ABSTRACT

Forecasting heavy precipitation associated with warm-season cutoff cyclones presents a particularly challenging forecast problem in the northeastern US. This challenge arises in part from physiographic features that modulate the distribution of precipitation and severe weather, and the rapid changes in the character of precipitation due to the evolution and motion of the cutoff cyclones. As part of the Collaborative Science, Technology, and Applied Research (CSTAR) program, this project contributes to an improved understanding of the distribution of heavy precipitation associated with cutoff cyclones as well as the reasons for precipitation enhancement. The results of a 51year (1948–1998) northeastern US climatology of precipitation associated with cutoff cyclones are presented based on the National Centers for Environmental Prediction/Climate Prediction Center (NCEP/CPC) Unified Precipitation Dataset (UPD). Other portions of the climatology including preferred warm season monthly cutoff cyclone tracks, are derived using four-times daily (0000, 0600, 1200 and 1800 UTC) 500 hPa gridded geopotential height analyses from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset. In this thesis, cutoff cyclones are identified objectively and are defined as a geopotential height minimum surrounded by at least one closed 30 m interval contour.

Two case studies involving cutoff cyclones that produced significant damage from severe weather and flooding across the Northeast were analyzed using the 40 km Eta model initialized dataset from NCEP/NCAR. Precipitation plots were also made for each day of each case using the UPD. The first case occurred on 30 June to 1 July 1998 and featured a cutoff low that tracked through the Great Lakes, producing significant severe weather in many parts of the Northeast. Severe weather included flash floods in Vermont, New York, and Rhode Island, and three tornadoes on Long Island, New York. This cutoff featured a strong upper-level jet on its equatorward side and a strong lowlevel jet on its eastern side. The heaviest rain fell along the New York and Pennsylvania border, eastward to Cape Cod. A result based on this case study is that entrance and exit regions of both upper- and lower- level jets can strongly enhance heavy precipitation as well as severe weather.

The second case was for a Hudson Bay category of a closed low occurring from 3 to 5 July, 1996 that produced large amounts of flooding in northern New York and Vermont, and in isolated pockets in the vicinity of significant orographic features (e.g., Adirondacks); however unlike the first case, there was no reported severe weather. An important result from this case study is that cyclonic vorticity advection can play a large role in determining the locations of heavy precipitation. Synoptic and mesoscale analyses were used in both cases to relate the severe weather and heavy precipitation to terrain features, lower- and upper-level jet interactions, and to the structure, speed, and track of the evolving cutoff.

I. Introduction

1.1 Overview

Forecasting heavy precipitation associated with warm-season cutoff cyclones (also known as closed lows) presents a particularly challenging forecast problem in the northeastern United States (US). These challenges arise in part from physiographic features that modulate the distribution of precipitation and severe weather, and the rapid changes in the character of precipitation due to the evolution and motion of the cutoff cyclone. It has been found that cutoff cyclones produce approximately 30% of the annual precipitation in the Northeast (Atallah and Aiyyer 2002). The northeastern U.S. has much complex terrain including many mountain ranges (e.g., the Adirondack, Green, Catskill, White Mountains). With many river valleys surrounding these mountainous areas (e.g., Hudson/Mohawk, Champlain River Valleys), flooding problems associated with slow-moving, precipitating closed lows can prove to be very difficult for forecasters to predict. Thus, one of the biggest challenges in operational meteorology relates to Quantitative Precipitation Forecasting (QPF) (e.g., Anthes 1983; Jensenius 1990; Junker and Hoke 1990).

Warm season cutoff cyclones in the northeastern U.S. tend to follow five main tracks (refer to Fig. 1.1 taken from Novak et al. 2002). These tracks include the Southwest Track, the Zonal Track, the Great Lakes Track, the Atlantic/Coastal Track, and the Northwest Track or sometimes referred to as the Hudson Bay Track. The Great Lakes Track, which originates in the central Canadian provinces/northern mid-west US, is the most common track of closed lows, followed by the Hudson Bay/Northwest Track.

In this thesis we will not distinguish between closed lows and cutoff lows and will adopt the closed low terminology. Most cutoff lows form equatorward of the main branch of the westerlies (e.g., Palmén 1949; Bell and Bosart 1989) and are often associated with blocking patterns (e.g., Rex 1950). Because they are mostly isolated from the westerlies, cutoff lows tend to be slow moving in comparison to open wave cyclones embedded in the westerlies. Cutoff lows can also form poleward of the main belt of the westerlies in conjunction with deepening baroclinic cold-core troughs. Cutoff lows in these cases are sometimes called closed lows in the literature. An important characteristic of closed/cutoff lows is that they are often associated with persistent 500 hPa height anomalies (e.g., Dole and Gordon 1983; Dole 1986).

The orientation (asymmetries), structure, and tilt of cutoff cyclones can make forecasting associated precipitation extremely challenging. The characteristic structure of a cutoff cyclone limits the predictability of the associated precipitation (e.g., Hawes and Colucci 1986). The vertical structure of closed lows and vertical tilt, though small, are a couple of factors which strongly affect precipitation distribution. A slight upshear or downshear tilt can hinder the amount and area where precipitation is produced. The indicators of synoptic scale forcing (e.g., the advection of temperature and/or vorticity) within cutoff cyclones tend to be weaker or more localized in cutoff lows than in more baroclinic, open-wave cyclones (Smith 2003). When forcing for ascent is weak and/or the cutoff cyclone is tracking over complex terrain, numerical weather prediction (NWP) models frequently have difficulty predicting precipitation distribution and amount in cutoff cyclones. The intent of this thesis is to improve the skill in forecasting the diverse precipitation patterns associated with cutoff cyclones partly by understanding the climatological behavior of these systems. To accomplish this objective, a 51-year closed low climatology of monthly precipitation distribution is created for the warm season (June-September). Monthly percentages of precipitation due to cutoff cyclones were also constructed, along with a set of common monthly cyclone tracks. These climatologies will complement a similar study of cool season northeastern US closed lows by Fracasso et al. (2004). This thesis is also a continuation of the research done by a previous University at Albany student, Matthew Novak.

The second part of the research is composed of an in-depth analysis of two case studies involving cutoff cyclones. Both case studies demonstrate the types of severe weather closed lows can produce, including flash floods, tornadoes, and hail. The first case study involves a Great Lakes Category of a closed low, which tracks across northern New York State into Maine during late June and early July of 1998. This particular closed low creates a huge swath of heavy precipitation, which falls over the New York and Pennsylvania border extending to Cape Cod. Three tornadoes are also produced over Long Island. A key aspect of this case is the existence of strong upper- and lower-level jet-dynamics; however there are no strong surface baroclinic zones present. A pre-frontal trough and a warm sector also act to inhibit the devastation in this case.

The second case involves a Hudson Bay category of a cutoff cyclone (July 1996) which tracks from northwest Pennsylvania through the New England states and up into Maine. This second cutoff system does not produce as much severe weather as the June-July 1998 case, although heavy precipitation amounts are more widespread over northern upstate New York and Vermont. The 500 hPa cutoff low in this case changes much more in orientation as it pivots from a positive to negative tilt. There are also two large vorticity maxima rotating around the cutoff that act to enhance the precipitation. Physiographic features also play a large role in where the heaviest precipitation is produced. Both of these events are excellent examples of how difficult the precipitation associated with cutoff cyclones is to forecast.

1.2 Literature Review

1.2.1 Theory of Evolution of Cutoff Cyclones

Crocker et al. (1947) first theorized that pools of cold air are often isolated equatorward of their source regions and pools of warm air are isolated poleward of the mean flow due to the deformation of the middle- and upper-tropospheric flow. The pools of cold air migrating equatorward undergo subsidence and associated stretching and horizontal convergence in the upper levels (e.g., 500 hPa) of the atmosphere. As the cold air slowly disappears from the mid levels, stretching and horizontal convergence act to increase the vorticity at the level of maximum convergence (Bluestein 1992, sec 4.5). In conjunction with the aforementioned deformation of the middle- and upper- tropospheric flow, there is a cutting off of the cold air from its polar source region on an upper level chart. This theory of cutoff cyclone formation was further developed by Palmén (1949) and again by Eliassen and Kleinschmidt (1957). Figure 1.2, taken from Fig. 2 of Palmén and Nagler (1949), illustrates this process.

Rossby (1940) showed that the conservation of potential vorticity can be written as:

$$PV = \underbrace{(\xi + f)}_{\Delta p} = \text{constant.}$$
(1)

In this relationship, ξ is the relative vorticity, f is the Coriolis parameter, Δp is the depth of a column in pressure coordinates. Based on discussion of Eq. (1) in Palmén and Newton (1969, sec 10.4), as a column of air is displaced equatorward from its source region, it experiences stretching (an increase in Δp), and a decrease in f so that an increase in ξ can be expected. Conservation of PV according to (1) under these conditions results in a strengthening of the cyclonic circulation of the column. A strong enough cyclonic circulation can deform the mean flow and cut off a pocket of cold air from the flow. Figure 1.3 (taken from Fig. 10.1 of Palmén and Newton 1969), illustrates the result of this process. An isolated pool of warm air and corresponding height maximum lies poleward of the cold air pool and corresponding height minimum. When a strong zonal current lies upstream of a blocking region this type of deformation pattern normally occurs as shown in Fig. 1.4 (taken from Berggren et al. 1949). Most disturbances, when approaching the blocking region, slow down and increase in amplitude, similar to patterns explained in Rex (1950). As a result of this increase in amplitude, there are five types of upper-level cyclones that can be formed as shown in Figs. 1.5a-e (taken from Figs. 10.4a-e of Palmén and Newton 1969). Figure 1.5d most closely depicts the cyclone described earlier (a cyclone resulting from a cold pool characterized by strong cyclonic circulation, displaced equatorward). Keyser and Shapiro

(1986, sec 2d), Bell and Bosart (1993), and Bell and Keyser (1993) all demonstrated this aspect of cutoff development. They also explained how as the wind maximum moves into the base of the trough, thus concentrating the vorticity near the trough axis, a closed circulation would develop.

1.2.2 Areas of Cutoff Cyclone Genesis and Lysis

There are a limited number of published studies on what areas of the globe are favored for the genesis and lysis of middle- and upper-tropospheric cutoff cyclones. However, the studies that have been completed clearly depict these geographically favored regions. Palmén and Newton (1969) found that the development of cold uppertropospheric cutoff cyclones is particularly favored in regions of the mean belt of the westerlies, mainly across the western US and southwestern Europe.

Twenty years later, Bell and Bosart (1989) produced a 15-year (1963-77) climatology of Northern Hemisphere 500 hPa closed cyclone and anticyclone centers. Bell and Bosart (1989) developed an objective analysis procedure for determining if a given grid point represents the minimum or maximum height value of a closed circulation system (Fig. 1.6 taken from Fig. 1 of Bell and Bosart 1989). This climatology was produced from larger and more comprehensive datasets and produced similar results as those illustrated in Palmén and Newton (1969). In addition, Bell and Bosart found that there were cutoff cyclone genesis maxima in north-central Canada near the Hudson Bay, across the North Pacific and Gulf of Alaska, over the southwest US, near the northeast coast of the US, and over southern Europe (Fig. 1.7a-d taken from Fig. 3 of Bell and

Bosart 1989). Bell and Bosart also found that lysis maxima occurred near or just downstream of genesis maxima. This close proximity of genesis and lysis maxima indicates that the cutoff systems in the southwest US, Gulf of Alaska, and Hudson Bay are slow moving systems. Lysis areas were found relatively farther upstream across the northwest Atlantic and across southern Europe, indicating more mobile systems. Several years later, Bell and Bosart (1994) went even further into cutoff cyclone and anticyclone genesis/lysis study. This research identified enhanced cutoff cyclone formation in the southwest and eastern US, as well as in the lee of the Alps.

For the North Atlantic, topography can have a large effect on the development of cutoff cyclones (Doyle and Shapiro 1999). The orographically induced jet off the southern tip of Greenland can cause cutoff cyclones to develop. More research on middle- and upper-tropospheric cutoff cyclone and anticyclone genesis/lysis and its effects on surface weather conditions needs to be done, hence the effort made towards the current research.

1.2.3 Typical Structure of Cutoff Cyclones

The typical structure of cutoff cyclones consists of a symmetrical distribution of geopotential height and temperature. The lowest height values generally exist in the center of the closed cold cyclonic circulation. At first, cutoff cyclones were considered middle-tropospheric systems with little or no connection to surface cyclogenesis (Palmén 1949; Palmén and Nagler 1949; Hsieh 1949). The structure of closed lows has been researched in various studies including an extensive case study of a cutoff cyclone over

Europe. This cutoff cyclone was first analyzed by Peltonen (1963), and again by Palmén and Newton (1969). Figures 1.8a-d, taken from Fig. 10.7a-d of Palmén and Newton 1969, show a vertical distribution of the cutoff cyclone's geopotential height and temperature structure extending from the surface to 300 hPa. Figure 1.8c shows the 500 hPa geopotential height contours and isotherms. Noteworthy is the core of coldest temperatures coinciding with the height minimum at 500 hPa. The thermal structure of this cyclone is also illustrated in Fig. 1.9 (taken from Fig. 10.8 of Palmén and Newton 1969), for a cross section along line a-a' in Fig.1.8c. Palmén and Newton refer to the lowered tropopause (drop in height values), shown by a dark solid line, as a "tropopause funnel", located near the center of the cyclone. Below this tropopause funnel the thermal symmetry is clearly shown by depressed isotherms surrounded by higher values of temperature and potential temperature, depicting the cold-core structure of cutoff cyclones. Another way of explaining cutoff cyclone symmetry is by showing potential vorticity overlayed on potential temperature surfaces. Hoskins et al. (1985) showed that cutoff cyclones generally consist of an isolated area of anomalously positive (high) potential vorticity with upward sloping isentropes, similar to the "tropopause funnel" shape shown in Fig. 1.9. Figure 1.10 (taken from Fig. 1.8 of Thorpe 1986), is a clear portrayal of this characteristic cutoff cyclone structure.

1.2.4 Cyclone Climatologies

1.2.4a Surface Cyclones

In earlier studies, cyclones not originating over the tropics, which also ran along the polar jet stream, were considered extratropical cyclones. Studies on the behavior of these extratropical cyclones were first conducted in 1950's as a result of increased use of observational networks such as the radiosonde in the late 1940's. Most of these studies evolved from a comprehensive climatological study of extratropical cyclones in the Northern Hemisphere done by Klein (1957). Klein found areas of maximized surface cyclone occurrence by using the US Weather Bureau [presently the National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS)] surface maps. These areas included: 1) the North Pacific from Japan to the Gulf of Alaska; 2) from central Canada through the Great Lakes region into the northeast US; 3) from the east coast of the US to the north central Atlantic; and 4) across southern Europe and the Mediterranean Basin.

The findings of Klein (1957) were extended as datasets grew and became more comprehensive. More recent researchers began to focus on the frequency and distribution of surface cyclones in North America. Ziska and Smith (1980) and Whittaker and Horn (1981) used the then National Meteorological Center (NMC), presently the National Centers for Environmental Prediction (NCEP), analyses, along with the NOAA Daily Weather Map Series (DWMS) and Mariners Weather Log to document areas of maximum cyclone activity. Their findings paralleled the findings of Klein (1957) very well over North America, especially near central Canada, the Great Lakes, and the east coast of the US. Even more studies conducted over the US were completed as time and data progressed. For example, Hosler and Gamage (1956), examined surface cyclones over the continental US from 1905-1954. Colucci (1976)

focused on winter cyclone frequencies over the eastern US from 1964-1973, where as Hayden (1981) looked at spatial and temporal variations in cyclone frequencies over the entire eastern North America and North Atlantic. All of these studies confirm the findings of Klein (1957) and document the areas of frequent cyclogenesis during the warm season. For this research, the main areas discussed are within the northeastern US including the Great Lakes.

The NCEP/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis dataset (Kalnay et al. 1996; Kistler et al 2001) and the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis are recent, larger, and more comprehensive datasets. These allow for more thorough studies of cyclone behavior on a global scale. The features of cool season surface cyclones (at multiple levels), were then studied by Hoskins and Hodges (2002). These features included density, track density, genesis (lysis) density, mean growth rate and mean intensity. These studies also agree with the mean sea-level pressure (MSLP) anomalies (e.g., cyclonic circulation) presented by Klein (1957).

1.2.4b Middle- and Upper- Tropospheric Cyclones

Compared to the number of studies made on surface cyclones, the number of studies performed on closed lows at 500 hPa is far less. Parker et al. (1989) and Bell and Bosart (1993) are the first two comprehensive analyses in the meteorological literature that illustrate the linkage between cyclones at the surface and cutoff cyclones at 500 hPa. Parker et al. (1989) used the then NMC gridded 500 hPa height datasets to create a 36-

year (1950-1985) climatology of 500 hPa cutoff cyclones for the western half of the Northern Hemisphere. Bell and Bosart (1993) also used the NMC dataset and developed an objective method of detecting cutoffs by isolating grid points corresponding to relative geopotential height minima. Both of these studies found four common areas of maximized warm season cutoff cyclone frequency including: 1) across the north Pacific and Gulf of Alaska (most common in earlier warm season months); 2) the southwest US; 3) north-central Canada in the vicinity of the Hudson Bay; and 4) and the northwest Atlantic. Bell and Bosart (1993) also found that cutoff (closed) cyclones are commonly found poleward of the mean belt of the westerlies.

1.2.5 Cyclone Tracking

Due to the absence of large datasets and sufficient computer power, early cyclone tracking techniques were mainly subjective. Bowie and Weightman (1914), Klein (1957), and Reitan (1974) conducted the first studies of cyclone tracking based on synoptic reasoning. Once observational datasets became larger and more complete, subjective cyclone analyses gave way to more innovative, objective cyclone analysis. Alpert et al. (1990) was one of the first to take advantage of the increase in datasets by executing a study of surface cyclones in the Mediterranean. Hoskins and Hodges (2002) concentrated on cyclones at multiple levels for the entire Northern Hemisphere. Konig et al. (1993), Hodges (1994), Sinclair (1997), Blender and Schubert (2000), and Geng and Sugi (2001) all centered their cyclone tracking studies on North America. Collectively, the results from their studies can be summarized in the following statement: Surface

cyclones generally follow three main tracks across North America: 1) northeastward moving cyclones that develop along the east coast of North America; 2) northeastward moving systems that develop over the southwest US; and 3) east-southeastward moving systems that develop over central and western Canada. Along with cyclone tracking, Geng and Sugi (2001) examined other behaviors of cyclones such as cyclone intensity, speed of movement, and deepening rates.

Even more recently, studies on middle- and upper- tropospheric cyclone tracks (i.e., 500 hPa cutoff cyclones) have been conducted (e.g., Smith 2003; Novak et al. 2002). Both developed an subjective tracking scheme, using 500 hPa geopotential heights from 1980-2000, to identify "cutoff cyclone freeways." Smith (2003) identified five main cutoff cyclone paths for the cold season months (October to April) and Novak et al. (2002) found five main paths for the warm season months (May through September). Warm season 500 hPa cutoff cyclone paths included: 1) the Southwest Track, originating in the southern Plains extending through Maine; 2) the Zonal Track, which forms in the central Plains and tracks through the mid-Atlantic states; 3) the Atlantic/Coastal Track, running along the eastern coast of the US; 4) the Great Lakes Track, extending from central Canada, across the Great Lakes, through northern New England; and 5) the Northwest Track, which originates over the Hudson Bay (refer to Fig. 1.1 taken from Novak et al. 2002).

1.2.6 Precipitation in Cutoff Cyclones

Prior to the 1960's, there was little understanding of how precipitation could be tied to upper-level systems due to a lack of real-time upper-air charts (Jorgensen 1963). Therefore, it was assumed that precipitation was generally associated with surface cyclones (i.e., fronts or baroclinic zones). A study of the precipitation distribution prepared by Hsieh (1949) illustrated how cutoff cyclones can be tied to precipitation events at the surface [Fig 1.11, taken from Fig. 13 of Hsieh (1949)]. Hsieh clearly explained how the precipitation distribution corresponds well with the general distribution of upper-level divergence described in Palmén and Newton (1969) (section 1.2.3). Precipitation fields are shown to be asymmetric with the heavier precipitation falling in the eastern portion of the system under the area of stronger upper-level divergence. However, the thermal and height fields appear to be symmetric. Jorgenson (1963) also dealt with the lack of upper-air data by studying 700 hPa lows over the Intermountain West (Jorgenson et al. 1967). He showed that the southeast quadrant of the cyclone was where precipitation occurred most frequently. This idea was analyzed further by Klein et al. (1968) and Korte et al. (1972), who showed that the maximum frequency of measurable precipitation in 500 hPa lows to be approximately 2.5° south and 3.5° east of the center of the upper-level low [see Fig. 1.12 taken from Fig. 8 of Klein] et al. (1968)]. The frequency of precipitation associated with cutoff cyclones was the next area of research performed. Klein et al. (1968) and Korte et al. (1972) found that precipitation occurs with approximately 50% of 500 hPa cutoff cyclones over the western plateau states. A recent objective study by Atallah and Aiyyer (2002) showed that cutoff cyclones produce about 30% of the annual precipitation in the northeastern US.

1.3 Study Goals

It must be stressed again that forecasting heavy precipitation associated with warm season cutoff cyclones (closed lows) can be very challenging. The diverse precipitation patterns produced by cutoff cyclones can lead to many unforecasted flash floods, a particularly difficult problem in the northeastern US. Cutoff cyclones can also produce severe weather, and there needs to be an improvement in the forecaster's ability to recognize when a cutoff cyclone is capable of producing such events. Therefore, the main goals of this thesis are: 1) to identify and explore the climatological behavior of cutoff cyclone tracks as identified in the composites developed by Matt Novak et al. (2002); and 3) to conduct warm season cutoff cyclone case studies which identify diverse precipitation signatures. As a result of completing these goals, it is intended that forecasters will have better tools and improved guidance to aid them in forecasting precipitation associated with cutoff cyclones.

The first part of this study involves the development of a precipitation distribution climatology from 1948-1998, centered over the northeastern US. This is a monthly distribution for warm season months, June to September. The percentage of monthly precipitation due to cutoff cyclones as opposed to any other mesoscale or synoptic feature is also calculated.

The second part of this study uses a subjective hand analysis to create an 18-year climatology of monthly tracks. This hand analysis evolves from plotting 500 hPa geopotential heights at 30 m intervals and yields a series of favored monthly cutoff

cyclone paths that cutoff cyclones follow. This analysis is also presented for the warm season months June through September and illustrates where cutoff cyclones track in the northeastern US.

The third part of this study involves the examination of the weather events of two case studies that demonstrate the severity and intensity that can accompany cutoff cyclones. Both cases involve closed lows, which produced heavy precipitation and flash floods across much of the Northeast. This finding again emphasizes the importance of the need for improved precipitation forecasts when dealing with cutoff cyclones. Various mesoscale precipitation signatures are analyzed when developing composites for each case study.



Fig. 1.1. Five main tracks followed by 500 hPa cutoff cyclones during the warm season months (May-September) developed from a subjective tracking scheme. The dataset ranges from 1980-2000 for a total of 170 cutoff cyclones cases. Source: Novak et al. (2002).



Fig. 1.2. Schematic meridional cross section through an upper-level trough showing the profile of the polar air before and after the formation of a cutoff low. Source: Palmén (1949), Fig. 2.



Fig. 1.3. 500 hPa isotherms (dashed lines, contour interval 2°C), upper-front boundary (thick dashed line), and geopotential height (solid lines, contour interval 200 ft) for 03Z 7 Feb 1947. Source: Palmén and Newton (1969), their Fig. 10.1.



Fig. 1.4. Idealized sketches of the development of unstable waves at 500 hPa in association with the establishment of a blocking anticyclone at high latitudes and a cutoff cyclone at low latitudes. Warm air (hatched) is separated from cold air (cross-hatched) by frontal boundaries (dashed lines). Solid lines represent streamlines. Source: Berggren et al. (1949), Fig. 26.



Fig. 1.5a–e. Five characteristic types of disturbances resulting from the extreme growth of upper-level waves. Thick solid lines represent fronts. Streamlines in warm (cold) air are represented by solid (dashed) arrows. Source: Palmén and Newton (1969), Figs. 10.4 a–e.



Fig. 1.6 Sample 500 mb geopotential height analysis illustrating the objective method used to identify closed circulation centers. (a) Three sample radial arms to identify a 30 m closed contour around the cyclone center point A, indicating a geopotential height rise and closed circulation. (b) Same as in (a) except that heights along the dashed radial arm do not exceed 30 m higher than point A before decreasing; thus point A is an open circulation center. Source: Bell and Bosart (1989), Fig. 1.

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Fig. 1.7a-d. Total number of closed cyclone center genesis events in any $2^{\circ} \times 5^{\circ}$ latitudelongitude grid box for (a) winter, (b) spring, (c) summer, and (d) fall. The contour interval is 2. Source: Bell and Bosart (1989), Fig. 3.



Fig. 1.8. (a) surface, (b) 850 hPa, (c) 500 hPa, (d) 300 hPa for 1200 UTC 16 November 1959. In (a), temperatures are in °C; precipitation areas are hatched, with areas exceeding 1 mm/12 h cross-hatched. In other charts, isotherms are at 1°C intervals and height contours are at 40 m intervals. Thick lines in (c) and (d) are the "tropopause intersection." The path of the 500 hPa low center is shown in (a) with the arrowheads indicating its location at 0000 UTC on the dates given. Source: Palmén and Newton (1969), Fig. 10.7a–d.



Fig. 1.9. Vertical cross section along line a-a' in Fig. 1.8c, showing the tropopause (thick solid line), isotherms (dashed lines, contour interval 5°C), and isentropes (solid lines, contour interval 5 K). Source: Palmén and Newton (1969), Fig. 10.8.



Fig. 1.10. Vertical cross section of an idealized cold-core, upper-level cyclone. Shown are isotachs (v; solid lines, contour interval 3 m s⁻¹), isentropes (θ '; solid lines, contour interval 5 K), the tropopause (thick solid line), and the axis of symmetry (represented by the "0" label on the horizontal axis). Source: Thorpe (1986), Fig. 1.



Fig. 1.11. Schematic representation of precipitation relative to upper-level geopotential height contours (solid lines). Heavier precipitation hatched, lighter precipitation stippled. Source: Hsieh (1949), Fig. 13.



Fig. 1.12. Areas of maximum frequency of occurrence of measurable precipitation associated with the most intense (Class III) lows, centered at the origin for 850, 700, 500, and 300 hPa. Symmetrical circles represent idealized contours about the low center at any level. Source: Klein et al. (1968), Fig. 8.

2. Data and Methodology

2.1 Data Sources

2.1.1 Climatology and Tracking

Most of the research in this project made use of the National Centers for the Environmental Prediction (NCEP)/Climate Prediction Center (CPC) Unified Precipitation Dataset (UPD) (Higgins et al. 1996). This is a 51-year dataset (1 January 1948–31 December 1998) used mainly for the objective climatology of the study, though currently the dataset has become available for more recent years (extended through 31 December 2002). The UPD is derived from daily observations from 1200-1200 UTC. It is gridded into 0.25° latitude by 0.25° longitude boxes over the continental US. This dataset is derived from three different sources: National Climatic Data Center (NCDC) daily Co-op stations, CPC dataset (River Forecast Centers data and first- order stations), and daily accumulations from hourly precipitation dataset. The UPD is provided by the National Oceanic and Atmospheric Administration (NOAA)-Cooperative Institute for Research in Environmental Sciences (CIRES) Climate Diagnostics Center (CDC), Boulder Colorado.

The tracking segment of the climatology made use of the NCEP/National Center for Atmospheric Research (NCAR) reanalysis dataset (Kalnay et al. 1996; Kistler et al. 2002). This global dataset uses a 2.5° latitude-longitude grid and 6 h temporal resolution. Four times daily gridded 500 hPa geopotential height analyses (contoured at 30 m intervals) for the period 1 Jan 1980 to 31 Dec 1998 were used for the climatologies. These plots were used for the subjective hand analyses.

2.1.2 Case Study Analyses

The UPD was also used in the case study analyses to create 24, 48, and 72 h precipitation distribution plots. Locally archived NCEP Eta model gridded short-range analyses were used for the two cases studies (30 June-01 July 1998 and 03-05 July 1996). This dataset was available at 80 km resolution and used to produce horizontal maps. In order to examine cases in more detail, the 40 km Eta grids were also used in the analyses, when available. The archived National Weather Service (NWS) Automated Surface Observing System (ASOS) provided surface observations for the creation of surface potential temperature (θ) and mixing ratio (w) plots. Radar images for the 30 June 1 July 1998 case were obtained from NCAR (available at http://locust.mmm.ucar.edu/case-selection). Sounding data were also obtained from the University of Wyoming Web page (http://weather.uwyo.edu).

2.2 Methodology

2.2.1 Objective Climatology

The methodology used for developing a set of closed lows for the 51-year period is nearly identical to that of Smith (2003), Novak et al. (2002), and Fracasso et al. (2004), and is adapted from Bell and Bosart (1989). The objective procedure locates cutoff cyclones defined by at least one 30 m height rise in all directions from a grid point (as

discussed in chapter 1, Fig. 1.6). See Smith (2003, section 2.2.1) for a detailed explanation of how the program objectively determines a cutoff cyclone.

This study, along with the cool season study done by Fracasso (2004), uses only the cutoff cyclones bounded by the outer domain shown seen in Figure 2.1. The outer domain is bounded by 34°-53°N and 60°-91°W, which basically centers on the Northeast. Dates and locations of the cutoff cyclones were then catalogued. Another algorithm used both the catalogued dates and the UPD to distinguish whether or not there was precipitation at the grid points within the outer domain. The daily precipitation produced by a closed low within the domain was then calculated from 1200–1200 UTC. This precipitation amount was summed at each grid point for each day and thus divided by the number of days used in that month. After viewing the initial results, it was decided that only days with nonzero precipitation (i.e., 0.01" or more) would be counted (Fracasso, 2004). This decision helped account for the times when a cutoff located in the far corner of the specified outer domain and does not pass through the Northeast but produces precipitation that effects the Northeast. The obstacle in this case that one corner of the domain could have measurable precipitation while an opposite corner is free of precipitation. In other words, a cutoff in Tennessee could produce rain in southern Pennsylvania but not likely in Maine (Fracasso, 2004). Though virtually nonexistent after viewing the many precipitation vs. cutoff occurrence maps, this procedure eliminated the possibility of counting a "dry" cutoff cyclone. The resultant average daily precipitation maps for the warm season months (June through September) are shown in Chapter 3.

The monthly percentage of precipitation associated with cutoff cyclones was also calculated. This calculation was done using the same outer domain and monthly count of lows summed up over the period in conjunction with the summed total precipitation and comparing it to climatology. These maps of the percent of climatology of precipitation associated with cutoff cyclones are also presented in Chapter 3.

2.2.2 Subjective Tracking of Cutoff Cyclones

Novak et al. (2002) and Smith (2003) performed a much more fine-scale objective approach to track cutoff cyclones (see Smith 2003, section 2.2.2). In this study, as well as the study done by Fracasso (2004), a subjective hand analysis of cutoff cyclone tracks was completed. Due to the large number of cutoff cyclones in the original set, a 19-year (1980–1998) subset was used to balance research time constraints. Four times daily 500 hPa geopotential height maps were produced for all days in the warm season over the 19year period (9,120 maps). Tracks of each cutoff within the outer domain were then plotted by hand for each month. Generally, no more than two or three years of cutoff cyclone tracks were plotted on a single map, thus keeping the tracks easily visible. This subjective system of following cutoff cyclone tracks allowed for initially closed cutoffs to open and then re-close. Cutoff systems following this evolution were considered one entity, a progression ignored in Bell and Bosart (1989), Novak et al. (2002), and Smith (2003). In order to locate common monthly tracks which cutoff cyclones follow, the individually hand plotted tracks were traced with a fine point pen onto tracing paper. This procedure allowed all or half of the cutoff tracks (depending on how many there

were that month over the 19 years) to be fit on a single map. Darkened areas were indicators of a common cutoff cyclone track. There were several tracks identified for each month and those results will also be shown in chapter 3.

2.2.3 Case Studies

A set of four case studies involving significant cutoff cyclones that impacted the Northeast was provided by focal points, Tom Wasula and Ken LaPenta of the National Weather Service Forecast Office in Albany, New York. Two of these cases were chosen for further analysis based on their varying precipitation distributions, differences in origin and track, as well as the abundance or lack of severe weather events. As discussed earlier, two cutoff cyclones passed through the Northeast US (30 June–1 July 1998 and 3–5 July 1996). Precipitation amounts were under-forecasted in both cases, resulting in several unforecasted localized flash flooding events, a very dangerous situation. The following maps were produced for analyses of these case studies:

- 1) 24, 48, and 72 h precipitation distribution plots (from the UPD) to locate and track areas of heavy precipitation produced by the cutoff cyclone.
- 2) 1000 hPa heights and 1000-500 hPa thickness (ΔZ) to investigate the overall dynamics associated with surface cyclone development.
- 3) 850 hPa geopotential height and wind speeds to locate areas of strong jet dynamics, thus determining the mean wind flow with respect to varying terrain.
- 4) 700 hPa relative humidity and vertical motion (ω) to investigate the availability of lower-tropospheric moisture as well as areas of strong ascent.

- 5) 500 hPa geopotential height and absolute vorticity in order to examine the track and position of the cutoff cyclone as well as its vorticity lobes.
- 6) 200 and 250 hPa geopotential height and wind speeds to identify strong uppertropospheric jet dynamics.
- 7) Maps and analyses of surface potential temperature (θ), surface observations, and mixing ratio (w) for the northeast US, to locate any surface boundaries conducive for precipitation.
- Radar reflectivity to verify and document the onset of precipitation development and distribution.

The General Meteorological Package (GEMPAK) (e.g., desJardins et al. 1991), version 5.6a, was primarily used to produce most of aforementioned maps. Other key aspects of the cases were identified on hand-drawn maps.



Fig. 2.1: Outer domain used for tracking cutoff cyclones with associated precipitation which impacts the Northeast.

3. Results

3.1 Climatology

The algorithms discussed in Chapter 2 were applied to the CPC Unified Precipitation Dataset for the period 1 January 1948 through 31 December 1998 for a total of 51 years. Algorithms will also made use of the NCEP/NCAR reanalysis dataset for the same period. The focus of the climatology in this thesis will be on precipitation distribution and amount associated with cutoff cyclones for the warm season (defined as the months June through September). The cool season portion of this climatology will not be presented in this thesis; refer to Fracasso (2004). The climatology will focus on 500 hPa cutoff cyclones that impact the Northeast US.

3.1.1 Average Daily Precipitation

The approximate amount of precipitation per day per month associated with a cutoff cyclone in the Northeast is shown in Figs. 3.1-3.4. Precipitation is measured in inches/day as well as mm/day. Figure 3.1 shows the daily average amount of precipitation, that can occur when a cutoff cyclone is present for the month of June. For most of the outer domain, cutoff cyclones produce approximately .12 inches or greater of precipitation per day in the month of June. Areas in southwestern New York and central Pennsylvania can receive greater than .20 inches of precipitation in one day when a cutoff cyclone is present. Areas along the US/Canada border can receive between .12 and .16 inches/day. There are some obvious orographic signals in New Hampshire (Mt.

Washington area) and southeastern New York (Catskill Mountains), which enhance precipitation to over .20 inches/day. The maximum value for June is slightly less than .28 inches/day and is located near Mt. Washington.

Figure 3.2 shows the daily average amount of precipitation for the month of July. Again, cutoff cyclones generally produce greater than .12 inches of precipitation per day in the month of July. Areas of greater than .20 inches of precipitation shift eastward to eastern Pennsylvania, New Jersey, southeastern New York, and Connecticut. However, there is also an area of less than .16 inches of precipitation along the Atlantic Coast from central Maine through Massachusetts. The orographic signal of Mt. Washington is again the location of the maximum value of approximately .26 inches/day. There are also a few more small areas of greater then .20 inches/day located in western Massachusetts, Maine and northern Vermont. The areas with precipitation values between .12 and .16 inches/day along the US/Canada border have extended southward into the Finger Lakes Region of New York, as well as along the Champlain valuey.

The daily average precipitation for August is shown in Fig. 3.3. August has the highest values of precipitation of all four warm season months. Parts of eastern Pennsylvania and central New Jersey can receive over .24 inches/day from cutoff cyclones. Areas of greater than .20 inches/day are more widespread in the northern New England states compared to June and July. The southern tier of western New York and northwestern Pennsylvania can also have greater than .20 inches of precipitation attributed to cutoff cyclones. Orographic signatures appear from the Adirondack Mountains of upstate New York and the Green Mountains in Vermont. The dip of less than .16 inches in central New York is still apparent. Overall precipitation amounts in

the majority of Maine have decreased as well. However, there has been an increase in precipitation associated with cutoff cyclones along the Atlantic Coast.

Figure 3.4 shows the daily average amount of precipitation for the month of September. September has the overall largest extent of heavier precipitation. Areas of greater than .20 inches/day cover most of Pennsylvania and spread westward into southwestern NY. However, areas of greater than .24 inches/day are not as widespread as in August. Precipitation amounts in the Finger Lakes region have increased in central New York, as well as an area of greater than .20 inches/day east of Lake Ontario. Heavier precipitation extends along the Atlantic Coast northward into Maine. All of Connecticut, Rhode Island, and most of Massachusetts receive greater than .20 inches of precipitation per day from cutoff cyclones. Orographic signatures are not as pronounced in September as the previous months.

Overall, August has the most intense daily precipitation associated with cutoff cyclones and July has the least. September has the most widespread distribution of heavy precipitation and there is a general eastward shift of heavy precipitation from June to September. Daily precipitation associated with cutoff cyclones is most intense and widespread along the Atlantic Coast for most warm season months.

3.1.2 Percent of Climatology Precipitation

The next step in this study for developing a cutoff cyclone precipitation distribution climatology was to find out the monthly percentage of precipitation associated with cutoff cyclones. Figures 3.5-3.8 show the percentage of precipitation

produced by cutoff cyclones for the warm season centered on the Northeast. The color bar indicates percent of climatology values. Figure 3.5 illustrates percent of precipitation due to 500 hPa cutoff lows for the month of June. Percentages are generally greater than 35% for the entire Northeast. Larger percentages of greater then 45% run along the Atlantic Coast from Connecticut to Maine. Almost all of Massachusetts and Rhode Island, along with portions of Pennsylvania, Maine, and New Hampshire, receive over half of their June precipitation from cutoff cyclones. New Jersey receives approximately 45% of its June precipitation from cutoff cyclones. June percentages in western and central New York are generally not as high.

Precipitation percentages for the month of July are shown in Fig. 3.6. In most areas of the Northeast, percentages drop by almost ten percent in July. Western to central New York and almost all of Pennsylvania have less than 35% of July precipitation attributed to 500 hPa cutoff cyclones. There are areas in central Pennsylvania and extreme southwestern New York that receive less than 30%. Areas of greater than 45% have almost completely disappeared from the Northeast. Most of Maine receives a little over 40% of its July precipitation from cutoff cyclones.

Precipitation percentages are even lower in the month of August as shown in Fig. 3.7. In August, most of the Northeast receives precipitation from systems other than cutoff cyclones. Most of the Northeast receives less than 35% of its August precipitation from 500 hPa cutoff cyclones. Only a few small portions of Vermont, New Hampshire, and Maine receive more than 35% of precipitation from cutoff cyclones.

In September, percentages rise slightly as shown in Fig. 3.8. Most of western and central New York receives more than 35% of precipitation from cutoff cyclones.
Between central New York and Maine, there is a decrease in percentages of less than 35%. Central Maine and a portion of central Pennsylvania receive more than 40% of precipitation from cutoff cyclones for the month of September.

The highest percentage of precipitation due to warm season 500 hPa cutoff cyclones occurs in the month of June and the lowest in the month of August. The months of July and September almost appear to be a reversal of each other. Where there are higher precipitation percentages in July, there are lower percentages in September. The highest percentages are generally located near or on the Atlantic Coast. On average, during the warm season, the Northeast receives approximately 40% of its precipitation from 500 hPa cutoff cyclones. Results from the precipitation climatology can be connected to the results from the precipitation distribution climatology; however, that aspect will be discussed later in Chapter 5.

3.1.3 Monthly Cutoff Cyclone Tracks

The subjective hand analysis used to plot all of the closed lows from the period 1980 through 1998 uncovered over 150 cutoff cyclones. Cyclones that impacted the Northeast were plotted at 6 h intervals. As mentioned before, a cutoff cyclone was defined by at least one 30 m height rise in all directions from a grid point (as discussed in chapter 1, Fig. 1.6). Once all of the tracks of these cutoff cyclones were plotted, they were overlayed on top of each other. Through an "eyeball" examination, the most common paths, or darkest lines were traced onto another map of the Northeast. These dark areas indicated locations of common 500 hPa cutoff cyclone tracks for each month.

Figure 3.9 displays the most common warm season monthly tracks followed by cutoff cyclones. There are several common tracks followed for each warm season month. Tracks lined in red indicate popular tracks during the month of June. Most of the June tracks except for one are located north of the Great Lakes. July tracks are indicated in green and are also located mainly above the Great Lakes. Both June and July tracks are most closely associated with the aforementioned Great Lakes track and Hudson Bay/Northwest track (refer to Fig. 1.1 in Chapter 1). There is a general southward shift of the August and September tracks shown in blue and black lines, respectively. This shift agrees with the findings of Novak et al. (2002) in that later in the season, cutoff lows tend to follow the Zonal track and the Southwest track. In September, there is a common track along the Atlantic Coast, which corresponds to the Atlantic Coastal track in Fig. 1.1).



Fig. 3.1. Northeastern US composite precipitation for days with 500 hPa cutoff cyclones, for the month of June (1948–1998). Precipitation values are in inches/day (top of color bar) and mm/day (bottom of color bar).



Fig. 3.2. As in Fig. 3.1 but for the month of July.



Fig. 3.3. As in Fig. 3.1 but for the month of August.



Fig. 3.4. As in Fig. 3.1 but for the month of September.



Fig. 3.5. Percent of climatology precipitation associated with 500 hPa cutoff cyclones for the month of June (1948–1998). Color bar values in %.



Fig. 3.6. As in Fig. 3.5 but for the month of July.



Fig. 3.7. As in Fig. 3.5 but for the month of August.



Fig. 3.8. As in Fig. 3.5 but for the month of September.



Fig. 3.9. Common monthly 500 hPa cutoff cyclone tracks for the period 1980–1998. Tracks in red are for the month of June, green for July, blue for August, and black for September.

4. Case Studies

4.1 Overview of Both Case Studies

As stated in section 1.3, two case studies were chosen for analysis based on their various precipitation distributions and accompanying severe weather. Both of these cutoff cyclone cases (30 June 1998 and 3 July 1996) created complex forecast situations, challenges, including several flash flood events across the Northeast. However, these cutoff cyclones differ in type of track and origin. Figure 4.1 shows a 48 h precipitation plot created from the UPD ending 1200 UTC 1 July 1998. The track of the 500 hPa cutoff low is overlayed on top of the precipitation data with each 12 h position plotted. The track of this cutoff low followed the Great Lakes track (Novak et al. 2002), originating west of Lake Superior. The cutoff low crossed over the Great Lakes by 1200 UTC 30 June 1998 and was located north of Lake Ontario. It continued its northeastward path along the St. Lawrence River Valley and through Maine. Several flash floods were produced within the eastern extent of a large swath of precipitation, which covered the New York and Pennsylvania state borders. The maximum precipitation of approximately 3.58 inches was located in Woonsocket, Rhode Island

Severe weather reports for this case are presented in Fig. 4.2, courtesy of the Storm Prediction Center (SPC). Figure 4.2 shows the amount and locations of hail, wind, and tornado reports for the period 1200 UTC 29 June 1998 through 0000 UTC 3 July 1998. However, the majority of the reports were from the beginning of the period until 1200 UTC 1 July 1998. This plot is divided into two regions in order to separate severe weather reports from two different systems that occurred over the five day period.

Region 1 indicates where there were severe weather reports due to Midwest nocturnal convection between 0000 UTC and 0900 UTC 30 June 1998. Region 2 shows severe weather reports associated with a prefrontal trough and warm sector, which will be discussed later in the analysis. The important aspect to notice in Fig. 4.2, is the number of severe weather reports that are associated with the cutoff cyclone, including three tornado reports on Long Island.

Figure 4.3 shows the same UPD plot as Fig. 4.1 but for the second case and is a 72 h plot ending 1200 UTC 5 July 1996. This cutoff low originated over Hudson Bay and followed the Hudson Bay/Northwest cutoff cyclone track (Novak et al. 2002). In this case, most of the heavy precipitation was located to the left of track with flash floods reported in northeastern New York and Maine. There were very few severe weather reports with this case. The main forecast issue was the intense long-term precipitation following the track of the 500 hPa cutoff cyclone.

4.2 Analysis of the 30 June-1 July 1998 Case Study

4.2.1 Discussion of Location of Heavy Precipitation

As discussed in section 4.1, a 500 hPa cutoff cyclone is responsible for the expansive swath of precipitation, which fell over the New York and Pennsylvania State borders (Fig. 4.1) from 30 June through 1 July 1998. Figures 4.4–4.7 are a series of radar images covering the period 0800 UTC to 2330 UTC on 30 June 1998, courtesy of NCAR (available at http://locust.mmm.ucar.edu/case-selection). These four radar composites

show the resulting precipitation associated with this cutoff cyclone that affects the Northeast. Overlayed on these images are the locations of the surface low-pressure system(s) and 500 hPa absolute vorticity maximum(a). The impacts of these features will be discussed later in the case study analysis. Figure 4.4 shows remnants of the antecedent nocturnal convective system located over the Ohio and Tennessee Valleys that provides a moisture source for the aforementioned swath of precipitation over the New York/Pennsylvania border. This large swath of precipitation has only begun to develop in Fig. 4.4. By 1300 UTC (Fig. 4.5), the swath is fully developed and has moved into most of New England. The image shows heavy precipitation (composite values of greater than 50 dBZ) concentrated from central New York eastward, along the New York/Pennsylvania border, to off the coast of Massachusetts.

Figures 4.6 and 4.7 illustrate the progression of that swath off the Atlantic Coast. The severe weather from this cutoff system, which impacts the Northeast, starts to develop in these images. At 1830 UTC (Fig. 4.6), there is a line of strong convection extending from western Pennsylvania through central New York, which strengthens as it moves across the Northeast. Figure 4.7 is a representative radar image of the convection occurring just prior to the three Long Island tornado reports. Notable are the greater than 60 dBZ composite values located just west of Long Island. These four radar images will be used as references for the location of precipitation throughout the case study analysis.

4.2.2 Atmospheric Conditions and Jet Dynamics

In order to examine the synoptic and mesoscale features of these cutoff cyclone cases, maps of the lower, middle, and upper levels of the troposphere are presented for the northeastern US. The analyses use data taken from Eta model reanalysis (80 km resolution, and 40 km resolution when available) archived at the University of Albany, State University of New York. Figures 4.8–4.10 are four-panel figures that illustrate data from four levels of the troposphere. Figure 4.8a-d is for 0000 UTC 30 June 1998, which is 12 h prior to the onset of the heavy line of precipitation that fell along the New York and Pennsylvania state borders. Displayed in Fig. 4.8a is the 1000 hPa geopotential heights at 30 m intervals and 1000-500 hPa thickness at 6 decameter (dam) intervals. Inspection of this figure reveals that the surface low pressure system has not yet become fully organized and is located well north of New York State. This figure also shows how the Bermuda high has set up and is drawing ample moisture from the Gulf Stream, later illustrated by 700 hPa relative humidity fields. The 1000-500 hPa thickness pattern shows warm air advection located over the Central Plains and also just off the New England coast. There is also no strong low-level jet development (Fig. 4.8b) as evident in the 850 hPa geopotential heights (shown at 20 m intervals) and isotachs (wind speeds shaded for $> 14 \text{ m s}^{-1}$). The 500 hPa geopotential heights (shown at 6 dam intervals) and absolute vorticity (shaded for > $12 \times 10^{-5} \text{ s}^{-1}$), displayed in Fig. 4.8c, show that the upper level trough has not yet cutoff. Figure 4.8d includes 250 hPa geopotential heights (shown at 12 dam intervals) and isotachs (wind speeds shaded for $> 30 \text{ m s}^{-1}$). The isotachs in Fig. 4.8d show that there is a strong upper-level jet approaching the Northeast with wind speeds greater than 65 m s⁻¹. Portions of upstate New York and New England will be on the cyclonic exit or left-front quadrant of the upper-level jet.

The same four-panel plot (using the same graphics and intervals) is shown for 1200 UTC 30 June 1998 in Figs. 4.9a-d. This is approximately the same time as the heavy precipitation development that occurs over the New York/Pennsylvania border (refer to radar image, Fig. 4.5). Figure 4.9a shows that the surface low-pressure system, now centered just north of Quebec, has strengthened and organized slightly. The 1000– 500 hPa thickness shows a strengthening thermal gradient, indicating weak frontogenesis, with warm air being advected into eastern New York and New England. This weak warm air advection helps generate the heavy precipitation over the New York/Pennsylvania border as well as produce the lines of severe convection that occur later in the day. More importantly, there has been a development of a strong low-level (850 hPa) jet south of Pennsylvania with wind speeds in excess of 23 m s⁻¹ (Fig. 4.9b) on the equatorward side of the 850 hPa cutoff low. This low-level jet works in conjunction with the upper-level (200 hPa) anticyclonic jet exit region (or left front quadrant), (Fig. 4.9d) to produce the corridor of heaviest precipitation along the New York/Pennsylvania border and east-to-southeast New England (refer to radar image, Fig. 4.5). Figure 4.9c shows that the 500 hPa trough has taken a positive tilt and a large vorticity lobe has formed on the equatorward side of the trough.

By 0000 UTC, 1 July 1998, most of the remaining convective precipitation is located over the New England coast (refer to radar image, Fig. 4.7). Figures 4.10a–d are plots from 0000 UTC 1 July 1998. The surface low-pressure system is now centered over Vermont (Fig. 4.10a) and the 850 hPa jet has wrapped around to the eastern side (off the North Atlantic Coast) of the corresponding 850 hPa cutoff cyclone (Fig. 4.10b). At 500 hPa, the now neutral trough is about to cut off (Fig. 4.10c) and the 200 hPa jet has drifted southward (Fig. 4.10d).

Dynamical forcing is evident from the strong jet structures but there is also strong 700 hPa ascent. Figures 4.11–4.13 are used to locate areas of ample low-level moisture with 700 hPa relative humidity (areas indicated by RH values > 70%) and omega to identify areas of strong vertical moisture transport. Figure 4.11, from 0000 UTC 30 June 1998, shows ample moisture (originating from the Gulf Stream) and strong ascent in the same vicinity as the nocturnal convection that preceded the heavy precipitation event in the Northeast. Ascent values at 700 hPa of less than -10×10^{-3} hPa s⁻¹ are found near Indiana where the war air seen in Fig. 4.8a is being lifted vertically beneath the equatorward jet entrance region seen in Fig. 4.8d. This area again is the moisture source for the large swath of precipitation that falls near the New York/Pennsylvania border. By 1200 UTC (Fig. 4.12), this region of ample moisture has progressed northward. The large area of RH values > 70% is oriented northwest to southeast over the Northeast and coincides with strong 700 hPa ascent values in central New York and New England. Figure 4.13 is for 0000 UTC 1 July 1998 and illustrates that the strongest 700 hPa ascent values are off the coast of Maine; however a lot of moisture still remains in the Northeast.

4.2.3 Pivoting Trough Axis and Rotating Vorticity Maxima

In order to examine the position, structure, and orientation of the cutoff cyclone and its vorticity lobes in closer detail, Figs. 4.14–4.17 show the 500 hPa geopotential height (shown at 3 dam intervals) and absolute vorticity (shaded for values greater than $12 \times 10^{-5} \text{ s}^{-1}$) centered over the Great Lakes. In these figures, individual vorticity maxima are labeled A and B (if more than one) in order to follow their progression. Figure 4.14 is from 0000 UTC 30 June 1998 and has the 500 hPa cutoff cyclone located just north of Lake Huron with a 561 dam closed contour. The 500 hPa flow is generally zonal despite a short wave with associated vorticity lobe over the Indiana/Illinois border. This short wave and vorticity lobe are the features associated with the nocturnal convection over the Midwest (region 1 of Fig.4.2). The vorticity maxima labeled A in Fig. 4.14 indicates the first lobe that will begin to rotate around the 500 hPa cutoff cyclone.

By 1200 UTC 30 June (Fig. 4.15), the 500 hPa geopotential height pattern is in the form of a positively tilted trough with strong vorticity maximum A (having values greater than $28 \times 10^{-5} \text{ s}^{-1}$) located at the western base of the trough. Lobe A has begun to interact with vorticity located over the Illinois/Indiana border, which has now grown. Also in Fig. 4.15 is a strong vorticity maxima labeled B that has formed just west of the closed 555 dam contour, well north of the Great Lakes. Lobes A and B will begin to rotate around the pivoting cutoff cyclone as shown in Figs. 4.16–4.17. Figure 4.16, for 0000 UTC 1 July (at the height of the severe weather) shows that the 500 hPa cutoff cyclone has deepened as indicated by the smaller closed 555 dam contour that is centered north of Lake Ontario. Vorticity lobe A has also strengthened with maximum vorticity values now greater than 24 x 10^{-5} s^{-1} . At this point, the trough still maintains a slightly positive tilt. By 1200 UTC 1 July 1998 (Fig. 4.17), the trough has a negative tilt and the two vorticity lobes are located east-west of each other. Vorticity lobe B is the stronger of the two and is on the western side of the cutoff cyclone. Precipitation activity in the Northeast is basically concentrated in Maine as the cutoff continues its northeastward path.

Referring back to the radar images presented in section 4.2.1, it can be shown that vorticity maxima rotating around a cutoff cyclone can play a large role in modulating the precipitation distribution. The 500 hPa vorticity maxima are overlayed on the radar images in red and are numbered. The radar image, Fig. 4.5, shows two vorticity maxima closely associated with Fig. 4.15. As the vorticity maximum southeast of Lake Michigan (V2) rotates, noticeable are the lines of convection that subsequently develop northeast of the Ohio Valley (radar image, Fig. 4.6). The vorticity maximum act to enhance this precipitation and drive it eastward into New England (Fig. 4.7).

4.2.4 Surface Conditions

In order to further understand the development of the New York/Pennsylvania heavy precipitation feature, there needs to be a search for any baroclinic boundaries near the surface. Thus, many hand analyses were made and examined using surface observations. Figure 4.18 shows sea level pressure contoured every 2 hPa for 1200 UTC 30 June 1998. During this time, the large swath of precipitation over the New York/Pennsylvania border is almost fully developed (Fig. 4.5). This analysis illustrates a well defined surface trough located from eastern Pennsylvania southward into Virginia, just ahead of the area of heavy precipitation.

Figures 4.19 and 4.20 show surface potential temperature contours (°C) and mixing ratio contours (g kg⁻¹). At 1200 UTC 30 June 1998 (Fig. 4.19), there is the initial

development of a warm sector located in western Pennsylvania, indicated by the northern extent of the 24°C contour line. Mixing ratio lines indicate a weak moisture gradient extending from central Pennsylvania through Massachusetts. This gradient is the result of remnant moisture left from the nocturnal convection that occurred over the Ohio/Tennessee Valley the night before. A strong southwesterly flow over western Pennsylvania favors drawing more low-level moisture into the warm sector. Also, at 1800 UTC 30 June 1998 (Fig. 4.20), potential temperature values have increased to greater than 28°C over most of Pennsylvania, with warm air advection still present; however, in both Figs. 4.19 and 4.20, there is no strong baroclinic zone present.

4.2.5 Convection Over Long Island

As illustrated earlier, this cutoff cyclone had many severe weather events associated with it (Fig 4.2). Along with numerous wind and hail reports, there were three tornado reports from Long Island. Most of this severe weather occurred after the large swath of precipitation had passed and were the result of several lines of convection forming around 1800 UTC (Fig 4.6). Figure 4.21 is a sounding taken at Pittsburgh, PA, at 1200 UTC 30 June 1998. This sounding is representative of the conditions for the large swath of precipitation. Notable is the extent of the low-level moisture along with the strong low-level jet (at 850 hPa there are wind speeds of approximately 24 m s⁻¹). There is also a strong upper-level jet at 200 hPa with wind speeds of 45 m s⁻¹. At this time however, severe weather was limited as indicated by a low value (only 250 J kg⁻¹) of

Convective Available Potential Energy (CAPE) and by a capping inversion at 800 hPa. Diurnal heating is limited by low-level clouds at approximately 1–2 km.

Conditions favorable for tornadic situations are more evident in the sounding taken from Upton, NY, at 0000 UTC 1 July 1998 (Fig. 4.22). In this sounding, taken just prior to the arrival of the lines of convection (Fig. 4.7), CAPE values have increased to almost 1000 J kg⁻¹. There is decent low-level shear as indicated by the 0–6 km wind direction veering from southerly to more southwesterly. The upper-level jet (200 hPa) seen in the Pittsburgh sounding (Fig. 4.21) has strengthened with wind speeds of over 50 m s⁻¹. The same upper- and lower-level jet features are seen in each sounding but at different times and locations. Surface mixing ratio values are approximately 14 g kg⁻¹ with a dewpoint of around 19°C, indicating very moist air. Figure 4.22 also indicates very unstable conditions based on a Showalter index (SI) of –4.6 and a lifted index (LI) of –3.8. There is also a high probability of thunderstorms as indicated by the K-index of approximately 40. Also, the Bulk Richardson number is 16.8, which is in the supercell range (Glickman 2000).

All of these features contribute to a very unstable environment over Long Island, NY. With abundant low-level moisture seen in Fig. 4.12 and CAPE values of around 1000 J kg⁻¹, the unstable warm air will ascend quickly (as seen by the strong 700 hPa ascent over Long Island, NY in Fig, 4.12). The combination of moderate CAPE values, adequate moisture, vigorous 700 hPa ascent, and 0-6 km shear values supportive of supercells, suggests the possibility for tornadic conditions.

4.3 Analysis of the 3-5 July 1996 Case Study

4.3.1 Discussion of Location of Heavy Precipitation

As discussed in section 4.1, a 500 hPa cutoff cyclone is responsible for producing heavy precipitation in northeastern New York and Maine (Fig. 4.3) from 3 July through 5 July 1996. Figures 4.23–4.25 are similar to Fig. 4.3, but they are 24 h precipitation totals with the location of the 500 hPa center at the end of each 24 h period indicated by the red letter L. The cutoff cyclone in this case study originates near Hudson Bay and sweeps through the Northeast off the coast of Maine while most of the heaviest precipitation remains left of track. During the initial 24 h of this case, precipitation amounts do not exceed 2 inches in the Northeast, as shown by Fig. 4.23, which has 24 h precipitation ending at 1200 UTC 3 July 1996. At this time, the 500 hPa cutoff cyclone is located in southwestern New York. Heaviest areas of precipitation for the Northeast are located in southwestern Pennsylvania; however most of the Northeast, with the exception of northern Maine, received more than a quarter inch of rain.

Figure 4.24 shows 24 h precipitation ending at 1200 UTC 4 July 1996. The heaviest precipitation occurred overnight, has moved left of track, and is located in northern New York and eastern Maine. These regions received more than 1.50 inches of precipitation in a 24 h period with a section in Maine having greater than 2 inches. The center of the 500 hPa cutoff cyclone has tracked eastward and in Fig. 4.24 is located near southwestern Connecticut.

Figure 4.25 is the last of the 24 h precipitation plots for this case and ends on 1200 UTC 5 July 1996. At this time, all of the precipitation associated with the 500 hPa

cutoff cyclone is located in northern New York into Maine. Central and western New York along with most of Pennsylvania received no precipitation during the last 24 h. Heaviest amounts are located near the Adirondack Mountain region of New York with values exceeding 1.50 inches. The center of the 500 hPa cutoff low is located near New Brunswick. These three precipitation plots, as well as the 72 h precipitation plot (Fig. 4.3), will be used as references for the location of precipitation throughout this case study analysis.

4.3.2 Atmospheric Conditions and Jet Dynamics

As stated in section 4.2.2, in order to examine the synoptic and mesoscale features of this cutoff cyclone case, maps of the lower, middle, and upper levels of the troposphere are presented for the northeastern US. Figures 4.26–4.31 illustrate the same fields as shown in the four-panel plots used in the previous case study. Figures 4.26a–d and 4.27a–d are for times 0000 UTC and 1200 UTC, respectively, for 3 July 1996. At the beginning of this case, 0000 UTC 3 July 1996, the surface low has not yet become organized over the Northeast, and there is also no suggestion of any significant thermal advection as indicated by the 1000–500 hPa thickness pattern and the 1000 hPa geopotential heights (Fig. 4.26a). There is no low-level jet development over the Northeast at this time (Fig. 4.26b). Figure 4.26c shows that the 500 hPa trough, which is associated with the widespread precipitation occurring at this time (Fig. 4.23), has a large absolute vorticity maximum with values in excess of 18 x 10^{-5} s⁻¹ located at its equatorward side. The trough seen in this image has a positive tilt and is located over the

Great Lakes. At 200 hPa, there is a fairly strong upper-level jet with isotach values greater than 45 m s⁻¹ located over central Pennsylvania (Fig. 4.26d). Figure 4.27a–d shows the atmospheric conditions 12 h later. The surface low pressure system has become organized and is centered over central New York (Fig. 4.27a). At the base of the 850 hPa cyclone, the initial formation of a low-level jet is indicated by shaded isotachs of greater than 14 m s⁻¹ (Fig. 4.27b). The 500 hPa trough has deepened and turned to a more neutral tilt while moving farther towards the Northeast (Fig. 4.27c). The vorticity maxima located in this trough has expanded and taken on a more north–south orientation. Figure 4.27d shows lowering 200 hPa geopotential heights, as well as a southward progression of the upper-level jet, over the northeastern US.

Atmospheric conditions for 0000 UTC and 1200 UTC on 4 July 1996 are presented in Figs. 4.28a–d and 4.29a–d. The heaviest precipitation at this time is mainly located in northern New York and Maine (Fig. 4.24). The surface low pressure system has strengthened further and is centered just off the coast of Connecticut (Fig. 4.28a). The thermal gradient has strengthened with warm air being advected into northern New York and New England. Figure 4.28b is similar to Fig. 4.27b in that there is the potential for low-level jet development as the 850 hPa cyclone continues to deepen. The 500 hPa trough has a neutral tilt and is just about to cutoff. The associated vorticity maximum maintains its strength with shaded values of greater than 18 x 10^{-5} s⁻¹ (Fig. 4.28c). At 250 hPa, the upper-level cyclone has strengthened and the jet contains wind speeds of greater than 50 m s⁻¹ (Fig. 4.28d). Portions of the upper-level jet have moved into northern New England and Maine. Figures 4.28a–d illustrates the progression of these atmospheric dynamics 12 h later. The surface cyclone has moved slightly northward along the Atlantic Coast and is centered over Vermont (Fig. 4.29a). At this point, the surface low has fully strengthened as the 500 hPa system closes off. Warm air is being advected into Maine, which coincides with the precipitation maxima location seen in Fig.4.24. An 850 hPa jet located over Virginia has strengthened with wind speeds exceeding 20 m s⁻¹ (Fig. 4.29b). This jet will progress into Maine in the next 12 h (Fig. 4.30b). At 500 hPa, the cutoff cyclone has completely closed off and is located over New York State (Fig. 4.29c). The vorticity maximum is starting to separate into two large lobes. The portions of the 200 hPa jet that moved into Maine have progressed northward such that there is a cyclonic exit region located south of Maine and an anticyclonic entrance region in northern Maine (Fig. 4.29d).

The last 24 h of this case study are shown in Figs. 4.30a–d and 4.31a–d. By 1200 UTC 5 July 1996, precipitation is limited to upstate New York northeastward through Maine (Fig. 4.25). There is little or no precipitation occurring in the rest of the Northeast and 24 h precipitation amounts have decreased accordingly. At 0000 UTC 5 July 1996, the thermal gradient has moved off the Atlantic Coast as the surface low pressure system progresses slightly poleward (Fig. 4.30a). At 850 hPa, the larger portion of the low-level jet has also progressed off the coast; however a region of wind speeds greater than 17 m s⁻¹ remains over eastern New York (Fig. 4.30b). The 850 hPa cyclone located over Vermont begins to weaken as indicated by the surrounding increase in geopotential height contour values as well as an increase in the center value. Figure 4.30c shows the 500 hPa cutoff cyclone has turned to a slight negative tilt and is also centered over Vermont. Absolute vorticity maxima continue to rotate around the low as the system shifts northeastward. The upper-level (200 hPa) jet has increased in strength; however, it

has moved off the Atlantic Coast and only a small portion remains over eastern Maine (Fig. 4.30d). Atmospheric conditions for the last 12 h of this case study are illustrated in Fig. 4.31a–d. Figure 4.31a shows the surface low pressure system located mainly outside of the Northeast. The 850 hPa cyclone has continued to fill and there are now two low centers (Fig. 4.31b). Low-level jet dynamics are no longer present as the 850 hPa jet continues to move off the Atlantic Coast. Figure 4.31c shows that the 500 hPa cutoff cyclone has opened up and appears as a negatively tilted trough. The vorticity maximum maintains its strength and what used to appear as separate lobes is now elongated from southeast to northwest along the trough axis. The 200 hPa jet has also completely moved off the Atlantic Coast (Fig. 4.31d).

4.3.3 Discussion of 700 hPa Ascent and Associated Moisture

As also discussed in section 4.2.2, dynamical forcing is evident in the first case study as well as the second, but like the first case study there is also strong 700 hPa ascent. Figures 4.32–4.35 are used to locate areas of ample low-level moisture with 700 hPa relative humidity (areas indicated by RH values > 70%) and omega to identify areas of strong vertical moisture transport.

Figure 4.32, for 0600 UTC 3 July 1996, shows ample moisture and decent 700 hPa ascent just west of the Northeast. Strong 700 hPa ascent values of -6×10^{-3} hPa s⁻¹ are found near eastern Ohio and values of -4×10^{-3} hPa s⁻¹ are found north of Lake Ontario. These regions of ascent coincide with the left entrance region and the left exit region seen in the 200 hPa jet (see Fig. 4.26d). The initial feed of high moisture from the

Atlantic Ocean is slow moving and can be seen just off the Maryland coast. These are the same interior regions where there has been consistent precipitation for 24 h (Fig. 4.23). By 0000 UTC 4 July 1996, the moisture transport from the Atlantic has moved into much of New England into New York and southern Maine where RH values are greater than 90% (Fig. 4.33). Ascent values at 700 hPa strengthen to around -8×10^{-3} hPa s⁻¹ in New England and north of Vermont. Referring back to Fig. 4.28, the 250 hPa jet is situated over New England with a south-to-north orientation, thus bringing jet entrance and exit region dynamics into play. This is again the time where there are regions of heavy precipitation in northern New York and Maine (Fig. 4.24).

Twelve hours later, 1200 UTC 4 July 1996, large regions of abundant 700 hPa moisture have continued to drift northward (Fig. 4.34). The largest area of vertical lift is located northwest of Maine with 700 hPa ascent values around -10×10^{-3} hPa s⁻¹. There is still a lot of moisture feed from the Atlantic just off the coast of Maine that again justifies the precipitation maximum in Maine (Fig. 4.24). Figure 4.35, for 0000 UTC 5 July 1996, clearly illustrates the northeastward moisture transport that follows the progression of precipitation in Fig. 4.25.

4.3.4 Pivoting Trough Axis and Rotating Vorticity Maxima

As in section 4.2.3, the 500 hPa geopotential height (shown at 3 dam intervals) and absolute vorticity (shaded for values greater than $12 \times 10^{-5} \text{ s}^{-1}$ and significant vorticity maxima labeled) are used to illustrate the position, structure, and orientation of the cutoff cyclone and its vorticity lobes in closer detail (Figs. 4.36–4.41). This case is an

excellent example of a 500 hPa trough system pivoting from a positive to neutral to negative tilt. Figure 4.36 is for 0000 UTC 3 July 1996 and shows that the 500 hPa trough system is not yet cutoff but is positively tilted over the Great Lakes. Vorticity lobe A, with values of greater than 20 x 10^{-5} s⁻¹, is located over Lake Huron. This vorticity lobe coincides with a generally large region of precipitation covering most of the Northeast (Fig. 4.23). Precipitation begins to follow the path of the 500 hPa trough system as time progresses.

By 1200 UTC 3 July 1996 (Fig. 4.37), the 500 hPa trough appears to be just about to cut off as indicated by the almost closed 561 dam contour. The 500 hPa trough has now moved eastward and shifted to a more neutral tilt. Vorticity lobe A, located at the center of the trough, has also strengthened. Figure 4.38, for 0000 UTC 4 July 1996, shows that the 500 hPa trough system has cut off and is centered over central New York, maintaining a neutral tilt. Also apparent is a newly formed vorticity lobe (lobe B) of greater than 20 x 10^{-5} s⁻¹ that split from elongated vorticity lobe A seen in Fig. 4.37. Vorticity lobes A and B will begin to rotate around the 500 hPa cutoff cyclone, enhancing precipitation over northern New York and Maine (Fig. 4.24). At 1200 UTC 4 July 1996 (Fig. 4.39), the 561 dam closed contour is centered over New England and the two vorticity lobes have strengthened. Lobe A, previously located in central Pennsylvania, is now over Vermont and lobe B, previously over northwestern Pennsylvania, has drifted southward into West Virginia and Maryland.

Figures 4.40–4.41 are for 0000 UTC and 1200 UTC of 5 July 1996, respectively. At 0000 UTC, the center of the 500 hPa cutoff cyclone is located over New Hampshire and has taken on a slightly negative tilt. Vorticity lobe A has taken on an elongated orientation and is located north of Vermont. Heavy precipitation is located near the Adirondack Mountains of New York State and also in Maine at this time, and is being driven by vorticity lobes A and B to move northeastward off the coast of Maine (Fig. 4.25). Figure 4.40 also shows that vorticity lobe B has moved off the coast of Massachusetts and has strengthened with values greater than $24 \times 10^{-5} \text{ s}^{-1}$. By 1200 UTC 5 July 1996 (Fig. 4.41), the cutoff cyclone system has opened up and has almost moved completely off the North Atlantic Coast. Heavy precipitation is limited to regions of extreme northern New York, New Hampshire, and Maine. Vorticity lobe B is located over the Atlantic Ocean and the remnant of lobe A is still lingering over northern New York; however precipitation has ceased in much of the Northeast by this time. Both lobes A and B have acted to push most of the precipitation northeastward into Maine and off the Atlantic Coast (Fig. 4.25).

4.3.5 Surface Conditions

In order to further understand the development of the heavier precipitation features on 4 July 1996 and 5 July 1996, there needs to be a search for any baroclinic boundaries at the surface. Therefore, many hand analyses needed to be made for this case, just as in the first case. Figure 4.42 is a surface pressure analysis (with contours drawn at 2 hPa intervals) made from surface station plots for 0000 UTC 4 July 1996. The analysis shows an elongated coastal low centered over Rhode Island. At this time, heavy precipitation is just beginning to form over northern New York and Maine. The cyclonic

circulation around the surface low acts to turn on the Atlantic moisture tap, thus drawing moisture into the heavy precipitation areas.

Figure 4.43 shows mixing ratio contoured at 2 g kg⁻¹ intervals and potential temperature contoured at 4°C intervals for 1200 UTC 3 July 1996. Centered over eastern Massachusetts is a closed 20°C contour indicating the onset of weak inland heating that will increase in the next 6 h. A weak moisture gradient indicates the initiation of the Atlantic moisture transport along the coast. This moisture gradient is especially apparent near the Maryland coast, which agrees with the 700 hPa relative humidity and omega plots discussed earlier in section 4.3.3 (Fig. 4.32).

Figure 4.44 shows surface potential temperature and mixing ratio for 1800 UTC on 3 July 1996. Potential temperature contours indicate the presence of a weak baroclinic zone near the New England coast. The closed 24°C contour located over interior New England indicates moderate heating occurring inland. Wind barbs on the station plots illustrate a bit of an onshore flow that cools the coast but makes for party cloudy conditions over New England. As time progresses, this inland heating/weak coastal baroclinic zone progresses northward and results in the over night heavy precipitation which occurs overnight in Maine (Fig. 4.24).

In this case, although no severe weather occurred, the 500 hPa cutoff cyclone produced many devastating flash floods. A combination of upper-level jet dynamics increasing the vertical moisture transport created stratiform but heavy precipitation that flooded areas of northern New York, Vermont, and Maine. With the help of strong vorticity maxima rotating around the 500 hPa cutoff cyclone and enhancing the amount of precipitation that fell, several of these areas were able to receive significant rainfall totals in a three-day period (see Fig. 4.3).

4.4 Discussion and Comparison of the Two Case Studies

Both case studies involve a 500 hPa cutoff cyclone that produces heavy precipitation and associated flash floods. In the 30 June to 1 July 1998 case (referred to as Case 1 hereafter), heavy precipitation came in the form of a large swath of precipitation that encompasses almost the entire New York and Pennsylvania border. Heavy precipitation in Case 1 remains mainly to the right of track until it shifts to the left of track sometime between 1200 UTC 30 June and 0000 UTC 1 July 1998 (Fig. 4.1). In the 3 July to 5 July 1996 case (referred to as Case 2 hereafter), the heaviest precipitation remains to the left of the 500 hPa cutoff cyclone track through the entire 72 h period (Fig. 4.3). Precipitation amounts are much larger and more widespread in Case 1 than in Case 2. Case 1 also includes lines of convection that produce large amounts of severe weather including hail, high winds, and tornadoes (Fig. 4.2), unlike Case 2.

Both cases followed a similar 500 hPa cyclone track that progresses through the Northeast then off the coast through Maine; however both have different origins, Case 1 near the Great Lakes and Case 2 near Hudson Bay. Even though the initiation of Case 2 occurs poleward of the initiation of Case 1, the track of Case 2 through the Northeast dips farther equatorward than that of Case 1 (Figs. 4.1 and 4.3).

Some aspects of the atmospheric dynamics for both cases are similar at certain levels. Both cases involve a surface low pressure system that intensifies as the 500 hPa

system strengthens and cuts off. In both cases, the surface low pressure systems tends to follow the path of the precipitation as well as the path of the 500 hPa cutoff cyclone. On the contrary, several aspects of the atmospheric dynamics in both case studies are different. In Case 1, there is the development of a strong 850 hPa jet located over the Northeast, whereas in Case 2 there is very minimal low-level jet development (Fig 4.9b). The 850 hPa jet in Case 1 plays a moderate role in enhancing moisture transport to upper levels (Figs 4.26b–4.31b). Upper-level jet dynamics are also more apparent in Case 1. Case 2 features a strong upper-level jet with associated left front exit region; however, it is weak and remains slightly south of the Northeast and does not provide as much precipitation enhancement as does the upper-level jet in Case 1 (Figs. 4.8d–4.10d and Figs 4.26d–4.31d).

Case 1 and Case 2 both involve a trough axis that pivots from a positive to negative tilt; however, the pivoting trough axis is much more apparent and progresses more slowly in Case 2 (shown in the 500 hPa geopotential height and absolute vorticity fields in Figs. 4.14–4.17 and 4.36–4.41). The 500 hPa cutoff cyclone in Case 2 tracks through the Northeast over a period of 72 h whereas the 500 hPa cutoff cyclone in Case 1 passes through the Northeast in 48 hours. Both cases have two vorticity maxima that develop and rotate around the cutoff cyclone. Heavy precipitation appears to be enhanced underneath the locations of these vorticity maxima.

Moisture transport is an important feature in both cases. As illustrated in Case 1 and Case 2, sea surface temperatures off the northern Atlantic Coast are increased due to warm waters in the Gulf Stream. Combined with strong ascent, which is evident in both

cases (Figs. 4.11–4.13 and 4.32–4.35), this moisture advection and vertical lift can result in large areas of heavy precipitation.

Although surface hand analyses for both cases do not indicate any strong baroclinic zones, the warm air advection seen in both cases can act to enhance precipitation, especially in unstable environment. In Case 1, there is a weak thermal gradient near the warm sector located in central Pennsylvania that helps to produce the large swath of precipitation over the New York and Pennsylvania border (Figs. 4.19–4.20). Also illustrated in Case 1 is a prefrontal trough with an associated southwesterly wind flow, which enhances the aforementioned warm sector (Fig. 18). Case 2 involves a baroclinic zone resulting from inland heating located over Massachusetts (Figs. 4.43–4.44). The inland heating in Case 2 results from a surface low pressure centered over New England that draws moisture due to its cyclonic circulation creating a southeasterly flow (Fig. 4.42).

5. Discussion

5.1 Justification of Methodology

As discussed in section 2.2, the methodology used to identify cutoff cyclones in the present study is similar to that used in Bell and Bosart (1989), as well as in Smith (2003), Novak et al. (2002), and Fracasso (2004). The difference lies in that the more recent studies, including the tracking segment of the climatology in this study, use a newer, more comprehensive dataset with increased resolution [the NCEP/NCAR reanalysis at a 2.5° x 2.5° latitude–longitude grid versus the NMC 2° x 5° analysis used in Bell and Bosart (1989)]. As discussed in chapter 1, Fig. 1.6, a cutoff cyclone was defined by at least one 30 m height rise in all directions from a grid point. It should be noted that the terms "cutoff cyclone" used in the current study and "closed low" used in Bell and Bosart (1989) are essentially synonymous, and thus are used interchangeably. In this study, an even more recent dataset, the UPD, is used for the bulk of the objective portion of the precipitation climatology. This dataset allowed for consideration of a much longer record [51 years compared with 15 years used in Bell and Bosart (1989)] and also facilitated the analysis of monthly precipitation associated with 500 hPa cutoff cyclones.

5.2 Discussion of Climatology of 500 hPa Cutoff Cyclone Precipitation

5.2.1 Discussion of Average Daily Precipitation

Figures 3.1–3.4, discussed in Chapter 3, show the approximate amount of precipitation per day per month associated with a 500 hPa cutoff cyclone in the Northeast. In all four figures, heavier precipitation is generally located along the Atlantic Coast. Much of this heavier precipitation may be the result of the 500 hPa cutoff cyclone's counterclockwise circulation drawing moisture from the Atlantic Ocean. If the cutoff cyclone is slow moving, widespread flooding may occur as a result of the bands of precipitation rotating around the cutoff. This pattern can cause heavy rain to fall on the same locations repeatedly.

Most likely, the heavy precipitation occurring in much of Pennsylvania and along the Atlantic Coast is a result of southeasterly flow drawing in warm moist air into those regions. Later in the warm season, coastal water temperatures off the Atlantic are fairly warm, allowing for more tropical air masses. As seen in the case studies (refer to sections 4.2.2 and 4.3.2) 500 hPa cutoff cyclones have surface low pressure systems that develop and follow along a similar path as the 500 hPa cutoff cyclone. The counterclockwise flow associated with the surface low helps to create the aforementioned low-level southeasterly flow.

Previous research on cutoff cyclone activity is presented in Figs. 5.1–5.4 from Bell and Bosart (1989) and Smith (2003). Figure 5.1, taken from Fig. 11 in Bell and Bosart (1989) shows selected areas favoring cutoff cyclone activity. For the Northeast, we will focus on Box L5 in Fig. 5.1. Figure 5.2 shows a monthly distribution of the total number of closed lows observed in Box L5. A similar study done by Smith (2003), Figs. 5.3–5.4, shows the same favored areas for cutoff cyclone activity but using 6 h analyses instead of the 12 h analyses used in Bell and Bosart (1989). Both studies confirm that upper-level cutoff cyclones in the Northeast show an annual maximum in late spring and early fall. They also indicate that a sharp drop off in cutoff cyclone activity begins in mid-June. Therefore, in the months of July and August cutoff cyclones are less frequent than in early June and late September. This frequency difference may explain some of the results found in the current study. The most intense precipitation occurs in the month of August (Fig. 3.3) with the least in July (Fig. 3.2). In August, areas along the coast of the Northeast can receive 5–7 inches of precipitation when a cutoff cyclone is present. The reason for the minimum in intense rainfall for July may lie in the fact that there are fewer numbers of cutoff cyclones to produce such heavy precipitation distributions. During August, although there is a minimum of cutoff cyclone activity, late season warm coastal waters and warm air temperatures may enhance convective activity associated with these cutoffs, thus producing much larger daily rainfall amounts in the Northeast. The possibility also exists that August is biased toward tropical cyclone activity. Although possible in any summer month, late season cutoff cyclones, in conjunction with warmer and very moist air masses, can provide for very unstable and convective environments, creating conditions favorable for flash floods.

Topography and the development of cutoff cyclones is a common topic in the literature; however, very few studies address topography and its effect on cutoff cyclone precipitation distribution. Several topographic signatures are seen within Figs. 3.1–3.4, including high precipitation amounts within the Adirondack and Catskill Mountains of New York, the Green Mountains of Vermont, and especially Mt. Washington in the White Mountains of New Hampshire. These rainfall signatures result from cutoff

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cyclones producing orographic lift from the coastal plains to the inner mountain regions of the Northeast. Heavy precipitation is thus produced from upsloping occurring near these mountain ranges.

5.2.2 Percent of Climatology Precipitation

Figures 3.5–3.8, discussed in Chapter 3, show the percentage of precipitation associated with 500 hPa closed lows compared to the climatology. Highest percentage values are seen in June (Fig. 3.5) and the lowest in August (Fig. 3.7), suggesting that cutoff cyclones produce a substantial portion, approximately 40%, of the overall precipitation that occurs in June and very little of the overall precipitation produced in August. The coastal signature apparent in the later months of the daily precipitation composites (Figs. 3.3-3.4) is also evident for the month of June in the percentage composites (Fig. 3.5). In June, some regions of the northeastern Atlantic coast receive over half of their monthly precipitation from cutoff cyclones. Percentage values decrease in the months of July and August (Figs. 3.6 and 3.7), which agrees with the decrease in number of cutoff cyclone events discussed in section 5.2.1. With fewer cutoff cyclones, precipitation is thus produced by other mesoscale and synoptic-scale processes such as convection due to diurnal or lake breezes/boundaries and strong frontal boundaries not associated with cutoff cyclones, as well as the occasional tropical system. As the number of cutoff cyclone events increases towards September, so do the percentages of precipitation associated with cutoff cyclones. This increase could be a signal of the intense precipitation received from tropical systems in the Atlantic Basin.

What is notable is the result that the most intense precipitation produced by cutoff cyclones occurs in August (Fig. 3.3); however August is also the month with the lowest percentage of precipitation associated with cutoff cyclones (Fig. 3.7). This result implies that when a cutoff cyclone enters the northeastern US during August, though August has fewer cutoff cyclones that the other warm season months, precipitation associated with them may be intense especially along the Atlantic coast. Note, however, that the precipitation produced by the cutoff cyclone is only a small fraction of the overall precipitation produced for all of August. Some of the August precipitation may be the result of landfalling tropical systems.

5.2.3 Monthly Cutoff Cyclone Tracks

The 500 hPa cutoff cyclone monthly tracks presented in chapter 3 (Fig. 3.9) show reasonable consistency with the five main tracks found in Novak et al. (2002), Fig. 1.1. Comparing Fig. 1.1 to Fig. 3.9, it is evident that the five basic tracks for warm season 500 hPa cutoff cyclones are represented; however monthly variations in those tracks are also present. As mentioned in section 3.1.3, the general southward shift of the tracks from June to September agrees with the findings of Novak et al. (2002) in that later in the season, cutoff cyclones tend to follow the Zonal track, the Southwest track, and the Atlantic Coastal track. Results from the monthly cutoff cyclone tracks agree with those found in the daily precipitation composites discussed earlier in that as the warm season months progress, heavy precipitation amounts associated with cutoff cyclones will most likely shift southward and eastward to be located near the Atlantic Coast.

5.3 Discussion of Case Studies

As discussed in section 4.1, the 30 June to 1 July, 1998 case includes several important key players. These key players involve two regions of severe weather reports produced by two different dynamic features (Fig. 4.2). Hail, wind, tornadoes, and flash floods were reported over much of the Northeast. An area of nocturnal convection that moved through the Midwest between 0000 UTC and 0800 UTC 30 June 1998 produces region 1, (Fig. 4.2). The second region of severe weather reports is due to a pre-frontal trough and associated warm sector, features produced by the 500 hPa cutoff cyclone, between 0600 UTC 30 June 1998 and 1400 UTC 1 July 1998 (Figs. 4.18-4.19). The cutoff cyclone produced a large swath of heavy precipitation (Fig. 4.1) that fell along the New York and Pennsylvania border eastward to Cape Cod. The jet dynamics of this case (Figs. 4.8–4.10) are well in place for enhancement of severe weather and heavy precipitation despite the lack of a strong baroclinic zone at the surface (Figs. 4.19–4.20). Vorticity lobes slowly rotating around the pivoting 500 hPa trough also assist in the production of the quasi-stationary swath of heavy precipitation (Figs. 4.14–4.17). Radar composites, shown in Figs. 4.4-4.7 and described in section 4.2.1, also portray the rotating vorticity lobes as well as indicate the location and progression of the heavy precipitation and lines of convection produced by the Great Lakes Category of a closed low. Vorticity lobes can also assist the jets in enhancing precipitation by increasing moisture transport to higher levels. The majority of the severe weather reports seen in Fig. 4.2 are not produced until after 1800 UTC, when convection acts as the key player in the case (Fig. 4.6–4.7). Soundings (Figs. 4.21 and 4.22) explicitly show the conditions just prior to the three tornado reports in Long Island, New York (Fig. 4.2).

In this 500 hPa cutoff cyclone case, a combination of important atmospheric dynamics required for producing heavy precipitation and severe weather came together. The antecedent convective system over the Ohio and Tennessee Valleys mentioned earlier provided a moisture source for the large swath of precipitation along the New York State and Pennsylvania border that extended into New England. There is strong dynamical forcing as evident by strong upper- (200–250 hPa) and lower- level (850 hPa) jets and strong 700 hPa ascent. The corridor of the heaviest precipitation associated with the swath fell near the anticyclonic jet-exit region at 200 hPa. Heaviest rainfall was also concentrated ahead of a well-defined surface trough, but only weak baroclinic zones were present. Flash floods resulting from heavy precipitation in northern New York and northern New England were driven by warm air advection beneath the 200 hPa jet. Convection in eastern Pennsylvania, New Jersey, and southeastern New York, late on 30 June 1998, occurs beneath the 200 hPa jet in conjunction with a strong 850 hPa jet.

The second case study, discussed in section 4.3, describes a flash flood producing Hudson Bay category of a closed low. Much of the heaviest precipitation from this cutoff remained in eastern New York, stretching into Maine (Fig. 4.3). Heavy areas of precipitation are seen either to the right or to the left of the cutoff low center based on the track overlayed on Fig. 4.3. As opposed to the first cutoff cyclone case, no severe weather was reported with the 3–5 July 1996 closed low. In the latter case, the atmospheric dynamics necessary for severe weather were absent. The lower-level (850 hPa) jet dynamics in the 30 June to 1 July 1998 case study are weak and also located in
areas outside of the Northeast. The upper-level (250 hPa) jet in the second case study is weaker than the upper-level jet in the first case study; however, prior to the onset of heaviest precipitation, the left-quadrant jet-exit region is situated between upstate New York and Maine. The jet entrance and exit regions found at upper- and lower-levels in the first case study provide for lines of convection that are not seen in the 3–5 July, 1996 case. Though more so in the second case, signals of upslope precipitation are apparent near the Adirondack Mountains of New York for both case studies. The cutoff cyclone in the second case study progresses more slowly through the Northeast compared to the 30 June to 1 July 1998 case, which allows for low-level flow to be normal to the windward side of mountain regions for a longer period of time. Adequate moisture provided by the Atlantic Ocean/Gulf Stream combined with favorable low-level flow will produce heavy precipitation near mountainous regions, as produced in this case study. Rainfall duration is one of the key attributes of the second case study.

Cyclonic vorticity advection is also a key player in the July 1996 case. As discussed in section 4.2.3, two large vorticity lobes rotate around the pivoting 500 hPa cutoff cyclone (Figs. 4.14–4.17). These vorticity lobes coupled with the weak 250 hPa jet dynamics, help to enhance the Atlantic moisture flow and produce precipitation fields around the cutoff cyclone as it progresses northeastward. Regions of persistent vorticity advection exist in the northern quadrant of the low center, producing bands of precipitation affecting the same area. The vorticity lobes are slow moving as the low center pivots to the south and east of the area of heavier precipitation. The strong surface low that develops in this case provides the southeasterly flow near the coast that also

draws in adequate moisture. As in the first case, only weak baroclinic zones are present at the surface.

Both of the case studies help support some of the results found in the cutoff cyclone climatology. As seen in the July composite for average daily precipitation associated with 500 hPa cutoff cyclones (Fig. 4.2), much of the heaviest precipitation is found near the coast and in northern New England. Despite the huge swath of precipitation on the New York and Pennsylvania border, some of the heaviest precipitation amounts in the 30 June to 1 July 1998 case are found in Connecticut and near the Massachusetts coast. There is also a large bulls eye in northern New York that more than likely corresponds to the same precipitation signal seen in northern Vermont in the July composite. Research on the location of heavy precipitation produced by cutoff cyclones done by Jorgenson (1967) agrees with the results from this case study. Jorgenson (1967) showed that the southeast quadrant of the cutoff cyclone was where precipitation occurred most frequently. When overlaying the track of the 30 June to 1 July 1998 cutoff cyclone over the 48 h precipitation plot (Fig. 4.1), the majority of the heaviest precipitation is to the south and east of the track. This result also agrees with Klein et al. (1968) and Korte et al. (1972), who showed that the maximum frequency of measurable precipitation in 500 hPa cutoff lows is approximately 2.5° south and 3.5° east of the center of the upper-level cutoff low [see Fig. 1.12 taken from Fig. 8 of Klein et al. (1968)].

Areas of heavy precipitation produced by the cutoff cyclone in the second case study are also located in similar regions of the July average daily precipitation composite. As discussed in section 5.2.1, heavy precipitation signatures resulting from upsloping are

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seen in some of the daily precipitation plots (Figs. 3.1–3.4). The second case study confirms those results with the heavy precipitation amounts seen near the Adirondack Mountains.

Forecasters in the Northeast know that cutoff cyclones are a very big forecast challenge. Unfortunately, numerical models do not always handle all of the features associated with 500 hPa cutoff cyclones properly. Small variations in cutoff cyclone location and orientation produced by numerical models can result in huge errors in forecasts for precipitation location and amount. Precipitation produced by cutoff cyclones frequently results in major flooding when these cutoffs move through the Northeast. The results of this thesis can be summarized in a few steps that forecasters can use to improve their precipitation forecasts when dealing with 500 hPa cutoff cyclones. These steps include:

1) Understand the results of the monthly cutoff cyclone precipitation climatology to be aware of favored areas for, as well as the amount of, heavy precipitation associated with cutoff lows during each warm season month. Cutoff cyclones often involve high precipitable water values, so that there is abundant moisture advection to consider when dealing with closed lows.

2) Pay special attention to the location, speed, and track of the cutoff cyclone by using satellite and radar composites to watch where precipitation bands will rotate around the low.

3) Pay attention to the location, as well as the role, of upper- and lower-level jet dynamics in enhancing heavy precipitation and aiding in the formation of lines of convection capable of producing severe weather.

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4) Pay attention to the locations of the vorticity lobes that rotate around the cutoff cyclone in order to follow the progression and possible enhancement of precipitation, particularly in relation to the track of the low.

5) Watch for surface cyclone development and the creation low-level flows that help draw in moisture into areas of strong ascent.

6) Understand where upsloping may come into play by looking at low-level flow regimes when a cutoff cyclone is in the forecast.

The previous list gives forecasters a subjective approach to forecasting precipitation distributions associated with 500 hPa cutoff cyclones. Numerical models usually do well in indicating that a cutoff cyclone is in the forecast. However, once the cutoff moves into the area, all of the aforementioned features need to be considered. Figure 5.5 is a schematic that illustrates an example of the evolution of a 500 hPa geopotential height pattern with the associated upper-level jet dynamics, cyclonic vorticity advection, and resulting precipitation pattern, as discussed in the previous list. In this figure, time increments can be in 12 h–36 h, depending on the rate of progression of the cutoff cyclone.

Figure 5.5a shows that the 500 hPa trough has not yet cutoff and has a positively tilted axis. The 250 hPa jet is entering a region of diffluence and there is only one lobe of vorticity at the base of the trough. Heavy precipitation at time $t - \Delta t$, is limited to a small region resulting from both vorticity advection and associated jet dynamics. Figure 5.5b, at time t, shows that the 500 hPa trough is cutoff and has evolved to a neutral tilt. Two vorticity lobes begin to rotate cyclonically around the low. Juxtaposed with the left-front quadrant or exit region of the 250 hPa jet, a region of strong ascent has formed, thus

producing a large area of heavy precipitation. A separate region of heavy precipitation downstream is also produced from vorticity advection (V₁). Figure 5.5c shows that the 500 hPa pattern has taken on a slightly negative tilt, and the 250 hPa jet, as well as both regions of heavy precipitation, have progressed towards the right side of the cutoff cyclone. If this schematic were centered over the Northeast, by time $t + \Delta t$ (Fig. 5.5c), much of the heavy precipitation would be off the Atlantic Coast. Forecasters might apply this schematic in conjunction with real-time radar imagery, satellite imagery, water vapor imagery, and METAR data to locate the areas of heaviest precipitation when a cutoff cyclone is present.



Fig. 5.1. Selected areas of favored closed cyclone (solid boxes) and anticyclone (dashed boxes) activity (Northeast activity in Box L5). Source: Bell and Bosart (1989), Fig. 11.



Fig. 5.2. The monthly distribution of the total number of 12 h analyses in which a closed cyclone is observed in the Northeast, Box L5 (top curve, solid line), the number of distinct closed cyclones identified in Box L5 (middle curve, dashed line), and the number of closed cyclones forming within BoxL5 (bottom curve, solid line). Asterisks identify one standard deviation interval centered about the mean value for the top curve [see section 4 of Bell and Bosart (1989) for further details]. All values are normalized to a 30-day month. Source: Bell and Bosart (1989), Fig. 12.



Fig. 5.3. Favored areas for cutoff cyclone activity for the NH, focusing on Box 6N for the Northeast. Source: Smith (2003), Fig. 3.11.



Fig. 5.4. Number of cutoff cyclones (dashed line), 6 h analyses with a cutoff cyclone (thick solid line), and percentage of 6 h analyses that exceed number of events (thin solid line) for box 6N, as defined in Fig. 5.3. Source: Smith (2003), Fig. 3.12f.



Fig. 5.5. Schematic of the time evolution of 500 hPa geopotential height with associated upper-level jet dynamics (shown by orange and red shaded contours) and cyclonic vorticity advection (shown by vorticity lobes V1 and V2). Areas of heavy precipitation are illustrated in blue. a. $t - \Delta t$, b. t, c. $t + \Delta t$.