Cutoff Cyclones:
A Global and Regional Climatology and Two Case Studies

Abstract of a thesis presented to the Faculty
of the University at Albany, State University of New York
in partial fulfillment of the requirements
for the degree of

Masters of Science
College of Arts & Sciences
Department of Earth and Atmospheric Sciences

Brandon A. Smith
2003
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The thesis for the master’s degree submitted by
Brandon A. Smith
under the title

Cutoff Cyclones:
A Global and Regional Climatology and Two Case Studies

Has been read by the undersigned. It is hereby recommended
for acceptance by the Faculty with credit to the amount of
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Recommendation accepted by the Dean of Graduate Studies
for the Graduate Academic Council

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ABSTRACT

Cutoff cyclones are associated with many significant forecasting problems in the northeastern United States. Given the complex terrain in the Northeast, the precipitation distribution associated with slow-moving cutoff cyclones is often challenging to predict. An understanding of the behavior of cutoff cyclones in the Northeast is a first step to improving the precipitation forecasts associated with them. To gain a perspective of northeast US cutoff cyclones, an understanding of the global distribution of cutoff cyclone activity must be developed. As an initial step toward addressing this challenge and as part of the Collaborative Science and Technology Applied Research (CSTAR) program, the results of a 54-year (1948–2001) global and regional climatology of 500 hPa cutoff cyclones is presented in order to map the spatial and temporal distributions of these features. This task is accomplished by 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.

Cutoff cyclones are identified objectively. For our purposes, a cutoff cyclone is defined as a geopotential height minimum surrounded by at least one closed 30 m interval contour. Cutoff cyclones are identified and catalogued, and cyclone tracks are constructed, to delineate favored areas for genesis/lysis and to locate “cutoff freeways.” Frequency diagrams showing total number of cutoff cyclones and number of “cutoff 6 h analyses” are presented for the Northern and Southern Hemispheres, the Tropics, and for eastern North America. Also shown are maps of observed genesis/lysis, the “cutoff grid
point of the year,” as well as the “cutoff day of the year.” Graphs of cutoff activity for selected areas in the Northern and Southern Hemispheres and the Tropics are presented as well.

Case studies of two cutoff cyclone climatology members that impacted the northeast US are presented. The two cutoffs shown were both forecast to produce heavy precipitation in the NWS Burlington, Vermont, CWA, whereas in reality only one of the systems produced heavy precipitation. Diagnostic analyses are conducted to identify reasons for the unexpected differences in cutoff behavior and to illustrate forecast differences.
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I. Introduction

1.1 Overview

Accurate Quantitative Precipitation Forecasting (QPF) has proven to be a challenge in operational meteorology and its need is well documented (e.g., Anthes 1983; Jensenius 1990; Junker and Hoke 1990). This is especially true in the case of cutoff cyclones (also known as closed lows). Cutoff cyclones produce about 30% of the annual precipitation in the northeast US (Atallah and Aiyyer 2002), and, when moving over complex terrain, can present unique forecasting issues. By definition, cutoffs tend to be displaced from the mean steering flow (e.g., Palmén 1949; Bell and Bosart 1989, hereafter referred to as BB). Therefore, their forward speed is generally less then that of an open wave cyclone still embedded in the flow. These slow-moving cyclones are of interest because they are often associated with blocking patterns (e.g., Rex 1950), which can impede the progression of upstream systems. The longer-lasting systems can be associated with persistent 500 hPa height anomalies (e.g., Dole and Gordon 1983; Dole 1986). It is no surprise then that significant precipitation can occur with cutoff cyclones. For example, a cutoff cyclone passing through the northeastern US during the period 14–17 July 2002 produced as much as 30 cm of rain in southeastern New York State (see Novak et al. 2002 for details).

The characteristic structure of a cutoff cyclone limits the predictability of the associated precipitation (e.g., Hawes and Colucci 1986). These systems tend to have little vertical tilt. The indicators of synoptic and mesoscale forcing (e.g., the advection of
temperature and/or vorticity) within cutoff cyclones tends to be weaker or less widespread than in more baroclinic, open-wave cyclones. Existing numerical weather prediction models often have difficulty forecasting the precipitation distribution and amount in cutoff cyclones, especially when the forcing for ascent is weak and/or the low is traversing complex terrain.

To begin to understand the distribution of precipitation within cutoff cyclones, it is necessary to understand the climatological behavior of these systems. As an initial step in addressing this and the other challenges associated with the precipitation distribution in cutoff cyclones, the results of a 54-year cutoff cyclone climatology are shown. Annual, seasonal and monthly cutoff cyclone frequencies and statistics are presented for the Northern Hemisphere, the Southern Hemisphere, the Tropics, and eastern North America. From this climatology, tracks of individual cutoff cyclones are constructed objectively and used to develop composite mean cutoff tracks across eastern North America. Case studies of two representative cutoff cyclones are presented to emphasize the forecast challenges that operational meteorologists face.

1.2 Literature Review

1.2.1 Theory of Evolution of Cutoff Cyclones

It is has been theorized that the deformation of the middle- and upper-tropospheric flow often results in the isolation of pools of cold air equatorward of their source regions and pools of warm air poleward of the mean flow (e.g., Crocker et al.
Cold polar air masses moving equatorward undergo sinking. The incipient stretching and horizontal convergence in the upper levels of the atmosphere increase the vorticity at the level of maximum convergence (Bluestein 1992, sec. 4.5) creating the aforementioned deformation. Rossby (1940) showed that the conservation of potential vorticity (PV) can be written as:

\[
\frac{\zeta + f}{\Delta p} = \text{constant.} \tag{1}
\]

Here, \(\zeta\) is the relative vorticity, \(f\) is the Coriolis parameter, and \(\Delta p\) is the depth of a column in pressure coordinates. Based on discussion of Eq. (1) in Palmén and Newton (1969, sec 10.4, hereafter PN1), a column of air displaced equatorward from its source region that undergoes stretching (and subsequent increase in \(\Delta p\)) must experience an increase in relative vorticity sufficient enough to offset the decrease in \(f\), and increase in \(\Delta p\). This increase in relative vorticity is normally realized as a strengthening in the cyclonic circulation of the column, with deep (shallow) pools having strong (weak) cyclonic circulations. The resulting strong cyclonic circulation deforms the mean flow and on occasion, isolates or “cuts-off” a pocket of cold air from the flow. Fig. 1.2 (taken from Fig. 10.1 of PN1) shows the ultimate result of this process. A pool of cold air coinciding with a minimum in the 500 hPa height field lies equatorward of an isolated pool of warm air and coincident height maximum. Berggren et al. (1949) found that this type of deformation regularly occurs when strong zonal current lies upstream of a blocking region, and when disturbances approach the blocking region they slow down.
and increase in amplitude. This idea is illustrated in Fig. 1.3 (taken from Fig. 26 of Berggren et al. 1949), and shows patterns similar to those found in Rex (1950) in his discussion of atmospheric blocking patterns. Figures 1.4a–e (taken from Figs. 10.4 in PN1) show five characteristic types of upper-level cyclones that can result from such amplification. The cyclone in Fig. 1.4d closely resembles that which was just described, with a cold pool of air characterized by strong cyclonic motion displaced equatorward of the mean jet. Hsieh (1949, 1950) also studied this type of upper-level system. This theory of cutoff development, where a cutoff cyclone is the result of the interaction of a pre-existing trough or wave with an upstream wind maximum is described in detail in Keyser and Shapiro (1986, sec. 2d), Bell and Bosart (1993), and Bell and Keyser (1993). These three studies found that a closed circulation develops as the wind maximum moves into the base of the trough, concentrating the vorticity near the trough axis.

Much insight into the evolution of cutoff cyclone has been gained from the use of (PV) to diagnose atmospheric structure. PN1 (p. 274) describes the evolution of a cutoff cyclone over North America as a cold cyclonic vortex cutoff from the polar source region, but “still united by an umbilical cord in the form of a shear line”. Hoskins et al. (1985, hereafter HMR), using PV maps, show this “umbilical cord” as a band of higher PV connected to what becomes an isolated area of PV (see Fig. 5 of HMR). This was followed by Thorncroft et al. (1993), who showed that areas of isolated positive PV associated with cutoff cyclones develop as part of two different life cycles (LC1 and LC2) of baroclinic waves [refer to Fig. 1.5 taken from Fig. 12 of Thorncroft et al. (1993) during the following discussion]. In this study, cyclones of type LC1 and LC2 are distinguished by either anticyclonic (LC1) or cyclonic (LC2) “wrapping” of PV. LC1
type behavior features cutoff cyclones developing on the equatorward side of the mean westerly jet. Toward the end of the life cycle, the mean trough undergoes what is described as “Rossby-wave breaking,” described in McIntyre and Palmer (1984), and Clough et al. (1985) This process results in a strong anticyclonic, relatively compact wrap-up and thinning of the trough equatorward of the mean jet. The thin extended trough is similar to the “umbilical cord” structure described earlier in PN1 and HMR. Eventually an isolated area of higher PV, characteristic of a cutoff cyclone, is displaced equatorward. This type of evolution of cutoff cyclones is consistent with studies of closed-low formation near the exit regions of jets (e.g., Bell and Bosart 1993). LC1 type behavior is dominated by northeast–southwest tilt, favoring anticyclonic shear and the poleward flux of low PV air. This results in the amplification of a ridge poleward of the incipient cutoff. This scenario is similar to theory of the eddy reinforcement of blocking studied by Illari and Marshall (1983); Shutts (1986), and Hoskins and Sardeshmukh (1987). vanHeerden and Taljaard (1998) describe cutoff cyclone development over South Africa. The development is similar to that of an LC1 life cycle, in which the circulation is largely anticyclonic, and a cutoff cyclone develops equatorward of a strong anticyclone.

In the LC2 type scenario, the tilt is northwest–southeast, cyclonic wrapping dominates, and a cutoff develops poleward of the mean jet. This development is consistent with Rodgers and Bosart (1986), who found that in the explosive (or rapid deepening) and mature stage of explosively deepening oceanic cyclones [bombs, see Sanders and Gyakum (1980) for details] a cutoff cyclone developed at 500 hPa. As the decaying stage was reached, the cutoff cyclone lay poleward of the mean westerly jet. For example, In contrast, Konrad and Colucci (1988, hereafter referred to as KC) found that
in certain rapidly deepening oceanic cyclone (bomb) events, this type of cutoff cyclone develops about 24 h prior to the midpoint of the rapid pressure falls at the surface. These cutoff cyclones in particular are usually part of a closed cyclone/anticyclone vortex pair (e.g., Lejenäs and Okland 1983) at 500 hPa, and are commonly associated with blocking patterns (e.g., Berggren et al 1949; Rex 1950; Colucci 1985, 1987)

1.2.2 Areas of Cutoff Cyclone Genesis/Lysis

Relatively few studies on the distribution of genesis/lysis of middle- and upper-tropospheric cutoff cyclones have been conducted, however these completed studies give a solid perspective of the geographically favored regions. PN1 found that the development of cold upper-level cyclones is favored particular regions of the mean belt of the westerlies, including the western US and southwestern Europe. More recent studies have shown similar results, and, with the incorporation of larger, more comprehensive datasets, have discovered other favored areas as well. BB showed the distribution of genesis/lysis for 500 hPa closed cyclones/anticyclones for the Northern Hemisphere for the period 1963–1977. Genesis maxima in BB were found across the north Pacific and Gulf of Alaska, the southwest US, north-central Canada in the vicinity of Hudson Bay, the northeast coast of the US, and across southern Europe. In general, lysis occurred downstream of the genesis areas. BB also found that lysis maxima occurred near or just downstream of genesis maxima, indicating the slow movement of systems in the southwest US, Gulf of Alaska, and Hudson Bay. Lysis areas were found relatively farther
upstream across the northwest Atlantic and across southern Europe, indicating more mobile systems.

Bell and Bosart (1994) conducted a more in-depth study into the cutoff cyclone formation across the southwest, the eastern US, and in the lee of the Alps. In the relatively data sparse regions of the Southern Hemisphere, early cutoff cyclone studies were done by Kerr (1953) and van Loon (1956), reporting that cutoff cyclones are common in the Australia–New Zealand region. Tyson (1986) and Taljaard and Steyn (1991) found that wet spells over southern Africa are typically characterized by the formation of middle- and upper-tropospheric cutoff cyclones over the western part of southern Africa. More recently, Tennant and Van Heerden (1994) found that topography is partially responsible for cutoff cyclone genesis, which is common across the South African subcontinent. Doyle and Shapiro (1994) also address the effect of topography on the development of cutoff cyclones, but for the North Atlantic. They found that cutoffs develop off the southern tip of Greenland in response to an orographically induced jet. Further study of middle- and upper-tropospheric cyclogenesis and how it impacts sensible weather conditions at the surface is still needed (and is stated in KC), and is a motivation for the current research.

1.2.3 Typical Structure of Cutoff Cyclones

Closed cyclonic circulations, termed cutoff lows, were initially described as mid-tropospheric entities with little or no subsequent cyclogenesis at the surface (Palmén 1949; Palmén and Nagler 1949; Hsieh 1949). Cutoff cyclones are generally characterized
by a symmetrical distribution of geopotential height and temperature, with the lowest values in the center. This structure has been shown in numerous studies. For example, an in-depth case study of a cutoff cyclone over Europe was done by Peltonen (1963). This cyclone was further studied by PN1. Figure 1.6a–d taken from Figs. 10.7a–d of PN1, show the structure of this cutoff cyclone at the surface, 850 hPa, 500 hPa and 300 hPa, respectively. Figure 1.6c shows the 500 hPa geopotential height contours and isotherms. Notable is the core of coldest temperatures coinciding with the height minimum at 500 hPa. Figure 1.7, taken from Fig. 10.8 of PN1, is a cross section along line $a-a'$ in Fig. 1.6c, and clearly shows the thermal structure of this cyclone. The tropopause exhibits a marked drop in height toward the center of the cutoff cyclone. This feature is referred to hereafter as a “tropopause funnel” after PN1. Once again, the thermal symmetry can be seen, with a core of lower values of temperature/potential temperature ($\theta$) surrounded by higher values located below the tropopause. This structure exemplifies the cold-core structure of cutoff cyclones. Above the tropopause, areas of higher values of temperature/$\theta$ are surrounded by lower values. In Fig. 1.8 taken from Fig. 10.9 of PN1, the potential temperature structure of a cutoff cyclone analyzed by Omoto (1966), centered near Ft. Worth TX (then, GSW) is shown. Thermal symmetry is evident here as well. Values of both temperature and $\theta$ decrease toward the latitude of GSW, up to a level of approximately 500 hPa, with a reversal in this pattern above that level. Isotachs of wind speed greater than 70 ms$^{-1}$ at approximately 400 hPa are shown as E, denoting easterly flow and W, denoting westerly flow. The signature of a small-scale cutoff cyclone is found in the proximity of the opposing wind flow.
More recently, considerable insight into the structure of cutoff cyclones has been gained from the use of PV to describe the symmetrical nature of cutoffs. HMR described cutoff cyclones on terms of PV on θ surfaces. They showed that a characteristic pattern within a cutoff cyclone is an isolated area of anomalously high (positive) PV with isentropes sloping upward to meet the tropopause, which dips into the funnel shape discussed earlier. The preceding observational studies can be related to theoretical studies of the structure of cutoff cyclone. Thorpe (1986), using coordinate transformations on axisymmetric, or circular flow in gradient balance, developed idealized models of synoptic-scale atmospheric structures. This development uses the invertibility principal initially formulated by Eliassen and Kleinschmidt (1957), in which balanced disturbances (i.e., those with symmetry) can be described by first calculating the potential temperature at the ground and at the tropopause, then generating the potential temperature field in the vicinity of the disturbance. The PV can then be used to describe the structure of the disturbance. Figure 1.9, taken from Fig. 1 of Thorpe (1986), shows the idealized structure of a cold-core upper-level structure. This figure clearly shows symmetry in the thermal anomaly near the center, which changes sign at the tropopause. Also noteworthy is the classic tropopause funnel and sloping isentropes seen in PN1. This study was followed by Davies et al. (1991), who deduced from similar simulations that cold pools represent isolated areas of PV associated with cutoff cyclones. Cutoff cyclones are also observed as isolated areas of anomalously high PV, as shown in Bell and Keyser (1993).

1.2.4 Cyclone Climatologies
1.2.4a Surface Cyclones

Studies of extratropical cyclone behavior have evolved as a popular subject in the meteorological literature. The implementation of more widespread observational networks, such as the radiosonde in the late 1940’s, led to more comprehensive climatological studies of extratropical cyclones since the 1950’s and later. Historical studies of the behavior of surface cyclones have provided meteorologists with a solid documentation of their activity across the Northern Hemisphere. A classic study done by Klein (1957), using US Weather Bureau [now, the National Oceanographic and Atmospheric Association/National Weather Service (NOAA/NWS)] surface maps, showed that the frequency of surface cyclones is maximized in the following areas: 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. Other recent studies, which utilize more modern and comprehensive datasets, reinforce the findings of Klein (1957). Two comprehensive studies on the frequency and distribution of North American surface cyclones and cyclogenesis were conducted by Ziska and Smith (1980) and Whittaker and Horn (1981). These two studies used National Meteorological Center (NMC), now the National Centers for Environmental Prediction (NCEP), analyses, in addition to other data sources such as the Mariners Weather Log and the NOAA Daily Weather Map Series (DWMS). Areas of maximum cyclone activity in these two studies correspond well to Klein (1957), and include the North Pacific, central Canada and the Great Lakes, and the east coast of the US into the north Atlantic. Numerous studies
covering North America have been completed as well. For example, Hosler and Gamage (1956) looked at cyclone frequencies for the 48 contiguous United States from 1905–1954. Colucci (1976) focused on winter cyclone frequencies over the eastern US from 1964–1973. Hayden (1981) studied the spatial and temporal variations in cyclone frequency for eastern North America and the north Atlantic. The collective results of these studies further reinforce the findings of Klein (1957), and document the well-known areas frequented by cyclones during the cool season. The two main areas discussed in these studies are the US East Coast, and a band extending from the southwest US to the Great Lakes.

The development of even larger and more comprehensive datasets, such as the National Centers for Environmental Prediction/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, allows for more comprehensive studies of cyclone behavior. These global scale datasets also make possible the study of cyclones in data sparse regions, such as the Southern Hemisphere. For example, Sinclair (1994) found that the frequency of cyclones is maximized near New Zealand, the east coast of South America, and in the Southern Indian Ocean.

1.2.4b Middle- and Upper- Tropospheric Cyclones.

The link between cyclones at the surface and closed lows at 500 hPa has been studied as well, although far less frequently. In addition to Rodgers and Bosart (1986)
mentioned earlier, KC found that in the cases of weak bomb events, 500 hPa closed lows
developed near the region of explosive cyclogenesis in a storm-relative sense.

Relatively few studies of the distribution of mid-tropospheric cyclones with
respect to geography existed before BB and Parker et al. (1989, hereafter referred to as
PHCH). These two studies are important in that they are the first comprehensive
examination of the behavior of cutoff cyclones in the literature. BB, using the NMC
dataset, developed a method of objectively detecting cutoffs by isolating grid points
corresponding to relative geopotential height minima. PHCH created a 36-year
(1950–1985) climatology of 500 hPa cutoff cyclones for the western half of the Northern
Hemisphere, also using the NMC dataset. Findings common to these two studies are that
the frequency of cool season cutoff cyclones is maximized in four general areas: 1) across
the north Pacific and the Gulf of Alaska; 2) the southwest US; 3) north-central Canada in
the vicinity of Hudson Bay; 4) and the northwest Atlantic. BB, which covers the entire
Northern Hemisphere, reported cutoff cyclone frequency maximized in a band across the
Mediterranean and southern Europe, in addition to those areas discussed in PHCH. BB
also showed that closed cyclones are commonly found poleward of the mean belt of the
westerlies. Both BB and PHCH were used as an accuracy check and lay some of the
fundamental groundwork for the current research.

A comprehensive study on mid-tropospheric cutoff cyclones in the South African
region was completed by Talaard (1985), who developed comprehensive case studies on
numerous cutoff cyclones stratified by the amount of precipitation received in the region.

1.2.5 Cyclone Tracking
Early cyclone tracking studies were generally subjective in nature (e.g., Bowie and Weightman 1914; Klein 1957; Reitan 1974). The benefit of this type of analysis was that synoptic reasoning could be applied to the determination of a specific cyclone event. The corresponding obstacle was that large amounts of data were generally not available, and prior to the International Geophysical Year (IGY) in 1957–1958, much of the observational data were incomplete. The problem of incomplete data will be discussed in more detail in the results section. Once again, the benefit of larger and more comprehensive datasets is the facilitation of objective cyclone tracking (e.g., Alpert et al. 1990; Konig et al. 1993; Hodges 1994; Sinclair 1997; Blender and Schubert 2000). Geng and Sugi (2001) tracked surface cyclones over the North Atlantic for the period 1958–1998 using a methodology similar to that of the current research. Geng and Sugi (2001) also address the less documented features of cyclone activity such as cyclone intensity, deepening rates, and speed of movement, although the relationship between direction of movement of cyclones and pressure changes was addressed earlier by Hurley (1954). The aforementioned studies, with the exception of Alpert et al. (1990) who studied surface cyclones in the Mediterranean, focus on surface cyclones and the collective results for North America can be represented by the following statement: Surface cyclones favor three mean tracks: 1) northeastward moving cyclones that develop in the mid-Atlantic region; 2) northeastward moving systems that develop over the southwest US; and 3) east-southeastward moving systems that develop over central and western Canada. Comprehensive studies on the tracks of middle- and upper-tropospheric circulations (i.e., 500 hPa cutoff cyclones) have not yet been completed.
1.2.6 Precipitation in cutoff cyclones

The precipitation associated with a given weather system has commonly been tied with that surface cyclone. While meteorologists realized that precipitation could be tied to various upper-level features, the lack of readily available upper-air charts prior to the 1960’s made these kind of studies difficult (Jorgensen 1963). Studies linking precipitation with mid-tropospheric cyclones completed after the advent of more widespread observational networks have led to a better understanding of the actual distributions. An earlier study done by Hsieh (1949) shows schematically the precipitation distribution generally associated with a cutoff cyclone. In this study, the schematic of precipitation distribution [Fig. 1.10, taken from Fig. 13 of Hsieh (1949)] closely matches the general distribution of upper-level divergence described in PN1 (sec 12.6). While the thermal and height fields are symmetric, the precipitation fields are markedly asymmetric, with the heavier precipitation occurring under the area of stronger upper-level divergence in the eastern portion of the system. Jorgensen et al. (1967) studied 700 mb lows over the intermountain West and concluded that precipitation occurred most commonly in the southeast quadrant of the cyclone. This study was followed by Klein et al. (1968) and Korte et al. (1972), who showed the maximum frequency of measurable precipitation in 500 mb lows to be about 2.5° south and 3.5° east of the upper-low center [see Fig. 1.11, taken from Fig. 8 of Klein et al. (1968)]. Taljaard (1985) found that for cutoff cyclones over the South African region, that the heaviest precipitation occurs 500 to 1500 kilometers west of the cyclone center, which reinforces the findings of the two previous studies involving Northern Hemisphere
cyclones. As far as frequency of precipitation from cutoff cyclones, Klein et al. (1968) and Korte et al. (1972), also showed that precipitation occurs with about 50% of closed lows at 500 mb over the western plateau states. Taljaard (1985) also investigated the structure of cutoff cyclones relevant to precipitation distribution and reported that one out of every five cutoff cyclones produces potentially flooding rainfall over South Africa. More recently, Atallah and Aiyyer (2002) showed objectively that cutoff cyclones produce about 30% of the annual precipitation in the northeastern US.

1.3 Study Goals

As stated earlier, the precipitation distribution within cutoff cyclones is often a challenge to predict. To begin to address this challenge, one must be familiar with the mean frequencies and favored tracks of cutoffs. Thus, the primary goals of this research are threefold: 1) to exhibit and diagnose the climatological behavior of cutoff cyclones on hemispheric and regional scales; 2) to document preferred cutoff cyclone tracks; and 3) to construct representative case studies of cutoff cyclones. This research is intended to provide forecasters with tools to aid in the prediction of cutoff cyclones so that they may better forecast the precipitation distributions associated with these features. The study focuses on the frequency of occurrence of cutoff cyclones, and how it changes over different temporal scales. The database constructed for this study contains all cutoff cyclones objectively derived from the NCEP/NCAR reanalysis and is a potent research tool because of its completeness.
The first part of this study develops a climatology that documents the frequency of cutoff cyclones. It is first presented on a hemispheric scale, and subsequently extended to the regional scale. The primary means of presenting the data are maps and histograms of cutoff cyclone frequency for selected geographical areas.

The second part of this study uses the climatology data and generated tracks for each cutoff cyclones categorized as significant according to the author’s definition. The cyclone tracks are then used to determine the favored paths of cutoff cyclones in selected geographical areas. Composite mean tracks are produced primarily for the eastern half of North America. As a means of studying where 500 hPa cutoff cyclones develop, the tracking algorithms are used to delineate favored areas of genesis and lysis.

The third part of this study presents representative case studies of two members of the cutoff cyclone climatology. The accurate prediction of the distribution of precipitation associated with these two cutoff cyclones was difficult in these two events. Both events were forecast to provide heavy precipitation to portions of the NWS Burlington, Vermont, County Warning Area (CWA). In reality, heavy precipitation fell with only one of the cutoff cyclones. Diagnostic analyses are performed in an effort to determine the vastly different results from these two seemingly similar cutoff cyclones.
Fig. 1.1. Schematic meridional cross section through an upper-level trough showing the profile of the polar air before and after the formation of a “cut-off” low. Source: Palmén and Nagler (1949), their Fig. 2.

Fig. 1.2. 500 hPa isotherms (dashed lines, contour interval is 2°C), upper-front boundary (thick dashed line), and geopotential height (solid lines, contour interval is 200 ft), for 03Z 07 Feb, 1947. Source: Palmén and Newton (1969), their Fig. 10.1.
Fig. 1.3. 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 by cold air (cross-hatched) by frontal boundaries (dashed lines). Solid lines represent streamlines. Source: Palmén and Newton (1969) Fig. 10.3.

Fig. 1.4a–e. Five characteristic types of disturbances resulting from the extreme growth of upper-level waves. Thick solid lines represent fronts. Streamlines in warm (cold) are represented by solid (dashed) arrows. Source: Palmén and Newton (1969) Fig. 10.4 a–e.
Fig. 1.5. Schematic of a PV-θ contour (solid line) in an Atlantic storm track sharing its main characteristics with (a) an LC1-type lifecycle and (b) an LC2-type lifecycle. The mean jet at each is represented by the dashed arrows. Source: Thorncroft et al. (1993) Fig. 12.

Fig. 1.6 (a) surface, (b) 850 hPa, (c) 500 hPa, (d) 300 hPa for 1200 UTC 16 Nov, 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 intervals at 40m intervals. Thick line in (c) and (d) is 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. 1.6. Continued

Fig. 1.7. Vertical cross-section along line a–a’ in Fig. 1.6c. Shown is the tropopause (thick solid line), isotherms (dashed lines, contour interval is 5°C), and isentropes (solid lines (contour interval is 5 K). Source: Palmén and Newton (1969) Fig. 10.8.
Fig. 1.8. North-south cross-section through a cold cutoff low centered near Fort Worth, Texas (then, GSW), at 1200Z 05 Feb, 1964. Shown are isotherms (dashed lines, contour interval is 10°C), isentropes (solid lines, contour interval is 2 K, and isotachs [thick solid lines, in ms\(^{-1}\) indicating positions of jet streams.(W, westerly current; E, easterly current)]. Source: Palmén and Newton (1969) Fig. 10.8.

Fig. 1.9. Simulated cross-section of a cold core, upper-level cyclone. Shown are isotachs (v, solid lines, contour interval is 6 ms\(^{-1}\)), isentropes (θ', solid lines, contour interval is 2 K), the tropopause (thick solid line), and the axis or symmetry (represented by the “0” label in the horizontal axis. Source: Thorpe (1986), Fig. 1.
Fig. 1.10. 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. 1.11. 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, tracking, genesis/lysis, cutoff day and grid point of the year

The National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996; Kistler et al. 2002) was utilized for the objective climatology and tracking portions of the study. This global dataset has a 2.5° latitude–longitude spatial resolution and a 6 h temporal resolution. Four times daily 500 hPa geopotential height analysis grids for the period 01 Jan 1948 to 31 Dec 2001 were used. Subjective analyses, where applicable, were performed using data from the NOAA Daily Weather Map Series (DWMS) and NOAA/NWS DIFAX charts. The DWMS provides daily North American surface sea-level pressure analysis, surface snow cover, and 500 hPa geopotential height maps valid at 1200 UTC each day. In addition, recorded maximum and minimum temperatures, and 24 h precipitation ending 1200 UTC are plotted for over 120 stations in the US.

2.1.2 Case Study Analyses

Locally archived NCEP ETA model gridded short-range analyses and forecasts for the two case studies (16 Nov 1999 and 03 Mar 2000), interpolated to 80 km resolution, were used to produce horizontal maps and cross-section analyses. AVN model
data, interpolated to a resolution of provided Archived NWS Automated Surface Observing System (ASOS) and cooperative reporting station data in New York, Vermont, and Massachusetts were used in the development of verification maps. These verification data were acquired via the Internet from the National Climatic Data Center (NCDC, http://www.ncdc.noaa.gov/oa/ncdc.html).

2.2 Methodology

2.2.1 Climatology

Data from 80°N to 80°S latitude for all longitudes were used in this study. Areas poleward of these limits were not considered due to extreme compression of the data caused by closeness of grid points at high latitudes. An objective procedure was developed that locates cutoff cyclones, defined as geopotential height minima with at least a 30 m height rise in all directions, and maintains that height rise for at least three consecutive 6 h analyses, or equivalently, 12 h. This procedure is similar to that developed in BB. The algorithms perform the following functions:

1) Read in 500 hPa gridded geopotential height data.

2) Compare the geopotential height value of each grid point with that of the eight surrounding grid points.

3) Consider the grid point a geopotential height minimum if it is the lowest.

4) Test all geopotential height minima against the 30 m geopotential height-rise requirement.
To perform step 4, the algorithm extends radial arms from the geopotential height minima every 20° (for a total of 18 arms). Geopotential heights are interpolated along the radial arms at a 40 km interval until either a 30 m rise is detected or the distance from the geopotential height minimum reaches 500 km. This interpolation is done for all 18 arms.

Initially, geopotential heights were interpolated along each arm at an interval of 76 km, which is equivalent to 2° longitude at 70°N latitude and was the interval used in BB. It was discovered, however, that with the finer resolution of the NCEP/NCAR reanalysis relative to that of the coarser resolution NMC analyses used in BB, that the algorithms were missing smaller-scale geopotential height changes. Thus, certain smaller cyclones that were deemed to be cutoff by visual comparison with NWS DIFAX maps were not being detected. The interpolation distance was reduced from 76 km to 40 km (approximately by half) to account for the difference in longitude between the NCEP/NCAR reanalysis and the NMC analysis (5° and 2.5°, respectively). This reduction in interpolation distance resulted in the detection of many of the cutoff cyclones that went previously undetected.

Initially, it was required that the 30 m geopotential height rise be detected on all 18 radial arms, following the idea in Fig. 2.1a, taken from Fig. 1a of BB. This requirement proved to be too restrictive, with certain cyclones deemed cutoff by visual inspection not being detected. By reducing this threshold to 16 of 18 arms, the algorithm detected nearly all cyclones deemed cutoff by visual inspection. Figure 2.1b, taken from Fig. 1b of BB, shows an example of a geopotential height minimum where a 30 m geopotential height rise was not detected in all directions. One of the fundamental
differences between this study and BB is that BB required all geopotential height minima to have the 30 m geopotential height rise present in all directions.

The final condition for a geopotential height minimum to be considered a cutoff cyclone was that the 30 m height rise must be maintained for a minimum of three consecutive 6 h analyses (at least two 6 h periods, or 12 h). To construct the subset of cutoff cyclones with a lifespan of at least 12 h, the tracking portion of the algorithm was implemented. The tracking algorithm will be described in detail in section 2.2.2. The climatology consists of only those cutoff cyclones that could be objectively tracked for at least three consecutive 6 h analysis periods, showing good time continuity. After lengthy subjective comparison with NWS DIFAX maps and the DWMS, it is believed that the current algorithms detect nearly all cutoff cyclones between 80°N and 80°S latitude.

The climatology data were stratified by the number of cutoff cyclones passing through a given grid point (termed an “event frequency”), and the number of 6 h analyses where a cutoff cyclone was present at a given grid point (termed a “6 h analysis frequency”). Event frequency distributions are computed such that a given cutoff cyclone is counted only once at each grid point, thus showing the number of cutoff cyclones passing through a particular grid point over the time period stated on each map. The 6 h analysis frequency distributions are computed by counting the number of 6 h analyses where a cutoff cyclone was located at a given grid point over the time period stated on each map.

The General Meteorological Package (GEMPAK) (desJardins et al. 1991), version 5.6 was used extensively to create event and 6 h analysis frequency distributions. The distributions are smoothed using a nine-point smoothing technique built into
GEMPAK 5.6. Hemispheric event and 6 h analysis frequency distributions are shown on annual and seasonal timescales. For this research, Northern Hemisphere (Southern Hemisphere) winter is defined as December, January, and February (June, July, and August); spring as March, April, and May (September, October, and November); and fall as September, October, and November (March, April, and May). Event and 6 h analysis frequency distributions for the Tropics (eastern North America) are shown on the previously defined seasonal (monthly) timescales. This pattern of space/time display is extended to genesis, lysis and genesis minus lysis plots as well. Line graphs are used to show, the frequency of and delineate trends in cutoff cyclone behavior for selected geographical areas.

2.2.2 Cutoff Cyclone Tracking

Once all cutoff cyclones have been detected, they are tracked as long as they meet the definition of a cutoff cyclone stated earlier. In order to track a particular cyclone, an objective kinematic tracking scheme was developed. The reader is encouraged to refer to Figures 2.2 and 2.3 during the following discussion. The algorithm takes the initial position of a cutoff cyclone (termed C) and constructs a 10° (the box perimeter is located 5° from the geopotential height minimum to the north, south, east, and west) box around it. This box (solid border) is shown in Fig. 2.2.2. The mean geostrophic wind vector is then computed for the 25 grid points inside the box. This wind vector is termed $V_g$ and subsequently applied as the total wind at C. It should be noted that because of the symmetrical nature of cutoff cyclones, the magnitude of $V_g$ would be relatively small.
Thus, $V_g$ is primarily used to determine the direction of movement of the cutoff cyclone. In fact, in subjective comparison with NWS DIFAX maps, it was empirically deduced that most cutoff cyclones moved at a speed twice that of the magnitude of $V_g$. Following this deduction, the cyclone’s position at the next 6 h analysis time is computed using a speed of twice the u-component and twice the v-component of $V_g$. Once this predicted position is determined, the box is extended 2.5° north and south, and 300 km east and west of the new position. This is done to account for rapidly moving closed lows still under the influence of strong flow and is shown as the dashed box in Fig. 2.2.

As a final continuity check, the algorithm also confirms that the current position of the cyclone matches logically with the previous position. To perform this check, the same box structures are constructed, but using a direction opposite to that of $V_g$. This is demonstrated as the dotted box in Fig. 2.2. The conditions for the size of the dotted box are exactly the same as in the determination of the dashed box described earlier. The dashed (dotted) boxes is shown in greater detail in Fig. 2.3a (b). A cutoff cyclone is tracked as being the previously existing cyclone if the next (previous) position fell within the confines of the box depicted in Fig. 2.3a (b).

It should be noted that if $V_g = 0$, then an initial box, centered on the geopotential height minimum, with east-west length of 600 km and north-south length of 500 km was used (not shown). It was empirically observed in cases of $V_g = 0$, that a 600 km by 500 km box was sufficient to capture cutoff cyclone motion. Using the $V_g$ as the initial motion vector of the cutoff cyclone accounts for both eastward-moving cyclones influenced by the mean westerlies, as well as quasi-stationary or westward-moving cyclones that are removed from the main belt of the westerlies. It should also be noted
that Figs. 2.3a–b shows that the original, previous and subsequent cutoff cyclone positions are located at a grid point. This is done to account for the fact that the geopotential height centers in the climatology are interpolated to a grid point.

No attempt was made to track cyclones that “open up” and then close off again later. In that case, two cyclones would be counted, provided each met the conditions of the definition of a cutoff cyclone.

2.2.3 Genesis/Lysis/Genesis minus Lysis

The genesis/lysis database is a direct product of the objectively derived cutoff cyclone tracks described in sec. 2.2.1. The method of locating a particular genesis or lysis event is fundamentally similar to that used in BB. A genesis (lysis) event is defined as the first (last) analysis period when the definition of a cutoff cyclone is met. Genesis (lysis) events are taken from the tracking results as the first (last) positions in a cutoff cyclone track. Genesis minus Lysis plots are produced by subtracting the two previous fields, and are created in order to highlight areas where cutoff cyclone genesis exceeds lysis and vice-versa.

2.2.4 Cutoff cyclone day/grid point of the year

The climatology data were further stratified by number of cutoff cyclones per day at any gridpoint, and number of cutoff cyclones at any gridpoint. The day with the most number of cutoff cyclones for each year [termed the cutoff day of the year (CDOY)], are
graphed for the Northern Hemisphere, for each of the 54 years in the study in order to
delineate any trends. The gridpoint with the most number of cutoff cyclones passing
through it [termed the cutoff grid point of the year (CGOY)], is hand-plotted for each of
the 54 years in the study on a Northern Hemisphere map in order to emphasize areas
where cutoff cyclones tend to cluster and how those areas change.

2.2.5 Case Studies

The two case studies conducted were chosen because of the vastly different
distributions of precipitation within them. As stated earlier, two cutoff cyclones passed
through the Northeast US (15–17 NOV 1999 and 02–04 MAR 2000). Both cutoff
cyclones were forecast to produce heavy precipitation within the NWS Burlington
(BTV), VT, CWA. In reality, heavy precipitation occurred with only the 1999 event. The
maps produced and their purpose are as follows:

1) 500 hPa geopotential height, vorticity, and wind speed and direction barbs, in
   order to investigate the track and position of the cutoff cyclone.

2) 850 hPa geopotential height, temperature, and wind speed and direction, in
   order to determine the mean wind flow with respect to the varying terrain in
   the BTV CWA.

3) 950 hPa geopotential height, relative humidity, temperature and wind speed
   and direction, same as in (2) but also to investigate the availability of low-
   level moisture.
4) Mean sea-level pressure, 1000-500 hPa thickness (ΔZ), and 300 hPa wind speed, to investigate the overall dynamics associated with surface cyclone development (used for analysis only, not shown).

5) Vertical cross sections of relative humidity, wind speed and direction, potential temperature and vertical velocity (omega) centered on BTV, in order to investigate moisture and stability profiles of the two cutoff cyclones.

6) Maps of surface potential temperature (θ), wind barbs and mixing ratio (q) for the northeast US, in order to analyze the presence and potential effects of surface boundaries.

GEMPAK was used to produce the aforementioned maps. Precipitation verifications were plotted mechanically using ASOS and Cooperative observer data.
Fig. 2.1. Sample 500 hPa geopotential height analysis illustrating the objective method used to identify cutoff cyclones. (a) Three sample radial arms out of the actual 20 used to identify a 30 m closed contour around the center grid point of a cutoff cyclone. A geopotential height rise of at least 30 m before a decrease along all arms. (b) As in (a) except that geopotential heights along the dashed radial arm do not exceed 30 m higher than point A before decreasing. Source: Bell and Bosart (1989), Fig. 1a–b.
Fig. 2.2. Schematic representation of the objective method used to track a cutoff cyclone initially located at C. $V_g$ is the twice the mean vector geostrophic wind, which is calculated by averaging the zonal ($u$) and meridional ($v$) wind component at each of the 25 grid points within the solid box. $-V_g$ is calculated the same as $V_g$ but with opposite sign. $C'$ ($C''$) is the predicted position of the cyclone center 6 h later (earlier). The dashed (dotted) box represents the area in which the next (previous) position of the cutoff cyclone must be located in order to have those positions counted in a continuous track.

Fig. 2.3. Close-up schematic of the dashed (a) and dotted (b) boxes shown in Fig. 2.2. $V_g$, $-V_g$, $C'$, $C''$, $u$, and $v$ are as in Fig. 2.2.
Fig. 3.1. For the NH, a) the number of cutoff cyclone events (thick solid line) with 5-year running mean (thin solid line) for 1948–2001, b) the average number of cutoff cyclones per day (thick solid line) with 5-day running mean (thin solid line), c) the grid point with the most number of observed cutoff cyclones.
Fig. 3.1. continued.

Fig. 3.2. Total number of cutoff cyclone events (shaded and contoured every 24 events) per grid point for the NH for 1948–2001.
Fig. 3.3. Total number of 6 h analyses with a cutoff cyclone (shaded and contoured every 24 analyses) per grid point for the NH for 1948–2001.

Fig. 3.4. Total number of 6 h analyses that exceed number of events (shaded and contoured every 12 analyses) per grid point for the NH for 1948–2001.
Fig. 3.5. Number of cutoff cyclone events (shaded and contoured every 12) per grid point for NH fall.

Fig. 3.6. Number of 6 h analyses with a cutoff cyclone (shaded and contoured every 12) per grid point for NH fall.
Fig. 3.7. As in Fig. 3.5 but for NH winter.

Fig. 3.8. As in Fig. 3.6 but for NH winter.
Fig. 3.9. As in Fig. 3.5 but for NH spring.

Fig. 3.10. As in Fig. 3.6 but for NH spring.
Fig. 3.11. Favored areas for cutoff cyclone activity for the NH.

Fig. 3.12. 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 (a) box 1N, (b) box 2N, (c) box 3N, (d) box 4N, (e) box 5N, (f) box 6N, (g) box 7N, (h) box 8N, (i) box 9N, (j) box 10N, as defined in Fig. 3.11.
Fig. 3.12. continued.
Fig. 3.12. continued.
Fig. 3.12. continued.
Fig. 3.13. Total number of cutoff cyclone genesis events (contoured and shaded every 6 events) per grid point for the NH for 1948–2001.

Fig. 3.14. As in Fig. 3.14 but for cutoff cyclone lysis events.
Fig. 3.15. (a) Total number of cutoff cyclone genesis (lysis) events that exceed lysis (genesis) events [solid (dashed) contours and shaded every 3 events] per grid point for the NH for 1948–2001 and (b) composite mean 250 hPa wind direction (in the direction of the arrow) and speed (shaded every 5 m s$^{-1}$) for 1948–2001.
Fig. 3.16. Number of cutoff cyclone genesis events (contoured and shaded every 3 events) per grid point for NH fall.

Fig. 3.17. Number of cutoff cyclone lysis events (contoured and shaded every 3 events) per grid point for NH fall.
Fig. 3.18. As in Fig. 3.16 but for NH winter.

Fig. 3.19. As in Fig. 3.17 but for NH winter.
Fig. 3.20. As in Fig. 3.16 but for NH spring.

Fig. 3.21. As in Fig. 3.17 but for NH spring.
Fig. 3.22. a) As in Fig. 3.1a but for the SH; b) as in Fig. 3.1b but for the SH.
Fig. 3.23. Topographic map of Antarctica.
Fig. 3.24. As in Fig. 3.2 but for the SH.

Fig. 3.25. As in Fig. 3.3 but for the SH.
Fig. 3.26. As in Fig. 3.4 but for the SH.

Fig. 3.27. As in Fig. 3.5 but for SH fall.
Fig. 3.28. As in Fig. 3.6 but for SH fall.

Fig. 3.29. As in Fig. 3.7 but for SH winter.
Fig. 3.30. As in Fig. 3.8 but for SH winter.

Fig. 3.31. As in Fig. 3.9 but for SH spring.
Fig. 3.32. As in Fig. 3.10 but for SH spring.

Fig. 3.33. As in Fig. 3.11 but for the SH.
Fig. 3.34. As in Fig. 3.12 but for (a) box 1S, (b) box 2S, (c) box 3S, (d) box 4S, (e) box 5S.
Fig. 3.34 continued.
Fig. 3.35. As in Fig. 3.13 but for the SH.

Fig. 3.36. As in Fig. 3.14 but for the SH.
Fig. 3.37a. As in Fig. 3.15a but for the SH.

Fig. 3.37b. As in Fig. 3.2b but for the SH.
Fig. 3.38. As in Fig. 3.16 but for SH fall.

Fig. 3.39. As in Fig. 3.17 but for SH fall.
Fig. 3.40. As in Fig. 3.18 but for SH winter.

Fig. 3.41. As in Fig. 3.19 but for SH winter.
Fig. 3.42. As in Fig. 3.20 but for SH spring.

Fig. 3.43. As in Fig. 3.21 but for SH spring.
Fig. 3.44. a) As in Fig. 3.1a but for the Tropics, b) as in Fig. 3.1b but for the Tropics.

Fig. 3.45. As in Fig. 3.2 but for the western hemisphere Tropics. Contour interval is every 3 through 6, then every 6 through 24, then every 12 through 48, then every 24. Latitude and longitude lines are plotted every 10º and labeled every 20º.
Fig. 3.46. As in Fig. 3.3 but for the western Hemisphere Tropics. Contour interval as in Fig. 3.45.

Fig. 3.47. As in Fig. 3.4 but for the western hemisphere Tropics. Contour interval as in Fig. 3.45.

Fig. 3.48. As in Fig. 3.45 but for the eastern hemisphere Tropics.
Fig. 3.49. As in Fig. 3.46 but for the eastern hemisphere Tropics.

Fig. 3.50. As in Fig. 3.47 but for the eastern hemisphere Tropics.

Fig. 3.51. Cutoff cyclone events for the western hemisphere Tropics (contoured and shaded every event through six, then every six events through 24, then every 12 events) per grid point for September, October and November.)
Fig. 3.52. Number of 6 h analyses with a cutoff cyclone for the western hemisphere Tropics (contoured and shaded every event through six, then every six events through 24, then every 12 events) per grid point for September, October and November.

Fig. 3.53 As in Fig. 3.51 but for the eastern hemisphere Tropics.

Fig. 3.54. As in Fig. 3.52 but for the eastern hemisphere Tropics.
Fig. 3.55. As in Fig. 3.51 but for December, January and February.

Fig. 3.56. As in Fig. 3.52 but for December, January and February.

Fig. 3.57. As in Fig. 3.53 but for December, January and February.
Fig. 3.58. As in Fig. 3.54 but for December, January and February.

Fig. 3.59. As in Fig. 3.51 but for March, April and May.

Fig. 3.60. As in Fig. 3.52 but for March, April and May.
Fig. 3.61. As in Fig. 3.53 but for March, April and May.

Fig. 3.62. As in Fig. 3.54 but for March, April and May.

Fig. 3.63. As in Fig. 3.12 but for box 1T in Fig. 3.50.
Fig. 3.64. As in Fig. 3.13 but for the western hemisphere Tropics. Contour interval is as in Fig. 3.45.

Fig. 3.65. As in Fig. 3.14 but for the western hemisphere Tropics. Contour interval is as in Fig. 3.45.

Fig. 3.66. As in Fig. 3.15a but for the western hemisphere Tropics. Contour interval is every three events.
Fig. 3.67. As in Fig. 3.13 but for the eastern hemisphere Tropics. Contour interval is as in Fig. 3.45.

Fig. 3.68. As in Fig. 3.14 but for the eastern hemisphere Tropics. Contour interval is as in Fig. 3.45.

Fig. 3.69. As in Fig. 3.15 but for the eastern hemisphere Tropics. Contour interval is every three events.
Fig. 3.70. As in Fig. 3.13 but for the western hemisphere Tropics: September, October and November. Contour interval is as in Fig. 3.45.

Fig. 3.71. As in Fig. 3.14 but for the western hemisphere Tropics: September, October and November. Contour interval is as in Fig. 3.45.

Fig. 3.72. As in Fig. 3.13 but for the eastern hemisphere Tropics: September, October and November. Contour interval is as in Fig. 3.45.
Fig. 3.73. As in Fig. 3.14 but for the eastern hemisphere Tropics: September, October and November. Contour interval is as in Fig. 3.45.

Fig. 3.74. As in Fig. 3.13 but for the western hemisphere Tropics: December, January and February. Contour interval is as in Fig. 3.45.

Fig. 3.75. As in Fig. 3.14 but for the western hemisphere Tropics: December, January and February. Contour interval is as in Fig. 3.45.
Fig. 3.76. As in Fig. 3.13 but for the eastern hemisphere Tropics, December, January and February. Contour interval is as in Fig. 3.45.

Fig. 3.77. As in Fig. 3.14 but for the eastern hemisphere Tropics, December, January and February. Contour interval is as in Fig. 3.45.

Fig. 3.78. As in Fig. 3.13 but for the western hemisphere Tropics, March, April, May. Contour interval is as in Fig. 3.45.
Fig. 3.79. As in Fig. 3.14 but for the western hemisphere Tropics: March, April, May. Contour interval is as in Fig. 3.45.

Fig. 3.80. As in Fig. 3.13 but for the eastern hemisphere Tropics: March, April, May. Contour interval is as in Fig. 3.45.

Fig. 3.81. As in Fig. 3.14 but for the eastern hemisphere Tropics: March, April, May. Contour interval is as in Fig. 3.45.
Fig. 3.82. Number of cutoff cyclone events (contoured and shaded every three events) per grid point for eastern North America for (a) October; (b) November; (c) December; (d) January; (e) February; (f) March; (g) April; (h) May 1948–2001.
Fig. 3.83 As in Fig. 3.82 but for number of 6 h analyses with a cutoff cyclone.
Fig. 3.83 continued.
Fig. 3.84. Composite mean cutoff cyclone tracks impacting eastern North America.
NCEP/NCAR Reanalysis
250mb Vector Wind (m/s) Composite Mean

Dec to Feb: 1949 to 2001
3. Results

3.1 Climatology

The algorithms described in Chapter 2 were applied to the NCEP/NCAR reanalysis dataset for the period 01 January 1948 through 31 December 2001 for a total of 54 years. During this period a total of 304,998 500 hPa cutoff cyclones were detected between 80°N and 80°S latitude for all longitudes. Although the climatology includes all months of the year, the primary focus of this study is on annual and cool season (defined as 01 October through 31 May for the Northern Hemisphere, and 01 Mar through 30 Nov for the Southern Hemisphere) cutoff cyclone behavior. Thus, for the Northern (Southern) Hemisphere, the first complete fall (spring) presented is September, October and November 1948, the first winter presented is December 1948 and January and February 1949 (June, July and August 1948), and the first spring (fall) is March, April and May 1948. The warm season for the Northern (Southern) Hemisphere, defined as June, July and August (December, January, and February), will not be addressed in this thesis.

3.1.1 Northern Hemisphere

3.1.1a Total cutoff cyclone events/6 h analyses, cutoff day/grid point of the year.

The total number of cutoff cyclones per year for the Northern Hemisphere (hereafter NH) is shown in Fig. 3.1a. The number of cutoff cyclone events is shown as the thick solid line, with a 5-year running mean shown as the thin solid line. This graph
shows that on average, about 3500 cutoff cyclones occur over the NH each year, or roughly 10 per day. The number of cutoff cyclones is seen to increase from 1948 to 1957–1958, which is the International Geophysical Year (IGY). Atmospheric upper-air data became more reliable and frequent with increased spatial resolution after the IGY due to the implementation of more consistent and accurate observing networks. It is highly likely that the number of cutoff cyclones did not in fact increase from about 2600 in 1948 to about 3500 in 1958, but rather the observing networks in the late 1940’s and most of the 1950’s were of insufficient density to capture cutoff cyclones, especially over the vast oceans. Also noteworthy is the consistency in the number of cutoff cyclones from year to year after the IGY, with a standard deviation of 115 events, or about 3% from year to year.

Figure 3.1b shows the average number of cutoff cyclones objectively detected per day of the year in the NH. Cutoff cyclones exhibit a fairly smooth overall pattern of a seasonal maximum (minimum) occurring in late spring/early summer (winter). About 8 cutoff cyclones occur per day in the cool season, increasing to about 11 per day during late spring and early summer. The highest number of cutoff cyclones objectively observed on one day in the 54-year period was 20 on 22 June 1975 (not shown). Figure 3.1c shows the grid points that featured the greatest number of cutoff cyclone events in a given year. It can be seen from Fig. 3.1c that the most prolific cutoff cyclone region is the northern Pacific Ocean, with nearly half of the most active grid points in this region. Other favored regions for large numbers of cutoff cyclones are across southern Europe and the northern Mediterranean Sea, near Hudson Bay, the north-central Atlantic Ocean, and across eastern India. These areas, as well as other important features, will be
discussed in more detail in the following sections. Please note that the cutoff day/grid point of the year will only be shown for the NH.

Frequency distributions of total number of cutoff cyclone events (6 h analyses) for the NH are shown in Fig. 3.2 (3.3). Inspection of Fig. 3.2 reveals that the event distribution pattern shows distinct areas favorable for cutoff cyclones. Conversely there are areas where very few cutoff cyclones exist. This pattern suggests that cutoff cyclones require a specific set of conditions to exist, and that these conditions exist in relatively few parts of the NH. A large frequency maximum exists over the northwest Pacific Ocean, in a band from extreme northeast Asia eastward to the Gulf of Alaska. This band of cutoff activity includes some smaller-scale imbedded maxima in the northern Sea of Okhotsk, near 50°N and the International Date Line, over the central Aleutians, and in the central Gulf of Alaska. Other favored areas include over the southwest US, Hudson Bay, the northeast US/Canadian Maritimes extending northeastward to just east of the southern tip of Greenland, the east coast of the Iberian Peninsula, the Mediterranean basin, including the Turkish Plateau and Caspian Sea region, and the Indian subcontinent. Reference to cutoff cyclone activity over India will be brief in this section, but will be discussed further in section 3.1.3 (Tropics).

The southwest US maximum appears to be connected to the maximum over Hudson bay and the northeast US/Canadian maximum by a narrow corridor of relatively higher numbers of events. This feature will be referred to hereafter as the “cutoff freeway.” Also notable are the relatively weak frequency maxima that extend southwestward toward Hawaii and the subtropical central Atlantic Ocean. Cutoff cyclones are relatively less likely to be observed in the following areas: over the US and
Canadian Rockies; over Greenland; and over much of Mongolia and China and the Himalayan plateau. The relatively small number of observed cutoff cyclones in these areas is most likely due to terrain with high enough elevation either to inhibit or prevent detection of cutoff cyclones at 500 hPa. The maximum over the Indian subcontinent most likely represents the development of frequent low pressure systems associated with the summer regime of the Asian monsoon. Cutoff cyclones are also relatively less likely to be observed in the Atlantic and Pacific Ocean basins near semi-permanent surface high pressure centers.

Figure 3.3 shows the number of 6 h analyses where a cutoff cyclone was detected at a grid point. Inspection of Fig. 3.3 reveals that nearly all of the maxima of 6 h analysis frequency coincide with maxima in event frequency in Fig. 3.2, which reinforces the idea that many cutoff cyclones are slow moving or quasi-stationary. This pattern of cutoff cyclone distribution is the premise behind Fig. 3.4, which shows the number of 6 h analyses that exceed the number of cutoff events for the 54-year period. Maxima occur in fundamentally similar regions to that of Figs. 3.2 and 3.3. This similarity not only indicates that cutoff cyclones tend to be slow moving, but also that the favored areas have characteristic synoptic-scale dynamics that may not exist in the less favorable regions. The favorable areas include the North Pacific from the Sea of Okhotsk to the Gulf of Alaska, the southwest US, Hudson Bay, the Iberian Peninsula, the central Mediterranean, the Turkish Plateau, just northeast of the Caspian Sea, and across the Indian subcontinent. The Caspian Sea and southwest US regions are particularly interesting in that the number of 6 h analyses noted in Fig. 3.3 is nearly double the number of events shown in Fig. 3.2, indicating that the majority of cutoff cyclones in these areas are quasi-stationary at some
point in their lifecycle. Areas where an event maximum exists in Fig. 3.2 but where the number of 6 h analyses is not as excessive include the northeast US Coast/Canadian Maritimes. The closer proximity of the event and 6 h analyses over the northeast US/Canadian Maritimes suggests that cutoff cyclones are more mobile than in the other favored regions. This and other specific regions of cutoff cyclone activity will be discussed further in section 3.1.1c.

3.1.1b Seasonal cutoff cyclone events/6 h analyses

Frequency distributions of cool-season cutoff cyclone events (6 h analyses) begin with fall and are shown in Figs. 3.5 (3.6). Inspection of Fig. 3.5 shows that fall cutoff cyclone maxima follow a similar pattern to that in the annual distributions shown in Fig. 3.2. A notable difference is that the axis of cutoff cyclone activity over the north Pacific and US/Canadian Maritimes appear to be shifted slightly poleward when compared to Fig 3.2. This shift is most likely depicting the more poleward positioning of the mean westerlies in the warmer months and will be discussed in greater detail in section 5.

Inspection of Fig. 3.6 reveals that the distribution of number of 6 h analyses with a cutoff cyclone in fall follows a similar pattern to that of the entire year, which was previously shown in Fig. 3.3. Maxima in fall occur over the Sea of Okhotsk, The Gulf of Alaska, the southwest US, Hudson Bay, east of the southern tip of Greenland, the eastern Iberian Peninsula, and the Mediterranean east of Italy, the Turkish Plateau and the Indian subcontinent. Cutoff cyclones that tend to be more mobile are likely to be found in the cutoff freeway across the central US and the band of cutoff activity across the
US/Canadian Maritimes. Also notable are the “tails” of cutoff activity that extend southwest from the west coasts of the US and Europe. Although much weaker than their poleward counterparts, they are as consistent throughout the cool season.

The winter months, defined as December, January and February, are shown in Figs. 3.7–3.8. The overall distribution of cutoff cyclone events is similar to that of fall, but with some localized differences. Cutoff cyclones tend to be found in more defined bands in winter than in fall. Other notable differences include an increase (a decrease) in the number of cutoff cyclones over the northwest Pacific (Gulf of Alaska).

Maps of cutoff cyclone events and 6 h analyses with a cutoff for the NH spring are shown in Figs. 3.9 and 3.10. In general, the distribution of cutoff cyclone activity is consistent with that of winter, but the frequency in the favored areas increases. This increase leads to a better defined pattern overall, and in many regions the strongest signals of the year exist in spring. The maximum over the north Pacific extends farther westward into northeastern Asia and farther east into the Gulf of Alaska. This extension is also seen in the broad maximum over the Mediterranean, which now reaches smartly over the Caspian Sea, with a weaker maximum stretching across Afghanistan and northern Pakistan. The cutoff freeway across the central US also shows a marked increase over that of winter, consistent with a more active spring storm track. Figure 3.10 also shows that a 6 h analysis maximum reappears in the Gulf of Alaska.

3.1.1c Specific areas of cutoff cyclone activity
As stated and discussed in the previous paragraphs, cutoff cyclone activity appears to be confined to selected regions. In an effort to further address these specific areas, the data in Figs. 3.2–3.10 were used to create Fig. 3.11, which shows ten mechanically constructed boxes, which were subjectively chosen as cutoff cyclone “hot spots” for the NH. For each of these 10 boxes, a graph of total number of cutoff cyclone events (dashed line), number of 6 h analyses with a cutoff cyclone (thick solid line), and percentage of 6 h analyses that exceed events, or “stationary analyses” (thin solid line), in 14-day increments, for the entire year. These graphs are shown in Fig. 3.12a–j as boxes 1N through 10N. Note that the number of cutoff cyclone events and 6 h analyses (percentage of stationary analyses) is read using the left (right) axis.

Box 1N, located over northeast Asia and the Sea of Okhotsk, is represented in Fig. 3.12a. It can be seen from this figure that cutoff cyclones are fairly consistent in number throughout the year, as is the tendency for stationary cutoffs. Weak maxima (minima) in the number of events occur in winter and summer (transition seasons). Cutoff cyclones in this region tend to be more stationary (mobile) in the winter and summer (transition seasons) as well, as indicated by higher (lower) percentage of stationary analyses.

Box 2N represents the region in the North Pacific from Kamchatka, eastward to about 160W. Figure 3.12b shows that cutoff cyclones in this region increase significantly from late spring, peak in early summer, and begin to decline by mid-summer. After a weak secondary maximum in early fall, the cool season features a fairly consistent pattern of cutoff cyclone activity. Cutoff cyclones are more (less) likely to be quasi-stationary in summer (winter). A strong similarity exists between Boxes 1N and 2N, despite a clear
break in the maxima seen in Figs. 3.2–3.4. This similarity suggests that similar synoptic-scale processes are at work in these regions, and the mountainous terrain of Kamchatka is disruptive enough to cutoff cyclones to create the relative minimum in activity.

The Gulf of Alaska (box 3N) cutoff cyclone activity is shown in Fig. 3.12c. Strong seasonal dependence is seen in this region, with a distinct maximum (minimum) in summer (winter). Summer appears to have the largest occurrence of quasi-stationary cutoffs as well, with relatively more mobile systems indicated in the cool season.

Box 4N represents the southwest US and is shown in Fig. 3.12d. Cutoff cyclones are most prevalent in the cool season, with a sharp decline from June through September. The percentage of stationary analyses increases from an early spring minimum, reaching a maximum in summer. 6 h analyses exceed events by as much as 50% during the warm season in the southwest US, however the very low numbers of cutoff cyclones during summer may be skewing the results.

The area of activity near Hudson Bay (box 5N) is shown in Fig 3.12e. This area most likely represents the meteorological North Pole and is one of the most consistent areas for cutoff cyclones. Summer and winter (spring and fall) are the most (least) active seasons, although the seasonal change is relatively small. There is a strong signal for the existence of quasi-stationary cutoff cyclones to in all seasons as indicated by the relatively large and stable percentage of stationary analyses.

Box 6N covers the US/Canadian Maritimes and is shown in Fig. 3.12f. Cutoff cyclones increase from a summer minimum through the cool season, and are maximized in spring. The active North Atlantic storm track well known to meteorologists is
manifested in the low percentage of stationary analyses from fall through early spring, with an increase as the storm track weakens toward summer.

The exit region of the North Atlantic storm track (box 7N) is shown in Fig. 3.12g. A general maximum occurs from early summer and is maintained until fall, with a seasonal minimum from late fall through late winter. Cutoff cyclones are relatively mobile when compared to other major areas of activity, with the indication of more stationary cyclones occurring from spring through early fall.

Box 8N represents the region of cutoff cyclone activity just east of the Iberian Peninsula. Fig. 3.12h reveals that the frequency of number of cutoff cyclones in this region is fairly consistent throughout the year, with a relatively brief minimum in late summer. The percentage of stationary analyses is also quite consistent in this area.

Box 9N and 10N represent the Turkish Plateau and the region northeast of the Caspian Sea, respectively. The cutoff cyclone activity in these two regions is fairly similar and is shown in Figs. 3.12i–j. Cutoff cyclones increase from a later summer minimum to a maximum in spring. Consistency is also seen in the percentage of stationary periods in both regions, with very little seasonal variation.

3.1.1d Cutoff cyclone genesis/lysis

Figures 3.13 and 3.14 show the total number of cutoff cyclone genesis and lysis events for the NH for the period 1948–2001. Areas of activity with regard to these two parameters will be discussed with regard to their geographical position and seasonal variation, as well as their relative position to each other.
1) North Pacific Ocean

Genesis events occur most frequently between 45°N and 60°N, with specific maxima over the northern tip of Sakhalin Island, near 51°N 175°E, and in the north central Gulf of Alaska. Inspection of Fig. 3.14 reveals that lysis maxima occur in a band from the north central Sea of Okhotsk across the southern tip of Kamchatka to about 175°E longitude. This eastward displacement of lysis maxima relative to genesis maxima suggests a mean eastward movement to cutoff cyclones in this region. In contrast, a lysis maximum occurs in virtually the same position as the genesis maximum in the Gulf of Alaska, suggesting more slow-moving or quasi-stationary cutoff cyclones.

2) US and Canadian west coast and southwest region of the US.

A relatively weaker band of cutoff cyclone genesis events extends from the eastern Gulf of Alaska along the US and Canadian west coast to a maximum over and northern California and Nevada. Lysis events in this region appear as more-separate areas, with relative maxima in the Gulf of Alaska and over the central and southern US Rockies. This pattern also suggests that cutoff cyclones that develop over the Gulf of Alaska tend to be more quasi-stationary, while their southwest US counterparts show general movement toward the southeast.

3) Cutoff freeway

Figure 3.13 shows that a relatively weak band of cutoff cyclone genesis events extends northeastward out of the southwest US, across the central US, and into the Great Lakes region. Figure 3.14 shows that a relatively more broad area of lysis events exists across the central US. This pattern of a relatively narrow genesis band compared with the
lysis band suggests that cutoff cyclones in this band are generally mobile and can follow varied paths within the band.

4) Eastern North America

Three distinct areas of cutoff cyclone genesis/lysis appear in Figs. 3.13–3.14 over eastern North America. A maximum of both genesis and lysis exists over the eastern portion of Hudson Bay, suggesting a tendency for slow-moving or quasi-stationary cutoff cyclones to exist. Note that in this region the genesis area has greater spatial coverage with a smaller maximum value, while the lysis maxima appears more concentrated. This distribution indicates that the Hudson Bay region is a graveyard for cutoff cyclones that originate in multiple areas. Other genesis maxima occur over eastern Labrador and off the southern tip of Greenland. Lysis maxima occur in the Davis Strait and between Greenland and Iceland. This distribution suggests that cutoff cyclones developing off eastern Labrador (east of the southern tip of Greenland) are mobile and move north-northeast (northeast).

5) Mediterranean region

Cutoff cyclone genesis and lysis occur regularly in the Mediterranean region but are favored in a few distinct areas. Genesis and lysis maxima exist off the southeast coast of Portugal. The close proximity of these two areas reinforces the idea that cutoff cyclones that develop in this area tend to be stationary. A genesis maximum also occurs over northern Italy along with a lysis maximum over southern Italy. This distribution suggests the likelihood of cutoff cyclones developing in the lee of the Alps and moving south before dissipating over the Mediterranean. A third area of genesis is located over the Turkish Plateau, extending poleward to the region near the Black Sea. Lysis events in
this region show a similar pattern, but extend farther poleward. This pattern suggests that although most cutoff cyclones in this region may be quasi-stationary, there may be some that actually move poleward from the Turkish Plateau and dissipate.

Figure 3.15a shows areas where number of genesis events exceeds number of lysis events (shaded with solid contours) and areas where lysis exceeds genesis (shaded with dashed contours) for the 54-year period. Fig 3.15b shows the 300 hPa composite mean wind for the NH for the same 54-year period. According to Fig. 3.15b, mean jet entrance regions can be found across northeast Asia, the southwest US, and across northern Africa. Mean jet exit regions are found over the northeast Pacific and north-central Atlantic Oceans. Note that in the aforementioned jet entrance regions, areas where genesis dominates lie poleward of areas where lysis dominates. This pattern occurs across the extreme northwest Pacific, the southwest US, and the north central Mediterranean region, as indicated with a solid box. It can also be seen that in mean jet exit regions, areas where lysis dominates lie poleward of areas where genesis dominates (indicated by dashed boxes). These areas include the Gulf of Alaska and across the north-central Atlantic Ocean. Seasonal variation of the features in Fig. 3.15 is small; therefore seasonal plots will not be shown.

3.1.1e Seasonal cutoff cyclone genesis/lysis

Figure. 3.16 (3.17) shows the distribution of cutoff cyclone genesis (lysis) for NH fall. Winter is shown in Figs. 3.18–3.19, and spring in Figs. 3.20–3.21. The overall pattern seen in Figs. 3.16 and 3.17 these two figures is that genesis and lysis in fall is
similar to that of the entire year (shown previously in Figs. 3.14 and 3.14). Subtle changes that indicate a seasonal dependence are the lower values of cutoff cyclone genesis/lysis in fall (Figs. 3.16–3.17), with an increase in numbers through winter (Figs. 3.18–3.19). The exception is the Gulf of Alaska, where a decrease in overall genesis/lysis activity occurs. As spring (Figs. 3.20–3.21) approaches, the incidents of cutoff cyclone genesis and lysis shift eastward across the Pacific Ocean. An increase in activity continues across the Turkish Plateau, with a more defined pattern of genesis and lysis than in fall or winter.

3.1.2 Southern Hemisphere

3.1.2a Total cutoff cyclone events/6 h analyses

The total number of cutoff cyclones per year for the Southern Hemisphere (SH) is shown in Fig. 3.22a by a thick solid line, with the 5-year running mean by the thin solid line. The number of cutoff cyclones is very consistent from year to year, and averages about 2200, or roughly six per day. An interesting note is that the increase in cutoff cyclone activity after the IGY in the NH (Fig. 3.1) does not exist for the SH. This apparent discrepancy will require further investigation. Figure 3.22b shows that the average number of cutoff cyclones per day in the SH is about 6 in the cool season, and rises to about 7 in the warm season. A similar pattern to that of the NH is seen, with a maximum occurring in SH summer. The number of cutoff cyclones is minimized during SH fall and spring, with a weak secondary maximum appearing during SH winter.
A topographic map of Antarctica is shown in Fig. 3.23 for reference during this section. Please note that the orientation of Antarctica in the topographic map in Fig. 3.23 is rotated counter-clockwise 90º from its original orientation to coincide with the orientation of Antarctica in the subsequent figures in section 3.1.2. Frequency distributions for number of cutoff cyclone events (6 h analyses) for the SH begin with Fig. 3.24 (3.25). The vast majority of cutoff cyclones cluster in a band around Antarctica, with the highest numbers between 50°S and 65°S latitude. A strong maximum within this band stretches westward between 120°E and 10°W longitude. This maximum is separated from another maxima near 80°W by the Antarctic Peninsula. A distinct maximum is located near the Amery Ice Shelf (near 60°E) and actually contains the highest concentration of cutoff cyclones in the SH despite its relatively small size. Other distinct maxima in the band around Antarctica occur over the Ross (near 150°E) and Amundsen (near 170°W) Seas.

Cutoff cyclones occur away from Antarctica, but at much lower frequencies. A band of cutoff cyclone events stretches eastward from eastern Australia to about 130°W longitude. Smaller maxima occur off southeast South America and southwest Africa, as well in the Mozambique Channel. The tendency for cutoff cyclones in the SH to be slow moving or quasi-stationary is relatively high in the favored areas just mentioned. Fig. 3.25 reveals maxima of 6 h analyses with a cutoff in all of the favored cutoff cyclone event regions, and this distribution shows up consistently in Fig. 3.26, which shows the number of 6 h analyses that exceed the number of events. The patterns in this latter figure emphasize the areas where cutoff cyclones tend to be stationary or slow moving.
3.1.2b Seasonal cutoff cyclone events/6 h analyses.

Figures 3.27–3.28 show distributions of cutoff cyclone events and 6 h analyses with a cutoff cyclone for SH fall. Inspection of these two figures reveals that fall cutoff cyclones are similar in their distribution to that of the entire year (as shown in Figs. 3.24–3.25). In fact, the spatial distribution in the SH appears to be much more consistent from season to season than in the NH. This consistency can be seen from inspection of Figs. 3.29–3.30 (winter) and 3.31–3.32 (spring). An increase in the number of cutoff cyclones in general within the favored regions as the cool-season progresses is seen. This increase in activity is indicated by the higher values in winter and spring when compared to fall. This pattern of increasing cutoff cyclone activity is similar to that seen in the NH (see the discussion in section 3.1.1c).

3.1.2c Specific areas of cutoff cyclone activity

Figure 3.33 shows the five predominant areas of cutoff cyclone activity in the SH, subjectively chosen using the distributions shown in Figs. 3.24–3.26. Box 1S represents the area, off the southeast coast of Chile. Figure 3.34a shows that cutoff cyclones are at a seasonal minimum during SH summer and increase gradually through the cool season to a late spring maximum. A relatively sharp drop off is seen as summer approaches. A relatively stable pattern is seen in the high percentage of stationary analyses, indicating that stationary cutoff cyclones can occur at any time of year.
Box 2S covers the region just west of the Antarctic Peninsula over the Bellingshausen Sea. Fig. 3.34b shows that cutoff cyclones are maximized during the warm season, with a gradual decline during SH fall, to a winter minimum. A subsequent rise takes place during SH spring. Mobile cutoff cyclones are consistently indicated by the relatively low percentage of stationary analyses.

Figure 3.34c shows that cutoff cyclones over eastern Australia and the Tasmanian Sea (box 3S) occur preferentially in SH fall and spring, although the seasonal variation is relatively small. Cutoff cyclones are more likely to be stationary (mobile) in summer (winter) although the seasonal variation is small.

The very active region of cutoff cyclone activity extending eastward from the Amery Ice Shelf (box 4S) is the focus of Fig. 3.34d. A strong seasonal dependence is seen with a warm season maximum occurring, which drops off smartly to a fall minimum. The frequency of cutoff cyclones increases gradually through the cool season, then more rapidly as the warm season approaches again. The largest percentage of stationary analyses occurs with the SH summer maximum, with a secondary maximum occurring in SH winter. Mobility is indicated to be highest in SH fall and spring.

Box 5S covers the region adjacent to the Fimbul Ice Shelf (east of the Weddell Sea, near 10ºW) and is represented by Fig. 3.34e. Cutoff cyclone activity in this region is similar to that seen in the previous Fig. 3.34d. Cutoff cyclone frequency is maximized in the warm season but steadily drops to a SH fall minimum. A gradual increase is observed through the cool season. The highest percentage of stationary analyses occurs in the warm season, with a fairly consistent minimum lasting from late fall through spring.
Cutoff cyclone genesis and lysis will be discussed in the same format used for the NH. Figure 3.35 (3.36) shows the genesis (lysis) events for the SH. The difference in genesis and lysis is shown in Fig. 3.37a. Figure 3.37b shows the 250 hPa composite mean vector wind for the SH. The most active regions in general occur where maxima of cutoff cyclone events occur, reinforcing the idea of slow movement of these systems.

1) Southeast of Chile

A genesis maximum seen in Fig. 3.35 occurs in almost the same position as the lysis maximum seen in Fig. 3.36, indicating consistently slow-moving cutoff cyclones. This genesis-lysis distribution is reinforced in the previous section (refer to discussion of Fig. 3.34a).

2) The Antarctic Peninsula

A maximum of cutoff cyclone genesis straddles the peninsula, with dominant genesis (lysis) maxima occurring east (west) of the peninsula. This pattern is reinforced by Fig. 3.37a, which shows genesis (lysis) dominating east (west) of the peninsula. The indication here is that cutoff cyclones develop in the Weddell Sea east of the peninsula, are mobile, and move east. Cutoff cyclones that develop in the Bellingshausen Sea are less mobile and decay close to their genesis location.

3) Australia and the Tasmanian Sea

Cutoff cyclones develop over both extreme southeast Australia and over New Zealand with similar frequency, as seen in Fig. 3.35. Lysis occurs preferentially toward New Zealand, however, as seen in Fig. 3.36. This pattern is reinforced by Fig. 3.37a,
which shows genesis (lysis) favored across southeast Australia (the Tasmanian Sea). One possible explanation of this pattern is that cutoff cyclone activity here is similar to the region near the Antarctic Peninsula, where the distributions suggest mobile (stationary) cutoff cyclones develop in the Weddell Sea (Bellingshausen Sea). It is possible that cutoff cyclones that develop in the genesis region over New Zealand are relatively stationary, while the Australian-born systems tend to be more mobile, moving east and decaying near New Zealand. This would help to explain the larger number of lysis events near New Zealand.

4) Extreme South Indian Ocean/Amery Ice Shelf.

This region is quite active with respect to cutoff cyclones and the relatively strong maxima in both genesis (Fig. 3.35) and lysis (Fig. 3.36) are likely linked to the presence of the Antarctic jet. As discussed in the previous section, the mobility of cutoff cyclones changes with the season in this region (see the discussion of box 4S). A pattern that arises from this discussion, and one that was also seen in the NH (see the discussion of Fig. 3.15 in section 3.1.1d), is that near the entrance region of the mean jet (shown in Fig. 3.37b) around Antarctica, areas where genesis dominates lysis lie poleward of areas where lysis dominates. The genesis/lysis activity near the entrance region of the mean jet is denoted by the solid box. This pattern flips near the exit region of the mean jet, denoted by the dashed box. There appear to be two separate genesis/lysis “couplets” of activity within the dashed box. This separation is possibly due a seasonal migration of the exit region. The eastern couplet is dominant in the SH warm season, whereas the western couplet is stronger during the cool season (not shown).
3.1.2e Seasonal cutoff cyclone genesis/lysis

SH cool-season plots of genesis and lysis are shown in Figs. 3.38 through 3.43. The distribution of cutoff cyclone genesis and lysis in fall (Figs. 3.38–3.39) is similar to that for the entire year (as shown in Figs. 3.35 and 3.36). The most active areas of genesis are located primarily around Antarctica between 20°W and 130°E. Lysis areas that occur within this band appear to lie primarily to the west, suggesting the mobility discussed in the previous 3.1.2c. A band of cutoff cyclone genesis and lysis stretches from southeast Australia to New Zealand. In SH winter the patterns of genesis (Fig. 3.40) and lysis (Fig. 3.41) remain intact from the fall, but the frequencies increase as shown by the relatively higher values over those of fall. The exception is over the Bellingshausen Sea, where a decrease in both genesis and lysis events is noted in SH winter. Also notable is that genesis/lysis activity between Australia and New Zealand now extends farther east into the south Pacific. The weak maxima in genesis and lysis off the west coast of Chile appear to be independent of this band. SH spring (Figs. 3.42–3.43) exhibits a further strengthening of the pattern overall, with many of the favored areas seeing an increase in activity. An interesting exception is the band of genesis/lysis extending eastward from New Zealand, which shows a slight decrease in values in SH spring.

3.1.3 Tropics

3.1.3a Total cutoff cyclone events/6 h analyses
The interannual (annual) cutoff cyclone activity for the Tropics (defined for this study as the region between 20°N and 20°S latitude) is shown in Figs. 3.44(a,b). Note that the Tropics plots extend to 30°N and 30°S latitude for viewing purposes. Cutoff cyclones are not common in the tropical regions, which is not surprising given the historical perspectives on cutoff cyclone evolution given in chapter 1. Fig. 3.44a reveals that the number of cutoff cyclones has increased from about 100 per year in the 1950’s and 1960’s to about 150 in recent years. This increase may be due to the implementation of better observation platforms in recent years. Figure 3.44b shows that the highest (lowest) number of cutoff cyclones per day occurs from June through November (March through May). This trend is most likely a result of the warm phase of the Indian monsoon. Maps of cutoff cyclone activity in the Tropics are divided by hemisphere, using 0° and 180° longitude as boundaries. The western (eastern) hemisphere Tropics covers 180° to 0° (0° to 180°).

Cutoff cyclone events, 6 h analyses, and number 6 h analyses that exceed events for the western (eastern) hemisphere tropics are shown in Figs. 3.45–3.47 (3.48–3.50). Figures 3.45–3.47 reveal that cutoff cyclones do not occur equatorward of 10°N or 10°S latitude in the Western Hemisphere. Note the tail of cutoff cyclone activity extending southwest across the Hawaiian Islands in the Pacific Ocean and across the central Atlantic Ocean. These tails are the same features discussed in section 3.1.1a. Cutoff cyclones that develop in the Pacific band are commonly referred to as “Kona” lows (Simpson 1952; Ramage 1962; Businger 2001) because they can have a significant impact on the weather in the Hawaiian Islands (Schroeder 1977a,b; Kodama and Barnes 1997). The weak lobe of cutoff cyclone activity extending equatorward from the
California Baja is likely a manifestation of transitioning tropical cyclones. Cutoff cyclones are more common on either side of the Andes Mountains in South America.

In the Eastern Hemisphere, two distinct areas of cutoff cyclone activity exist north of the equator. A double maximum straddles the Indian subcontinent, while another band of cutoff cyclone activity is found in the tropical Pacific between Southeast Asia and about 150°W longitude. These two regions are the only place on Earth where cutoff cyclones extend equatorward of 10°N. In the SH tropics, cutoff cyclones occur preferentially in the Mozambique Channel, across northern Australia, and in a weaker band along about 15°S in the Indian Ocean. This band in the Indian Ocean is most likely a representation of SH tropical cyclone activity in this region. Very few cutoff cyclones are found equatorward of 10°S. Figure 3.50 reveals that the likelihood of stationary cutoff cyclones is greatest across India, with the solid box indicating the area represented in an upcoming graph. A weak maximum of cutoff cyclone frequency appears over central Africa. This maximum likely represents the occasional cutoff cyclone that fractures from the stronger band of cutoff activity to the North.

3.1.3b Seasonal cutoff cyclone events/6 h analyses

Cutoff cyclone events and 6 h analyses for September, October and November (SON) for the western (eastern) hemisphere Tropics are shown in Figs. 3.51–3.52 (3.53–3.54). Figure 3.51 shows that in general cutoff cyclone distributions in SON are similar to those of the entire year (shown in Fig. 3.45). A notable difference in SON is across southern South America, where cutoff cyclones east of the Andes do not extend as far
equatorward as in the entire year. Fig. 3.51 shows that nearly one-third of the cutoff cyclones that occur near Hawaii occur during SON. In the eastern hemisphere Tropics (Fig. 3.53), the maximum over central Africa in of interest in that it contains nearly all of the cutoff cyclones for the entire year (shown in Fig. 3.48). This result suggests that there is something about the large-scale flow that allows cutoffs to enter this region in SON that does not occur in other times of the year. The cutoff cyclone activity across India is comprised of a maximum over coastal India and the Bay of Bengal, with a weaker lobe of activity across eastern India. This distribution supports the claim that these maxima are a manifestation of the Asiatic summer monsoon.

December, January and February (DJF) are shown for the western hemisphere Tropics in Figs. 3.55 and 3.56. The distribution of cutoff cyclones in general remains similar to that of SON (Figs. 3.51–3.52). A notable difference is the disappearance (persistency) of cutoff cyclone activity over the Gulf of Mexico (eastern Caribbean), suggesting cutoff cyclones in this area have a NH warm-season (cool-season) dependence. The tail of cutoff cyclone activity extending northeastward from the eastern Caribbean is the Atlantic counterpart to the tail seen in the Pacific near the Hawaiian Islands. Another notable difference is over South America, where the presence of cutoff cyclones pushes farther equatorward in DJF, suggesting a SH warm season dependence to these cutoff cyclones. In the eastern hemisphere Tropics (Figs. 3.57–3.58), cutoff cyclone activity ceases over India with respect to SON (Figs. 3.53–3.54), as one would expect if this activity were a summer monsoon feature. Weak areas of activity on either side of the southern tip of India are most likely the result of an occasional tropical cyclone. The maximum over the western Pacific decreases and moves equatorward,
suggesting that it represents the tropical cyclone belt in this part of the world, which although active during all months of the year, is minimized in DJF. In the SH Tropics, activity is shown to increase in the Mozambique Channel, across the southern Indian Ocean, and over Australia.

March, April and May (MAM) are shown for the western hemisphere Tropics in Figs. 3.59–3.60. The overall distribution is similar to that of the previous two seasons, but again with some subtle differences. Cutoff cyclones return to the Gulf of Mexico, but are less frequent than in SON (Figs 3.51 and 3.52). The suggestion here is that a few cutoff cyclones impinge on the Gulf of Mexico from the US to the north (during MAM), but most are likely associated with tropical cyclones during the latter part of the warm season (SON). In the eastern hemisphere Tropics (Figs. 3.61–3.62), cutoff cyclones reappear across India. The double maxima seen in the yearly plots (Figs. 3.48 and 3.49) is evident, although the maxima are slightly more spread apart in MAM than during the whole year. This distribution further suggests that these cutoffs are linked to the summer monsoon. For the maxima to occur as they do in Figs. 3.61 and 3.62, JJA cutoff cyclones (not shown) must occur closer to the landmass of India. A strong but compact temperature gradient develops between the land and water during the warm season across India (not shown), and most of these cutoff cyclones would occur near the cool edge of this temperature gradient, which may lie farther from the coast in MAM. This would result in cutoff cyclone activity being maximized farther from the coast (as shown in Figs. 3.61 and 3.62) than in SON (Figs. 3.51–3.52). It is implied by the MAM distributions (Figs 3.61–3.62) and the yearly figures (Figs. 3.48–3.50) that cutoff cyclones associated with
the summer monsoon first develop out over the relatively cooler water then migrate closer to the coast as the temperature gradient strengthens during summer.

3.1.3c Specific areas of cutoff cyclone activity

The most obvious region warranting further study is the region dominated by the Indian Monsoon. The solid box in Fig. 3.50 was chosen subjectively based on the distributions presented in Figs. 3.48–3.50. Figure 3.63 shows the number of cutoff cyclone events (dashed line), number of 6 h periods with a cutoff cyclone (thick solid line), and the percentage of stationary 6 h analyses (thin solid line) as defined for the NH and SH. Figure 3.63 shows the seasonal dependence of cutoff cyclones in India. A distinct rise in the occurrence of cutoff cyclones begins in late spring, peaking in mid-summer. A steady decline is noted through fall, with cutoff cyclone activity ceasing as winter approaches. The probability that a cutoff cyclone will be stationary during its life is quite high in this region, with the stationary analyses consistent at 45% during the active season. Note that the stationary analyses graph is truncated when very small numbers of cutoff cyclones exist.

3.1.3d Cutoff cyclone genesis/lysis

Genesis and lysis of cutoff cyclones in the Tropics will be discussed by geographical region as in sections 3.1.1d (NH) and 3.1.2d (SH). For the western hemisphere Tropics (Figs. 3.64–3.66) there are three significant areas.
1) The central north Pacific

Genesis and lysis are favored in a band stretching from northwest of the Hawaiian Islands eastward to about 130˚W longitude. The close proximity of the genesis and lysis maxima in this region suggest that either stationary cutoff cyclones exist, or that cutoff cyclones in this region move slowly enough not to meander out of the genesis band before they die. This idea of slow-moving cutoffs is also implied in Fig. 3.66, which shows no indication if genesis or lysis dominance in the central north Pacific. The lysis-dominated region over Mexico in Fig. 3.66 is the southern extent of the region over the southwest US in Fig. 3.15a and is not associated with the central Pacific activity.

Genesis and lysis occurs fairly uniformly across the SH Tropics with no areas with strong genesis or lysis preference.

In the eastern hemisphere Tropics (Figs. 3.67–3.69), the notable areas of interest are in the NH.

1) India

The distribution of cutoff cyclone genesis and lysis across India features a double maximum, with the highest numbers occurring just equatorward of the India-Pakistani border and along the western coast of India. It appears that there is a general northwest drift to cutoff cyclones in this region, as evidenced by the lysis maxima extending slightly farther onto the Indian mainland than the genesis maximum. Clearer evidence of this drift is shown in Fig. 3.69. An area dominated by genesis lies southeast of an area dominated by lysis, suggesting that these cyclones move northwest. Another suggestion that arises from these maps is the occurrence a seasonal shift in genesis and lysis, which will be addressed shortly.
2) Western Pacific Ocean

The region of cutoff cyclone activity over the western Pacific Ocean features a genesis maximum across the South China Sea, with a lysis maximum located slightly farther northwest. This displacement suggests a northwest drift to cutoff cyclones in this region, consistent with the notion that they are associated with tropical cyclones. The idea that this drift exists is reinforced by Fig. 3.69, which shows that genesis dominates the western Pacific east of the Philippine Archipelago, with lysis dominant over SE Asia. This pattern suggests that cutoff cyclones, most likely associated with tropical cyclones, develop over the waters of the western Pacific and move ashore in southeast Asia and decay. It is well known that this region of the western Pacific is the most prolific tropical cyclone area in the world. The relatively low number of cutoff cyclone genesis and lysis events, as well as cutoff cyclone events in general from the previous figures is most likely due the fact that tropical systems are warm core. Warm core cyclones typically weaken with height and thus in many cases may not be detectable at 500 hPa.

3.1.3e Seasonal cutoff cyclone genesis/lysis

Seasonal changes in genesis/lysis across the western hemisphere Tropics are generally more robust than in the eastern hemisphere Tropics. For the western hemisphere Tropics, SON (Figs. 3.70–3.71) feature genesis/lysis maxima in the North Pacific (North Atlantic) extending northeast from Hawaii (the eastern Caribbean). These maxima are manifestations of the cutoff cyclone activity described in the second paragraph of section 3.1.3a. In the eastern hemisphere Tropics, genesis (Fig. 3.72) and
lysis (Fig. 3.73) maxima occur over India and the western Pacific. Genesis/lysis distributions for DJF for the western hemisphere shows that genesis (Fig. 3.74) and lysis (Fig. 3.75) occurrences are consistent in location and frequency across the North Pacific and North Atlantic as in SON (Figs. 3.70–3.71). In the eastern Hemisphere Tropics, the DJF genesis (Fig. 3.76) and lysis (Fig. 3.77) distributions show that cutoff cyclones cease to develop in the north of the equator with the onset of winter. Genesis and lysis regions appear in the SH, with a band of activity stretching from a weak maximum in the Mozambique Channel across the south Indian Ocean. Cutoff cyclones also develop and decay more readily in DJF than in SON across northern Australia. Genesis (Fig. 3.78) and lysis (Fig. 3.79) for MAM in the western hemisphere Tropics features very little activity. Weak maxima in genesis and lysis are seen across the north Pacific near Hawaii. In the North Atlantic, the genesis/lysis maxima have retreated to just poleward of the Azores. In the eastern hemisphere Tropics, very little genesis (Fig. 3.80) or lysis (Fig. 3.81) activity takes place in MAM. A few occurrences are noted in the Bay of Bengal as well as over northern Australia.

3.1.4 Eastern North America

3.1.4a Cutoff cyclone event/6 h analyses

Cutoff cyclone activity will be discussed for eastern North America with respect to cutoff cyclone events and 6 h analyses with a cutoff cyclone on a monthly time scale. Genesis, lysis, their difference, and events/6 h analyses graphs (such as Fig. 3.1) were not
done on for this region, and any mention of these parameters will be in reference to
distributions already presented in section 3.1.1. Cutoff cyclone events for each month of
the cool season are presented in Fig. 3.82 a–h. Number of 6 h analyses with a cutoff is
shown in Fig. 3.83a–h. Inspection of these figures reveals many characteristics of cutoff
cyclone behavior not seen in the large-scale plots shown in section 3.1.1.

October, shown in Fig. 3.82a, features a cutoff cyclone maximum over the
southwest US, with the cutoff freeway introduced in sec 3.1.1 stretching across the
central US. The freeway connects with a broad maximum over the Great Lakes region.
Other maxima occur in Canada near Hudson Bay, and in a band stretching from the
Canadian Maritimes into the north Atlantic indicating the presence of an early winter
storm track. A weak area of enhanced activity extends south off the mid-Atlantic Coast
and another dips into the central Gulf of Mexico, most likely manifestations of late-
season transitioning tropical cyclones.

In November (Fig. 3.82b) the distribution appears to shift equatorward and
become better defined. A new maximum appears along the eastern shores of the
Canadian Maritime Provinces, the early winter storm track mentioned in the previous
paragraph becoming visible across the northeast US. The maximum over the Great Lakes
appears to be connected to the Hudson Bay (southwest US) maximum to the north
(southwest). A lobe of higher values extends westward from the southern portion of the
Hudson Bay maximum into central Manitoba into Saskatchewan.

By December (Fig 3.82c) the US east coast storm track is well defined through
southern New England, with a hint of increased activity appearing along the mid-Atlantic
coast. Note that any connection to the Tropics has vanished by December.
There is very little change in the overall distribution from December to January (Fig. 3.82d), except a gradual increase in the number of cutoff occurrences in the favored regions. The occurrence of cutoff cyclones associated with the US east coast storm track is evident as far south as North Carolina, with the maximum over the Canadian Maritimes continuing to redevelop south and west.

Cutoff cyclones continue to increase in frequency through February (Fig. 3.82e), with most of the favored regions reaching a peak in March (Fig. 3.82f) and April (Fig. 3.82g). By April, the cutoff freeway across the central US is very well defined, with a tight gradient on either side suggesting that mobile cutoff cyclones do not readily deviated from this favored path.

There is a fairly significant difference between April and May (Fig. 3.82h). The distribution as a whole looks less well defined and has shifted slightly poleward with the retreat of cold air in spring. With the exception of the southwest US region, the number of cutoff cyclones decreases. As the southern Plains begins to undergo stronger heating in spring, cutoff cyclones become nonexistent across southern Texas.

Figure 3.83, showing the number of 6 h periods with a cutoff, follows a similar pattern overall to that of Fig. 3.82. Higher numbers of analyses exist in areas defined in section 3.1.1 to feature the presence of stationary or slow-moving cutoff cyclones. These areas include the southwest US and near Hudson Bay, where values in Fig. 3.83 nearly double those in corresponding figures in Fig. 3.82 (e.g. Fig. 3.82c for the southwest US in December, and 3.82d for Hudson Bay in January).
3.2 Cutoff cyclone tracks

3.2.1. Eastern North America

Tracks of cutoff cyclones for the every cyclone in the 54-year climatology have been produced and catalogued. For the purposes of this research, only cool-season cutoff cyclones impacting eastern North America with regard to track will be discussed. Tracks were objectively derived using the methodology described in section 2.3. Using individual tracks, composite mean tracks were subjectively derived. Five mean tracks involve cutoff cyclones that pass through or near eastern North America during the cool season. Figure 3.84 shows the subjective derived tracks.

1) Hudson Bay track

This track includes primarily deep, slow-moving cutoff cyclones that migrate equatorward and that are often associated with a large polar vortex. This track is most active in winter.

2) Clipper track

Cutoff cyclones that follow this track are generally weaker that their Hudson Bay counterparts. They are typically closed lows associated with mobile systems that originate in Canada and move southeastward across the northern US (commonly referred to as “Alberta Clippers”). They can occur anytime during the cool season, but are more likely in winter and spring.

3) Southwest Freeway.
These are generally mobile, weak cutoff cyclones that eject northeastward from the southwest US across the central Plains. They are most common in winter and spring. Deeper systems in spring are often the site of genesis of severe weather outbreaks in the southeast US.

4) Mid-Atlantic track

These systems typically develop from cyclones that originate across the southern US and are generally mobile and weak. It was observed that a portion of these systems develop near the end of the mean track (not shown), and eventually move in to the US/Canadian Maritime track. This track is most active in winter.

5) US/Canadian Maritime track

These are deep cutoff cyclones commonly resulting from robust cyclogenesis along the US east coast. The track is most active in winter and spring.
4. Case Studies

4.1 Overview

As stated in section 1.3, two case studies were chosen for further analysis because they presented challenges to forecasters in the prediction of the distribution of precipitation. As also mentioned, both cutoff cyclones (16 Nov 1999 and 03 Mar 2000) were forecast to produce heavy precipitation [7 in of snow or greater within 24 h, equivalent to the threshold for a Winter Storm Warning (WSW)] within the NWS Burlington, Vermont, county warning area (CWA). Figure 4.1 shows the Eta QPF for the 24 h ending 0000 UTC 17 Nov 1999 (initialized 0000 UTC 16 Nov 1999). Light precipitation (0.5 cm or less) was forecast to occur across extreme northern New York and Vermont. The 24 h Eta QPF valid 1200 UTC 03 MAR 2000 (initialized 1200 UTC 02 Mar 2000) is shown for the same region in Fig. 4.2. Light precipitation was forecast by the model to occur with this system as well, with amounts generally less that 0.5 cm.

Figure 4.3 shows the verification for the 16 Nov 1999 event. Snowfall (in) is plotted on a terrain map of northern New York and Vermont. The terrain maps used in Figs. 4.3 and 4.4 show terrain height as a function of gray shade, with the highest (lowest) elevations indicated as lightest (darkest). The Champlain Valley (labeled) shows up as the dark swath, with the Adirondack Mountains (New York) and the Green Mountains (Vermont) appearing as lighter gray on either side. Although white shades indicate the highest terrain, the terrain images used in Figs. 4.3–4.4 are taken from color enhanced satellite data and have been converted to gray shades. It is therefore important
to note that terrain elevation and gray shade are not necessarily correlated. For example, note the lighter shading just east and west of the immediate Champlain Valley. This region is not higher in elevation than the darker shaded terrain farther east (west) in Vermont (New York).

It is clear from Fig. 4.3 that there was a significant difference in precipitation with elevation, with much higher (lower) snowfall amounts reported in mountain (valley) locations. Snowfall values in excess of 12 in were reported along the eastern slopes of the Green Mountains of Vermont, with the highest total (29 in) at Mt. Mansfield. More commonly, amounts of 5–10 in were observed in the mountainous terrain of northern New York. Note that even across the higher terrain of New York that the higher precipitation totals occurred on the west and northwest facing areas. Much lighter amounts, on the order of a trace to 1 in, were reported in the Champlain Valley. The precipitation from this system was generally light in intensity, but lasted up to 36 h in some locations.

Verification for the 03 Mar 2000 event is shown in Fig. 4.4. Snowfall amounts of 1 in were common throughout the lower elevations in the Champlain Valley and across northern New York. Some locations in the higher elevations of northern Vermont received 3 to 4 in of snow, but not enough to verify the threshold of heavy precipitation. The 9 in report is not included in the verification of heavy precipitation because it occurred atop Mt. Mansfield, which is unpopulated.

4.2 Analysis
In an effort to diagnose some of the synoptic- and mesoscale features of the two cutoff cyclones involved in these cases, maps of the lower and middle levels of the atmosphere are presented for the northeastern US. The analyses shown in Figs. 4.5–4.8 use data taken from Eta model analyses (80 km resolution) archived at the State University of New York at Albany. Figure 4.5a(b) shows the 500 hPa geopotential heights, absolute vorticity, and winds for 1200 UTC 16 Nov 1999 (0000 UTC 03 Mar 2000), times which represent approximately the mid-point of the precipitation events described in the previous section. Inspection of Figs. 4.5a, b reveals that both systems were cutoff at the analysis time according to the 30 m geopotential height rise criterion adopted in section 2.1. Also note that the 16 Nov 1999 cutoff cyclone (Fig. 4.5a) was deeper than the 03 Mar 2000 cyclone (Fig. 4.5b), as shown by relatively lower geopotential height values near the center. The track (thick solid line, taken from positions objectively derived, and verified using NWS DIFAX 500 hPa charts) of the cutoff cyclone in the 16 Nov 1999 case was farther north than in the 03 Mar 2000 case. The 12 h positions, denoted with black dots, shows that the 16 Nov 1999 cutoff cyclone virtually stalled over SE Canada between T=0 and T+12 h. The 03 Mar 2000 cutoff cyclone was more progressive throughout its journey through the northeast US.

Figures 4.6a–b shows the 850 hPa geopotential heights, wind barbs, and wind speed (shaded) for the two systems. The cutoff cyclone at 850 hPa at 1200 UTC 16 Nov 1999 (Fig. 4.6a) was located just northeast of Maine. This position supported a mean northwesterly flow across the higher terrain of northern New York and Vermont, with wind speeds of 10–15 m s\(^{-1}\) indicated. At 0000 UTC 03 Mar 2000 the corresponding 850 hPa cutoff cyclone (Fig. 4.6b) is located over the Gulf of Maine. A weakness in the
geopotential height gradient is evident poleward of a 10–15 m s⁻¹ wind speed maximum over eastern Pennsylvania, southeastern New York and New Jersey. This geopotential height weakness resulted in much lighter winds (generally 5 m s⁻¹ or less), with a more northerly component over northern New York and Vermont than in the 16 Nov 1999 event.

Figure 4.7 shows the 950 hPa geopotential heights, relative humidity and winds for (a) 1200 UTC 16 Nov 1999 and (b) 0000 UTC 03 Mar 2000. Once again, the 16 Nov 1999 event (Fig. 4.7a) had a stronger and more northwesterly wind component than the 03 Mar 2000 event (Fig. 4.7b). Figures 4.7a–b reveal that ample low-level moisture (indicated by RH values > 70%) was present during both events.

Maps showing surface station plots of potential temperature (θ, solid contours), wind barbs, mixing ratio (shaded above 5 g kg⁻¹), and present weather symbols for the two cases are shown in Figure 4.8. Fig. 4.8a shows the aforementioned parameters for 1200 UTC 16 Nov 1999. The gradient of θ is relatively small over northern New York and Vermont, with only weak cold advection indicated upstream (west-northwest) into Quebec and Ontario. This weak θ gradient contrasts with the stronger north–south θ gradient located over the Great Lakes region, suggesting that any forcing associated with surface boundaries would be small over northern New York and Vermont. The mean wind flow at the surface is generally northwest across northern New York and Vermont, with wind speeds of 7–12 m s⁻¹ observed. Mixing ratio values of 2–3 g kg⁻¹ were observed throughout the northeast US and southeastern Canada. Maps similar to those shown in Fig. 4.8, but for 24 h prior and subsequent to 1200 UTC 16 Nov (not shown) reveal little change in the overall pattern, and that the features just discussed were in
place throughout the entire precipitation event. This persistent pattern is consistent with
the idea of a slow-moving cutoff cyclone moving through the region.

Figure 4.8b shows the same data as discussed in the previous paragraph, but for
0000 UTC 03 Mar 2000. Inspection of this figure reveals that although a weak gradient of
\( \theta \) also exists across northern New York and Vermont, the cold advection in this region is
a little stronger than in the 16 Nov 1999 case (Fig. 4.8a). The surface winds were
observed to be generally northwesterly across the northeast US, but with wind speeds of
5 m s\(^{-1}\) or less over northern New York and Vermont. Mixing ratios are generally 2–3 g
kg\(^{-1}\) throughout the northeastern US.

Time–height plots for Burlington, Vermont (KBT V), showing profiles of
initialized Eta model potential temperature (\( \theta \)), relative humidity (40–100\%), and winds
for the two case studies are shown in Fig. 4.9. The vertical coordinate is pressure with
mandatory levels from 1000 to 200 hPa used in the creation of the time series. Note that
the beginning and end times chosen for the time series were chosen to depict the vertical
structure of the atmosphere before, during, and slightly after the precipitation events. The
consistency in the wind profiles in Fig. 4.9a (0000 UTC 15–1200 UTC 17 Nov 1999)
indicates the relatively slow movement of the cutoff cyclone mentioned previously, with
little variation throughout the time series. The center of a cutoff cyclone would
presumably lie east of the station given the mean west to northwest flow at all levels.
Also note the consistency of the wind speeds from 1000 to 850 hPa, which is
approximately the vertical range of the terrain in northern Vermont. There is warm air
advection indicated by the veering signature in the wind profile between 0000 UTC 16
and 0000 UTC 17 Nov in the 1000–850 hPa level as well. The relative humidity profiles
indicate the presence of moisture (RH values > 70%) below about 700 hPa for the period shown in the time series.

An approximate measure of static stability in pressure coordinates (defined by Bluestein 1992) can be written as:

\[ \frac{-\partial \theta}{\partial p}, \]  

(2)

where small (large) values indicate areas where low (high) stability exists. From this definition, it can be said that areas where isentropes are spread apart indicate lower stability than in areas where they are closer together. The distribution of \( \theta \) in Fig. 4.9a indicates that static stability is relatively low below approximately 850 hPa. The static stability between 850 and 700 hPa is higher in general that in the lowest levels of the troposphere, and shows a general increase after about 0600 UTC 16 Nov.

The time–height plot for 0000 UTC 02 Mar–1200 UTC 04 Mar 2000 is shown in Fig. 4.9b. The wind profiles in this time series show that low–level wind directions at BTV veered from southerly at 0000 UTC 02 Mar to northwesterly by 1200 UTC 04 Mar. This veering was part of the reason that the upslope component to the wind in the lower levels of the troposphere was inhibited in this case. The relatively weak wind speeds below 850 hPa, which were alluded to in the discussion of Fig. 4.6b (850 hPa) and Fig. 4.8b (surface station plots) can also be seen throughout the time series in Fig. 4.8b. Relative humidity values were generally above 70 % below 700 hPa through 1200 UTC 03 Mar, with the 70% isopleth dropping to about 850 hPa after about 1800 UTC 03 Mar. Static stability appears to be relatively low in approximately the lowest 100 hPa of the troposphere through 1200 UTC 03 Mar, but increases slightly thereafter.
Time height series showing $\theta$ plotted along with pressure coordinate vertical velocity ($\omega$) are shown for the two case studies in Figs. 4.10a–b. Please note that for the 16 Nov 1999 case (Fig. 4.10a), initialized Eta model data were incomplete (for $\omega$). Therefore, initialized AVN data, at a resolution of 1° by 1° were used. Initialized Eta grids were used for the 03 Mar 2000 case (Fig. 4.10b). The standard definition used for $\omega$ is such that negative (positive) values correspond to ascent (descent).

Figure 4.10a shows that for the period 0000 UTC 15–1200 17 Nov 1999, negative values of $\omega$ (0 to $-1 \mu b \ s^{-1}$) persisted below about 900 hPa for the duration of the time–height series. Negative values of $\omega$ rose to between 800 and 700 hPa for the 12 h ending 0000 UTC 17 Nov.

For the 03 Mar 2000 case, negative values of $\omega$ (0 to $-2 \mu b \ s^{-1}$) were observed below 850 hPa throughout the duration of the time–height series, with the most vigorous ascent occurring prior to 0000 UTC 03 Mar.

4.3 Discussion

As stated in sections 1.3 and 4.1, these two cutoff cyclones were chosen as case studies because of the vastly different distributions of the precipitation created by each cyclone. As also mentioned, heavy precipitation was forecast by NWS Burlington to occur with each event, with the 16 Nov 1999 (03 Mar 2000) event verifying (not verifying). Both of the cutoff cyclones presented in this section followed the Clipper track shown in Fig. 3.84.
Thorough analysis of the forecast products produced by NWS Burlington, including area forecast discussions (AFD) and zone and short-term forecasts (not shown), reveal the following:

1) For the 16 Nov 1999 event, the forecast was quite good. The AFD’s allude to a long-lived precipitation event with generally light, upslope-enhanced precipitation. Forecasters also indicated the possibility that the cutoff cyclone would in fact stall for a period of time between 15–16 Nov. Forecasters also mentioned that the 48 h Eta model forecast initialized at 0000 UTC 15 Nov (not shown) predicted the cutoff cyclone track to be similar to that which actually occurred (shown in Fig. 4.5a).

2) For the 03 Mar 2000 event, in which a WSW was issued for several NWS BTV zones, it appears that forecast errors are primarily a result of the failure of the computer model/human forecasters to accurately predict the mean wind flow at and below ridge level across northern New York and Vermont. AFD’s issued by NWS BTV mention that the heaviest precipitation would occur across the higher terrain, consistent with an upslope precipitation event. The AFD’s prior to the onset of precipitation did not discuss the track of the 500 hPa cutoff cyclone.

The data presented in section 4.1 and the discussion in this section suggest that significant similarities existed between these two cutoff cyclones. Relatively high (low) relative humidity (static stability) was evident near and below ridge level for both events, although the higher relative humidity values in the 16 Nov 1999 case persisted longer than in the 03 Mar 2000 case. Vertical velocity patterns show that ascent was present in the low levels for both cases. In fact the 03 Mar 2000 case featured more vigorous ascent (as much as −2 μb s⁻¹; see Fig. 4.10b) than did the 16 Nov 1999 case (0 to −1 μb s⁻¹). It
should be noted, however, that the resolutions of the Eta (80 km) and AVN (1° by 1°) may not be sufficient to resolve the finer details of the vertical motion in the presence of the complex terrain in northern New York and Vermont. The main idea is that weak ascent was present in both cases.

What appears to be a “smoking gun” as a reason for the vastly different precipitation distributions was the strength and duration of the upslope component of the low-level wind. The 16 Nov 1999 case featured an upslope wind component that was significantly stronger in speed and longer in duration, in conjunction with higher relative humidity below 700 hPa, than in the Mar 2000 case. This stronger upslope component of the wind can be seen by comparing the surface winds in the 16 Nov 1999 case (Fig. 4.8a) and the wind profiles in the time–height series in Fig. 4.9a with those of the 03 Mar 2000 case (Figs. 4.8b and 4.9b respectively). Note the consistent 10–15 m s⁻¹ northwesterly winds at and below ridge level in Fig. 4.9a. This wind is nearly perpendicular to the spine of the Green Mountains, which are the north-south oriented mountains that form the eastern boundary of the Champlain Valley. It appears that the persistence of both the upslope component to the winds and higher relative humidity values at and below ridge level were able to produce a long-lived precipitation event resulting in large amounts of snowfall in the 16 Nov 1999 event. Lighter wind speeds and cyclonic turning with time in the winds at and below ridge level in the Mar 2000 event (see Fig. 4.9b) did not allow a sustained upslope component and thus the precipitation was much lighter.
Fig. 4.1. 24 h Eta QPF (cm) from 0000 UTC 16 Nov 1999. Valid 0000 UTC 17 Nov.

Fig. 4.2. 24 h Eta QPF (cm) from 1200 UTC 02 Mar 2000. Valid 1200 UTC 03 Mar 03.
Fig. 4.3. Event snowfall totals (in inches) ending 0000 UTC 17 Nov 1999.

Fig. 4.4. As in Fig. 4.3 but ending 1200 UTC 03 Mar 2000.
Fig. 4.5. 500 hPa geopotential height (solid), absolute vorticity (shaded), and wind barbs (m s$^{-1}$) for a) 1200 UTC 16 Nov 1999 and b) 0000 UTC 03 Mar 2000. The dark arrow indicates the cutoff cyclone track, with the position at 12 h increments denoted with a black dot.
Fig. 4.6. 850 hPa geopotential height (solid), wind speed (shaded), wind barbs (m s$^{-1}$) and temperature (°C) for a) 1200 UTC 16 Nov 1999 and b) 0000 UTC 03 Mar 2000
Fig. 4.7. 950 hPa geopotential height (solid lines), relative humidity (%, shaded), wind barbs (m s$^{-1}$) and temperature (°C) for a) 1200 UTC 16 Nov 1999 and b) 0000 UTC 03 Mar 2000
Fig. 4.8. Surface station plots of mixing ratio (q, shaded above 5 g kg\(^{-1}\)), θ (solid lines, contoured every 4 K), and wind barbs (in m s\(^{-1}\)) for a) 1200 UTC 16 Nov 1999 and b) 0000 UTC 03 Mar 2000.
Fig. 4.9. Time–height diagram for KBTV showing Eta initialized potential temperature ($\theta$, solid lines every 4 K), relative humidity (dashed lines every 10% above 40%), and wind barbs (in m s$^{-1}$) for (a) 15–17 November 1999 and (b) 02–04 Mar 2000.
Fig. 4.10a. Time–height diagram for KBTV showing initialized AVN potential temperature ($\theta$, solid lines every 4 K), vertical velocity (dashed lines, every $\mu b$ s$^{-1}$), and wind barbs (in ms$^{-1}$) for 0000 UTC 15–1200 UTC 17 November 1999.

Fig. 4.10b. As in Fig. 4.10a but using initialized Eta model data for 0000 UTC 02–1200 UTC 04 Mar 2000.
5. Discussion

5.1 Justification of methodology

As stated in section 2.2, the methodology used to identify cutoff cyclones is fundamentally similar to that used in BB. The significant difference is that a newer, more comprehensive dataset with an increased resolution is used (the NCEP/NCAR reanalysis at a 2.5° X 2.5° latitude–longitude grid vice the NMC reanalysis at 2° X 5°). Also, a much longer time scale was introduced (54 years vice 15 years). As an initial accuracy check, the algorithms used in the current study were run for the same 15-year period addressed in BB (1963–1977) with the results (not shown) nearly identical. PHCH, as also stated in section 2.2, completed a climatology of 500 hPa cyclones (defined as a geopotential height center with at least one closed 60 m height contour) for the western Northern Hemisphere, and was also used as validation of for the current methodology. Selected figures from BB, as well as PHCH are shown to promulgate the consistency (for the Northern Hemisphere) between these studies and the current study. Other studies will be used for comparison of cutoff cyclone activity for various geographical locations where applicable.

The results presented in chapter 3 show good consistency with that of BB and PHCH for the Northern Hemisphere. It should be noted that the terms “cutoff cyclone” used in the current study and “closed low” used in BB and PHCH are essentially the same, and will used interchangeably hereafter. Figure 5.1, taken from Fig. 1 of PHCH, shows that percentage of days in which a closed 500 hPa cyclone was present.
Comparing Fig. 5.1 with Fig. 3.3 (number of 6 h analyses with a cutoff cyclone), it is evident that the favored regions for cutoff cyclone activity are similar; those being the North Pacific, Gulf of Alaska and the southwest US. Weaker maxima are indicated near Hudson Bay, the Canadian Maritimes, and across northwest Africa and the Iberian Peninsula. The relative frequency maxima in the form of “tails” of cutoff cyclone activity seen extending southwest from the frequency maxima near the Iberian Peninsula (in the Atlantic Ocean) and from the southwest US (into the Pacific Ocean; see section 3.1.1a for further details) do not appear in Fig. 5.1. This is likely due to the coarser resolution of the NMC analyses used in PHCH.

For comparison of seasonal cutoff cyclone activity, Fig. 5.2, taken from Fig. 2 of BB, is used. This figure shows the number of 12 h analyses in which a closed cyclone at 500 hPa was present for each season in the Northern Hemisphere. Note that the time sequence in which the data were presented in chapter 3 is not necessarily the same as in other studies (e.g., this study displays the cool season starting with fall; BB displays all seasons beginning with winter). It is therefore necessary at times to discuss figures out of order.

Figure 5.2d, taken from Fig. 2d of BB, shows the number of 12 h analyses with a cutoff cyclone for fall (defined as SON for both studies). Comparing this figure with Fig. 3.6 (number of 6 h analyses with a cutoff cyclone for fall), it is evident that the two studies show similar results. Areas of favored cutoff cyclone activity that match up in both studies are northeast Asia and the North Pacific, the Gulf of Alaska, the southwest US, the vicinity of Hudson Bay, between the southern tip of Greenland and Iceland, and in a band across the Mediterranean region, with maxima along the coast of Portugal as
well as over Italy. Other notable features in Fig. 3.6 that are represented in Fig. 5.2d are the manifestation of cutoff cyclones as “tails” of activity in the Atlantic and Pacific Oceans, as well as the cutoff freeway stretching northeastward from the southwest US (discussed in section 3.1.1b). Although much weaker in Fig. 5.2d, there is an indication that the freeway exists. Once again, the coarser resolution of the NMC analyses used in BB is a likely reason that these features are less distinct than in the current study. Comparing Fig. 5.2a (number of 12 h analyses with a cutoff cyclone for Northern Hemisphere winter, taken from Fig. 2a of BB) with Fig. 3.8 (number of 6 h analyses with a cutoff cyclone for the same time period) shows that the distribution of cutoff cyclone activity is consistent within the two studies for winter (defined as DJF for both studies). All of the major areas of cutoff cyclone activity are agreed upon. The increase in activity is seen in many of the favored areas of cutoff cyclones between fall and winter discussed in section 3.1.1b is also seen in Figs. 5.2d (BB, fall) and 5.2a (BB, winter). Also note the decrease in cutoff cyclone activity in the Gulf Alaska between fall and winter, which is also noted in section 3.1.1b.

Figure 5.2b, taken from Fig. 2b of BB, can be compared with Fig. 3.10. These two figures show the number of analyses (12 h for Fig. 5.2b, 6 h for Fig. 3.10) in which a cutoff cyclone was present for spring (defined as MAM for both studies). Once again, good agreement is shown between the current study and BB. The increase in cutoff cyclone activity from winter to spring described in section 3.2 is seen in BB as well (compare Fig. 5.2a and 5.2b). Note also that the cutoff freeway has become better defined in Fig. 5.2b (BB, spring) over that in Fig. 5.2a (BB, winter). This better definition coincides with the increase in activity noted in section 3.1.1b.
Specific areas of cutoff cyclone activity were selected for further study by BB, similar to that which was done in section 3.1.1c of the current study. Figure 5.3, taken from Fig. 11 of BB, shows the areas they selected for more in-depth study. It can be seen from Fig. 5.3 that certain areas chosen by BB are similar to that chosen in section 3.1.1b (see also the selected areas in Fig. 3.11). Figures 5.4a–d, taken from Figs. 12a, 13a, 13c, and 14d, respectively, show four of the areas from BB that are geographically similar to those in the current study. These areas include the southwest US (box 4N in Fig. 3.11, L1 in Fig. 5.3), the northeast US coast and Canadian Maritimes (box 6N in Fig. 3.11, L5 in Fig. 5.3), the area off the Iberian Peninsula (box 8N in Fig. 3.11, L8 in Fig. 5.3), and the area just east of the Caspian Sea (box 10N in Fig. 3.11, L12 in Fig. 5.3). The graphs shown in Figs. 5.4a–d correspond to Figs. 3.12d, f, h, and j respectively, in the current study. As stated in section 3.1.1c, the graphs in the current study (Fig. 3.12) feature number of 6 h analyses with a cutoff cyclone (thick solid line), number of cutoff cyclone events (dashed line), and the percentage of 6 h analyses exceeding events (thin solid line), the latter of which is used to diagnose the existence of stationary cutoff cyclones. As a further reminder, the data in Fig. 3.12 were computed using 14-day increments from January through December. The BB graphs shown in Fig. 5.4 show number of 12 h analyses with a cutoff cyclone (top curve, solid line), number of cutoff cyclones (middle curve, dashed line), and number of cutoff cyclones developing within the given box (bottom curve, solid line). The BB graphs were computed using normalized 30-day increments and run from December to November. General comparisons between Fig. 5.4 and Fig. 3.12 will be made in regard to the number of analyses and number of cutoff cyclone events only.
Figure 5.4a, taken from Fig. 12a in BB, shows the area covering the southwest US stretching westward into the Pacific Ocean. Figure 3.12d shows the corresponding area in the current study. Note that the area chosen by BB extends farther out into the open water than the area in the current study. Comparison of the two graphs reveals that both studies show an increase in cutoff cyclone activity over the southwest US through spring, a sharp decrease during the summer months, and a subsequent rise with the onset of fall. Note that with finer temporal resolution in the current study (14 days) over that of BB (30 days), as well as the finer resolution of the NCEP/NCAR reanalysis dataset, the sharp dropoff of cutoff cyclone activity actually begins in mid-June. Both studies show that two annual maxima in cutoff cyclone activity occur, those being late spring and early fall. The graph of number of analyses with a cutoff cyclone is similar in the two studies. An interesting difference, however, is that in the current study there are about 35% fewer events (roughly 400) than 6 h analyses (roughly 600) during the spring. This implies that nearly one-third of cutoff cyclones are quasi-stationary during their life cycle. For the same period in BB, there appears to be an average of three events and nine analyses. This would mean cutoff cyclones are quasi-stationary nearly two-thirds of the time. Further study is needed to diagnose this difference.

Figure 5.4b, taken from Fig. 13a in BB, covers the northeast US coast and Canadian Maritimes (shown in Fig. 3.12f in the current study). Comparison of these two figures shows good agreement in the overall trend of cutoff cyclone activity. A spring (summer) maximum (minimum) is seen in both figures. A notable difference in the two graphs is the large number of 12 h analyses that exceed number of cutoff cyclones in Fig.
5.4b. This large difference is not seen in Fig. 3.12f, where the number of 6 h analyses is much closer to the number of cutoff cyclone events.

Figure 5.4c, taken from Fig. 13c in BB, corresponds to Fig. 3.12h in the current study and covers the region near the Iberian Peninsula. Once again, there is good agreement in the BB graph (Fig. 5.4c) and that shown in the current study (Fig. 3.12h). A slow increase in cutoff cyclone activity is seen through spring, with a distinct maximum in June. A sharp decrease is noted through late summer with the annual minimum occurring in August.

Figure 5.4d, taken from Fig. 14d in BB, covers the region just east of the Caspian Sea and corresponds to Fig. 3.12j in the current study. Both graphs show a spring maximum in cutoff cyclone activity, followed by a steady decline through mid-summer, then a steady rise into winter.

Favored areas of cutoff cyclone genesis and lysis as presented in BB were also compared with results shown in section 3.1.2d–e. There is good agreement between the seasonal plots presented by BB and those shown in this study.

Southern Hemisphere frequency distributions were compared with the findings of Sinclair (1994, 1997) for consistency in the overall pattern of cyclone activity. Although Sinclair’s work deals with surface cyclones, good agreement exists with the distribution of cutoff cyclones at 500 hPa. In addition, the cutoff cyclone event frequency and 6 h analysis maxima seen over southern Africa (see Figs. 3.24–3.25) is consistent with Taljaard (1985).

A few words should be said about the monthly plots of cutoff cyclone frequency in Figs. 3.82–3.83. The distribution of cutoff cyclone frequency shown in Fig. 3.82 is in
good agreement with the well known climatological studies on Northern Hemisphere cyclones (although most deal with surface cyclones, including Petterssen 1958, Ch. 13; Klein 1957; Ziska and Smith 1980; Geng and Sugi 2001; Hoskins and Hodges 2002). The cutoff freeway and the increased number of cutoff cyclones in winter and spring over that of fall (seen in the frequency distributions in Fig. 3.82) coincides nicely with the increased surface cyclone activity across the central US in the above studies. The favored cyclogenesis areas and depicted in Whittaker and Horn (1981) and Hoskins and Hodges (2002) are also in agreement with Northern Hemisphere cutoff cyclogenesis distributions shown in the current study.

5.2 Discussion of cutoff cyclone activity

As stated in section 3.1, cutoff cyclones seem to favor particular regions, and also seem to avoid others. Much of the fundamental groundwork on cutoff cyclones was summarized by PN1. As discussed in section 1.2.1, much of this work focused on the idea that cutoff cyclones were essentially pools of cold air that were displaced equatorward from their source regions, and have characteristic cyclonic motion associated with them. It is no surprise then that the vast majority of cutoff cyclones are found at middle and high latitudes. Cutoff cyclones are also relatively rare outside of the favored regions, occurring on less than 10% of the days studied by PHCH. This rarity is also seen in other climatologies, such as Lahey et al. (1958), who, using time averaged 500 hPa maps, revealed that the only closed cyclone to appear in the time mean was over northeastern Canada during January, February, and March. Nonetheless, the
unpredictability issues associated with cutoff cyclones (see section 1.1) support the completion of these climatological studies using newer and more comprehensive datasets.

The current study reinforces the collective ideas shown in PN1 (e.g. that cutoff cyclones are isolated pools of cold air with a relatively high amount of cyclonic vorticity) but also suggests that cutoff cyclone development occurs in a number of characteristic synoptic patterns. Section 5.2.1 addresses this issue.

5.2.1 Categories of cutoff cyclones

The distributions presented in section 3.1 give a comprehensive view into cutoff cyclone activity in the Northern and Southern Hemispheres as well as the Tropics. From these results, most cutoff cyclones can be stratified into four identifiable categories during the cool season. These categories are polar, jet entrance, jet exit, and orographic.

5.2.1a Polar

Slow-moving cutoff cyclones are strongly concentrated around Hudson Bay (Figs. 3.5–3.10, as well as the graph in Fig. 3.12e) during the cool-season, with a maximum occurring in winter (Fig. 3.7). This concentration likely represents the meteorological “North Pole,” where the coldest air in the Northern Hemisphere often resides near Hudson Bay in winter. Observation of individual cutoff cyclone tracks over the Northern Hemisphere (not shown) and the distribution of genesis and lysis of cutoff cyclones reflects the quasi-stationary nature of the “Hudson Bay” cutoff cyclone, and the
likelihood that baroclinically active individual cyclones propagate around the periphery of the persistent cutoff cyclone in this region. It is difficult to perform a more in-depth investigation into the actual origin of the Hudson Bay cutoff cyclones at this point in the research; however, possibilities into their origin arise from the distributions shown in section 3.1.1 and the cutoff cyclone tracks discussed in section 3.2. Inspection of numerous individual cutoff cyclone tracks (not shown) reveals that cutoff cyclones that follow the US/Canadian Maritimes track (see Fig. 3.84) have two mean paths; one being east-northeastward into the north-central Atlantic Ocean and a second, less dominant “recurving” track, where cutoff cyclones travel northeast initially, but then turn more northerly then northwesterly. This second track would allow the cutoff cyclone to merge with the persistent Hudson Bay cutoff cyclone. Hoskins and Hodges (2002; Fig. 6b, which shows the mean paths of 850 hPa positive vorticity centers) suggest that these two paths exist, and that the first path is favored. The two paths are also supported by Figs. 3.2–3.4 and 3.5–3.10, which show a connection between the maximum adjacent to the US/Canadian Maritimes to the maxima near Hudson Bay and the southern tip of Greenland. Figure 3.15a also supports two mean paths due to the fact the genesis-dominated areas adjacent to the Canadian Maritimes are flanked by areas where lysis is dominant (just east of Hudson Bay and over the Davis Strait). This distribution suggests that cutoff cyclones that originate in the genesis-dominated area adjacent to the Canadian Maritimes progress along either of the two tracks described above. It is unclear, however, whether or not the lysis maximum east of Hudson Bay is a result of northwest-moving, decaying cutoff cyclones from the Atlantic storm track, or southeastward-moving cutoff cyclones that originate in the genesis maximum over northern Hudson Bay. This latter
scenario is a favored track for cutoff cyclones to penetrate into the northeast US, as seen in Fig. 3.84.

Cutoff cyclones in the Southern Hemisphere are not distributed at all like their Northern Hemisphere counterparts. Cutoff cyclones are maximized around the edge of the Antarctic mainland, with a distribution that mirrors the quasi-circular geography of Antarctica. Figures 3.24–3.26 reveal that cutoff cyclones that occur farther inland do so over the relatively lower-elevation ice shelves (e.g., the Amery Ice Shelf). The vast majority of cutoff cyclones in the higher latitudes of the Southern Hemisphere occur over oceanic regions but near the coast. This distribution also suggests the likelihood that cutoff cyclones in this region favor some level of baroclinicity that can be found in the thermal gradient between the mainland and the oceans. An equally likely explanation is that the relatively circular distribution of cutoff cyclones circumnavigating the Antarctic mainland is linked to jet-stream patterns that are similarly oriented (e.g., the relatively circular composite mean jet shown in Fig. 3.37b).

5.2.1b Jet-entrance region cutoff cyclones

As noted in section 3.1.1d (last paragraph), there appear to be characteristic patterns of cutoff cyclone behavior near jet-entrance regions. Figure 3.15b (3.37b) shows the composite mean 250 hPa wind speed and direction for the Northern Hemisphere (Southern Hemisphere). Mean jet entrance regions in the Northern Hemisphere (Southern Hemisphere) are found over the northwest Pacific Ocean, across Baja California and northern Mexico, and across northeastern Africa (northeast of the southern tip of South
America and west of southwestern Australia). In the Northern Hemisphere, these active areas occur poleward of the entrance regions of the subtropical jet, whereas in the Southern Hemisphere, the activity noted above lies equatorward of the entrance regions of the polar jet. It can be seen from Fig. 3.15a that near these jet entrance regions, areas where genesis is favored lie poleward of areas where lysis is favored.

Cool-season cutoff cyclones occur preferentially well poleward and somewhat eastward of the mean jet entrance regions seen in Fig. 3.15b. In the Northern Hemisphere, this occurrence is seen in the maxima over the northwestern Pacific and extreme northeastern Asia, over the southwest U.S., and across the Iberian Peninsula (see Figs. 3.5–3.10). In the Southern Hemisphere, this preference is possibly represented by the cutoff cyclone maxima that occur in the Bellingshausen and Weddell Seas (shown in Figs. 3.24, 3.25, and 3.34b).

The prevalent frequency maximum in the northwestern Pacific Ocean seen throughout the cool season (Figs. 3.5–3.10 and in Fig. 3.12a) is evidence of the persistent synoptic-scale dynamical forcing in this region. The relative proximity of the genesis and lysis maxima in this region (see Fig. 3.13–3.14) are testimony to the rather slow-moving cutoff cyclones well known to operational meteorologists with forecasting experience in this region. Gyakum et al. (1989) showed that surface cyclones are relatively common across the area just west of Kamchatka in the Sea of Okhotsk, in agreement with Petterssen’s (1958, Ch. 13) climatology of that area. It was reported by Gyakum et al. (1989), however, that less than 50% of the cyclones in this region show deepening, consistent with the idea that mature cyclones are common in this area. In fact, according to Gyakum et al. (1989), the mean 24 h pressure change across this region was +5 mb,
indicating that this area is dominated by decaying cyclones. This indication is consistent with Fig. 3.15a, which shows the area just west of Kamchatka dominated by cutoff cyclone lysis. The cutoff cyclone maximum across northeast Asia is shifted slightly farther west in fall and spring than in winter. This shift is consistent with the findings of Chen et al. (1991, 1992) and possibly indicates that terrain influences are at work. This seasonal shift and possible terrain interactions will be discussed in the next section.

Cutoff cyclones in the southwest US are well known to meteorologists and are most common during fall, winter, and spring, as seen in Fig. 3.12d. Large-amplitude trough passages poleward of this region often displace isolated areas of PV equatorward. Cutoff cyclones develop near the southwestern end of a long tail of higher PV (referred to as an “umbilical cord” by HMR), which can extend into the subtropics from higher latitudes. After close inspection of numerous middle- and upper-level weather maps, it was empirically determined that cutoff cyclones in this region are associated with this type of behavior, which is consistent with LC1 type development described by Thornicroft et al. (1993). Bell and Bosart (1994) found that 1–2 days prior to cutoff cyclone development over the southwest US, vigorous amplification occurred in the upstream ridge, which is also consistent with LC1 type behavior. Cutoff cyclone development in conjunction with upstream ridge amplification was also reported to occur across the southern lee of the Alps (hereafter Alpine, Bell and Bosart 1994). Note the contrast of this scenario of Alpine cutoff cyclogenesis with that of Rodgers and Bosart (1986), who found that ridge amplification occurs downstream of a developing cutoff cyclone associated with explosively deepening oceanic cyclones (bombs). Significant differences likely exist in the structure of Alpine cutoff cyclones and those associated
with bombs, so future study into the relationship of cutoff cyclone development and ridge amplification may be warranted to investigate the differences.

The active cutoff cyclone region near the Iberian Peninsula (see Figs. 3.2–3.3 as well as the graph in Fig. 3.12h) features cutoff cyclone development that is similar to the southwest US (see previous paragraph). Cutoff cyclones in this area also often develop from isolated PV anomalies left behind by larger troughs and are often associated with LC1 type development, as noted in Thorncroft et al. (1993).

The type of development described in the previous two paragraphs is also found in the tail of cutoff cyclone activity that stretches northeastward from the Hawaiian Islands. As discussed in section 3.1.3a, “Kona Lows” are common in this region (Simpson 1952; Morrison and Businger 2001). Further study involving comparison of the structure of cutoff cyclones associated with Kona Lows and the cutoff cyclones in the Atlantic tail is required to substantiate any similarities between the two. It should also be noted that cutoff cyclones in the southwest US and near the Iberian Peninsula occur in the seam between the entrance region of the subtropical jet lying to the south and the exit region of the polar jet lying to the north, which suggests that large-scale deformation may play a role in the development of cutoff cyclones. Cutoff cyclones can develop farther east over the Sahara, as shown in Fig. 3.2, although this scenario is not as common. These cutoff cyclones have been known to progress eastward across the northern Sahara, as in the case study completed by Thorncroft and Flocas (1997). They concluded that a cutoff cyclone developed from an isolated PV anomaly, and was consistent with LC1 type behavior (Thorncroft et al. 1993). An interesting note is that the path of the cutoff cyclone studied by Thorncroft and Flocas (1997) is about as far south as any cutoff...
cyclone path observed in this part of the world (see Figs. 3.2–3.4 and Fig. 3.48 for reference).

In the Southern Hemisphere, cutoff cyclones develop poleward and just west of the jet maximum east of the southern tip of South America (shown in Fig. 3.37b). This development takes place over the Bellingshausen and Weddell Seas (see Figs. 3.24–3.25 and Figs. 3.27–3.32, as well as Fig. 3.34b) and is active throughout the Southern Hemisphere coolseason.

5.2.1c Jet-exit region cutoff cyclones

Figure 3.15b shows that for the Northern Hemisphere, mean jet exit regions are found in the north Pacific near the Gulf of Alaska and in the north Atlantic south of Iceland. In the Southern Hemisphere, jet exit regions exist poleward of southwestern Australia as well as in the south Pacific Ocean well east and somewhat equatorward of New Zealand (near 130ºW, see Fig. 3.37b). Comparisons of the jet exit regions in Fig. 3.15b (3.37b) and the cutoff cyclone activity in Figs. 3.2–3.4 for the Northern Hemisphere (Figs. 3.24–3.26 for the Southern Hemisphere) reveal that cutoff cyclones occur preferentially poleward of jet exit regions.

Cutoff cyclone activity in the Gulf of Alaska is prominent in all seasons except winter, when it is weakest (see Figs. 3.5–3.10, as well as Fig. 3.12c). Jet exit region development is consistent with LC2 type behavior described in Thorncroft et al. (1993), where cyclonic “wrapping” dominates resulting in a deep cutoff cyclone developing poleward of the mean jet. Note that there is seasonal dependence in the cutoff cyclone
frequency, with winter being the least active season. This seasonal dependence suggests that there is terrain influence at work in this region. This suggestion will be discussed in the next section.

Cutoff cyclone activity in the North Atlantic appears to be more characteristic of LC2 type behavior than in the Gulf of Alaska. Deep oceanic cyclones develop in the well known storm track off the US east coast during the cool season. This activity is seen in the hemispheric plots in Figs. 3.5–3.10, as well as Fig. 3.12g, and with greater detail in Figs. 3.82 and 3.83. The cutoff cyclone activity in the North Atlantic Ocean likely is a partial manifestation of the graveyard for the very active US east coast storm track. Support for this hypothesis is given by the genesis/lysis patterns seen in Fig. 3.15a, where lysis is observed to occur more often then genesis for the area just south of Iceland. Some influence on cutoff cyclone activity by the terrain of Greenland may be at work and will be addressed in the next section.

The Southern Hemisphere jet exit region poleward of southwestern Australia may be linked to the band of cutoff cyclone activity that hugs the Antarctic coast between 60° and 110° E. Cutoff cyclone activity in this region is fairly consistent throughout the Southern Hemisphere cool season (see Figs. 3.27–3.32), and the elongated shape of the maximum suggests that it is possibly tied to a seasonal zonal migration of the jet exit region.

The band of cutoff cyclone activity extending eastward from southeast Australia may have ties to the mean jet exit region that lies well east and somewhat equatorward of New Zealand near 130°W. Cutoff cyclones in this region occur preferentially in the seam between the Southern Hemisphere split jet, which is well documented in the literature
(e.g. Taljaard 1972; Hurrell et al. 1998, van Heerden and Taljaard 1998; Vincent and Silva Dias; Bals-Elsholz et al. 2001). This positioning suggests the possibility that deformation associated with the split jet structure may play a role in the existence of cutoff cyclones in this region. Cutoff cyclone activity in this region may be linked to surface cyclone activity, as it is a favored region of surface cyclogenesis (Sinclair 1995).

5.2.1d Orographic cutoff cyclones

The relationship between orography and cyclone distribution is a common topic in the literature, but with relatively few addressing terrain influence on cutoff cyclones (e.g., Bell and Bosart 1993). The distributions presented in this study lead to some speculation of the role of terrain in the development of cutoff cyclones as well. Possible linkage between cutoff cyclone development and terrain can be seen in the Northern Hemisphere across northwest Asia, the Gulf of Alaska, in the North Atlantic near Greenland, across the Turkish Plateau, and northeast of the Caspian Sea.

The very active cutoff cyclone region in the northwest Pacific Ocean and extreme northeastern Asia appears to undergo a seasonal shift within the cool season. As mentioned in the previous section, the cutoff cyclone maximum across northeastern Asia is shifted slightly farther west in fall and spring than in winter. This shift is consistent with the findings of Chen et al. (1991, 1992), who showed that surface cyclogenesis in the warmer months appears to back westward from its mean winter position, so that it lies just downstream of the major mountain barriers in northeast Asia (e.g., the Altai Sayan). According to Chen et al. (1991, 1992), virtually no surface cyclones develop in the lee of
the major mountain barriers in northwest Asia during winter, presumably due to the high static stability associated with intense high pressure near the surface. Lee cyclogenesis is much more prevalent in spring (and to a lesser extent in summer). The consistency with which cutoff cyclone activity pairs with surface cyclone activity in the region (see the graph in Fig. 3.12a) suggests that the terrain may play a role in the case of cutoff cyclones as well.

The Gulf of Alaska is bounded to the north by the Alaska Mountains and to the east by the Canadian Rockies. During spring, summer and fall, it is likely that the higher terrain acts as an elevated heat source and helps to trap cold pools of air over the Gulf of Alaska. Atallah et al. (2001) showed that from May through August, higher values of 1000–500 hPa thickness surround the Gulf of Alaska to the east and north, effectively isolating persistent pools of relatively cold air over the Gulf in the form of a low thickness anomaly. The occurrence of this low thickness anomaly coincides with the annual maximum of cutoff cyclone frequency shown in Fig. 3.12c. During the cooler months, the lack of solar insolation equalizes the temperature gradient seen during the warmer months, and fewer cutoff cyclones are observed. The seasonal shift in cutoff cyclone frequency is also consistent with the sea-level cyclone and cyclogenesis frequencies depicted in Petterssen (1958, Ch. 13).

Cutoff cyclone activity near the southern tip of Greenland is possibly due to interactions with the steeply sloped terrain found in this region. Doyle and Shapiro (1999, section 4) found that in a numerical simulation, perturbations in the background PV field and an eventual larger-scale vortex occurred downstream of where strong westerly flow encountered idealized terrain similar to that of southern Greenland. It is interesting to
note that the strong winds observed in nature in this region are believed to be enhanced by the topography of Greenland itself.

Typically, development of cyclones near mountain barriers is associated with vortex tube stretching, which increases the cyclonic vorticity downstream of the higher terrain itself. This may be the case in cutoff cyclone activity just northeast of the Caspian Sea, which is most active in winter and spring (compare Figs. 3.5–3.6 with Figs. 3.7–3.10 and use the graph in Fig. 3.12j). Middle- and upper level troughs progressing eastward across southern Russia and the Ukraine encounter the Caucasus Mountains, which, due to their elevation (above 5000 m in many places), may disrupt the lower- and middle-tropospheric structure of cyclones. As the upper-level system moves east of the mountains, the middle-level cyclone can regenerate and become a cutoff cyclone. The relatively high percentage of stationary cutoff cyclones (deduced from Fig. 3.12j) further suggests that cutoff cyclone development in this region is tied to the terrain.

In the Southern Hemisphere, there may be significant ties with terrain and cutoff cyclone activity in the vicinity of the Antarctic Peninsula. As mentioned in section 3.1.2d, it appears that cutoff cyclones that develop in the Bellingshausen Sea to the west (the Weddell Sea to the east) of the Antarctic Peninsula are mobile (stationary). Given a mean westerly flow (seen in Fig. 3.37b for 250 hPa), it is possible that the Bellingshausen Sea cutoff cyclones are effectively blocked by the higher terrain of the Antarctica Peninsula (which approaches 5000 m near the base of the peninsula).

5.3 Case studies
The role of orography in the precipitation process is of obvious importance to meteorologists, primarily because it alters the distribution of precipitation from what might otherwise occur in the absence of such terrain (e.g., Bergeron 1949, 1965; Sawyer 1956). The uneven terrain in the northeast US, coupled with the slow-moving nature of cutoff cyclones, is often a recipe for forecast derailment, as seen in the two case studies presented in chapter 4.

Orographic (or upslope) precipitation is a common topic in the literature and various studies focus on many specific geographical regions. Despite its complex terrain, the northeast US has been the focus of relatively few studies on the impact of upslope precipitation. Passarelli and Boheme (1983) is one of the few comprehensive studies that focus on the impact of upsloping in the northeast US. This study found that upsloping was responsible for a 20–60% increase in local precipitation amounts at windward reporting stations over that of leeward reporting stations. It should be noted that Passarelli and Boheme (1983) studied precipitation distributions in the pre-warm-frontal region of 12 northeast US winter storms.

Regardless of the lack of study on upslope precipitation in the northeast US, operational meteorologists in the region are exposed to this forecast challenge throughout the cool season. One of the goals of this study is to utilize the data presented in chapter 4 to provide a better understanding of some of the problems that forecasters face when dealing with cutoff cyclones in the Northeast, and to provide suggestions on how to better deal with these challenges.

Recall from section 4.1 that the two cutoff cyclones used as case studies in this thesis (16 Nov 1999 and 03 Mar 2000) were forecast to produce heavy upslope-enhanced
precipitation. In reality, only the 16 Nov 1999 forecast event verified. The culprit appears to be the strength and duration of the low-level wind component normal to the north–south mountain barriers in northern New York and Vermont. This normal wind component was stronger and more persistent in the 16 Nov 1999 case than in the 03 Mar 2002 case (see the vertical wind profiles in Figs. 4.9–4.10). The lowlevels in both case studies were moist (e.g., RH values > 70% below 700 hPa for both cases, although the higher values of RH persisted longer in the 16 Nov 1999 case) and featured weak static stability.

From an operational point of view, the production of precipitation with a sustained low-level flow normal to the mountains in the presence of moisture and weak stability is not a difficult concept to grasp. However, forecasting it can be. It is common knowledge that numerical models do not always accurately predict the mesoscale wind, moisture, stability and vertical motion features that are crucial to a successful local forecast. This problem is even more of an issue in uneven terrain. Given this fact, forecasters must take even greater care in preparing precipitation forecasts when upsloping, especially in the presence of low-level moisture and weak stability, might occur (such as those situations where a cutoff cyclone is present). The results of this study can be distilled into a few steps that forecasters can use to help produce a more accurate forecast when dealing with cutoff cyclones. These steps are:

1) Understand the critical flow regimes in the area that create upslope conditions.

2) Understand that persistent low-level flow and weak stability are typically associated with cutoff cyclones.
3) Understand that current numerical weather models do not always accurately predict the mesoscale details of precipitation in the presence of uneven terrain.

4) Understand of the behavior of the cutoff cyclone in regard to its position and movement, especially in the presence of low-level moisture and weak stability.

5) Use real-time data (e.g., satellite and radar imagery) to gain a sense of cyclone motion between numerical model runs and to diagnose track errors within model forecasts.

The previous list gives forecasters a systematic approach to addressing the challenges in precipitation forecasting in the presence of a cutoff cyclone. Steps (1) through (3) in the above list are primarily rules of thumb that stem from the current research, but are not new concepts. Step (4) addresses the importance of the cutoff cyclone position relative to mountains. As stated in section 4.2, the track of the 16 Nov 1999 500 hPa cutoff cyclone was farther north and less progressive than the 03 Mar 2000 case, which helped to induce the sustained upslope component to the wind. A more progressive and southerly track associated with the 03 Mar 2000 cutoff cyclone likely prevented persistent upsloping. Step (5) can aid in achieving step (4) by using satellite imagery (specifically water vapor imagery, which shows middle- and upper-tropospheric cyclones quite well) to help verify cutoff cyclone positions in numerical model runs. The use of real-time data is also useful in the maintaining accuracy of forecasts after they are issued (e.g., using satellite, radar and hourly METAR data to monitor stations in upslope-prone areas and to taylor forecasts accordingly).
Fig. 5.1. Percentage of days in which 500 hPa cyclones were observed in each 10° by 10° quadrangle: 1950–1985. Source: PHCH, their Fig. 1.
Fig. 5.2. Total number of analysis periods (twice daily) in which distinct closed cyclone centers at 500 hPa are located in a given 2º X 5º latitude–longitude grid box for a) winter, b) spring, c) summer, and d) fall. Contour interval is 6, except 3 where dashed. Source: BB, their Fig. 2.
Fig. 5.3. Selected areas of favored closed cyclone (solid boxes) and anticyclone (dashed boxes) activity. Source: BB, their Fig. 11.

Fig. 5.4. The monthly distribution of the total number of 12 h analyses in which a closed cyclone is observed in the specified box (top curve, solid line), the number of distinct closed cyclones identified in the specified box (middle curve, dashed line), and the number of closed cyclones forming within the specified box (bottom curve, solid line). Asterisks identify one standard deviation interval centered about the mean value for the top curve (see section 4 of BB for further details). Boxed regions are a) L1, b) L5, c) L8, and d) L12 as defined in Fig. 5.3. All values are normalized to a 30-day month. Source: BB, their Fig. 12.
Fig. 5.4. *Continued.*
6. Conclusion and Future Work

6.1 Conclusions

The results of a 54-year (1948–2001) global and regional climatology of cool-season (defined as October–May for the NH, March–November for the SH) 500 hPa cutoff cyclones are shown. Cutoff cyclones are objectively identified using the NCEP/NCAR reanalysis dataset. Distributions of cutoff cyclone events, 6 h analyses, genesis, and lysis are shown for the Northern and Southern Hemispheres and the Tropics. Cutoff cyclones tend to be favored in selected regions while being sparse in others. Regions of favored cutoff cyclone activity in the NH include the northern Pacific Ocean, the southwest US, Hudson Bay, the northeast US and Canadian Maritimes, the north-central Atlantic Ocean, the Iberian Peninsula, the Mediterranean basin and Turkish Plateau. Cutoff cyclones are also favored across India in the summer months. In the SH, cutoff cyclone activity surrounds the Antarctic mainland, with individual maxima over the Bellingshausen and Weddell Seas, the Amery Ice Shelf and the Ross Ice Shelf. Other favored areas in the SH are across southern Africa, both east and west of southern Chile and Argentina, and in a band from southeast Australia eastward to the central south Pacific Ocean. In general, cutoff cyclones increase in frequency during the progression of the cool season, reaching a maximum in spring. Certain areas, however, are different such as the Gulf of Alaska and India, where summer maxima occur. Cutoff cyclones are not detectable over the major mountain ranges of the world (where the terrain rises above 500 hPa) and are rarely observed near oceanic semi-permanent high pressure systems or in the deep Tropics.
Cutoff cyclone genesis and lysis maxima occur relatively close to each other, reinforcing the well known idea that cutoff cyclones tend to be slow moving. This pattern is seen in the NH across the northwest Pacific Ocean, the Gulf of Alaska, the southwest US, east of the Iberian Peninsula, the Turkish Plateau, east of the Caspian Sea, and across India. In the SH, stationary cutoff cyclones (as suggested by relative closeness of genesis and lysis maxima) are observed across the major ice shelves in Antarctica, as well as in the Bellingshausen Sea and across southern Africa. Areas where more mobile cutoff cyclones are observed in the NH are the cutoff freeway across the central US, and in the US/Canadian Maritimes storm track. SH mobile cutoff cyclones occur over the Weddell Sea, east of southeast Australia and in the south Pacific Ocean east of New Zealand.

From the data presented in this study, it appears that there are basically four types of cutoff cyclones. These types are polar, jet-entrance, jet-exit, and orographic. Polar cutoff cyclones occur primarily near Hudson Bay in winter. Jet entrance region cutoff cyclones are found over northwestern Pacific and extreme northeastern Asia, over the southwest US, and across the Iberian Peninsula. In the SH, they occur over the Bellingshausen and Weddell Seas. Jet exit region cutoff cyclones are observed across the North Atlantic Ocean and possibly in the Gulf of Alaska in the NH, and east of southeast Australia in the SH. Orographic cutoff cyclones are observed in the NH across northwest Asia, the Gulf of Alaska, in the north Atlantic near Greenland, across the Turkish Plateau, and northeast of the Caspian Sea. In the SH, orographic cutoff cyclones are observed near the Antarctic Peninsula.

Monthly cool-season plots of eastern North America cutoff cyclone activity reveal that cutoff cyclones increase in number from fall into winter, and further as spring
approaches. The importance of the cutoff freeway in evident across the central US, and is best defined during the spring months.

Case studies involving two of the climatology members are presented as evidence of the forecast challenges associated with cutoff cyclones over uneven terrain. Both cutoff cyclones (16 Nov 1999 and 03 Mar 2000) were forecast to produce heavy precipitation within the NWS Burlington, VT, CWA, primarily as an upslope event across the higher terrain of northern New York and Vermont. In reality, only the 16 Nov 1999 event produced heavy precipitation. What appears to be the critical forecasting issue was the strength and duration of the low-level wind normal to the higher terrain in the presence of low-level moisture and weak stability. Although the lowlevels were relatively moist and weakly stable in both cases, the track of the 16 Nov 1999 cutoff cyclone was slower and farther north, allowing a stronger upslope wind component to persist.

6.1 Future work

The current study is the first comprehensive multi-scale look at cutoff cyclone behavior in some time. Many research opportunities arise from the results. Some of the more important aspects of this study that warrant further investigation are:

1) Correlate the total and seasonal frequency of cutoff cyclone events and 6 h analyses presented in chapter 3 with teleconnection indices, such as the North Atlantic Oscillation (NAO) and Pacific/North American Index (PNA), as well
as other important large-scale features such as the El Niño/Southern Oscillation (ENSO).

2) A deeper look into the highlighted regions in sections 3.1.1c and 3.1.2c, such as the US/Canadien Maritimes, the southwest US, and Hudson Bay. These areas are some of the most prolific regions of cutoff cyclone activity on the planet and offer healthy sample sizes of cutoff cyclones for research. In addition, these three areas are the source regions for cutoff cyclones that impact the northeast US. Specific areas of study should focus on calculating parameters such as cutoff cyclone movement, and deepening and filling rates. It should be noted, however, that the NCEP/NCAR reanalysis dataset, although a powerful tool for conducting climatologies, may not be the best source of data for more detailed work due to its resolution. It is suggested that more detailed case study work be done using a dataset with a finer resolution such as the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis dataset, which is on a 1° X 1° latitude–longitude grid spacing.

3) Develop a database of cutoff cyclone case studies for the northeast US. Given the challenging forecast issues at hand concerning cutoff cyclones, it is suggested that the precipitation distributions from multiple cutoff cyclone events be stratified by cyclone track. The composite mean tracks presented in section 3.2 can be used as a basis for this step. Precipitation distributions can be obtained via the Unified Precipitation Dataset (UPD, http://www.cdc.noaa.gov/cdc/data.unified.html). This national dataset
incorporates the NOAA first-order station precipitation measurements, daily cooperative observation measurements, and River Forecast Center data, representing over 13,000 stations in the US (after 1992). After 1996, WSR–88D precipitation estimates were used in regions where surface measurements were absent (e.g., near coastal waters, large lakes). Precipitation amounts represent 24 h accumulation ending at 1200 UTC, interpolated to a 0.25° latitude–longitude grid. The UPD is available from 1948 through 1998.

4) Using the stratified precipitation distributions of northeast US cutoff cyclones, develop a conceptual model of the precipitation distribution associated with each of the composite mean tracks.
REFERENCES


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         2. Seasonal
   B. Eastern North America.
      i. Annual w/histogram
      ii. Seasonal
      iii. Monthly
C. TRACKS
   i. Mean tracks for cold season
   ii. Areas of Genesis/Lysis.
   iii. Areas of Genesis minus Lysis.

D. Cutoff Day of the Year (NH/SH/Tropics)
   i. Objectively derived CDOY
   ii. Average CDOY

F. CGOY.
   i. Stratified into 5 yr increments

Case Studies:

03 Mar 00 vs. 16 Nov 99

Shows how slightly different low level flow wrt to orientation of terrain produced large differences in precip.