 8% of the rainfall in the southeastern US during the Atlantic hurricane season is from tropical cyclones. However, the most significant form of precipitation in North Carolina results from the passage of midlatitude cyclones.

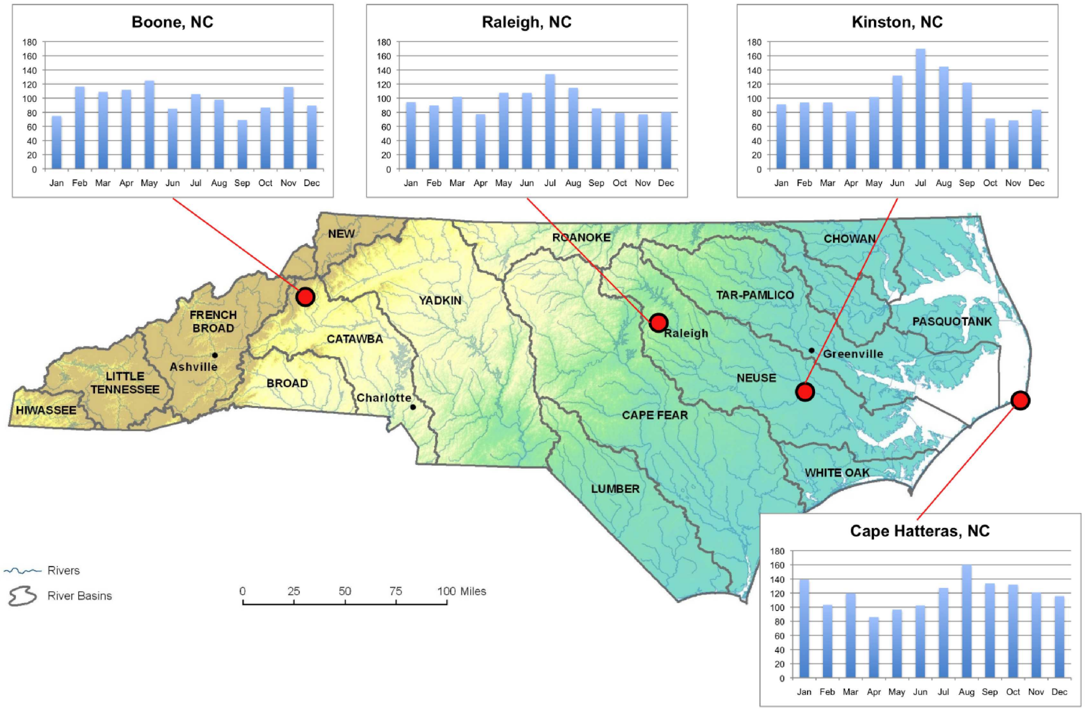
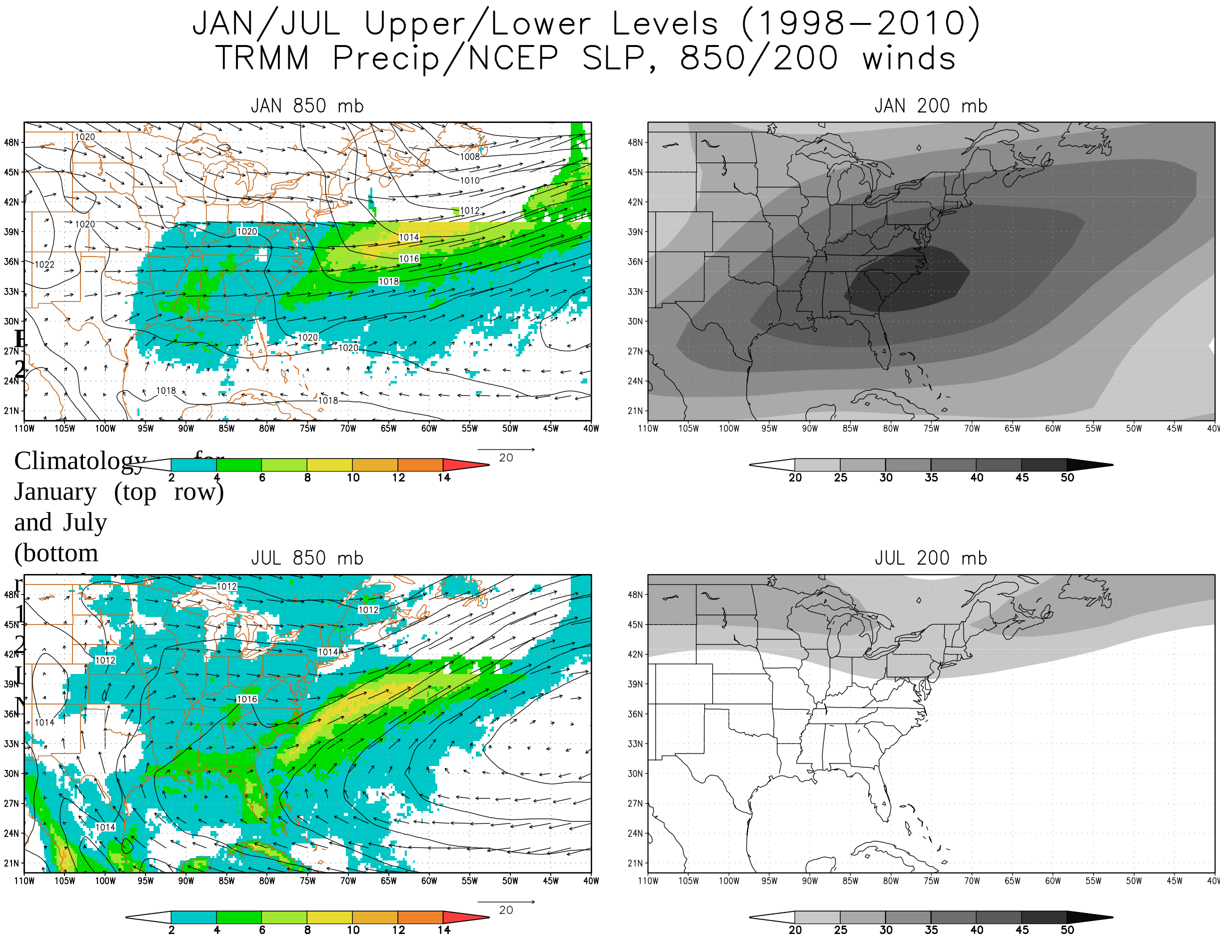


Figure 1: The 1950-1995 seasonal cycle of precipitation for North Carolina is shown above. Boone representing western North Carolina, Raleigh for the Piedmont region, Kinston for the coastal plain, and Cape Hatteras for the Outer Banks. This map is courtesy of the ECU Center for Geographic Information Science, and the precipitation data is from the Global Historical Climatology Network of the National Climate Data Center.

Midlatitude cyclone passages are the most significant form of precipitation delivery for North Carolina. Over 65% of all heavy rainfall events happen in the presence of fronts (Konrad 1997). Unlike tropical cyclones, midlatitude cyclones bring precipitation to North Carolina year-round. Midlatitude cyclone frequency peaks in late March (Curtis 2006). Their tracks, along the Atlantic coastline, are based largely on the position of the Bermuda High (Robinson, 2006).



Climatology for January (top row) and July (bottom

Reanalysis SLP (mb) and 850 mb winds (m/s), and TRMM precipitation (mm/day; left column). NCEP Reanalysis zonal winds (m/s; right column).

Figure 2 shows aspects of the January/July Eastern US climatology for 1998-2010. Precipitation greater than 2 mm/day in the January plot extends from the Gulf of Mexico northward into LA, AR, TN, MS, and AL, and over the Gulf Stream. The states of NC, SC, and VA receive relatively less rainfall, likely due to the rain shadow effect from the Appalachian Mountains. In July, precipitation is scattered across the SE US. There is a larger area of high precipitation in the July as compared to January off the East Coast and over Florida. In January and July, the strongest precipitation occurs off of the coast. The SLP values show a significant difference as well. In January, the Bermuda High is much less prominent, but in July, it clearly affects the moisture transport and precipitation off the East Coast. The 850 mb winds are affected by the Bermuda High in the July plot, but this relationship is less defined in January.

In the upper levels (200 mb), significant seasonal differences can be seen as well. The zonal winds are much stronger in January (45 m/s max over NC) than in July (15 m/s max over NC). In January, the jet streak maximum is over North Carolina, but is located northward into Canada in July. Since midlatitude cyclones are steered by the polar jet (Ahrens 2008), and since the jet stream shifts southward in the winter, there are more midlatitude cyclone passages in NC in January than in July due to the polar jet migrating with the seasons

2.1 Midlatitude Cyclones and Fronts:

Midlatitude cyclones, also known as extratropical cyclones, are important rainmakers in North Carolina during all seasons. Konrad (1997) found that over 65% of the heavy rainfall events during summer, where amounts exceeded 5 cm over a 6 hour period, happen in the presence of weak slow-moving or stationary fronts. Only about 10% of the heavy rainfall events occurred when no significant synoptic-scale forcing was present. Generally, a mid-latitude cyclone is seen as a northeast tracking, closed-low pressure system at the surface, with a distinct center of cyclonic circulation (Dunlop 2008).

Mid-latitude cyclones can be devastating as well. Mid-latitude cyclones are generally much larger than hurricanes, so the extent of the damage is more widespread. In March 1993, the east and central United States were hit by a large mid-latitude system that was later known as the “Storm of the Century”, or the “Superstorm” (Galvin 2009). During this event, large amounts of snow fell, which shattered snowfall records, 2.5 million people were left without power, and even tornadoes were witnessed (Galvin 2009). This storm demonstrates the devastation caused by storms in the mid-latitudes, and how widespread the damage can be. The 1993 Superstorm is currently on the National Climatic Data Center’s (NCDC) list of billion-dollar weather events (NCDC 2011).

Blender et al. (1997) classified cyclone tracks in the North Atlantic into three different categories: stationary, northeastward traveling storms, and zonally traveling storms. North Carolina is mostly affected by the northeastward tracking storms due to influence of the jet stream. In North Carolina, mid-latitude cyclone activity generally peaks in the late-winter and early-spring months. Curtis (2006) found that the maximum number of mid-latitude cyclones occurs in March for the Southeastern US.

Unlike tropical cyclones, mid-latitude cyclones are characterized by the presence of fronts (Bjerknes 1919). Frontal passages are the major contributors for mid-latitude cyclone precipitation in North Carolina. Mid-latitude cyclones are steered by the jet stream. In the winter, the polar jet moves farther south and its meandering troughs and ridges not only steer, but also aid in the formation of mid-latitude cyclones (Ahrens 2008). Generally, mid-latitude cyclones that cause a direct frontal passage for North Carolina travel either west or north of North Carolina. As a mid-latitude cyclone propagates toward the Atlantic Ocean, fronts cross North Carolina, resulting in precipitation.

2.2 Midlatitude Cyclone Structure:

The classical Norwegian front model (Bjerknes 1919, Bjerknes and Solberg 1921) describes the extratropical cyclone lifecycle from its beginning at the time of formation of the warm and cold fronts to its decay stage when an occluded front is present.

A. Warm Fronts

A warm front is the leading edge of advancing warm air. Precipitation associated with warm fronts is also seen as generally different from cold fronts. While some can result in heavy rainfall and severe weather, warm fronts are usually associated with steady drizzle or no rainfall.

Winds before the passage of a warm front are from the south/southeast. During the frontal passage, winds become variable, and after passage shift to the south/southwest. Temperatures generally rise as the front passes, leveling off after the front passes. Pressure falls as the front approaches and rises slightly after passage.

Changes in weather conditions associated with warm fronts are not as well defined as those associated with cold fronts. In the datasets, warm fronts are best evidenced by the changes in temperatures and winds (Ahrens 2008).

B. Cold Fronts

Cold fronts are the zone where cold, stable air replaces warm moist air. Due to the cold air forcing warm air upwards, as the front passes there is a sudden drop in temperature and pressure. Winds generally shift from the south/southwest to west/northwest during the frontal passage.

Precipitation associated with cold fronts can vary greatly. Before the cold front passes, isolated showers occur. As the cold front passes, there can be severe weather (hail, tornadoes, lightning), rain, or snow. After the front passes, precipitation decreases in intensity and finally clears.

Cold fronts cause sudden changes in weather conditions. In the datasets, cold fronts are best seen with the onset of rainfall, as well as a sudden drop in temperature and rise in pressure as the front passes (Ahrens 2008).

C. Occluded Fronts

Toward the end of the midlatitude cyclone life cycle, the frontal boundary created from the interaction of the warm and cold fronts causes occlusion. These are considered warm (cold) if the air temperature on the passing side is warmer (colder) than the air ahead of the front.

There are some typical weather patterns associated with occluded fronts. During the passage of an occluded front, winds generally shift from the east/southeast/south to the west/northwest. Temperatures drop (rise) with the passage of a warm (cold) type occluded front. Pressure falls to a minimum, and then rises again as the front passes. Precipitation associated with occlusion can be light, moderate, or heavy, with continuous showers as the front passes (Ahrens 2008).

While midlatitude cyclones are large in size, detection can be tricky due to structural changes through maturation. Drops in SLP allow for midlatitude cyclones to be detected (Chang and Song 2006; Bengtsson et al. 2006; Hirsch et al. 2006). Midlatitude cyclone phenomena, such as fronts, exhibit pressure fluctuations throughout passage. Therefore, midlatitude cyclone detection is accomplished using a pressure drop with a subsequent pressure increase on a following day.

2.3 Interannual Variability: Southern Oscillation Effect on Midlatitude Weather

The El-Niño Southern Oscillation (ENSO) plays a large role in seasonal variability of precipitation in North Carolina. El Niño is characterized by warm sea surface temperature (SST) anomalies in the equatorial Pacific Ocean, whereas La Niña is characterized by cold SST anomalies in the equatorial Pacific (Ahrens 2008). North Carolina's typical weather during an El Niño event is cool and wet (Fig. 5, top) during the winter season. This is due to a strong low pressure system off the northeastern coast of the United States, which directs the jet stream further south (Ahrens 2008). The opposite occurs during a La Niña event. During La Niña events, the typical weather pattern in North Carolina is warmer and drier (Fig. 3, bottom) during the winter season. The same jet stream that affects North Carolina during an El Niño event is directed northward as a persistent high pressure system develops off the northwest coast of the US (Ahrens 2008).

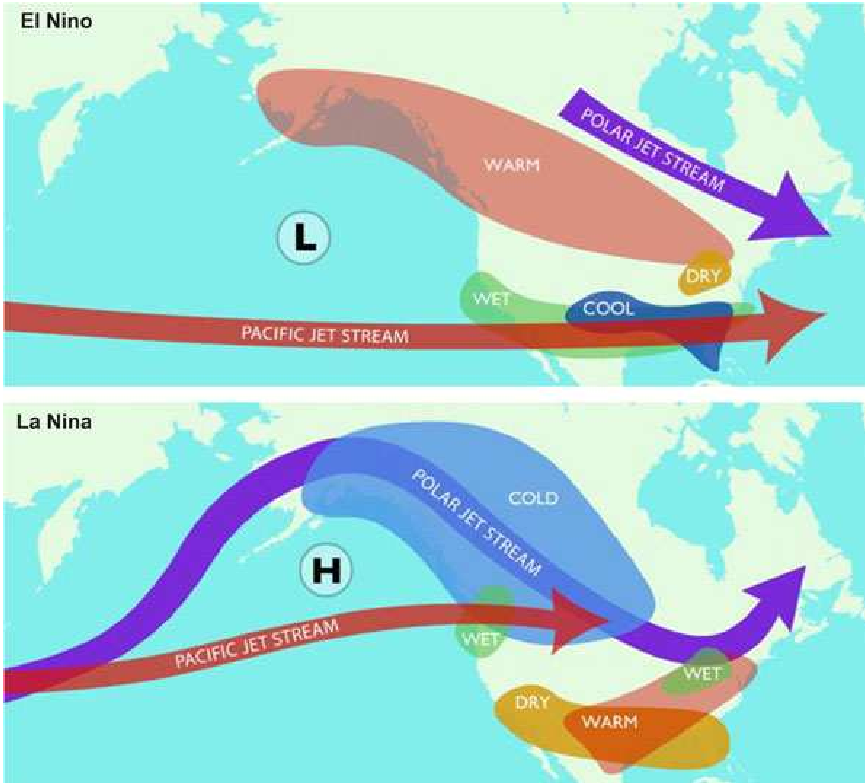


Figure 3: This shows the normal weather patterns for the United States during a La Niña and El Niño winter period. As seen here, the southeastern U.S. generally experience warmer, drier winters during La Niña, whereas cooler, wetter winters are experienced in El Niño winters. Photo courtesy of the Southwest Climate Change Network (www.southwestclimatechange.org)

ENSO also affects midlatitude cyclogenesis during the wintertime along the eastern seaboard. Although tropical storms are more widely known for destruction, mid-latitude cyclones have devastating effects on the southeastern portion of the United States as well. Kunkel and Angel (1999) found that there was a higher frequency of extratropical storms in the southeastern U.S. during an El Niño year. The highest concentration of extratropical cyclones occurred in February and March (Curtis 2006). The relationship of ENSO and the wintertime climate of the southeastern U.S. is illustrated on large (Ropelewski and Halpert 1986) and small (McCabe and Muller 2002) scales. In these scenarios, more storms were found in the Gulf of Mexico region, but the strongest storms were found off the coast of North Carolina (Curtis 2006).

El Niño is measured by the Oceanic Niño Index (ONI), which is a product from the National Weather Service. ONI is a three month mean of SSTs in the Niño 3-4 region (5^oN-5^oS, 120^o-170^oW) in the Pacific Ocean (Goldman 2011). El Niño events are characterized by five consecutive months above the +0.5°anomaly for El Niño events and below the -0.5°anomaly for La Niña events (Goldman 2011). The last strong El Niño event occurred in the 2009-2010 winter. Following the trend of increased snowfall and cyclogenesis, the 2009-2010 winter was accompanied by a surplus of snow in North Carolina. On the other hand, the last significant La Niña occurred in 2008.

3. Research Questions:

1) What are the synoptic-scale structure and propagation of midlatitude cyclones that produce rainfall in NC? How does the structure and propagation of midlatitude cyclones change over the seasons?

2) What is the interannual variability of midlatitude cyclones in NC? How does ENSO affect the structure, propagation and variability of midlatitude cyclones and frontal passages in NC?

3) What are the overall synoptic forcings present for each season?

4. Data and Methodology

4.1 NCEP Reanalysis

The daily National Center for Environmental Prediction (NCEP) Reanalysis products were used (Kalnay et al. 1996) to study sea-level pressure (SLP), geopotential height, temperature, and winds at the 850mb and 200 mb levels. NCEP reanalysis data has a horizontal resolution of 2.5˚x 2.5˚. This data was used to make composites of the synoptic-scale features of midlatitude cyclones that affect NC year round.

4.2 Tropical Rainfall Measuring Mission (TRMM) Datasets

Precipitation was studied using the daily mean TRMM's 3b42 precipitation dataset (Kempler 2011; Huffman et al. 2007). The TRMM 3b42 dataset is a high-resolution (0.25˚X0.25˚) multi-satellite precipitation dataset that covers the Earth from 50°S - 50°N (Kempler, 2011) and is available from 1998-present. It is adjusted monthly to gauge-based data.

4.3 Study Area

This study focuses on the synoptic-scale features of midlatitude cyclones that affect NC. In order to capture their lifecycle from beginning in the Central Plains/Gulf of Mexico, to end in the Atlantic Ocean, the study area covers 20°-50° N and 120°-40° W.

4.4 Midlatitude Cyclone Identification

The first step in the classification is identifying midlatitude cyclones. Past studies disagree on using SLP minima as a form of midlatitude cyclone identification. Chang and Song (2006) identified midlatitude cyclones by minima in mean sea-level pressure (MSLP). Conversely, Dacre and Gray (2006) concluded that MSLP minima do not identify midlatitude cyclones in their early life cycle.

The current method of identification, however, differs from these past studies. My identification algorithm, instead of simply using minima in MSLP, uses a sea-level pressure (SLP) threshold in order to correctly identify each midlatitude cyclone passage over North Carolina. In this identification, a midlatitude cyclone passage is defined as a SLP decrease of 2 mb over 24 hours. To check the accuracy of my algorithm, the Daily Surface Weather Maps (www.hpc.ncep.noaa.gov/dailywxmap), provided by the National Weather Service, were checked for each midlatitude cyclone track.

The algorithm outputs midlatitude cyclone passages over North Carolina as a list of dates. The only limitation to the identification algorithm occurred when the SLP would decrease 2 mb over the course of two successive days or more. This caused the identification algorithm to output subsequent dates. To fix this, I checked the NWS Daily Weather Maps (as mentioned earlier) to find the date of the actual midlatitude cyclone passage. Overall, the algorithm was successful in correctly identifying midlatitude cyclone passages for North Carolina.

4.5 Seasonal Midlatitude Cyclone Composites

To examine the structure of midlatitude cyclones, 6-day composites were created. The composites ranged from Day-3 to Day+2, with Day0 corresponding to the 2mb decrease in surface pressure. Each composite used sea-level pressure (SLP), horizontal winds (850 and 200mb levels), and geopotential height (200mb) from the National Centers for Environmental Prediction (NCEP) Reanalysis datasets. Precipitation data came from the TRMM 4b43 algorithm. Data was collected for the 1998-2010 time period.

Two sets of composites were created, one for each of the upper (200mb) and lower (850mb) levels of the troposphere for each season. A season was determined to be a 3-month period. Table 1 shows the designation of seasons.

Season	**Months Included**
Winter	December, January, February
Spring	March, April, May
Summer	June, July, August
Fall	September, October, November

Table 1: This shows the seasonal designation for midlatitude cyclone passages.

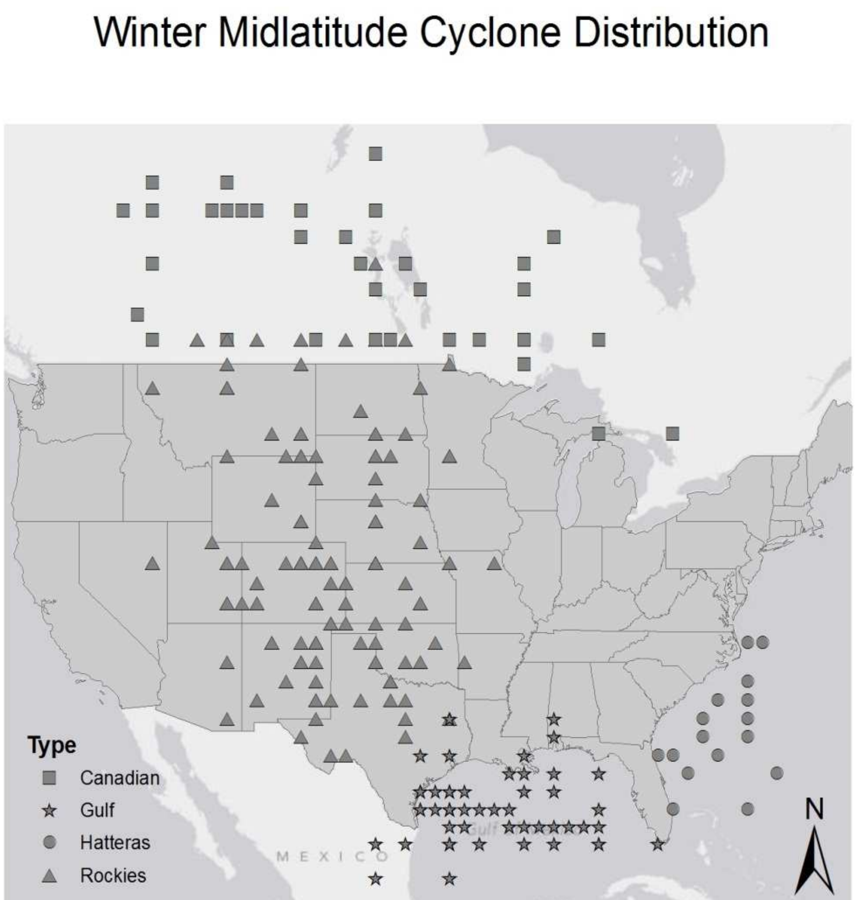


Figure 4: The distribution of midlatitude cyclone origins. Most midlatitude cyclones occur near the Rocky Mountains in the United States and Canada.

4.6 Midlatitude Cyclone Classification

Using the dates output from the midlatitude cyclone identification algorithm, the NWS Daily Surface Weather Maps were used to classify each midlatitude cyclone into different types based on their point of origin. There was a total of 864 storms identified from 1998 to 2010. The area in which the cyclone first exhibited closed isobars determined point of origin. Figure 4 shows the midlatitude cyclone origination points.

Some midlatitude cyclones originated on the United States/Canada border. To distinguish between these cyclones, the general track of the midlatitude cyclone was taken into consideration as well. For example, if the point of origin occurred on the United States/Canada border, and tracked mainly in the United States, it was determined to be a Rockies-type midlatitude cyclone. These five different types (four of which shown in figure 4) of midlatitude cyclones: Rockies, Canadian, Gulf, Hatteras, Stationary, give a geographical identification, which allowed for easier spatial and temporal analysis.

4.7 Seasonal Midlatitude Cyclone Composites by Midlatitude Cyclone Type

Midlatitude cyclone passages were grouped by midlatitude cyclone type as well. The same climatology datasets from NCEP and TRMM were used to create a 6-day seasonal by type midlatitude cyclone composite for each the 200mb and 850mb levels. Seasons from Table 1 were the designated seasons in these composites.

Only peak seasons of midlatitude cyclones were used in the composites. For instance, since there were no stationary type midlatitude cyclones during the winter season, composites were not created for this season.

4.8 ENSO Midlatitude Cyclone Composites

Interannual midlatitude cyclone variability was examined as well. Using the dates output from the original midlatitude cyclone identification algorithm, ENSO events were examined. Similar to the three month average in the seasonal composites, the ONI (figure 5) uses a three-month average in SSTs to determine the presence of an ENSO event. Consequently, the process for grouping dates into ENSO events paralleled the seasonal dates. From this, 6-day composites were created for El Niño and La Niña events. These composites consisted of NCEP SLP, horizontal winds and geopotential heights at the 850mb and 200mb levels, and TRMM Precipitation.

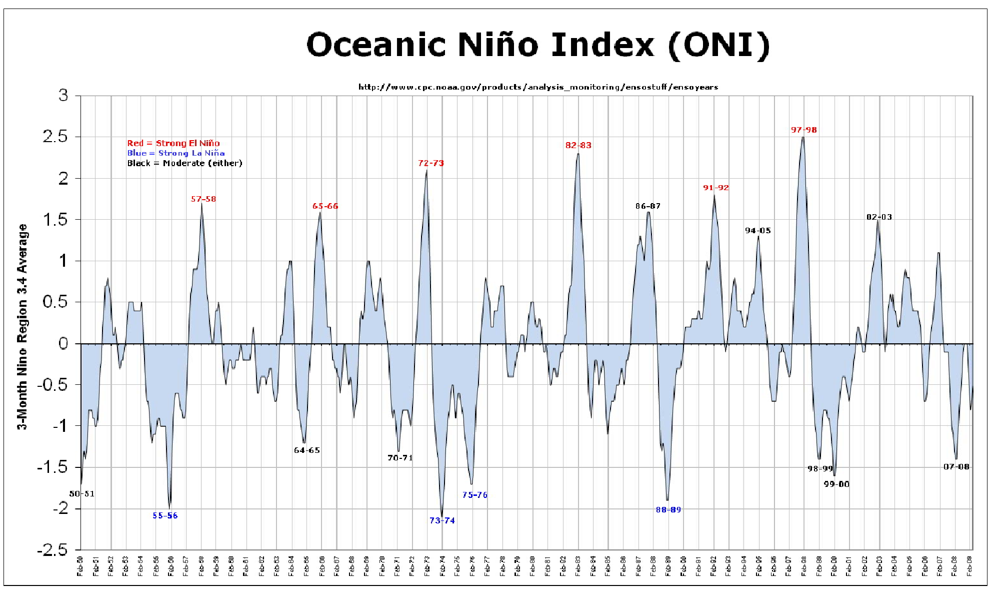


Figure 5: The Oceanic Niño Index (ONI). This index shows the El Niño and La Niña events based on three month averages in SSTs. Only significant ENSO events were used in this study. Source: (http://www.dartmouth.edu/~floods/ElNino.html)

ENSO events peak in the winter months. Similarly, the most midlatitude cyclone passages occur during the winter. For these reasons, only the winter season (December, January, and February) was used to create the 6-day composites.

5. Results

5.1 Seasonal Midlatitude Cyclone Patterns

This section presents results on the seasonal patterns of midlatitude cyclones. Seasonal patterns in the structure, frequency, and propagation are shown in figures 5 – 12. Examining the seasonal patterns is important because it gives an understanding of the overall synoptic forcings present for each season. This section is divided into four parts for each season. Each part examines the structure, frequency, and propagation of midlatitude cyclones.

5.1.1 Winter (December, January, February)

Figure 6 shows the low-level composite of precipitation, SLP, and 850mb winds for the winter months. The number of midlatitude cyclone passages was 279, which was the highest frequency of all seasons.

In this composite, precipitation occurs only in association with the synoptic-scale forcing by the midlatitude cyclone. A large area of precipitation occurs over LA, MS, AR, and TN on day-2 and extends over the SE US by day-1 continuing to move eastward over the ocean on day0 and later. Although there is constant offshore precipitation over the Gulf Stream, the strongest precipitation occurs ahead of the midlatitude trough on day0. Interestingly, on day+1 when the midlatitude trough is far out in the ocean, a region of no precipitation that is a few hundred kilometers wide stretches along the East Coast of the U.S.

On Day-3, a high pressure center dominates the SE US. On Day-2, the high pressure begins to propagate to the east, and by Day-1, has moved offshore into the Atlantic Ocean.

The midlatitude cyclone becomes visible on Day-1 near the Great Lakes as it intensifies. Regarding precipitation, the largest effect from the midlatitude cyclone on NC occurs between Day-1 and Day0. The midlatitude cyclone passes on Day0. Here, the cyclone begins to tilt to the northeast. By Day+1, the midlatitude cyclone has moved offshore. As the cyclone moves offshore, high pressure returns to the SE US.

Southwesterly winds ahead of the eastward propagating midlatitude cyclone provide the warm, moist air that fuels rainfall. Southwesterly winds are first detected along the western Gulf of Mexico and Texas on day-3 and then strengthen and move eastward over Mississippi/Louisiana on day-1, to over the Gulf Stream on day0 and deeper into the Atlantic Ocean on days +2 and +3. This composite also displays strong northwesterly winds behind the midlatitude cyclone over the continent. This northwesterly wind component is most visible on days 0 and +1.

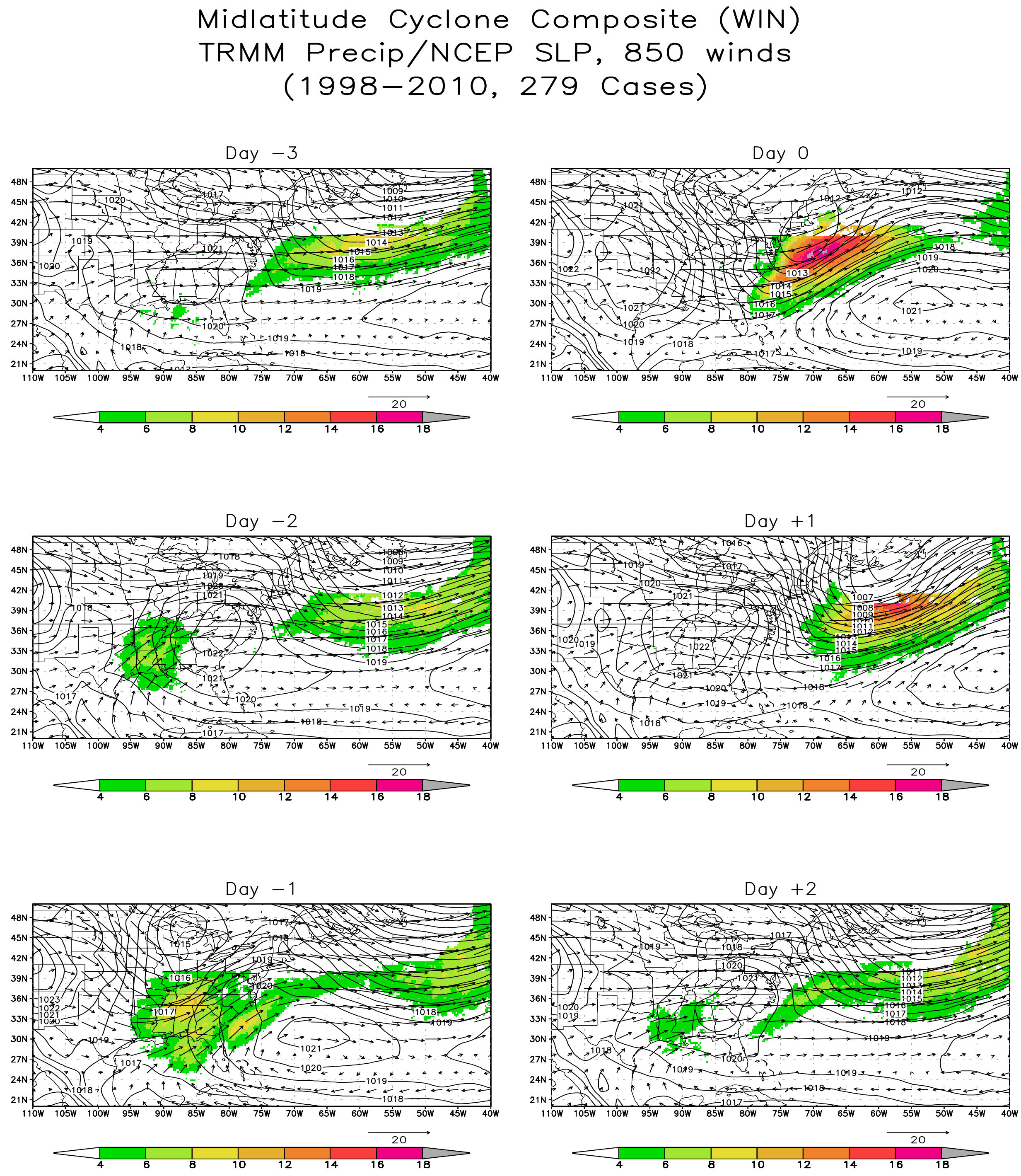


Figure 6: Midlatitude cyclone composite for all events that crossed NC during the winter from 1998-2010. Plots show precipitation (mm/day), winds (m/s), and SLP (mb).

Figure 7 shows the upper-level composite of geopotential height anomalies and 200mb wind intensities. Here, the position of the jet streak (highest wind intensities) sits over the SE US during the winter season. Here, the jet streak is represented by the darker shades. This jet streak affects NC on Day0 where it becomes northeastward. The northeastward tilt of the jet stream is significant. An increase in jet stream tilt signifies an increase in baroclinic wind shear (Petterssen 1952). This wind shear aids in the intensification of midlatitude cyclones.

The geopotential anomalies show a distinct cycle between upper-level troughs and ridges. On Day-2, an upper-level trough moves eastward. The midlatitude cyclone is just to the east of this upper-level trough. As the trough moves eastward, it begins to tilt in a northeastward direction. This is consistent with the position and northeast tilt of the jet streak. Ahead and behind the trough, two upper-level ridges are present. Ahead of these ridges are the areas of high pressure near the surface that propagate eastward. Specifically, the ridge behind our observed upper-level trough will result in the replacement of high pressure to the SE US on Day+1.

In comparison to other seasons, the highest frequency of midlatitude cyclone passages occurs during winter. During winter warm tropical air from the Gulf of Mexico and the cold dry air on land interact. This interaction provides the differential heating necessary for midlatitude cyclone development. This development is best seen during winter months. Notice the structure of the ridges and troughs in figure 6. These features are well defined, and develop and propagate in sequence. In other words, passage of the midlatitude cyclone is clearly seen in the lower and upper-levels.

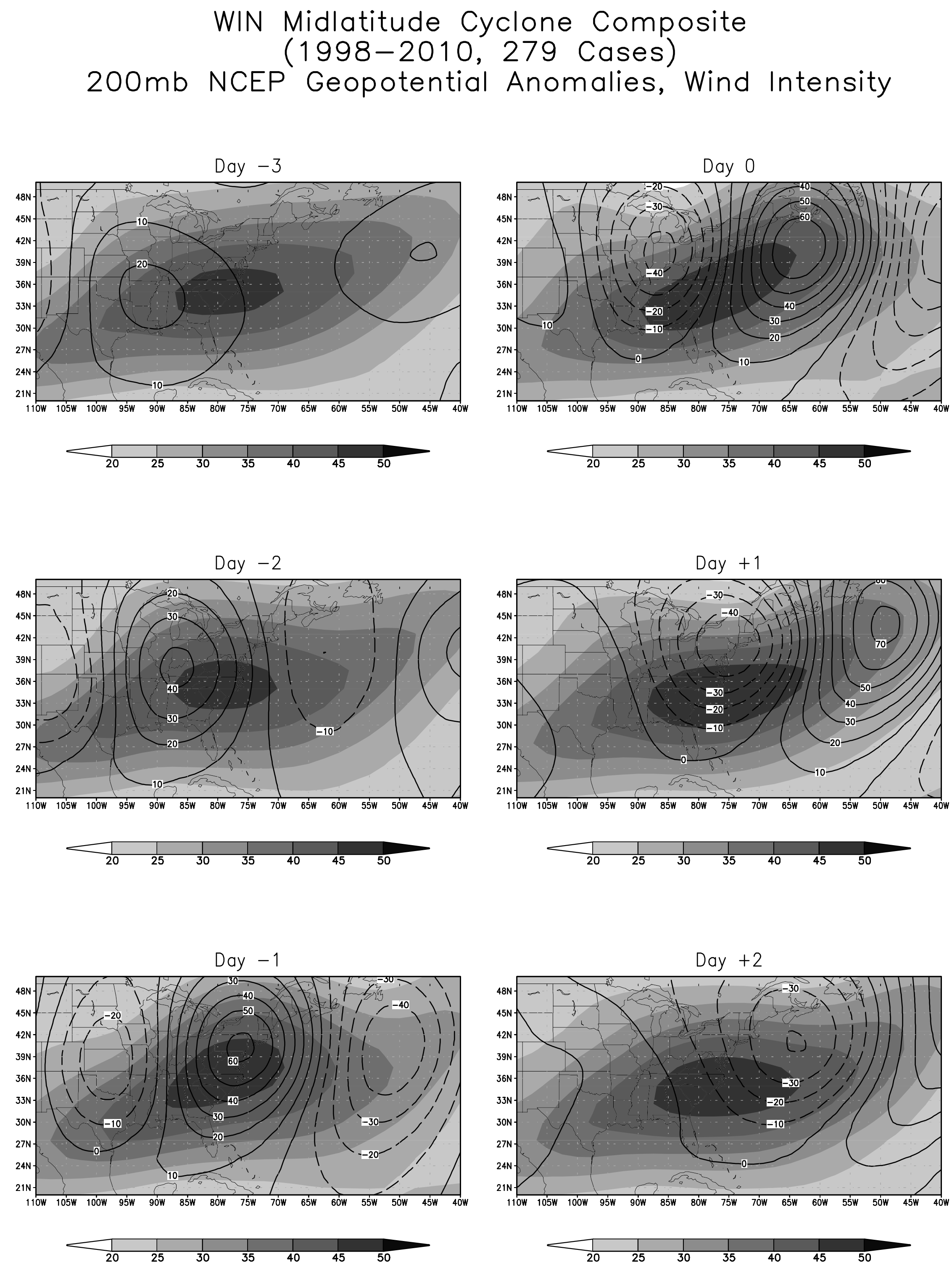


Figure 7: The wind intensities (shaded) and geopotential height (contoured) at the 200 mb level as the midlatitude cyclones passes North Carolina for winter (1998-2010). 279 cases were observed.

5.1.2 Spring (March, April, May)

Figure 8 shows the low-level composite of precipitation, SLP, and 850mb winds for the spring months. Midlatitude cyclone passages totaled 242 during spring.

Like the winter composite (fig. 6), precipitation occurs over LA, MS, TN, and AR on Day-2, and covers much of the SE US on Day-1. Most of the precipitation affects NC between Day-1 and Day0 as the fronts associated with the midlatitude cyclone pass. On Day0, the precipitation continues to intensify, but is mainly offshore by this point. On Days+1 and +2, precipitation associated with the midlatitude cyclone occurs mainly offshore. During the spring months, precipitation along the Gulf Stream only occurs as the midlatitude cyclone passes. This differs from the organized precipitation seen in the winter composite.

On Day-3, a weak area of high pressure, where isobars are not closed, dominates the SE US. On Day-2, the high pressure begins to move offshore. The midlatitude cyclone becomes visible on Day-1 south of the Great Lakes. As the midlatitude cyclone passes NC, it continues to intensify. Unlike the winter months, the midlatitude cyclone does not begin to show a northeastward tilt on Day0. Here, the midlatitude cyclone retains its symmetrical structure at the lower-levels as it moves offshore. By Day+1, the cyclone is offshore, just south of Nova Scotia. On Day+2, the midlatitude cyclone has moved well offshore, and has no effect on NC. Also, high pressure moves back into the SE US on Day +2.

Like the winter composite (fig. 6), southwesterly winds provide fuel for precipitation ahead of the midlatitude cyclone. The main difference from the winter composite is the winds are more meridional on Day-3 in the spring composite. However, this difference does not affect the formation of the midlatitude cyclone. In both the winter and spring composites, the midlatitude cyclone forms in the same area even though the wind directions are different.

As the midlatitude cyclone propagates eastward on Day-1, the winds strengthen over the SE US. On Day0, the winds shift to a northwesterly direction behind the midlatitude cyclone.

Figure 9 shows the upper-level composite of geopotential height anomalies and 200mb wind intensities. In contrast to the winter composite, the jet streak is much weaker during the spring. This weaker jet stream results in a slower moving midlatitude cyclone in the spring. In the winter composite (fig. 7), the upper-level trough moves quickly offshore on Days+1 and +2. However, during spring, a large portion of the upper-level trough remains in the northeast U.S. Furthermore, even as the midlatitude cyclone passes, the jet streak does not intensify as it does during the winter.

The 200mb geopotential anomalies during the spring have a weaker signal than in winter. However, the presence of an eastward propagating upper-level trough with ridges ahead and behind, is similar to the winter composite. The upper-level trough retains a symmetrical structure throughout the composite. Unlike the winter composite, the spring upper-level trough retains its upper-level symmetry. A symmetrical upper-level trough allows the midlatitude cyclone to continue developing ahead of the trough.

As a transition season, spring shows characteristics of both winter and summer. However, winter characteristics are more dominant in spring. Since the water and land temperatures still contrast, strong midlatitude development occurs. Therefore, features such as the upper-level trough associated with the midlatitude cyclone are still well defined. However, the summer composites in the next section are not well defined.

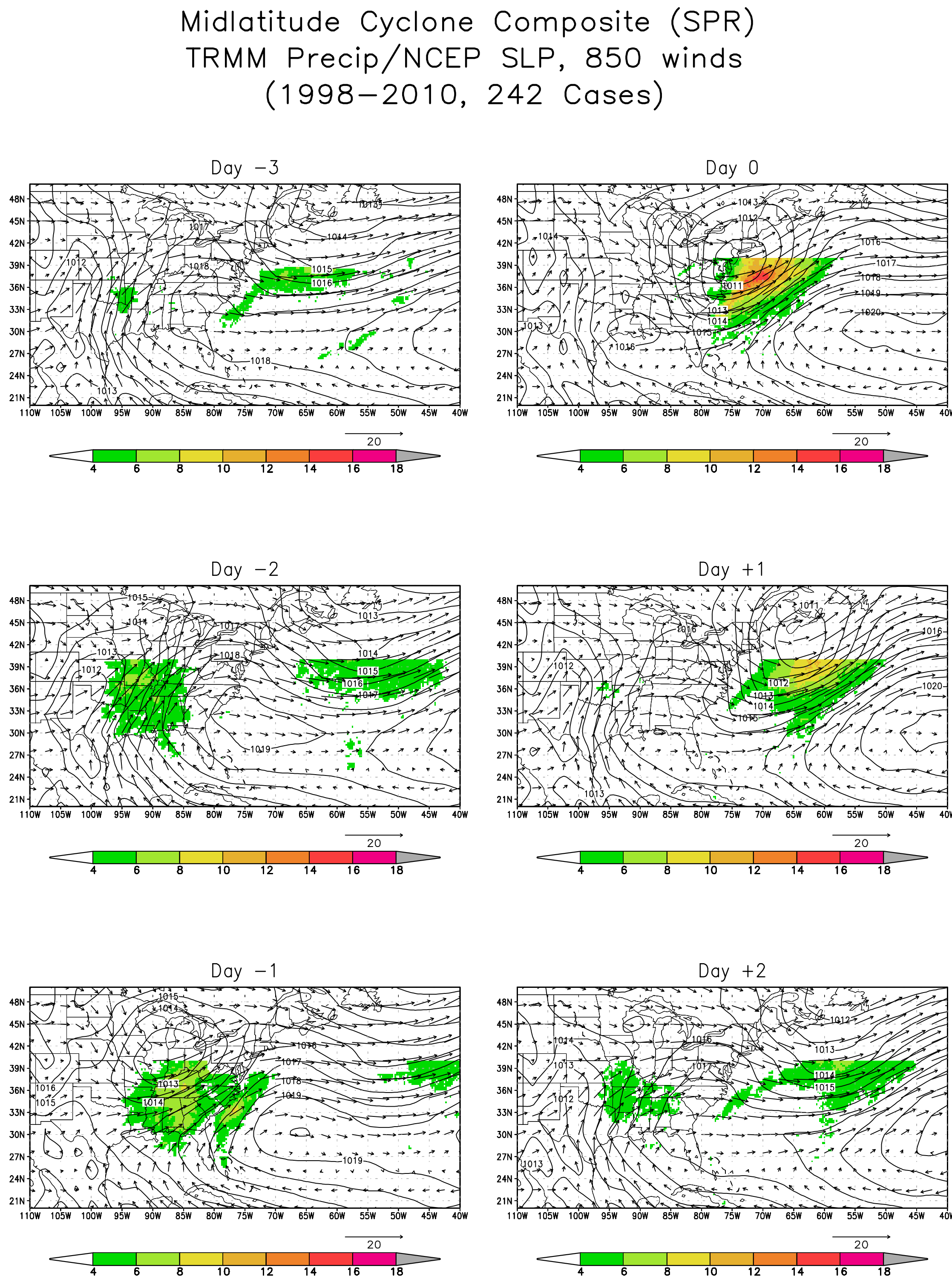


Figure 8: Midlatitude cyclone composite for all events that crossed NC during spring from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

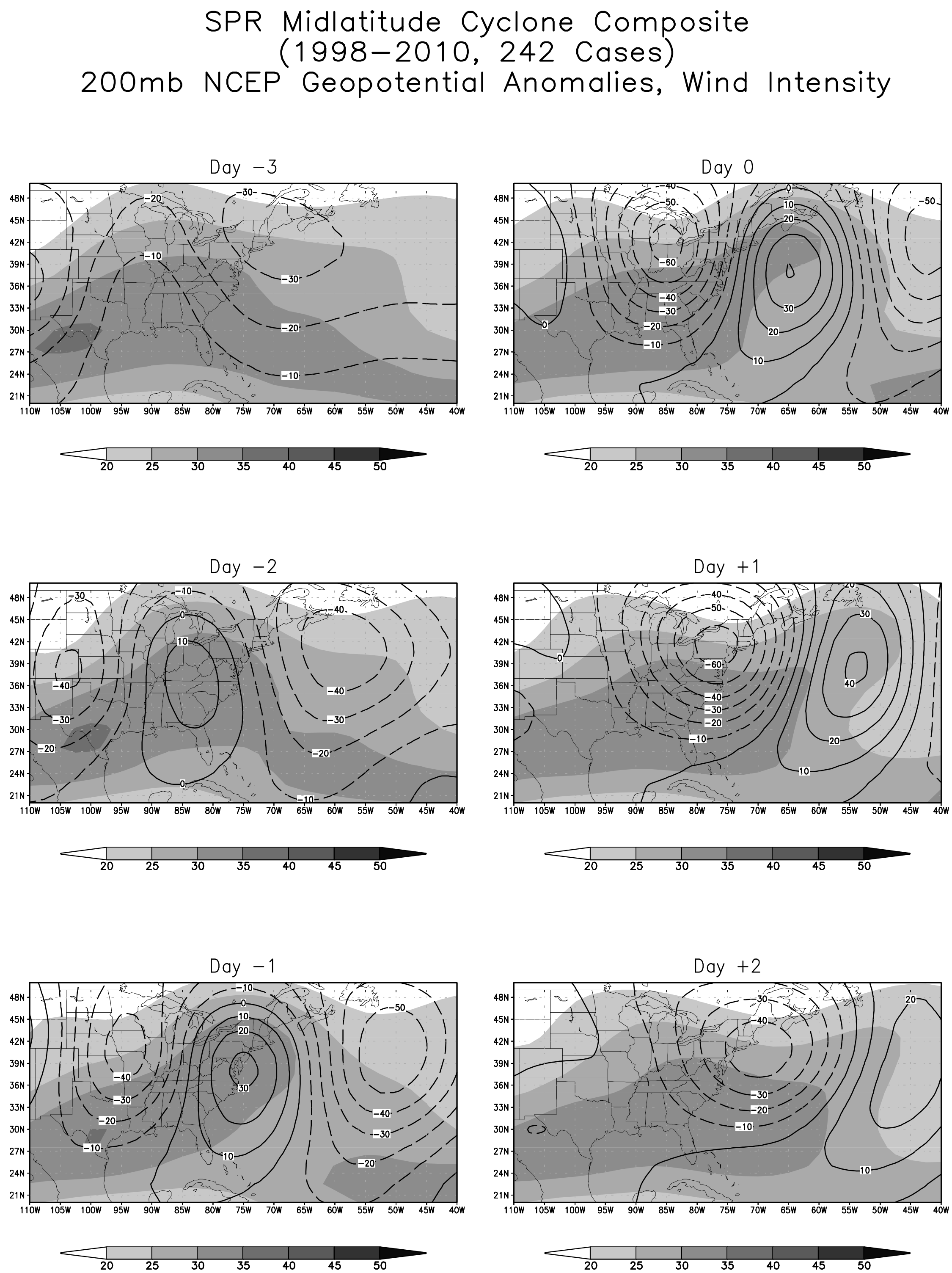


Figure 9: The wind intensities and geopotential height at the 200 mb level as the midlatitude cyclones passes North Carolina for spring (1998-2010). 242 cases were observed.

5.1.3 Summer (June, July August)

Figure 10 shows the low-level composite of precipitation, SLP, and 850mb winds for the summer months. Midlatitude cyclone passages totaled 162 during summer, which was the lowest for any season. In contrast to the winter months, the temperature gradient is much lower, and the jet is further northward.

The main difference in summer precipitation compared to winter or spring, is that precipitation occurs every day in the summer composite. While precipitation occurred mainly around the midlatitude cyclone in winter (fig. 8) and spring (fig. 10), precipitation results from less organized rainfall during summer. On Day-1, rainfall begins to fill in as the midlatitude cyclone passes, and the most intense precipitation occurs just off the NC coast over the Gulf Stream. Interestingly, rain is persistent along the Gulf of Mexico, and in Florida, throughout the composite. Here, the moisture is transported onto land from the warm waters of the Gulf of Mexico.

A notable synoptic-scale feature during the summer is the presence of the Bermuda High. During the winter and spring, high pressure propagates eastward into the Atlantic Ocean. However, in the summer composite, the Bermuda High persists throughout the composite. Its effects reach as far west as Texas, and bring warm, moist air onto land. This moist air provides fuel for the precipitation in the Gulf Coast states.

Most of the midlatitude cyclones that affect NC during the summer are generally much farther to the north. In the summer composite, the midlatitude cyclone is so far to the north, it can only clearly be seen on Day0 and Day+1. Interestingly, the midlatitude cyclone passage increases the rainfall along the Gulf Stream. By Day+2, the Bermuda High pushes the midlatitude cyclone offshore to the northeast.

The southerly moisture transport coming from the Gulf of Mexico differs in the summer. Instead of southwesterly winds in the winter and spring composites, the summer composite shows a southerly moisture transport. This southerly wind fuels the persistent rainfall for the Gulf States throughout the composite. As the midlatitude cyclone passes on Day0, the winds shift to the northeast ahead of the cyclone. On Day+1, the winds return to the south.

Figure 11 shows the upper-level composite of geopotential height anomalies and 200mb wind intensities for the summer. Here, the jet is largely zonal for the SE US. The jet streak associated with midlatitude cyclone formation and intensification has moved into Canada. Also, the upper-level winds are much weaker during the summer.

Unlike the winter and spring composites, there is no distinct cycle of upper-level troughs and ridges for the continental US. An upper-level trough is almost stationary between Days -3 and -2. On Day-1, the trough moves off to the northeast, and an upper-level ridge dominates the eastern US. On Day0, another upper-level trough dips into the continental US as the ridge weakens rapidly. This upper-level trough becomes stationary through Day+2. It is notable that the upper-level trough in the summer is much weaker than the winter or summer composites.

Summer midlatitude cyclones have the least effect on North Carolina than all other seasons. There is little difference in the land and ocean temperatures, and thus less fewer midlatitude cyclones develop. Most of the midlatitude cyclone activity is in Canada.

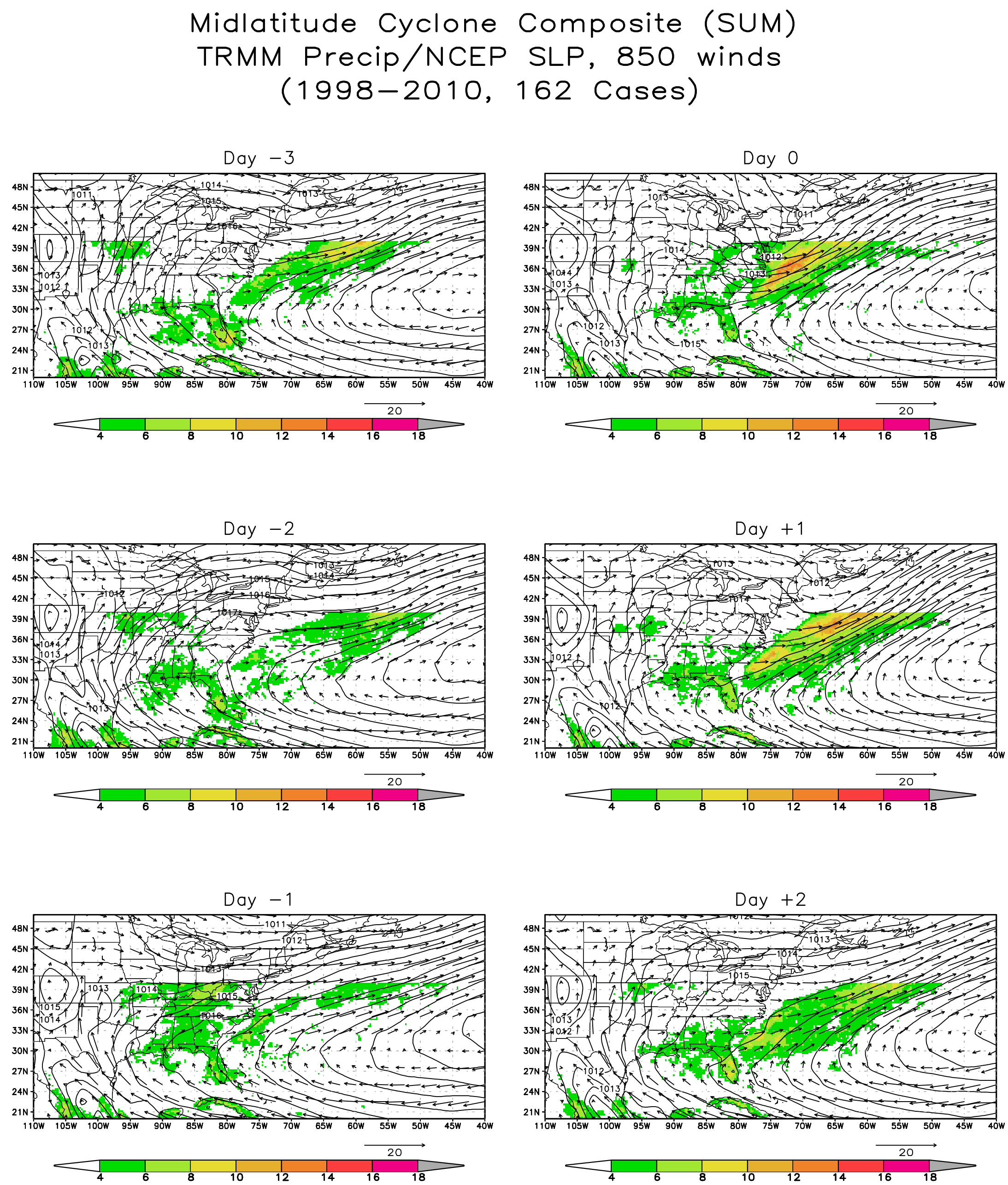


Figure 10: Midlatitude cyclone composite for all events that crossed NC during summer from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

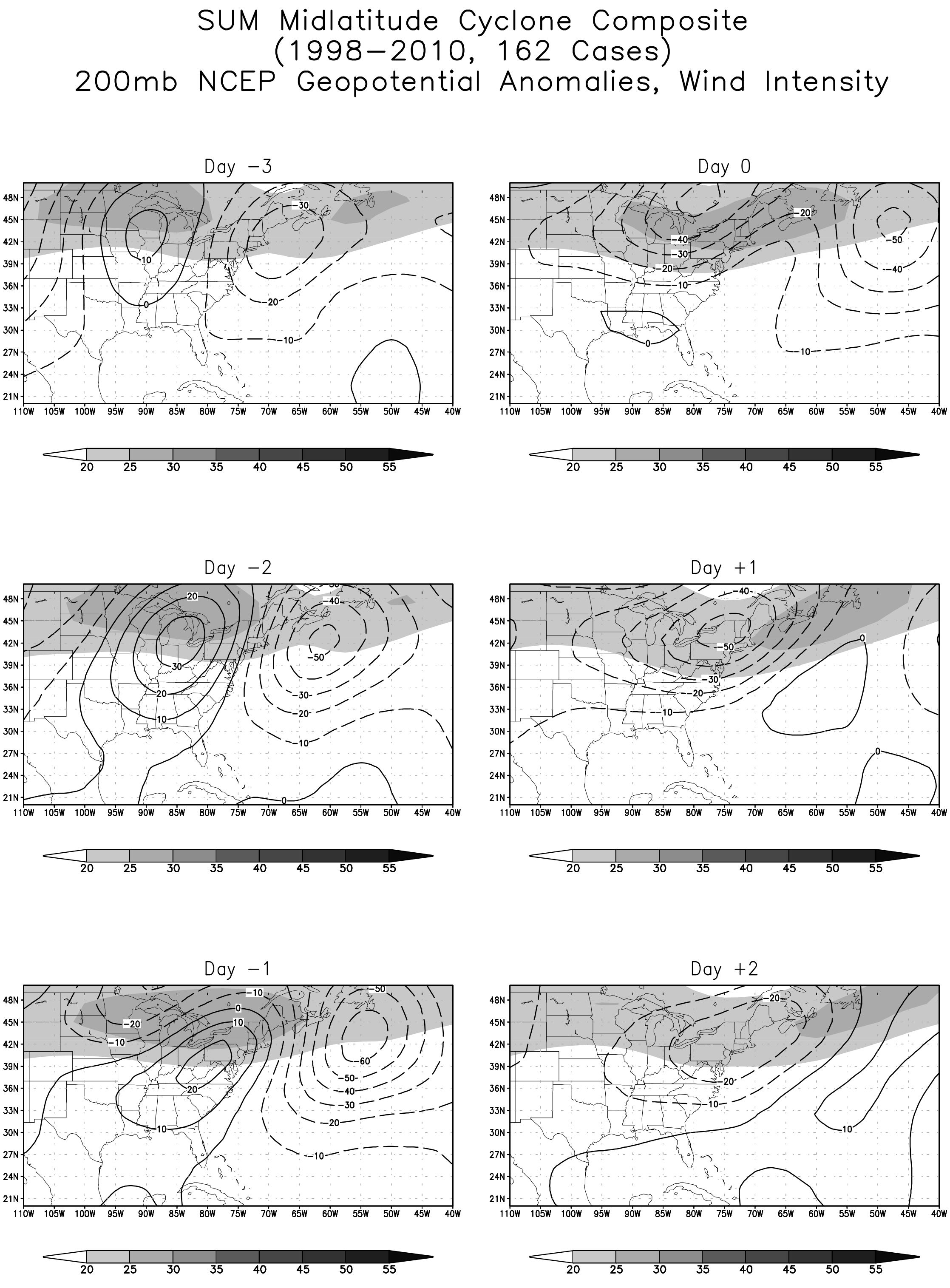


Figure 11: The wind intensities and geopotential height at the 200 mb level as the midlatitude cyclones passes North Carolina for summer (1998-2010). 162 cases were observed.

5.1.4 Fall (September, October, November)

Figure 12 shows the low-level composite of precipitation, SLP, and 850mb winds for the fall months. There were 200 midlatitude cyclone passages during this season. The fall was an interesting season for two reasons. First, the overall synoptic setup, while most similar to the summer, is largely different than the other three seasons. During Fall, precipitation is largely unorganized until the midlatitude cyclone develops. Upon midlatitude cyclone formation, precipitation becomes organized, similar to the winter and spring seasons. Another interesting feature in the original date collection was the detection of every tropical cyclone that came within a few hundred kilometers of NC. These dates were excluded from this study, and could be examined further in a later project.

In this composite, much of the continental US is dry on Day-3. Precipitation begins to form west of the Appalachian Mountains on Day-2, and fills in most of the SE US on Day-1. Like the winter (fig. 6) and spring (fig. 8) composites, the rainfall continues to intensify as the midlatitude cyclone passes on Day0, but has moved offshore. Rainfall over the Gulf Stream is persistent throughout the composite. On the other hand, there is precipitation elsewhere in the SE US before the midlatitude cyclone passage. This suggests that isolated convection, similar to the summer months, is still present during the fall. Dry air returns to the SE US on Day+1.

During the fall, the high pressure does not move offshore quickly, and prevails through Day-2. Interestingly, the Bermuda High does not have as much effect on the SE US as in the summer months. The closed high pressure center over the SE US is evidence of the Bermuda High losing its effect. As the midlatitude cyclone approaches NC, the high pressure has moved offshore. The midlatitude cyclone itself resembles ones that occurred during the summer. Note how far north the midlatitude cyclone is, but also how far south its effects reach. This is due to the postion of the upper level trough (fig. 13). As the midlatitude cyclone moves off to the northeast on Day+1, the high pressure center returns to the SE US, bringing drier air in.

During the fall, a notable wind feature is how the Bermuda High begins to lose its effect on the winds in the SE US. The winds on Day-3 are more southwesterly, which is similar to the winter and spring composites. As the midlatitude cyclone moves eastward, the southwesterly winds intensify. On Day0, after the midlatitude cyclone has passed, winds become northwesterly.

Figure 13 shows the upper-level composite of geopotential anomalies and 200mb wind intensities. Here, the jet streak has moved southward into the continental US. It is also stronger than the summer composite (fig. 11). On Day-1, as the midlatitude cyclone begins to approach NC, the jet streak intensifies and tilts northeastward. The jet streak is strongest on Day0 as the midlatitude cyclone passes. Although the jet streak weakens on Days+1 and +2, it still retains its northeastward tilt, which aids in midlatitude cyclone continued intensification.

The structure of the upper-level circulation is not as organized as the winter (fig. 7) and spring (fig. 9). However, the upper-level trough is stronger than the summer months. This trough intensifies on Day-1. Note the symmetrical structure of the upper-level trough. Unlike the winter composite, there is no northeastward tilting of this trough. On Days+1 and +2, the upper-level trough becomes almost stationary over the northeast US.

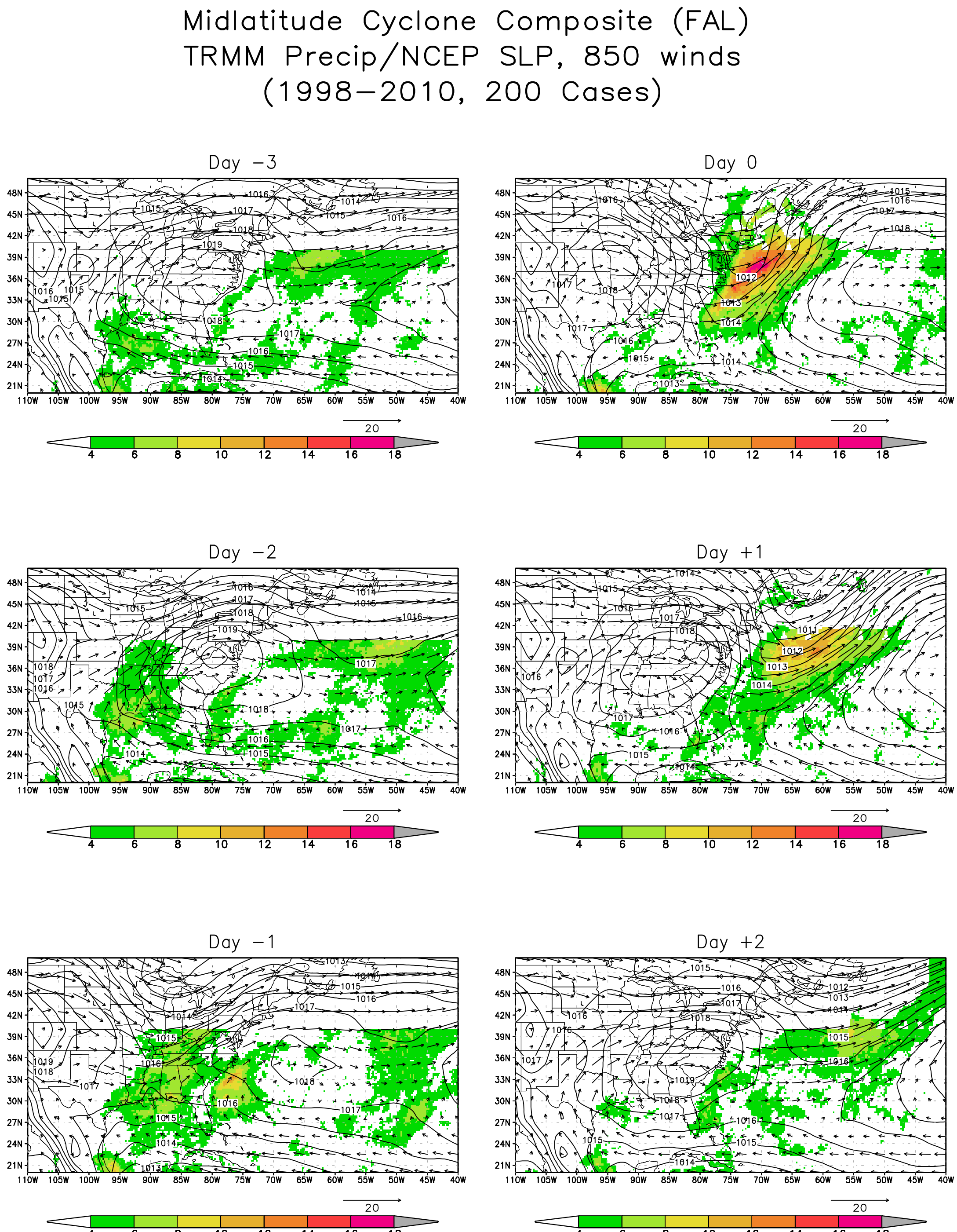


Figure 12: Midlatitude cyclone composite for all events that crossed NC during fall from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

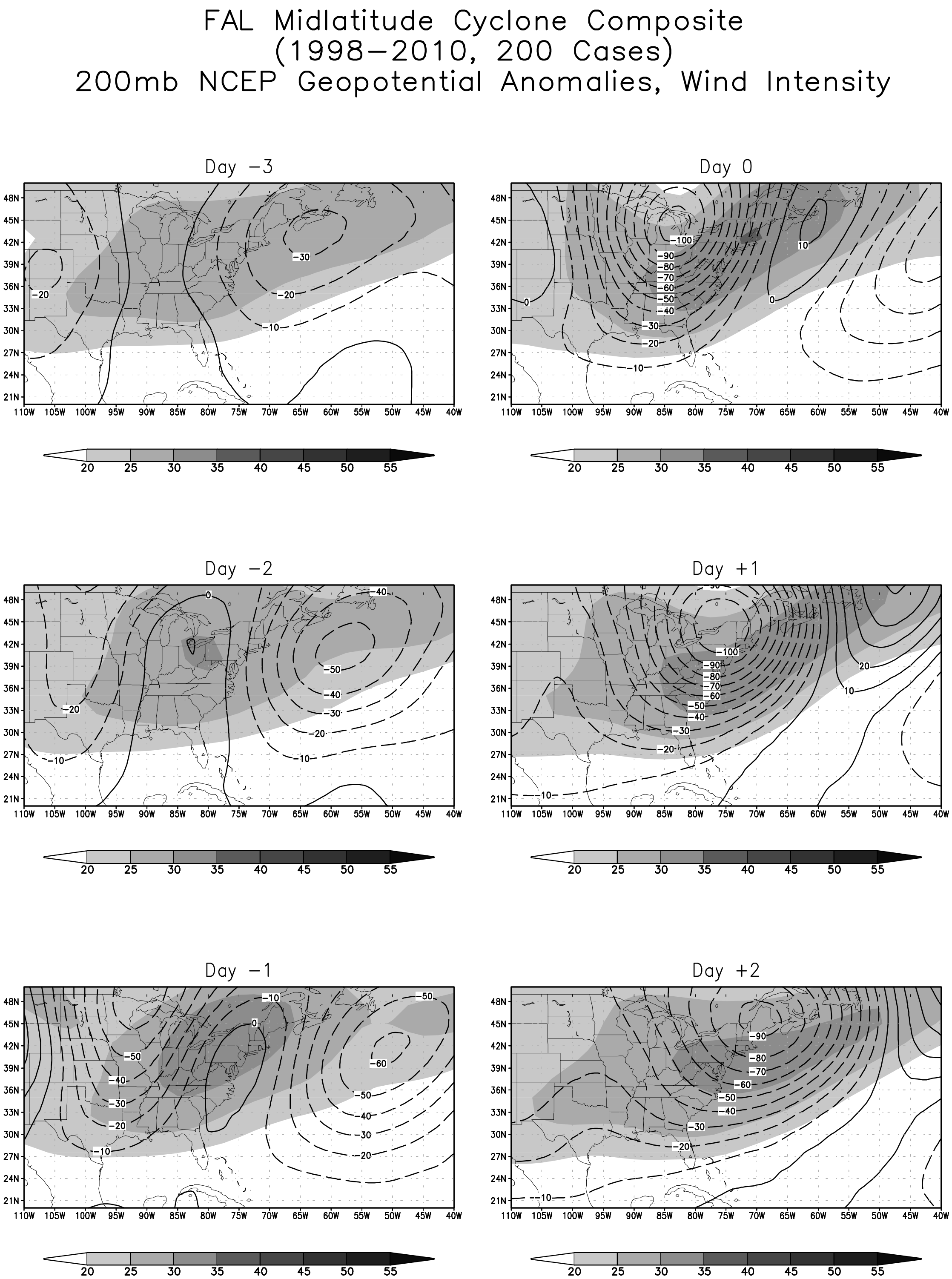


Figure 13: The wind intensities and geopotential height at the 200 mb level as the midlatitude cyclones passes North Carolina for fall (1998-2010). 200 cases were observed.

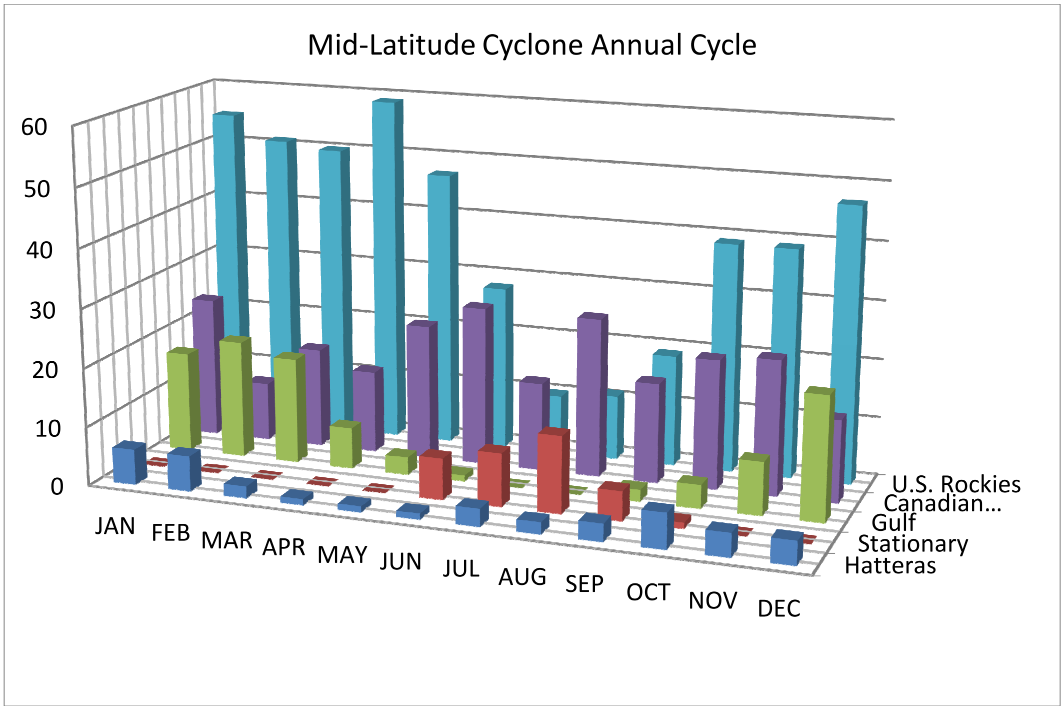


Figure 14: The annual cycle of midlatitude cyclone passages between 1998-2010. The five types of midlatitude cyclones are listed above.

5.2 Seasonal Midlatitude Cyclones by Type

As stated earlier, five midlatitude cyclone types were determined to affect NC. Each type was based on the geographical point of cyclone origin. The geographic origin of midlatitude cyclones is important because each track is different. Figure 14 shows the annual cycle of each midlatitude cyclone type. Winter is the peak season for all types except for stationary and Canadian Rockies midlatitude cyclones. Rockies type cyclones dominate every month except August and September. These midlatitude cyclones peak during winter while reaching a minimum in summer.

This section presents the seasonal patterns for each midlatitude cyclone type. However, some types do not occur every season. Therefore, not every type of midlatitude cyclone is shown for all seasons. The midlatitude cyclone types covered for the winter and spring months: Rockies, Canadian, Gulf, and Hatteras. The midlatitude cyclone types covered for the summer: Rockies, Canadian, and Stationary. Finally, the midlatitude cyclone types covered for the fall: Rockies, Canadian, and Hatteras. Overall, the Rockies and Canadian midlatitude cyclone types are the most frequent, and are covered in all seasons. The Gulf and Hatteras types are special midlatitude cyclones which rely on the temperature differential between water and land to aid in their rapid formations. The stationary midlatitude cyclone types are only seen during the summer months, and are the least frequent.

5.2.1 Winter (December, January, February)

a. Rockies

Figure 15 shows the low-level composite of precipitation, SLP, and 850mb winds for the Rockies type midlatitude cyclones during the winter. There were 153 Rockies type passages for NC. Since this is the most frequent cyclone type in the winter, the Rockies type cyclones are most similar to the winter seasonal composite (fig. 5).

As the midlatitude cyclone approaches NC, precipitation intensifies, and fills in the whole SE US. Here, precipitation is most intense near the Appalachian Mountains, in the SE quadrant of the cyclone. Precipitation continues to intensify after the midlatitude cyclone passage. However, the most intense rainfall is offshore. By Day+1, precipitation has moved offshore. There is one interesting precipitation features in this composite. Consistent with the winter seasonal composite, precipitation is localized around the midlatitude cyclone.

On Day-2, this high pressure begins to broaden, and move eastward. As the midlatitude cyclone moves eastward on Day-1, the high pressure has moved offshore. The midlatitude cyclone continues to intensify after passage on Day0, and is located in the NE

US. This cyclone quickly moves offshore on Day+1. Also, another high pressure center returns on Day+1.

Southwesterly winds ahead of the midlatitude cyclone on Day-2 provide warm, moist air for precipitation. Winds continue to prevail from the southwest as the midlatitude cyclone approaches NC. After the midlatitude cyclone passage, winds become northwesterly. On Days +1 and +2, winds become zonal as the high pressure center moves into the SE US.

Figure 15 shows the upper-level composite of geopotential height anomalies and 200mb wind intensities. Here, the jet is zonal on Day-3. As the midlatitude cyclone moves eastward, the jet intensifies, and the presence of a jet streak can be seen in Appalachian NC/VA. On Day-1, as the midlatitude cyclone approaches NC, the jet begins to tilt northeastward, and the jet streak broadens. On Day0, the jet streak is positioned over the SE US. After the passage of the midlatitude cyclone, the jet weakens and becomes zonal.

The upper-level circulation is different than the winter composite on Days-3 and -2. Here, a northeastward tilting upper-level trough dominates the eastern U.S. An upper-level trough is present on Day-2. As the upper-level trough moves eastward with the midlatitude cyclone, the upper-level circulation becomes more organized. On Day0, after the passage of the midlatitude cyclone, notice the boomerang shape of the upper-level trough. This occurs due to the influence of the jet streak on the upper-level trough. This trough continues to move eastward after the midlatitude cyclone passage.

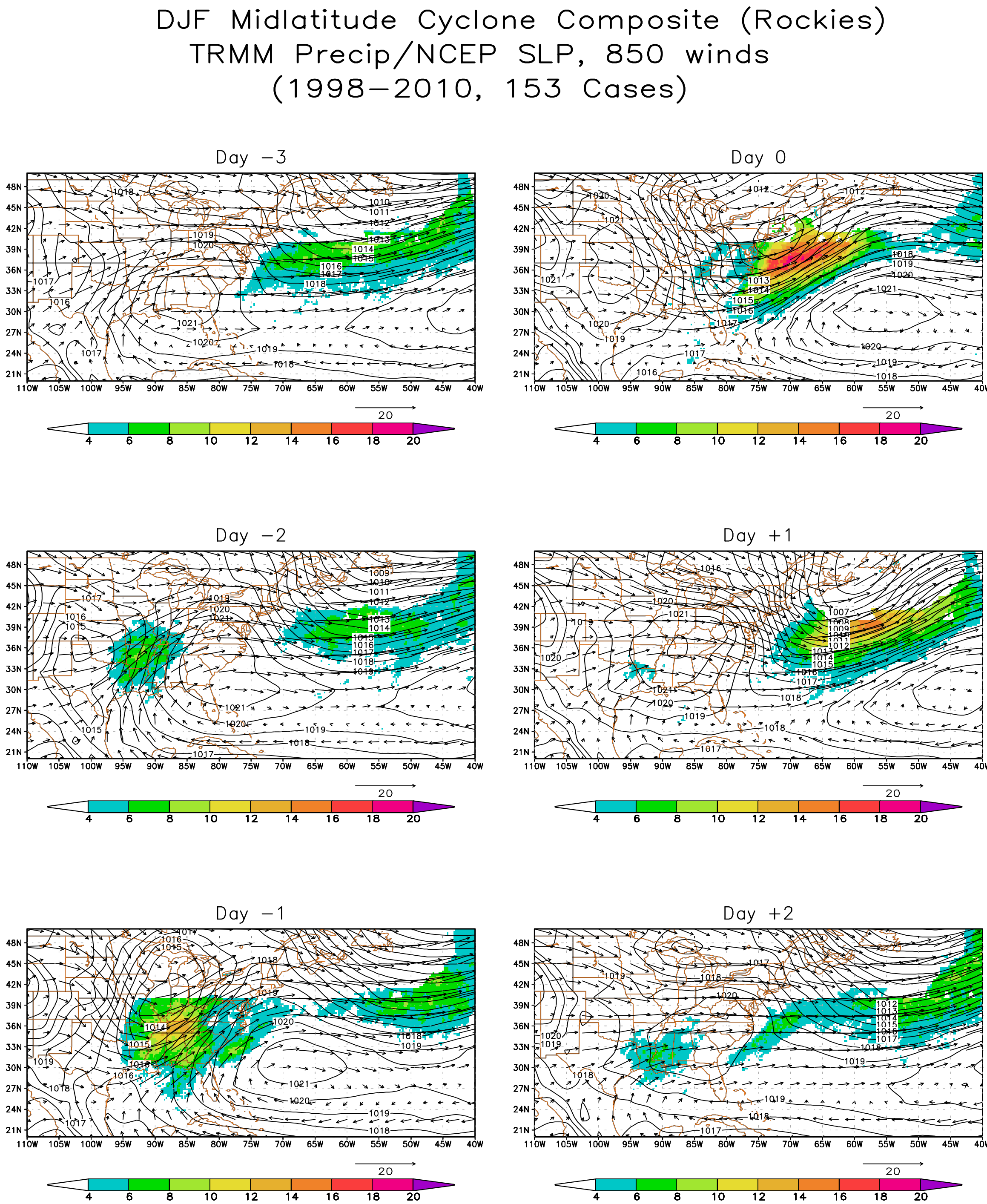


Figure 15: Midlatitude cyclone composite for all Rockies type events that crossed NC during winter from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

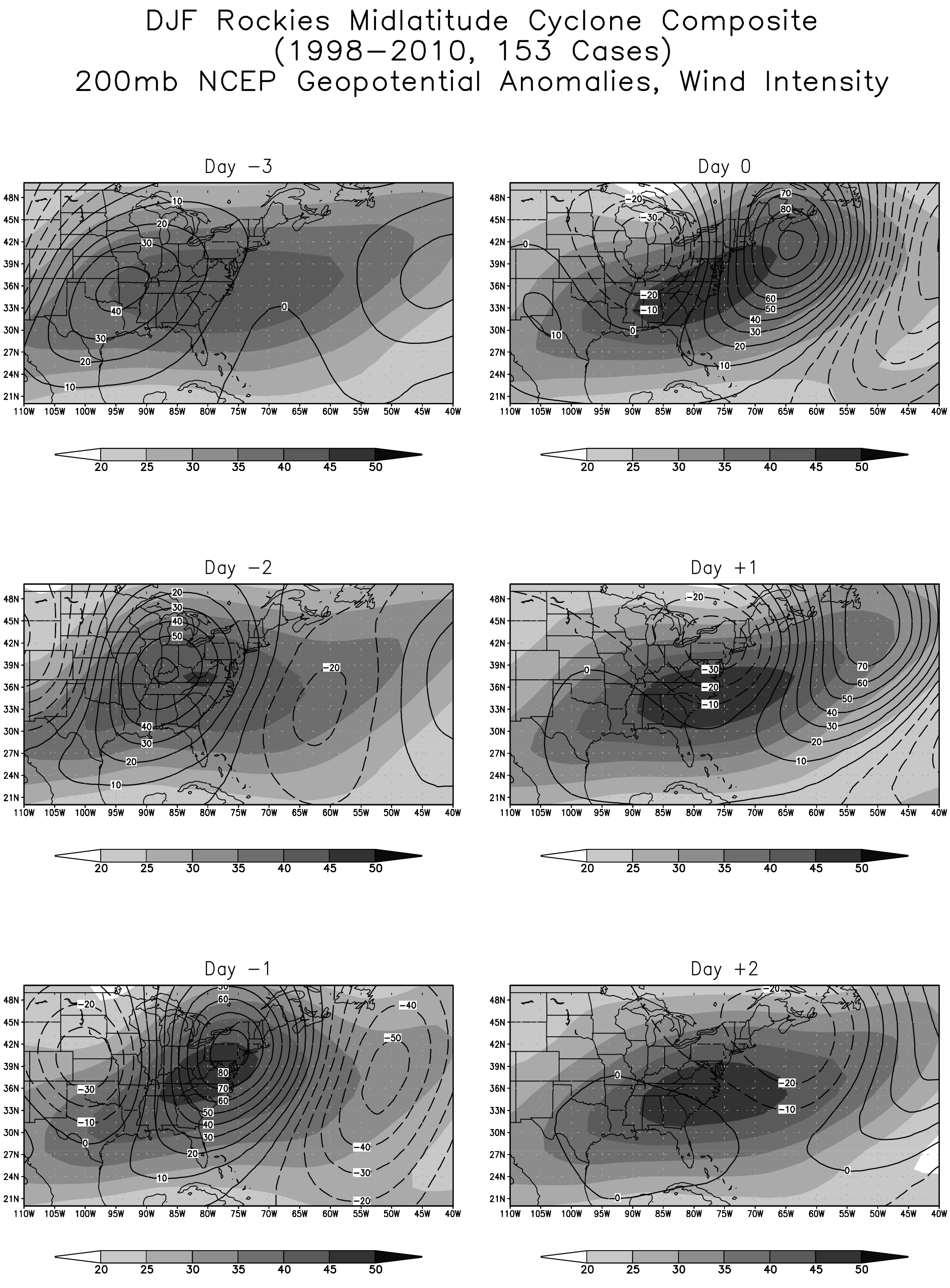


Figure 16: The wind intensities and geopotential height at the 200 mb level as the Rockies type midlatitude cyclones passes North Carolina for winter (1998-2010). 153 cases were observed.

b. Canadian

Figure 17 shows the low-level composite of precipitation, SLP, and 850mb winds for the Canadian type midlatitude cyclones during winter. While Canadian midlatitude cyclones are the second most frequent for all seasons, the 48 cases during winter is the third most frequent. They occur much farther to the north than the other midlatitude cyclone types, so they have less effect on NC.

Unlike the other midlatitude cyclones, precipitation is scarce in the SE US throughout the composite. Interestingly, most of the rainfall associated with the cyclone does not affect NC. Precipitation is strongest around the midlatitude cyclone, which is consistent with winter midlatitude cyclones. However, the rainfall is further to the north for Canadian type cyclones. This precipitation can be attributed to the southwesterly winds bringing moisture onshore from the Gulf of Mexico.

High pressure does not dominate the SE US on Day-3. The high pressure moves into the SE US on Day-2, and moves southward as the midlatitude cyclone approaches. As the midlatitude cyclone passes on Day0, the high pressure dissipates, but quickly returns on Day+1. The midlatitude cyclone moves quickly to the northeast on Day+1.

Winds are largely zonal on Day-3. As the high pressure moves eastward, the winds shift northwesterly on Day-2, but quickly become slightly southwesterly on Day-1. Here, the midlatitude cyclone is approaching NC. Winds become northwesterly after the midlatitude cyclone passes on Day0. The strongest winds are associated with the midlatitude cyclone on Day0. However, these winds do not affect NC. Finally, zonal winds prevail on Day+1, becoming slightly southwesterly on Day+2. The winds in this composite have no overall effect on NC.

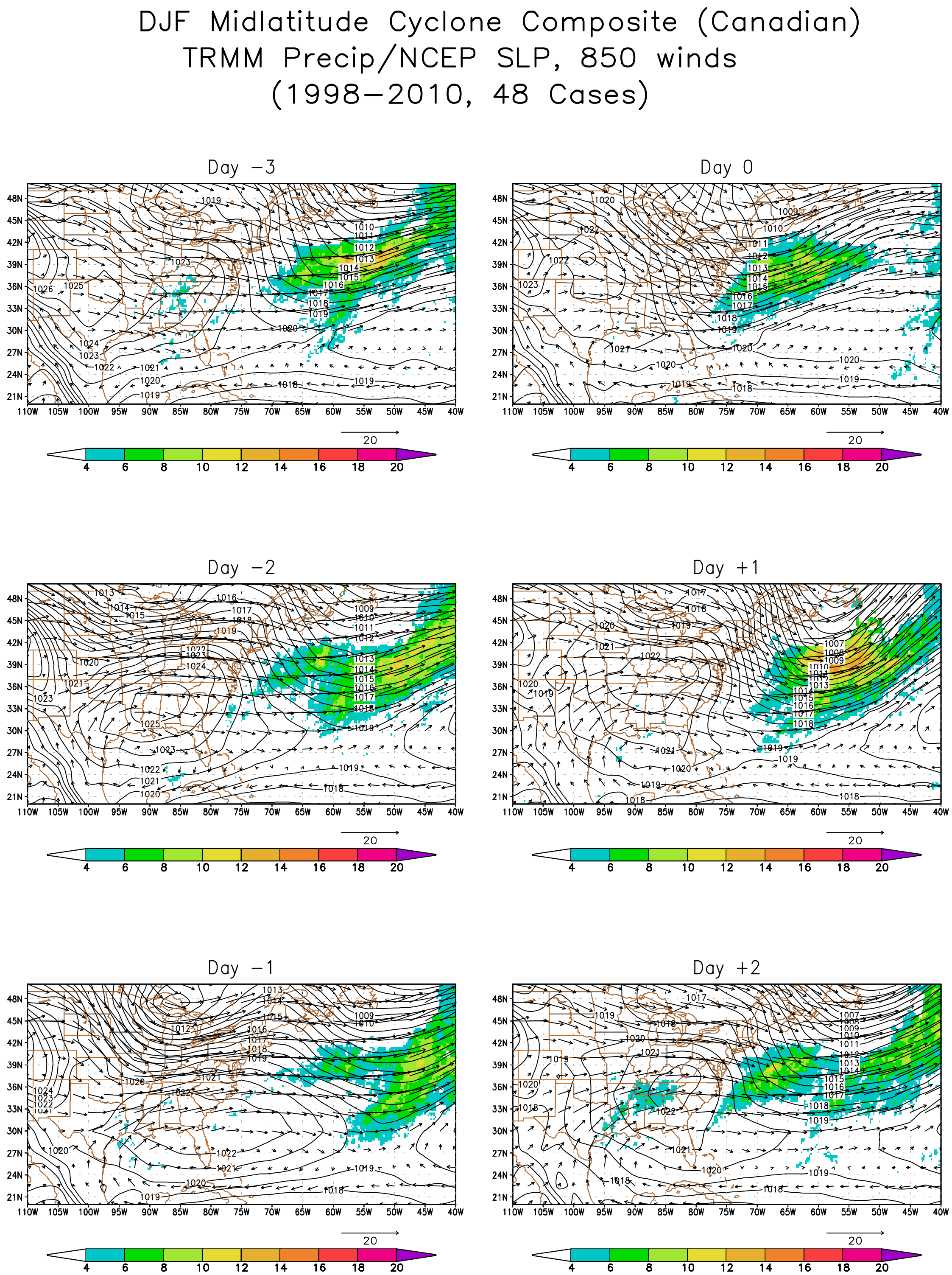


Figure 17: Midlatitude cyclone composite for all Canadian type events that crossed NC during winter from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

Figure 18 shows the upper-level composite of geopotential height anomalies and 200mb wind intensities. On Day-2, it becomes more zonal, and actually has a southeastern tilt on Day-1. However, the actual midlatitude cyclone is farther north than the Rockies-type. Therefore, the jet stream does not have an affect on the development or propagation of the Canadian midlatitude cyclone. This upper-level jet stream pattern is consistent throughout the winter season. After the midlatitude cyclone passes on Day0, the jet streak broadens and becomes zonal.

Despite the northward track of the Canadian type midlatitude cyclone, an upper-level trough remains organized in the continental US throughout the composite. In other words, the midlatitude cyclone is not associated with this upper-level trough. However, the upper-level structure does not differ significantly from the Rockies composite. On Day-1, notice that while the upper-level trough is organized; the ridge to the west of this trough is very unorganized. As the midlatitude cyclone passes on Day0, it dips to the south. In this composite, rather than the upper-level ridge following to the west of the trough, the ridge is to the southwest of the trough on Day0. On Day+1, the ridge moves to the north, becoming west of the upper-level trough.

Overall, the Canadian-type midlatitude cyclone has the least effect on NC. It is simply too far north to bring significant amounts of precipitation to NC. By the time any significant precipitation occurs it is off the east coast of the U.S. The upper-level jet stream has little or no effect on the formation of the Canadian-type midlatitude cyclone. The biggest similarity between the Rockies and Canadian-type cyclones is the upper-level ridge moving into the eastern U.S. after passage.

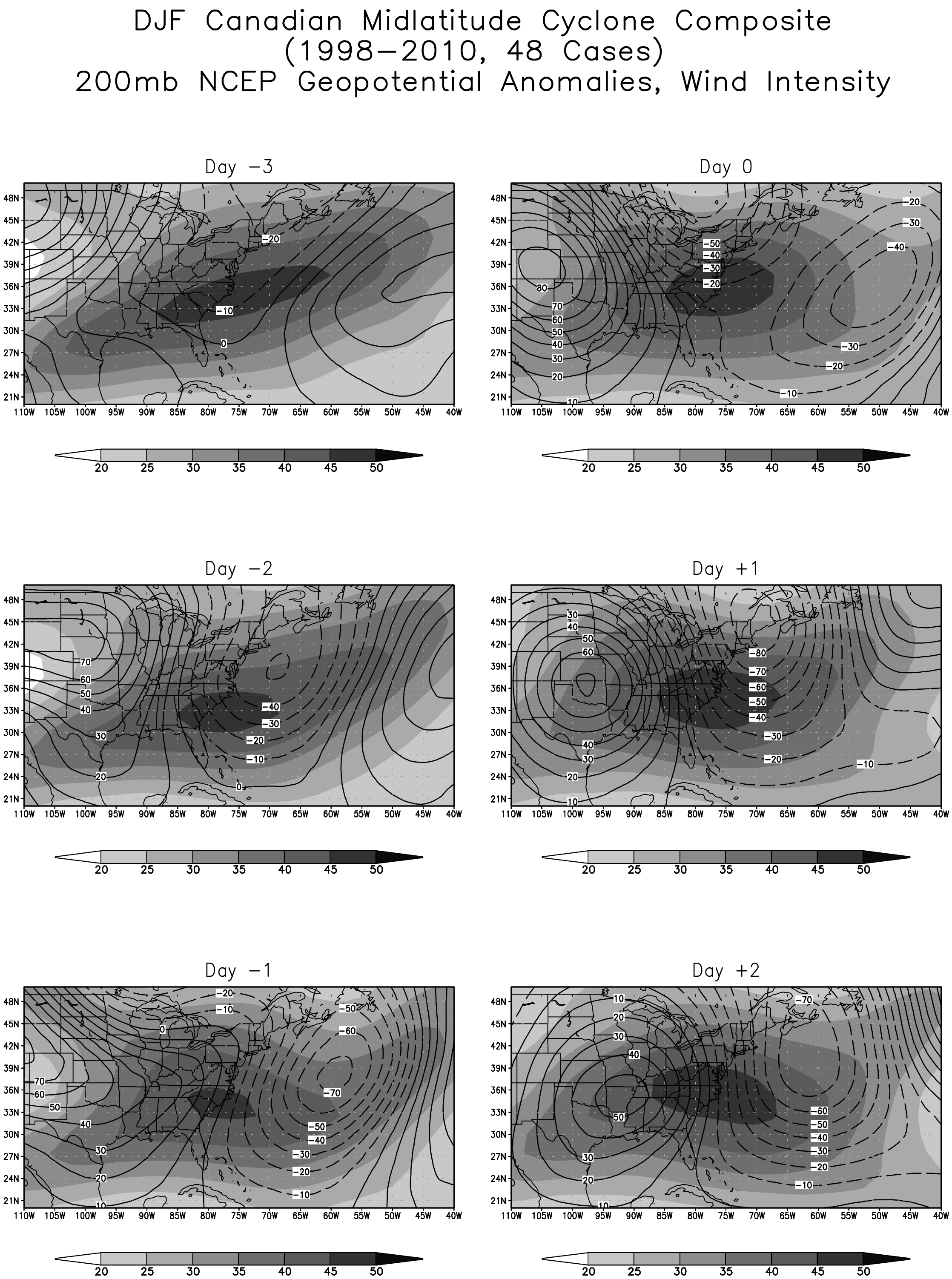


Figure 18: The wind intensities and geopotential height at the 200mb level as the Canadian type midlatitude cyclones passes North Carolina for winter (1998-2010). 48 cases were observed.

c. Gulf

Figure 19 shows the low-level composite of precipitation, SLP, and 850mb winds for the Gulf type midlatitude cyclones during winter. Winter is the most frequent season for Gulf type midlatitude cyclones. While Rockies type midlatitude cyclones are the most frequent, Gulf cyclones are more intense in terms of SLP, winds, and precipitation for North Carolina.

Precipitation in the Gulf of Mexico occurs on Day-3 ahead of the midlatitude cyclone. On Day-2, precipitation intensifies, and begins to move onshore into TX, MS, LA, AR, TN, and AL. As the midlatitude cyclone nears NC, precipitation has intensified further and filled in the entire SE US. On Day-1, the most precipitation affects NC. After the passage of the midlatitude cyclone on Day0, the precipitation is most intense. However, the most intense precipitation is offshore. By Day+1, the midlatitude cyclone has moved well offshore, as well as the precipitation associated with the storm. On Day+2, precipitation has returned to the Gulf of Mexico.

Like the Canadian type midlatitude cyclone (fig. 16), high pressure moves into the SE US on Day-2, bringing clear weather with it. However, this clear weather is short lived. On Day-1, the high pressure moves off to the northeast and the midlatitude cyclone begins to come onshore from the Gulf of Mexico. The midlatitude cyclone is clearly seen as it moves to the northeast. The Gulf-type midlatitude cyclone has the most effect on NC on Day-1. Interestingly, there are two high pressure areas near the midlatitude cyclone on Day-1. One high pressure area is northeast of the cyclone, and the other is to the east in the Atlantic Ocean. These high pressure areas seem to direct the midlatitude cyclone to the northeast. The high pressure to the east strengthens through Day+1, while the other is absorbed by the midlatitude cyclone on Day0. The Gulf-type midlatitude cyclone intensifies dramatically between Days-1 and 0. On Day0, it fully matures, and continues to intensify on Day+1 as it moves away. The most defining feature of a Gulf-type midlatitude cyclone track is that it moves from the Gulf of Mexico and crosses over Florida into the Atlantic Ocean. On Day0, the midlatitude cyclone continues to intensify as it moves away from NC. By Day+1, high pressure returns to the area, suggesting that these storms do not usually happen one after the other.

Between Day-3 and -2, winds shift from westerly to southwesterly for NC. This shift brings moist air from the Gulf of Mexico onshore. This increase in moisture is consistent with precipitation increasing over the SE US on Day-1. Winds increase in intensity between Days-2 and 0. The southwesterly winds prevail until the passage of the midlatitude cyclone on Day0. As the midlatitude cyclone passes, winds intensify. After this passage, winds become northwesterly. By Day+2, the winds become zonal.

Overall, the lower-level structure of the Gulf-type midlatitude cyclone is the most interesting during winter. These storms go through a rapid development that is consistent in most of the cases. Also, unlike the Rockies-type cyclone, which has a wide array of origination points, the Gulf-type forms in the Gulf of Mexico. These cyclones do not have much variation in their points of origin. In terms of precipitation, the winter Gulf-type cyclone is the most intense.

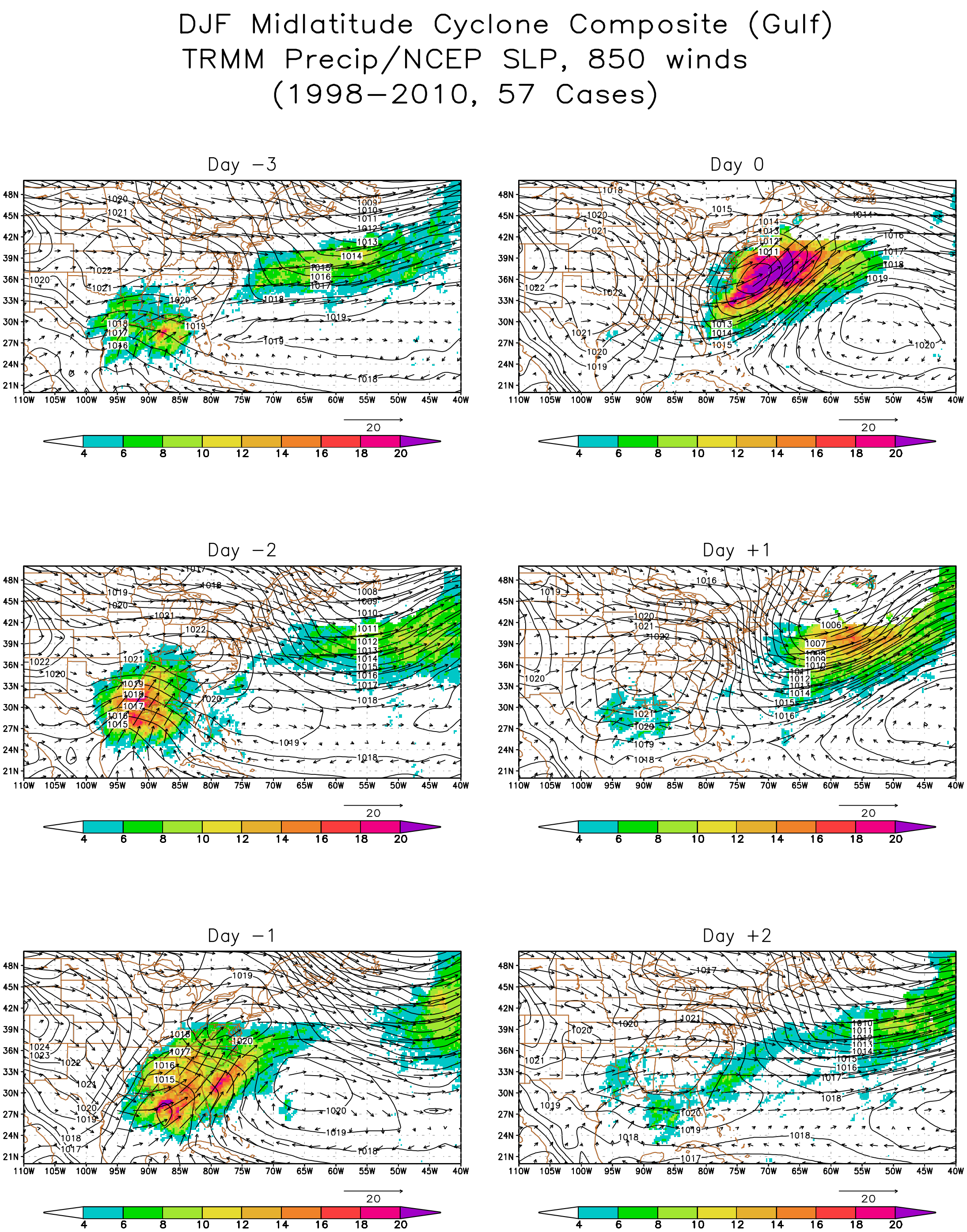


Figure 19: Midlatitude cyclone composite for all Gulf type events that crossed NC during winter from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

Figure 20 shows the upper-level composite of geopotential height anomalies and 200mb wind intensities. Here, the jet is tilted to the northeast on Day-3. This tilt occurs throughout the composite and aids in the rapid intensification of the midlatitude cyclone by increasing baroclinic wind shear. The jet streak intensifies and broadens through Day0 when the midlatitude cyclone passes. As this jet streak intensifies, the midlatitude cyclone intensifies. On Day+1, the jet begins to tilt zonally, and the jet streak moves slightly to the south. By Day+2, the jet has weakened.

One defining feature associated with the Gulf type midlatitude cyclone is the longer duration of the upper-level trough. This trough originates in the SW US, and travels eastward between Days -3 and -1. On Day-2, as the midlatitude cyclone is beginning to be seen in the Gulf of Mexico, an upper-level ridge in the Midwest US intensifies into Day-1. However, once the upper-level trough begins to move eastward, this ridge moves to the northeast. Unlike the other composites, once the upper-level trough reaches the Midwest US, it begins to tilt and broaden after the midlatitude cyclone passage on Day0. The core of this trough actually splits into two smaller cores on Day+1. Note that the upper-level ridge ahead of this trough begins to show the same boomerang shape that the upper-level trough in the Canadian type composite (fig. 17) showed. On Day+2, the upper-level ridge has moved off to the northeast, and the westernmost core of the upper-level trough intensifies. This could signify the formation of another midlatitude cyclone.

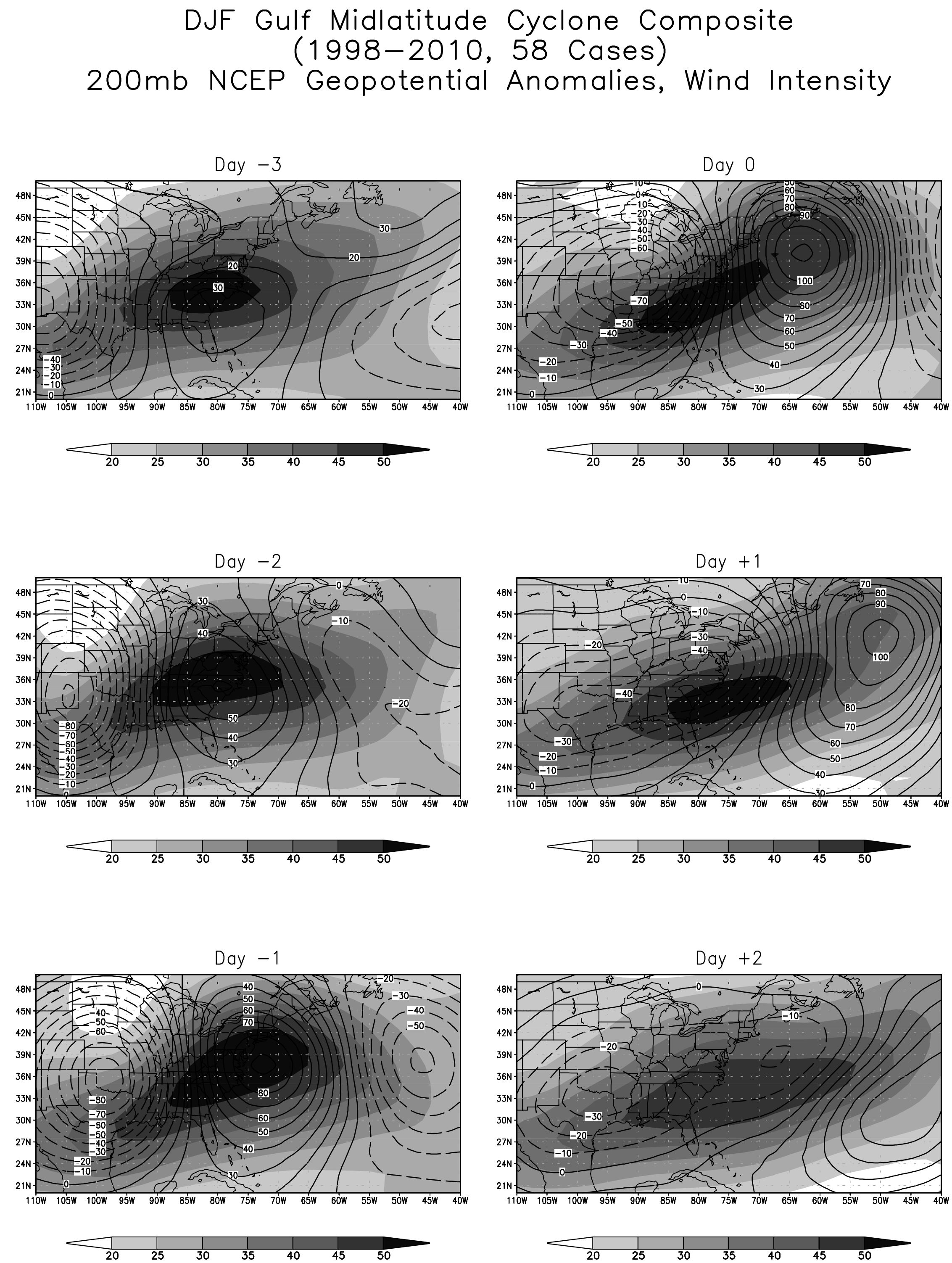


Figure 20: The wind intensities and geopotential height at the 200 mb level as the Gulf type midlatitude cyclones passes North Carolina for winter (1998-2010). 58 cases were observed.

d. Hatteras

Figure 21 shows the low-level composite of precipitation, SLP, and 850mb winds for the Hatteras type midlatitude cyclone during the winter months. Hatteras cyclones most resemble “nor’easter” storms (Davis et al. 1993). Characterized by their sudden formation, they track up the Atlantic coastline, bringing heavy precipitation and winds. Hatteras-type cyclones are the second most intense for winter only behind Gulf-types. However, these midlatitude cyclones do not have a consistent occurrence. With only 16 cases, the winter Hatteras-type midlatitude cyclone is the least frequent type of midlatitude cyclone other than the stationary type, which only occurs during summer. However, the rapid intensification of these midlatitude cyclones makes forecasting difficult.

Unlike all other winter composites, precipitation covers the SE US on Day-3. As this precipitation moves eastward, high pressure moves in behind it. On Day-1, note how precipitation intensifies on the east coast of Florida. On Day0, a closed-isobar low pressure center forms off the NC coast. This closed low signifies midlatitude cyclone formation, while precipitation continues to intensify rapidly. The heaviest precipitation is on the eastern side of the storm off the coast of NC. Most of the precipitation for NC occurs along the Outer Banks on Day0. By Day+1, the precipitation moves well offshore and continues to intensify. Precipitation returns to the Gulf Stream on Day+2 as the cyclone moves northeastward.

High pressure in the Atlantic Ocean provides moisture transport for the east coast of the United States on Day-3. As this high pressure weakens, another high pressure area moves in from the west. On Day-1, the high pressure intensifies, and southerly winds on the SE quadrant bring in warm, moist air from the south. From this, the midlatitude cyclone forms as the high pressure center moves into the Atlantic Ocean on Day0. The high pressure from

Day-1 is now on the eastern side of the midlatitude cyclone. Notice how the high pressure area aids in the rapid intensification of the Hatteras cyclone. Another defining feature of the Hatteras type midlatitude cyclone is the northeastward tilt of the storm. By Day+2 the cyclone moves to the north, and no longer has any effect on NC. On Day+1, high pressure returns to the SE US. However, this high pressure is does not dominate the eastern US as it does in the Rockies and Gulf-types.

Northwesterly winds dominate the SE US on Days-3 and -2. This brings in cold, dry air from the north. As the high pressure moves eastward, it suddenly shifts winds to southwesterly, which brings in warm, moist air from the south. This sudden shift aids in midlatitude cyclone formation. Winds intensify rapidly on between Day-1 and Day0. For NC, these winds are northwesterly, meaning that colder air is being moved into NC. After the Hatteras type midlatitude cyclone passes on Day0, winds become northwesterly. Winds do not decrease throughout the rest of the composite. Zonal winds occur over NC on Day+2.

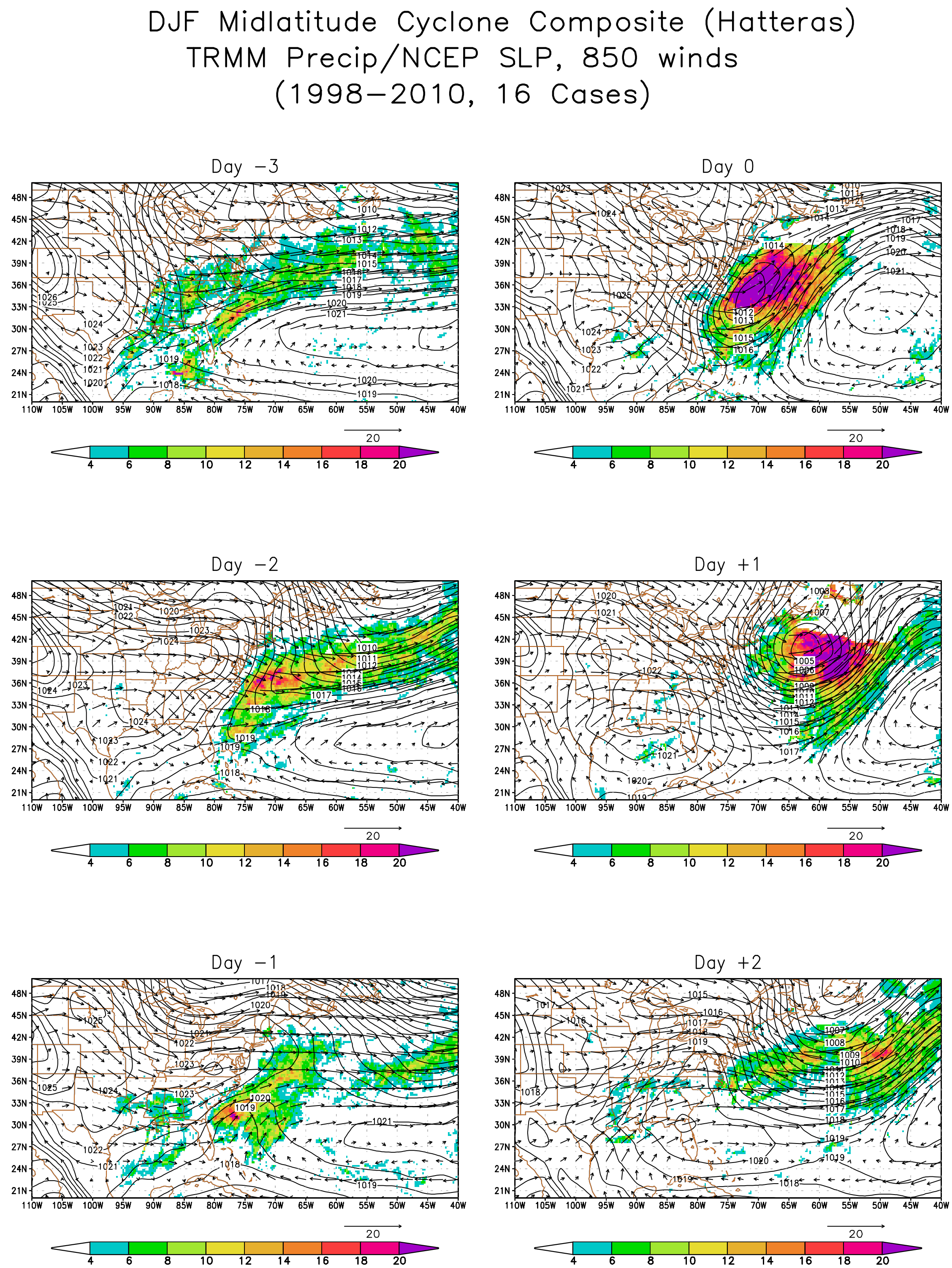


Figure 21: Midlatitude cyclone composite for all Hatteras type events that crossed NC during winter from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

Figure 22 shows the upper-level composite of geopotential height anomalies and 200mb wind intensities. Here, a jet streak is present on Day-3, and is tilted to the northeast. This northeast tilt persists until the midlatitude cyclone passes on Day0. The jet streak intensifies on Day0 offshore in the Atlantic Ocean. On Day+1, the jet weakens, and the jet streak moves southward. Also, the jet becomes more zonal after the midlatitude cyclone passage. This jet becoming zonal signifies a decrease in baroclinic wind shear. Consequently, midlatitude intensification is dampened. This jet stream progression occurs in all winter midlatitude cyclones. This northeastward tilt aids in the intensification and northeastward track of these storms. The position of the jet stream determines whether storms will affect NC, except with Canadian-type cyclones.

A defining feature of the upper-level structure in the Hatteras type composite is the absence of an upper-level trough until Day-1. While there is the presence of negative geopotential height anomalies, there is no strong signal of an upper-level trough or ridge. On Day-1, an upper-level trough forms in the SE US. This trough intensifies quickly, and on Day0, has become a strong upper-level trough as the midlatitude cyclone passes. This feature aids in the rapid intensification of the midlatitude cyclone between Day-1 and Day0. Also, notice the intensification of an upper-level ridge to the east of this trough. The position of these upper-level features aid in the track of the midlatitude cyclone as it travels up the Atlantic coastline. On Day+1, the upper-level trough moves eastward, and become symmetrical. This trough continues to move northeastward on Day+2, but weakens. Notice how the propagation of the trough is consistent with the northeast tilt of the jet stream. This propagation is consistent with all other winter midlatitude cyclone types, except the Canadian-type.

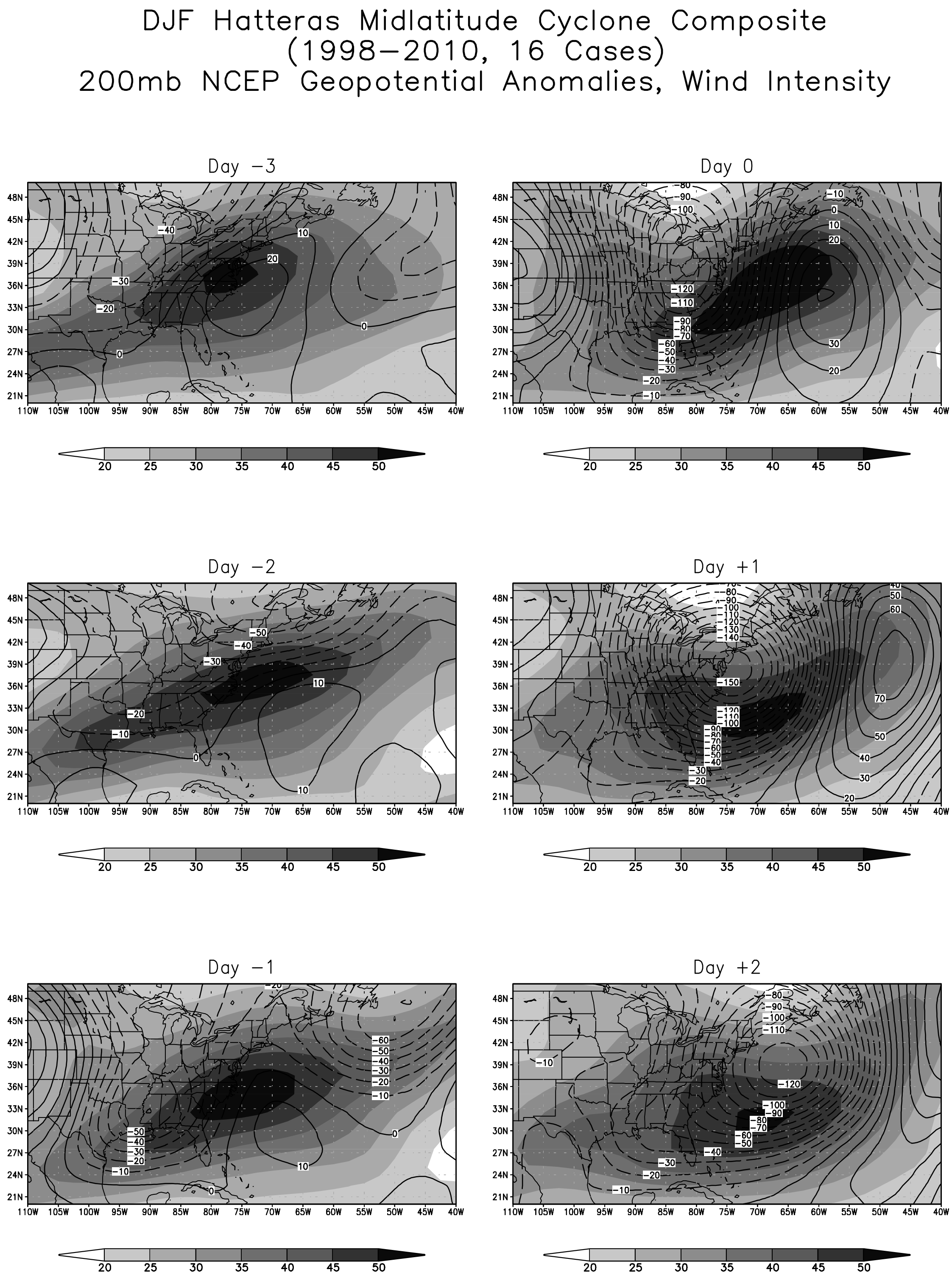


Figure 22: The wind intensities and geopotential height at the 200 mb level as the Hatteras type midlatitude cyclones passes North Carolina for winter (1998-2010). 16 cases were observed.

5.2 ENSO Influence on Midlatitude Cyclone Structure

To show interannual patterns in midlatitude cyclones, the El Niño Southern Oscillation (ENSO) is examined to detect differences in midlatitude cyclone structure, frequency, and propagation. Note that there were only a few significant ENSO events between 1998-2010. However, examining these significant events was beneficial to observing patterns in the structure, frequency, and propagation of midlatitude cyclones on an interannual timescale. Also, only the winter months are analyzed. The winter is the peak ENSO season, and therefore, is the best time to study the interannual effect ENSO has on midlatitude cyclones that impact NC. To obtain the midlatitude cyclone passages for each ENSO classification, dates were compiled based on the date and whether it was a Niño or Niña time period. ENSO phases are determined using the Oceanic Niño Index (ONI) from the National Weather Service's Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring). This section is set up as follows: Niño, Niña, and finally, ENSO anomalies.

Figure 23 shows the midlatitude cyclone type distribution for ENSO. The blue columns represent Niño and the red are Niña cyclones. Notice how Gulf midlatitude cyclones increase dramatically during Niño, while Rockies type increase during Niña events. There is not a substantial increase in Canadian or Hatteras types during Niño or Niña events.

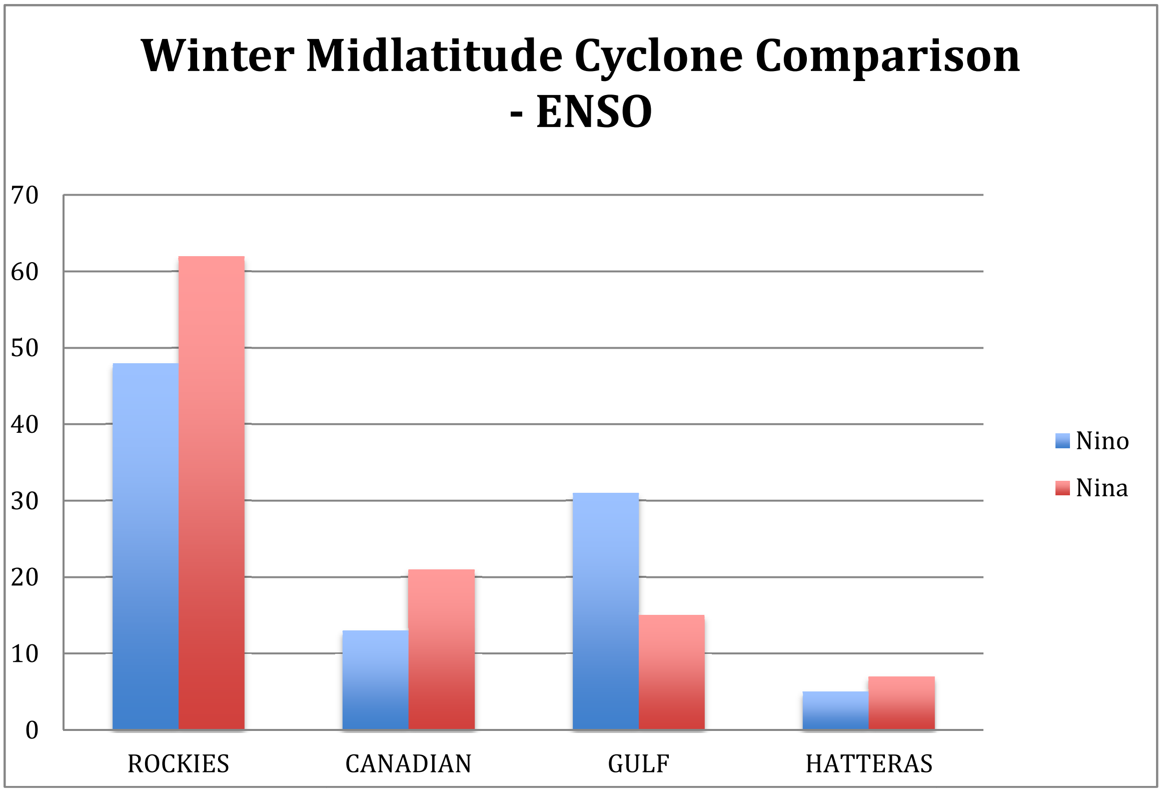


Figure 23: The winter midlatitude cyclone distribution for ENSO events between 1998-2010.

	98	99	00	01	02	03	04	05	06	07	08	09	10
ONI	**2.2**	**-1.5**	**-1.7**	**-0.7**	-0.2	**1.1**	0.3	**0.6**	**-0.9**	**0.7**	**-1.5**	**-0.9**	**1.6**

Table 2: ENSO Classification using the ONI for all events between 1998-2010.

5.2.1 El Niño

Figure 24 shows the low-level composite of precipitation, SLP, and 850mb winds for the El Niño midlatitude cyclone passages for all midlatitude cyclone types between 1998-2010. There were 98 cases in this time period. Since there were more Niña events than Niño, there will be more Niña midlatitude cyclone passages between 1998-2010. For all winters between 1998-2010, there were 106 Niña midlatitude cyclone passages, whereas Niño events accounted for 98 passages.

Precipitation occurs mainly over the Gulf of Mexico on Day-3. By Day-1, precipitation intensifies and covers the SE US. After the midlatitude cyclone passes on Day0, the precipitation has reached its strongest point, but only affects the Outer Banks in NC. By Day+1, the precipitation is well offshore. There are striking similarities in the precipitation in this composite, and the winter Gulf type midlatitude cyclone.

The midlatitude cyclone is over the Gulf of Mexico through Day-1, where it intensifies and moves to the northeast. It rapidly intensifies upon landfall, and becomes strongest on Day0. In terms of precipitation, the El Niño plot resembles the Gulf type midlatitude cyclone. However, in terms of SLP, this composite resembles a Rockies type midlatitude cyclone. Therefore, the two dominant midlatitude cyclone types in an El Niño event are the Rockies and Gulf types (fig. 23).

Winds are largely zonal for the SE US on Day-3. As the midlatitude cyclone forms and intensifies, winds become southwesterly over the SE US. On Day-1, the southwesterly winds intensify as the midlatitude cyclone begins to travel over land. After the midlatitude cyclone passes on Day0, the winds remain strong, but are northwesterly. Winds weaken after the cyclone moves offshore, and return to a zonal flow on Day+2.

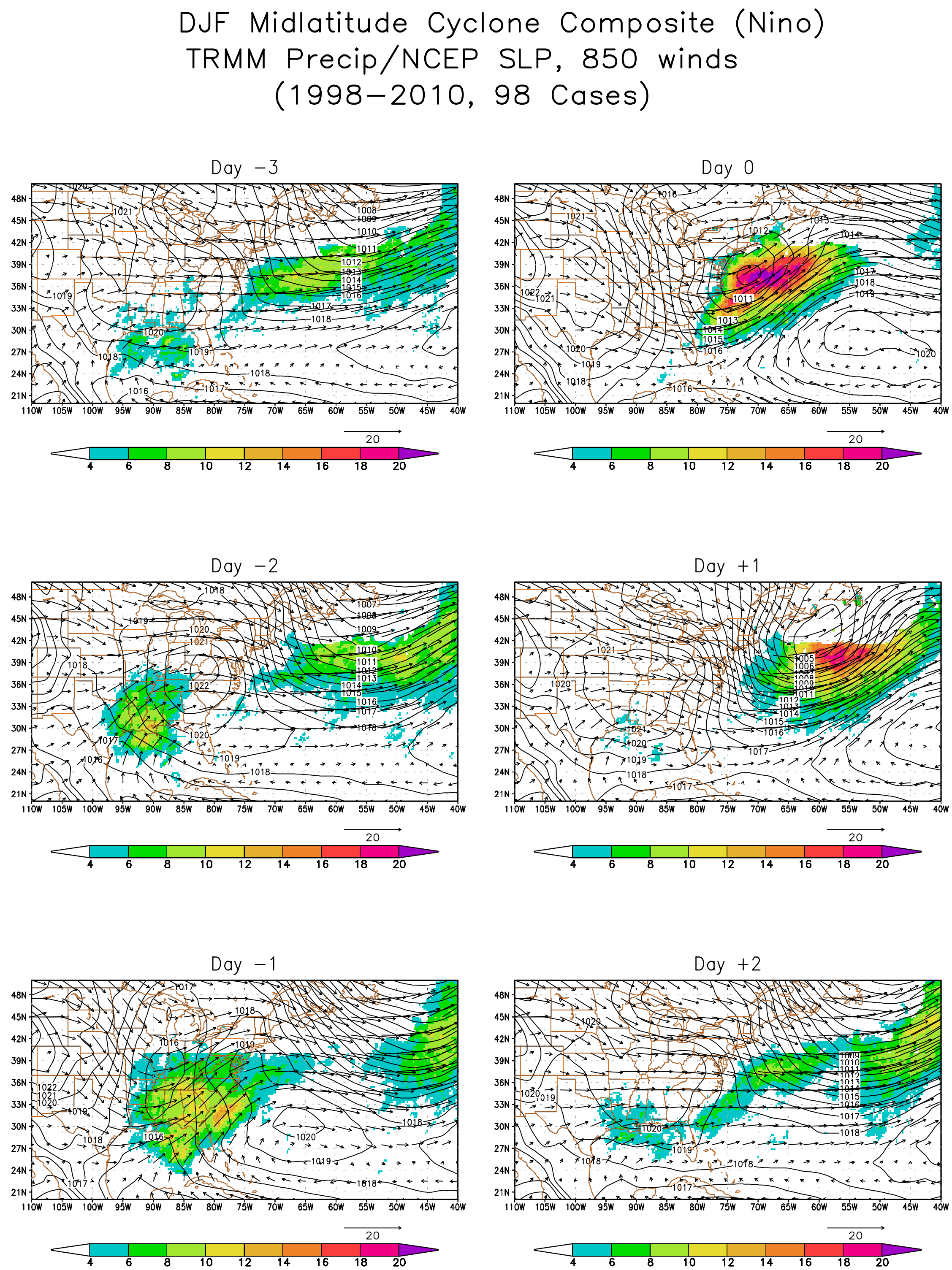


Figure 24: Midlatitude cyclone composite for all events that crossed NC during El Niño from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

Figure 25 shows the upper-level composite of geopotential anomalies and 200mb wind intensities. The key feature here is the northeast tilted jet streak that persists throughout the composite. This jet streak aids in midlatitude cyclone formation. In this composite, the jet actually weakens between Day-3 and Day-1. However, on Day0, the jet streak reappears after the midlatitude cyclone passes. The jet maintains its position throughout the composite. This jet setup is really a “perfect situation” for midlatitude cyclones affecting NC. With this setup, the most baroclinic instability is over the SE US, which increases the chance of a significant midlatitude cyclone passage for NC. The jet streak remains strong throughout the rest of the composite. Overall, the upper-level jet stream is similar to the winter composite. The northeastward tilting jet stream on Day0 occurs throughout all of the winter composites.

The upper-level structure is unorganized on Day-3. However, organization occurs on Day-2. Here, an eastward moving upper-level trough is seen over the western US, and a strengthening upper-level ridge over the eastern US. Similar to the winter seasonal composite, a trough is surrounded by two upper-level ridges on Day-1. Note how much weaker the ridge is than the trough. On Day0, after the midlatitude cyclone passage, the upper-level ridge has moved offshore, and the trough is over the eastern US. Here, the trough is at its strongest point. The position of this trough is similar to the Gulf and Rockies type midlatitude cyclones for Day0. This upper-level trough is west of the midlatitude cyclone on Day0. Therefore, the midlatitude cyclone passes over NC. On Day+1, the trough begins to tilt slightly, signifying that it is reaching the end of its lifecycle.

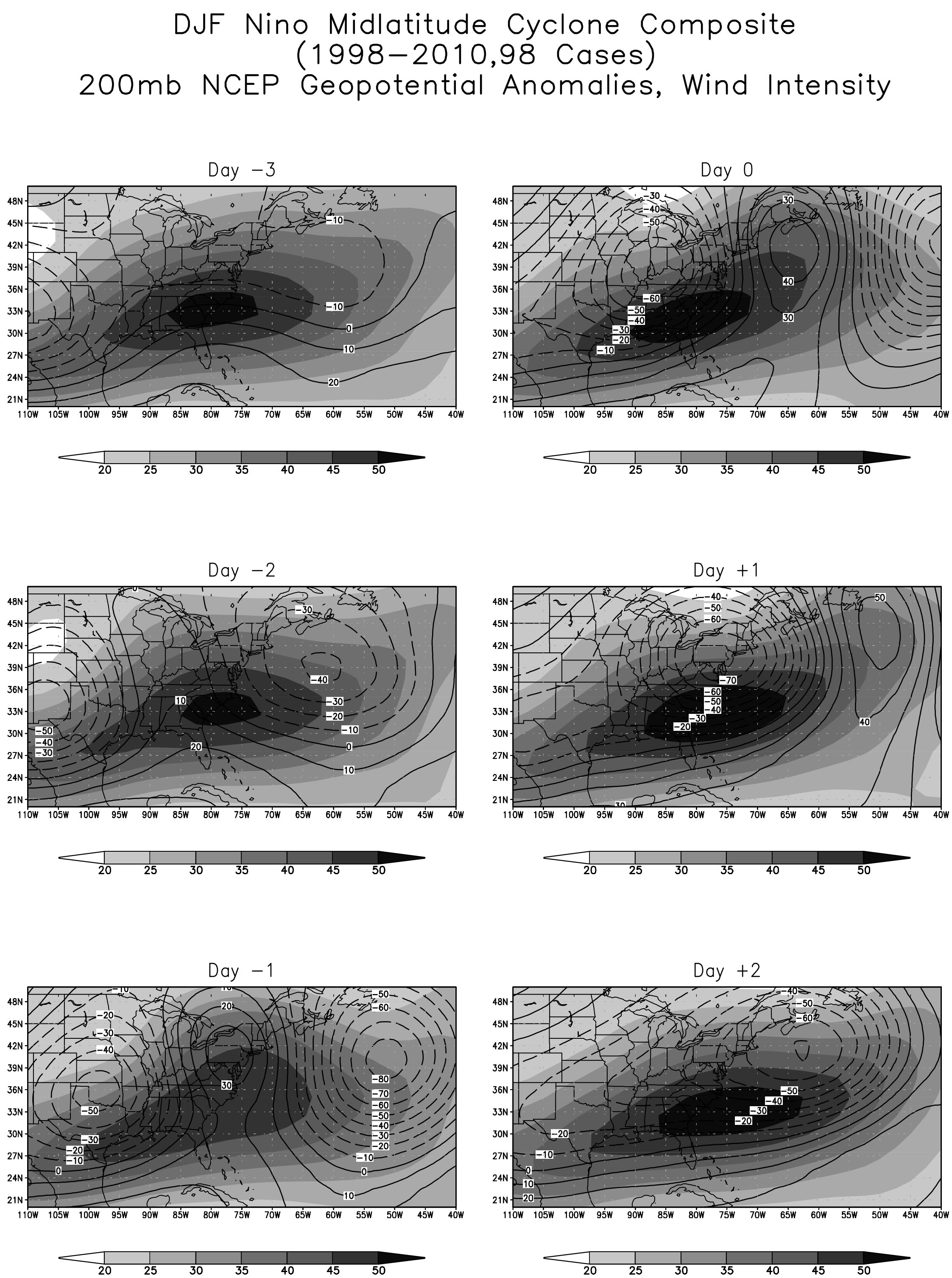


Figure 25: The wind intensities and geopotential height at the 200 mb level as the midlatitude cyclones passes North Carolina during El Niño (1998-2010). 98 cases were observed

5.2.2 La Niña

Figure 26 shows the low-level composite of precipitation, SLP, and 850mb winds for the La Niña midlatitude cyclone passages between 1998-2010. There were 106 midlatitude cyclone passages for La Niña. The La Niña midlatitude cyclone most resembles the Rockies type midlatitude cyclone. Rockies and Canadian type cyclones are the most frequent during La Niña events (fig.23).

On Day-2, precipitation forms ahead of the midlatitude cyclone. Precipitation fills in over the SE US on Day-1. Areas on the lee of the Appalachian Mountains are dry. These mountains create a rain shadow effect for areas to the east. Significant rainfall occurs for areas east of the Appalachian Mountains on Day0.

As a high pressure center moves eastward on Day-2, rainfall occurs along its western side. On Day-1, the midlatitude cyclone is fully visible for the first time. Here, the cyclone intensifies, resulting in an increase in precipitation. This cyclone continues to intensify as it moves eastward.

Figure 27 shows the upper-level composite of geopotential height anomalies and 200mb wind intensities. The La Niña jet streak is smaller and weaker than during an El Niño event. Also, the northeast tilt of the jet stream is not as extreme during El Niño. By Day+1, the jet streak weakens considerably, and on Day+2, disappears altogether.

An upper-level ridge intensifies on Day-1 and moves eastward slowly. On Day0, a weak upper-level trough forms on the western side of the ridge. This trough is located over the Great Lakes. The upper-level ridge is further to the northeast than in the El Niño composite. Also, this ridge is stronger on Day0. Interestingly, it seems the midlatitude cyclone intensifies in the weaker areas on the backside of the upper-level ridge.

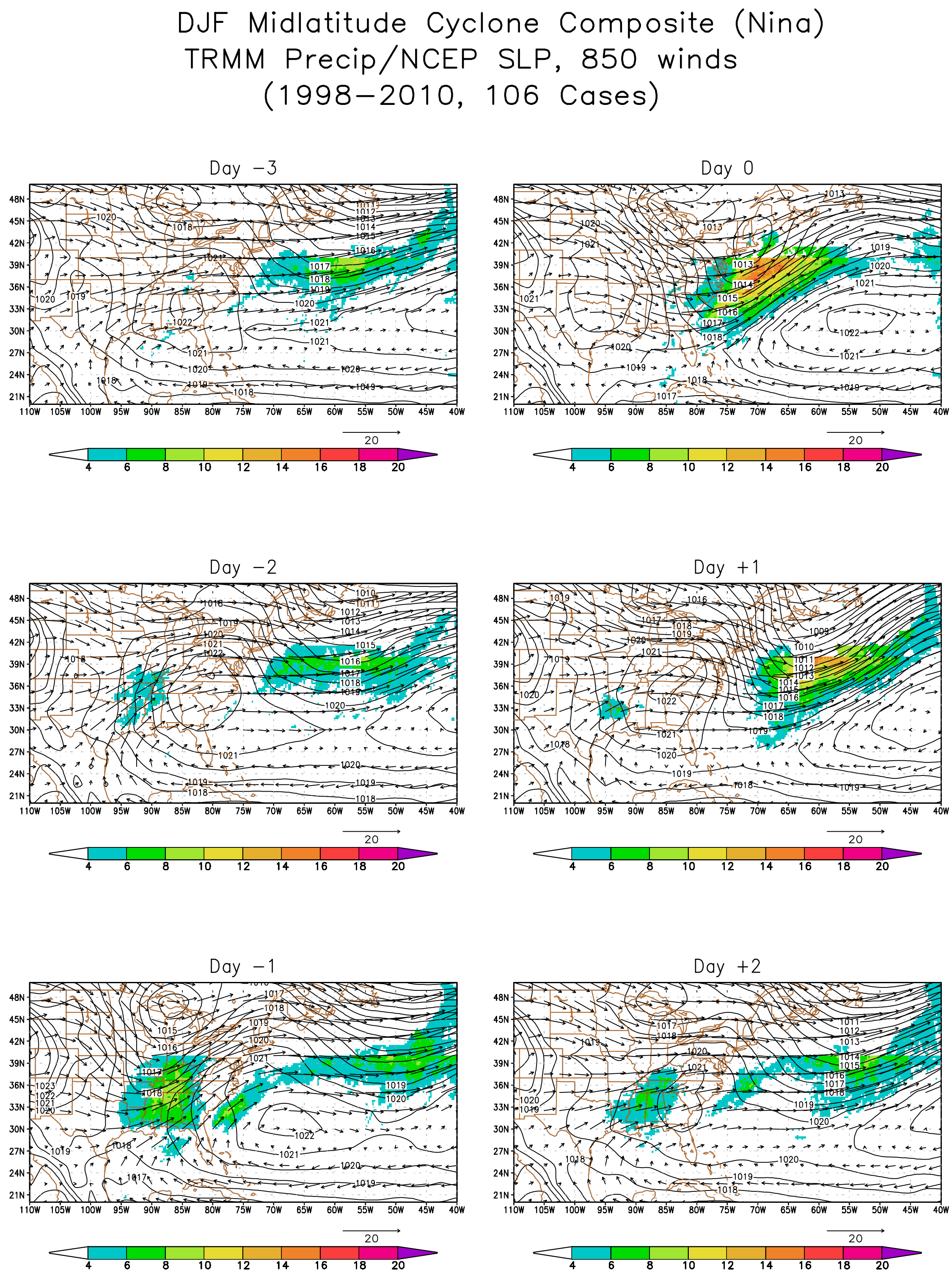


Figure 26: Midlatitude cyclone composite for all events that crossed NC during La Niña from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

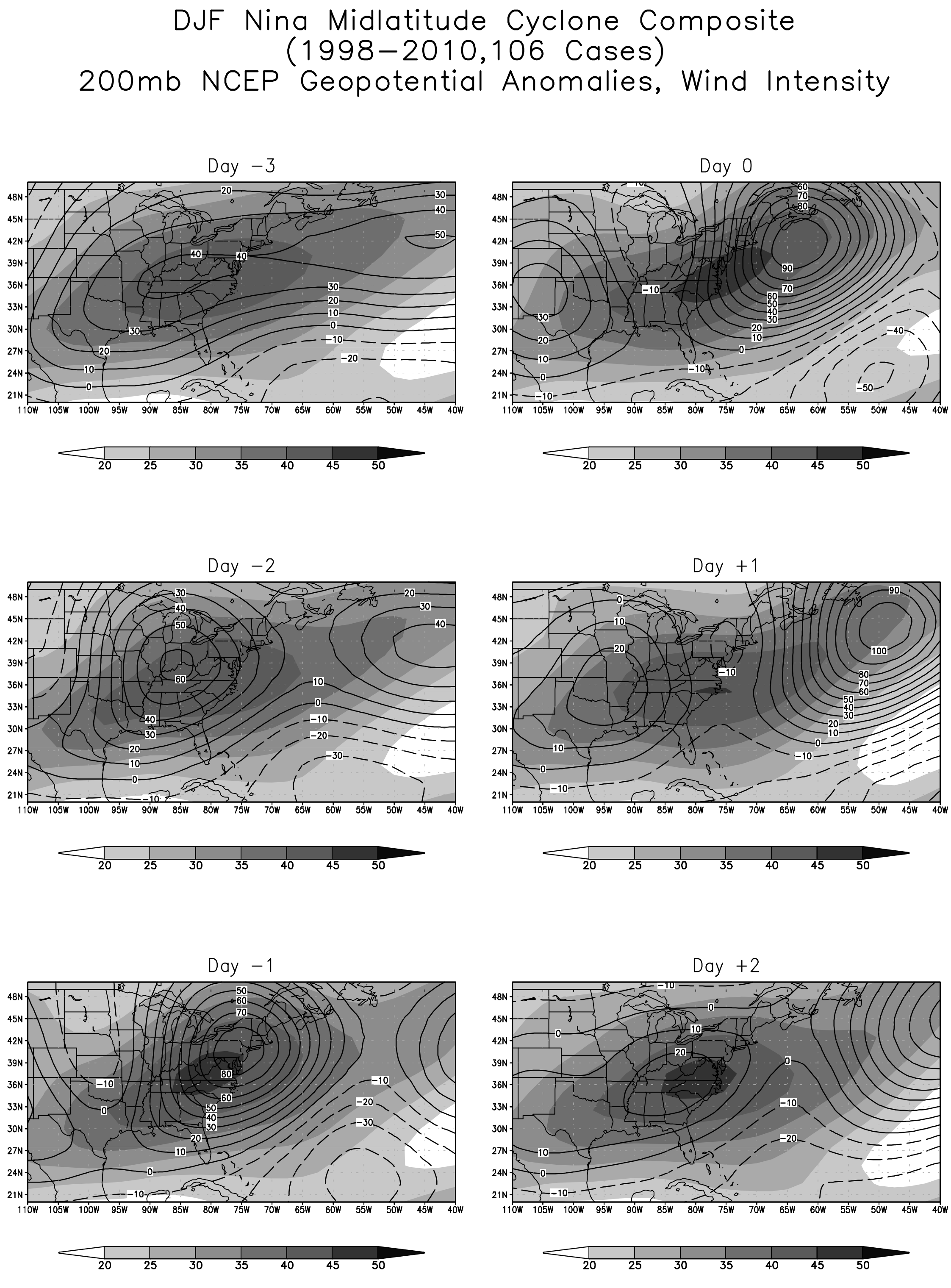


Figure 27: The wind intensities and geopotential height at the 200 mb level as the midlatitude cyclones passes North Carolina during La Niña (1998-2010). 106 cases were observed.

6. Discussion and Conclusions

This study highlights seasonal changes in the structure, frequency and propagation of midlatitude cyclones that affect North Carolina. Six-day composites of NCEP Reanalysis winds, geopotential and SLP and TRMM precipitation were used to analyze the seasonal changes in patterns in midlatitude cyclones.

In winter, precipitation is localized around the southern side of midlatitude cyclone. The strongest upper-level troughs and jet streaks are present during the winter as well, aiding in midlatitude cyclone intensification. High pressure returns to the southeastern U.S. after the midlatitude cyclone passage.

During the summer, the midlatitude cyclone does not dip into the continental US. Precipitation is much more widespread due to the diurnal heating of the continent. On Day0 in the summer composite, a low-level trough dips south into NC, bringing some organized precipitation to the area. The upper-level troughs and jet do not interact with the midlatitude cyclone in the U.S. These upper-level features are farther to the north during the summer.

The transition seasons of spring and fall share characteristics of winter and summer, respectively. Spring mostly resembles the winter season, while fall resembles the summer. Spring midlatitude cyclones resemble winter midlatitude cyclones. However, the midlatitude cyclone dips farther to the south than in winter. There is also a presence of scattered rainfall that is not associated with the midlatitude cyclone, which most resembles summertime rainfall patterns.

During fall, the midlatitude cyclone is much further to the north than during winter or spring, like summer midlatitude cyclones. Fall shows the presence of scattered rainfall throughout the composite, like rainfall during summer. However, as the midlatitude cyclone moves eastward, the large portion of the rainfall occurs around the southern side of the midlatitude cyclone. This localization of rainfall is a characteristic of winter midlatitude cyclones.

The largest number midlatitude cyclones occur during the winter months. The lowest midlatitude cyclone frequency occurs during summer. However, most of these summertime midlatitude cyclones do not affect NC.

Midlatitude cyclone propagation changes throughout the seasons. During the winter, midlatitude cyclones generally affect NC by a northeastward propagation at passage on Day0. A northeast tilting jet streak aids in this propagation. During the spring and fall, the same northeast tracking midlatitude cyclones occur. However, the summer is most different when it comes to midlatitude cyclone propagation. Most summertime midlatitude cyclones are further to north and exhibit a more eastward propagation instead of the northeastward tracking storms seen in the other seasons.

Although the seasonal composites show that the patterns of rainfall associated with the cyclones change with the seasons, the amount of rainfall brought by the cyclones to NC does not change significantly with the seasons. Midlatitude cyclones bring an average of 4.2 mm/day of rainfall to NC as they traverse the state.

The second part of this study classifies all midlatitude cyclones that affected North Carolina into the following 5 types: Rockies, Canadian, Gulf, Hatteras, and Stationary.

The Rockies type midlatitude cyclone was the most frequent type for all seasons except summer. These midlatitude cyclones bring the most rainfall to NC due to high frequency in passages. Rockies-type midlatitude cyclones were strongest during winter, and weakest during summer.

The Canadian type cyclone was similar to the Rockies type in terms of intensification and track direction. However, its track is much farther to the north, and had no significant effect on NC other than a drop in SLP. The Canadian type peaks in frequency during the summer season.

Gulf type midlatitude cyclones occur mainly during winter. This midlatitude cyclone originates in the Gulf of Mexico, and takes a NE track over the SE US into the Atlantic Ocean and beyond. This type of midlatitude cyclone brings the most intense rain to NC than any other midlatitude cyclone during winter and spring.

The Hatteras type of midlatitude cyclone is the most intense, and has the most rapid intensification. Although it is the most intense midlatitude cyclone type, it does not have much of an effect on NC in terms of rainfall. The most intense precipitation in a Hatteras type cyclone occurs offshore on its eastern side. It becomes a midlatitude cyclone between Days-1 and 0, which is later than the other midlatitude cyclones.

The final midlatitude cyclone type that had a significant amount of effect on NC was the Stationary type. In fact, summer is the only season that features this midlatitude cyclone type. These cyclones are distinctive in that they do not form into a closed-isobar system until one day after the pressure drop is recorded. The most interesting feature is the SE tilting upper-level trough. Here, a SE tilting jet streak around the Canadian border causes the trough to tilt SE. This does not happen in any other composite as jet streaks generally tilt to the NE in the other composites.

In terms of frequency, the overall number of cases is not as important since there were more La Niña events between 1998-2010. However, the number of midlatitude cyclones per event increases during El Niño. There were around 22 midlatitude cyclones per El Niño event, which are about two more cases than La Niña. During La Niña, more Rockies type midlatitude cyclones occur. The rainfall patterns are similar to the Rockies type. There was less overall precipitation during La Niña.

Midlatitude cyclones during El Niño exhibit characteristics of the winter Gulf type midlatitude cyclones. Many El Niño midlatitude cyclones originate in the Gulf of Mexico. Rainfall increases in the Gulf from Days-3 to -1, which is an indicator of Gulf type formation. Precipitation is more intense than La Niña precipitation. There are more Gulf type midlatitude cyclones during El Niño than the other types.

The rich seasonal-to-interannual variability of midlatitude cyclone structure, frequency, and propagation shown in this study can help improve precipitation forecasting in climate timescales and ultimately be used to help improve water resource management in North Carolina. Since North Carolina is a state of climate extremes, an improved long-range forecast method will aid in managing how much precipitation occurs for each storm, as well as improving our seasonal usage of water resources. Improved forecasting and water resource management will dampen the effect of climate extremes, such as droughts and floods on North Carolina. These improvements, in turn, dampen the socioeconomic issues presented by these climate extremes.

References

Adams, David and A. Comrie, The North American Monsoon. *Bulletin of the American Meteorological Society,* 2197-2213, 1997.

Ahrens, C. D., Ed., 2008: *Essentials of meteorology.* 5e ed. Thomson, Brooks, Cole, .

Ambaum, M. H. P., B. J. Hoskins, and D. B. Stephenson, Arctic Oscillation or North Atlantic Oscillation? *Journal of Climate,* **14,** 3495-3507, 2001.

Ayrault, F., F. Lalaurette, and A. Joly, North Atlantic ultra high frequency variability. *Tellus A,* **47,** 671-696, 1995.

Bengtsson, L., K. Hodges, and E. Roeckner, Storm tracks and climate change. *J. Climate,* **19,** 3518-3543, 2006.

Bergeron, T., On the physics of fronts. *Bulletin of the American Meteorological Society,* **18,** 265-275, 1937.

Bjerknes, J and H. Solberg, Meteorological conditions for the formation of rain. **2,** 1-60, 1921.

________., On the structure of moving cyclones. **45,** 95-99, doi:10.1175/1520-0493(1919)47<95:OTSOMC>2.0.CO;2, 1919.

Blender, R., K.Fraedrich, and F. Lunkeit, Identification of cyclone-track regimes in the North Atlantic. *Quarterly Journal of the Royal Meteorological Society,* **123,** 727-741, 1997.

Bordoni, Simona, P. Ciesielski, R. Johnson, B. McNoldy, and B. Stevens, The Low-level Circulation of the North American Monsoon as Revealed by QuikSCAT. *Geophysical Research Letters,* **4,** 1-4, 2004.

Boruff, B.J., C. Emrich, and S.L. Cutter, Erosion Hazard Vulnerability of US Coastal Counties. *Journal of Coastal Research,* **21,** 932-942, 2005.

Browning, K. A. and C. W. Pardoe, Structure of low-level jet streams ahead of midlatitude cold fronts. *Quarterly Journal of the Royal Meteorological Society,* **99,** 619-638, 1973.

________________., and G. A. Monk, A simple model for the synoptic analysis of cold fronts. *Quarterly Journal of the Royal Meteorological Society,* **108,** 435-452, 1981.

Chang, E.K.M, and S. Song, The seasonal cycles in the distribution of precipitation around cyclones in the Western North Pacific and Atlantic. *J. Atmos. Sci.*, **63,** 815-839, 2006.

Climate Prediction Center Internet Team, 2005: North Atlantic Oscillation. [Available online at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml].

Climate Prediction Center Internet Team, 2011: Cold and Warm Episodes by Season. [Available online: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring].

Curtis, S., Developing a climatology of the South's 'other' storm season: ENSO impacts on winter extratropical cyclogenesis. *Southeastern Geographer,* **46,** 231-244, 2006.

Curtis, S., and S. Wuensch, Can satellites be used to detect extreme precipitation events? *Southeastern Geographer,* **50,** 244-257, 2010.

Dacre, H.F., and S.L. Gray, Life cycle simulations of shallow frontal waves and the impact of deformation strain. *Quart. J. Roy. Meteor. Soc.*, **132,** 2171-2190, 2006.

Davis, Robert E., R. Dolan, The "All Hallows' Eve" Coastal Storm - October 1991. *Journal of Coastal Research,* **4,** 978-983, 1992.

Davis, Robert E., R. Dolan, G. Demme, Syntoptic climatology of Atlantic Coast North-Easters. *International Journal of Climatology,* **13,** 171-189, 1993.

Dunlop, S., Ed., 2008: *Oxford Dictionary of Weather.*

Galvin, J., Superstorm: Eastern and Central U.S., March 1993. *Popular Mechanics,* 2009.

Goldman, J., 5/9/2011: NOAA's El Nino Page. [Available online at http://www.elnino.noaa.gov/].

Gulev, S. K., Climate variability of the intensity of synoptic processes in the North Atlantic midlatitudes. *Journal of Climatology,* **10,** 574-592, 1997.

Gulev, S. K., O. Zolina, and Y. Reva, Synoptic and sub-synoptic variability in the North Atlantic as revealed by the Ocean Weather Station data. *Tellus A,* **52,** 323-329, 2000.

Gulev, S. K., O. Zolina, S. Grigoriev, Extratropical cyclone variability in the Northern Hemisphere winter from NCEP/NCAR reanalysis data. *Climate Dynamics,* **17,** 795-809, 2001.

Hansen, J., A. Hodges, and J. Jones, ENSO Influences on Agriculture in the Southeastern United States. *Journal of Climate,* **11,** 404-411, 1998.

Harrold, T. W., Mechanisms influencing the distribution of precipitation within baroclinic disturbances. *Quarterly Journal of the Royal Meteorological Society*, **99,** 232-251, 1973.

Higgins, R.W., and W. Shi, Intercomparison of the principal modes of interannual and intraseasonal variability of the North American monsoon season. *Journal of Climate*, **14,** 403-417, 2001.

Higgins, R.W., Y. Yao, and X.L. Wang, Influence of the North American Monsoon System on the U.S. summer precipitation regime. *Journal of Climate*, **10,** 2600-2622, 1997.

Hirsch, M.E., A.T. DeGaetano, and S.J. Colucci, An East Coast winter storm climatology. *Journal of Climate*, **14,** 882-899, 2000.

Hobbs, P. V., J. D. Locatelli, and J. E. Martin, Cold fronts aloft and the forecasting of precipitation and severe weather east of the Rocky Mountains. *Weather Forecasting*, **5,** 613-626, 1990.

Hoskins, B.J., and W.A. Heckley, Cold and Warm Fronts in Baroclinic Waves. *Quarterly Journal of the Royal Meteorological Society*, 79-90, 1980.

Houze, R.A., B.F. Smull, and P. Dodge, Mesoscale Organization of springtime rainstorms in Oklahoma. *Monthly Weather Review*, **118,** 613-654, 1990.

Huffman, G.J., D.T. Bolvin, E.J. Nelkin, D.B. Wolff, R. Adler, G. Gu, Y. Hong, K.P. Bowman, and E.F. Stocker, The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-Global, Multiyear, Combined-Sensor Precipitation Estimates at Fine Scales. *J. Hydrometeor*, **8,** 38-55, 2007.

James, P. K., and K. A. Browning, Mesoscale structure of line convection at surface cold fronts. *Quarterly Journal of the Royal Meteorological Society*, **105,** 371-382, 1979.

Kalnay, E. a. C., The NCEP/NCAR 40-Year Re-analysis Project. *Bulletin of the American Meteorological Society*, 437-472, 1996.

Kempler, S., 2011: Contents of TRMM and Other Satellites Precipitation Product 3B42. [Available online: http://disc.sci.gsfc.nasa.gov/precipitation/documentation].

Klotzbach, P., Recent Developments in Statistical Prediction of Seasonal Atlantic Basin Tropical Cyclone Activity. *Tellus A*, **59,** 511-518, 2007.

Knutson, T., J.L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J.P. Kossin, A.K. Srivastava, and M. Sugi, Tropical Cyclones and Climate Change. *Nature Geoscience*, **3,** 163, 2010.

Koch, S. and C. Ray, Mesoanalysis of Summertime Convergence Zones in Central and Eastern North Carolina. *Weather and Forecasting,* **12,** 56-77, 1997.

Konrad, C. E. I., Synoptic-Scale Features Associated with Warm-Season Heavy Rainfall Over the Interior Southeastern United States. *Weather and Forecasting,* **12,** 557-571, 1997.

Kunkel, K. E., and J.R. Angel, Relationship of ENSO to snowfall and related cyclone activity in the contiguous United States. *Journal of Geophysical Research*, **104,** 19425-19434, 1999.

McCabe, G.J., and R.A. Muller, Effects of ENSO on Weather-Type Frequencies and Properties at New Orleans, Lousiana, USA. *Climate Research,* 2002.

National Climatic Data Center (NCDC), 2011: NCDC: Billion Dollar U.S. Weather Disasters. [Available online at http://www.ncdc.noaa.gov/oa/reports/billionz.html].

National Hurricane Center, Hurricane Sandy. 2012.

NWS Internet Services Team, 2011: Closed Low Definition. [Available online at http://www.weather.gov/glossary/index.php?letter=c].

Parker, M. D. and D. A. Ahijevych, Convective episodes in the east-central United States. *Monthly Weather Review*, **135,** 3707-3727, 2007.

Robinson, P., Implications of long-term precipitation amount changes for water sustainability in North Carolina. *Physical Geography,* **27,** 286-296, 2006.

Rogers, J. C., The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere. *Monthly Weather Review,* **112,** 1999-2015, 1984.

Ropelewski, C.F., and M.S. Halpert, North American Precipitation and Temperature Patterns Associated with the El Niño/Southern Oscillation (ENSO). *Monthly Weather Review,* 1986.

Schmitz, Jeffrey, and S. Mullen, Water Vapor Transport Associated with the Summertime North American Monsoon as Depicted by ECMWF Analyses. *Journal of Climate,* **9,** 1621-1634, 1996.

Shepherd, J. M., A. Grundstein, and T. Mote, Quantifying the contribution of tropical cyclones to extreme rainfall along the coastal southeastern United States. *Geophysical Research Letters,* **34,** doi:10.1029/2007GL031694, 2007.

Shultz, D.M., and G. Vaughan, Occluded Fronts and the Occlusion Process: A Fresh Look at Conventional Wisdom. *Bulletin of the American Meteorological Society,* **92,** 443-466, 2011.

Sterling, J., 'A loss for everybody': Communities Start Cleanup after Sandy. 2012.

Uccellini, L. W., Operational diagnostic applications of isentropic analysis. *National Weather Digest,* **1,** 4-12, 1976.

Uccellini, L. W., and P. J. Kocin, The interation of jet streak circulations during heavy snow events along the East Coast of the United States. *Weather Forecasting,* **2,** 289-309, 1987.

Zaitseva, N. A., 1992: North Atlantic Oscillation. [Available online at http://nsidc.org/arcticmet/glossary/north_atlantic_oscillation.html].

_______________., 2011: North Atlantic Oscillation(glossary). [Available online at http://nsidc.org/arcticmet/glossary/north_atlantic_oscillation.html].

Appendix A: Midlatitude Cyclone Formation Coordinates

OBJECT_ID	X	Y	Type	Date		
1	-109	46	Rockies	1998	1	4
2	-103	45	Rockies	1998	1	11
3	-110	51	Rockies	1998	1	18
4	-110	50	Rockies	1998	1	20
5	-104	37	Rockies	1998	1	24
6	-95	35	Rockies	1998	1	28
7	-110	47	Rockies	1999	1	3
8	-105	35	Rockies	1999	1	10
9	-110	50	Rockies	1999	1	12
10	-102	37	Rockies	1999	1	15
11	-117	50	Rockies	1999	1	19
12	-100	36	Rockies	1999	1	24
13	-110	40	Rockies	1999	1	28
14	-105	40	Rockies	2000	1	5
15	-107	45	Rockies	2000	1	13
16	-103	44	Rockies	2000	1	20
17	-105	37	Rockies	2001	1	16
18	-125	40	Rockies	2001	1	27
19	-103	31	Rockies	2001	1	31
20	-100	35	Rockies	2002	1	11
21	-100	40	Rockies	2002	1	15
22	-100	38	Rockies	2002	1	20
23	-105	46	Rockies	2002	1	25
24	-110	45	Rockies	2002	1	29
25	-106	45	Rockies	2003	1	2
26	-100	50	Rockies	2003	1	6
27	-107	43	Rockies	2003	1	17
28	-102	50	Rockies	2004	1	5
29	-102	38	Rockies	2004	1	10
30	-100	53	Rockies	2004	1	15
31	-105	40	Rockies	2004	1	19
32	-110	45	Rockies	2004	1	27
33	-110	48	Rockies	2004	1	30
34	-110	40	Rockies	2005	1	6
35	-115	40	Rockies	2005	1	14
36	-100	45	Rockies	2005	1	23
37	-105	40	Rockies	2006	1	3
38	-105	50	Rockies	2006	1	6

39	-101	33	Rockies	2006	1	12
40	-112	50	Rockies	2006	1	14
41	-108	50	Rockies	2006	1	18
42	-112	50	Rockies	2006	1	21
43	-100	40	Rockies	2006	1	31
44	-100	35	Rockies	2007	1	2
45	-107	36	Rockies	2007	1	16
46	-108	39	Rockies	2008	1	9
47	-105	49	Rockies	2008	1	11
48	-105	40	Rockies	2008	1	24
49	-100	42	Rockies	2008	1	30
50	-104	40	Rockies	2009	1	7
51	-100	42	Rockies	2009	1	11
52	-98	46	Rockies	2009	1	14
53	-97	48	Rockies	2009	1	20
54	-104	32	Rockies	2009	1	29
55	-104	36	Rockies	2010	1	8
56	-98	39	Rockies	2010	1	22
57	-100	40	Rockies	2010	1	25
58	-108	33	Rockies	2010	1	31
59	-110	54	Canadian	1998	1	13
60	-115	53	Canadian	1999	1	7
61	-130	52	Canadian	2000	1	7
62	-110	56	Canadian	2000	1	10
63	-110	50	Canadian	2000	1	17
64	-100	52	Canadian	2001	1	6
65	-117	55	Canadian	2001	1	8
66	-90	53	Canadian	2001	1	12
67	-95	59	Canadian	2002	1	13
68	-100	55	Canadian	2003	1	9
69	-93	50	Canadian	2003	1	21
70	-88	54	Canadian	2003	1	27
71	-100	57	Canadian	2003	1	29
72	-108	55	Canadian	2004	1	13
73	-109	55	Canadian	2004	1	23
74	-102	54	Canadian	2005	1	21
75	-99	50	Canadian	2005	1	26
76	-105	60	Canadian	2006	1	25
77	-88	54	Canadian	2007	1	25
78	-98	53	Canadian	2007	1	28
79	-105	55	Canadian	2007	1	31

80	-115	50	Canadian	2008	1	6
81	-100	50	Canadian	2009	1	3
82	-100	55	Canadian	2009	1	24
83	-115	55	Canadian	2010	1	12
84	-90	30	Gulf	1998	1	9
85	-95	28	Gulf	1998	1	16
86	-90	26	Gulf	2000	1	25
87	-91	27	Gulf	2000	1	31
88	-95	28	Gulf	2001	1	20
89	-86	26	Gulf	2002	1	3
90	-97	28	Gulf	2002	1	7
91	-95	23	Gulf	2003	1	14
92	-95	25	Gulf	2005	1	31
93	-95	25	Gulf	2007	1	6
94	-95	27	Gulf	2007	1	8
95	-97	27	Gulf	2007	1	23
96	-93	25	Gulf	2008	1	14
97	-94	28	Gulf	2008	1	18
98	-97	27	Gulf	2008	1	27
99	-88	31	Gulf	2010	1	2
100	-90	28	Gulf	2010	1	18
101	-75	31	Hatteras	2001	1	24
102	-77	30	Hatteras	2002	1	1
103	-74	36	Hatteras	2002	1	18
104	-78	32	Hatteras	2003	1	23
105	-79	29	Hatteras	2005	1	17
106	-81	30	Hatteras	2007	1	19
107	-100	45	Rockies	1998	2	12
108	-110	40	Rockies	1998	2	18
109	-115	40	Rockies	1998	2	28
110	-104	40	Rockies	1999	2	8
111	-95	45	Rockies	1999	2	19
112	-104	33	Rockies	1999	2	26
113	-98	35	Rockies	2000	2	14
114	-110	35	Rockies	2000	2	19
115	-104	36	Rockies	2000	2	25
116	-103	39	Rockies	2000	2	28
117	-110	38	Rockies	2001	2	10
118	-99	45	Rockies	2001	2	15
119	-103	30	Rockies	2001	2	17
120	-98	32	Rockies	2001	2	23

121	-104	36	Rockies	2001	2	26
122	-98	31	Rockies	2002	2	1
123	-97	38	Rockies	2002	2	11
124	-97	41	Rockies	2002	2	21
125	-105	35	Rockies	2002	2	27
126	-103	40	Rockies	2003	2	1
127	-100	40	Rockies	2003	2	4
128	-105	46	Rockies	2003	2	7
129	-102	39	Rockies	2003	2	15
130	-102	39	Rockies	2003	2	17
131	-104	35	Rockies	2004	2	3
132	-100	40	Rockies	2004	2	21
133	-101	47	Rockies	2005	2	10
134	-98	37	Rockies	2005	2	17
135	-100	40	Rockies	2005	2	22
136	-98	33	Rockies	2005	2	25
137	-100	46	Rockies	2006	2	5
138	-100	44	Rockies	2006	2	18
139	-106	40	Rockies	2006	2	23
140	-105	46	Rockies	2007	2	7
141	-105	42	Rockies	2007	2	14
142	-100	46	Rockies	2007	2	18
143	-95	49	Rockies	2007	2	21
144	-100	43	Rockies	2007	2	26
145	-104	38	Rockies	2008	2	7
146	-105	42	Rockies	2008	2	13
147	-110	49	Rockies	2008	2	16
148	-110	32	Rockies	2008	2	18
149	-110	48	Rockies	2008	2	23
150	-100	40	Rockies	2008	2	27
151	-104	40	Rockies	2009	2	12
152	-105	35	Rockies	2009	2	15
153	-103	40	Rockies	2009	2	19
154	-104	45	Rockies	2009	2	22
155	-95	45	Rockies	2010	2	10
156	-100	42	Rockies	2010	2	16
157	-103	33	Rockies	2010	2	23
158	-105	55	Canadian	1999	2	3
159	-90	52	Canadian	1999	2	13
160	-101	53	Canadian	2000	2	4
161	-116	51	Canadian	2001	2	21

162	-135	51	Canadian	2002	2	4
163	-101	53	Canadian	2002	2	13
164	-100	55	Canadian	2004	2	11
165	-100	50	Canadian	2006	2	21
166	-104	50	Canadian	2009	2	3
167	-110	50	Canadian	2009	2	8
168	-91	26	Gulf	1998	2	5
169	-87	26	Gulf	1998	2	8
170	-88	29	Gulf	1998	2	24
171	-95	27	Gulf	2002	2	8
172	-95	27	Gulf	2002	2	17
173	-95	27	Gulf	2003	2	10
174	-100	23	Gulf	2003	2	23
175	-93	27	Gulf	2003	2	28
176	-95	30	Gulf	2004	2	7
177	-96	27	Gulf	2004	2	13
178	-85	29	Gulf	2004	2	15
179	-90	29	Gulf	2004	2	25
180	-88	28	Gulf	2004	2	27
181	-94	27	Gulf	2005	2	4
182	-85	27	Gulf	2005	2	28
183	-100	25	Gulf	2006	2	12
184	-91	29	Gulf	2007	2	2
185	-85	25	Gulf	2010	2	3
186	-97	27	Gulf	2010	2	6
187	-89	26	Gulf	2010	2	13
188	-75	32	Hatteras	1999	2	24
189	-78	31	Hatteras	2000	2	10
190	-80	27	Hatteras	2001	2	5
191	-75	34	Hatteras	2004	2	18
192	-75	33	Hatteras	2006	2	26
193	-73	29	Hatteras	2010	2	25
194	-97	38	Rockies	1999	12	7
195	-107	36	Rockies	1999	12	11
196	-95	40	Rockies	1999	12	24
197	-97	35	Rockies	2000	12	7
198	-111	41	Rockies	2000	12	12
199	-105	36	Rockies	2000	12	14
200	-105	45	Rockies	2000	12	17
201	-95	40	Rockies	2000	12	20
202	-102	37	Rockies	2000	12	22

203	-94	35	Rockies	2001	12	9
204	-104	38	Rockies	2001	12	14
205	-98	50	Rockies	2001	12	18
206	-107	46	Rockies	2001	12	24
207	-97	43	Rockies	2002	12	3
208	-105	31	Rockies	2002	12	5
209	-101	36	Rockies	2002	12	20
210	-102	30	Rockies	2002	12	25
211	-96	36	Rockies	2003	12	6
212	-99	34	Rockies	2003	12	11
213	-106	34	Rockies	2003	12	15
214	-100	40	Rockies	2003	12	18
215	-100	37	Rockies	2003	12	24
216	-99	34	Rockies	2004	12	1
217	-103	37	Rockies	2004	12	8
218	-99	33	Rockies	2004	12	24
219	-104	36	Rockies	2005	12	4
220	-99	34	Rockies	2005	12	26
221	-103	37	Rockies	2005	12	29
222	-104	34	Rockies	2006	12	1
223	-100	36	Rockies	2006	12	23
224	-109	40	Rockies	2007	12	3
225	-110	50	Rockies	2007	12	5
226	-109	38	Rockies	2007	12	13
227	-100	35	Rockies	2007	12	16
228	-95	32	Rockies	2007	12	20
229	-104	44	Rockies	2007	12	24
230	-92	40	Rockies	2008	12	12
231	-110	38	Rockies	2008	12	21
232	-115	48	Rockies	2008	12	25
233	-105	40	Rockies	2008	12	29
234	-108	38	Rockies	2009	12	10
235	-105	40	Rockies	2009	12	14
236	-104	33	Rockies	2009	12	26
237	-105	45	Rockies	2010	12	5
238	-110	48	Rockies	2010	12	13
239	-104	41	Rockies	2010	12	17
240	-105	42	Rockies	2010	12	22
241	-90	50	Canadian	1998	12	1
242	-80	46	Canadian	1998	12	3
243	-97	52	Canadian	1998	12	11

244	-111	55	Canadian	1998	12	20
245	-85	46	Canadian	1998	12	22
246	-90	60	Canadian	2003	12	1
247	-85	50	Canadian	2005	12	1
248	-90	50	Canadian	2005	12	11
249	-95	50	Canadian	2006	12	7
250	-115	56	Canadian	2006	12	15
251	-105	55	Canadian	2008	12	7
252	-105	54	Canadian	2008	12	17
253	-90	49	Canadian	2009	12	28
254	-110	55	Canadian	2010	12	1
255	-95	27	Gulf	1998	12	14
256	-95	28	Gulf	1998	12	24
257	-97	30	Gulf	1999	12	14
258	-95	32	Gulf	1999	12	20
259	-96	28	Gulf	2001	12	1
260	-88	26	Gulf	2001	12	11
261	-85	25	Gulf	2002	12	11
262	-97	28	Gulf	2002	12	14
263	-95	25	Gulf	2004	12	3
264	-98	25	Gulf	2004	12	11
265	-90	25	Gulf	2004	12	26
266	-95	26	Gulf	2005	12	6
267	-92	27	Gulf	2005	12	9
268	-88	32	Gulf	2005	12	16
269	-88	25	Gulf	2005	12	19
270	-85	26	Gulf	2006	12	4
271	-94	26	Gulf	2006	12	26
272	-91	26	Gulf	2009	12	3
273	-81	25	Gulf	2009	12	5
274	-95	27	Gulf	2009	12	19
275	-95	25	Gulf	2010	12	19
276	-75	27	Hatteras	1998	12	16
277	-75	36	Hatteras	2001	12	26
278	-77	33	Hatteras	2004	12	20
279	-80	30	Hatteras	2007	12	26

Appendix B: Midlatitude Cyclones By Type (Spring – Fall)

Spring (March, April, May)

a. Rockies

Figure 28 shows the low-level composite of precipitation, SLP, and 850mb winds for the Rockies type midlatitude cyclones during the spring months. There were 151 midlatitude cyclone passages. Like the winter season, the Rockies type was the most frequent midlatitude cyclone for the spring.

Precipitation patterns are similar to the winter Rockies composite. Like the winter Rockies-type midlatitude cyclones, precipitation fills in over the SE US between Days-3 and 0. However, precipitation is less intense during spring. One notable feature in this composite is the lack of constant rainfall in the Gulf Stream that occurred throughout the winter composites. During spring, rainfall only occurs over the Gulf Stream except as the midlatitude cyclone passes.

While there is high pressure over the SE US on Day-3, there is no closed isobar system that is present for the Rockies type during the winter months. This signifies the strengthening of the Bermuda High seen here as the strengthened area of high pressure off the coast of Florida just before the midlatitude cyclone passage. This midlatitude cyclone becomes strongest just after its passage over NC on Day0. During the winter, Rockies type cyclones move faster, and last longer than the six-day composite.

Figure 29 shows the upper-level composite of geopotential height anomalies and 200mb wind intensities. While the jet stream tilts to the northeast on Day-1, it is much weaker than during winter.

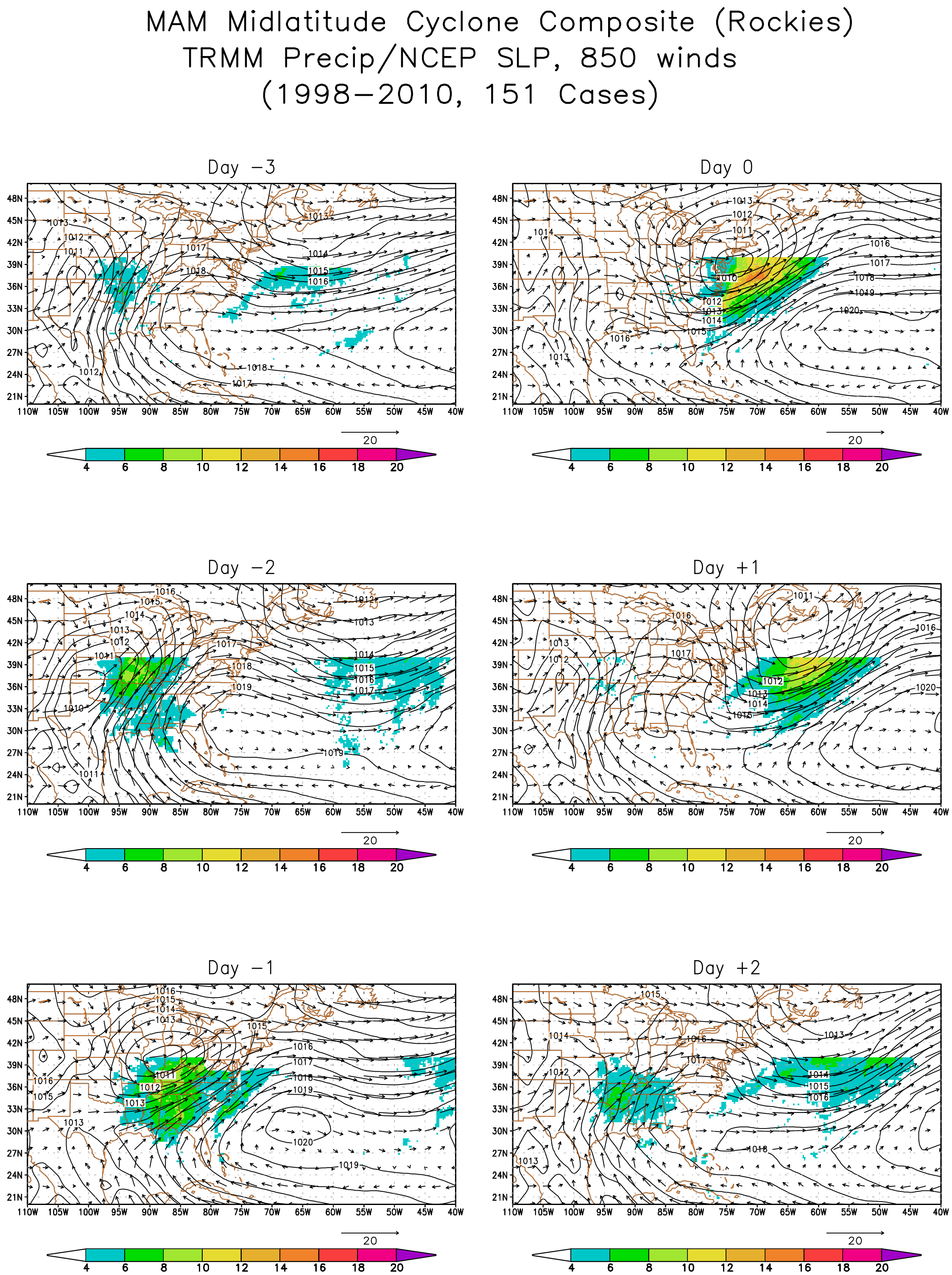


Figure 28: Midlatitude cyclone composite for all Rockies type events that crossed NC during spring from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

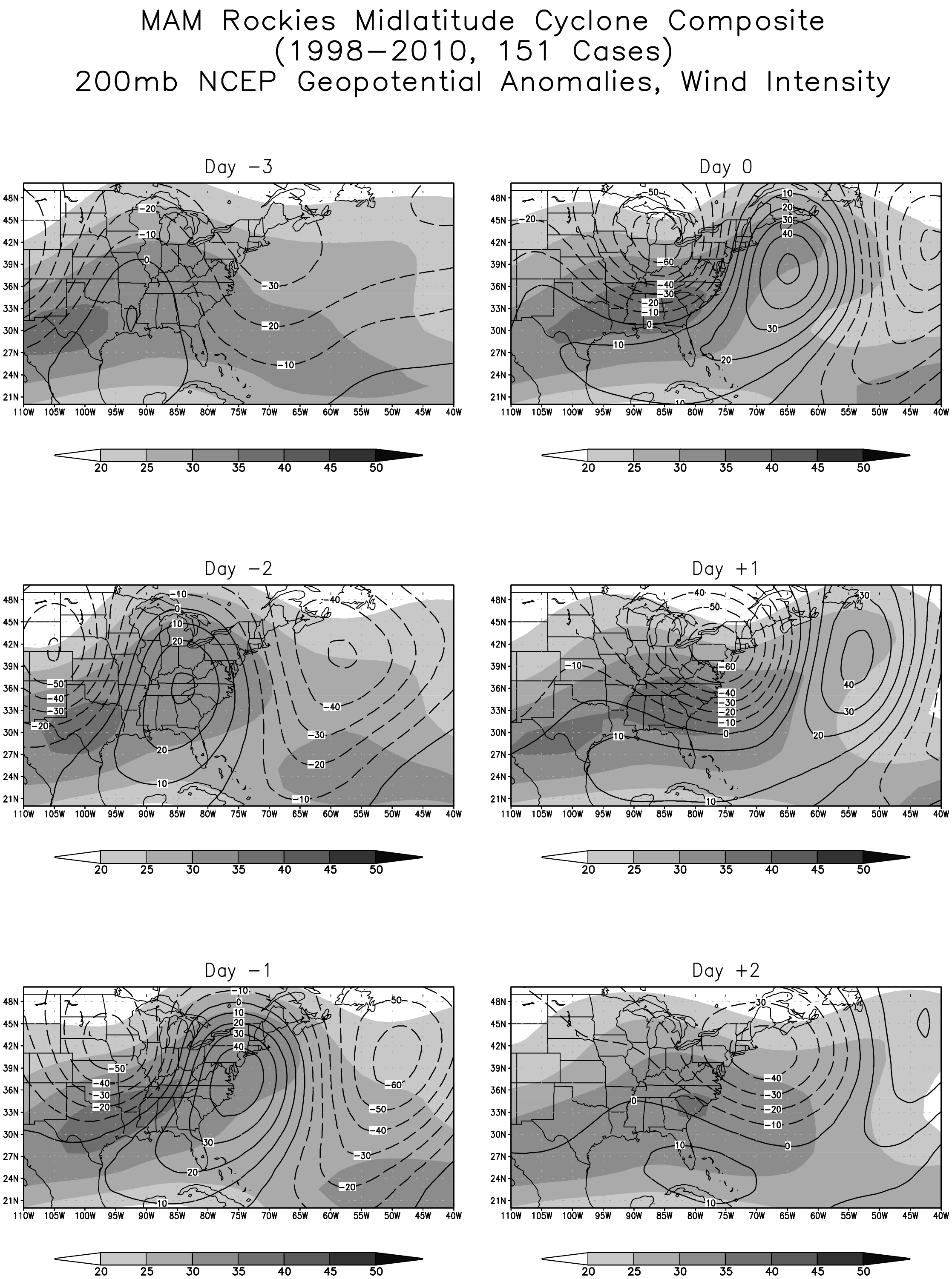


Figure 29: The wind intensities and geopotential height at the 200 mb level as the Rockies type midlatitude cyclones passes North Carolina for spring (1998-2010). 151 cases were observed.

b. Canadian

Figure 30 shows the low-level composite of precipitation, SLP, and 850mb winds for the Canadian type midlatitude cyclones during the spring. There were 54 Canadian type midlatitude cyclone passages during spring. Unlike the winter Canadian composite, more rainfall affects the SE US. However, Canadian-type midlatitude cyclones still have little affect on NC during spring.

Like the spring Rockies type composite, the high pressure center develops on Day-2. In this case, however, the high pressure becomes organized over land, rather than over the Atlantic Ocean. After the midlatitude cyclone passage on Day0, the Bermuda High absorbs the eastward moving high pressure area. Here, the midlatitude cyclone is over the NE US, and continues to intensify.

Figure 31 shows the upper-level composite of geopotential height anomalies and 200mb wind intensities. Here, the jet is weaker than the winter composite. The strongest part of this jet is located further to the north, near the Canadian border. Also, notice that there is no jet streak through Day-1. On Day0, after the midlatitude cyclone passes NC, the jet becomes zonal.

During spring, an upper-level trough dips into the NE US on Day0. The southward movement of this trough is consistent with the midlatitude cyclone, which also dips further south than winter Canadian-types. This upper-level trough quickly moves northward. By Day+1, the trough has moved into the Canada.

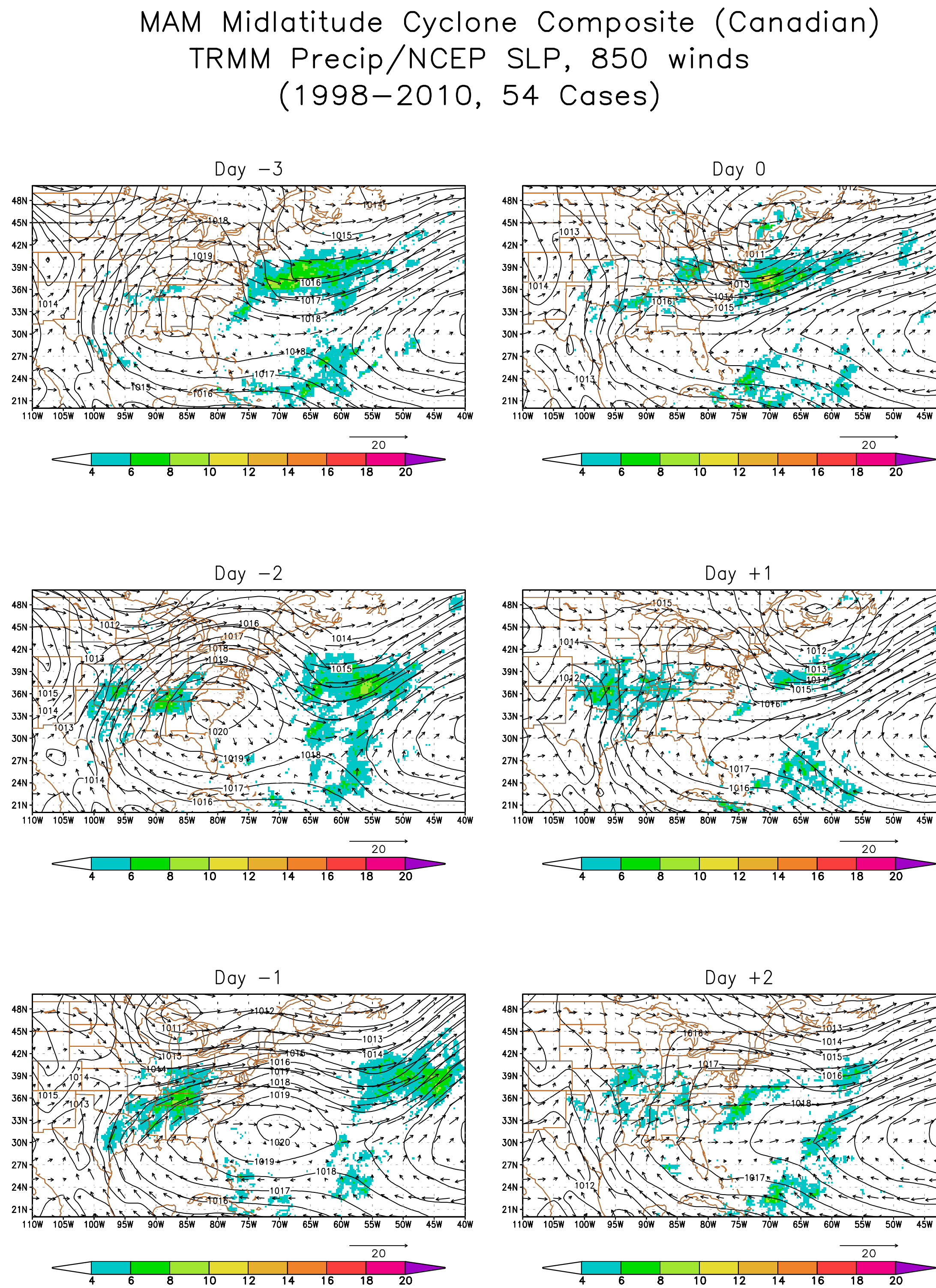


Figure 30: Midlatitude cyclone composite for all Canadian type events that crossed NC during spring from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

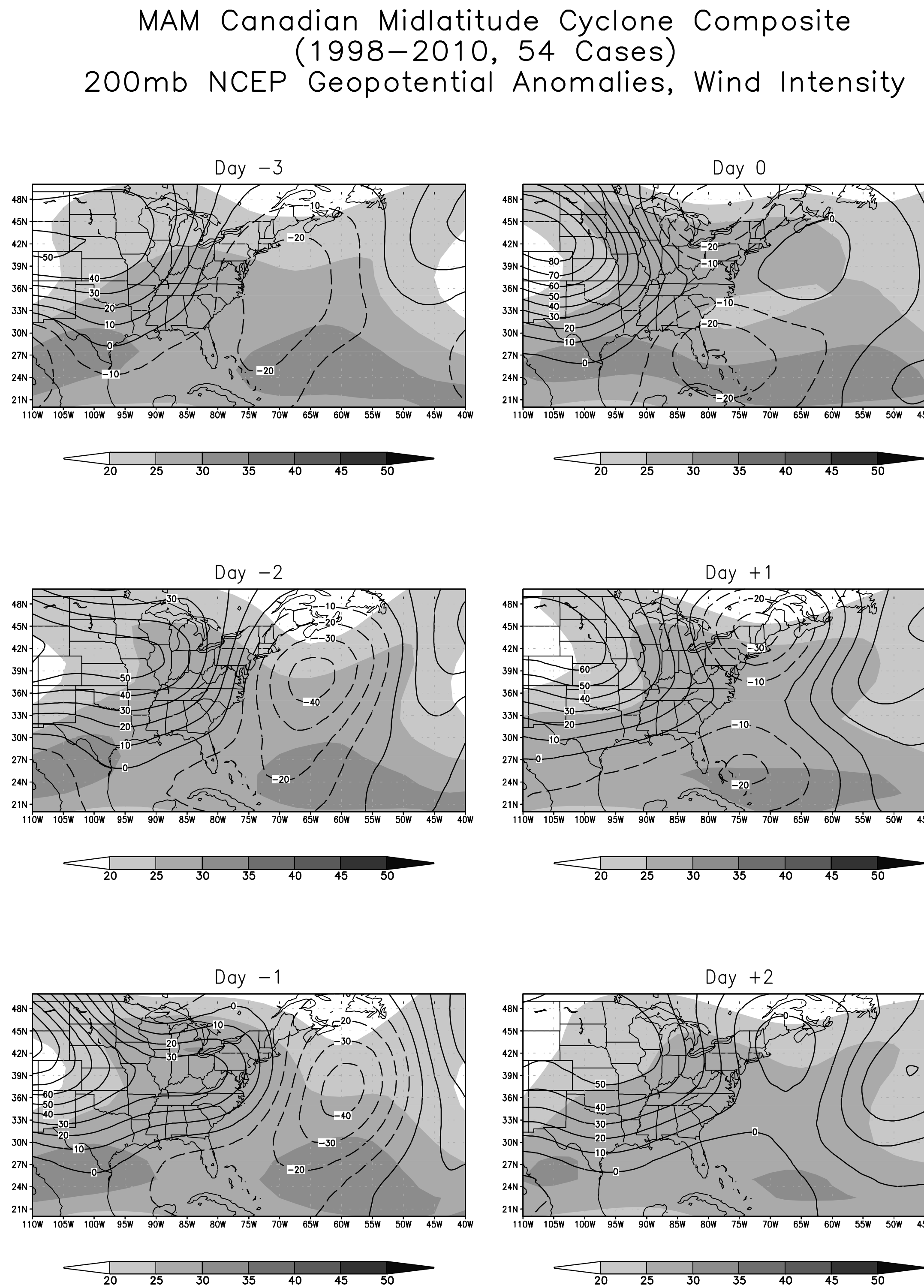


Figure 31: The wind intensities and geopotential height at the 200 mb level as the Canadian type midlatitude cyclones passes North Carolina for spring (1998-2010). 54 cases were observed.

c. Gulf

Figure 32 shows the low-level composite of precipitation, SLP, and 850mb winds for the Gulf type midlatitude cyclone during spring. There were 28 cases of the Gulf type cyclone during spring. However, this type of midlatitude cyclone brought the most rainfall to the SE US.

Precipitation covers much of the southeast on Day-3 due to moisture transport from the Gulf of Mexico. Judging by the isolated areas of intense precipitation, there is likely a lot of instability and convection in these areas. This precipitation is most intense on Day-1, as the midlatitude cyclone approaches NC. This is the most intense rainfall that affects NC than any other composite.

On Day-3, a strong center of high pressure is stationary east of Florida. The position of this high pressure aids in the moisture transport onshore from the Gulf of Mexico. On Day-2, this high pressure center broadens. Here, the midlatitude cyclone is intensifying in the Gulf of Mexico. As the midlatitude cyclone comes onshore, the Bermuda High strengthens.

Figure 33 shows the upper-level composite of geopotential height anomalies and 250mb wind intensities. Overall, the jet stream is not as strong during spring as it is in winter. Furthermore, even though the jet stream is tilted to the northeast, it is not completely northeastward like in the winter composites. Notice how the southwestern portion of the jet stream curves westward. This area, which is located over the southern portion of the composite, actually aids in the intensification of the upper-level trough to the north of the jet stream due to its west to northeastward wind direction. From this, baroclinic wind shear increases, causing midlatitude cyclone intensification.

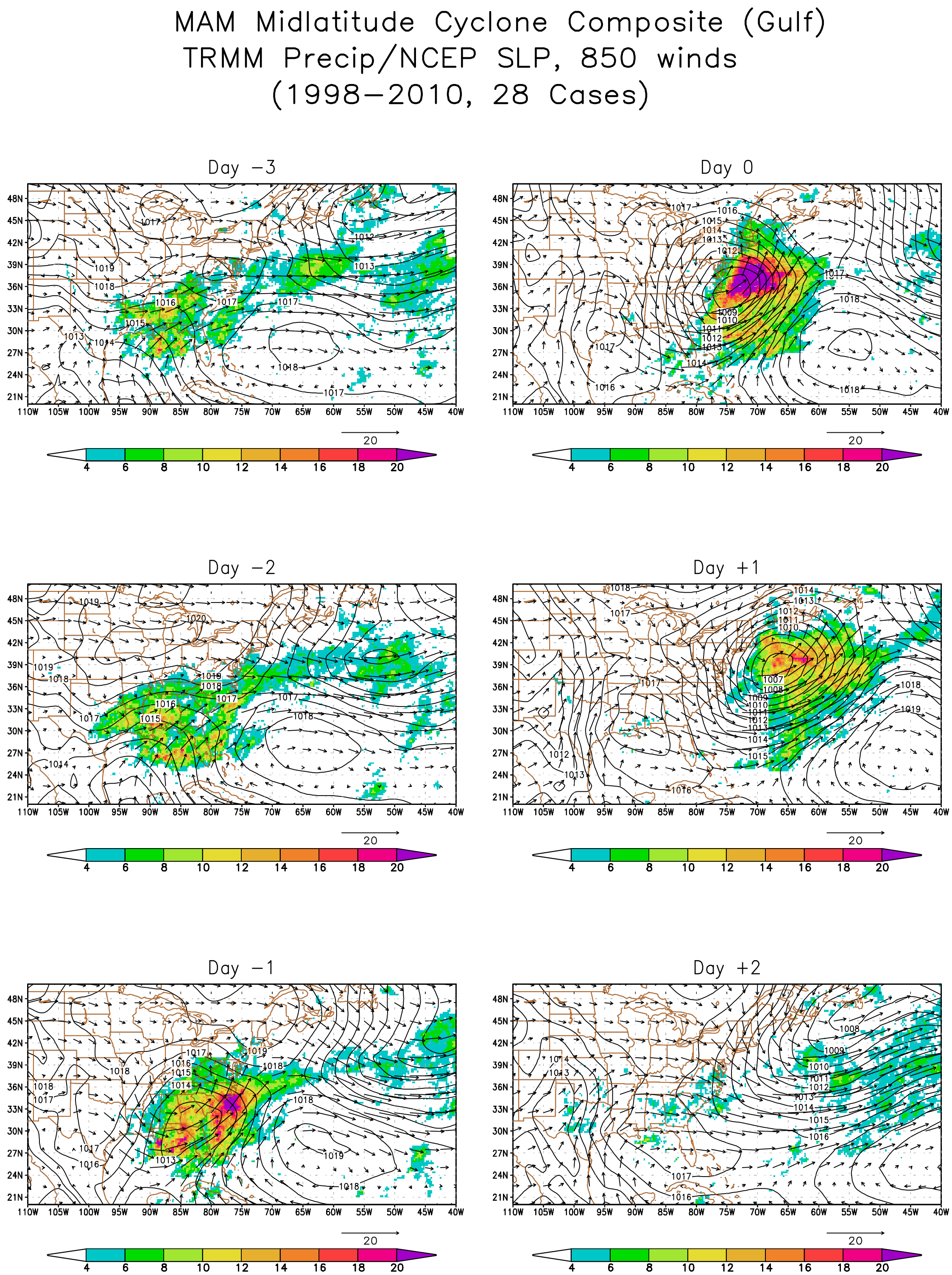


Figure 32: Midlatitude cyclone composite for all Gulf type events that crossed NC during spring from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

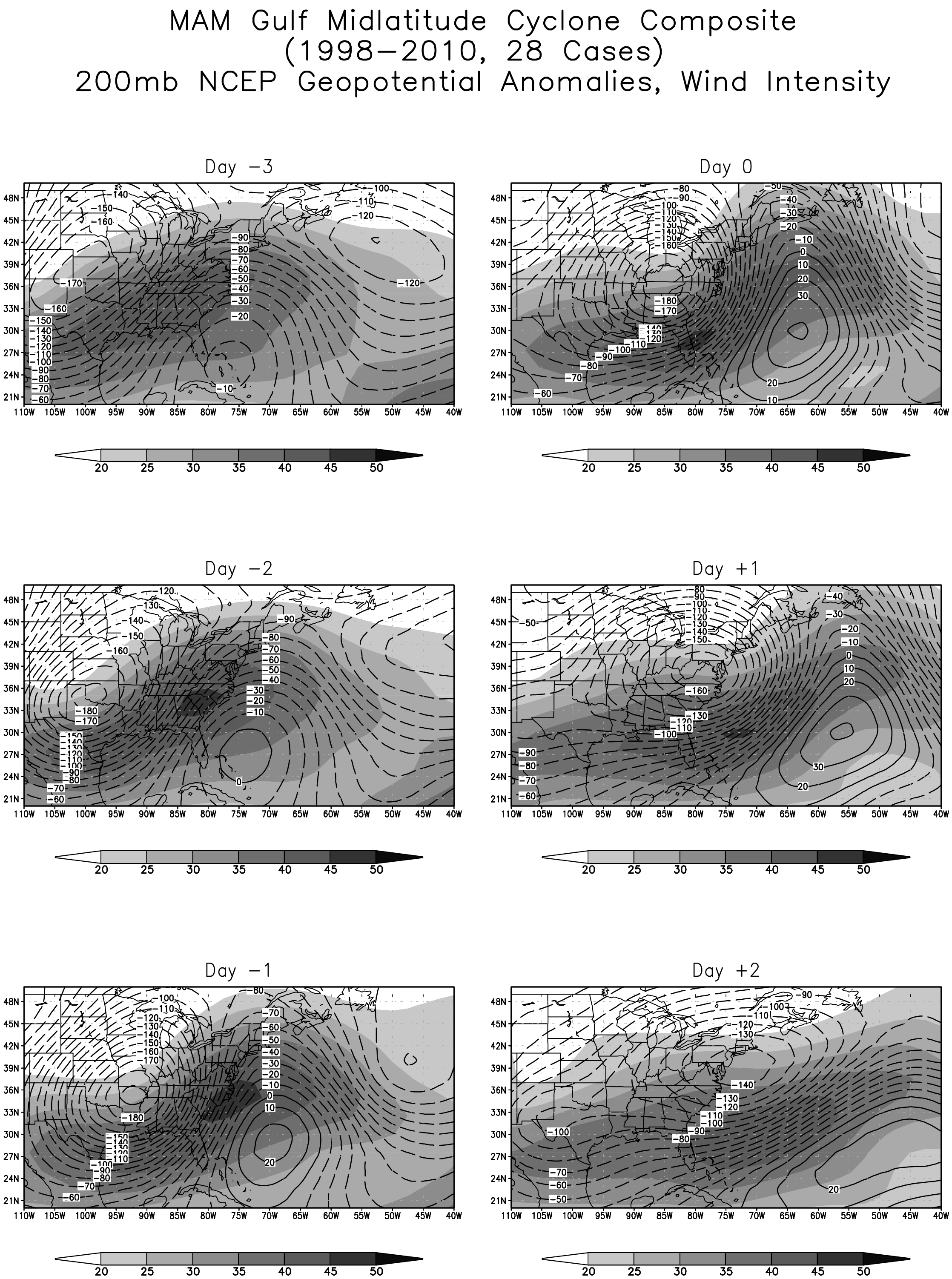


Figure 33: The wind intensities and geopotential height at the 200 mb level as the Gulf type midlatitude cyclones passes North Carolina for spring (1998-2010). 28 cases were observed.

Summer (June, July, August)

a. Rockies

Figure 34 shows the low-level composite of precipitation, SLP, and 850mb winds for the Rockies type midlatitude cyclone during the summer. The summer was the least frequent season overall for midlatitude cyclone passages. At 49 cases, the Rockies type cyclone was the second most frequent cyclone passage for the summer. Summer is the only season that Rockies are not the most frequent type of midlatitude cyclone passage for NC. The summer Rockies-type midlatitude cyclone is weaker than the winter Rockies-type.

Throughout the composite, precipitation is widespread across the SE US before and after the midlatitude cyclone passage. The Florida peninsula has rainfall all six days. Notice the area of rainfall to the east of the Rockies. On Day-2, this area of rainfall spreads and intensifies. This can be attributed to the combination of the midlatitude cyclone formation and eastward traversal, and the moisture transport onshore from the Gulf of Mexico. The rainfall east of the Rocky Mountains occurs as the midlatitude cyclone passes.

During the summer, the Bermuda High is at its strongest. Here, it has an affect on the rainfall in the Gulf of Mexico states. On Day-1, as the precipitation increases, notice the coupling of the moisture transport from the Bermuda High and the instability from the midlatitude cyclone. Here, the midlatitude cyclone intensifies and moves eastward. After the cyclone passes on Day0, it reaches its most intense just east of PA. The most intense area of the summer Rockies-type cyclone is illustrated by the closed isobars just east of PA. Here, the Bermuda High affects the midlatitude cyclone and pulling it offshore quickly.

Southerly winds from the Gulf of Mexico pull moisture onshore, resulting in rainfall in the states along the Gulf throughout the composite. These southerly winds result from the

Bermuda High. These southerly winds couple with the northwesterly winds behind the midlatitude cyclone resulting in increased precipitation and intensification. For NC, winds become northwesterly as the midlatitude cyclone passes on Day0.

Figure 35 shows the upper-level composite of geopotential height anomalies and 200mb wind intensities. Here, a zonal jet sits over the continental US. The strongest areas of the jet are to the north in Canada. During the summer, the jet is much weaker than in winter. On Day0, a weak jet streak moves into the NE US, which aids in the intensification of the midlatitude cyclone. This jet streak also moves the cyclone offshore quickly.

Two upper-level troughs dominate the US east of the Rockies through Day-2. This upper-level setup is not seen in any other composite. On Day-1, an upper-level trough moves eastward, crossing the Rocky Mountains. After the midlatitude cyclone passage on Day0, the trough has moved over the Great Lakes. This trough is asymmetrical and seems to have an area of negative geopotential anomaly extending to the west. On Day+1, this extending continues, and by Day+2, connects with another upper-level trough in the western US.

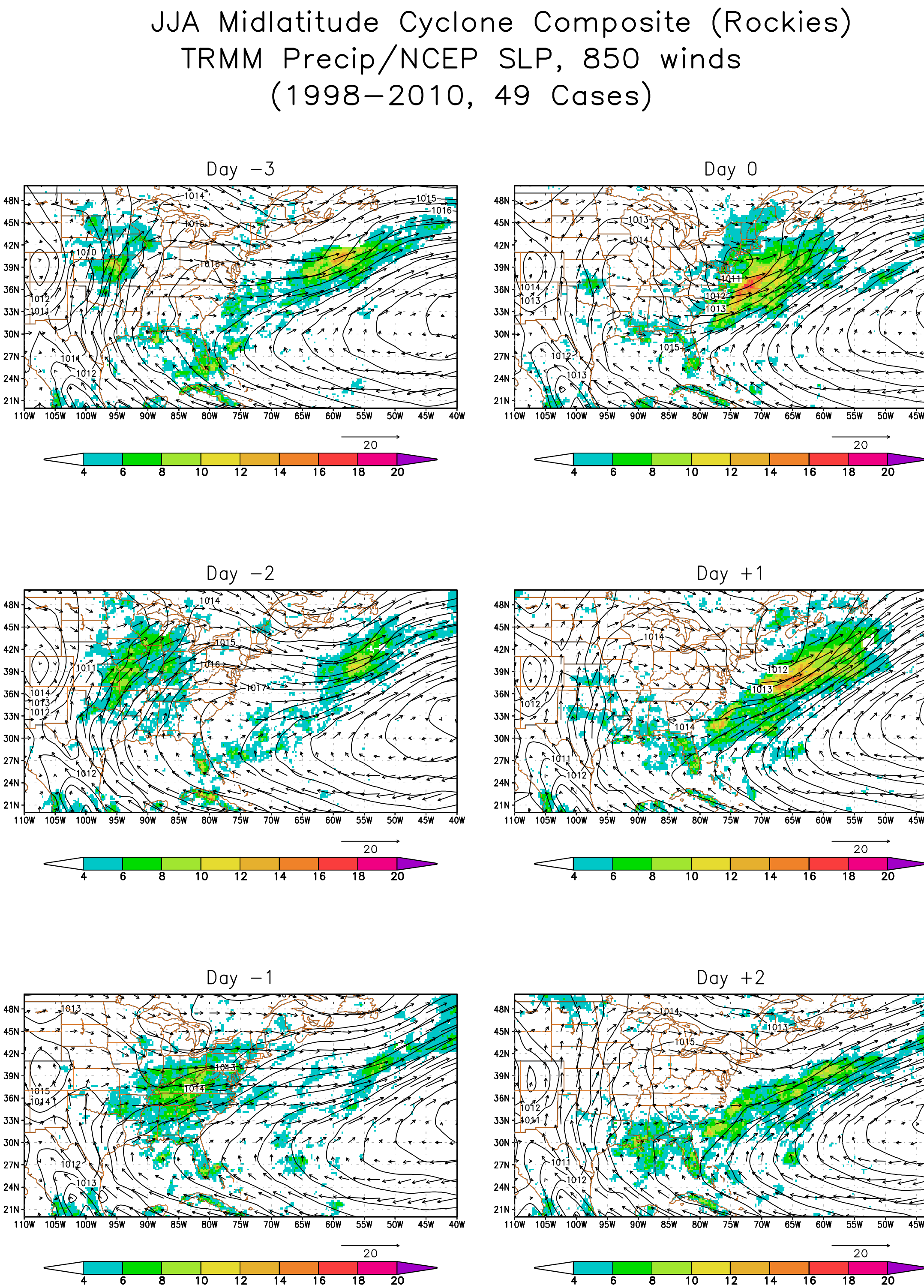


Figure 34: Midlatitude cyclone composite for all Rockies type events that crossed NC during summer from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

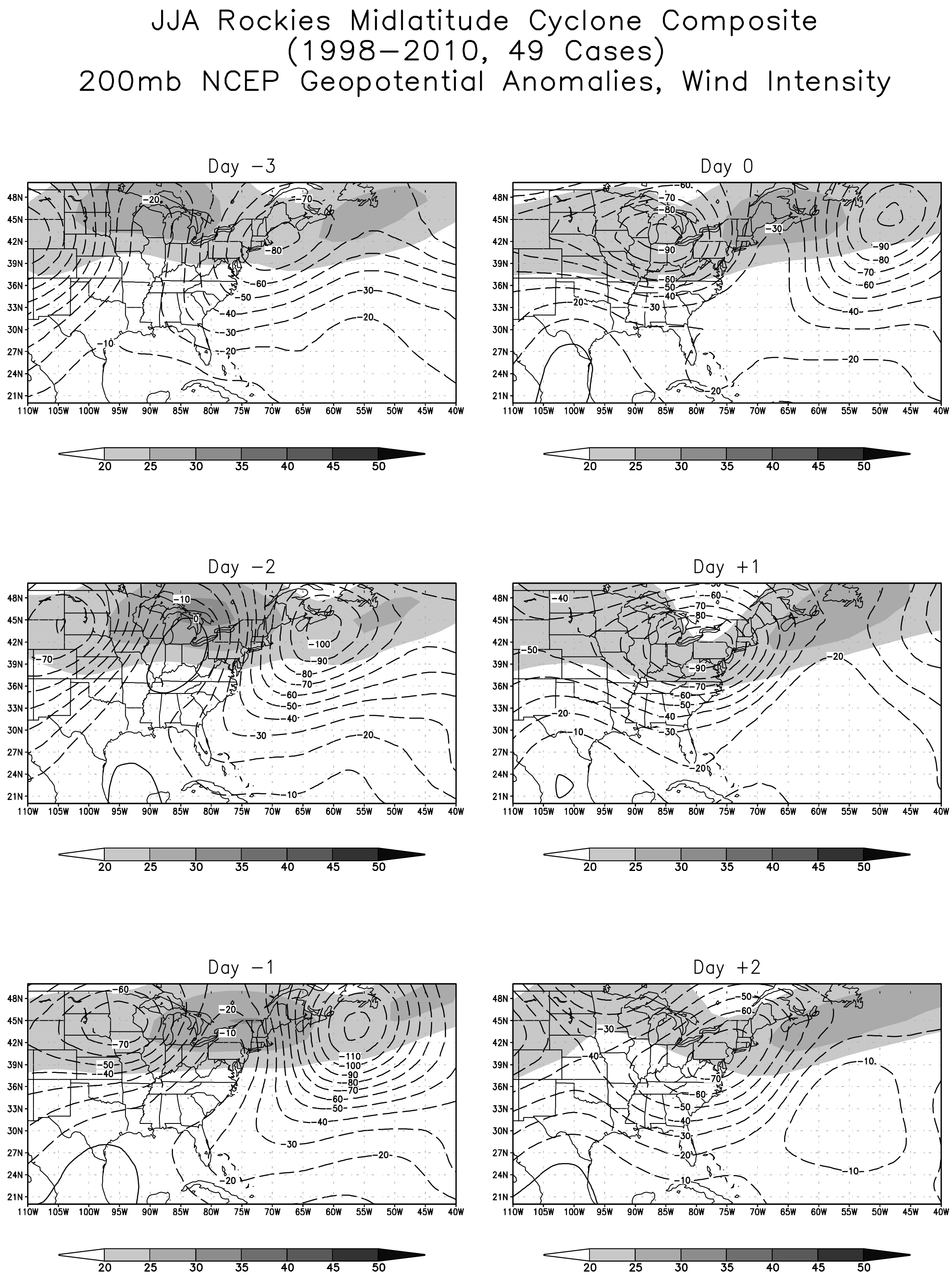


Figure 35: The wind intensities and geopotential height at the 200 mb level as the Rockies type midlatitude cyclones passes North Carolina for summer (1998-2010). 49 cases were observed.

b. Canadian

Figure 36 shows the low-level composite of precipitation, SLP, and 850mb winds for the Canadian type midlatitude cyclone during summer. Like the Canadian type during the winter and spring, there is little effect on NC by the cyclone itself. However, there were 69 cases, which is the most frequent midlatitude cyclone passage during the summer.

Like the summer Rockies type, there is widespread precipitation in the states neighboring the Gulf of Mexico. On Day-1, the precipitation intensifies and begins to fill in for the Ohio Valley. However, no precipitation occurs in NC. After the midlatitude cyclone passes on Day0, there is precipitation in the mountainous western NC and the eastern coastal plains NC, but not in the piedmont region. There is a dry area through NC, SC and GA, just east of the Appalachian Mountains, suggesting a rain shadow effect for the piedmont. On Day+1, the midlatitude cyclone has moved off, and widespread precipitation occurs over the SE US. The source of this precipitation is the Bermuda High, which persists throughout the composite.

The Bermuda High is the main feature in this composite. It is the source of most of the rainfall in the SE US. The isobars associated with the cyclone dip into NC on Day0. By Day+1, the midlatitude cyclone has moved well offshore, and dry air returns to NC. One major difference from the Rockies type composite is that a high pressure center does not return to the area after the midlatitude cyclone passage. There is only high pressure resulting from the Bermuda High in the SE US.

Southerly winds resulting from the Bermuda High dominate this composite. There is no real difference in the Rockies and Canadian type composites for winds. Winds become northwesterly after the midlatitude cyclone passage on Day0.

Figure 37 shows the upper-level composite of geopotential height anomalies and 200mb wind intensities. The jet is zonal throughout the composite, and is similar to the Rockies type composite. The major difference is that the jet is farther northward of the Rockies composite. Also, the jet stream is farther to the north than during winter. The northward position of the jet stream causes midlatitude cyclone formation to occur farther north as well. A jet streak appears north of the Great Lakes on Day-1. This jet streak is weaker than in the Rockies type composite. On Day0, after the midlatitude cyclone passage, the jet streak broadens, covering the NE US. On Days+1 and +2, the jet streak moves offshore, but it does not weaken during this time.

However, it becomes tilted between these days, and on Day-1, weakens considerably. This early tilt is not present during any other season. A tilting upper-level trough signifies that it is weakening and the midlatitude cyclone is losing its upper-level support. Thus, the midlatitude cyclone essentially dissipates as a result. Consequently, this trough breaks into two separate troughs, one to the north and south. The southern trough dissipates between Day-1 and Day0. The northern trough becomes more organized on Day0. On Day+1, this trough moves slowly eastward, and become stationary.

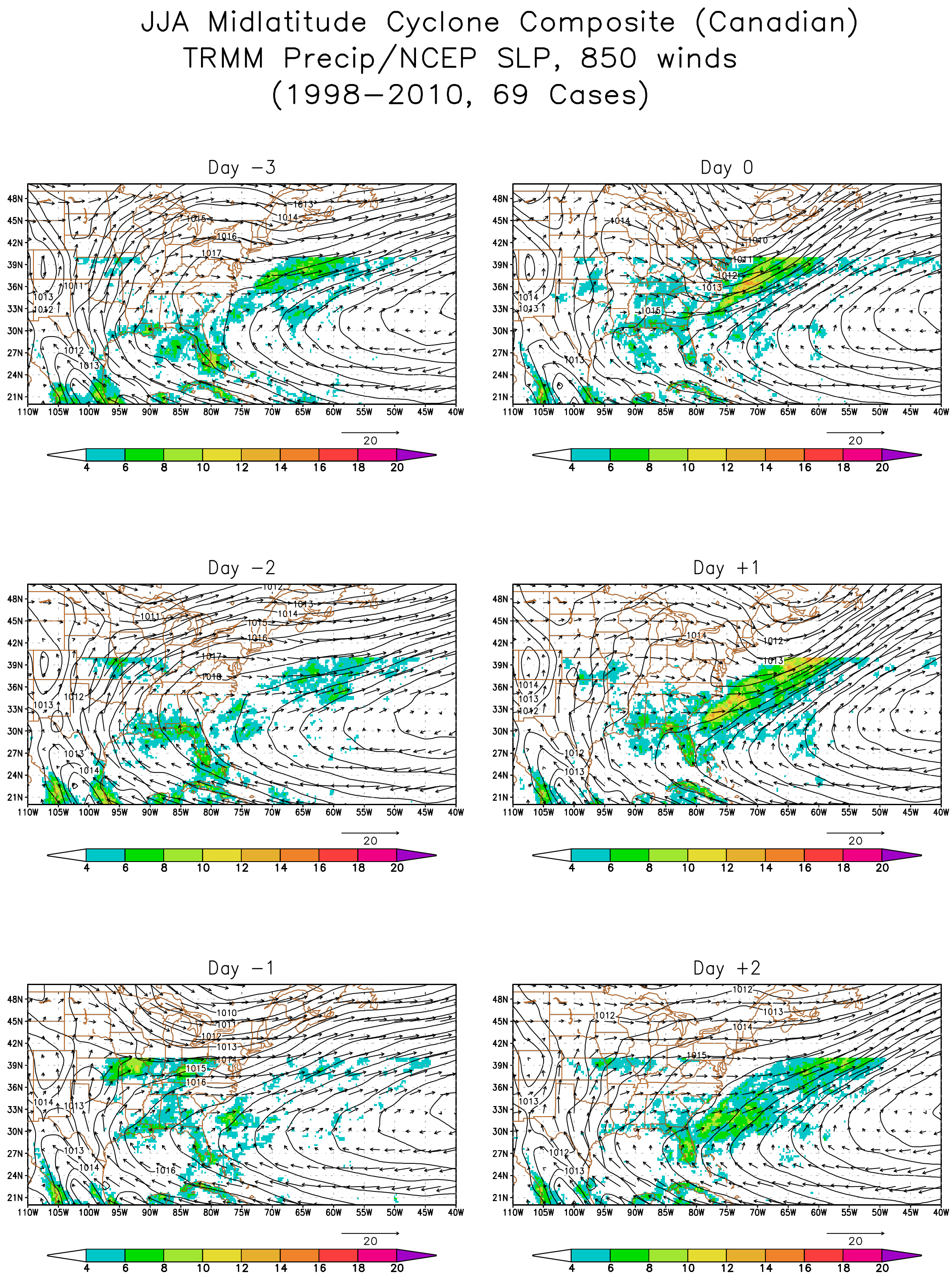


Figure 36: Midlatitude cyclone composite for all Canadian type events that crossed NC during summer from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

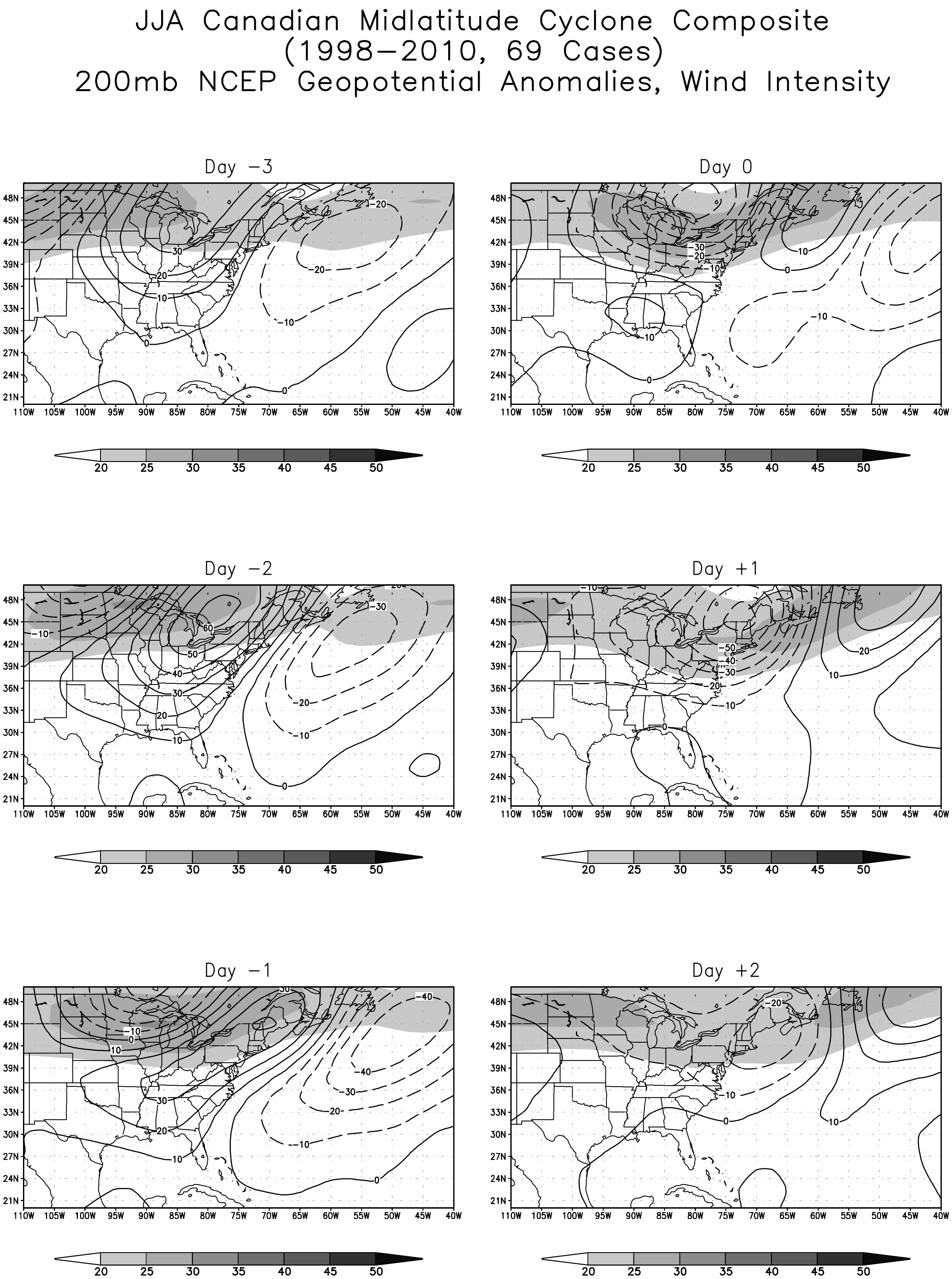


Figure 37: The wind intensities and geopotential height at the 200 mb level as the Canadian type midlatitude cyclones passes North Carolina for summer (1998-2010). 69 cases were observed.

c. Stationary

Figure 38 shows the low-level composite of precipitation, SLP, and 850mb winds for the Stationary type midlatitude cyclone during the summer. At 29 cases, this type of cyclone is only significantly present during the summer. In fact, it is not even an actual midlatitude cyclone throughout the composite. However, these areas of low pressure bring significant amounts of rainfall for consecutive days. Since the summer is known for widespread rainfall, it is important to include this type in the study.

Isolated precipitation dominates the SE US between Days-3 and -2. On Day-1, the precipitation spreads throughout the SE US. However, there is no midlatitude cyclone present. On Day0, an area of low pressure (where the isobars dip to the south) forms over NC. While the rainfall is still isolated to some degree, there is a significant amount of rainfall over NC between Days-1 and 0. The rainfall persists through Day+1. On Day+2, dry air begins to move back into the SE US. However, there is still rainfall along the coast, signifying instability along the Atlantic coastline. While rainfall along the Gulf of Mexico happens in the other summer composites, it does not occur along the Atlantic coastline to this extent. The rainfall persists here between Days0 and +2, hence the stationary pattern in this composite.

A weak area of high pressure persists over the SE US on Day-3. The Bermuda High absorbs this high pressure on Day-2. On Day0, the pressure has dropped, and the 1014 mb isobar dips into NC. This area of low pressure persists through Day+1. By Day+2, the low pressure area has become a closed low pressure center over NC. Therefore, while the midlatitude cyclone does not travel over NC, it actually forms over NC. Furthermore, the same features, such as increased rainfall, which occur near the formation of other types of cyclones, happen in NC.

The same wind patterns from the other summer composites happen here as well. On Day0, when the low pressure can first be seen, winds become slightly northwesterly. These northwesterly winds persist throughout the rest of the composite. Notice how the southwesterly winds associated with the Bermuda High meet with northwesterly winds causing convergence to occur. This convergence causes uplift and cloud formation, which ultimately results in midlatitude cyclone formation. Once the weak midlatitude cyclone forms on Day+2, the winds become southwesterly for NC.

Figure 39 shows the upper-level composite of geopotential height anomalies and 200mb wind intensities. Like the other summer composites (fig. 29; fig.31), the jet is zonal throughout the composite. However, a southeasterly jet streak forms around the Canadian border. This jet streak is over the NE US on Day0. On Day+1, the jet streak moves off to the northeast.

A slow moving upper-level trough intensifies between Days-3 and -1. However, the position of the jet streak causes this trough to tilt to the southeast. This feature is not present in any other composite. An upper-level ridge is also present through Day0. It also begins to tilt to the southeast, and weakens quickly throughout the rest of the composite. On Day+1, as the upper-level trough moves offshore, it begins to tilt to the northeast, along with the jet streak. By Day+2, this trough has moved well offshore.

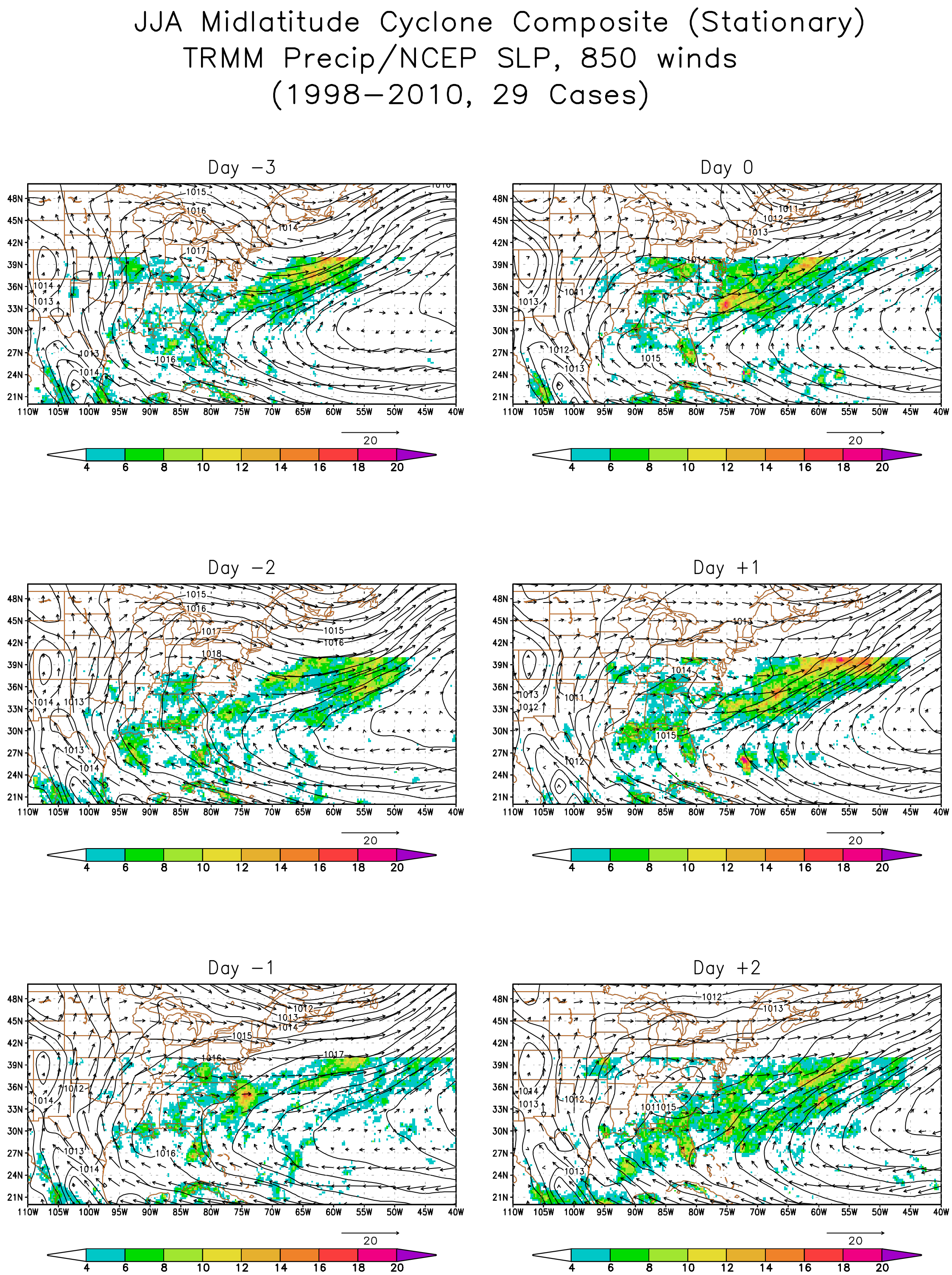


Figure 38: Midlatitude cyclone composite for all Stationary type events that crossed NC during summer from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

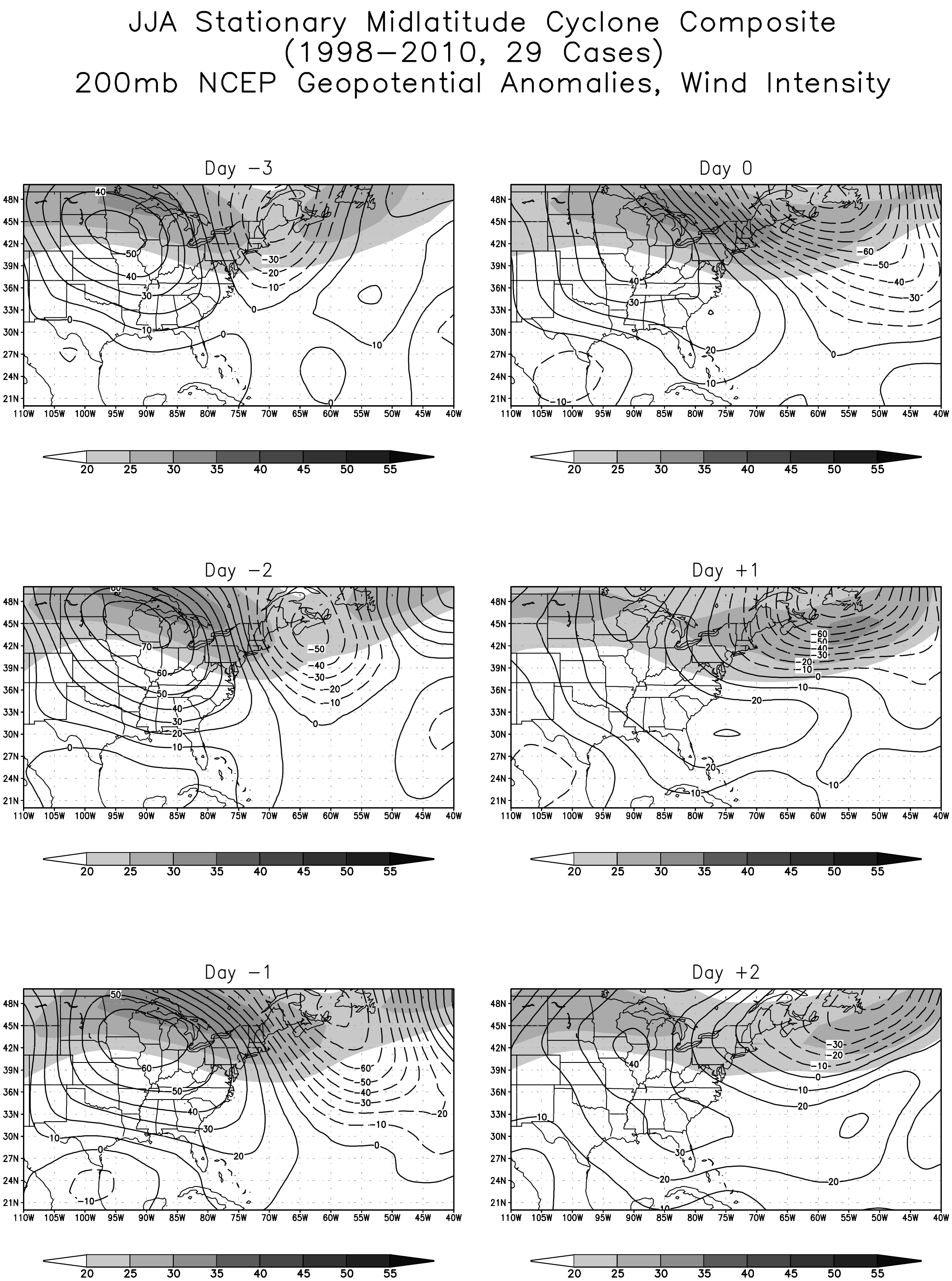


Figure 39: The wind intensities and geopotential height at the 200 mb level as the Stationary type midlatitude cyclones passes North Carolina for summer (1998-2010). 29 cases were observed.

Fall (September, October, November)

a. Rockies

Figure 40 shows the low-level composite of precipitation, SLP, and 850mb winds for the Rockies type midlatitude cyclone during the fall season. Once again, the Rockies type has the most midlatitude cyclone passages with 97 cases. While the fall resembles the summer composite, it shows some of the winter and spring characteristics as well. The most distinct characteristic is the organization of rainfall, which is present during the winter and spring seasons.

On Day-1, as the midlatitude cyclone moves eastward, precipitation intensifies further and almost completely covers the whole SE US. This coverage is similar to the winter Rockies composite. Here, rainfall covers all of NC except for the Coastal Plains. The Coastal Plains are still affected by the high pressure sitting off the coast of NC. On Day0, most of the SE US is dry once again, except rainfall occurs over Coastal Plains NC. The only precipitation in the SE US is in the FL panhandle, AL, and MS. This dry air persists through Day+1.

On Day-2, a high pressure center begins to move eastward. The detached high pressure center from the Bermuda High resembles the spring composite. Like the spring composite, the high pressure moves eastward before being absorbed by the Bermuda High. As the midlatitude cyclone is first visible on Day-1, the high pressure moves well offshore, and only affects the Atlantic coastline. The midlatitude cyclone intensifies, and brings intense rainfall to a large portion of the SE US. After the midlatitude cyclone passes on Day0, it has intensified further, but only affects the coastal plains of NC. By Day+1, the midlatitude cyclone moves well offshore, and no longer affects NC. High pressure returns to the SE US on Day+1.

The wind patterns resemble the spring composite. Since a high pressure center hangs over the SE US, the southerly winds are a result of this high pressure, and not the Bermuda High. After the midlatitude cyclone passes on Day0, winds become northwesterly, similar to the winter composites. As the high pressure center moves back into the SE US, winds become zonal.

Figure 41 shows the upper-level composite of geopotential height anomalies and 200mb wind intensities. Here, an eastward moving jet streak forms over Midwest US. This jet streak intensifies through Day-1. On Day0, the jet streak reaches its strongest point over the east coast. This feature is similar to the winter composites. Its northeastward tilt aids in the intensification of the Rockies type midlatitude cyclone. On Day+1, the jet weakens considerably.

An upper-level trough begins to move eastward on Day-2. As this trough travels eastward, it strengthens and broadens. This particular trough is larger then the other composites. On Day0, after the midlatitude passage, the trough becomes symmetrical as it reaches its strongest point. However, the upper-level trough weakens rapidly, and by Day+2 has almost completely dissipated.

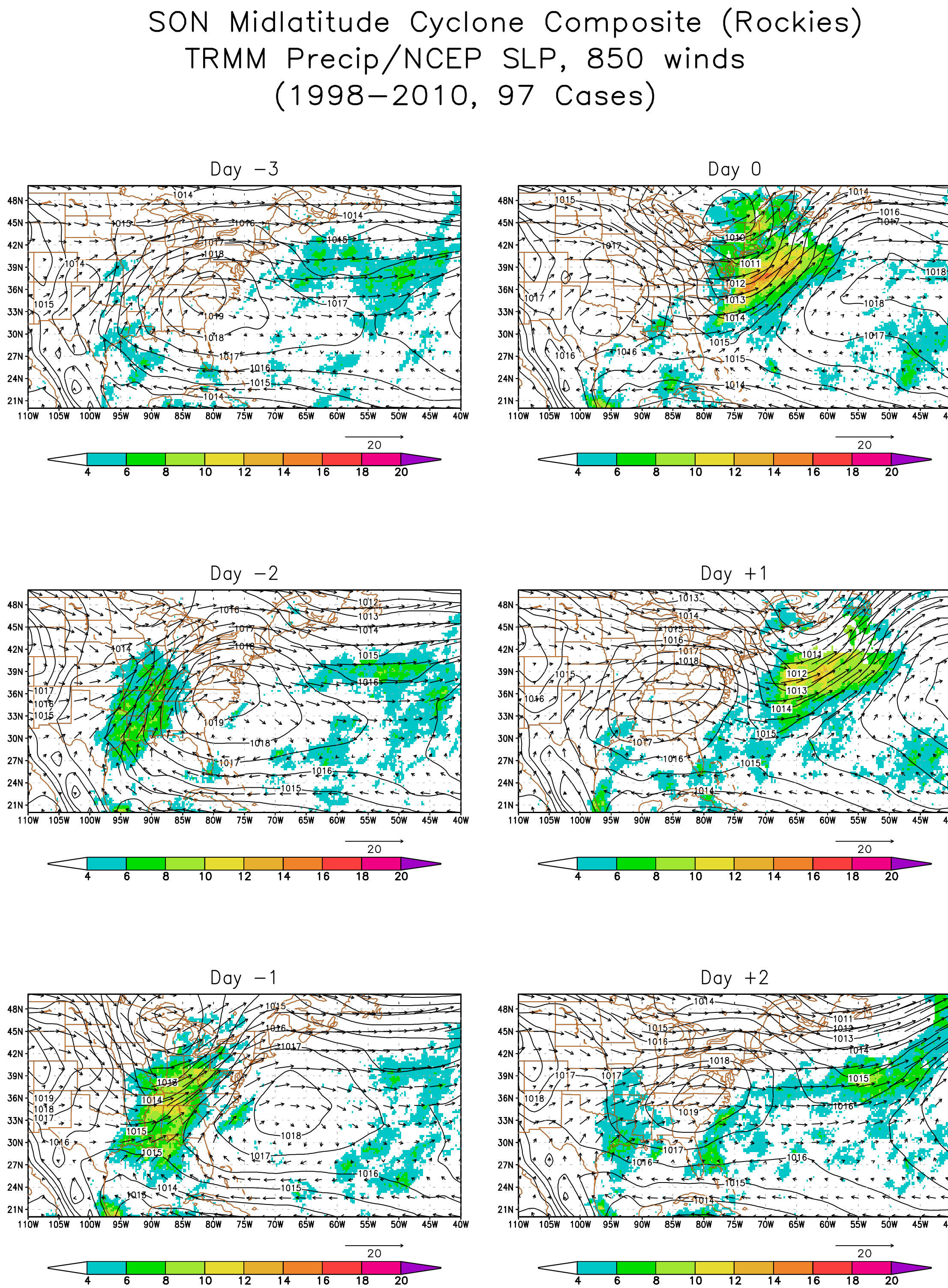


Figure 40: Midlatitude cyclone composite for all Rockies type events that crossed NC during fall from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

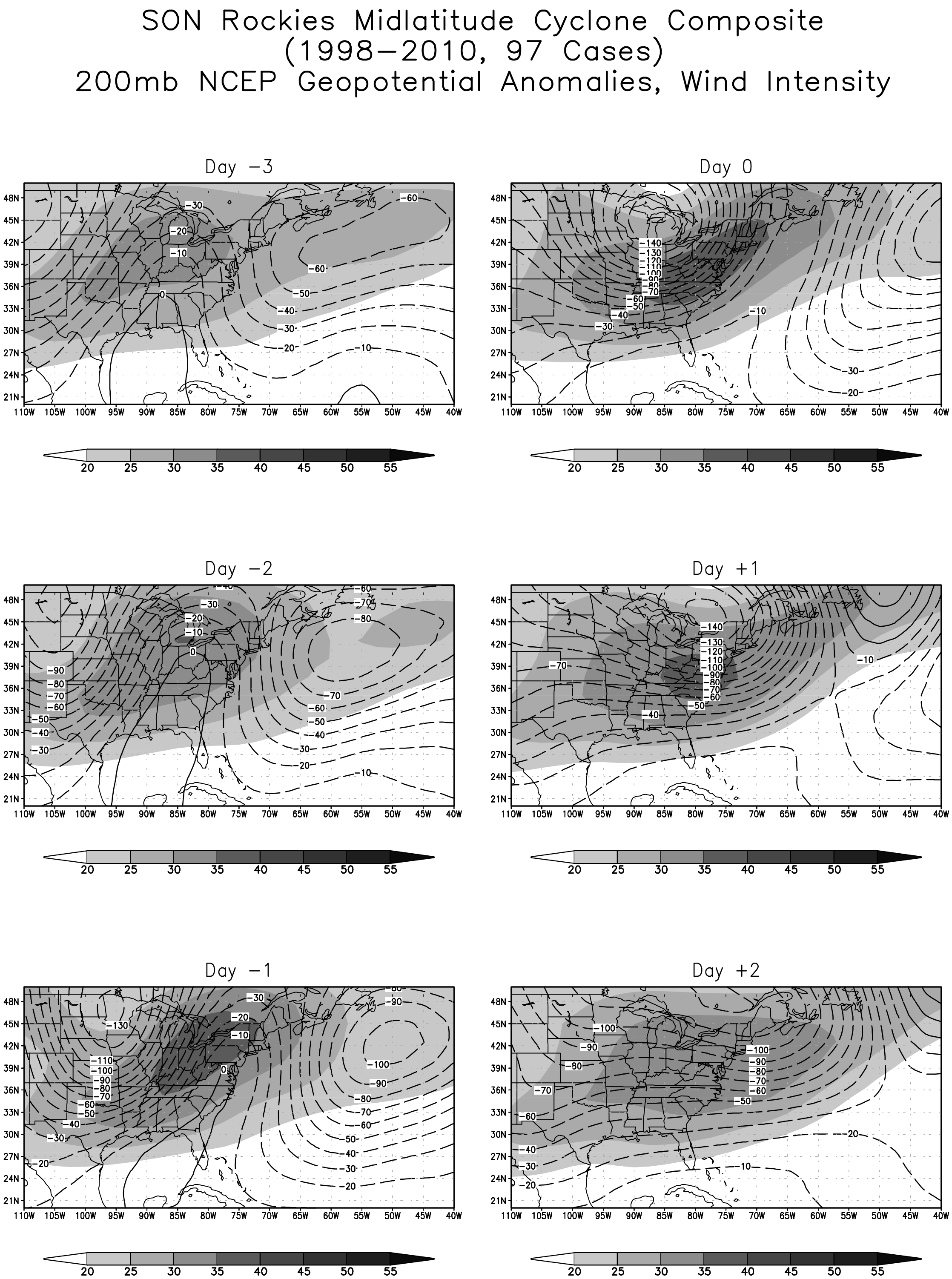


Figure 41: The wind intensities and geopotential height at the 200 mb level as the Rockies type midlatitude cyclones passes North Carolina for fall (1998-2010). 97 cases were observed.

b. Canadian

Figure 42 shows the low-level composite of precipitation, SLP, and 850mb winds for the Canadian type midlatitude cyclones during fall. While the Canadian types do not have a significant affect on NC throughout the study, the fall season shows significant rainfall in the coastal plains of NC. At 62 cases, the Canadian-type was the second most frequent midlatitude cyclone passage for fall. However, the Canadian-type still has the least effect on NC.

As the midlatitude cyclone moves eastward, rainfall begins to spread over the SE US. However, the rainfall is still relatively light since the cyclone is further to the north than the Rockies type. On Day-1, the midlatitude cyclone moves farther south than any other Canadian-type composite. On Day0, the midlatitude cyclone reaches its southernmost point. Here, there is significant rainfall in the coastal plains of NC.

Notice how the fall Canadian-type midlatitude cyclone moves far enough south to bring rainfall to the southeast. This is the only time the Canadian-type affects the SE US on Day-1. However, NC still does not receive much rainfall from this midlatitude cyclone.

Figure 43 shows the upper-level composite of geopotential height anomalies and 200mb wind intensities. Here, the jet is south of where it is in the Rockies composite. On Day0, a jet streak forms in the NE US. The jet streak moves southward on Day+1. This extreme tilt is concurrent with the intensification with the upper-level trough. As the jet stream returns to a more zonal flow on Day+1, the upper-level trough begins to tilt and weaken.

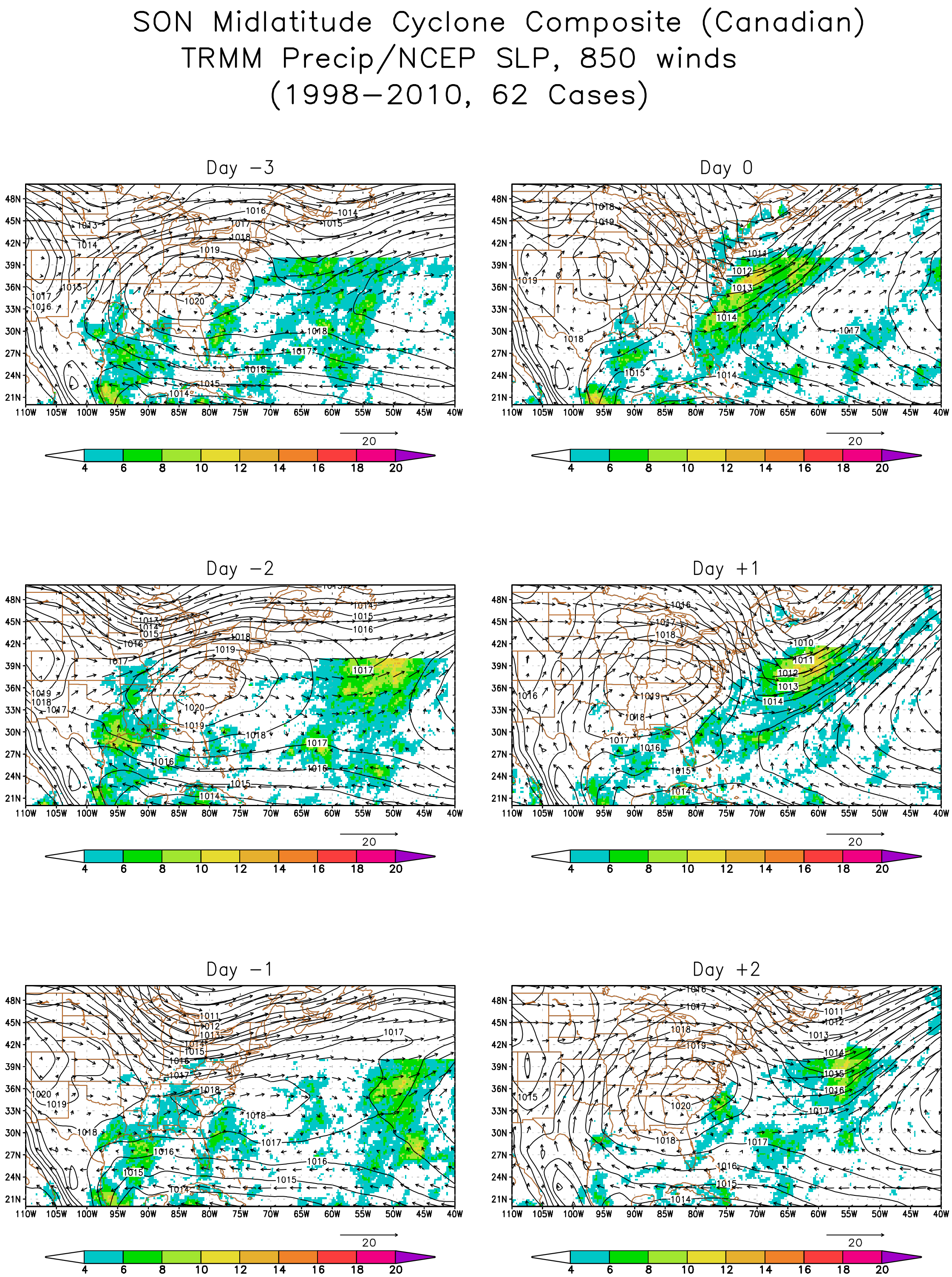


Figure 42: Midlatitude cyclone composite for all Canadian type events that crossed NC during fall from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

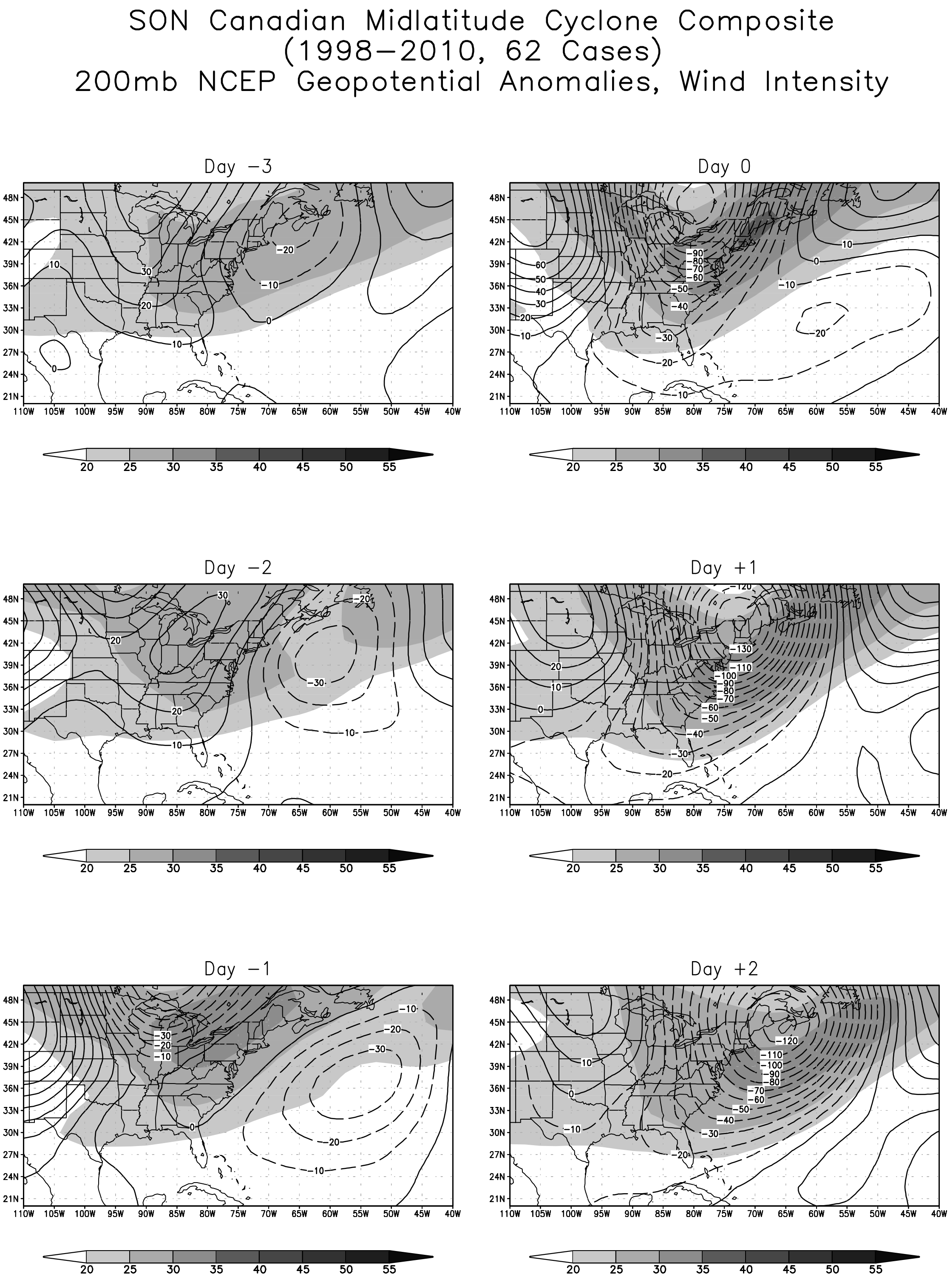


Figure 43: The wind intensities and geopotential height at the 200 mb level as the Canadian type midlatitude cyclones passes North Carolina for fall (1998-2010). 62 cases were observed.

c. Hatteras

Figure 44 shows the low-level composite of precipitation, SLP, and 850mb winds for the Hatteras type midlatitude cyclone during fall. There were only 13 cases of Hatteras type cyclones during fall. The fall Hatteras-type midlatitude cyclones were an interesting case. The detection algorithm picked up tropical cyclones as well. In fact, the algorithm detected almost every tropical cyclone that tracked along the east coast between 1998-2010. To correct this, tropical cyclones were removed from the date datasets manually. Fall Hatteras-type midlatitude cyclones were the only type that required the manual removal of tropical cyclone dates. Tropical cyclones were detected due to their tracks being similar to the Hatteras-type midlatitude cyclone.

On Day-3, heavy precipitation occurs off the east coast of FL. This rainfall intensifies and begins to organize between Day-2 and Day-1. On Day-1, the rainfall has organized around the midlatitude cyclone. After the midlatitude cyclone completely forms and intensifies on Day0, the rainfall is its most intense. The rainfall covers much of NC east of the Appalachian Mountains. The most intense rainfall occurs in the coastal plains of NC, especially in the Outer Banks. By Day+1, the rainfall has moved well offshore, and no longer affects NC.

The first signs of the fall Hatteras type midlatitude cyclone show on Day-3. Notice the disturbance in the isobars off the east coast of FL. This disturbance strengthens through Day-1. Notice the interaction of the cyclone with a high pressure area to the NW, and the Bermuda High to the east. These two high pressure areas aid in the rapid intensification of the midlatitude cyclone. On Day0, the midlatitude cyclone has formed and intensified quickly. The fall Hatteras type cyclone is strongest on Day0. After the midlatitude cyclone moves into the Atlantic Ocean, the NW high pressure area follows it to the northeast. Also, another high pressure center breaks off from the Bermuda High and follows the midlatitude cyclone as it travels offshore. By Day+2, the NW high pressure area travels slightly southward and settles in over the SE US.

Due to the high pressure center west of the Appalachian Mountains, the winds are northwesterly for NC. This high pressure keeps most of the SE US dry over land. However, the converging winds of this high pressure and the Bermuda High aid in the rapid formation and intensification of the Hatteras type midlatitude cyclone. After the midlatitude cyclone forms on Day0, the winds intensify rapidly, becoming northeasterly over NC.

Figure 45 shows the upper-level composite of geopotential anomalies and 200mb wind intensities. The upper-level jet is very unorganized between Days-3 and -2. On Day-1, a jet streak forms just off the coast of NC. This jet streak broadens on Day0, but does not intensify rapidly. After the midlatitude cyclone passes, the jet streak moves offshore, and returns to its unorganized structure.

Throughout the composite, an upper-level trough persists over the SE US. This trough intensifies slightly through Day-2. In this composite, the ridges actually intensify while the trough weakens. As both ridges strengthen, and move slightly southward, the upper-level trough weakens and is pushed further south. On Day+1, after the midlatitude cyclone has moved offshore, the upper-level trough is almost completely absorbed by the ridges. The western ridge, begins to move eastward on Day+1, and pushes the eastern ridge eastward by Day+2. Here, the upper-level trough weakens further and has no affect on the Hatteras type midlatitude cyclone.

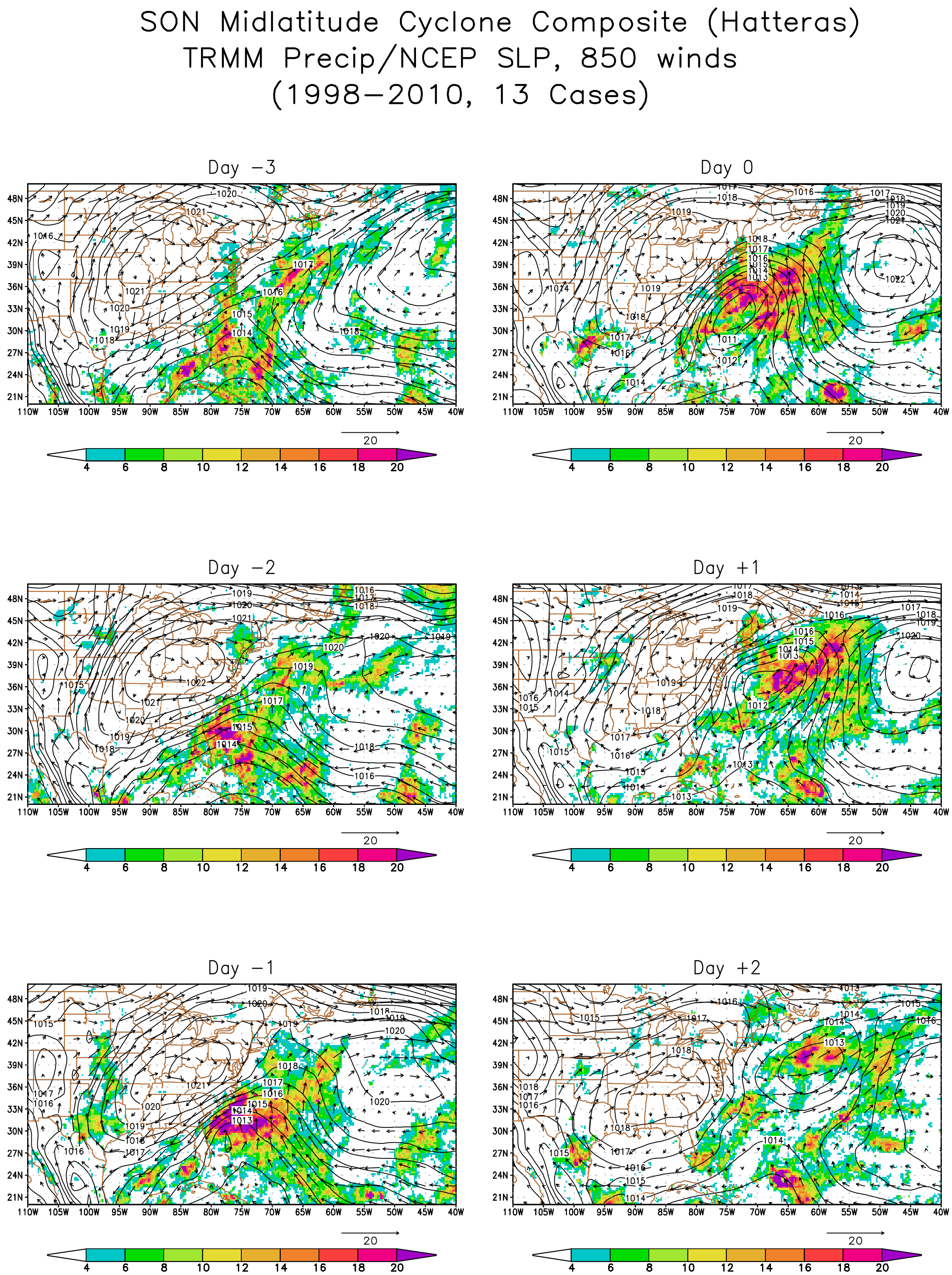


Figure 44: Midlatitude cyclone composite for all Hatteras type events that crossed NC during fall from 1998-2010. Plots show precipitation (mm/day), 850mb winds (m/s), and SLP (mb).

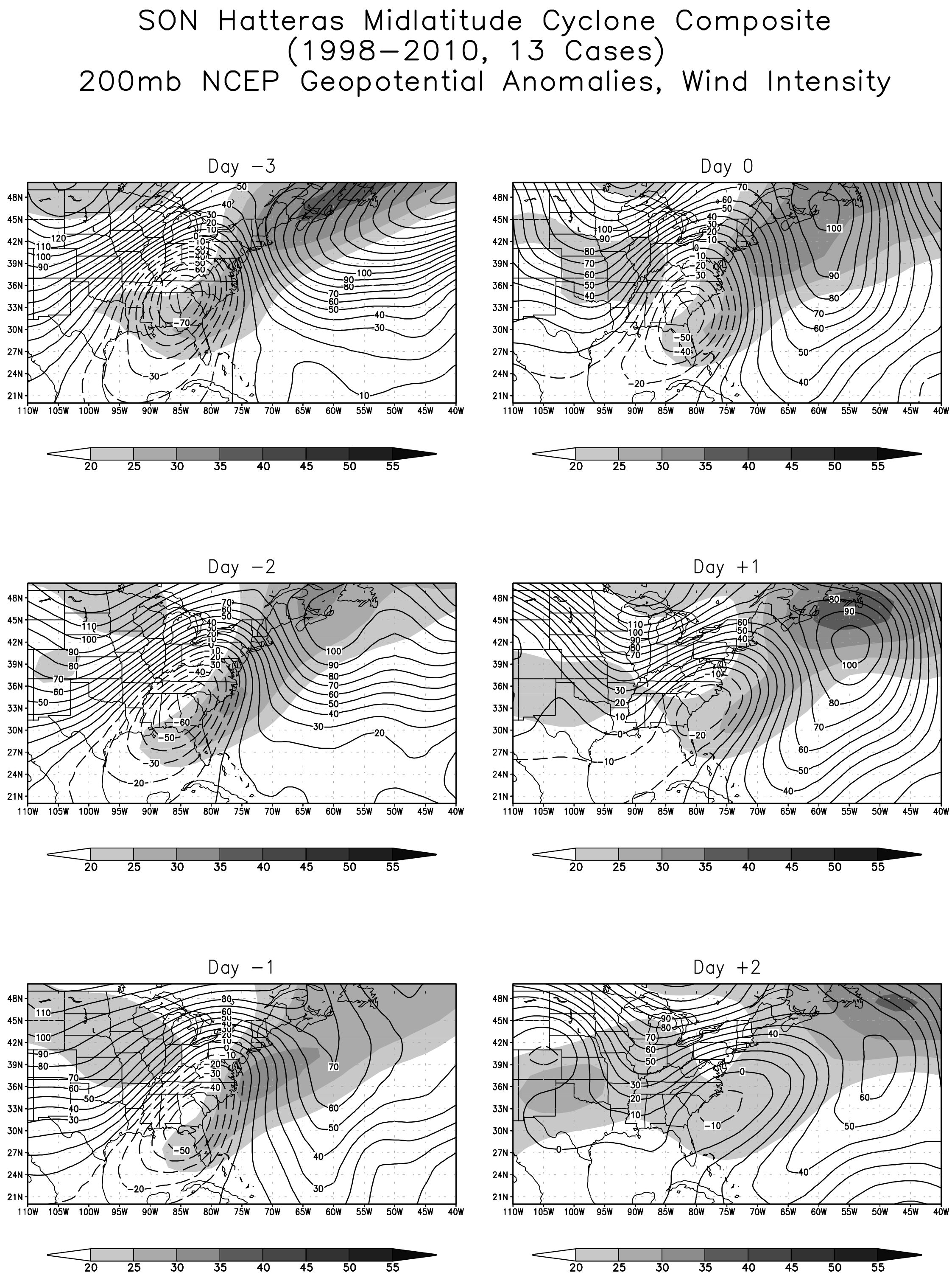


Figure 45: The wind intensities and geopotential height at the 200 mb level as the Hatteras type midlatitude cyclones passes North Carolina for fall (1998-2010). 13 cases were observed.