Warm-Season Lake-/Sea-Breeze

Severe Weather in the Northeast

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

Master of Science

College of Arts & Sciences

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Patrick H. Wilson
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Abstract

Thunderstorms that form along lake-/sea-breeze convergence zones over the northeastern U.S. sometimes are observed to become severe when they migrate from their source regions. These thunderstorms can be challenging to forecast because they can form in the absence of clearly defined synoptic-scale or mesoscale precursor disturbances. The dynamical and thermodynamical processes, modulated by physiographic effects, that are responsible for creating severe weather from lake-/sea-breeze convergence zones are discussed through selected case studies.

Eleven cases were selected for analysis in the northeastern U.S. between 2000 and 2006 where lake-/sea-breeze circulations helped to initiate or suppress convection. The National Centers for Environmental Prediction–North American Regional Reanalysis gridded dataset, the Rapid Update Cycle gridded dataset, radar data, soundings, and surface observations were used to construct the analyses. These 11 cases were divided into two categories: pure cases, where lake-/sea-breeze convergence zones were primarily responsible for initiating severe weather in the apparent absence of synoptic-scale forcing, and mixed cases, where synoptic-scale forcing acted in conjunction with mesoscale forcing from the lake and sea breezes to generate severe weather. The 11-case sample includes one null event where the arrival of marine air from a sea breeze suppressed convection.

Pure cases typically featured: 1) a ridge axis at the surface or aloft, 2)

surface temperatures (dewpoints) of at least 30°C (20°C), and 3) CAPE values of at least 1500 J kg^{-1} at 1200 UTC before the event. In contrast, mixed cases typically featured: 1) a trough at the surface or aloft, 2) surface temperatures (dewpoints) ranging from 20°C to 30°C (10°C to 20°C), and 3) cyclonic vorticity advection increasing with height. Perhaps the most important general finding for all cases was the prevalence of multiple synoptic and mesoscale boundary intersections. These boundary intersections served as locations where convergence and lift were enhanced to the point where deep convection was initiated. In the null case, however, the interaction of preexisting convection with a marine planetary boundary layer, which was relatively cool and stable with limited CAPE and considerable CIN, behind a sea-breeze front suppressed convection.

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Acknowledgments

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I also would like to thank the National Oceanic and Atmospheric Administration (NOAA) for funding this research under the Collaborative Science, Technology, and Applied Research (CSTAR) program (Grant #NA04NWS4680005). This program has allowed me to learn more about the operational perspectives of atmospheric science through the National Weather Service (NWS). Meteorologists throughout the NWS offices in the northeastern U.S. have provided generous feedback for my work. For example, I received four additional lake-/sea-breeze cases for my research from the Eighth Northeast Regional Operational Workshop that was held in Albany, NY, on 1–2 November 2006. Tom Wasula from the NWS in Albany, NY, served as my CSTAR focal point, and I appreciate his efforts in aiding me with my research and providing me several lake-/sea-breeze severe weather cases previously documented in the literature, which have been added to my literature review in this thesis. Tom Wasula plans to work together with my co-advisors in the aspirations of making a publishable paper from this research in the near future.

Completion of this research would not have been possible without the moral support from my family and friends. I strongly believe that God puts everyone on this planet for a purpose, and I am so thankful to Him for surrounding me with wonderful people who never gave up on me. I treasure the friendships that I have gained from my undergraduate years at the Pennsylvania State University and my graduate years at the University at Albany. I especially wish to thank Matthew Cote and Jared Klein, two of my graduate classmates who also worked on CSTAR projects, for all of their support and friendship during the past three years. Thanks to everyone whom I have acknowledged in this section, my dream of establishing a career in the field of atmospheric science, a field that has interested me since elementary school, is now coming true.

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1. Introduction

1.1 Purpose and Motivation

This research was conducted as a warm-season, defined as April–October, project of the Collaborative Science, Technology, and Applied Research (CSTAR) program to address the forecasting and scientific challenges of lake-/sea-breeze severe weather. The purpose of this thesis is to examine the role of lake and sea breezes in promoting severe convection in the northeastern U.S. (hereafter referred to as the Northeast). A major goal of this research is to complete a multiscale analysis of the thermodynamical and dynamical processes involved in lake-/sea-breeze-induced convection. The analysis also aims to document and understand the evolution of flow patterns that can lead to lake-/sea-breeze-induced severe weather in an effort to help improve forecasting accuracy. Improved understanding of lake-/sea-breeze convection can help refine severe weather warnings issued by the National Weather Service (NWS). It is hoped that the results of this CSTAR research will raise awareness, encourage further studies, and begin a library of cases that others may extend to build a large sample of cases adequate for detailed statistical analyses. The remainder of this chapter serves as a general overview of lake and sea breezes and the interactions with convection and other mesoscale processes.

Lake and sea breezes occur frequently over the Northeast because of the proximity of the Great Lakes and the Atlantic Ocean. During the warm season, the unequal heat capacities of land and water cause the land to warm faster than the water. Lake and sea breezes tap into the available potential energy from the resulting temperature gradient to create a 3D circulation along the shore. The updraft portion of this circulation can lift air parcels to their LCL and form cumulus clouds. If the air parcels can reach their LFC, however, lake-/sea-breeze circulations can generate thunderstorms. Synoptic-scale lift from a preexisting trough or a low LFC due to a hot and moist PBL can promote stronger updrafts, so combining all of these factors with a lake or sea breeze could result in severe convection. NWS offices throughout the Northeast have noted the important role that lake and sea breezes have played in convective initiation.

Four factors pose a major challenge for forecasting lake-/sea-breeze severe weather in the Northeast. First, the region is heavily populated with major cities in close proximity to the shores of the Great Lakes and the Atlantic Ocean. Since lake-breeze storms from the Great Lakes can migrate eastward to the East coast during the afternoon, urban regions farther away could face a serious threat of severe weather conditions during the evening rush hour. The high population density promotes a significant risk for death and property damage, given the occurrence of a severe weather event. Second, there is an uncertainty in predicting if, when, and where a lake-/sea-breeze boundary will initiate or enhance convection. The interactions between the synoptic-scale environment and mesoscale lake-/sea-breeze boundaries are difficult for NWP models to resolve accurately. Evidence presented later in this thesis will show that some lake-/sea-breeze convection cases can occur in conditions of weak to negligible synoptic-scale ascent, which further masks detection of these cases in NWP model forecasts. Third, lake and sea breezes can also suppress preexisting convection that was triggered from other sources. Forecasters must monitor conditions carefully for both possible scenarios of convection being triggered or suppressed by lake and sea breezes. Fourth, lake-/sea-breeze severe weather in the Northeast has not been well publicized and studied in adequate detail. Despite these major forecasting challenges, a wealth of literature exists in explaining the dynamical and thermodynamical properties of lake and sea breezes, and recent studies have resulted in improved understanding of lake-/sea-breeze convection.

1.2 History of Sea Breezes

1.2.1 Early Observations

While lake-/sea-breeze convection in the Northeast has only entered the literature limelight over the last several decades, research on sea breezes dates back to well before the twentieth century. Ward (1914) summarized several findings concerning sea breezes, including an observation from a London navigator in the early 1700s and a report published by the Harvard College Observatory concerning a sea-breeze study conducted by the New England Meteorological Society in the summer of 1887. These two sources explained that sea breezes occurred in response to the uneven diurnal heating of land and water (Ward 1914). Interestingly, Clowes (1917) showed temperature patterns indicating the presence of sea breezes over Long Island, NY, within the domain of this thesis research. The average temperature during a sea-breeze day would increase in the morning but suddenly stop rising around midday before warming resumed in the late afternoon. The cessation of the temperature rise was argued by Clowes (1917) to be associated with cooling from a sea breeze advecting cooler marine air onshore. The thermodynamical concept of land–sea differential heating emerged successfully from these early observations. Documenting the dependence of lake and sea breezes on prevailing synoptic-scale conditions and determining the 3D structure of lake and sea breezes, however, would not take place until the middle of the twentieth century.

1.2.2 Numerical Investigations

A rigorous analysis of the evolution of lake-/sea-breeze circulations first became possible when computers became fast enough to enable NWP models to be employed to simulate the circulations. Estoque (1962) tested cases of different geostrophic wind conditions (no wind, 5 m s^{-1} onshore wind, and 5 m s^{-1} offshore wind) to determine what role, if any, the prevailing environment played in sea-breeze evolution. The direction and magnitude of the prevailing geostrophic wind proves to be a significant factor in the evolution and intensity of a sea breeze. In the case where there is no geostrophic wind (Fig. 1.1a), the sea breeze extends well inland by over 30 km. Having a 5 m s^{-1} offshore geostrophic wind (Fig. 1.1b) produces an even more intense sea-breeze circulation that is positioned along the coast. The updrafts and downdrafts of this circulation, and the horizontal temperature gradient along the sea-breeze front (SBF), are stronger than the simulation shown in Fig. 1.1a. A 5 m s^{-1} onshore geostrophic wind (Fig. 1.1c), however, causes sufficient onshore advection of cooler, marine air to weaken the horizontal temperature gradient and suppress the sea-breeze circulation. Because of computational limitations, Estoque (1962) could not take into account other important processes such as turbulence, radiation, and latent heat release through condensation. More recent numerical studies have introduced these processes through various parameterizations to simulate a more realistic picture of the sea breeze. For example, Bechtold et al. (1991) showed that the maximum sea-breeze intensity occurs when the speed of the SBF is compensated exactly by the prevailing geostrophic wind. This result agrees with that of Estoque (1962), but Bechtold et al. (1991) also showed that most of the PBL turbulence in the vicinity of the sea-breeze circulation exists over the land.

Analytical solutions are difficult to find when incorporating the effects of the PBL, which led some scientists to attack the problem using dimensional analysis. Biggs and Graves (1962) wanted to create a parameter that could be easily used to determine if a lake breeze would form on a certain day. The authors derived a dimensionless quantity, referred to as the lake-breeze index (LBI), given as $U^2/C_p\Delta T$, where U is the background wind speed, C_p is the specific heat capacity of air (1004 J K^{-1} kg^{-1}), and ΔT is the difference between the land temperature and the lakewater temperature. This dimensionless expression can be thought as a simple ratio between the inertial force (U^2) and the buoyancy force (ΔT). When the LBI was less than three, lake breezes were observed, but a LBI greater than three did not support a lake breeze (Biggs and Graves 1962). The LBI was only tested along the western shores of Lake Erie, so it is uncertain whether this parameter can be applied elsewhere with satisfactory skill. The LBI is promising in that the dependence of prevailing synoptic-scale conditions illustrated in Estoque (1962) is clearly emphasized.

1.2.3 International Mesoscale Studies

Investigations of lake and sea breezes outside of the Northeast are widely available in the literature and have yielded important findings on the modifications of lake-/sea-breeze circulations from preexisting mesoscale boundaries, orographic forcing, and PBL instability. For example, Bastin et al. (2006) explored how the inland penetration of the Mediterranean sea breeze was halted by the mistral, a topographically channeled flow surrounded by the highlands of the Massif Central and the French Alps in the Rhône Valley of southeastern France. How far inland the Mediterranean sea breeze penetrates is an important local forecasting problem. For example, air quality (e.g., ozone concentration) is dramatically affected in the city of Marseille within the Rhône Valley depending on which air mass is situated over the city (Bastin et al. 2006). Geography plays a major role in the formation of multiple sea breezes in the New York City region from the Atlantic Ocean and Long Island Sound (Novak and Colle 2006). Hills can block the advance of the cooler, denser air from a sea breeze in south Devon, located in southwestern England (Galvin 2006). In addition, the SBF can take on a lobe-and-cleft structure even in coastal plains (Galvin 2006). The idealized SBF in Fig. 1.2 clearly shows that the top surface of the SBF undulates in space where portions of this surface extend higher into the atmosphere than other sections. The findings from Bastin et al. (2006), Novak and Colle (2006), and Galvin (2006) have accelerated the need for more analyses of the complex evolution of lake and sea breezes.

Forecasting challenges arise when trying to obtain sufficient amounts of data to represent lake-/sea-breeze circulations accurately. Tethered balloons, aircraft observations, ship or buoy observations, and surface stations were employed by Fisher (1960) to study Rhode Island sea breezes and by Estoque et al. (1976) to study southern Lake Ontario lake breezes. These enhanced datasets were used to construct special analyses (e.g., cross sections) and to initialize numerical models. The observation network required to replicate these enhanced datasets for real-time forecasting would be quite costly and time-consuming even with current technology. Collecting sufficient amounts of data to forecast lake and sea breezes accurately remains nontrivial even today.

1.3 Convection and Role of Boundaries

1.3.1 Diurnal Variations

Studying how lake and sea breezes promote deep convection is an important research problem. Lake and sea breezes act as a boundary separating cooler air originating over the water and warmer air originating over the land. As a result, lake and sea breezes can produce concentrated regions of PBL convergence and possibly trigger convection if air parcels can be lifted to their LFC. Several diurnal controls of the sea-breeze circulation exist in the atmosphere. The direction of the sea breeze rotates in accordance with the

Coriolis force, so that sea-breeze convergence zones shift along the coast with time (Nielsen-Gammon 2002). As a result, locations where convection may be triggered can also shift along the coast with time.

Wallace (1975) found that the observed maximum of precipitation and thunderstorms during summer evenings in the New England states was likely associated with sea breezes. A closer inspection between the diurnal heating cycle and sea-breeze convection was performed by Burpee and Lahiff (1984) on southern Florida rainfall variations during sea-breeze days. Sea breezes can develop on both Florida coasts due to the proximity of the Gulf of Mexico and the Atlantic Ocean. In a study from June–September in 1973–1976, Burpee and Lahiff (1984) found that sea breezes account for about 35–40% of the summer rainfall in south Florida with 91% of the rainfall occurring between 1001–2200 Eastern Standard Time (EST) during the days that sea breezes were present. Diurnal variations are commonly found in observing the behavior of convection, so forecasters must account for these diurnal variations when predicting lake-/sea-breeze convection.

1.3.2 Boundaries and Severe Weather

Boundaries such as drylines, outflow boundaries, squall lines, and lake-/sea-breeze boundaries are all types of baroclinic mesoscale boundaries. Studying the general behavior of these baroclinic mesoscale boundaries has yielded important knowledge that can be applied to severe weather. For example, variations in cloud-to-ground lightning and radar characteristics were detected when several supercells crossed a preexisting mesoscale outflow boundary in western Texas during 2–3 June 1995 (Gilmore and Wicker 2002). This mesoscale boundary divided the PBL environment significantly in terms of CAPE, mixing ratio, and low-level vertical wind shear. Some of the preexisting supercells intensified when crossing this baroclinic boundary into an environment more conducive to severe weather (Gilmore and Wicker 2002).

In addition to convective intensification, mesoscale boundaries can also promote tornadogenesis. While convective cells are responsible for most tornadoes, squall lines and bow echoes account for 18% of U.S. tornadoes according to data for 1998–2000 (Trapp et al. 2005). Gust fronts can develop in these squall lines where cooler, drier downdraft air interacts with warmer, moister updraft air. As a result, gust fronts can generate enough low-level wind shear and vorticity to spin up tornadoes, downbursts, and microbursts as shown by Forbes and Wakimoto (1983) during a severe weather outbreak in Springfield, IL, on 6 August 1977. A majority of significant (>F1 on the Fujita Scale) tornadoes have been found in close proximity to mesoscale boundaries during the Verifications of the Origin of Rotation in Tornadoes Experiment (VORTEX) in 1995 (Rasmussen et al. 2000). A VORTEX case study on 2 June 1995 in eastern New Mexico and western Texas led Rasmussen et al. (2000) to suggest that a preexisting outflow boundary helped to generate and enhance both vertical and horizontal components of vector vorticity to trigger multiple tornadogenesis events.

1.3.3 Sea-Breeze Convection

Initiation of sea-breeze convection often occurs along the SBF where PBL air parcels are lifted to their LFC, but convection can also develop ahead of a SBF. Fovell (2005) created a model simulation where convection was initiated from horizontal convective rolls in the PBL ahead of an advancing SBF before both features merged and promoted further intensification of the convection. The presence of the SBF was found to be vital in aiding convective initiation from the horizontal convective rolls. Kingsmill (1995) presented a case from 15 July 1991 in east-central Florida where convection was triggered by a SBF, a gust front, and the subsequent merging of these two respective boundaries. Studies of how circulations associated with convective horizontal rolls are influenced by orographic forcing (e.g., upslope or downslope flow and topographical flow channeling) in the presence of varying PBL moisture, temperature, and wind profiles and combine to trigger convection in the United Kingdom, including during sea-breeze events, have been performed by Bennett et al. (2006). Sea-breeze convection can also be triggered from the low-level convergence and lift in the SBF itself in the essence of horizontal convective rolls or other mesoscale boundaries. For example, Medlin and Croft (1998) compiled 13 events near the Alabama coast during June–July 1996 of sea-breeze convection in weak vertical wind shear (<7.5 m s^{-1} for the 0–2.5 km layer) and nearly negligible synoptic-scale forcing. The surface parcel was found to be the most unstable parcel in the well-mixed PBL with an average CAPE of 2700–3000 J kg^{-1} and mixing ratios of 16–19 g kg^{-1} at 1800 UTC in these events (Medlin and Croft 1998). The PBL was rich with warm and moist air to create enough instability that convection was able to develop despite the lack of significant vertical wind shear and synoptic-scale forcing.

1.4 Lake-Breeze Events

1.4.1 Seasonal Effects

The Great Lakes have been extensively studied for wintertime snowstorms. In winter the land cools faster than the lakes, and this lake–land temperature contrast is the primary energy source for lake-effect snow. Thanks to radar-based investigations from Passarelli and Braham (1981), Winstead and Mourad (2000), and other studies, a greater understanding and awareness has been gained on the physical mechanisms associated with lake-effect snow (e.g., convergent flow over the lakes, onshore flow over the land, and cold air flowing over warmer water). Schematic diagrams of lake-effect snow events shown in Passarelli and Braham (1981) and Winstead and Mourad (2000) could provide a reasonably accurate thermodynamic representation of warm-season lake-breeze events by reversing the lake–land temperature gradient. Fewer cases of warm-season lake-breeze convection have been documented relative to their wintertime counterparts. While the importance of lake-effect snow to the Northeast is widely appreciated, this CSTAR-funded research focuses on the less-studied role that the Great Lakes can play for promoting lake-breeze severe convection during the warm season.

1.4.2 Northeast Mesoscale Issues

Forecasters in the Northeast face substantial mesoscale challenges when predicting lake-/sea-breeze convection. Interacting mesoscale boundaries pose a difficult forecast challenge. At issue is whether the low-level convergence associated with interacting boundaries is sufficiently deep to lift air parcels to their LFC. One example of interacting mesoscale boundaries was a case from 22 July 1964 by Moroz and Hewson (1966) when a lake breeze initiated convection over the eastern Lake Michigan shore where the land was 10°C warmer than the lakewater temperature. The lake breeze is clearly defined by the sharp contrast in wind velocity components perpendicular to the lakeshore during 0900–0930 EST (Fig. 1.3a) and at 1500 EST (Fig. 1.3b). Offshore flow at the surface was replaced by onshore flow within this 6-h period. An outflow boundary from the convection triggered by the SBF subsequently would develop and turn the surface winds back to offshore during the next 2 h. Thus, the outflow boundary from the convection shut down the lake-breeze circulation and ended the threat for any further convective development along the eastern Lake Michigan shore (Moroz and Hewson 1966). Another major challenge is the complex regional physiography (Fig. 1.4) and its relationship to convective storm formation (Wasula et al. 2002). The Northeast is dominated by the Appalachian Mountains and numerous river valleys, which create sharp elevation gradients. The distribution of severe weather seems to be affected by the terrain and its orientation relative to the low-level flow configuration in eastern New York and western New England (e.g., Wasula et al. 2002; LaPenta et al. 2005; Bosart et al.

2006). Interacting mesoscale boundaries and the complex physiography must be considered when forecasting Northeast lake-/sea-breeze convection.

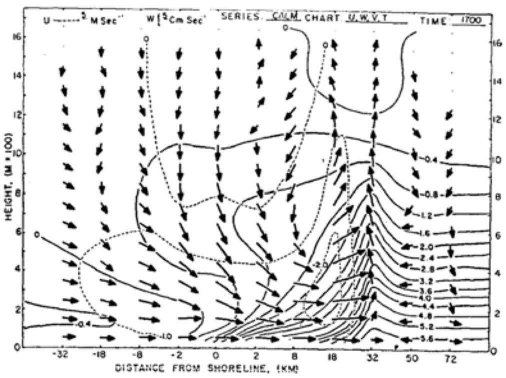
1.4.3 Great Lakes Studies

In recent years several studies have been conducted on lake-breeze convection in the vicinity of the Great Lakes. For example, King et al. (2003) conducted a study of lake-breeze events and generated a tornado climatology over southern Ontario, a region surrounded by Lakes Huron, Erie, and Ontario. The association between lake-breeze events and tornado occurrences was most dependent on the direction of the prevailing synoptic-scale flow. Figure 1.5 from King et al. (2003) shows two lake-breeze severe convection cases originating from Lakes Huron and Erie for 21 July 1994 (left satellite image) and for 31 May 1985 (right satellite image). The 21 July 1994 lake-breeze convection was aided by synoptic-scale lift from an approaching cold front in eastern Michigan, while the 31 May 1985 lake-breeze convection would play a significant role in a major tornado outbreak in Ontario, Ohio, and Pennsylvania. Another study of southern Ontario lake-breeze events was done by Clodman and Chisholm (1994) where the authors were correlating high lightning flash density to the storms generated near the surrounding lakes. The authors found two distinct synoptic-scale situations where lake-breeze cases could occur in southern Ontario: One case occurred on 20 July 1989 near a synoptic-scale front, but another case was found on 25 July 1989 when the entire region was under an upper-level ridge with weak synoptic-scale forcing for ascent available. The potential for lake-breeze events occurring is present despite whether synoptic-scale troughs are near the Northeast or are completely absent.

Tornadogenesis occurred in northwestern Illinois on 14 June 2003 from a lake-breeze that migrated away from Lake Michigan (Wolf 2004). Six tornadoes, short-lived and rated F0 on the Fujita scale, were observed even though the prestorm environment had PBL winds observed to be 2.5–5 m s^{-1} within a unidirectional, low-level northeasterly flow on this day (Wolf 2004). During the warm season of 1999–2000, Kristovich et al. (2003) found that the storm motion relative to the orientation of the lake-breeze front (LBF) considerably affected convective intensity for Lake Erie events. Days with storms propagating within 30–40° of the orientation of the LBF resulted in stronger storms closer to the LBF, but days with storms propagating more perpendicular to the LBF resulted in stronger storms away from the LBF. The findings from these recent Great Lake studies are important to understanding the role that the Great Lakes play on lake-breeze severe convection.

1.5 Outline of Thesis Chapters

This first chapter of the thesis provides the reader with an overview of lake and sea breezes and their interactions with convection, other mesoscale processes (e.g., orographic forcing and merging with other mesoscale boundaries such as outflow boundaries), and PBL stability, moisture, and shear profiles. Chapter 2 will focus on the methodology and sources of data used in finding cases in the Northeast where severe convection was influenced to any degree by lake-/sea-breeze processes. Three types of cases will be categorized in Chapter 2: pure, mixed, and null. The categorization is necessary because the synoptic-scale and mesoscale forcing varying significantly among the cases. Chapter 3 will explore the results of this research. Section 3.1 will focus on pure cases, defined as those events where synoptic-scale forcing was weak to almost absent. Thus, the mesoscale processes of the lake-/sea-breeze will be the major, but not the only, contributor to pure cases. Section 3.2 will investigate the results of mixed cases, defined as those events where a synoptic-scale disturbance was present and interactions between synoptic-scale processes and lake-/sea-breezes are of comparable importance. Section 3.3 will present the results of a null case, defined as an event where the lake-/sea-breeze suppressed convection, in contrast to the pure and mixed cases where convection was enhanced. A discussion of the results of this research is the topic of Chapter 4, which will be followed by the conclusions of this research in Chapter 5.



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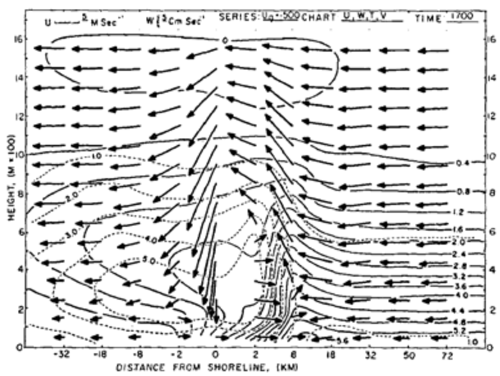

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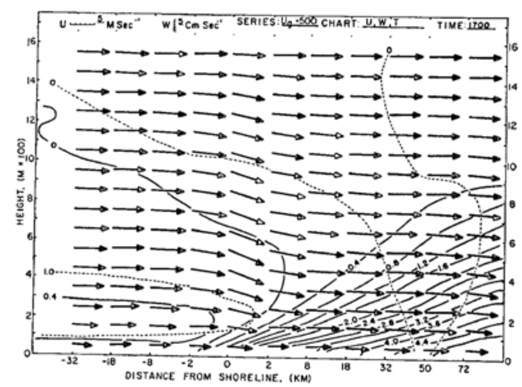


c)

Fig. 1.1. Cross section of numerical model results of simulated sea-breeze circulations 9 h after model initiation time for a) no geostrophic wind, b) 5 m s^{-1} offshore geostrophic wind, and c) 5 m s^{-1} onshore geostrophic wind. Vectors give the landward and vertical circulation, full lines give the 9-h temperature change in °C, and dashed lines are wind velocity components in m s^{-1} into the figure. Figures and caption adapted from Estoque (1962).

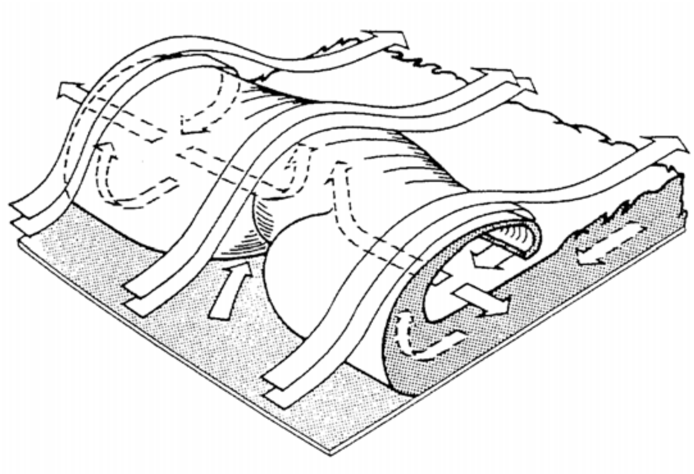
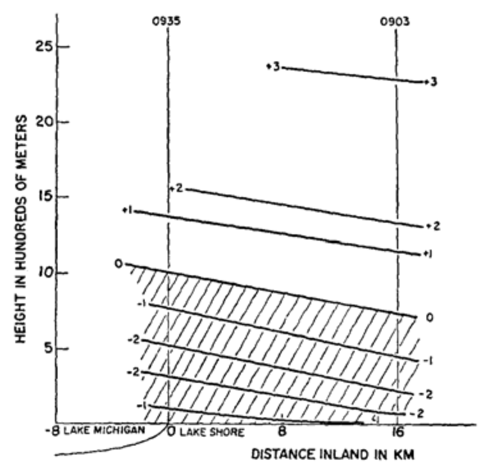


Fig. 1.2. Schematic diagram of the flow at a SBF with flow pattern denoted by arrows. Note the lobe-and-cleft structure indicating the complexity of this front. Figure and caption adapted from Galvin (2006).

a) 

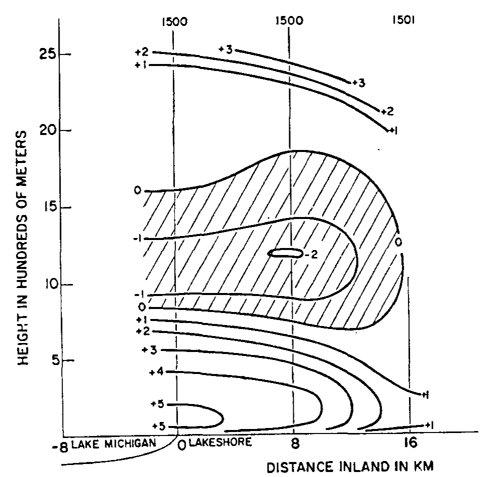
b) 

Fig. 1.3. Cross section of a lake-breeze case on 22 Jul 1964 for a) 0900–0930 EST and b) 1500 EST. Solid lines show the wind velocity components in m s^{-1} perpendicular to the lakeshore. The hatched area represents offshore flow. Figures and caption adapted from Moroz and Hewson (1966).

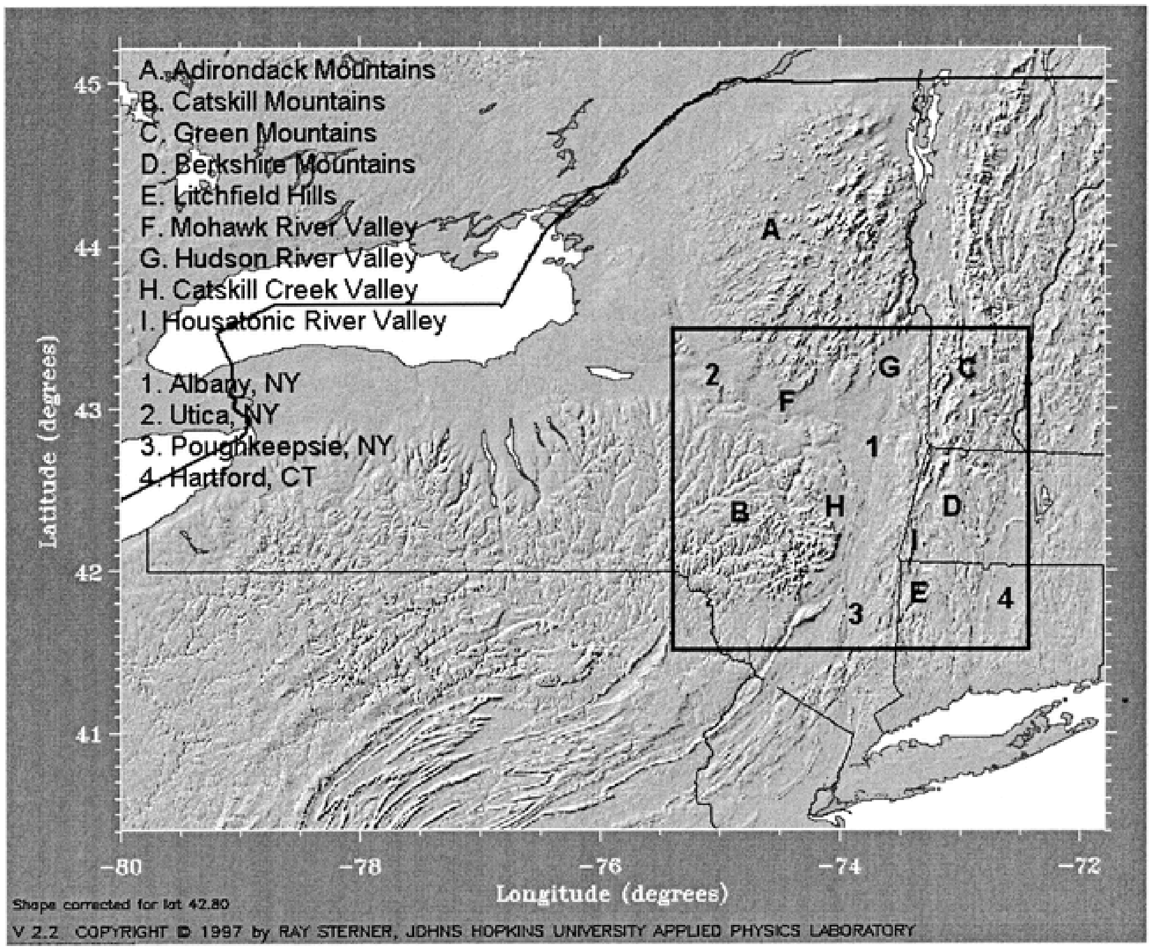


Fig. 1.4. Terrain map showing the complex physiography of NY and western New England with important terrain features and cities labeled. Figure and caption adapted from Wasula et al. (2002).

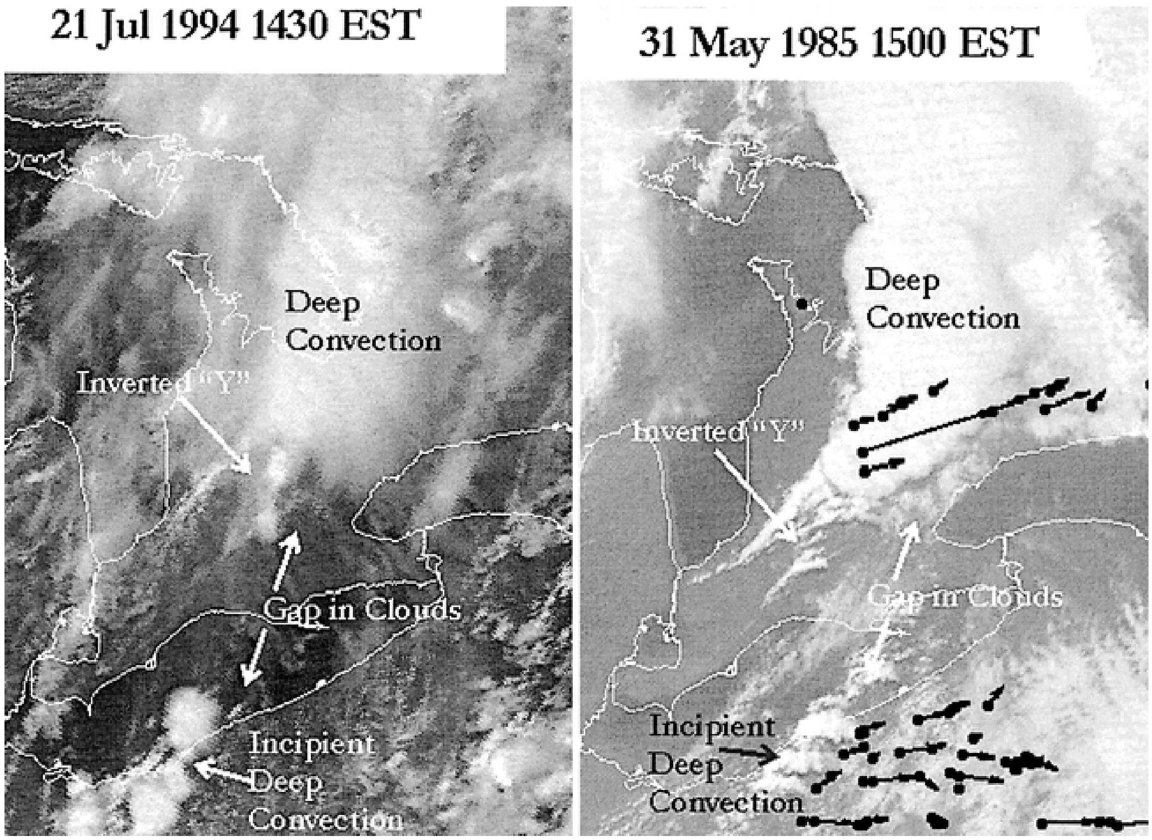


Fig. 1.5. Cloud patterns from lake-breeze events on 21 Jul 1994 and 31 May 1985 as labeled above. Figure and caption adapted from King et al. (2003).

2. Data and Methodology

2.1 Case Selection Process

2.1.1 Domain Setup and Data Sources

The first phase of this research commenced with data collection of lake-/sea-breeze cases that promoted or suppressed severe convection. The Northeast domain was defined by the state abbreviations given in Fig. 2.1. This choice was made to include the coastal shores of the eastern Great Lakes (Lakes Erie and Ontario), the Chesapeake Bay, and the Atlantic Ocean. Cases selected for detailed analysis were from the warm season, defined as April–October, for the years 2000–2006 to take advantage of recent surface observations and available operational Doppler radar imagery. Gridded datasets include the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis at 2.5° resolution (Kalnay et al. 1996; Kistler et al. 2001), the NCEP North American Regional Reanalysis (NARR) at 32 km-resolution (Mesinger et al. 2006), and the Rapid Update Cycle gridded dataset at 20-km resolution (RUC-20) (Benjamin et al. 2004).

2.1.2 Case Retrieval

The search for lake-/sea-breeze severe weather cases commenced with an examination of the online Storm Prediction Center (SPC) storm reports (http://www.spc.noaa.gov/climo/reports/) during the 2000–2006 warm seasons. This search was inherently subjective as patterns of storm reports that seemed to indicate convection arising from the Great Lakes, the Chesapeake Bay, and the

Atlantic Ocean were the primary basis for determining whether to accept a certain event for further investigation or to reject the event. This crude retrieval technique certainly led to some actual lake-/sea-breeze severe weather cases being missed. Consequently, no overall conclusions can be made into how many of these lake-/sea-breeze severe weather cases occur on average annually. Once the potential case dates were recorded, the National Climatic Data Center (NCDC) online archive (http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?WWNEXRAD~Images2) of Next-Generation Radar (NEXRAD) data was investigated for each event deemed worthy of further investigation to determine if indeed lake and sea breezes seemed to play a role in severe convection. The NEXRAD data were only available at hourly intervals in the NCDC archive, so resolution was an issue in finding cases.

Six cases were identified from the initial search for analysis. Four additional cases were added thanks to personal communication with several NWS meteorologists during the Eighth Northeast Regional Operation Workshop in Albany, NY, on 1–2 November 2006. One other unique case was discovered by Lance Bosart on 11 July 2006 of an event where a sea breeze actually suppressed preexisting convection. The search for lake-/sea-breeze severe weather cases resulted in 11 total cases deemed worthy of analysis.

2.2 Case Analyses

2.2.1 Gridded Dataset Analysis

Two gridded datasets were employed to perform a synoptic-scale analysis for the aforementioned 11-case sample. These datasets were used to analyze and depict synoptic-scale patterns associated with lake-/sea-breeze severe convection in the Northeast. The first dataset was the NCEP–NCAR reanalysis. Although the NCEP–NCAR gridded reanalysis provided an adequate starting point for synoptic-scale analysis of the 11 cases, a brief survey revealed that lake and sea breezes were not well represented at the coarse 2.5° resolution. As a result, a second gridded dataset, the NARR, was employed to provide a higher-resolution analysis relative to the NCEP–NCAR reanalysis. The NARR gridded datasets were downloaded from the NOAA National Operational Model Archive and Distribution System website (http://nomads.ncdc.noaa.gov) (Rutledge et al. 2006). The NARR datasets were able to provide more information on the synoptic-scale to mesoscale structures of features depicted with these 11 cases that were not as well represented in the NCEP–NCAR reanalysis. The NARR gridded datasets were relatively noisy compared to the NCEP–NCAR gridded reanalyses. Accordingly, a Gaussian-weighted low-pass filter was used to smooth some of the small-scale noise. Thus, a full synoptic-scale analysis was performed with the aid of the smoothed NARR gridded datasets.

2.2.2 Gathering of Observations

Although gridded datasets are valuable for conducting case studies, it was necessary to supplement these datasets with actual observations to further examine the 11 lake-/sea-breeze severe convection cases. Upper-air soundings were downloaded from the University of Wyoming website (http://weather.uwyo.edu/upperair/sounding.html) to examine the prestorm environment. Surface observations, including land-based station reports and ship and buoy reports, were retrieved from archived surface tapes stored within the Department of Earth and Atmospheric Sciences at the University at Albany. Radar data were retrieved from the NCDC NEXRAD Data Inventory website (http://www.ncdc.noaa.gov/nexradinv/). In addition, satellite-derived water temperature data were gathered from the Physical Oceanography Distributed Active Archive Center (PODAAC) of the National Aeronautics and Space Administration website (http://poet.jpl.nasa.gov) to supplement the ship and buoy reports from the archived surface tapes. Visible satellite images from the University of Wisconsin website (http://dcdbs.ssec.wisc.edu/inventory/) were also retrieved for this research. All of these observations were vital in documenting the thermodynamical and dynamical aspects of the lake-/sea-breeze severe convection cases for this research.

2.2.3 Synoptic-Scale Analysis

The General Meteorology Package (GEMPAK) (Koch et al. 1983) was used to plot various weather data for all 11 cases from the NARR gridded datasets and all the actual observations described in the previous section. Basic weather variables, including geopotential heights, winds, wind shear, mixing ratio, relative vorticity (ζ), potential temperature (θ), equivalent potential temperature (θ_e), and sea-level pressure (SLP), were plotted at 200 hPa, 500 hPa, 700 hPa, 850 hPa, 925 hPa, and the surface. Cross sections were also constructed from the NARR gridded datasets in an attempt to capture the lake-/sea-breeze circulation and vertical motion (ω) patterns along the LBF/SBF.

2.3 Case Classification and Further Analysis

2.3.1 Classification Definitions

Based on examination of the 11 cases selected for this research, it was apparent that not all cases exhibited the same behavior. Accordingly, the 11 cases were classified into three separate categories based on the prevailing synoptic-scale and mesoscale flow patterns. Four cases featured little or no synoptic-scale forcing, indicating that the mesoscale features of the lake-/sea-breeze circulation were the primary forcing for severe convection in these cases. These four cases are referred to as pure cases. All four pure cases featured nonzero synoptic-scale forcing, which is considered secondary compared to mesoscale forcing, but not negligible. Of the remaining seven cases, six featured severe convection that was enhanced by lake-/sea-breeze circulations and synoptic-scale forcing from a preexisting trough or disturbance. Mesoscale and synoptic-scale forcing were of similar importance in these six cases, which are collectively referred to as mixed cases. The last (11th) case did not fit into the pure or mixed categories as new convection was not generated during this event. Instead, preexisting thunderstorms were suppressed by a sea breeze, so this event is categorized as a null case.

One major caution should be pointed out about pure and mixed cases. Lake-/sea-breeze severe weather cases occur from a combination of synoptic-scale and mesoscale forcing that may not be equally important, so these cases are part of a continuous spectrum of synoptic-scale and mesoscale forcing possibilities. Consequently, there is likely no such thing as a “true” pure case. The classification system is designed to distinguish the fact that pure cases and mixed cases exhibit different behaviors under contrasting background conditions. The complex picture of how lake and sea breezes can contribute to either support or suppress convection further illustrates the need for a mesoscale analysis of these cases in addition to the synoptic-scale analyses performed with the NARR gridded datasets.

2.3.2 Mesoscale Analysis

The 32-km resolution of the NARR is too coarse to resolve many of the mesoscale aspects of lake and sea breezes. The presence of convection also complicates the usefulness of the NARR for case study analyses. Upon completion of the synoptic-scale analyses (section 2.2.3), one case that was deemed a worthy representative of each of the three categories was selected for further analysis. These three cases were further analyzed with the RUC-20 gridded datasets at 20-km resolution, which were obtained from the Atmospheric Radiation Measurement website (http://www.arm.gov/xds/static/ruc.stm). These gridded datasets were used to perform a mesoscale analysis. The RUC-20 gridded datasets were used to plot all the weather parameters previously done for the NARR in the synoptic-scale analyses and additionally to create CAPE, convective inhibition (CIN), and 1000–700 hPa wind shear plots. Table I shows the final 11-case list for this research. The three selected cases for RUC-20 analysis were 2 August 2006 (pure case), 19 June 2002 (mixed case), and 11 July 2006 (null case), and are highlighted in Table I. The mesoscale analyses of these three cases proved useful in understanding the thermodynamical and dynamical features involved in these cases that could not be resolved previously in the NARR gridded datasets.

2.4 SPC Verifications

The SPC usually gives the first notice to all NWS offices for severe weather by issuing severe thunderstorm watches, but most of these watches are for apparent severe weather threats from significant synoptic-scale forcing that makes detection of these threats possible by SPC meteorologists. Lake-/sea-breeze severe weather, however, is often harder to forecast due to the lesser role of synoptic-scale forcing and the greater importance of mesoscale forcing. The archived SPC convective outlook reports that were issued after 1200 UTC (http://www.spc.noaa.gov/products/outlook/) on the day of each case were verified against the actual impacts of the 11 lake-/sea-breeze cases. Since the convective outlook reports are only archived back to 2003, one pure case and two mixed cases could not be verified. As shown in Table I, the SPC issued a slight risk for two of the three pure cases, leaving only general thunderstorms forecast for the remaining pure case. The mixed cases were not handled as well by the SPC based upon the issuance of slight risk outlooks for only one of the four cases. The other three mixed cases had general thunderstorms forecast. In regard to the null case, the SPC issued a slight risk for the region where preexisting convection entering that region would be suppressed within five hours. The verification results in Table I emphasize that lake-/sea-breeze severe weather cases are not handled well by the SPC as compared to more apparent severe weather outbreaks, so local NWS offices in the Northeast must play a major role in predicting if, when, and where these cases may occur.

TABLE I. List of 11 lake-/sea-breeze cases with dates, bodies of water responsible, category classifications, states affected (storm reports for pure and mixed cases, no reports for null case), synoptic-scale disturbances present (mixed cases only), and SPC convective outlook risks issued (2003–2006) after 1200 UTC on the day of each case. Cases chosen for analysis with the RUC-20 gridded dataset are highlighted.

Case Date	Lake or Sea Responsible	Case Category	States Affected	Synoptic Event	SPC Risk
9 Aug 2001	Lake Ontario	Pure	ME, NH, NY, VT	N/A	N/A
19 Apr 2002	Lake Erie	Mixed	OH, PA	Cold front	N/A
19 Jun 2002	**Atlantic Ocean**	**Mixed**	**DE, NJ**	**Upper-level trough**	**N/A**
6 Jul 2003	Lake Erie	Pure	DE, MD, NJ, PA	N/A	Slight Risk
24 Jul 2003	Lake Erie, Lake Ontario	Mixed	NY	Cutoff low	General T-Storms
1 Aug 2005	Lake Huron, Lake Ontario	Mixed	NH, NY, VT	Low-level trough	Slight Risk
7 Aug 2005	Chesapeake Bay	Pure	DE, MD	N/A	General T-Storms
30 Jun 2006	Lake Erie, Lake Ontario	Mixed	NY, PA	Upper-level trough	General T-Storms
11 Jul 2006	**Atlantic Ocean**	**Null**	**CT, MA, RI**	**N/A**	**Slight Risk**
23 Jul 2006	Lake Erie, Lake Ontario	Mixed	NY	Upper-level trough	General T-Storms
2 Aug 2006	**Lake Ontario**	**Pure**	**CT, MA, NY, RI**	**N/A**	**Slight Risk**

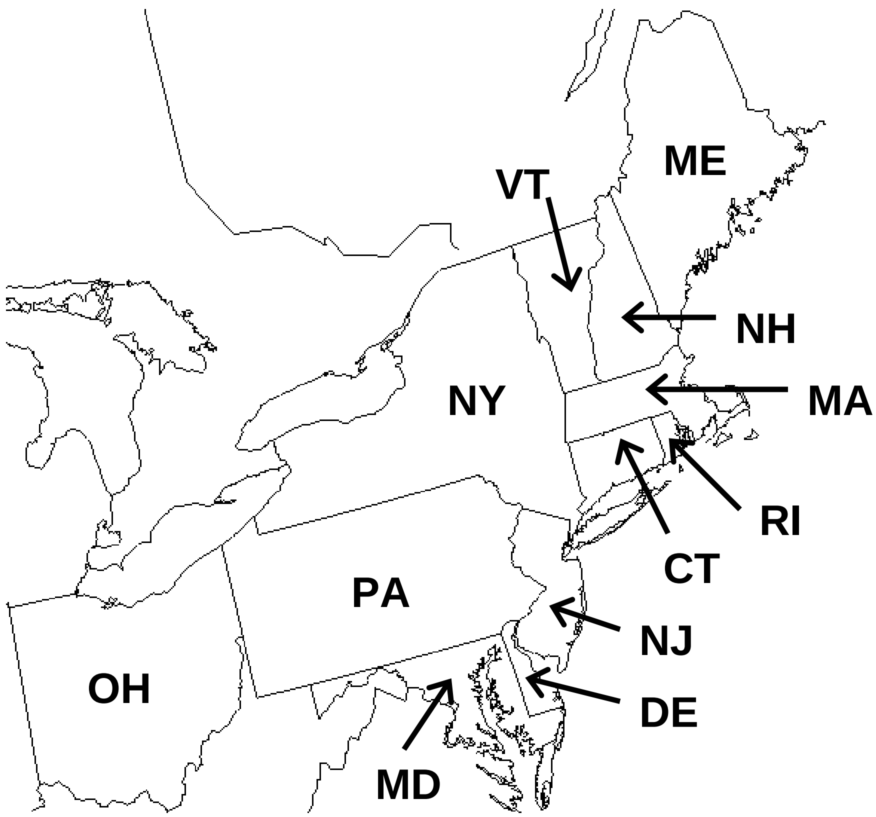


Fig. 2.1. Map of the Northeast domain, which is defined by the displayed state abbreviations.

3. Results

3.1 Pure Cases

3.1.1 Prestorm Synoptic-Scale Environment

The pure case chosen for detailed analysis was 2 August 2006 (Table I). This section will focus on the results from this particular pure case and briefly review the results of the other three pure cases. The Northeast was in a significant heat wave on 2 August 2006 with an upper-level ridge over the eastern U.S. and a trough over the western U.S., which can be seen from the 1200 UTC NARR 200-hPa analysis in Fig. 3.1. With the 200-hPa jet stream located north of the Northeast and the equatorward jet-entrance region located over the western Great Lakes, no favorable environmental pattern for upper-level divergence over Lake Ontario, which is where the convection would begin in this case, was evident. Further confirmation of the relatively featureless synoptic-scale flow over the Northeast is apparent in the 500-hPa analysis from the same time (Fig. 3.2). No significant cyclonic vorticity advection (CVA) can be found over the Northeast at 500 hPa. The upper-level ridge remains as the dominant synoptic-scale feature over the eastern U.S., although a weak short-wave trough was analyzed by the NARR farther to the west over Wisconsin in Fig. 3.2. A NARR surface analysis at 1200 UTC 2 August shows a SLP ridge axis extending northeastward towards Lake Ontario with 1000–500 hPa thickness values >579 dam throughout the Northeast, confirming the presence of the heat wave in the region (Fig. 3.3).

The synoptic-scale pattern did not seem to illustrate any significant forcing for ascent, and this pattern persisted throughout the remainder of 2 August. A sounding from Buffalo, NY (BUF), at 1200 UTC 2 August reveals that the CAPE value already exceeds 1600 J kg^{-1} (Fig. 3.4). Wind shear between the surface and 700 hPa is <15 kt at BUF, and warm air advection in the lower troposphere is insignificant with most of the wind veering likely associated with the relaxation of friction in the PBL. The precipitable water (PW) was observed to be 41.17 mm, and the lifted index (LI) was −6.0°C. Both the surface dewpoint and the surface temperature were >20°C at 1200 UTC, implying a warm and moist PBL was present.

3.1.2 Mesoscale Evolution

By 1600 UTC, the warm and moist PBL represented in the BUF sounding (Fig. 3.4) had been heated sufficiently to where θ_e values at 925 hPa were >360 K as shown in the 925-hPa analysis from the RUC-20 (Fig. 3.5). A θ_e-difference ≥15 K was present between Lake Ontario and just inland over New York. The presence of a 925-hPa ridge axis located directly over Lake Ontario at 1600 UTC is consistent with the upper-air pattern at 200 and 500 hPa over the region (Figs. 3.1,3.2). At this same time, the 925-hPa analysis also showed CAPE values ≥3500 J kg^{-1} along the Mohawk Valley in central New York. Also of interest is that this high-CAPE zone was collocated with a region of 25 kt of 1000–700 hPa wind shear (Fig. 3.6). The near absence of CIN in the high-CAPE corridor at 1600 UTC 2 August suggests that any deep convection, once initiated, would be able to develop in the absence of strong forcing for synoptic-scale ascent.

One hour later, at 1700 UTC, surface observations revealed a noteworthy pattern near the eastern shore of Lake Ontario. Temperatures were above 30°C with dewpoints above 20°C south of Lake Ontario (Fig. 3.7). Southwesterly winds were present over most of western New York, but two buoys in Lake Ontario reported a westerly wind. It is possible that the 925-hPa ridge axis in place over Lake Ontario as shown in Fig. 3.5 may have aided in strengthening this onshore flow over the eastern shore due to the prevailing geopotential height gradient. The temperature difference between the lake and inland was ≥6°C according to the surface observations. The buoys in Lake Ontario reported a lake surface temperature (LST) of 24°C, which agree with the PODAAC satellite-derived water temperature shown in Fig. 3.8.

A NARR cross section was derived for 1800 UTC along the line shown in Fig. 3.9a to investigate the lake-breeze circulation. (The RUC-20 was originally planned for this cross section, but it featured too much small-scale noise in the ω field.) The NARR cross section, shown in Fig. 3.9b, reveals negative ω (upward motion) values inland at $-2\ \mu b\ s^{-1}$ with small positive ω (downward motion) values over the lake. These vertical motions are consistent with a lake breeze with air rising over the warmer land and sinking over the cooler water. The diurnal heating of an already hot and moist PBL resulted in the lowering of the LFC from ~800 hPa at 1200 UTC (Fig. 3.4) to ~900 hPa at 1800 UTC based on modifying the BUF sounding to incorporate the observed surface temperatures near the eastern shore of Lake Ontario (~33°C) and surface dewpoints (~25°C). The NARR analysis of inland ω at $-2\ \mu b\ s^{-1}$ may be an underestimate of the sea-breeze scale ascent. This inference is based upon the ~12 h time for surface air parcels to their LFC at ~900 hPa, given an ω value of -2 μb s^{-1}.

3.1.3 Convective Impacts

The convection propagating along the Mohawk Valley from 1700 to 1900 UTC is shown by the radar images in Fig. 3.10 and the visible satellite images in Fig. 3.11. Thunderstorms began to develop around 1700 UTC (Fig. 3.10a and 3.11a) just inland of eastern Lake Ontario and soon merged into a line that propagated downshear along the Mohawk Valley between 1800 and 1900 UTC (Figs. 3.10b–c,3.11b–c). The storms were most intense by radar reflectivity where θ_e was >360 K (Fig. 3.5), CAPE was >3500 J kg^{-1}, and the 1000−700 hPa wind shear was >25 kt along the Mohawk Valley at 1600 UTC 2 August (Fig. 3.6). As the convection reached the Hudson Valley around 2000 UTC, the line of storms began to dissipate. Evidence in Fig. 3.12 suggests that the dissipation of these storms over the Hudson Valley could be related to the lower values of CAPE (<1500 J kg^{-1}) and higher values of CIN (<−100 J kg^{-1}) analyzed by the RUC-20 over eastern New York. Meanwhile, an outflow boundary that had formed ahead of the line of storms propagated across the Mohawk Valley. This outflow boundary is denoted in the yellow-circled region on the visible satellite images at 1825 and 1902 UTC 2 August (Figs. 3.11b,c). This boundary could have lowered the CAPE and increased the CIN in the PBL, which would further inhibit convective development over the Hudson Valley.

Radar images presented in Fig. 3.13 and visible satellite images shown in Fig. 3.14 further show the evolution of this secondary line of storms from 2000 to 2300 UTC. Once the outflow boundary crossed into western Massachusetts, where higher CAPE values (>1500 J kg^{-1}) existed (Fig. 3.12), a new line of convection formed along this boundary at 2000 UTC (Figs. 3.13a,3.14a). The new line of thunderstorms intensified and propagated southeastward over Connecticut, Massachusetts, and Rhode Island between 2100 and 2200 UTC (Figs. 3.13b–c,3.14b–c). Subsequently, this line of storms weakened around 2300 UTC over the immediate coastal waters of Cape Cod and dissipated farther offshore (Figs. 3.13d, 3.14d). The observed weakening trend in the storms was consistent with the observed 2200 UTC surface temperatures from 35–36°C well inland to 31–32°C over Cape Cod and to <30°C offshore where marine influences were stronger (Fig. 3.15). The observed sounding from Chatham, MA, at 0000 UTC 3 August (actual balloon release was at 2319 UTC, which is important to note as this sounding captures the PBL during the final moments before convection had completely dissipated) supports this inference based on observed CAPE/CIN values of 1643/−125 J kg^{-1} and the existence of a near-surface marine layer (not shown). This case resulted in a total of 40 severe wind reports and five severe hail reports in New York, Connecticut, and Rhode Island. The spatial coverage of these storm reports from 2 August 2006 is shown in Fig. 3.16, where the black-circled area represents the region impacted by this pure case.

3.1.4 Additional Pure Cases

Three other pure cases were documented in addition to the 2 August 2006 case: 9 August 2001, 6 July 2003, and 7 August 2005. Analyses with the NARR revealed that these three cases exhibited similarities to the 2 August 2006 case as shown in Table II. A ridge axis was in place either aloft or at the surface for all pure cases. Additionally, the 1000−500 hPa thickness was found to be ≥570 dam, and PW was found to be ≥40 mm for all pure cases. The 1200 UTC soundings from BUF on 9 August 2001, from Wallops Island, VA (WAL), on 7 August 2005, and from BUF on 2 August 2006, launched near where convection started 6 h later in each case, revealed CAPE ≥1500 J kg^{-1}. The LFC from the 1200 UTC soundings was ≥800 hPa during 7 August 2005 and 2 August 2006, and CIN was found to be ≥−125 J kg^{-1} for all cases except 9 August 2001. Surface temperatures were ≥30°C for all cases except 7 August 2005, and surface dewpoints were ≥20°C for all pure cases. The temperature difference between land and water was ≥5°C with 1000–700 hPa wind shear ≥15 kt during the afternoon hours in all pure cases except 7 August 2005. The 925-hPa θ_e was also found to be large (>335 K) in all pure cases (not shown). Thus, a hot and humid PBL was common in all pure cases. Storms during the 9 August 2001 pure case began near Lake Ontario and moved eastward, resulting in 21 severe wind reports in New York, Vermont, New Hampshire, and Maine. A total of 29 severe wind reports and one severe hail report were observed in Pennsylvania, Maryland, New Jersey, and Delaware during the 6 July 2003 pure case, which began near Lake Erie. Storms in the 7 August 2005 pure case started over the

Chesapeake Bay and resulted in four severe wind reports over Maryland and Delaware.

Storms that originated from Lakes Erie and Ontario in all of the pure cases also tended to evolve into squall lines and migrate eastward considerable distances away from their source regions. The low-level wind shear vector can be quasiparallel with the low-level temperature gradient vector once convection-triggered cold pools have formed and the convection has migrated away from the Great Lakes. The orientation of the wind shear and temperature gradient vectors in a situation where both vectors are quasiparallel can provide a favorable environment for the growth of new convective cells if enough mesoscale instability is generated on the southern side of the cold pool to provide sufficient lift for air parcels to reach their LFC. All pure cases occurred in a conditionally unstable environment with no apparent synoptic-scale disturbance, but the contributions from the synoptic-scale environment are not negligible. Thus, the "purity" of these cases is not perfect but significant enough to demonstrate the importance of mesoscale forcing from the SBF or LBF lifting hot and moist PBL air parcels to a lowered LFC.

3.2 Mixed Cases

3.2.1 Prestorm Synoptic-Scale Environment

The mixed case chosen for analysis was from 19 June 2002 (Table I). This section will focus on the results from this mixed case and briefly review the results of the other five mixed cases. A significantly different upper-air pattern was present on 1200 UTC 19 June 2002 (Fig. 3.17) compared to 1200 UTC 2 August 2006 (Fig. 3.1) as a 200-hPa trough was located over the Northeast. The upper-level trough is more evident at 500 hPa than at 200 hPa with ζ values of 12–16 $\times$ 10^{-5} s^{-1} over Pennsylvania according to the NARR, allowing for CVA over Delaware, New Jersey, and southeastern Pennsylvania at 1200 UTC based on the analyzed wind field (Fig. 3.18). The surface analysis for 1200 UTC 19 June, shown in Fig. 3.19, depicts a high-pressure center over northern New England. Given that a trough is depicted over the Northeast at upper levels in the prior analyses (Figs. 3.17,3.18), the presence of a 1000–500 hPa thickness trough over the region can be inferred, and Fig. 3.19 confirms this inference by depicting a thickness trough extending southward to Virginia. The thickness value over the case region (~558 dam) is lower than the analyzed 1000–500 hPa thickness values from all four pure case regions, indicating a key difference between pure and mixed cases.

The WAL soundings from 1200 UTC 19 June and 0000 UTC 20 June and the Aberdeen Proving Ground (APG), MD, sounding from 1200 UTC 19 June collectively show the evolution of the synoptic-scale environment and the PBL during the afternoon of 19 June. The 1200 UTC sounding from WAL (Fig. 3.20) shows 500 J kg^{-1} of CAPE and −72 J kg^{-1} of CIN. The surface-based morning inversion layer explains most of the CIN present. The LFC was analyzed to be 833 hPa from the WAL sounding. Winds are light and variable in the PBL, but there is significant speed shear between 700 hPa and 300 hPa, indicative of the approaching upper-level trough. The PW was 26.94 mm, and the surface temperature was <20°C at 1200 UTC. The 1200 UTC WAL sounding does not seem to represent an environment conducive to severe weather at first glance, but the PBL would be modified in terms of temperature by a sea-breeze circulation and diurnal heating later in the afternoon on 19 June. Meanwhile, the APG sounding from 1200 UTC 19 June reveals that the surface–6 km wind shear, a key parameter in determining the potential for supercells and organized convection, is larger (Fig. 3.21) than at WAL with low-level easterly flow from the sea-breeze circulation and upper-level westerly flow near the short-wave trough. The local increase in the vertical wind shear from the sea-breeze circulation was critical in improving the chances for convective development ahead of the short-wave trough over New Jersey and Delaware, which is where convection would occur in this case. Twelve hours later, the WAL sounding from 0000 UTC 20 June (Fig. 3.22) reveals that the PBL moisture, CAPE, and surface temperature have all increased in comparison to 12 h earlier (Fig. 3.20). The short-wave trough passage can be seen by the shift of the winds near 500 hPa from west-southwest at 1200 UTC 19 June to west-northwest at 0000 UTC 20 June.

3.2.2 Mesoscale Evolution

By 1800 UTC 19 June, the 500-hPa short-wave trough had reached eastern Pennsylvania and northern New Jersey (Fig. 3.23). Weak CVA associated with the trough extends from eastern Pennsylvania and eastern Maryland eastward across Long Island. The presence of CVA increasing with height is critical to examine as it can promote forcing for ascent according to the quasigeostrophic (QG) ω-equation as given by, for example, Eq. (5.6.11) in Bluestein (1992). CVA and temperature advection below 500 hPa (not shown) were virtually zero, so the dominating contribution to QG-forcing for ascent in the surface–500 hPa layer was from CVA increasing with height above 500 hPa due to the short-wave trough. While dynamical forcing was significant in the midtroposphere, the thermodynamic attributes of the PBL were not as impressive with the 925-hPa θ_e value just over 320 K in western Delaware and western New Jersey (Fig. 3.24). CAPE values of 500–1000 J kg^{-1} are also present over western Delaware and western New Jersey, and 20 kt of 1000–700 hPa wind shear exists over the same region (Fig. 3.25).

Meanwhile, a steady easterly surface wind persisted throughout 19 June 2002 across Delaware and New Jersey due to the pressure gradient associated with a high-pressure center located in Vermont and New Hampshire (Fig. 3.19). The easterly winds from the sea-breeze circulation and the steady synoptic-scale flow around the high-pressure center observed in Fig. 3.19 can be seen in the 1800 UTC surface observations with temperatures around 25°C and dewpoints approaching 20°C in New Jersey and Delaware (Fig. 3.26). Only two water temperatures were reported near the New Jersey coast: a passing ship reporting an SST of 20°C and a buoy closer to Long Island reporting an SST of 18°C (Fig. 3.26). The PODAAC satellite-derived water temperature data were employed to verify these SST observations. The PODAAC data revealed the SST to be 19–20°C on 19 June 2002 off the New Jersey coast (Fig. 3.27), which was in good agreement with the two SST observations. A 3–5°C air temperature difference between the land and the water suggests that a SBF was generated, but the presence of the 500-hPa short-wave trough was important to help lift air parcels to their LFC. Thunderstorms were already being reported near two stations in central New Jersey by 1800 UTC (Fig. 3.26) as the SBF had pushed inland to where CVA was present at 500 hPa (Fig. 3.23) and increasing with height in the surface–500 hPa layer (not shown).

3.2.3 Convective Impacts

Radar images in Fig. 3.28 and visible satellite imagery in Fig. 3.29 show the evolution of the convection from 1800 to 2100 UTC. Thunderstorms developed over Delaware and New Jersey around 1800 UTC (Figs. 3.28a,3.29a). These storms were mainly single-cellular pulse storms and began to intensify around 1900 UTC (Figs. 3.28b,3.29b). Visible satellite imagery from 1800–1900 UTC (Figs. 3.29a,b) also show where clouds were absent along the Delaware and New Jersey coast in association with the sea breeze. The inland penetration of the SBF is approximated by the position where the convection formed. These cells produced radar reflectivities greater than 60 dB*Z* at 2000 UTC with one cell in southern New Jersey reaching 70 dB*Z* as the clouds increased in coverage over Delaware and New Jersey (Figs. 3.28c,3.29c). The convective cells eventually drifted eastward towards the Atlantic coast where marine air had been advected onshore by the sea breeze at 2100 UTC, and the PBL was likely too stable to support the convection as the cells soon dissipated (Figs. 3.28d,3.29d). Hail was the main severe weather threat from this case as indicated in the SPC storm reports shown in Fig. 3.30. Overall, nine severe hail reports and one severe wind report were observed in Delaware and New Jersey for this case. The largest hail size reported was 4.45 cm (1.75 in.) by two different spotters in New Jersey, so this case was a significant severe weather event.

3.2.4 Additional Mixed Cases

Five other mixed cases were documented in addition to the 19 June 2002 case: 19 April 2002, 24 July 2003, 1 August 2005, 30 June 2006, and 23 July 2006. Analyses with the NARR revealed that these five cases exhibited similarities to the 19 June 2002 case as shown in Table III. All mixed cases occurred with an accompanying synoptic-scale disturbance or trough and 1000–500 hPa thickness values between 555 and 570 dam. Half of the six mixed cases featured PW ≥25 mm, and every case except 19 April 2002 had the LFC ≥750 hPa and CIN ≥−100 J kg^{-1} from the 1200 UTC soundings closest to each case. Additionally, CVA was present at 500 hPa in all mixed cases. Afternoon surface temperatures were observed to be ≥20°C in every case except for 24 July 2003, and all mixed cases had afternoon surface dewpoints ≥10°C. Four of the six mixed cases featured a land/water temperature difference ≥5°C and a 1000–700 hPa wind shear of ≥20 kt. All mixed cases had 320 K ≤ θ_e ≤ 350 K at 925 hPa (not shown). Thus, there was sufficient moisture and instability to promote severe convection once air parcels were lifted to their LFC from convergence associated with a LBF/SBF and an accompanying synoptic-scale trough.

Mixed cases appear more likely to produce severe hail than pure cases, given the lower 1000–500 hPa thickness values analyzed by the NARR. Severe wind and tornadoes, however, were also documented in mixed cases. The 19 April 2002 case originated from the interaction of a cold front and a Lake Erie LBF, culminating in 27 severe hail reports and three severe wind reports. A mixed case associated with a cutoff low over Lakes Erie and Ontario on 24 July 2003 resulted in six severe hail reports and one severe wind report. The 1 August 2005 mixed case formed in conjunction with a low-level trough over Lakes Huron and Ontario, producing 18 severe wind reports, nine severe hail reports, and one tornado (rated F0) report. The 30 June 2006 case was associated with an upper-level trough over Lakes Erie and Ontario and resulted in 10 severe hail reports, five severe wind reports, and one tornado (rated F0) report. The respective tornado reports from 1 August 2005 and 30 June 2006 were located near Buffalo, NY, which is situated close to where the LBF from Lake Erie can intersect with the LBF from Lake Ontario. The intersection of these two lake breezes can provide additional low-level convergence that would make tornadogenesis more likely to occur. The mixed case of 23 July 2006 originated from a weak upper-level trough over Lakes Erie and Ontario and yielded two severe hail reports. Mixed cases can come in many varieties as any synoptic-scale disturbance combining with a LBF/SBF is capable of producing severe weather, given the presence of sufficient instability and moisture in the PBL.

3.3 Null Case

3.3.1 Prestorm Synoptic-Scale Environment

This section will focus on the lone case where convection was suppressed by a sea breeze as opposed to the pure and mixed cases where convection was triggered or enhanced by a sea breeze. This case is deemed a null case due to how existing convection, which initiated over southeastern New York, western Massachusetts, and western Connecticut, decayed when it propagated eastward and encountered an Atlantic Ocean sea breeze on 11 July 2006 over southeastern Massachusetts, eastern Connecticut, and Rhode Island. The prestorm synoptic-scale environment was conducive to severe weather on this day. A 200-hPa trough was located over the Northeast at 1200 UTC (Fig. 3.31), and a compact 500-hPa short-wave trough can be seen over New York at the same time (Fig. 3.32) with ζ approaching $16 \times 10^{-5}\ s^{-1}$ within the trough.

Meanwhile, the surface analysis (Fig. 3.33) shows a low-pressure center north of Lake Ontario with the 1000–500 hPa thickness values approaching 570 dam throughout southern New York and the southern portion of the New England states. CVA at 500 hPa is present over eastern New York, western Massachusetts, and western Connecticut (Fig. 3.32), and CVA is also increasing with height between the surface and 500 hPa over the same region (not shown). Warm air advection also appears to exist at the surface (Fig. 3.33) and at 850 hPa (not shown) where CVA is increasing with height, so the overall dynamic pattern favors QG-forcing for ascent within this region. The sea-level pressure pattern (Fig. 3.33), however, suggests that onshore flow is present over southeastern Massachusetts, eastern Connecticut, and Rhode Island. This synoptically driven sea breeze was advecting stable marine air into the PBL at 1200 UTC and would persist throughout the remainder of the day.

Several key differences in the PBL stability would play a critical role in determining the type of weather conditions observed in the New England states on 11 July 2006. The 1200 UTC soundings from Upton, NY (OKX), shown in Fig. 3.34, and Chatham, MA (CHH), shown in Fig. 3.35, reveal these significant PBL stability differences. Although the CAPE value was >1800 J kg^{-1} at OKX, the CAPE value was <400 J kg^{-1} at CHH. The upper-air conditions at OKX were moist and unstable as evidenced by a PW of 41.35 mm and an LI of −5.2°C, but the CHH sounding exhibited much drier and stable conditions based on a PW of 28.37 mm and an LI of −1.3°C. The CIN value at OKX was −50 J kg^{-1}, while the CIN value at CHH was −139 J kg^{-1}. The moister PBL in OKX resulted in an LFC of 861 hPa in contrast to an LFC of 744 hPa for the drier PBL at CHH. Although the overall environment was conducive to severe weather for both soundings, the presence of less CIN and moister air at OKX suggests that severe weather would be more likely to occur there than at CHH where more CIN and drier air existed. The OKX sounding was never in the synoptically driven sea breeze flow, but the CHH sounding was situated directly within the sea-breeze flow all day.

3.3.2 Mesoscale Evolution

By 1600 UTC, the upper-level short-wave trough had advanced eastward to the New York–Vermont border. A CVA maximum (1×10^{-8} s^{-2}) was present at 500 hPa over southeastern New York and western Massachusetts (Fig. 3.36). The QG-forcing for ascent over this region can be expected as CVA increasing is with height and warm air advection is present (not shown). Convection would begin to fire in this ascent region shortly after 1600 UTC. The aforementioned 500-hPa trough not only provided synoptic-scale lift for these new thunderstorms, but also contributed to maintaining the southwesterly flow from the Atlantic Ocean over the southeastern portion of the New England states.

Two hours later at 1800 UTC, the difference in θ_e between the region within the synoptically driven sea-breeze flow (southeastern Massachusetts, eastern Connecticut, and Rhode Island) and the region outside of the sea-breeze flow (eastern New York, western Connecticut, and western Massachusetts) was ≥10 K as shown by the 925-hPa analysis (Fig. 3.37). A weak 925-hPa trough, marking a wind shift from southwest to west-southwest, was located over western Massachusetts and western Connecticut. The CAPE and the 1000–700 hPa wind shear were significantly larger over southeastern New York and western Connecticut (CAPE >2000 J kg^{-1} and 1000–700 hPa wind shear of 20–30 kt) compared to southeastern Massachusetts (CAPE <1000 J kg^{-1} and 1000–700 hPa wind shear of 15 kt) (Fig. 3.38). At 1800 UTC, surface temperatures were between 27 and 29°C with partly cloudy skies in eastern New York, western Massachusetts, and western Connecticut (where convection was forming), while surface temperatures were between 23 and 26°C with mostly cloudy skies in southeastern Massachusetts and Rhode Island (where the sea breeze was present with 15 kt of onshore wind) (Fig. 3.39). The PODAAC data agreed with the buoy reports of an SST of 19°C (not shown). A 1000–700 hPa cross section of ω was taken along the line shown in Fig. 3.40a, extending from central New York to offshore of Cape Cod and the coastal waters. Inland, maximum ascent of <−2.5 μb s^{-1} is found between 750 and 700 hPa, while over Cape Cod and the coastal waters, descent of >2.0 μb s^{-1} is centered between 925 and 850 hPa above the region where marine air is being advected onshore (Fig. 3.40b).

3.3.3 Convective Impacts

The storms involved with this null case can be seen in the radar images on Fig. 3.41. Convection fired between 1600 and 1700 UTC in southeastern New York, western Massachusetts, and western Connecticut (Figs. 3.41a,b), close to the region of CVA noted in Fig. 3.36. At least one of the convective cells reached 70 dB*Z* between 1800 and 1900 UTC (Figs. 3.41c,d), implying large hail was potentially a serious severe weather threat. Indeed, 32 severe hail reports were recorded with five of those reports revealing hail sizes measuring at least 5.1 cm in diameter (2.0 in.). In addition, 21 severe wind reports were observed. The spatial coverage for all of these storm reports is shown in Fig. 3.42. By 2000 UTC, however, the severe convection rapidly collapsed over southeastern Massachusetts, eastern Connecticut, and Rhode Island (Fig. 3.41e). The advected marine air from the synoptically driven sea breeze helped to make the PBL too stable to maintain the updrafts in the storms, causing the convection to dissipate completely over Connecticut and Rhode Island by 2100 UTC (Fig. 3.41f). The 24-h quantitative precipitation estimates from the

Hydrometeorological Prediction Center ending at 1200 UTC 12 July 2006 indicated that no rain fell over the region influenced by the synoptically driven sea breeze (Fig. 3.43). Although conditions were conducive to severe weather in the New England states on 11 July 2006, the synoptically driven sea breeze suppressed severe convection over southeastern Massachusetts, eastern Connecticut, and Rhode Island.

TABLE II. Summary of atmospheric conditions in proximity to each case and SPC storm reports from all four pure cases. Afternoon refers to local time.

Atmospheric Condition and Severe Weather	**9 Aug 2001**	**6 Jul 2003**	**7 Aug 2005**	**2 Aug 2006**
No synoptic-scale disturbance present during daylight hours	Yes	Yes	Yes	Yes
1000–500 hPa thickness ≥570 dam during daylight hours	Yes	Yes	Yes	Yes
PW ≥40 mm from 1200 UTC proximity sounding	Yes	Yes	Yes	Yes
CAPE ≥1500 J kg^{-1} from 1200 UTC proximity sounding	Yes	No	Yes	Yes
LFC ≥800 hPa from 1200 UTC proximity sounding	No	No	Yes	Yes
CIN ≥−125 J kg^{-1} from 1200 UTC proximity sounding	No	Yes	Yes	Yes
Observed surface temperature ≥30°C in the afternoon	Yes	Yes	No	Yes
Observed surface dewpoint ≥20°C in the afternoon	Yes	Yes	Yes	Yes
Observed land/water temperature difference ≥5°C in the afternoon	Yes	Yes	No	Yes
Analyzed 1000–700 hPa onshore wind shear ≥15 kt in the afternoon	Yes	Yes	No	Yes
SPC Storm Reports	21 wind 0 hail 0 tornado	29 wind 1 hail 0 tornado	4 wind 0 hail 0 tornado	40 wind 5 hail 0 tornado

TABLE III. Summary of atmospheric conditions in proximity to each case and SPC storm reports from all six mixed cases. Afternoon refers to local time. Abbreviations used in this table are the following: onshore (onsh.), temperature (temp.), and tornado (tor.).

Atmospheric Condition and Severe Weather	19 Apr 2002	19 Jun 2002	24 Jul 2003	1 Aug 2005	30 Jun 2006	23 Jul 2006
Synoptic-scale disturbance present during daylight hours	Yes	Yes	Yes	Yes	Yes	Yes
1000–500 hPa thickness ≥555 dam during daylight hours	Yes	Yes	Yes	Yes	Yes	Yes
PW ≥25 mm from 1200 UTC proximity sounding	No	Yes	Yes	Yes	No	No
LFC ≥750 hPa from 1200 UTC proximity sounding	No	Yes	Yes	Yes	Yes	Yes
CIN ≥ -100 J kg^{-1} from 1200 UTC proximity sounding	No	Yes	Yes	Yes	Yes	Yes
Analyzed 500 hPa ζ present in the afternoon	Yes	Yes	Yes	Yes	Yes	Yes
Observed surface temperature ≥20°C in the afternoon	Yes	Yes	No	Yes	Yes	Yes
Observed surface dewpoint ≥10°C in the afternoon	Yes	Yes	Yes	Yes	Yes	Yes
Observed land/water temp. difference ≥5°C in the afternoon	Yes	Yes	No	Yes	No	Yes
Analyzed 1000–700 hPa onsh. wind shear ≥20 kt in the afternoon	Yes	Yes	No	Yes	Yes	No
SPC Storm Reports	3 wind 27 hail 0 tor.	1 wind 9 hail 0 tor.	1 wind 6 hail 0 tor.	18 wind 9 hail 1 tor.	5 wind 10 hail 1 tor.	0 wind 2 hail 0 tor.

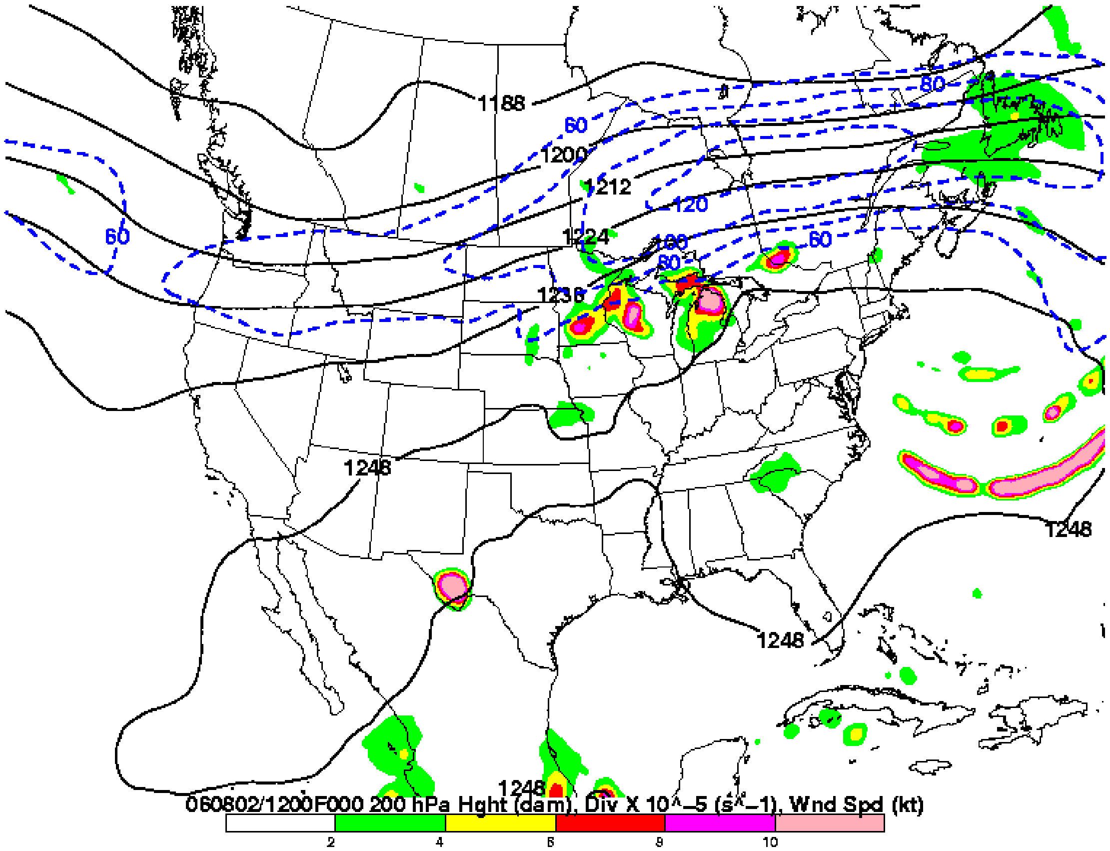


Fig. 3.1. 200-hPa geopotential height contoured every 6 dam, positive divergence shaded according to the color bar for values above $2 \times 10^{-5}\ s^{-1}$, and isotachs for wind speed dashed every 20 kt starting at values above 60 kt at 1200 UTC 2 Aug 2006 from the NARR.

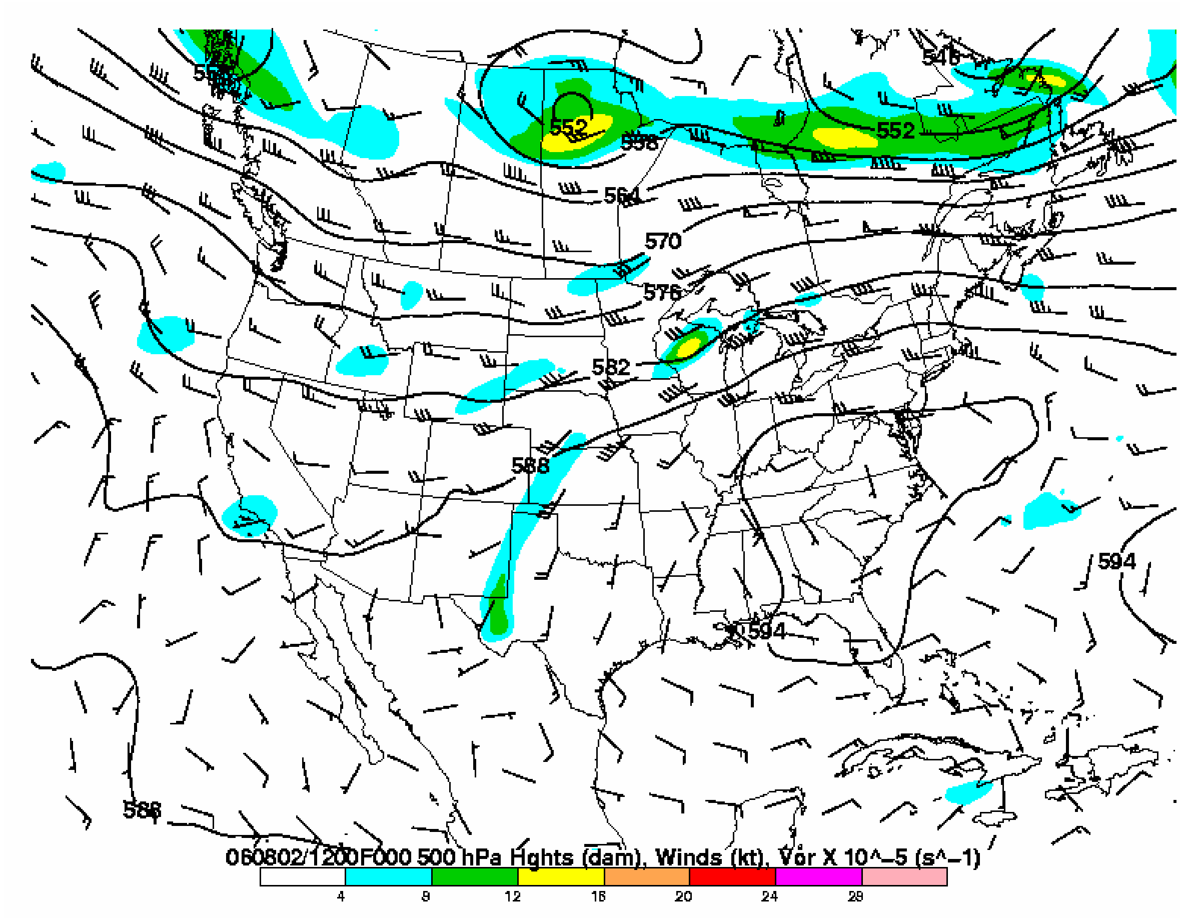


Fig. 3.2. 500-hPa geopotential height contoured every 6 dam, cyclonic ζ shaded according to the color bar starting at 4 × 10^{-5} s^{-1}, and wind in kt (standard notation of pennant representing 50 kt, full barb representing 10 kt, and half barb representing 5 kt) at the same time as in Fig. 3.1 from the NARR.

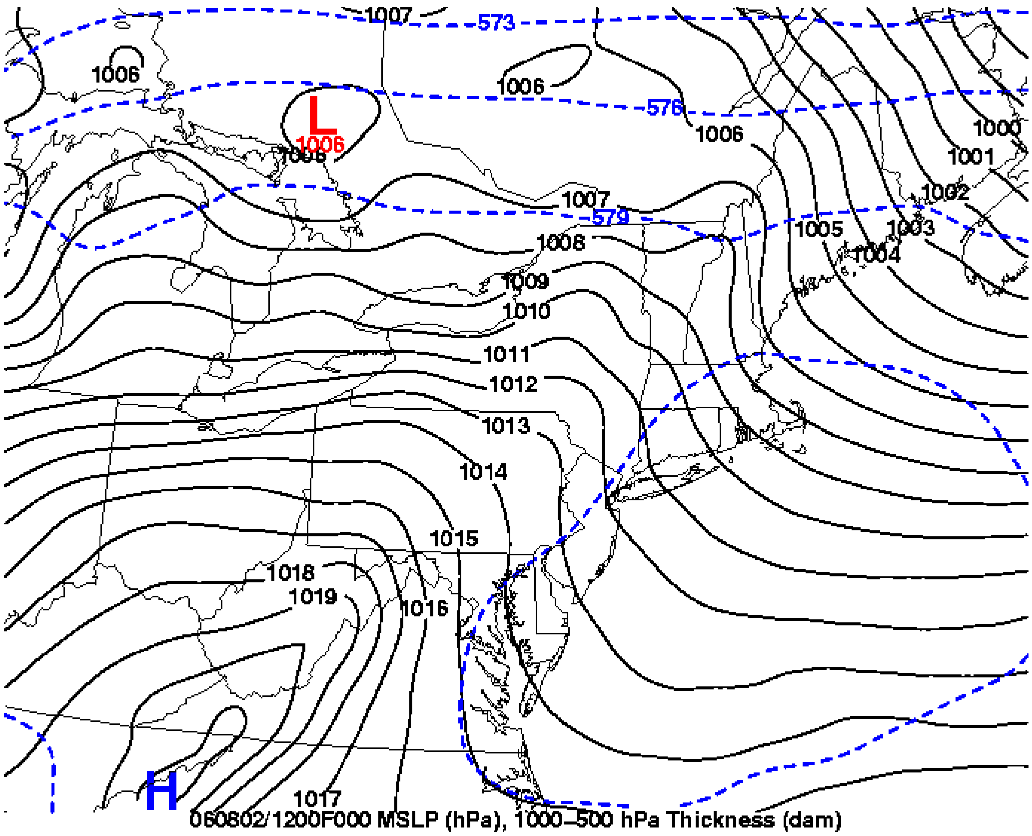


Fig. 3.3. NARR surface analysis with SLP contoured every 1 hPa and 1000–500 hPa thickness dashed every 3 dam at the same time as in Fig. 3.1.

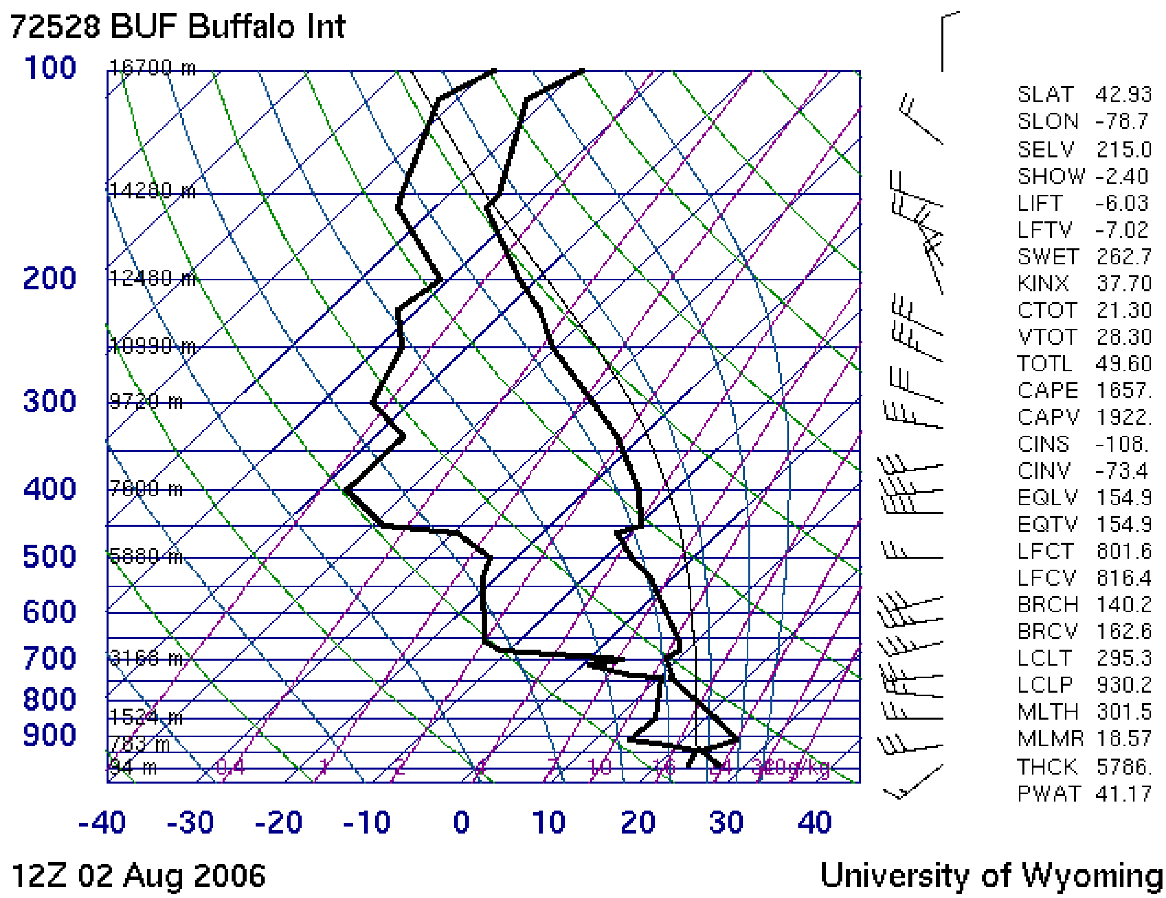


Fig. 3.4. Sounding taken from Buffalo, NY, at the same time as in Fig. 3.1. A parcel from the lowest 500 m of the atmosphere is used to determine the CAPE. (Available online at http://weather.uwyo.edu/upperair/sounding.html.).

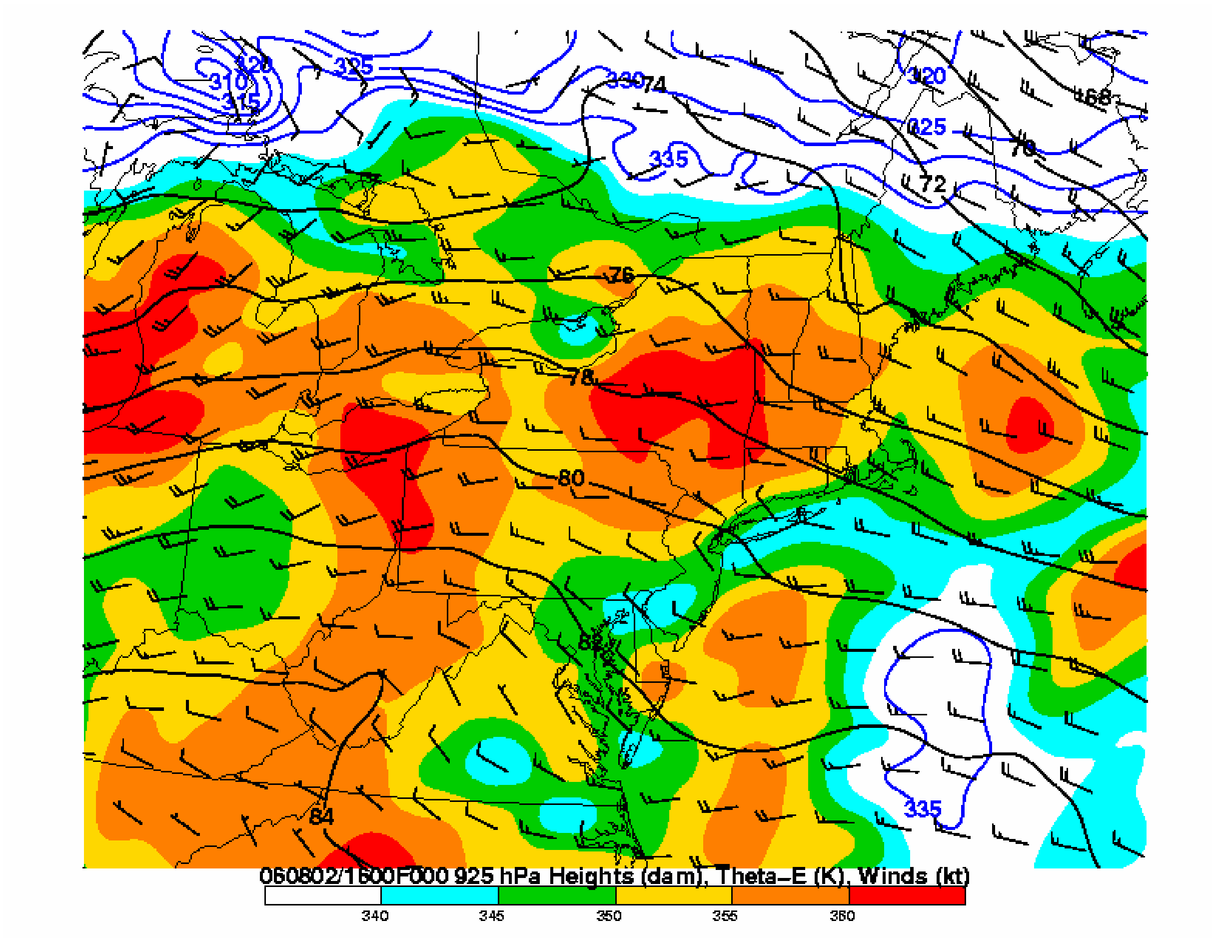


Fig. 3.5. RUC-20 analysis of the 925-hPa geopotential height contoured every 2 dam, wind denoted by standard wind barbs, and θ_e contoured every 5 K in blue <340 K (shaded every 5 K according to the color bar >340 K) at 1600 UTC 2 Aug 2006.

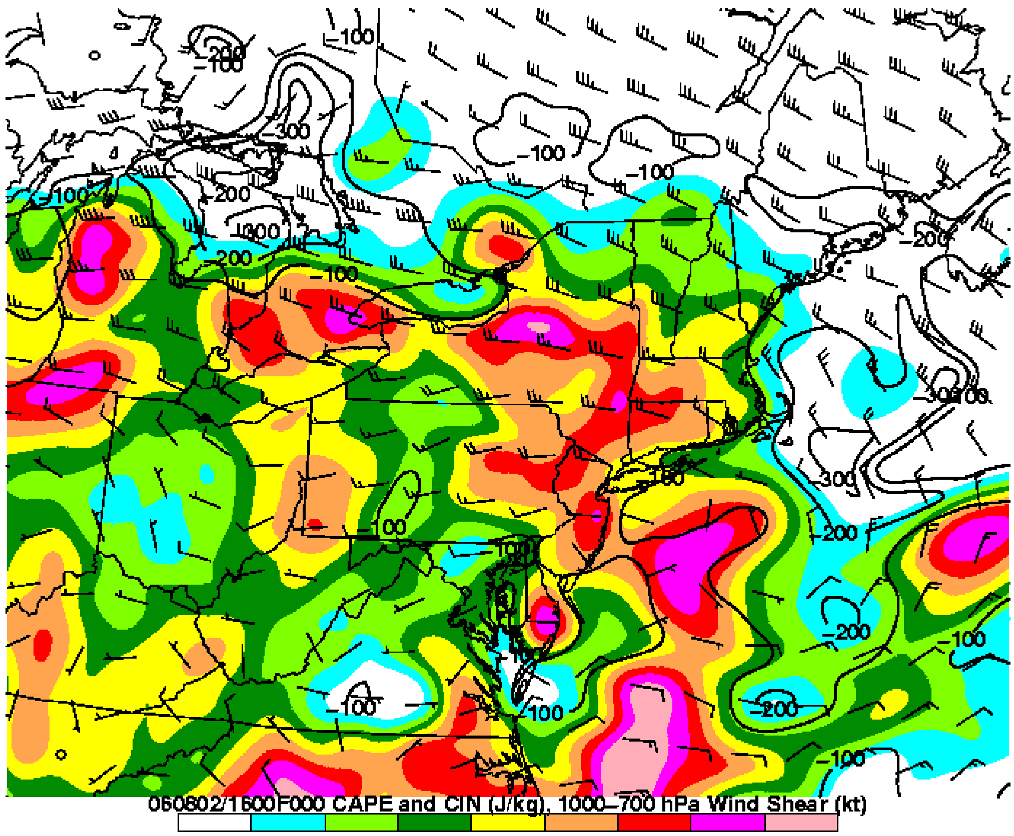


Fig. 3.6. RUC-20 analysis from the same time as in Fig. 3.5 of 925-hPa CAPE shaded according to the color bar >500 J kg^{-1}, CIN contoured <−100 J kg^{-1}, and the 1000−700 hPa wind shear vector as denoted by the standard wind barbs.

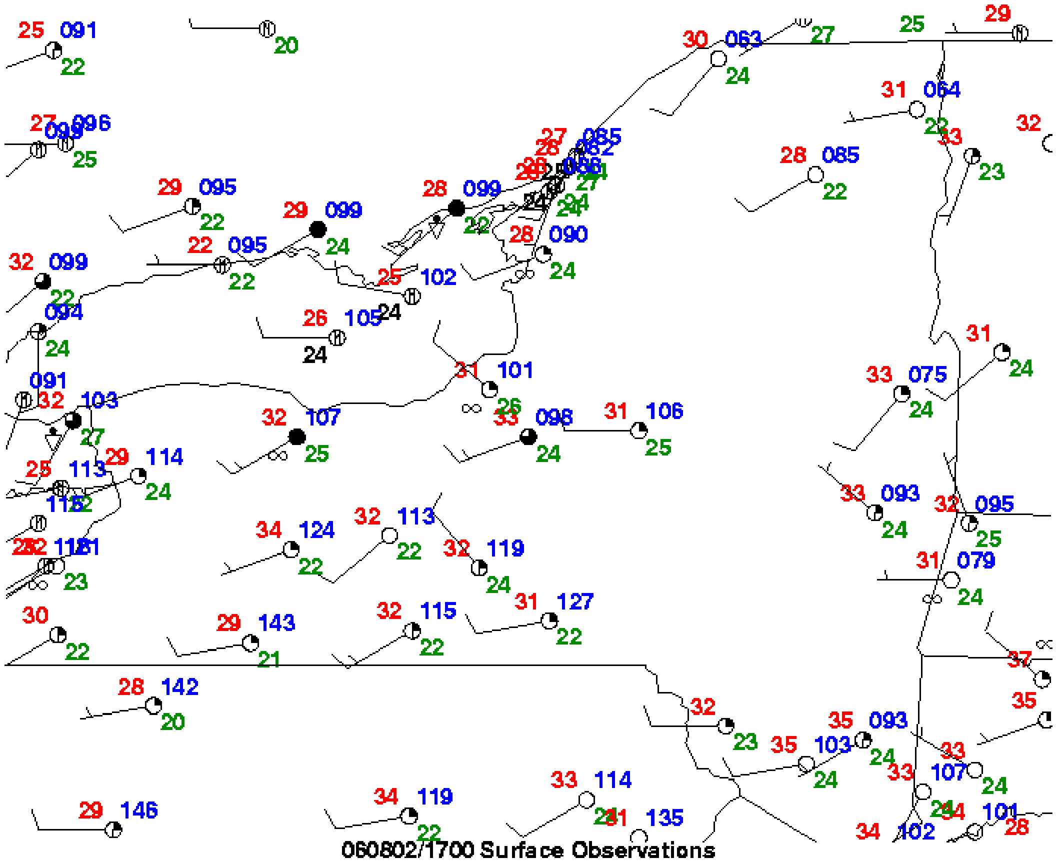


Fig. 3.7. Surface observations from 1700 UTC 2 Aug 2006 with temperature in red (°C), dewpoint in green (°C), SLP in blue (hPa), wind and weather conditions in standard notations, and LST in black (°C) if the observation is over a lake.

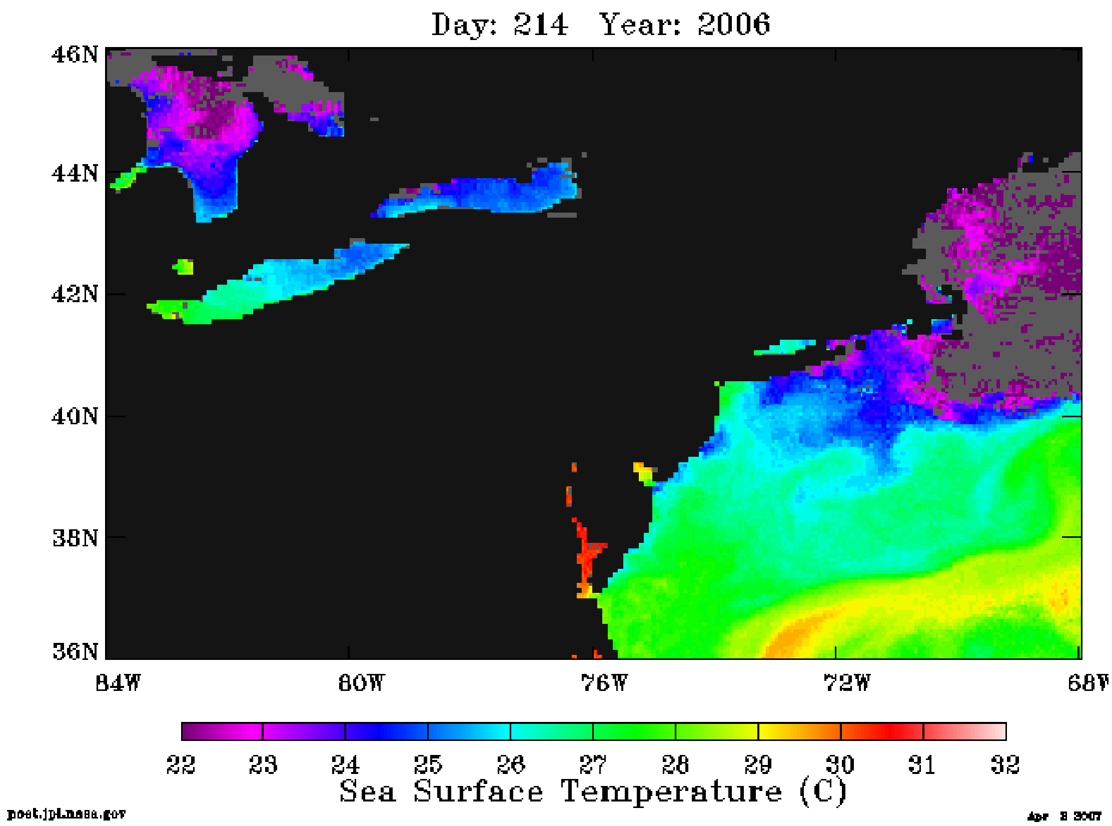
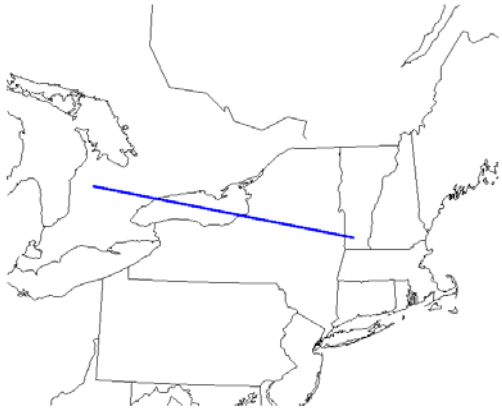
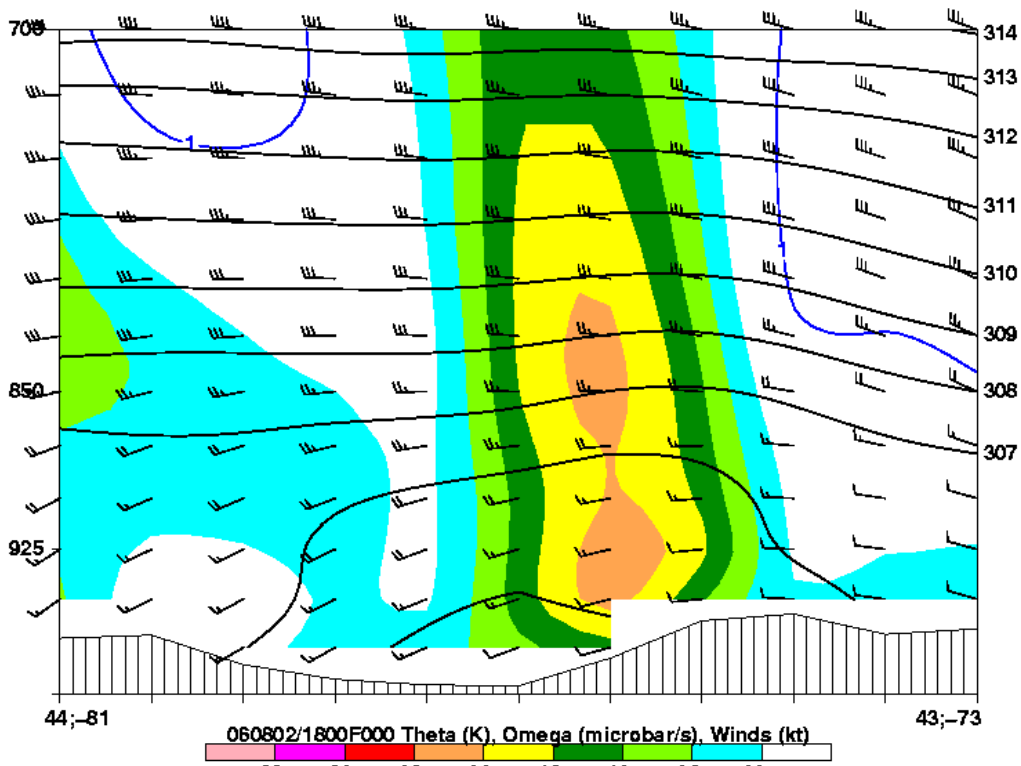


Fig. 3.8. PODACC plot of satellite-derived daily average water temperature for 2 Aug 2006. (Available online at http://poet.jpl.nasa.gov.)

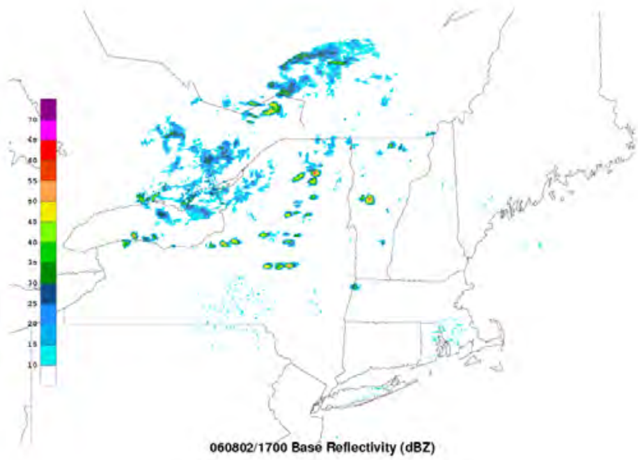


a)

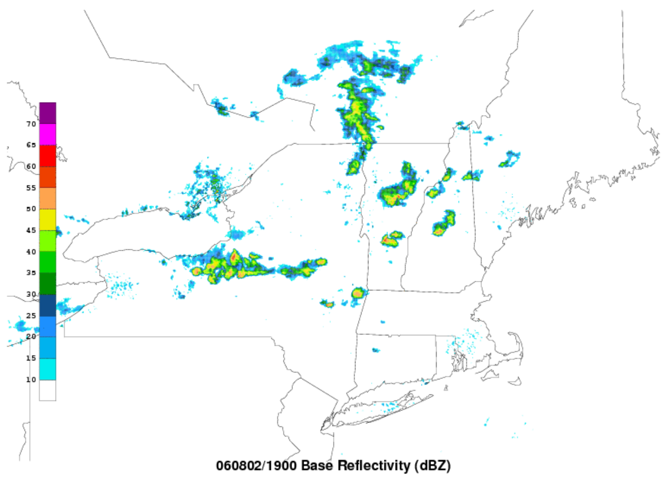


b)

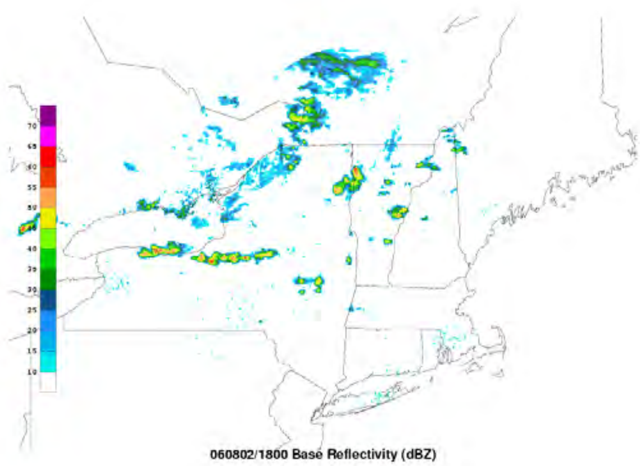
Fig. 3.9. NARR cross section at 1800 UTC 2 Aug 2006 from 1000 to 700 hPa along the line shown in (a) and plotted with wind in standard barbs, θ contoured every 1 K, ω shaded by the color bar every 0.5 μb s^{-1} for negative values (upward motion) [contoured every 1 μb s^{-1} for positive values (downward motion)].



a)

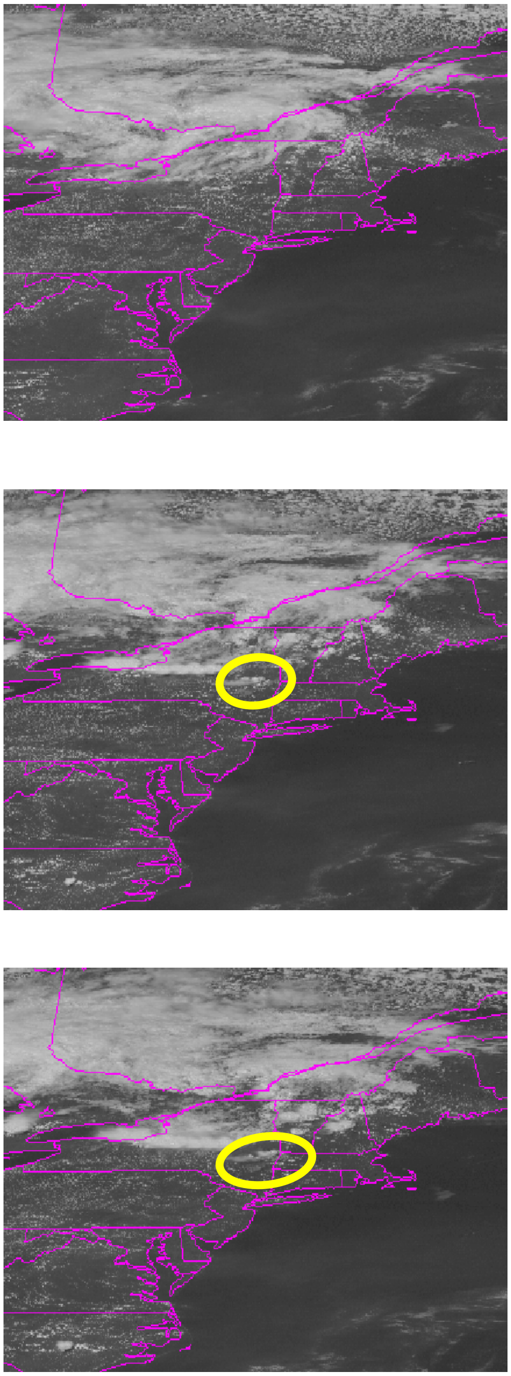


b)



c)

Fig. 3.10. Radar images from 2 Aug 2006 at (a) 1700 UTC, (b) 1800 UTC, and (c) 1900 UTC. The echoes are in dB*Z* and are shaded according to the color bar.



a)

b)

c)

Fig. 3.11. Visible satellite images from 2 Aug 2006 for (a) 1702 UTC, (b) 1825 UTC, and (c) 1902 UTC. The yellow-circled regions denote where the outflow boundary that later triggered the second line of convection is located after 1800 UTC. (Available online at http://dcdbs.ssec.wisc.edu/inventory.).

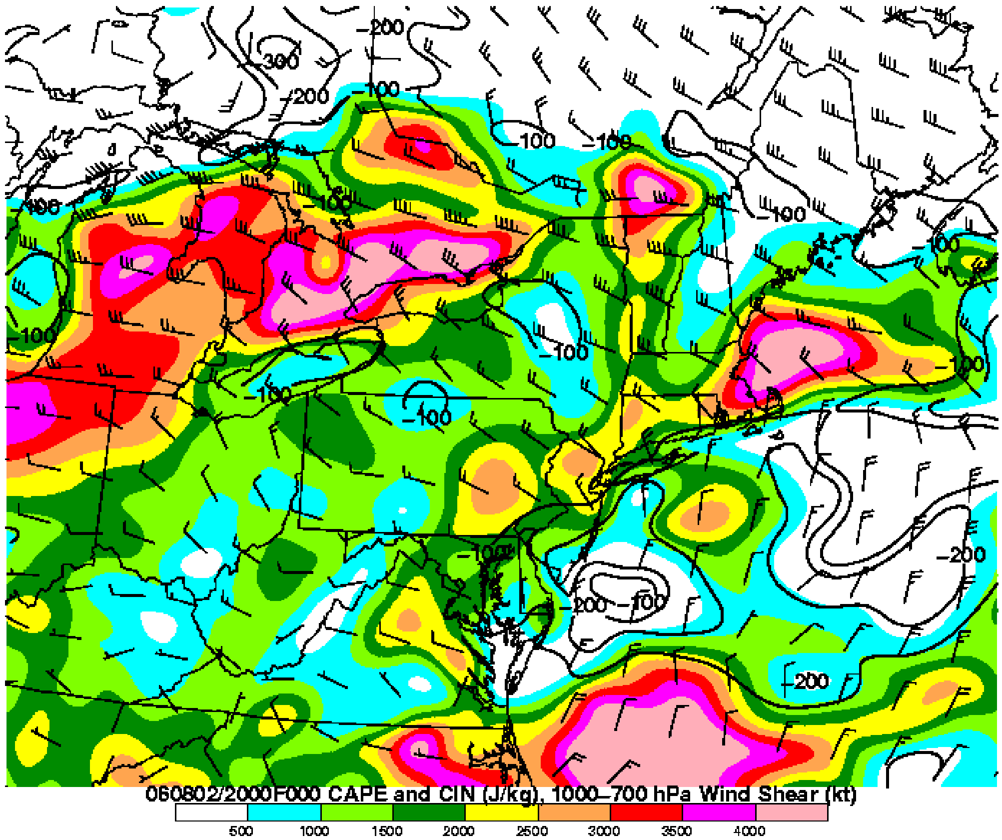


Fig. 3.12. Same as in Fig. 3.6 but for 2000 UTC.

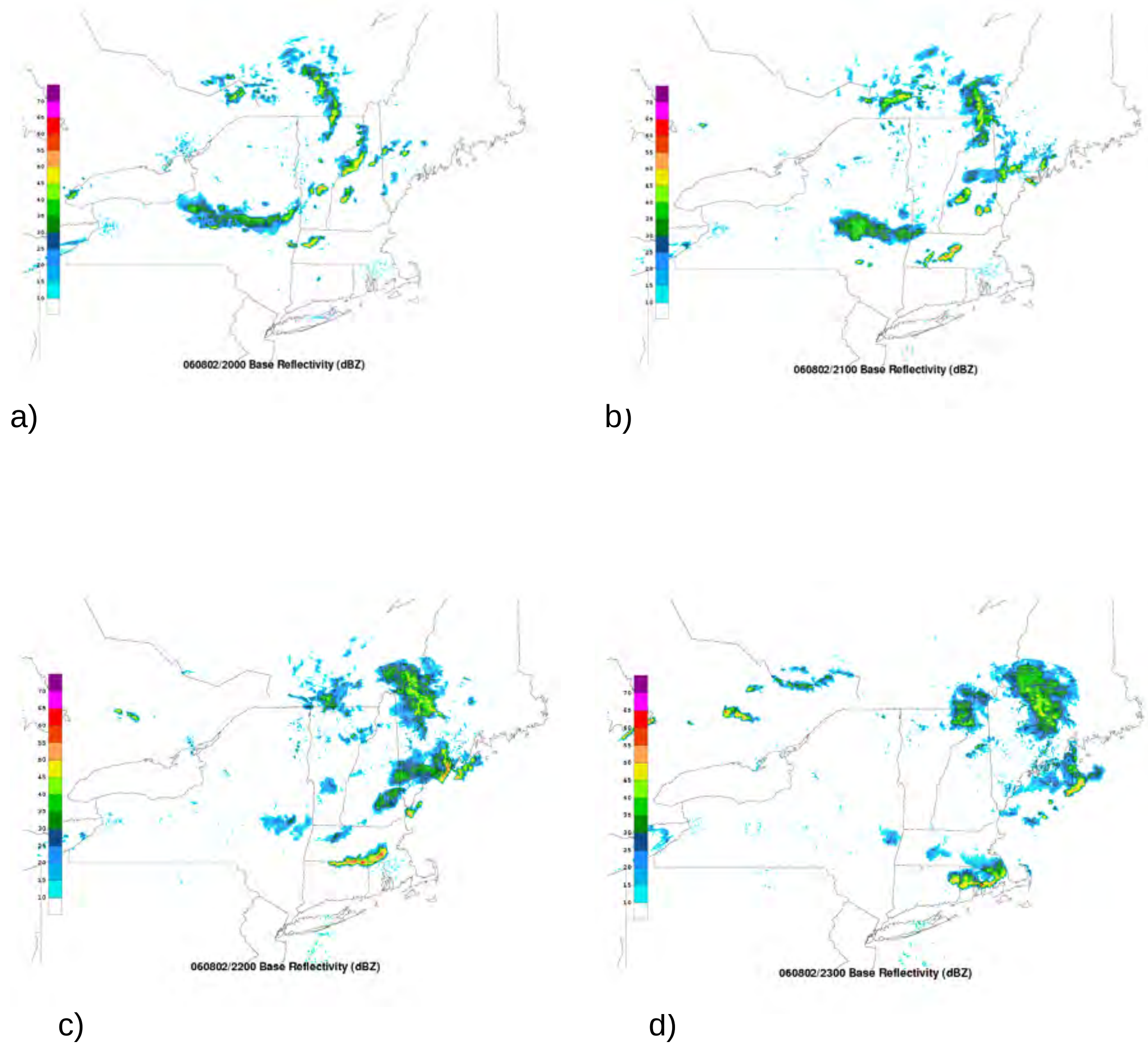
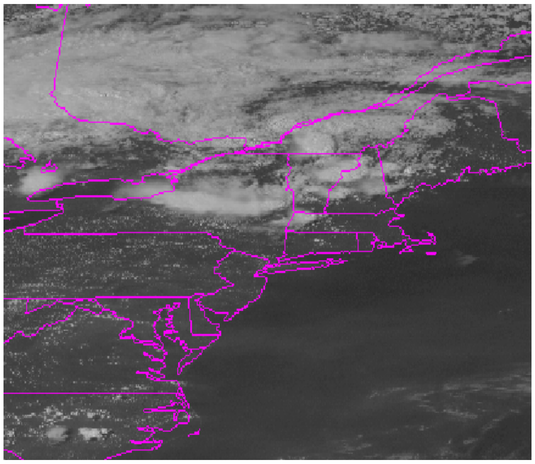
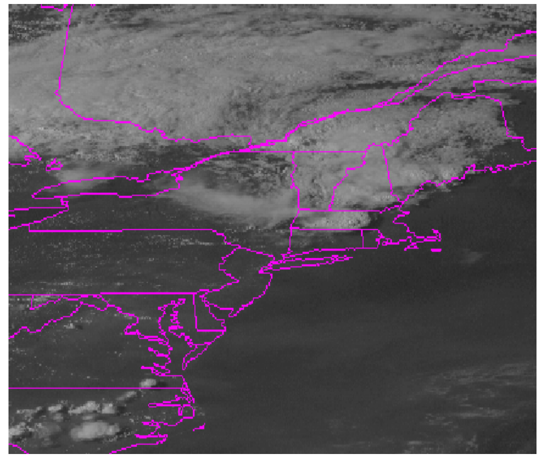


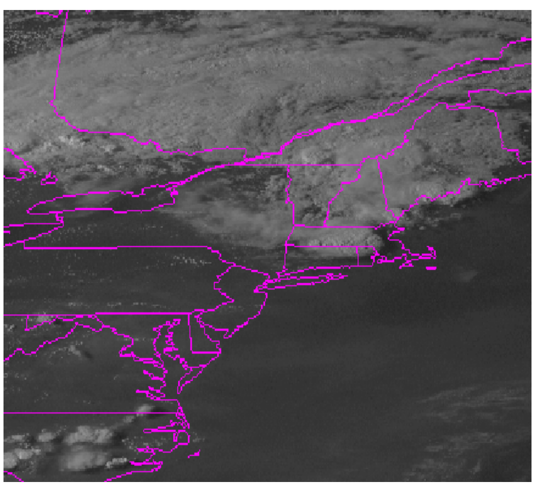
Fig. 3.13. Same as in Fig. 3.10 but for (a) 2000 UTC, (b) 2100 UTC, (c) 2200 UTC, and (d) 2300 UTC.



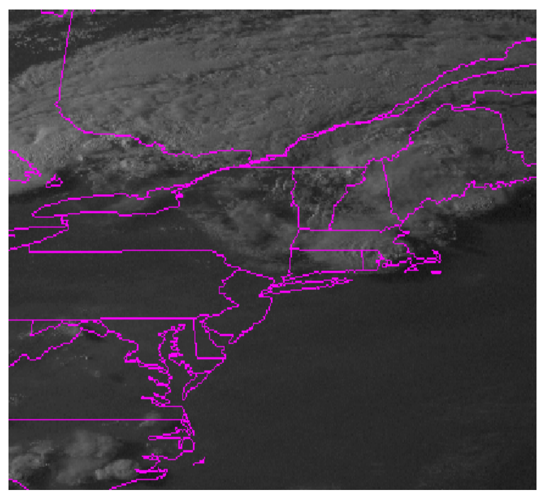
a)



b)



c)



d)

Fig. 3.14. Visible satellite images from 2 Aug 2006 for (a) 2002 UTC, (b) 2125 UTC, (c) 2202 UTC, and (d) 2302 UTC.

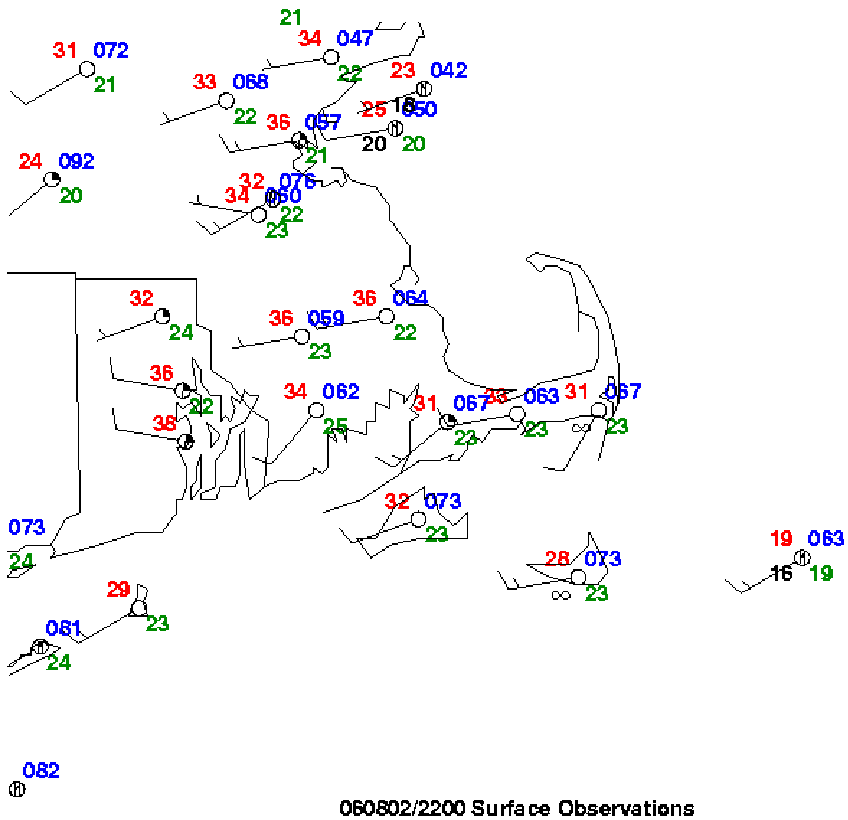


Fig. 3.15. Same as in Fig. 3.7 but for 2200 UTC 2 August 2006.

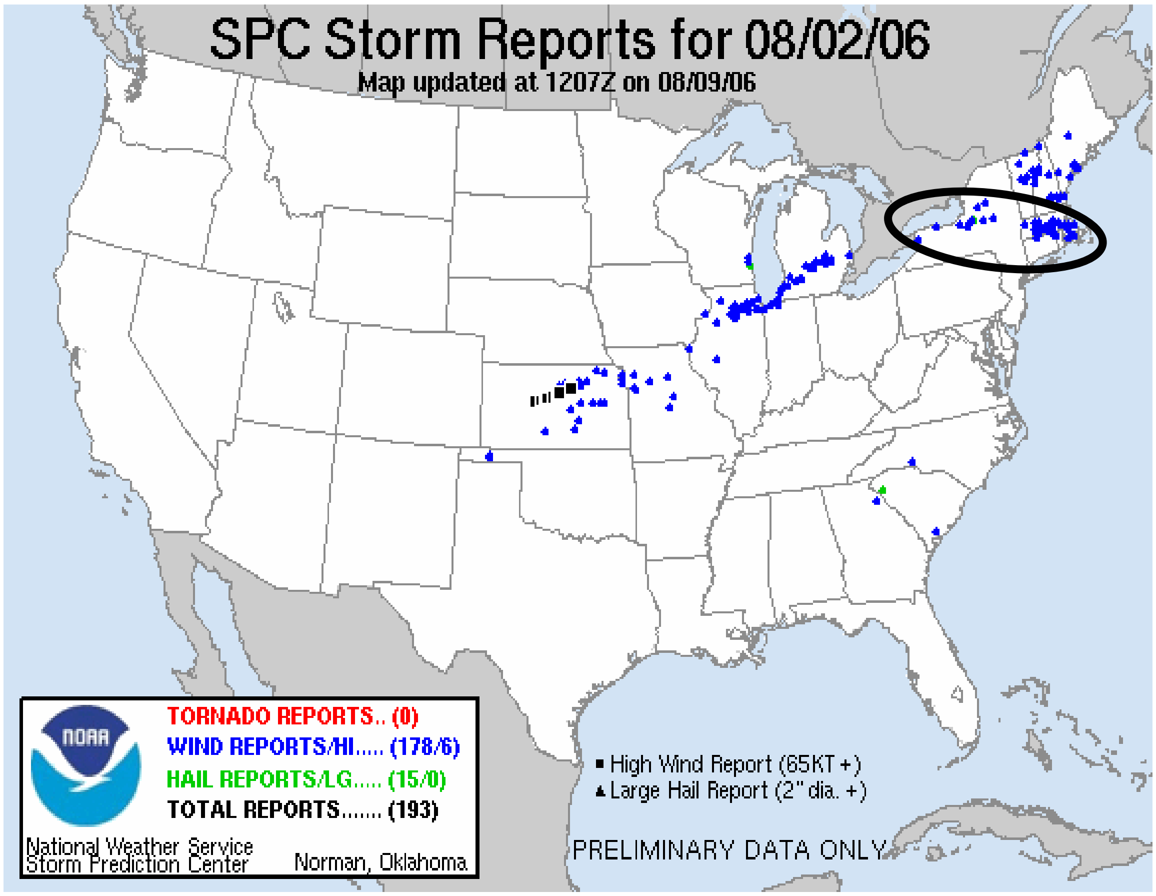


Fig. 3.16. SPC storm reports for 2 Aug 2006. The black-circled area represents the storm reports resulting from the convection in this case.

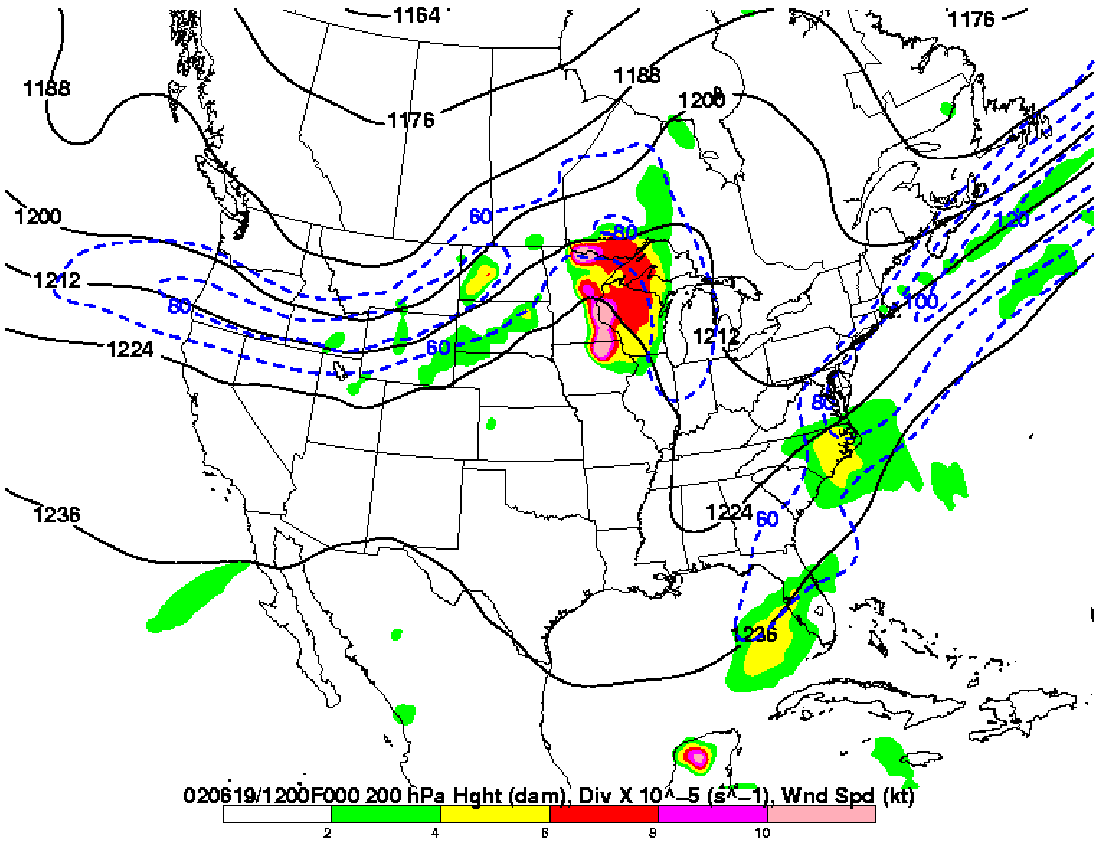


Fig. 3.17. Same as in Fig. 3.1 but for 1200 UTC 19 June 2002.

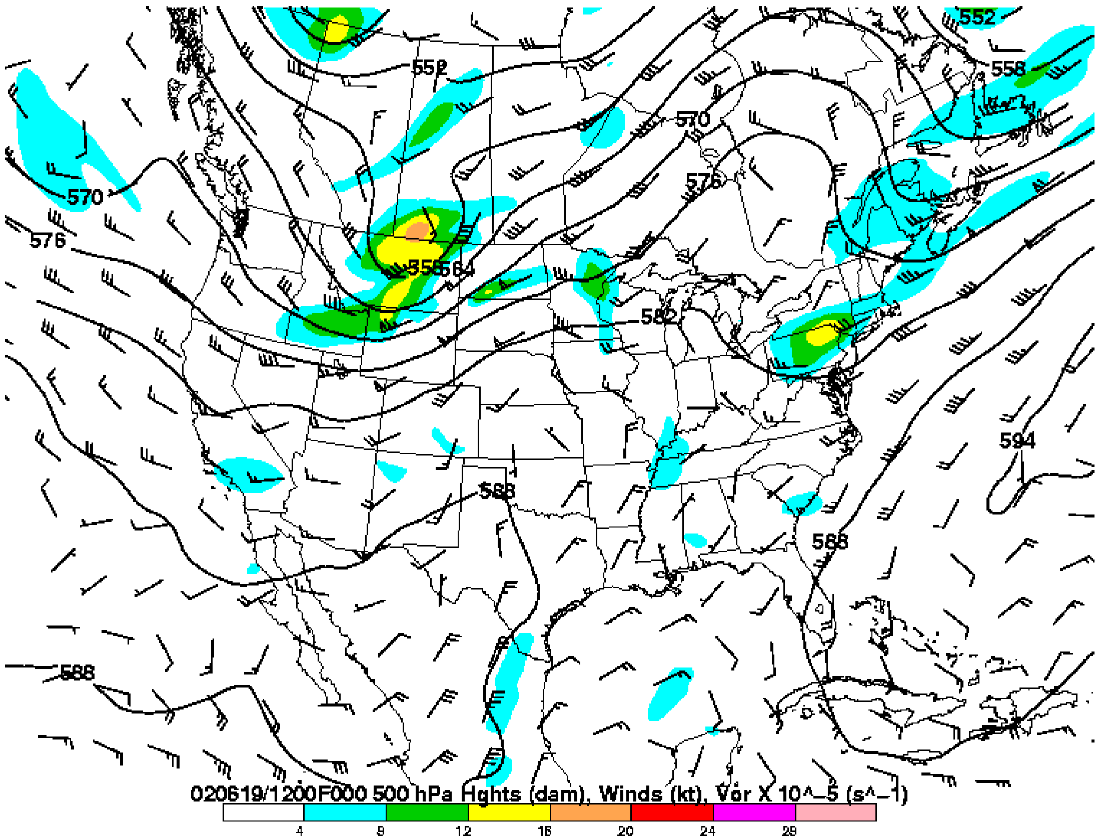


Fig. 3.18. Same as in Fig. 3.2 but for the same time as in Fig. 3.17.

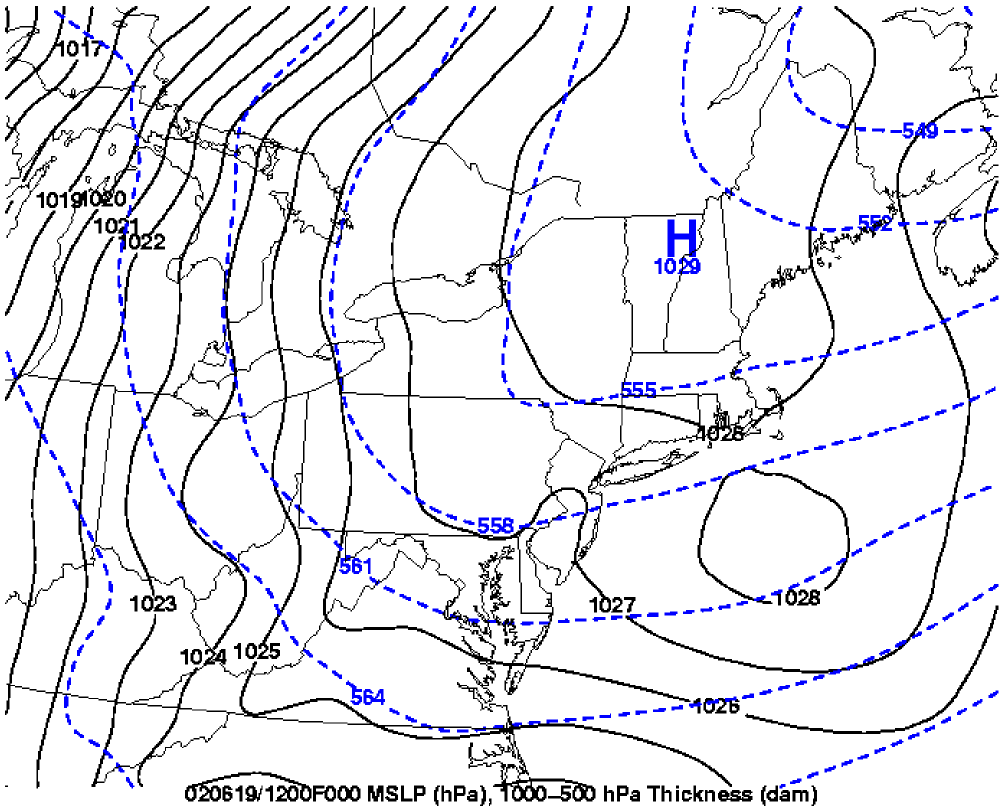


Fig. 3.19. Same as in Fig. 3.3 but for the same time as in Fig. 3.17.

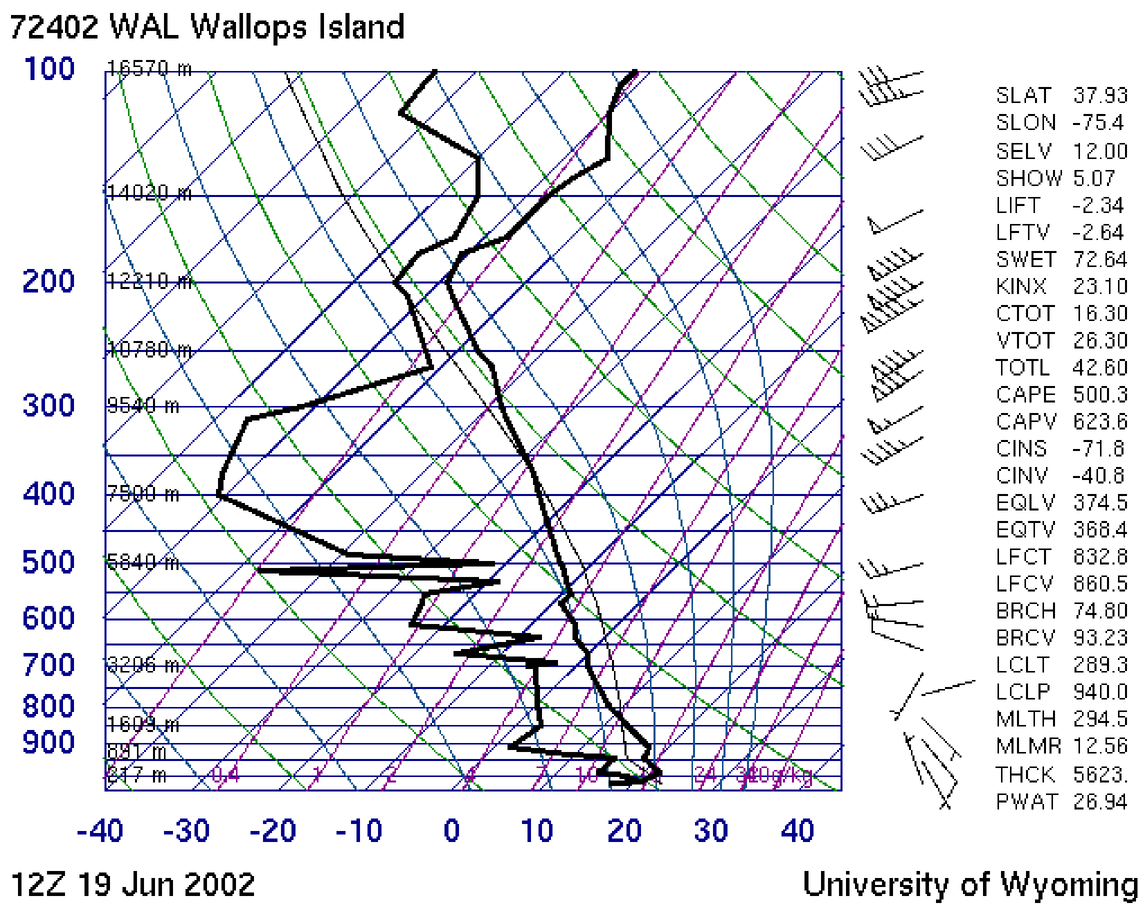


Fig. 3.20. Same as in Fig. 3.4 but taken from Wallops Island, VA, at the same time as in Fig. 3.17.

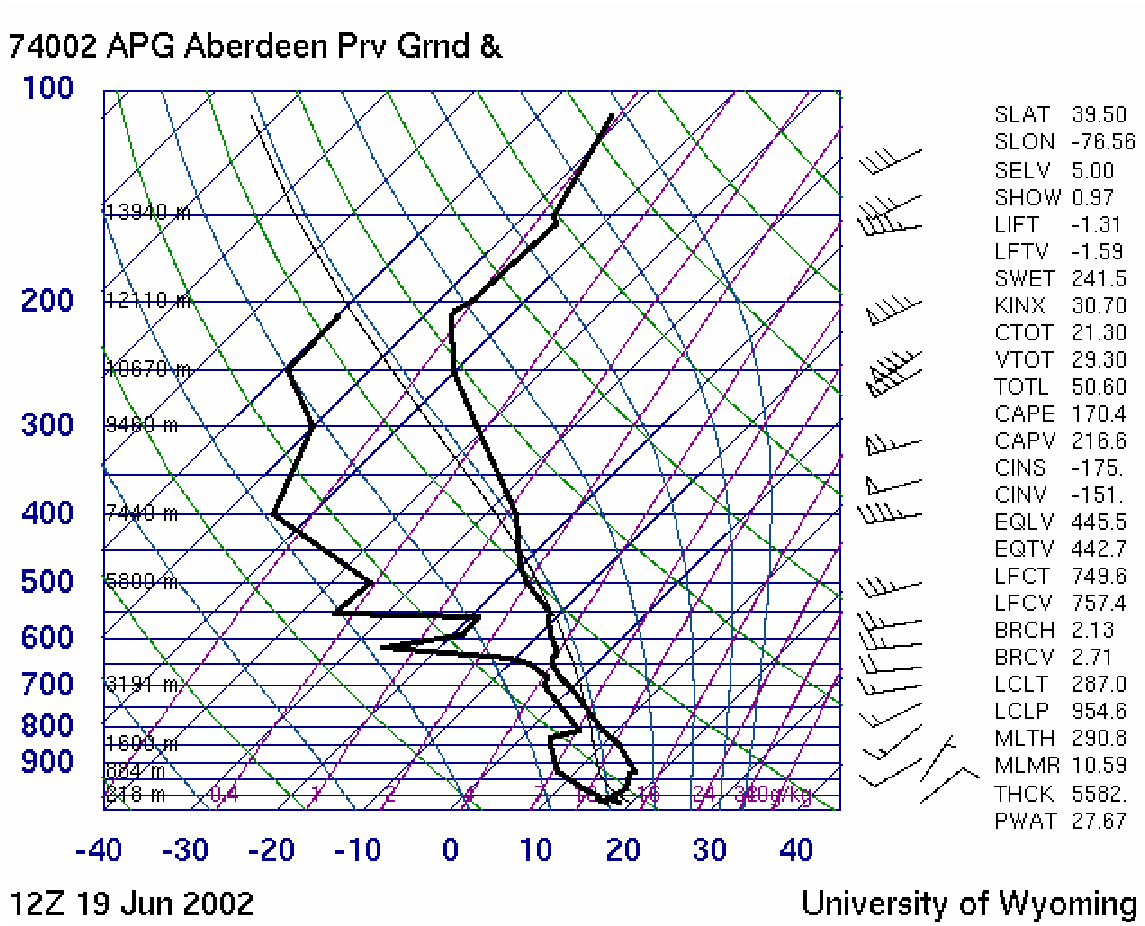


Fig. 3.21. Same as in Fig. 3.20 but taken from Aberdeen Proving Ground, MD.

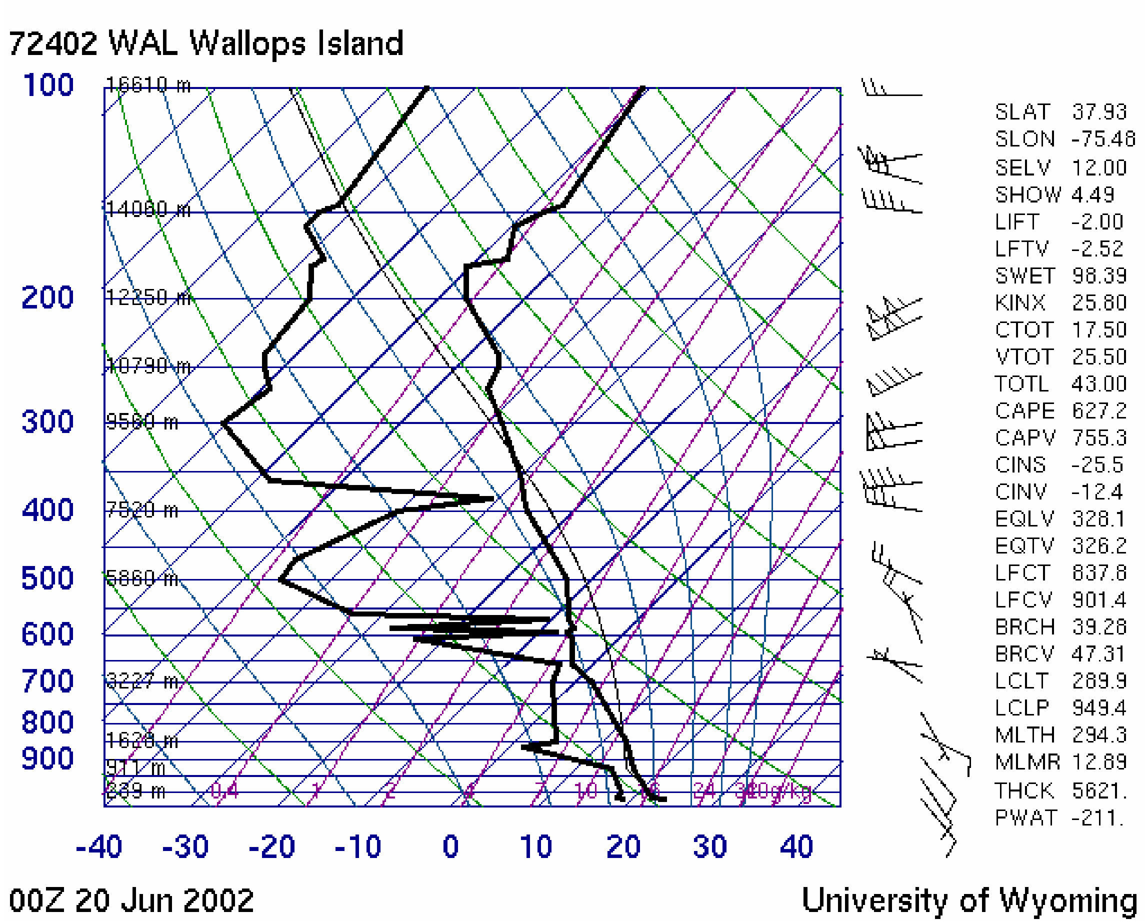


Fig. 3.22. Same as in Fig. 3.20 but at 0000 UTC 20 June 2002.

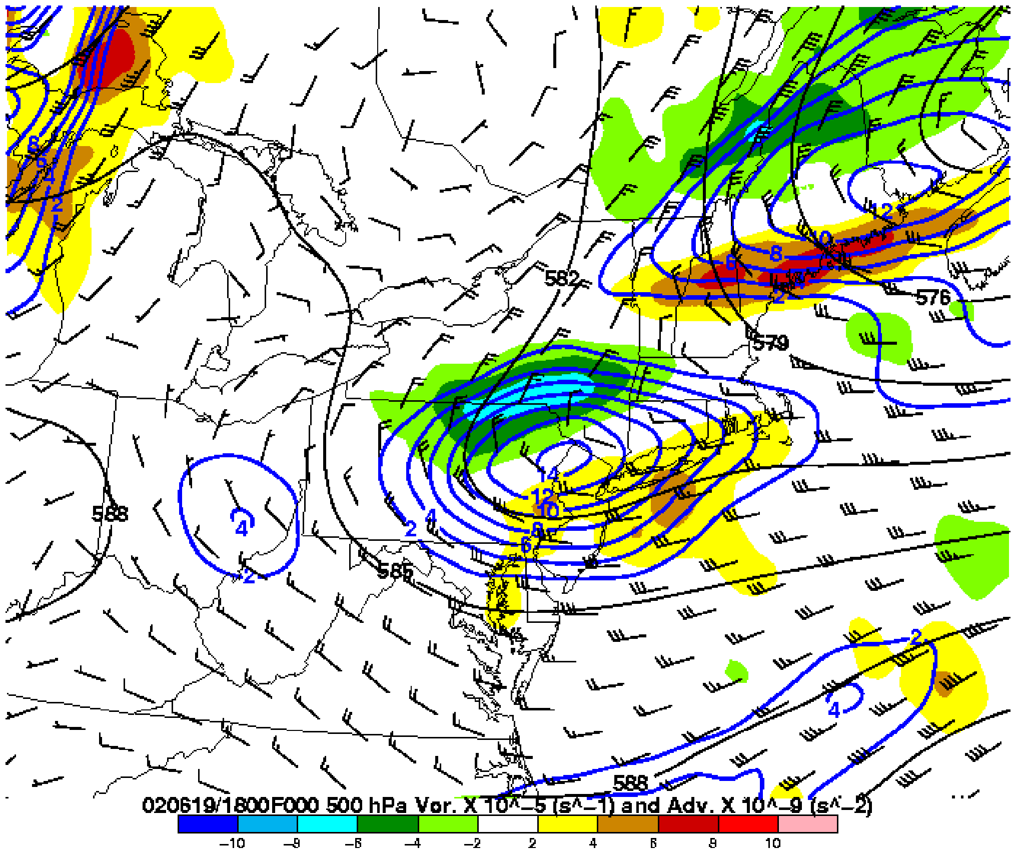


Fig. 3.23. NARR plot of 500-hPa ζ advection shaded according to the color bar every 2×10^{-9} s^{-2}, geopotential height contoured in black every 3 dam, wind in standard notation, and cyclonic ζ contoured in blue every 2×10^{-5} s^{-1} at 1800 UTC 19 June 2002.

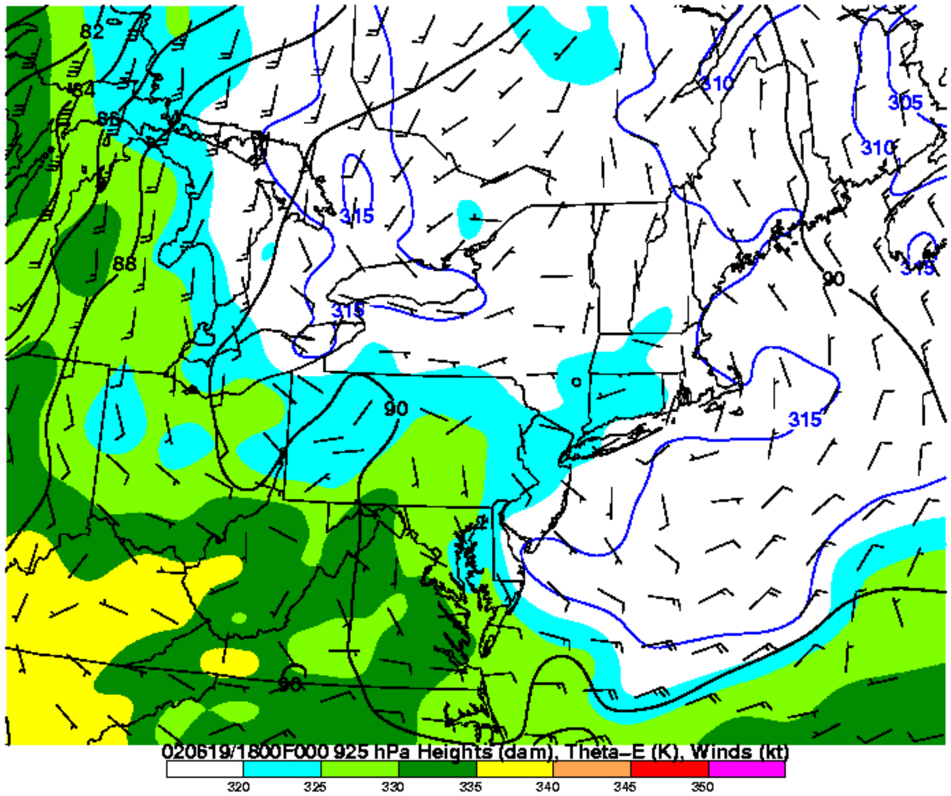


Fig. 3.24. Same as in Fig. 3.5 but for θ_e shaded according to the color bar every 5 K >320 K (contoured in blue every 5 K <320 K) at the same time as in Fig. 3.23.

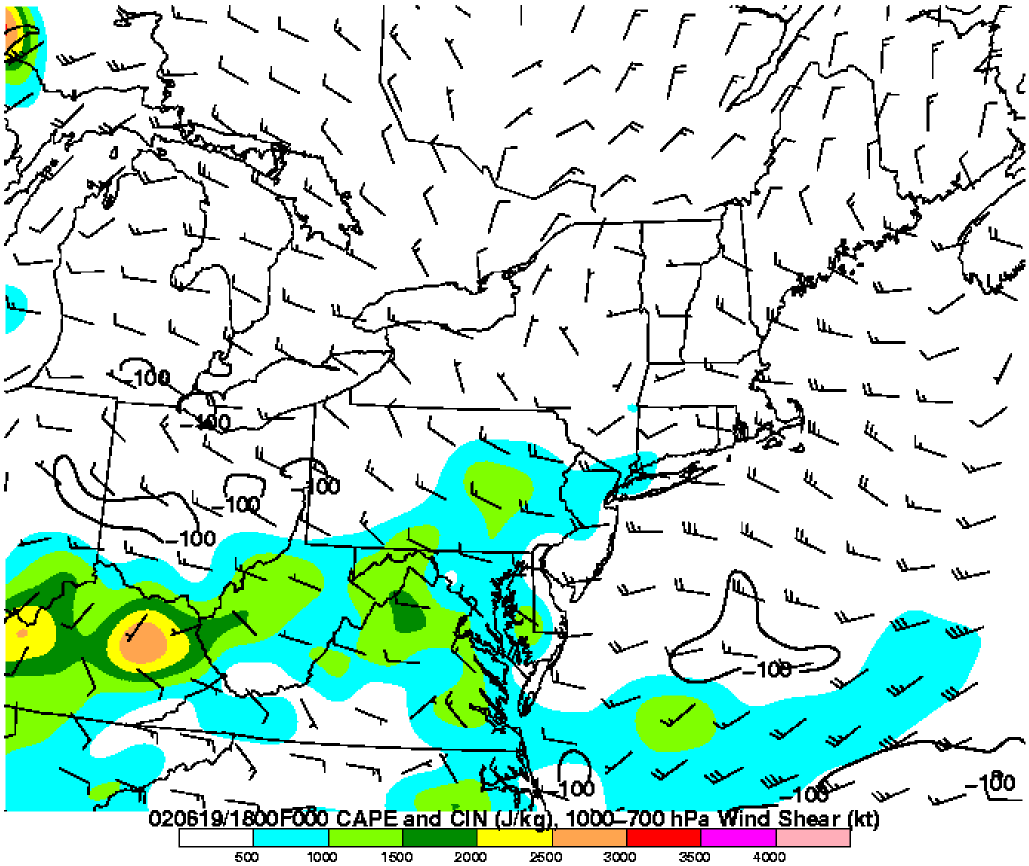


Fig. 3.25. Same as in Fig. 3.6 but for the same time as in Fig. 3.23.

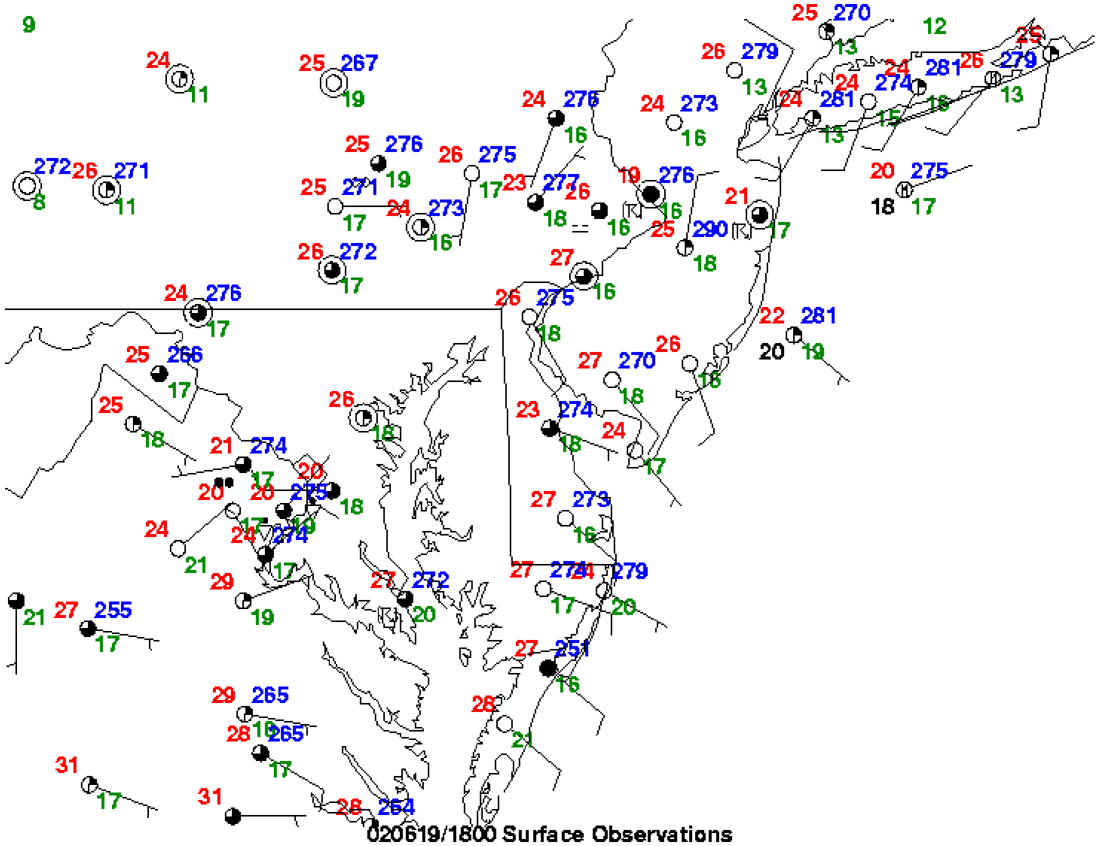


Fig. 3.26. Same as in Fig. 3.7 but for the same time as in Fig. 3.23 with SST in black.

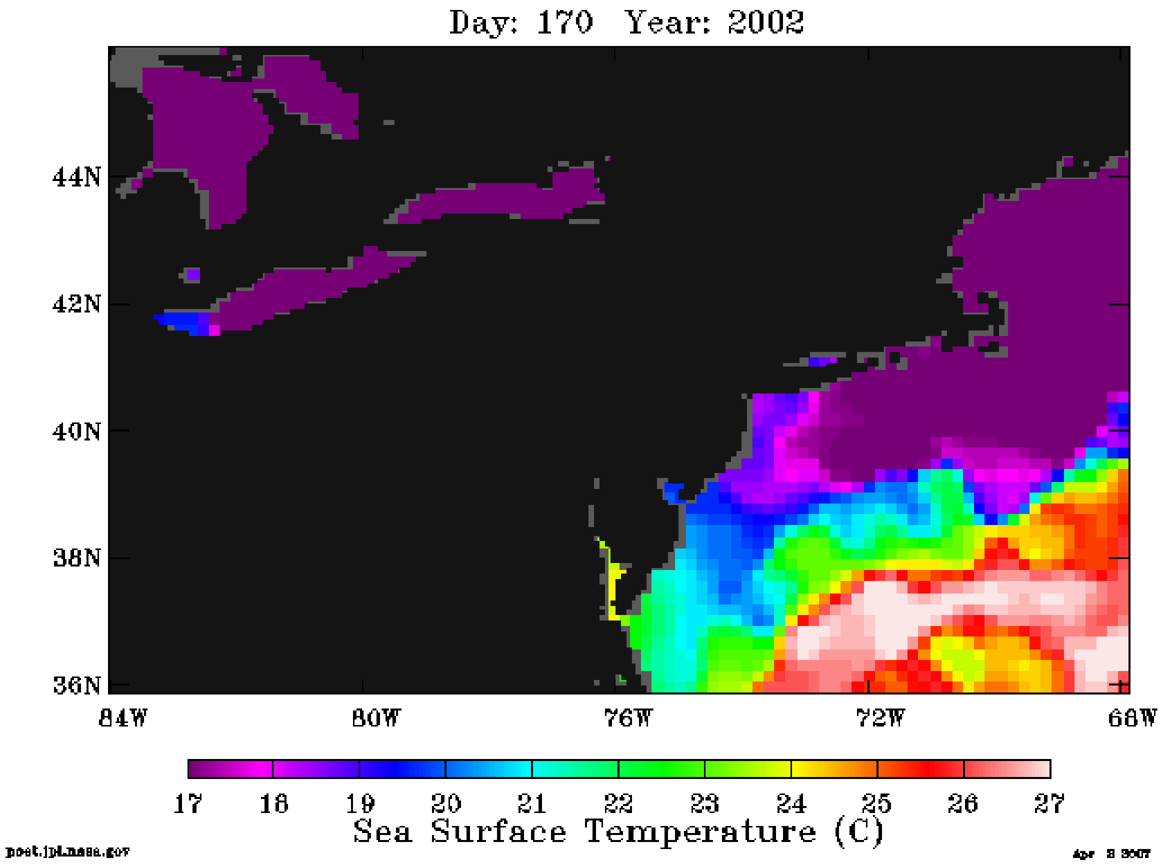
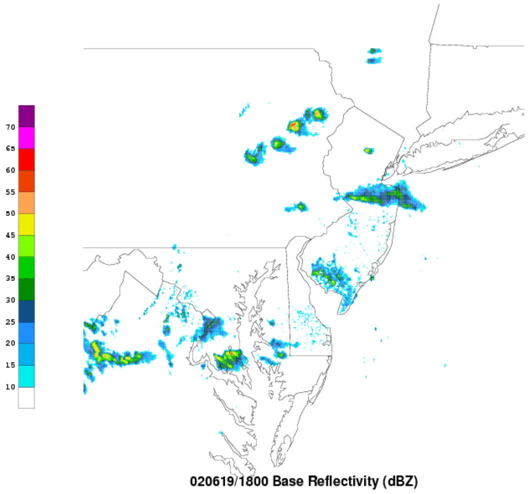
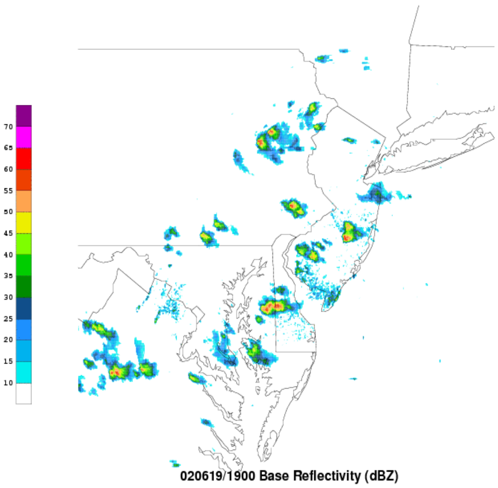


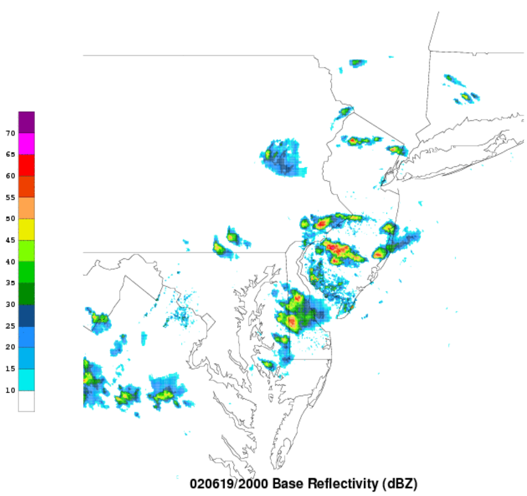
Fig. 3.27. Same as in Fig. 3.8 but for 19 June 2002.



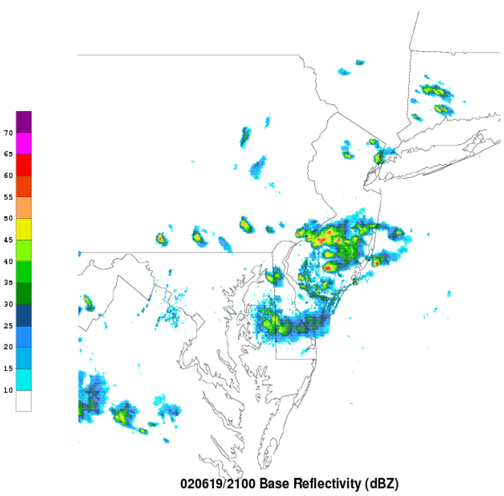
a)



b)

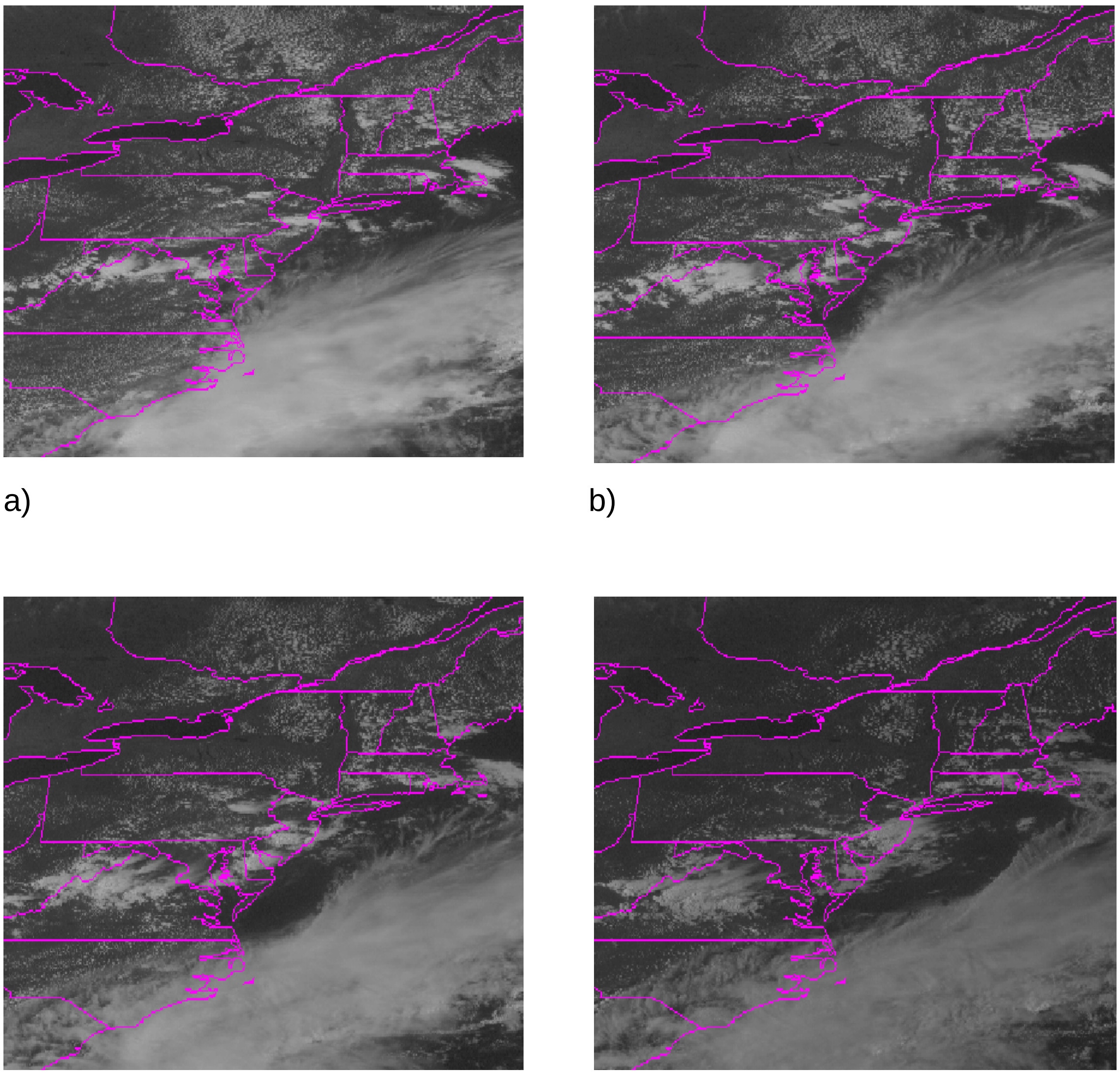


c)



d)

Fig. 3.28. Same as in Fig. 3.10 but from 19 June 2002 for (a) 1800 UTC, (b) 1900 UTC, (c) 2000 UTC, and (d) 2100 UTC.



a) b)

c) d)

Fig. 3.29. Same as in Fig. 3.15 but from 19 June 2002 for (a) 1732 UTC, (b) 1902 UTC, (c) 2002 UTC, and (d) 2132 UTC.

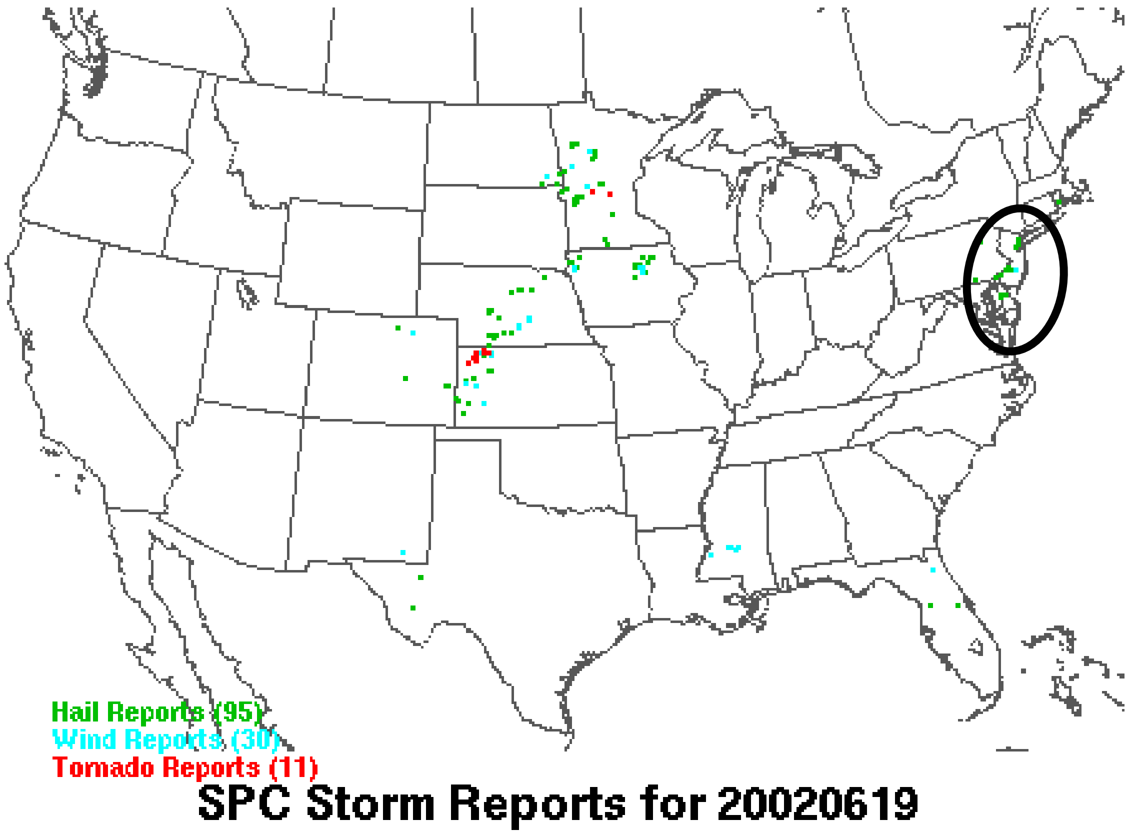


Fig. 3.30. Same as in Fig. 3.16 but for 19 June 2002.

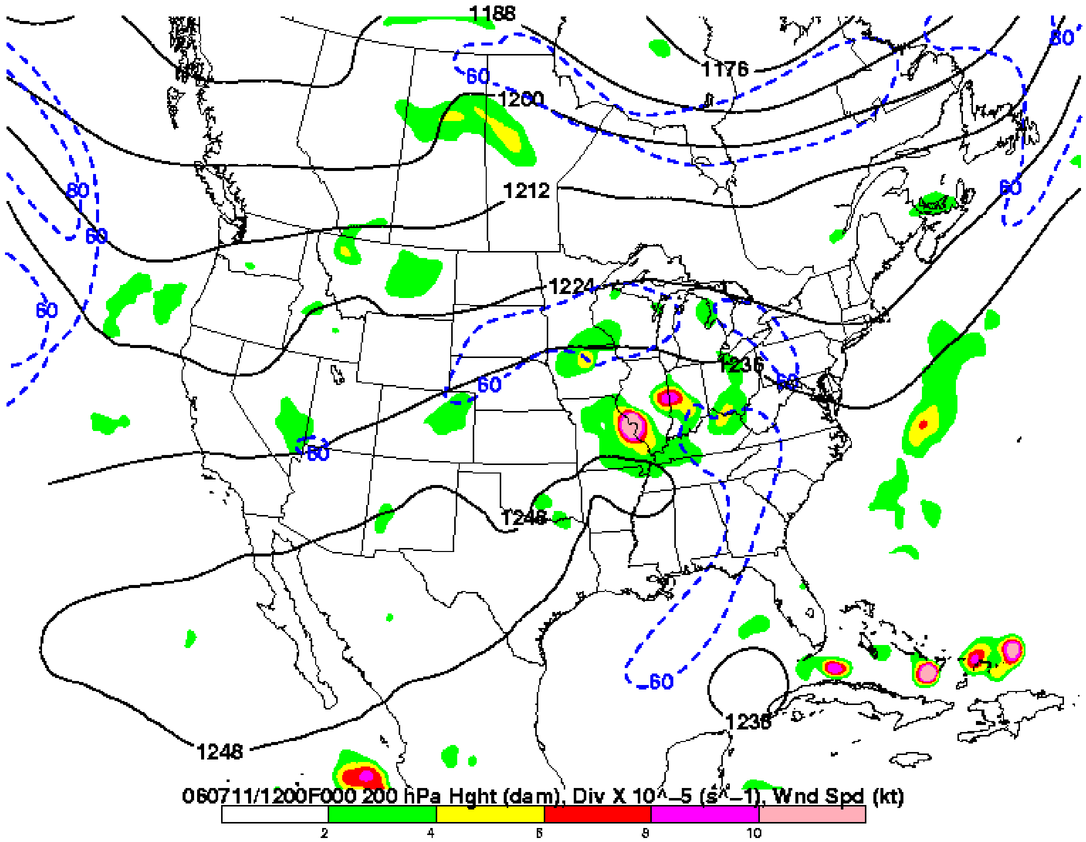


Fig. 3.31. Same as in Fig. 3.1 but for 1200 UTC 11 July 2006.

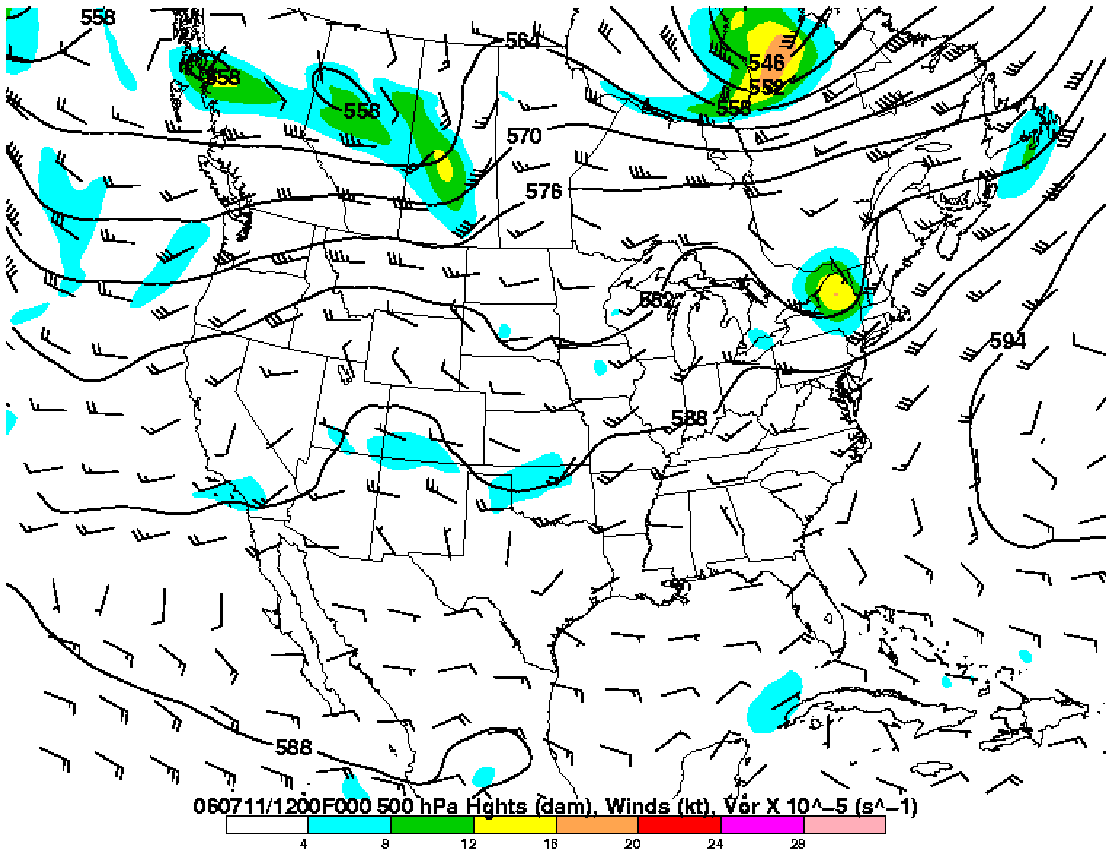


Fig. 3.32. Same as in Fig. 3.2 but for the same time as in Fig. 3.31.

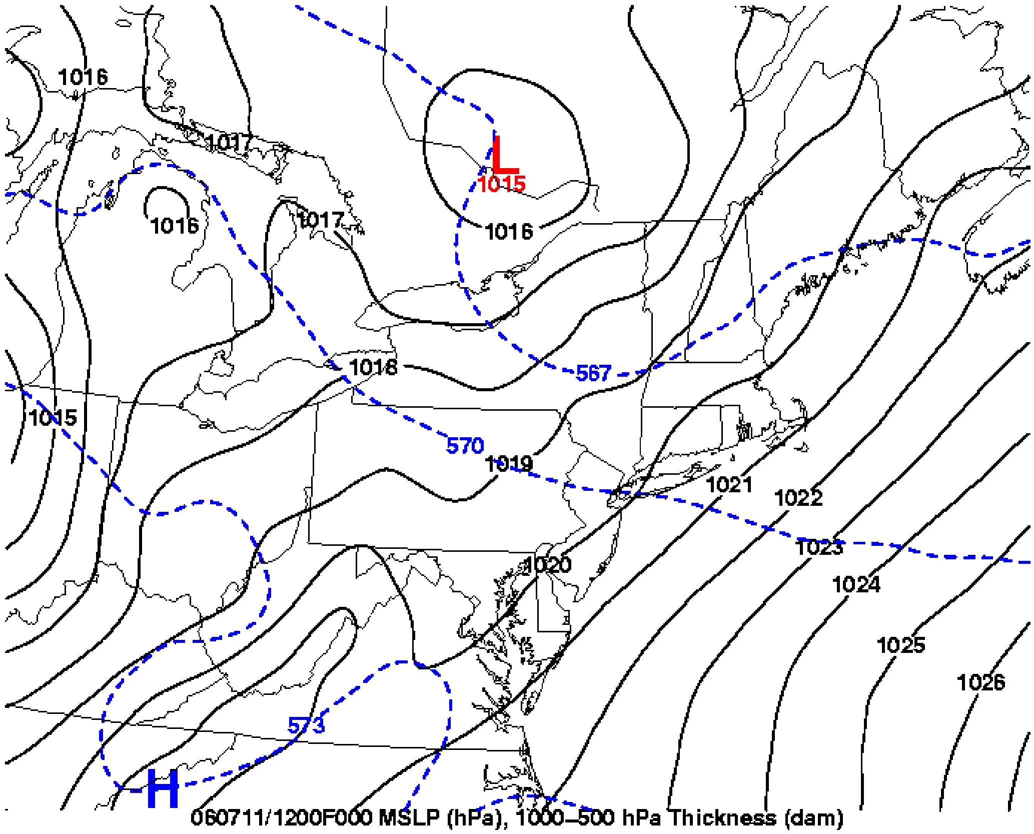


Fig. 3.33. Same as in Fig. 3.3 but for the same time as in Fig. 3.31.

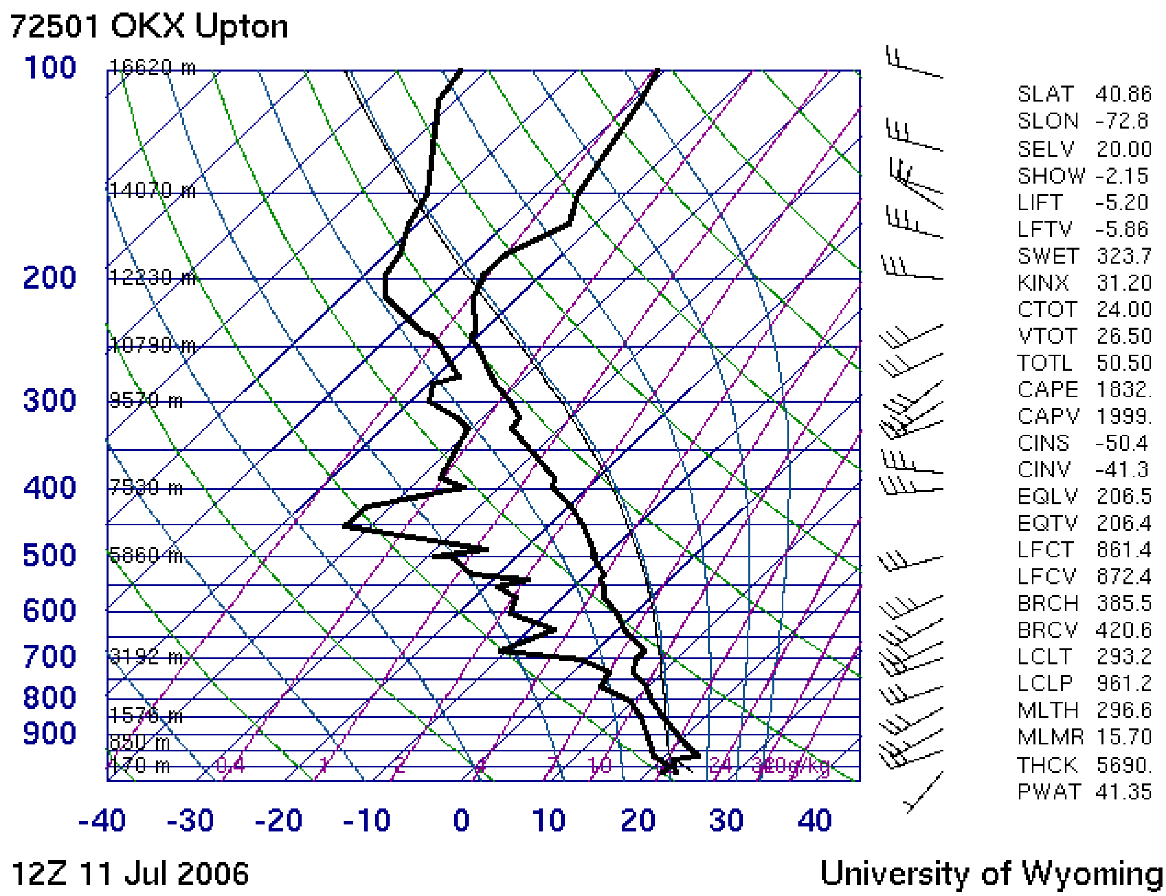


Fig. 3.34. Same as in Fig. 3.4 but taken from Upton, NY, at the same time as in Fig. 3.31.

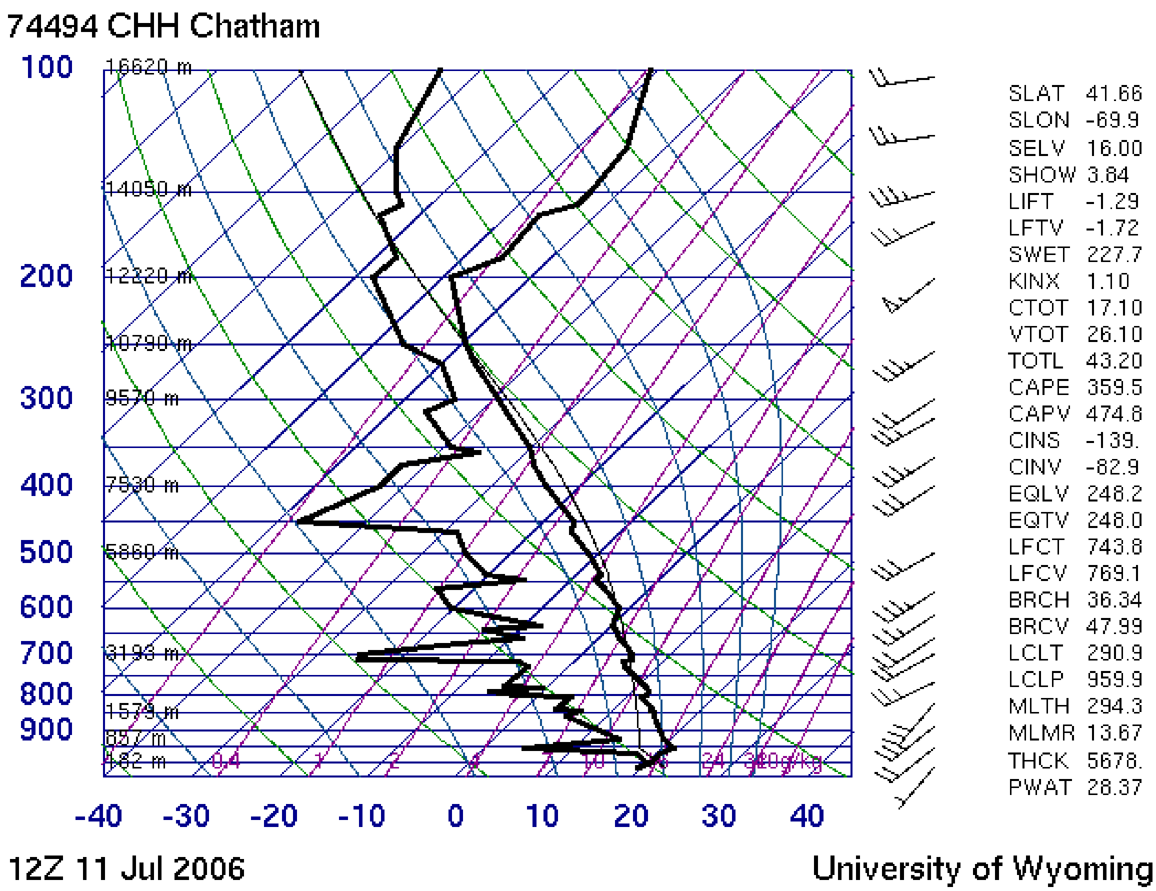


Fig. 3.35. Same as in Fig. 3.34 but taken from Chatham, MA.

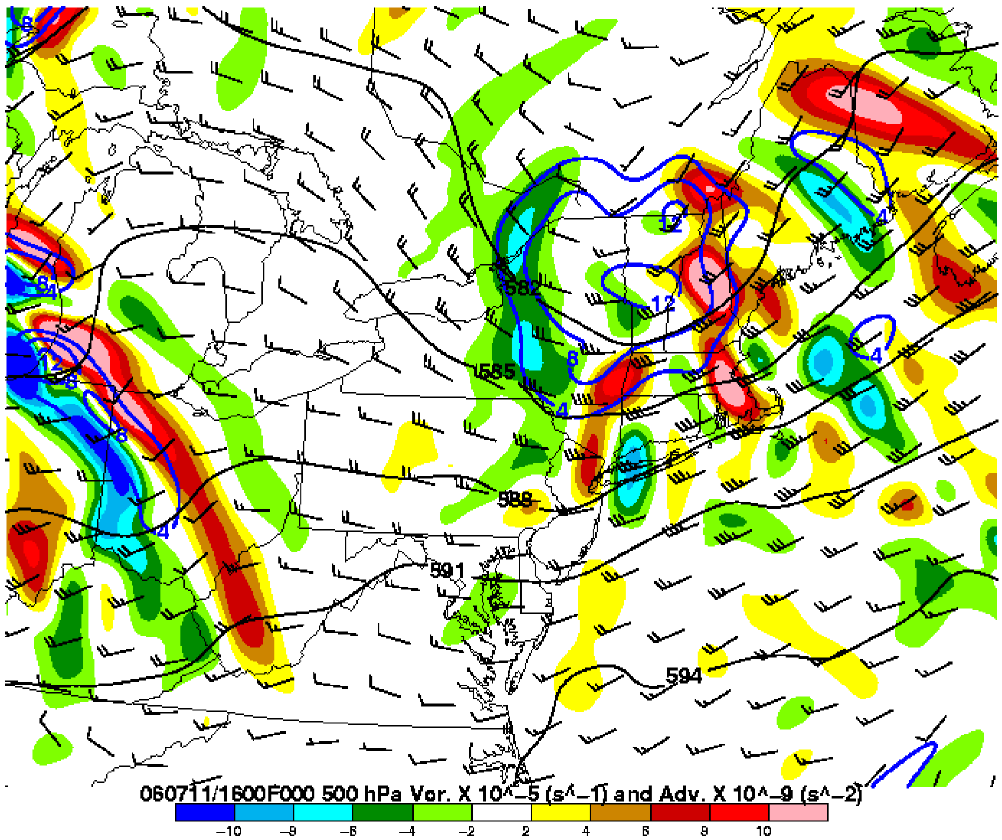


Fig. 3.36. Same as in Fig. 3.23 but for 1600 UTC 11 July 2006.

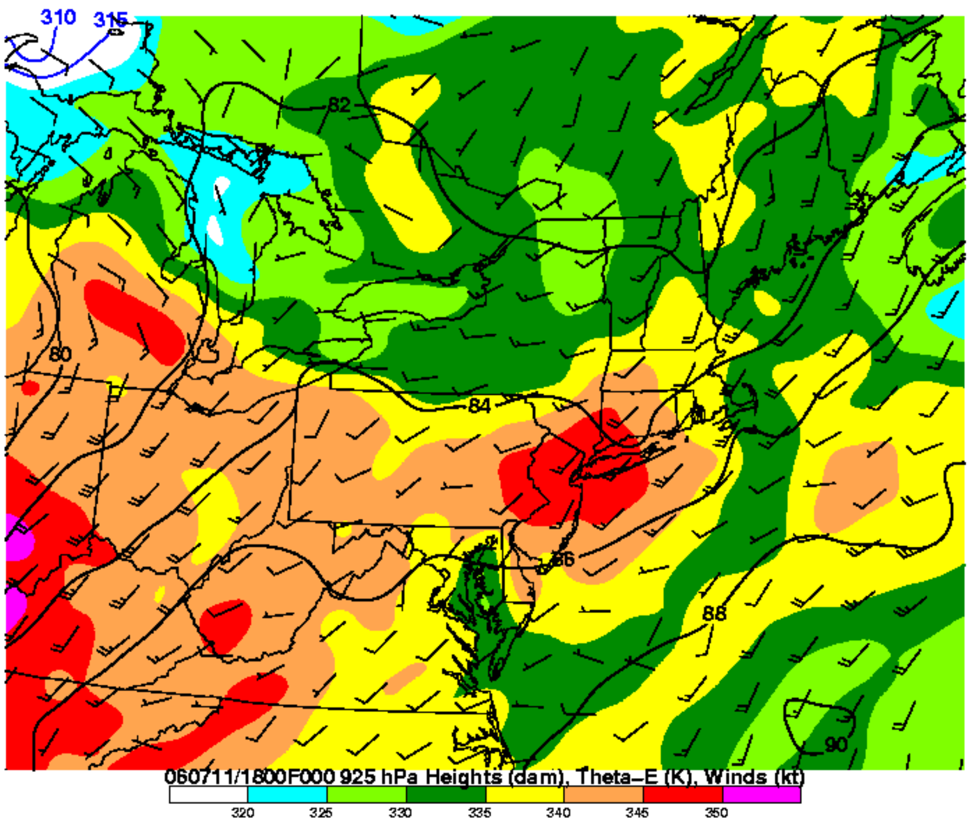


Fig. 3.37. Same as in Fig. 3.24 but for 1800 UTC 11 July 2006.

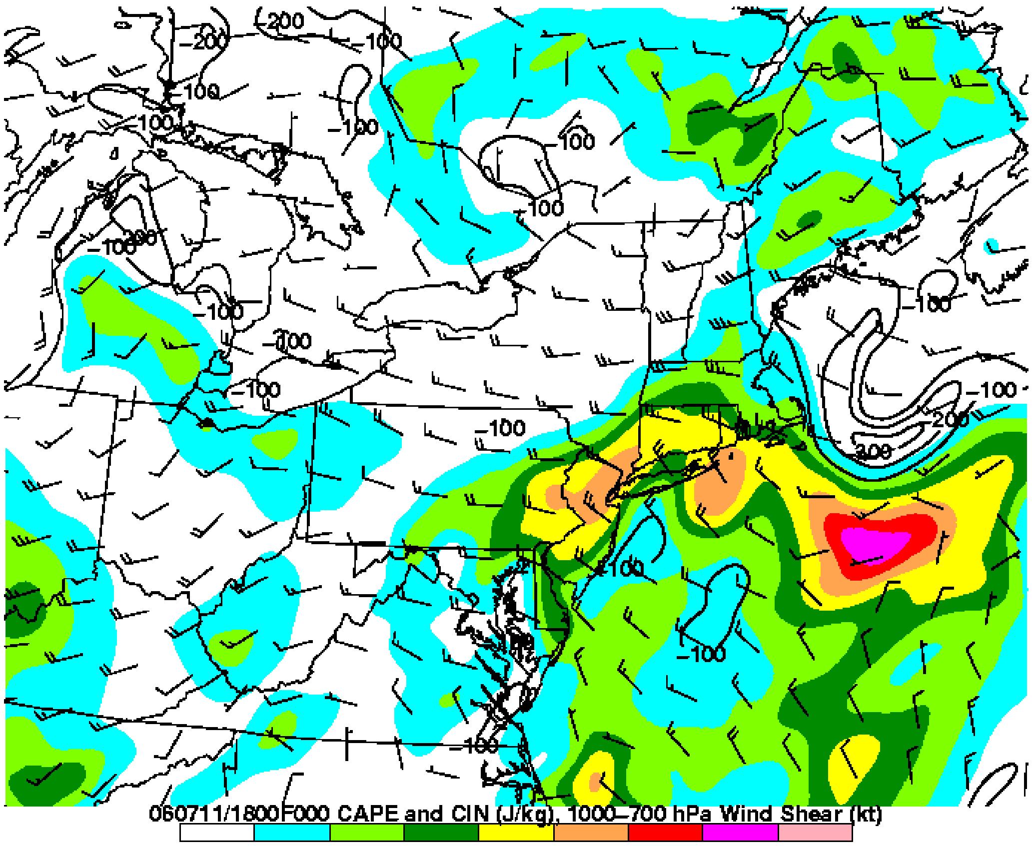


Fig. 3.38. Same as in Fig. 3.6 but for the same time as in Fig. 3.37.

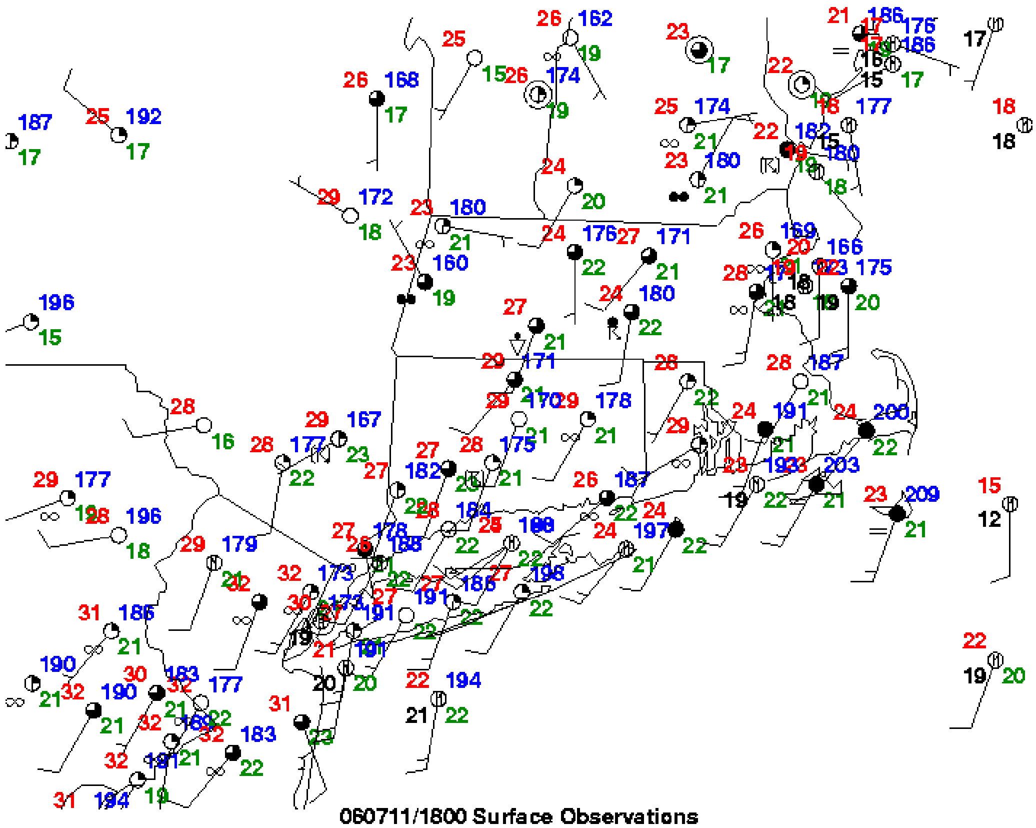
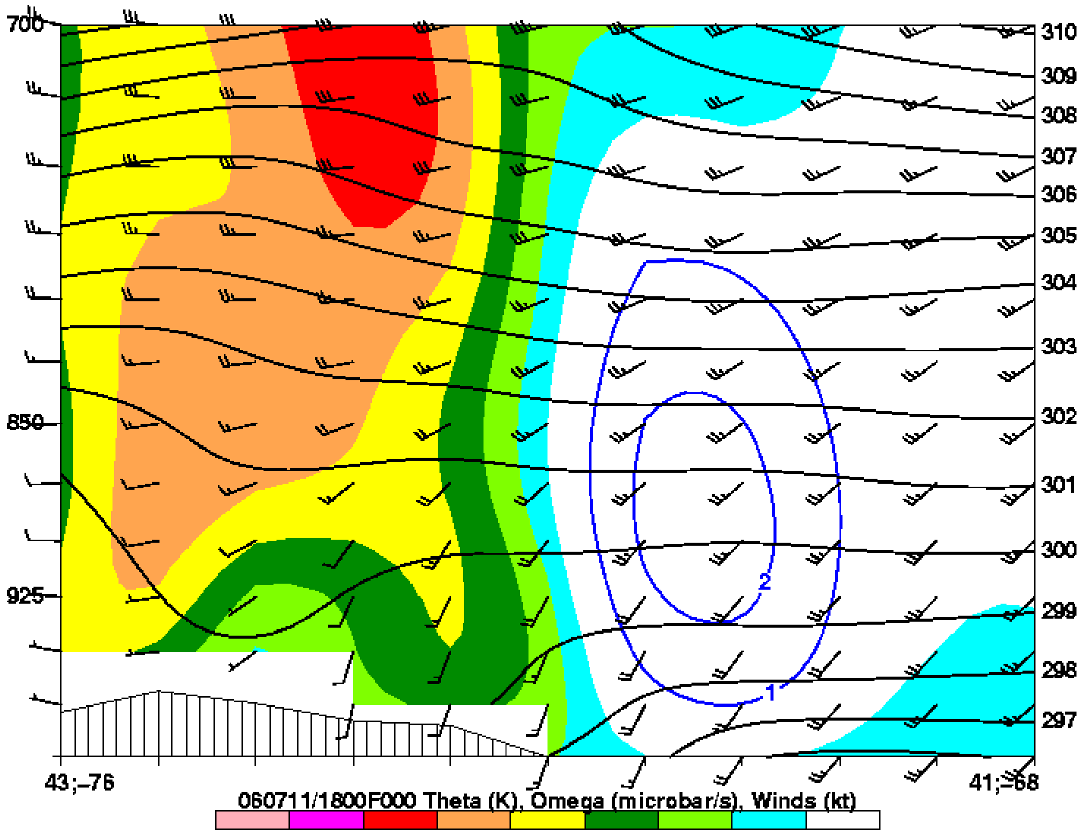


Fig. 3.39. Same as in Fig. 3.7 but for the same time as in Fig. 3.37.

a)



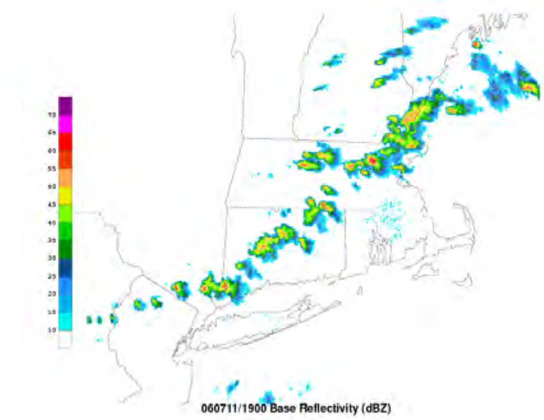
b)

Fig. 3.40. Same as in Fig. 3.9 but from the same time as in Fig. 3.37.

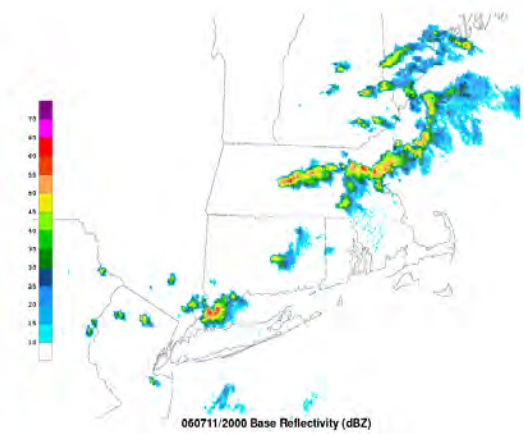
a)

b)

c)



d)



e)

f)

Fig. 3.41. Same as in Fig. 3.10 but for (a) 1600 UTC, (b) 1700 UTC, (c) 1800 UTC, (d) 1900 UTC, (e) 2000 UTC, and (f) 2100 UTC.

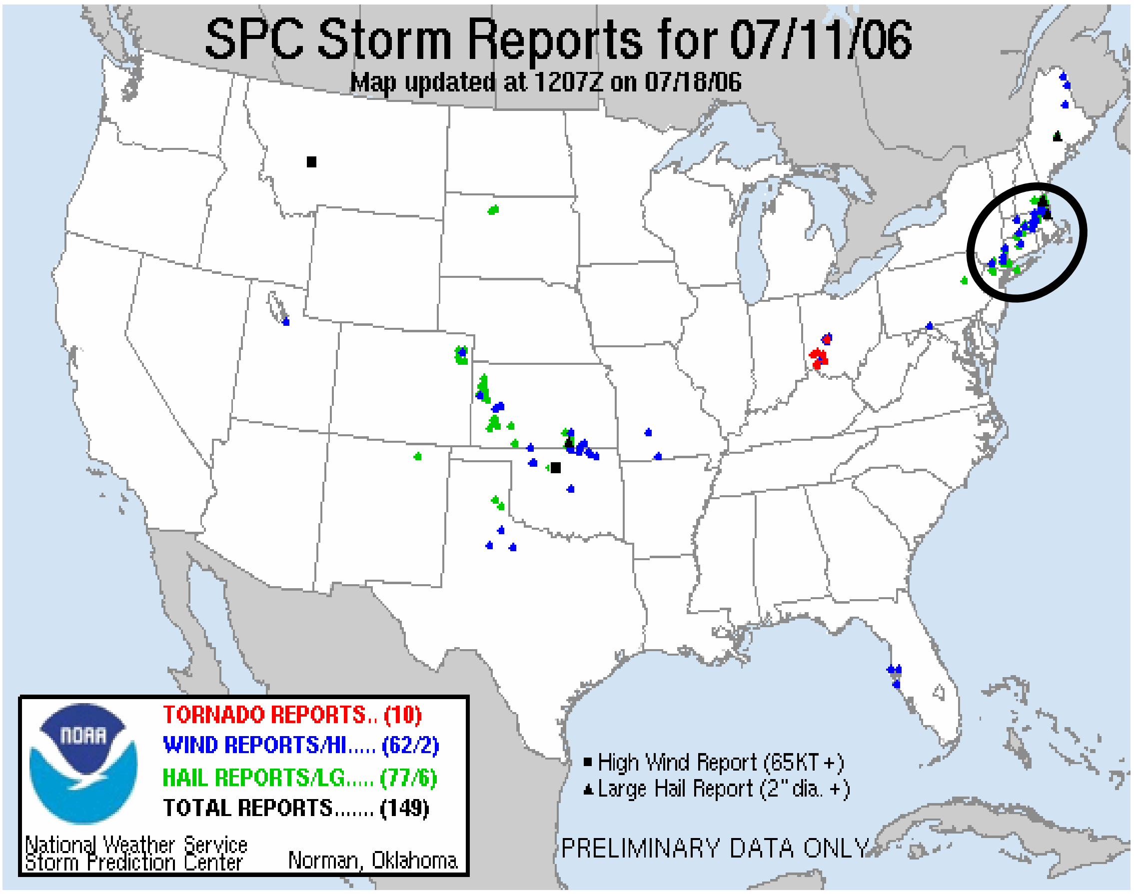


Fig. 3.42. Same as in Fig. 3.16 but for 11 July 2006. The black-circled area represents the storm reports from convection that was suppressed by the sea breeze, which can be detected by the lack of reports over southeastern Massachusetts, eastern Connecticut, and Rhode Island.

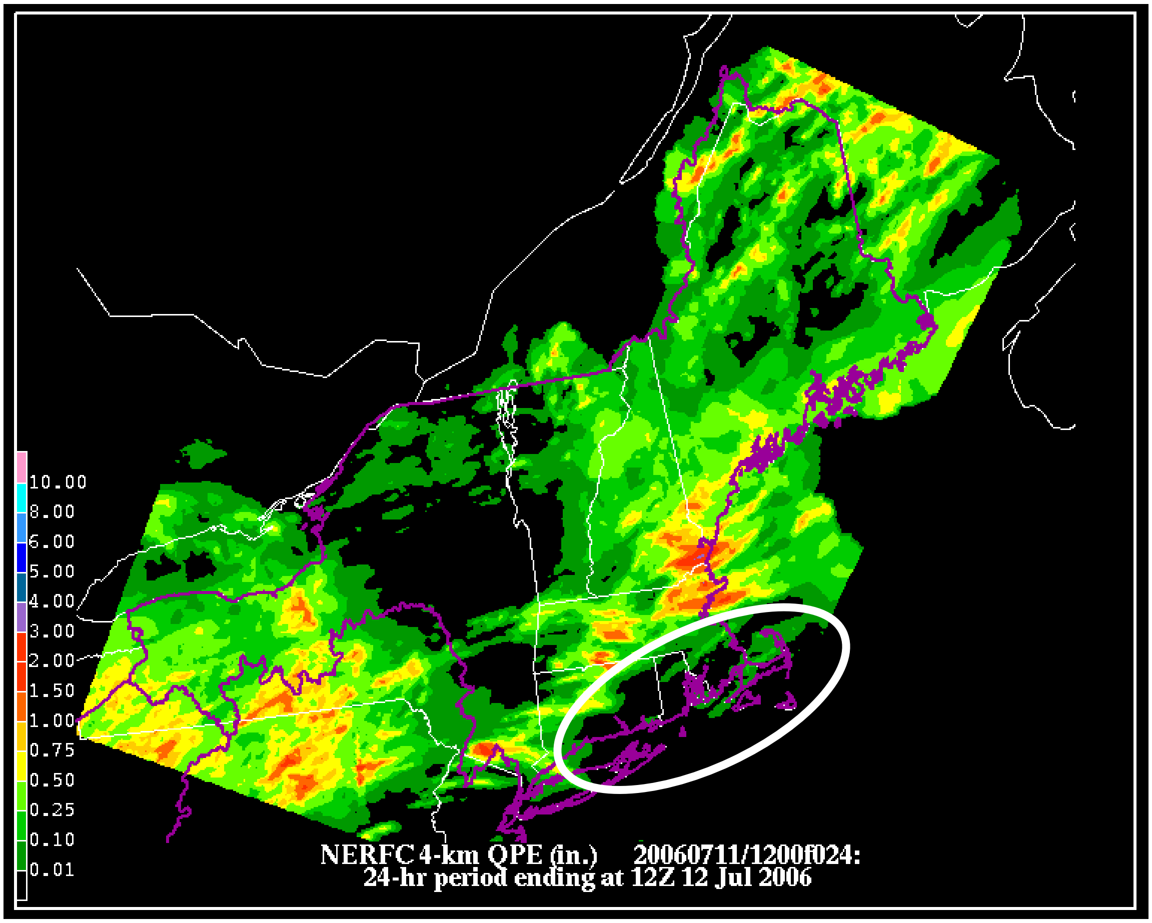


Fig. 3.43. 24-h quantitative precipitation estimate from the Hydrometeorological Prediction Center ending at 1200 UTC 12 July 2006. The white-circled area denotes the lack of rainfall where convection was suppressed by the sea breeze. (Available online at http://www.hpc.ncep.noaa.gov/npvu/archive/rfc.shtml.).

4. Discussion

4.1 Pure Cases

The results from section 3.1 show that high-CAPE environments with abundant heat and moisture in the PBL in the Northeast are favorable for pure cases. Although lake and sea breezes have been documented throughout the Northeast (e.g., Clowes 1917; Estoque et al. 1976; Novak and Colle 2006), only a small percentage of these lake and sea breezes are responsible for generating pure cases during any given warm season. Pure cases not only occur just in the Northeast but can also occur in the subtropical regions, and the subtropical regions of the U.S. experience lake-/sea-breeze convection far more often than the Northeast. When pure cases occur in both the Northeast and the subtropical regions of the U.S., the PBL and the overall synoptic-scale environment in both regions are similar in terms of CAPE, surface temperature, and θ_e. For example, Medlin and Croft (1998) studied 13 sea-breeze cases near the Alabama coast during June–July 1996 in nearly negligible synoptic-scale forcing, so all 13 cases can be classified as pure cases. The average 1200 UTC sounding from Mobile, AL, for these cases featured PW >38 mm and surface dewpoints >20°C (Medlin and Croft, 1998).

The conditions from Medlin and Croft (1998) in Mobile, AL, correlate well with the BUF sounding at 1200 UTC 2 August 2006 (Fig. 3.4). Both the 1600 UTC CAPE values (Fig. 3.6) and 1700 UTC surface temperatures (Fig. 3.7) from the 2 August 2006 case agree with the average modified 1800 UTC sounding from Mobile, AL, for the cases explored by Medlin and Croft (1998). Additionally, the 25 July 1989 case from southern Ontario that was examined by Clodman and Chisholm (1994), which also occurred within a ridge axis at the surface and aloft, featured PW >45 mm, CAPE values >1500 J kg^{-1}, surface temperature ~30°C, and surface dewpoint >20°C while convection was present. CAPE, temperature, dewpoint, and PW values that were obtained from Medlin and Croft (1998) and Clodman and Chisholm (1994) compare favorably with the values in Table II that were obtained from the pure cases of this research.

A schematic diagram of pure cases is provided in Fig. 4.1a for the horizontal view, and Fig. 4.1b provides the cross-sectional view along the line shown in Fig. 4.1a. A ridge axis is in place at the surface or aloft with 1000–500 hPa thickness values ≥570 dam. Convection from pure cases tends to propagate downshear away from the LBF/SBF, following the 1000–700 hPa wind shear vector, which is displayed in Fig. 4.1a. The synoptic-scale flow is usually weak based on the presence of a ridge axis aloft almost directly overhead of the LBF/SBF, resulting in almost negligible synoptic-scale forcing for ascent. While Fig. 4.1a reveals a general synoptic-scale pattern favorable for pure cases, Fig. 4.1b shows significant mesoscale features that help illustrate how a lake-/sea-breeze circulation can generate severe convection. The difference between the air temperatures over land and over water is ≥5°C. The PBL over land is hot and moist with surface temperatures ≥30°C, surface dewpoints ≥20°C, and 925-hPa θ_e ≥350 K. Meanwhile, the PBL over water is cooler with surface temperatures <30°C and the 925-hPa θ_e <350 K. This temperature difference over land and over water helps to strengthen the lake-/sea-breeze boundary and the associated thermally direct circulation. Air parcels are forced up the LBF/SBF to their LFC, allowing a thunderstorm to develop along the boundary. No thunderstorms form over the water as subsidence is occurring due to the thermally direct circulation. The processes occurring in the mesoscale clearly dominate convective initiation and the environmental setup in the PBL during pure cases.

4.2 Mixed Cases

The results from section 3.2 show that mixed cases depend on the strength of the lake-/sea-breeze circulation and the QG-forcing for ascent from CVA increasing with height due to a passing synoptic-scale trough. Lake and sea breezes occurring in conjunction with synoptic-scale and mesoscale features have been noted in the literature (e.g., Moroz and Hewson 1966; Kingsmill 1995; Bastin et al. 2006; Bennett et al. 2006). Mixed cases depend on the dynamical contributions from CVA increasing with height for rising motion associated with a synoptic-scale trough in the proximity of a lake or sea breeze. For example, Clodman and Chisholm (1994) studied a mixed case in southern Ontario on 20 July 1989, and King et al. (2003) studied another mixed case over the same region on 21 July 1994. Both of these cases featured lake breezes from the surrounding Great Lakes contributing mesoscale ascent ahead of an approaching surface cold front that was associated with synoptic-scale ascent. QG-forced for ascent from CVA increasing with height aided air parcels in reaching their LFC during both mixed cases. Having CVA aloft is critical as noted in Table III, and the 19 June 2002 mixed case, the primary focus of section

3.2, was no exception (see Figs. 3.18, 3.23).

The environmental modifications in terms of temperature, CAPE, and low-level wind shear from lake and sea breezes must also be considered in mixed cases. Clodman and Chisholm (1994) noted that convection was not widespread over southern Ontario on 20 July 1989, and King et al. (2003) also observed that convection was not widespread in the same location on 21 July 1994 (see Fig. 1.5) as there were significant mesoscale variations in terms of CAPE, low-level wind shear, and surface temperature from the lake breezes in both cases. These mesoscale variations can be seen more clearly during the 19 June 2002 mixed case in the 1200 UTC APG sounding (Fig. 3.21), where low-level wind shear was increased locally due to easterly (onshore) flow near the surface by the bay breeze on the west side of the Chesapeake Bay and westerly (offshore) flow above the PBL. These low-level wind shear variations can also occur along the upshear side of a water body oriented perpendicular to the prevailing flow (e.g., prevailing westerly flow over the north–south-oriented shorelines of the Great Lakes). On the downshear side of the aforementioned water body, the lake or sea breeze and flow aloft will have similar directions, resulting in locally decreased shear. These variations in local temperature, CAPE, and low-level wind shear from lake and sea breezes usually occur over distances smaller than the grid spacing in most operational NWP models, creating a forecasting challenge.

A schematic diagram for mixed cases is shown to illustrate the processes involved in the horizontal view (Fig. 4.2a) and the cross-sectional view (Fig. 4.2b) along the line shown in Fig. 4.2a. A trough axis is overhead of the LBF/SBF at the surface or aloft with 1000–500 hPa thickness values ≥555 dam. As in Fig. 4.1a, the 1000–700 hPa wind shear vector is shown in Fig. 4.2a as convection tends to propagate downshear away from the LBF/SBF. While the difference between the air temperatures over land and over water is ≥5°C, the air temperatures overall in the PBL are cooler in mixed cases than in pure cases. The surface temperatures are between 20°C and 30°C with surface dewpoints between 10°C and 20°C over land, but the surface temperatures are <20°C over water (see Fig. 3.39). The 925-hPa θ_e is between 320 K and 350 K over land but <320 K over water (see Fig. 3.37). Compared to pure cases, the LFC is higher during mixed cases due to the lower values of θ_e present in the PBL. The synoptic-scale trough shown in Fig. 4.2a provides CVA aloft as shown in Fig. 4.2b. This situation sets up an environment favorable for QG-forcing for ascent as CVA is increasing with height. Warm air advection near the surface is also possible if the trough is approaching the area, which further enhances QG-forcing for ascent. Air parcels are forced up the LBF/SBF and are able to reach their LFC with help from CVA aloft, which provides augmented synoptic-scale ascent. The subsidence over water inhibits convective initiation in this region even though the atmosphere above 850 hPa may be conducive to severe weather from elevated convection.

4.3 Null Cases

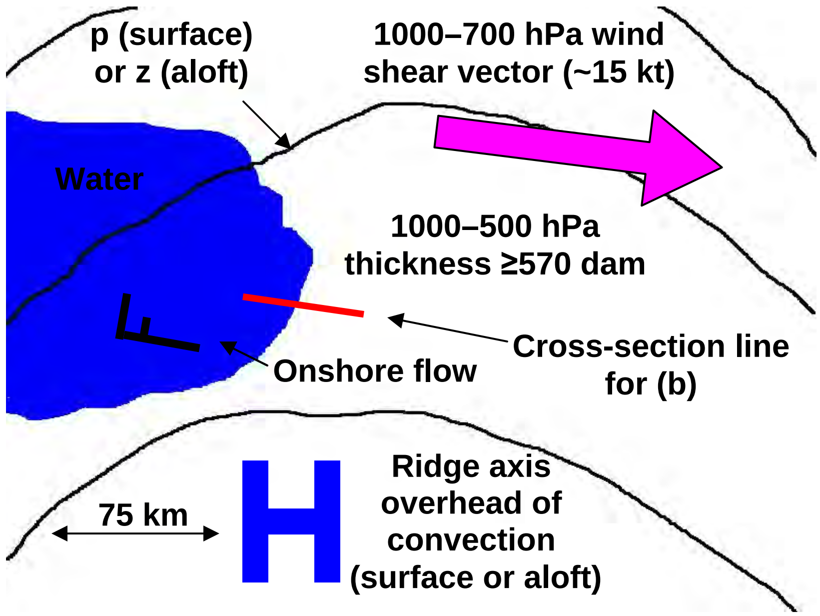
While most of this thesis has focused on how lake and sea breezes can initiate or enhance convection, the results of section 3.3 have shown that lake and sea breezes can also suppress convection. Although only one null case was examined in this research, there are likely many other occurrences of null cases throughout the Northeast that have not yet been documented. The modifications to the PBL in terms of temperature and low-level wind shear by lake and sea breezes, however, have been discussed (e.g., Bastin et al. 2006; Novak and Colle 2006). During the null case from this research (11 July 2006), a difference of about 5°C in air temperature between the land and the ocean was observed at 1800 UTC (Fig. 3.39). Fisher (1960) performed a sea-breeze study on 5 August 1958 near Block Island offshore of the Rhode Island coast, which was part of the region that was affected by the null case from this research. Fisher (1960) noted a difference of 5°C in air temperature between the land and the ocean during the sea breeze on 5 August 1958, similar to the findings at 1800 UTC 11 July 2006 (Fig. 3.39). This difference in air temperature, along with lower PW in the sea-breeze flow (Fig. 3.35) compared to outside of the sea-breeze flow (Fig. 3.34), led to a difference of >10°C in θ_e over the southern New England states during the null case (Fig. 3.37). While convection did form over eastern New York, western Massachusetts, and western Connecticut (outside of the sea-breeze flow), the convection would ultimately be suppressed over Rhode Island, eastern Massachusetts, and eastern Connecticut (within the sea-breeze flow) to where no convection (and no rainfall) was observed during this case (Fig. 3.43). The differences between PBL temperature and CAPE within and outside of the sea-breeze flow were responsible for this null case.

A schematic diagram is shown for the horizontal view (Fig. 4.3a) and the cross-sectional view (Fig. 4.3b) along the line shown in Fig. 4.3a of the evolution of a null case over time. Preexisting convection approaches the LBF/SBF, which separates two air masses that exhibit a difference of ≥10°C in 925-hPa θ_e. The convection can intensify briefly as it receives an additional thrust of upward-moving air rich in CAPE along the LBF/SBF. Once the convection has crossed over a PBL within the lake-/sea-breeze flow, however, the PBL is now low in CAPE but high in CIN. The convective updrafts become filled with air parcels that are less buoyant than the air parcels outside of the lake-/sea-breeze flow. The convection weakens rapidly and is ultimately suppressed as its supply of high-θ_e air is eliminated (Fig. 4.3b). It is likely that subsidence is occurring near the surface within the sea-breeze flow and is suppressing the convective updrafts, which would further stabilize the PBL (see Fig. 3.40).

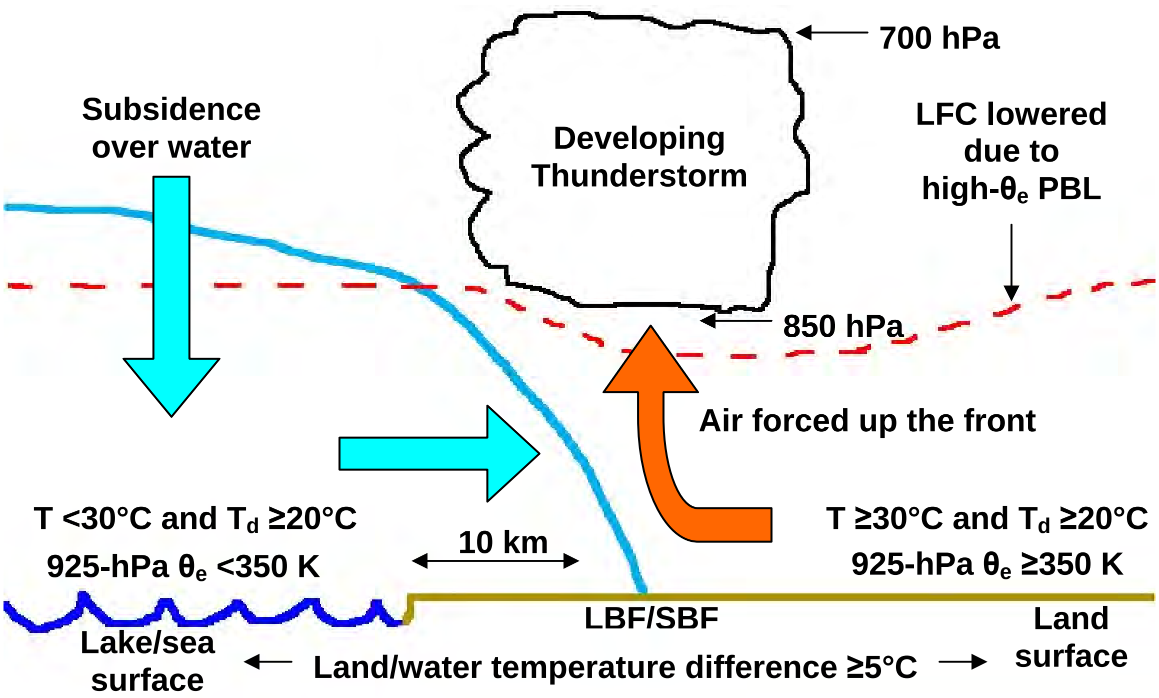
4.4 Regional Threat and Forecasting Implications

A significant finding of this research is the extensive coverage of lake-/sea-breeze severe weather in the Northeast. Although the storms form initially near the Great Lakes, the Chesapeake Bay, and the Atlantic Ocean, convective systems from the Great Lakes can migrate considerable distances and affect other areas of the Northeast. All 12 states within the domain of this research (Fig. 2.1) reported severe weather from the 10 pure and mixed cases that were investigated (Table I). This finding reveals that the entire Northeast is susceptible to lake-/sea-breeze related severe weather. The formation areas and tracks for all 11 cases of this research are shown in Fig. 4.4. Cases that form along the Great Lakes can migrate downshear, following the 1000–700 hPa wind shear vector, all the way to the Atlantic Ocean. A tornado risk area was placed in Fig. 4.4 to emphasize the convergence zone between the lake breezes from Lakes Erie and Ontario. Two tornadoes were reported within this area, which is situated close to Buffalo, NY, from two mixed cases. The null case area is shown along the southern New England states, where convection was suppressed on 11 July 2006.

Since all NWS forecast offices in the Northeast must be aware of lake-/sea-breeze related severe weather, a summary flowchart is provided in Fig. 4.5 to aid in forecasting the likelihood of pure and mixed cases. If conditions are conducive to severe weather (PW ≥25 mm at 1200 UTC and CAPE ≥500 J kg^{-1} by 1500 UTC), then the difference in temperature between the water and the air over land must be considered. The water should be ≥5°C cooler than the air over land after 1500 UTC for an adequate lake or sea breeze to form, and there should be at least 5 kt of onshore flow near the surface by 1500 UTC that will persist throughout the remainder of the daylight hours. If these criteria are met, then a lake-/sea-breeze case is likely to occur based upon the results of this research. The presence (absence) of a synoptic-scale disturbance determines whether the expected case will be a mixed case (pure case). Forecasters should monitor the lake or sea breezes present for the initiation of convection in pure and mixed cases, or for the suppression of preexisting convection in null cases. An awareness of the overall atmospheric conditions (synoptic-scale ridge or trough present, prevailing geostrophic flow, temperature, dewpoint, θ_e, CAPE, CIN, and low-level wind shear) is required to assess the likelihood of the occurrence of a pure, mixed, or null case.

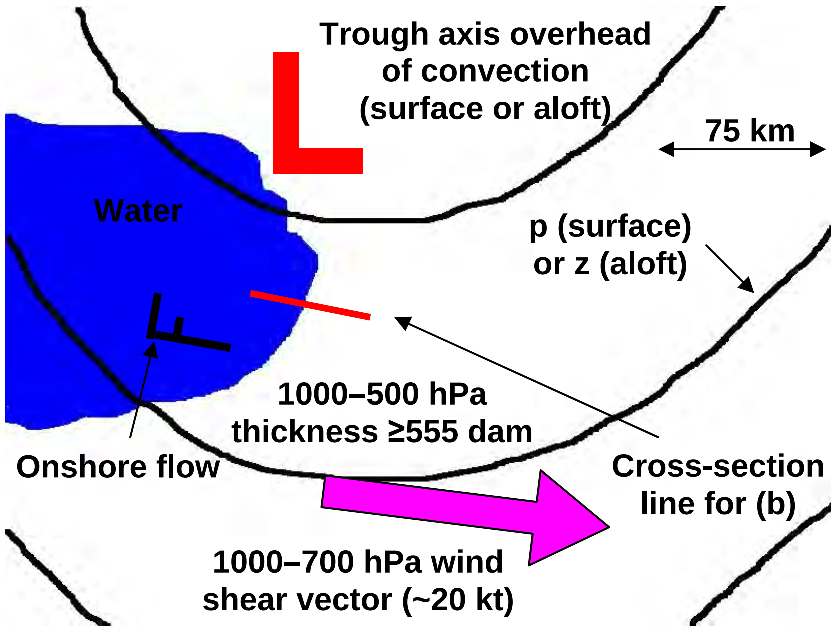


a)

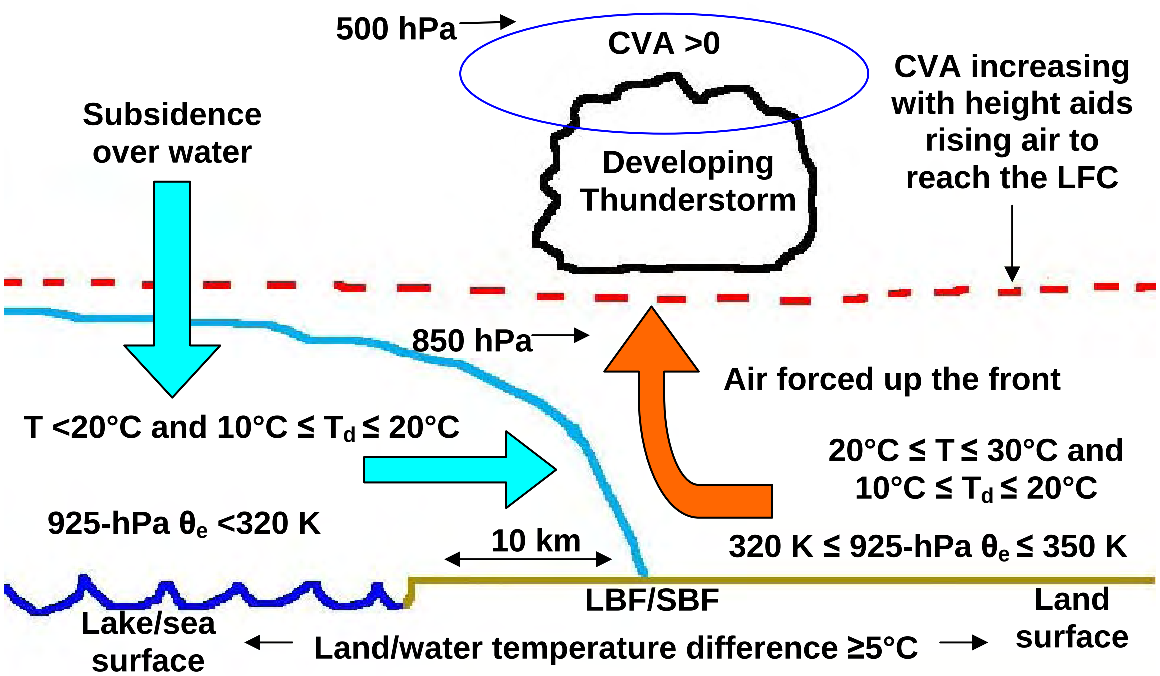


b)

Fig. 4.1. Schematic diagram of a pure case in the (a) horizontal view and the (b) cross-sectional view along the red line shown in (a).

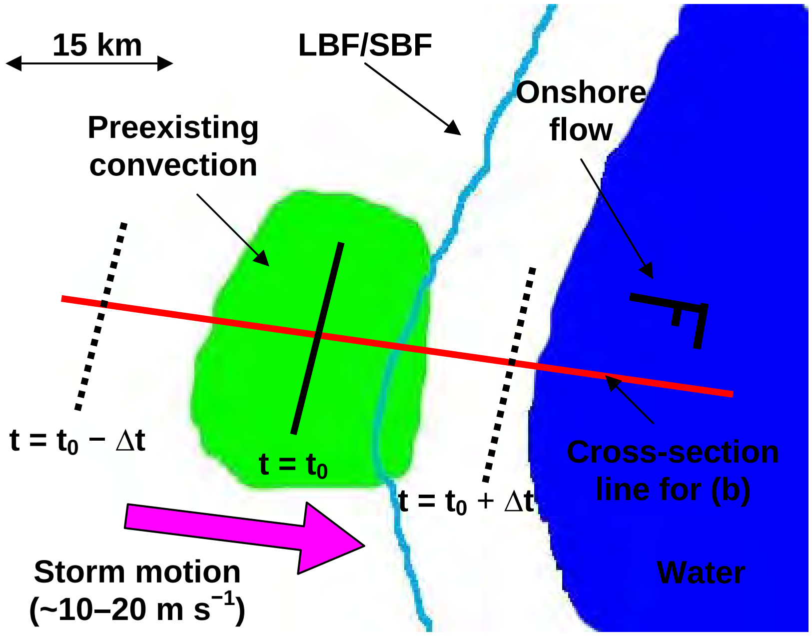


a)

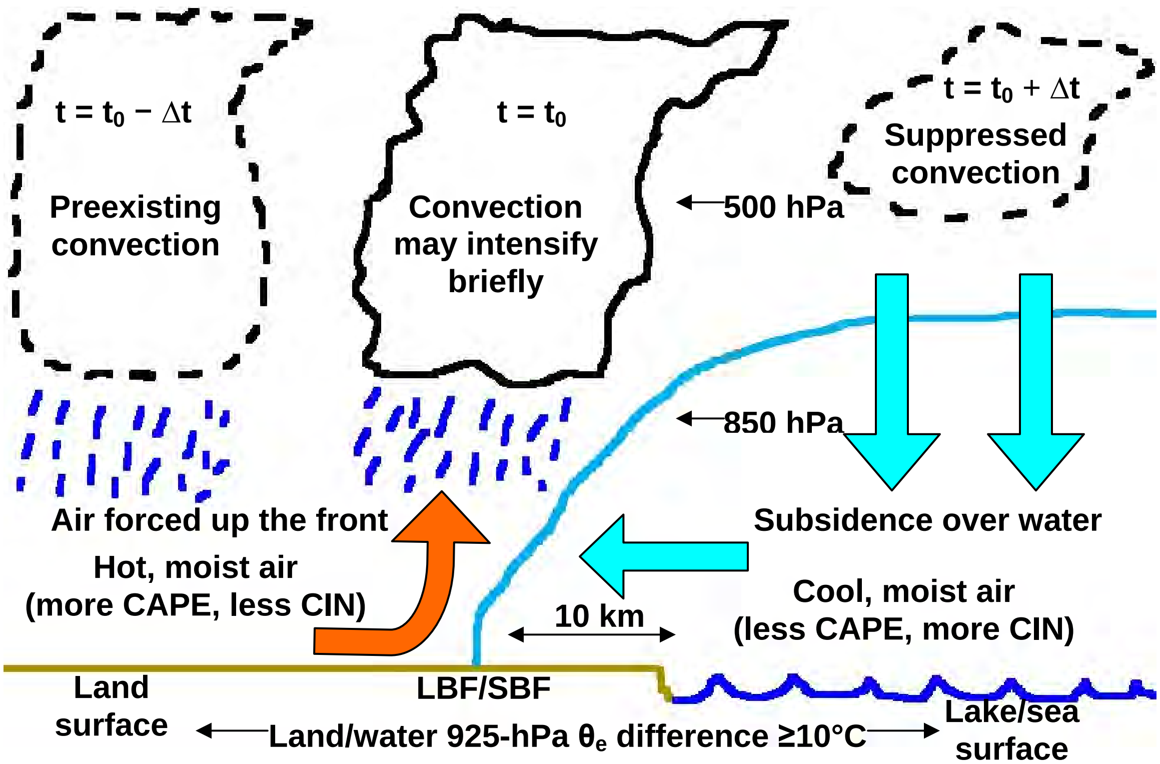


b)

Fig. 4.2. Same as in Fig. 4.1 but for a mixed case.



a)



b)

Fig. 4.3. Same as in Fig. 4.1 but for a null case.

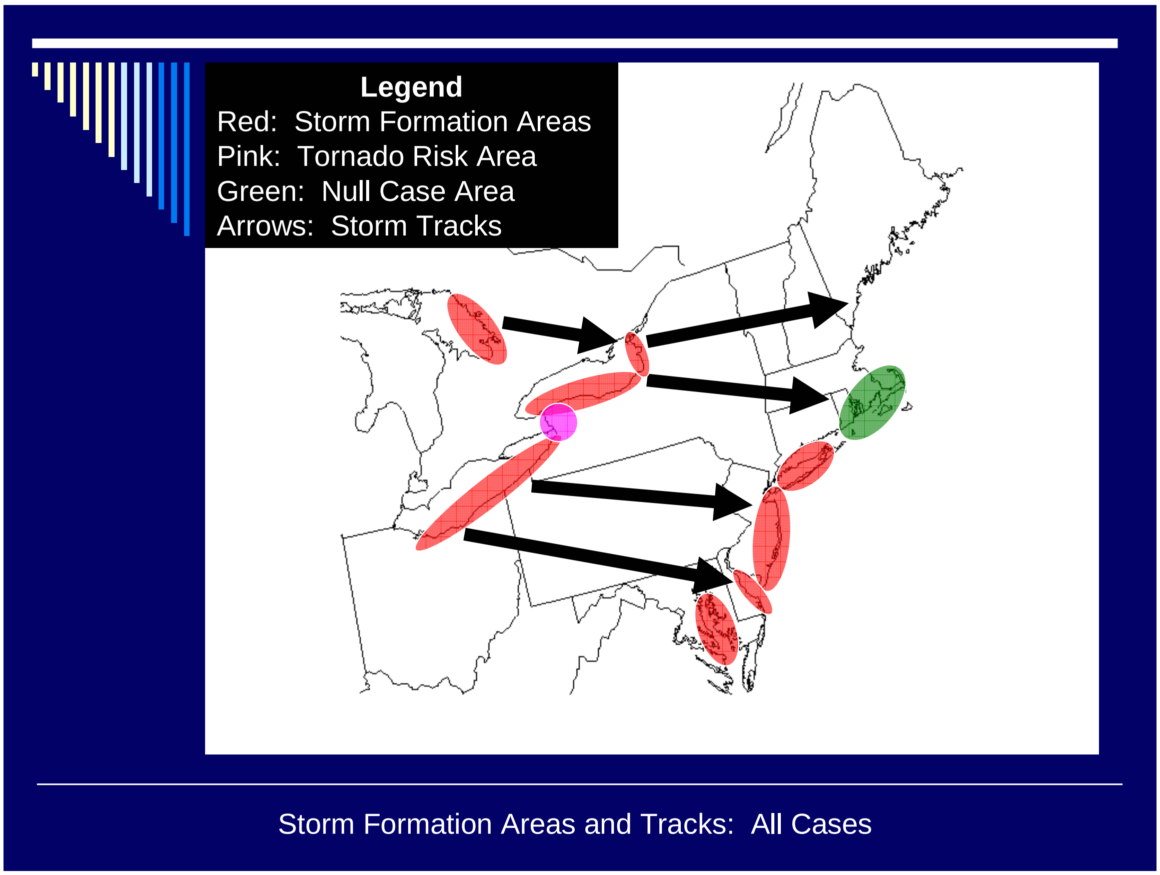


Fig. 4.4. Summary of formation areas and tracks from all cases of this research.

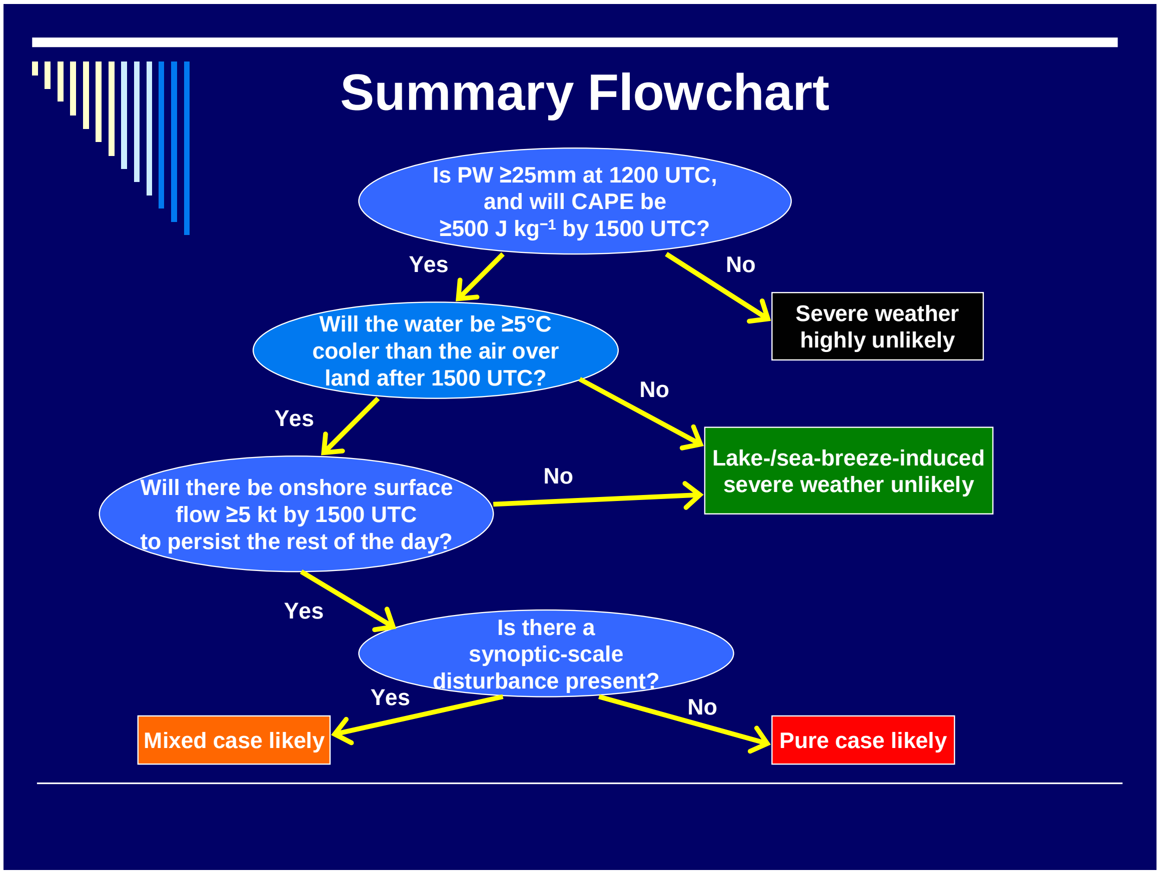


Fig. 4.5. Summary flowchart to aid in forecasting the likelihood of pure and mixed cases.

5. Conclusion

5.1 Summary

The purpose of this CSTAR research project was to examine the role that lake and sea breezes play in enhancing or suppressing convection in the Northeast. Eleven lake-/sea-breeze convection cases from the warm season, defined as April–October, were identified between 2000 and 2006. This analysis period was chosen because of the availability of reliable Doppler radar observations. The NARR and RUC gridded datasets, along with conventional surface and upper-air observations, water temperatures, and satellite and radar imagery, were used to analyze the 11 cases. Four of the 11 cases were classified as pure cases, defined as those cases where mesoscale forcing from lake-/sea-breeze circulations is primarily responsible for initiating severe convection. Six other cases were classified as mixed cases, defined as those cases where synoptic-scale forcing acts in conjunction with mesoscale forcing from lake-/sea-breeze circulations to initiate severe convection. One case was classified as a null case because lake-/sea-breeze circulations act to suppress preexisting convection.

5.2 Pure Cases

This research has shown that pure cases are favored in high-CAPE environments with significant heat and moisture available in the PBL. The Northeast experiences pure cases during the hottest times of the summer when a subtropical air mass is situated over the region. The high-θ_e air in the PBL helps to lower the LFC, which is critical for pure cases as there is negligible synoptic-scale ascent in the presence of a synoptic-scale ridge. Lake or sea breezes are capable of generating sufficient mesoscale ascent to raise air parcels to their LFC, initiating convection along the LBF/SBF. The four pure cases from this research and the findings from past literature on pure cases outside of the Northeast collectively show similar synoptic-scale and PBL environments with surface temperatures (dewpoints) ≥30°C (≥20°C) and CAPE values ≥1500 J kg^{-1} at 1200 UTC prior to the case. NWS forecasters in the Northeast can monitor PBL conditions (e.g., difference in air temperature over land and over water, CAPE, θ_e, and low-level wind shear) to predict when the occurrence of pure cases are favorable. The prevailing synoptic-scale flow in relation to the orientation of the lakeshore/seashore must also be considered. Although lake-/sea-breeze circulations can be advected farther inland when the prevailing synoptic-scale flow reinforces these circulations, the circulations may tend to lean downshear, resulting in less vigorous ascent along the LBF/SBF.

5.3 Mixed Cases

While pure cases rely almost entirely on mesoscale ascent, mixed cases require QG-forced ascent due to CVA increasing with height associated with a synoptic-scale trough in proximity to a lake-/-sea breeze circulation. The LFC is higher in mixed cases than in pure cases due to the presence of lower-θ_e air in the PBL. Since 1000–500 hPa thicknesses are lower in mixed cases than in pure cases, hail is a more significant severe weather threat in mixed cases. The six mixed cases that were analyzed in this research and past literature on mixed cases outside of the Northeast reveal similar synoptic-scale and PBL environments with surface temperatures (dewpoints) between 20°C and 30°C (10°C and 20°C) and CVA increasing with height. Convection generated near the shores of the Great Lakes in conjunction with pure and mixed cases can often migrate downshear in the approximate direction of the 1000–700 hPa wind shear. Schematic diagrams applicable to pure and mixed cases can provide forecasters with an indication of the likelihood of the occurrence of lake-/sea-breeze convection in the Northeast.

5.4 Null Cases

Unlike pure and mixed cases, null cases can occur when lake or sea breezes suppress preexisting convection. CAPE, CIN, θ_e, temperature, and low-level wind shear within and outside of the lake-/sea-breeze flow can vary significantly within the PBL. Temperature, moisture, and wind soundings are valuable in determining whether an air mass modified by the lake-/sea-breeze flow will support or suppress preexisting convection. A schematic diagram applicable to null cases is used to indicate how preexisting convection approaching a LBF/SBF is suppressed as this convection encounters a PBL that features less buoyant air parcels than outside of the lake-/sea-breeze flow. Because the lake-/sea-breeze circulation can be synoptically and/or mesoscale driven, a close examination of the surface winds and the PBL environment near the lakeshore/seashore is necessary to infer the likelihood of null cases.

5.5 Future Work

Current operational NWP models are unable to resolve the mesoscale differences in temperature, CAPE, and low-level wind shear across lake and sea breezes. Thus, NWS forecasters in the Northeast continue to confront a warm-season forecasting challenge, and it is hoped that the results of this research can lead to improved scientific understanding and predictive skill of the three categories of lake-/sea-breeze convection identified in this research. However, the sample size available for this research (four pure cases, six mixed cases, and one null case) is statistically insufficient to allow definitive conclusions to be drawn about the structure, characteristics, and life cycles of these cases. Additional cases need to be analyzed and compared to the results of the aforementioned 11 cases in this research before firmer conclusions can be made. NWS forecasters in the Northeast are encouraged to develop an archived catalog of lake-/sea-breeze convection cases that can be analyzed. Forecasters are also encouraged to assess the validity of the conclusions from this research. It is likely that these conclusions could be refined based on new results. It is important to continue to raise awareness on the severity and frequent occurrence of lake-/sea-breeze severe weather in the Northeast. The densely populated Northeast is surrounded by the Great Lakes, the Chesapeake Bay, and the Atlantic Ocean, so any lake-/sea-breeze severe weather can create a significant hazard to life and property.

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APPENDIX

List of Acronyms and Symbols

The following is a list of acronyms and symbols that were used in the text of this thesis, which are presented here in alphabetical order:

3D	Three-dimensional
CAPE	Convective available potential energy
CIN	Convective inhibition
CSTAR	Collaborative Science, Technology, and Applied Research
CVA	Cyclonic vorticity advection
EST	Eastern Standard Time
GEMPAK	General Meteorology Package
LBI	Lake-breeze index
LBF	Lake-breeze front
LCL	Lifted condensation level
LFC	Level of free convection
LI	Lifted index
LST	Lake surface temperature
NARR	North American Regional Reanalysis
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NEXRAD	Next-Generation Radar
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
NWP	Numerical weather prediction
PODAAC	Physical Oceanography Distributed Active Archive Center
PW	Precipitable water
QG	Quasigeostrophic
RUC-20	Rapid Update Cycle at 20-km resolution
SBF	Sea-breeze front
SLP	Sea-level pressure
SPC	Storm Prediction Center
SST	Sea surface temperature
VORTEX	Verifications of the Origin of Rotation in Tornadoes Experiment
ω	Vertical motion
θ	Potential temperature
θ_e	Equivalent potential temperature
ζ	Relative vorticity