Synoptic Analysis of Large Snowstorms Affecting Boston, Massachusetts

Thesis

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By

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Abstract

The synoptic conditions associated with the occurrence of snow storms in Southern New England are examined. “Blockbuster” snowstorms, defined as those with 19.5-27.5 inches of snowfall accumulation at Boston are compared to “Major” snowstorms having 8.0-13.2 inches of snow accumulation. Gridded NCEP/NCAR Reanalyses model data are used to determine the snowstorm synoptic conditions at lower and upper levels of the troposphere at times before and during peak snow. Surface features analyzed include relative position of the surface cyclone, cyclone track and intensification, coastal frontogenesis, position of the anticyclone and cold air damming. The 850 hPa level depicts placement and intensity of the baroclinic zone and moisture content via specific humidity. The upper troposphere, via 850, 700, 500, and 250 hPa charts, depicts how the upper level trough, positive vorticity, vertical motions, and jet streaks evolve over time and to what role they enhance surface cyclogenesis. Seven cases of each storm type are found and composite averages of the weather data fields are created, sorted by time at 6 hourly intervals from 24 hours prior to, and 48 hours after, the onset of snow.

The 7 Blockbuster storms developed more rapidly than Major storms due to more readily available upper level support. The upper-level trough was more amplified and...
located closer to the east coast prior to snow onset in these cases. Blockbuster events also had larger amounts of 500 hPa vorticity advection and 700 hPa vertical motion maxima over the exit region of the 250 hPa jet streak, further intensifying the divergence aloft and cyclone development. 850 hPa cold air advection was stronger initially over New England prior to snow onset in Blockbuster cases. Warm air advection also developed up the eastern seaboard more rapidly in Blockbuster cases providing an intense baroclinic zone for the surface cyclone to intensify and track northeast along. The greater initial temperature contrast along the coast also provides an explanation to why the surface cyclone developed sooner. Blockbuster storms became vertically stacked with the upper-level low up to the 500 hPa level at 18 hours after snow onset (T + 18). Major cases did not become vertically stacked to 500 hPa until T+30 hours. The vertically stacking of the cyclone southeast of New England in Blockbuster cases causes stalling and slowed eastward progression of the surface low, prolonging snow duration. The later development of a negatively tilted diffluent trough T+12 to T+30 hours in Major cases produces a steady northeastward track for these storms. The later development of upper-level divergence/difluence and slower developing 850 hPa baroclinic zone in Major cases resulted in their later development, having a more northward track hugging the coast. This causes some Major cases to include a changeover to rain and shorter snowfall duration.
Dedication

Dedicated to my Mom, Dad, and sister Julia.
Acknowledgements

I would like to thank Jeff Rogers, my adviser, for his support, edits, input, weekly meetings, and encouragement in making this thesis a reality. I would also like to thank Meng-Pai Hung who's help with IDL, NCEP/NCAR model data, and programming made the analysis possible. I would like to also thank; Dr Ningchuan Xiao for helping me use GIS to spatially analyze snowfall accumulation and storm tracks, and Dr. David Robinson, Rutgers University for his assistance in acquiring snowfall data that included all of my storms. Finally I would like to thank my family for their support and encouragement.
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# Table of Contents

Abstract.................................................................................................................................. ii

Dedication.............................................................................................................................. iv

Acknowledgements.............................................................................................................. v

Vita......................................................................................................................................... vi

List of Figures........................................................................................................................ viii

CHAPTER 1: INTRODUCTION.......................................................................................... 1

CHAPTER 2: PREVIOUS STUDIES AND RESEARCH.................................................... 4

CHAPTER 3: DATA AND METHODS................................................................................ 12

CHAPTER 4: RESULTS....................................................................................................... 18

CHAPTER 5: DISCUSSION AND CONCLUSIONS.......................................................... 103

CHAPTER 6: FUTURE RESEARCH................................................................................... 109

REFERENCES...................................................................................................................... 110
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The time of occurrence and snowfall amounts for Blockbuster and Major Snowstorms at Boston.</td>
</tr>
<tr>
<td>2</td>
<td>The track of each surface cyclone for Blockbuster and Major snowstorms.</td>
</tr>
<tr>
<td>3</td>
<td>Depicts snowfall distribution for Blockbuster and Major storms.</td>
</tr>
<tr>
<td>4</td>
<td>The composite duration of accumulating snowfall for Blockbuster and Major snowstorms.</td>
</tr>
<tr>
<td>5</td>
<td>The quantitative precipitation composite average of 3-hourly precipitation for Blockbuster and Major snowstorms.</td>
</tr>
<tr>
<td>6</td>
<td>T-24 hours Boston snowfall onset for Blockbuster and Major cases. From left to right: Sea Pressure (SLP), 500 hPa geopotential height, 500 hPa relative vorticity, 700 hPa geopotential height, 700 hPa Omega, and 250 hPa geopotential height and wind, 850 hPa geopotential height, 850 hPa Temperature and winds, and 850 hPa specific humidity: A Blockbuster, B Major.</td>
</tr>
<tr>
<td>7</td>
<td>Same as Fig 6 but for T-18: A Blockbuster, B Major.</td>
</tr>
<tr>
<td>8</td>
<td>Same as Fig 6 but for T-12: A Blockbuster, B Major.</td>
</tr>
<tr>
<td>9</td>
<td>Same as Fig 6 but for T-6: A Blockbuster, B Major.</td>
</tr>
<tr>
<td>10</td>
<td>Same as Fig 6 but for T-0: A Blockbuster, B Major.</td>
</tr>
<tr>
<td>11</td>
<td>Same as Fig 6 but for T+6: A Blockbuster, B Major.</td>
</tr>
<tr>
<td>12</td>
<td>Same as Fig 6 but for T+12: A Blockbuster, B Major.</td>
</tr>
<tr>
<td>13</td>
<td>Same as Fig 6 but for T+18: A Blockbuster, B Major.</td>
</tr>
<tr>
<td>14</td>
<td>Same as Fig 6 but for T+24: A Blockbuster, B Major.</td>
</tr>
<tr>
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<td>Description</td>
</tr>
<tr>
<td>---</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>15</td>
<td>Same as Fig 6 but for T+30</td>
</tr>
<tr>
<td>16</td>
<td>Same as Fig 6 but for T+36</td>
</tr>
<tr>
<td>17</td>
<td>Same as Fig 6 but for T+42</td>
</tr>
<tr>
<td>18</td>
<td>Same as Fig 6 but for T+48</td>
</tr>
</tbody>
</table>
CHAPTER 1: INTRODUCTION

Major snowstorms affecting the east coast of the United States, more commonly known as Nor'Easters, have tremendous economic consequences that can paralyze the transaction of goods and services, limit transportation, force people from going into work and school, and cause loss of human life. The combined effects of heavy snow, gusty winds, and bitter temperatures can cause havoc especially in a heavily populated and industrialized urban setting. The Northeast urban corridor has a population of nearly 50 million people that are significantly impacted by extratropical cyclones moving up the coastal plain during winter months. This study will look at the most damaging snowstorms to affect Southern New England and compare and contrast Blockbuster snowstorms (the top seven snowstorms in terms of accumulation to impact Boston) to Major snowstorms (seven snowstorms of 8.0-13.2 inches of snow accumulation). The synoptic conditions necessary for heavy snow will be examined using NCEP/NCAR reanalysis' model data. Other east coast snowstorm studies have focused on the entire northeast, while this study uniquely examines the conditions favorable for blockbuster and major snowstorms in the Boston area.

Better understanding the evolution and development of major east coast snowstorms is beneficial from an operational meteorology perspective because it allows forecasters to more accurately predict such events. A more accurate forecast will improve
the lead time for emergency management responders. This prepares the public for conditions that could disrupt their lives on economic, health, and social levels.

Changnon & Changnon (2004) found that 155 snowstorms occurred in the United States between 1949 and 2000 that resulted in total losses of $21.6 billion (2000 dollars). The study also found that the Northeastern United States had the maximum storm occurrence (79 storms) with a total loss of $7.3 billion. Nearly 155 patterns of loss were found with 29 storms confined to the northeast alone. Of these 29 events, the Northeast led with 40% of the 73 catastrophes experienced. For the 52 year period all New England States had occurrences exceeding 30 storms, which defined the Northeastern U.S. as the zone of "greatest frequency of snowstorm losses". The fact that the Northeastern U.S. had the greatest frequency of damages from snowstorms is of particular interest to insurance agencies directly impacted by damage claim losses from these storms. Understanding the distribution of damage prone locations for snow related events could help improve risk management decisions.

An additional study conducted in 2007 (Changnon & Changnon 2007) found that losses related to winter storms have been rapidly increasing. The results updated through 2003 found that 203 storms from 1949-2003 cost $35.3 billion (2003 dollars). The study found that 88% of the damage was concentrated in the eastern half of the U.S. with the highest frequency in the Northeast U.S. with 98 storms. Winter storms kill 30 to 40 people annually but the average loss from snowstorms ranks less than hurricanes, floods, and severe weather, although it exceeds hail and tornadoes. The average loss per storm was $174 million. A more comprehensive understanding of the factors involved in such destruction could be used to minimize future damage.
The Superstorm of March 2003, included and examined in this snowstorm data set, is the most costly winter related event to affect the U.S. The storm affected 20 states from Louisiana to Maine; caused $1.8 billion in insured property loss, and led to 270 deaths (the National Weather Service narrows the death toll down to 100). This storm was labeled as the nation's worst winter storm of the past 100 years (Changnon & Changnon 2004) and had a snowfall distribution that extended from the Gulf Coast northeast through Maine. Snowfall accumulations exceeding 40 inches occurred in 7 states. The Superstorm also had severe weather and flooding rains associated with it. It is estimated to have impacted the lives of 90 million people, nearly one-third of the United States population (Kocin et al. 1994). January 1996 had three severe snowstorms (one included in this study's dataset) that struck the Northeastern U.S., causing $1.1 billion dollars in losses. Just in 1993-1999 eleven major snowstorms caused 4.6 billion dollars in the Northeast U.S., which totaled 20% of the losses from the 155 snowstorm in the 1949-2000 dataset.
CHAPTER 2: PREVIOUS STUDIES AND RESEARCH

Brandes and Spar (1971) attempted to define necessary conditions for heavy snow along the east coast using a composite approach. This study found that there was a lot of variability between individual storm events and compositing eliminated important features seen in the synoptic and mesoscale fields. Kocin and Uccellini's (1990) monograph on east coast snowstorms chose to use a sequence of weather charts for each storm to identify patterns at the surface, lower troposphere, and upper troposphere that precede and accompany the development of each snowstorm. Because every storm has different characteristics, this method of sequencing fails to extract conditions that can be applied to all snowstorms. Brandes and Spar did however find a common 850 hPa field that was seen in most storms, with a somewhat high standard deviation. At 850 hPa during the onset of heavy snow there tended to be a low center, a pool of high humidity spreading to the coast, and temperatures 0 to -5°C in the coastal plain with heavy snow.

The United States coastline enhances cyclogenesis because it serves as a boundary between cold air trapped over the coastal plain (cold air damming) east of the Appalachian Mountains and boundary layer air that is warmed and moistened by the Atlantic Ocean (Bosart 1975). Cold air damming plays a crucial role in coastal frontogenesis (Bosart 1975). The coastline also plays a role via surface roughness that influences low level divergence and cyclonic circulation patterns. The coastline of North Carolina and New England has a concave shape prone to cyclogenesis (Kocin Uccellini 2004). Petterson (1956) noted that surface cyclones develop downstream of mountain ranges and along coastlines. This process is known as the "lee cyclogenesis" where
surface cyclones develop east of mountains as a result of vorticity stretching (Holton 1979). The Appalachian Mountains force cyclones to have a farther easterly and southerly track on the east coast via cold air damming which enhances a low-level baroclinic zone (O'Handley and Bosart 1996).

Miller (1946) examined 200 east coast cyclones over a 10 year period and found two different types that he categorized as Type A and Type B. Type A features cyclones that develop along a cold front located in the south east U.S. or Gulf of Mexico. Type A resembles a classic Norwegian cyclone model storm. The cold front, which is of polar origin, separates continental polar from maritime tropical air masses. The cyclone develops along a baroclinic zone moving along it towards the north east. Type B storms represent a more complex circulation pattern that involves secondary redevelopment. The primary cyclone occludes and dissipates west of the Appalachian Mountains, while a secondary cyclone develops along a warm front that is shared with the primary cyclone. A typical situation would have the warm front extending to the coastal waters where it connects with shallow boundaries. The process of redevelopment allows for the coastal front to develop and separate a shallow wedge of cold air east of the Appalachians, which results in cold air damming. (Kocin & Uccellini 2004). Miller Type B storms tend to have a broader transition zone of freezing rain and sleet because they lack the better defined warm air advection patterns found in Type A.

A surface anticyclone plays an important role in supplying cold low level flow during east coast cyclones. The orientation of the anticyclone relative to the cyclone allows for a low level airflow that passes overland, or for a limited distance over the
ocean. The cold air mass being supplied to the north of the approaching cyclone is not modified by latent and sensible heating from the ocean. The anticyclone acts as a positive feedback mechanism in that it enhances the low level thermal fields by supplying cold air advection at the surface. The anticyclone typically remains north northwest of the cyclone and is linked to the upper level confluence in northeast U.S or southeast Canada. It is located upwind of the upper-level trough, crossing eastern Canada, usually in the entrance region of a jet streak. The entrance region (to be discussed later) results in direct transverse circulation which maintains the anticyclone and enhances advection of cold air (Bell & Bosart 1989; Kocin & Uccellini 2004).

The orientation of the surface anticyclone and Appalachian mountain range permits frontogenesis to occur. The enhancement of the baroclinic zone along the coast is known as coastal frontogenesis (Bosart et al 1972). Cold air damming permits a narrow wedge of cold air to be channeled southward along the eastern slopes of the Appalachian Mountains which is maintained by frictional, isallobaric effects, evaporation, adiabatic ascent, and orographic effects (Bell & Bosart 1989). The mountains play a large role in trapping cold air between the coast and the eastern slopes which therefore enhances the baroclinic zone along the east coast. This process is marked by a distinctive inverted high pressure ridge extending southward along the coastal plain. The 850 hPa level is characterized by an "S pattern" in the isotherms depicting both the warm and cold air advection profiles in the lower troposphere. The circulation center at 850 hPa is near the coast, slightly west of the surface cyclone, close to the inflection point of the "S". Warm air advection is marked by 20-35 ms⁻¹ winds perpendicular to the isotherms. The thermal
advection profiles are intensified via cyclogenesis, baroclinic instability, topography, and sensible heat flux from the ocean on the boundary layer temperature (Kocin & Uccellini 2004)

Sensible heat fluxes also play a role in enhancing the thermal gradients/baroclinic zone along the coast. Sensible heat released over the Atlantic Ocean east of surface low increase temperature gradients along coastline. The surface low is affected by addition of diabatic heat and moisture, but also associated with increased baroclinic processes associated with increased temperature gradient. The more intense low level baroclinic zone also increases surface winds, and therefore increases warm air advection which helps to develop a cyclone. This process also aids in the development of a low level jet. The low level jet is an acceleration of air in an easterly to southeasterly flow through the precipitation region (850 to 600 hPa) located beneath southwest diffluent flow aloft (with trough-ridge system). Whitaker et al (1988) hypothesized that the transition layer between southeast airstream and southwest flow aloft results in increased mass divergence and cyclonic development (Kocin & Uccelini 2004).

A key requirement for cyclonic development is for upper-level divergence to produce net reduction of mass and therefore lower surface pressure. The net difference between surface convergence and upper-level divergence is a measure of the rate of cyclonic development, as described by Dines (1925), Sutcliffe (1939 & 1947), and (Kocin & Uccelini 2004). Bjerknes and Holmboe (1944) related convergence and divergence patterns to the presence of upper-level ridges and troughs. They found that subgeotrophic flow at the base of a trough and supergeostrophic at the crest of a ridge
combine to enhance the divergence downstream of a trough axis. An additional transverse ageostrophic motion was linked to upper level wind maxima, known as jet streaks (Palmen and Newton 1969). Jet streaks enhance the upper level divergence and also contribute to surface high and low pressure systems in the exit and entry regions of the jets. Sutcliffe and Forsdyke (1950) and Petterssen (1955, 1956) offered the concept that cyclone formation occurs when an upper level trough, with its associated cyclonic vorticity advection approached a frontal system/low level baroclinic zone. They termed this process self development, where the low level advection pattern could enhance the upper level vorticity pattern and therefore increase divergence aloft.

MacDonald and Reitter (1988) looked at explosive cyclogeneisis over the eastern United States. They found that “bombs” tend to show a decrease in vorticity with height in their incipient phase and explosive stage, whereas regular cyclones show only weak vertical vorticity gradients in the troposphere. Bombs also exhibited well marked zero-divergence level near 500 hPa which was associated with maximum rising motions. Latent heat released was maximized during the incipient phase of bombs and decreased in the explosive and mature phase. Regular cyclones showed less heating in the stages of development than was seen in bombs.

Kocin and Uccellini (2004) in their examination of 30 Northeast Coast snowstorms found similar characteristics in the upper-level ridge-trough patterns. They found most storms showed an increase in amplitude and a decreasing half-wavelength between the trough and downstream ridge axes during cyclogenesis. They noted that this was a nonlinear process that increased upper level divergence during cyclone
development. They also found an increase in diffluence downstream of the trough axis in the upper level height contours (another upper-level divergence signature). The diffluence tended to increase rapidly as the trough became negatively tilted. Each of the upper-level features contained one or multiple vorticity maxima which also indicated upper-level divergence. Kocin and Uccellini found the vorticity maxima to propagate northeastward with the cyclone and contain the region of heaviest snow, with rain or mixed precipitation occurring when the maxima passed to the north or northwest of an area. Merging of vorticity maxima into one cohesive maximum was found to play a major role in snowstorms because they strengthen the upper level divergence and cyclonic vorticity advection. It was noted that "phasing" of separate troughs/vorticity maxima plays a role in the prediction of heavy snowfall.

Jet Streaks also play an instrumental role in upper-level divergence. Bjerknes (1951) found that the contribution of transverse cross stream ageostrophic components in entrance and exit regions of a jet streak can be linked to surface cyclones and anticyclones. The entrance region of a jet streak is marked by a transverse ageostrophic component directed towards the cyclonic shear side of the jet. This represents the direct transverse circulation that converts potential energy into kinetic energy for air parcels to accelerate into the jet. This can be represented by rising motion on the anticyclonic or warm side of the jet. In the exit region ageostrophic flow is directed towards the anticyclonic-shear side of the jet, which converts kinetic energy into potential energy as air parcels decelerate exiting the jet. This creates rising motion on the cyclonic or cold side of the jet. The process is the following: (1) a well defined upper level trough located
in Ohio/Tennessee valley with a jet streak at base of trough entering a diffluent region downward of the trough axis. The cyclone develops downstream of trough axis and within the exit region of the jet streak, where upper level divergence is occurring; (2) a second upper level trough over southeast Canada with a jet streak embedded in a confluent zone over New England with high pressure found beneath the confluent entrance region of jet streak; (3) indirect and direct transverse circulations are located in exit/entrance regions of each jet streak; (4) rising branches of air in exit/entrance regions merge, contributing to wide spread ascent, clouds, precipitation between diffluent exit region downwind of trough (near east coast) and confluent entrance region located northeast U.S.; (5) advection of cold air south in lower branch of direct circulation, enhanced by ageostrophic flow associated with cold air advection; (6) northward advection of warm, moist air in lower branch of indirect circulation across southeast U.S. ascends over colder air to north of surface cyclone. A low level jet develops beneath diffluent exit region of upper level jet and increases moisture transport, interacts with the highly frontogenetic coastal plain, and increases thermal gradients (Kocin & Uccelini 2004).

It is clear that the interaction of both low level and upper level troposphere features are important for the development of a major east coast cyclone. Sutcliffe's self development concept relates the interactions between the dynamical and diabatic processes that contribute to rapid east coast snowstorm cyclogenesis. The basis developed by Sutcliffe and Forsdyke (1950) and later developed by Palmen and Newton (1969) and Roebber (1993) has the following: the approach of an upper level trough and/or a jet
streak toward a low-level baroclinic zone, with a pre-existing weak surface cyclone. This feature enhances the effects of warm air advection, sensible heat flux, and moisture fluxes in the boundary layer, with latent heat released above 850 hPa (north and east of surface cyclone). The net effect is to warm the lower to middle troposphere near axis of upper level ridge, and to increase divergence aloft between trough axis and ridge axis. The warming effects decrease the eastward progression of the upper level ridge, also increasing amplification. Upstream an upper level trough amplifies in response to cold air advection pattern west of the developing cyclone. This results in a decrease in wavelengths of ridge and trough system, increases in diffluence due to spread of height lines downstream of trough axis, and the maximum wind speeds associated with jet streak combine to enhance divergence in middle to upper troposphere. Enhancement of vorticity advection is a response to increased divergence. The cyclone deepens, the surface wind field increases north and east of center, where pressure falls and vertical motions are large. A low level jet develops north and east which enhances moisture and heat fluxes within the boundary layer. This moisture is transported into the heavy snow region where warm air advection east of cyclone further contributes to development until occlusion.
CHAPTER 3: DATA AND METHODS

Winter snowstorms used in this study for the Boston, MA are defined as being either "Blockbuster" storms or "Major" snowstorms. Intensity of a snowstorm is ranked by the accumulated snowfall measured from highest to lowest. The seven highest accumulation Boston snowstorms are defined as "Blockbuster Storms" and they had a range of 19.8-27.5 inches of snow. Snowstorm data are taken from the National Weather Service Forecast Office in Taunton, Ma (BOX) contained in their "Unique Local Climate Data" on snowstorms. Their list is inclusive up to 2001, is used to identify five of the seven blockbuster cases. A comprehensive list of all snowstorms covering 1997-present, also taken from "Unique Local Climate Data", is used to identify snowstorms that occurred post 2001. The "Major Snowstorms" are defined as those that meet winter storm warning criteria for Boston (more than 8 inches of snow in a 24 hour period or more than 6 inches of snow in a 12 hour period) but not more than 14 inches of snow for a given storm and the range for Major Storms was 8.1-13.3 inches. Major storms are determined by analyzing daily (December-April) Boston snowfall accumulation data from the Midwestern Regional Climate Center (MRCC) database between 1950-present. In addition to MRCC data major storms are identified from Kocin & Uccellini's (2004) monograph on East Coast snowstorms that includes 30 storms affecting much of the Northeastern United States. Storms from the Kocin & Uccellini are selected if they meet the major storms definition for warning criteria for Boston. An additional source in the selection of major storms was the "Unique Local Climate Data" from the National Weather Service Forecast office (BOX). The major storm selection was weighted more
heavily towards post 1997 storms (four of the seven) due to the availability of snowfall accumulation data sets covering the entire Southern New England region.

Snowstorm distributions covering Southern New England for each of the fourteen storms are obtained by collecting surface observations of accumulated snow. Storms after 1997 have extensive town and accumulation data taken from special weather statements (SPS) from the NWS BOX office website. These data are then geo-coded to latitude and longitude in ArcGIS via a join operation of town shape files for the six New England States and New York. The city and town shape file is obtained from the AWIPS Shapefile Database. Snowfall amounts for pre-1997 storms are obtained from Utah Climate Center (UCC) that have daily snowfall data for surface observation sites throughout the northeastern U.S. Observations are pulled during the days of each storm and then summed to determine the total snow amount for each location. These data are then exported with latitude and longitude coordinates and brought into ArcGIS as point files. Once each storm has reached a minimum of 100 points of snowfall data, a kriging interpolation is used to estimate the snowfall distribution for each case. Kriging weights surrounding measured values to derive a prediction in areas that are not measured (ESRI). The equation that defines the kriging method is:

\[
\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i)
\]
where: $Z(s_i)$ is the measured value at the $i^{th}$ location, $\lambda_i$ is an unknown weight for the measured value at the $i^{th}$ location, $s_0$ is the prediction location, and $N$ is the number of measured values.

Once a raster layer is created via the kriging interpolation the continuous layer is then masked to remove data that are outside of Southern New England, to exclude data covering the Atlantic Ocean, New York, and the three Northern New England States. The remaining data are then classified into five inch category ranges to depict the snowfall distribution for each respective storm. Snowfall accumulation data are not continuous and a "bulls-eye" effect tends to occur when one station measured a much greater snow amount than a nearby station. One potential data weakness is that observers have different methods of measuring snowfall. This allows for extremes on both the low and high ends in comparison to surrounding measurements. The kriging attempts to minimize these extremes but more data are needed to completely remove the extremes of particular stations. The interpolation of snowfall accumulation is the best method available given such few observation points covering the research area. Most recent storms have in excess of 200 stations (contained in the data from the special weather statements) while storms prior to 1997 have considerably fewer stations (around 100). More confidence in the post-1997 snow interpolation is a result of more data points.

NCEP/NCAR gridded reanalysis model data are used to analyze the state of the atmosphere at the time of Boston (BOS) snow onset and in 6 hr increments prior to and after peak snow, covering 24 hours prior and 48 hours post onset of snow. NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, are
acquired from their Web site at http://www.cdc.noaa.gov/. The NCEP/NCAR model is a T62 model with a horizontal resolution of 210 kilometers and 28 vertical levels. The reanalysis data includes that recovered from land surface, ship, rawinsonde, pibal, aircraft, satellite, and other observations that is quality controlled and assimilated to ensure a consistent analysis from 1949-present (Kalnay et al 1996). The model is global and IDL is used to create a domain that included the continental United States and a few hundred kilometers of the eastern seaboard. The domain covers 20°N to 60°N latitude and 130° to 60°W longitude with some covering a slightly smaller domain once the plot focused more closely on the northeastern U.S. Composites are created to compare Blockbuster events to Major events with the onset of snow for Boston in each case defined as "onset". Blockbuster events are compared to Major Events to evaluate similarities in the storm development and evolution between the two types of cases. Surface features that are analyzed include relative position of the surface cyclone, cyclone track and intensification, coastal frontogenesis, position of the anticyclone, and cold air damming. The 850 level will depict placement and intensity of the baroclinic zone as well as the thermal advection profiles throughout the development of blockbuster and major storms. The upper troposphere, via 850, 700, 500, and 250 hPa, depicts how the upper level trough/ridge, positive vorticity, and jet streaks evolve over time and to what role they enhance surface cyclogenesis. Variables that are analyzed include temperature (850 hPa), wind speed and direction (850, 250 hPa), wind speed (250 hPa to locate jet streaks/jet stream), relative vorticity (500 hPa), omega (700 hPa), specific
humidity (850 hPa), geopotential height (850, 700, 500, 250 hPa), and sea level pressure (surface).

Hourly surface observations taken from National Climatic Data Center (NCDC) for Logan International Airport (BOS) are used to determine onset of snow, that being the first observation of light snow in each case. Once the time is determined, IDL reads the data for each case and computes and plots a composite average of that given variable. This process is carried out [-24, +48] hours in relation to the first observation of snow for Boston. Composites of three hourly quantitative precipitation (qpf) amounts are computed for the Blockbuster and Major cases based on the surface observations from the NCDC data. The precipitation amounts are determined from the onset of light snow to the observation in which snow is no longer being measured or a changeover to rain occurs. A total time of accumulating snow (onset end of measurable snow) is determined for each case based on the three hour intervals. A composite of accumulated snow is computed for both blockbuster and major cases.

Surface low tracks for each individual storm are determined by locating (with IDL) the latitude and longitude of lowest pressure in each case. The data are then geocoded into a point layer in ArcGIS, which is then connected by a polyline based on the time sequence of each point. A major limitation of this method is that the surface low stalled and/or retrograded in several cases, making the surface track appear choppy. The ideal track also does not follow a straight path from time step to time step. The course resolution of the grid size and 6 hour time increments hinder a more accurate placement of the surface low. However this is the best data available that covers all cases involved
in this study. Each surface track for the Blockbuster and Major cases were overlaid to allow for a comparison between them. ArcGIS measurement tools were used to determine how far the surface low tracked in relation to Southern New England.
CHAPTER 4: RESULTS

a. Storm snowfall characteristics and cyclone tracks.

The Blockbuster cases had a range of 19.8 - 27.5 inches of Boston accumulated snow, while the Major cases had a range of 8.1- 13.3 inches. Figure 1 is a bar graph showing the accumulated snowfall of each storm. The top four snowstorms for Boston have maxima within two inches of each other with three of them occurring in February. The major cases have four events occurring in March and one event each for December, January, and April.

Figure 1. The time of occurrence and snowfall amounts for Blockbuster and Major snowstorms at Boston.
The storm track comparison between the Blockbuster and Major cases are depicted in Figure 2. The most noticeable feature differentiating the storm types is the fact that none of the Blockbuster cases tracked to the north or west of Southern New England, while two events the March 1993 and January 1999 major events tracked about 90 miles to the west of Boston. Both of these cases were marked by a changeover from snow to ice and rain, limiting the potential for higher accumulated snowfall. The March 2007 storm passed next closest to Boston, to be about 35 miles southeast of Boston. The March 2007 event also exhibited a changeover to rain, limiting snow amounts. Another

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Figure 2. The track of each surface cyclone for Blockbuster and Major Snowstorms.
Figure 2 continued

Major Storms
Surface Cyclone Track

Legend

- Pink: April 1982
- Blue: March 1993
- Green: December 1981
- Blue: March 2001
- Light blue: March 2004
- Orange: January 1999
- Purple: March 2007

DESCRIPTION:
This map depicts surface tracks of the 7 Major snowstorms based on 6 hour lowest latitude/longitude pressure coordinate.
pattern for the blockbuster cases is the track of the storm tended to follow a path northeastward up the coast (or from the southeast U.S. northeastward) to a position about 80 miles south of the Southern New England coast. Once the storm reached this position it generally moved due east with snow continuing to fall in the northwest quadrant of the cyclone. Six of the seven blockbuster cases followed a path of this nature, but variation occurred as to how far west the storm began its due eastward progression. The February 1978, March/April 1997, and January 2005 cases all began their eastward progression about 85 miles south of eastern Long Island. The March 1960 and February 2003 began their eastward progression about 170 miles southeast of Nantucket, and the February 1969 event began its eastward progression about 85 miles south of Nantucket. The one exception to an eastward progressing storm track was the January 1978 case that continued to track northeastward, passing about 55 miles southeast of Nantucket.

Storm tracks for the major cases can be generalized into 2 groups: (1) tracks that travel just southeast or west of Boston (March 1993, January 1999, March 2007); and (2) tracks that stay south of New England (December 1981, April 1982, March 2001, and March 2004). Those in group 1 had a changeover to ice and rain as warm air flooded mid-levels of the atmosphere, while group 2 had a lot of variation among each individual case. April 1982 and March 2001 followed the blockbuster recognized pattern of eastward progression, yet these cases did not develop along the coast or in the southeast U.S. The December 1981 case retrograded northwest once it was about 300 miles east-southeast of Nantucket and the March 2004 case tracked off the Mid Atlantic coast traveling east-northeast to about 165 miles southeast of Nantucket.
Figure 3. Depicts snowfall distribution for Blockbuster and Major storms.
Blockbuster Storms
Snowfall Accumulation Distribution

Legend
Snowfall (Inches)

- 5 - 10
- 10 - 15
- 15 - 20
- 20 - 25
- 25 - 30
- 30 - 35
- 35 - 40

January 24-25 2005

January 19-21 1978

March 3-4 1960

Continued
Figure 3 continued

### Major Storms

#### Snowfall Accumulation Distribution

- **April 6-7 1982**
- **March 14-15 1993**
- **December 5-6 1981**
- **March 6-7 2001**

#### Legend

- **Snowfall (inches)**
  - 0 - 5
  - 5 - 10
  - 10 - 15
  - 15 - 20
  - 20 - 25

Continued
Figure 3 continued

**Major Storms**

**Snowfall Accumulation Distribution**

**March 16-18 2004**

**January 14-17 1999**

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**Legend**

**Snowfall (Inches)**

- 0 - 5
- 5 - 10
- 10 - 15
- 15 - 20

**March 16-17 2007**
All of the blockbuster cases have the heaviest distribution of snow confined to areas in eastern Massachusetts with small deviations between each case. The February 2003 case had its heaviest snow accumulation from Boston to the South Shore while the February 1978 had its heaviest distribution from northern Rhode Island northeastward to the North Shore. The February 1969 event had its heaviest snow northwest of Boston around the Reading/North Shore area while the March/April 1997 case had 2 maximum areas of snow accumulation from Boston to points west covering east central Massachusetts. The January 2005 case had snow accumulation peaks at the North Shore, South Shore, and outer Cape Cod area. The January 1978 storm had peak snowfall amounts at the North Shore, with a broad 15-20 snowfall distribution covering the rest of the area, and the March 1960 event had the heaviest distribution of snow from Boston to points west, covering much of eastern central Massachusetts.

The January 1978 case separates itself from the other blockbuster cases in that it had the largest distribution of snowfall, covering all of Southern New England. Southern New England had a wide swath of 15-20 inches of snow, with 20-25 inches confined to northeast Massachusetts. The January 1978 surface low track distinguishes itself from the other tracks in that it traveled northeast up the coast, not following an eastward track when it reaches just south of New England like the other cases. This potentially gives an explanation to why the snowfall was evenly distributed. The February 1978, March/April 1997, and January 2005 events all followed an eastward progression initiating slightly west of the February 1969 and February 2003 cases. The February 1978 and March/April 1997 events both had higher amounts of accumulated snow farther west of Boston than
the March 1960 and February 2003 cases. The farther west track of the surface low might be an indication as to why this occurred. However the March 1960 case which also progressed eastward, but at a farther east initial position included a 20-25 inch snow accumulation covering much of central eastern Massachusetts. Not only the track of the surface low, but duration of accumulating snow should also be considered when trying to decipher the differences between each case.

Four of the seven major cases follow a pattern of heaviest snowfall decreasing from northwest to southeast, with some areas receiving no snowfall on Cape Cod and others minimal snow in the 5-10 inch range. The December 1981 case saw a maximum distribution of snow covering much of eastern New England, with a localized maximum over eastern Rhode Island. The 1981 case moved up the coast and retrograded westward. This explains why eastern areas of New England had maximum snowfall amounts. The January 1999 case had a maximum snowfall from Boston points southeast, to include the South Shore. The March 1993 and March 2007 storms were examples of surface tracks that either went west of Boston or just to the southeast. Mid-levels warmed up enough for a changeover to occur in these cases which explains the distribution of heaviest snowfall. However the January 1999 case tracked west of Boston but had its heaviest distribution right over Boston and points southeast. However, much of Connecticut, Rhode Island, and the Cape and Islands saw the smallest accumulation from that particular storm. The March 2004 event saw a widely distributed area of 5-10 inches of snow, with Cape Cod, southwest Rhode Island, and much of eastern Connecticut only receiving 0-5 inches. The April 1981 and March 2001 events followed the blockbuster recognized signature of
eastward progression and saw heavy snowfall amounts from Boston to points north and west, with heaviest amounts northwest of the Boston area. Perhaps these cases were late occurring snowstorms which had less cold air to work with than the blockbuster cases, occurring in earlier winter months.

Figure 4 represent the duration of accumulating snowfall (onset of precipitation until the observation site no longer measures quantitative snow type precipitation). There is no clear pattern in the blockbuster cases to link duration of snowfall with snowfall accumulation since Boston had the shortest duration of snowfall with the largest accumulation (February 2003). Four of the five eastwardly progressing storms had a longer duration than the northeastward track case (January 1978). The two storms that were farthest west (before eastward progression) also had long durations. Four of the five cases that had maximum snowfall accumulation covering central eastern Massachusetts, were also the top four duration events. Subtle patterns are evident in the blockbuster cases but no rule of thumb is apparent for the entire storm category. Major storms all follow a pattern in which the duration of snowfall usually matches accumulation. The longer it was snowing, the higher snow accumulation for Boston. A slight exception is the equal snow duration of December 1981 and March 2001 where more snow fell in the former than the latter. Beyond the snowfall duration versus accumulation there are no other patterns with storm track that can be inferred for Major storm type.
Figure 4. The duration of accumulating snowfall for Blockbuster and Major snowstorms.
In terms of an average composite of the Blockbuster and Major cases Blockbuster storms on average had a snowfall duration of 40.7 hours, while the Major cases had a snowfall duration of 29.1 hours. The result however is biased by the single 93 hour blockbuster storm in 1969 and otherwise durations are similarly around 30 hours.

Figure 6 breaks the accumulating snow average composites into three hourly measurable precipitation (water equivalent). The blockbuster storms had higher precipitation amount in every interval except the 3-6 hour interval and the 36-39 hour interval, though the 36-39 interval was minimal in general. During the 9-30 hour intervals the blockbuster storms received nearly double the amount of precipitation than the major cases received. This suggests that the bulk of the precipitation was heavier for blockbuster storms than major storms which contributed to higher snowfall totals. The recipe for larger snow accumulation is a product of snowfall duration and intensity of the precipitation. Blockbuster storms as seen in the average composite of those cases had both heavier precipitation and a longer duration of accumulating snow.
Figure 5. The quantitative precipitation composite average of 3-hourly precipitation for Blockbuster and Major snowstorms.
b. Composite time sequences of snowstorm development and evolution

Figure 6 depict surface and upper-level composites for both storm types at twenty-four hours prior to snow onset. A ridge of high pressure dominates the northern Plains states up through south central Canada in Blockbuster and Major cases. The surface anticyclone was around 1032 hPa, whereas the major cases had a weaker 1028 hPa anticyclone with a weaker ridge in the pressure field. The eastern Gulf of Mexico showed signs of cyclone development, via a weak 1016 hPa pressure field in the blockbuster cases but this was more diffuse in major cases. Blockbuster storms had a 500 hPa ridge in the western U.S., while the ridge in major cases was farther west. The trough in the central U.S. was deeper in blockbuster cases. A confluent flow also was evident where the height contours converged over southeast Canada and New England at 700, 500, and 250 hPa. Major cases had a zonal pattern covering the eastern continental U.S., with a 522 dm vortex in southeast Canada. In blockbuster cases a positively tilted trough axis initiated on a line from Illinois to northern Louisiana. A vorticity maximum covered the mid western states in Blockbuster cases and none was found in Major cases. There was a positive vorticity maximum in Major cases located in eastern Canada but this did not play a role in the Boston precipitation.

Much of New England and southeast Canada had positive 700 hPa omega Blockbuster values reflecting descending air under the anticyclone. Negative omega values are positioned over the southeast U.S. and moved northeastward at eighteen hours.
Major cases had positive omega values (sinking air) over the northern Great Lakes states and south-central Canada. There were also weak negative omega values in the southeast U.S. Both storm types had little evident jet streak activity favorable for east coast cyclone development at this time. The 250 hPa trough is further east from Illinois to the Gulf States in Blockbuster cases and through the Plains states in Major cases.

The 850 hPa pattern follows the 700 hPa and 500 hPa level in which the Blockbuster cases have a more defined trough in the eastern U.S. than seen in Major cases. However Major cases have a more defined trough at the 850 hPa level. The vortex in southeast Canada at 700 hPa is also seen at 850 hPa in major cases. The confluent flow over New England is also evident in the Blockbuster cases. Cold air advection is occurring over the northeastern U.S. in Blockbuster cases as noted by the wind blowing perpendicular to the isotherms (from cold to warm). The cold 850 hPa air is more expansive over southeast Canada in major cases than in Blockbuster cases. However cold air advection is not evident over New England twenty-four hours prior to snow in Major cases. Warm air advection is occurring over the southeastern United States in Blockbuster cases, suggesting that this thermal boundary/advection is fueling the development of the surface cyclone. Warm air advection is also occurring in major cases over the southeast U.S. but to a lesser extent than Blockbuster cases. Major cases were more humid than Blockbuster cases. The concentration of the highest specific 850 hPa humidity was in the southeastern U.S. covering the Gulf Of Mexico. The expanse of the higher specific humidity extended farther west in Major cases than in Blockbuster cases.
Figure 6. T-24 hours Boston snowfall onset for Blockbuster and Major cases. From left to right: Sea Pressure (SLP), 500 hPa geopotential height, 500 hPa relative vorticity, 700 hPa geopotential height, 700 hPa Omega, and 250 hPa geopotential height and wind, 850 hPa geopotential height, 850 hPa Temperature and winds, and 850 hPa specific humidity: A Blockbuster, B Major
Figure 6 Continued
Figure 6 continued
Figure 6 Continued
Figure 7 depicts the surface and upper-level composites for both storm types at eighteen hours prior to snow onset. In Blockbuster cases the high pressure ridge dominates the central U.S., extending into the northeast, while the weak surface cyclone has moved over the southeastern U.S. In major cases the anticyclone ridge is less well developed and covers much of the northern U.S. while the weak surface forming over the southeast has an appearance similar to that in Blockbuster cases at T-24 (Fig. 7A). The weak cyclone is now over the Gulf States. In Blockbuster cases at 500 hPa the central U.S. trough amplifies, with a more pronounced confluent flow over northern New England. In major cases the overall flow was zonal with signs of a weak trough that developed over northern Great Plains. The relative vorticity field intensified over the Great Lakes states in blockbuster cases and developed a weak vorticity maximum over the south-central U.S. in major cases. Warm air advection increased along the eastern seaboard to include up to southern New Jersey in Blockbuster cases. Warm air advection continued to be much weaker in Major cases. Cold air advection had increased over New England in Major cases and had continued in Blockbuster cases. 700 hPa rising air is now covering the southeast and reaching the coastal Atlantic in Blockbuster cases.
Figure 7. Same as Fig 6 but for T-18: A Blockbuster, B Major.
Figure 7 continued
Figure 7 continued
Figure 7 continued
Figures 8 and 9 depict the surface and upper-level composites for both storm types covering twelve and six hours prior to snow onset. The blockbuster and major cases surface anticyclone covered a wide spatial area extending from Texas northward through southern Canada spreading eastward into southeastern Canada and New England. This helps spread cold air over New England as is evident on the 850 hPa temperature chart. In both cases cold air advection around the eastern side of the anticyclone might be inferred to occur into the northeastern states. A wide area of weak low pressure covered the southeastern U.S., with a 1008 hPa center developing off the North Carolina coast six hours prior to onset of snow (Fig. 9A). A weak 1016 hPa Major cases low occurs in the Gulf States and southeastern portion of the U.S.

The blockbuster upper air trough continued to amplify over the Ohio Valley, with the trough axis extending from western Michigan to Louisiana, closing one isohype at 700 hPa at T-6 (Fig. 9A). The major cases also showed subtle signs of developing a weak ridge-trough pattern that tilted to the west with height (twelve to six hours prior) extending from the western U.S to the central U.S. The main difference between the two cases were (1) the upper trough developed much earlier in blockbuster cases than major cases and (2) the trough was more amplified in blockbuster cases. Upper level support (divergence east of the trough axis) is nearly reaching the Boston area in Blockbuster cases by six hours prior to snowfall, whereas upper-level support is much farther west in major cases. This is further reflected in the Blockbuster cases vorticity maximum over Lake Erie at twelve hours that moves to central New York State at six hours prior to onset. The vorticity maximum intensifies from 2.0 x10^{-5}s^{-1} at twelve hours and 3.0x10^{-5}s^{-1}
at six hours. At twelve hours prior to onset in Major cases less well defined a swath of positive vorticity was evident over southeastern/south-central Canada at six hours prior to onset. An area of 700 hPa rising air (omega) moves along the east coast at T-12 and over the ocean south of Boston at T-6 in Blockbuster cases. In Major cases such rising air is still further west. Positive omega values (sinking air) center over southeast Canada and northern New England in Major cases, representing the anticyclone position over southeast Canada that plays a role in supplying cold air to the northeast U.S.

A jet streak of 55 m/s was positioned in Blockbuster cases over central Mississippi and Alabama at twelve hours prior to onset and narrowly covered the central Alabama/Georgia border (60 m/s) six hours prior to onset. The surface cyclone was developing in Blockbuster cases in the southeast U.S. at twelve hours prior and off the Carolina coast at six hours prior, placing the developing surface low in the left exit region of the jet streak which favorably provides upper level divergence. This is also the area of maximum 700 hPa rising air on the omega panels. The jet streak in the blockbuster case during this time period played a direct role in cyclone development. A more poorly defined jet streak occur during this time period in Major cases along the east coast, but a local weakly organized maximum was located in the northeastern U.S. at 50 m/s by T-6. The Major case cyclone did not close off surface isobars until onset of precipitation, suggesting that placement of the jet streak aloft played a major role in development of the cyclone in blockbuster cases, but not in Major cases.

From twelve hours to six hours prior to onset the 850 hPa upper-level low in Blockbuster cases moves from central Ohio to northern Virginia and the confluent flow
lifts out of New England. In Major cases the upper-level 850 hPa low develops a closed isohypse over the Ohio Valley at six hours prior to onset of snow. The upper-level low in Major cases developed in the same location as Blockbuster cases, but twelve hours slower. From twelve hours to six hours prior to snowfall onset the Blockbuster cases warm air advection occurs up the eastern seaboard to just south of New England. There were also signs of weak cold air advection over northern New England at both twelve and six hours prior to onset, suggesting cold air damming provided the low-level cold air necessary for the precipitation to remain as snow. In Major cases warm air advection only developed at six hours prior to snow onset over the southeastern U.S. coastal plain. Cold air advection had intensified over the northeast U.S. at both twelve and six hours to onset of snow in major cases. From twelve to six hours prior to onset the expanse of humid air moves northeastward in both cases but shrinks in intensity by six hours prior. The Major cases had 8.0 g/kg area of specific humidity covering much of the southeast U.S. at twelve hours prior, but this was reduced to 6.0 g/kg at six hours prior. The Blockbuster cases had around 7.0 g/kg maximum specific humidity at twelve hours prior over the southeast U.S., which moved eastward and shrunk to 4.0 g/kg at six hours prior. At six hours prior to onset Blockbuster cases also had dry air positioned in the Gulf Of Mexico, whereas the Gulf of Mexico provided a conveyor of moisture northeastward in Major cases.
A Continued

Figure 8. Same as Fig 6 but for T-12: A Blockbuster, B Major.
Figure 8 continued
Figure 8 Continued
Figure 9. Same as Fig 6 but for T-6: A Blockbuster, B Major.
Figure 9 Continued
Figure 9 continued
Figure 9 continued
Figures 10 and 11 depict surface and upper-level composites for both storm types covering snow onset and six hours after. Snow onset marks the peak intensity of the surface ridge of high pressure in blockbuster cases. The east coast storm intensifies to 1008 hPa off the Mid-Atlantic coast and then to 1004 hPa six hours later while moving slightly east-northeast of the onset position. The developing Major southeastern U.S. cyclone at snow onset is farther southwest than in blockbuster cases and slightly weaker, positioned over North Carolina with pressure of 1008 hPa at T+6. The main differences between the two cases seen so far are (1) the blockbuster cyclone developed sooner, (2) the blockbuster high pressure ridge was initially stronger and covered a wider area, and (3) major case storms developed further west or southwest than blockbuster cases.

From onset of snowfall to six hours after, the 500 hPa trough in Major cases approaches the Appalachians and continues to amplify. Six hours after onset the trough axis develops a negative tilt. In Major cases the ridge-trough system amplifies during the same time frame, with the trough axis still well west of the blockbuster axis, extending roughly from Indiana to Alabama at 6 hours after. Earlier development in blockbuster cases is linked to various forms of upper-level support arranging simultaneously to support surface pressure falls that produce surface pressure falls. For example, during snowfall onset the vorticity maximum centers over southeastern New York in Blockbuster cases and moves to western Massachusetts at 6 hours after onset and it agrees well with the expected divergence ahead of the 500 hPa trough. The Blockbuster trough axis remains neutrally oriented but diffluence occurs in isohypses over Boston. The closing off of the 700 hPa height contours or the upper-level low to the northwest of the
surface cyclone in blockbuster cases begins the process of slowing the progression of the surface cyclone. Major cases develop a strong 500 hPa vorticity maximum just northeast of Michigan at onset which extended southeastward into New York State 6 hours later associated with the upper level trough axis. The 500 and 700 hPa trough amplified and took on a negative tilt six hours after onset of snowfall, extending from Ohio to Florida. The trough orientation helps explain the surface cyclone position just to its east along the coast and helps direct the cyclone to a more northerly component to its track by 6 hours afterwards. At onset of Blockbuster snowfall, the center of the maximum 700 hPa vertical motion moves southeast of Cape Cod with most of southeastern New England under negative omega values. At six hours however the maximum is much farther southeast over the Atlantic. The vertical motion maxima is in keeping with the divergence and positive vorticity advection east of the upper level troughs and with the PVA over the exit region of the 250 hPa jet streak. From onset to six hours after snowfall the jet streak center intensifies (60 m/s) and slowly moves from Alabama/Georgia (increases coverage area from six hours prior) to southern Georgia and southeast South Carolina. The omega minimum in major cases moves to a position around New Jersey at onset and progresses slightly northeast 6 hours later. The negative omega values (rising air) pattern was distinctly west of that in Blockbuster cases. The cyclone was in the southeastern portion of this 250 hPa wind speed maximum over the southeastern U.S. suggesting that it was located in the right entrance region of the jet streak which is also favorable for divergent air aloft. The 250 hPa panel at 6 hours (Fig. 11) even suggests that double jet streak contribution occurs, with additional vertical motion (apparent at 700 hPa) provided by the
exit region of the jet streak over Virginia and North Carolina. The Major cyclone intensified from 1012 hPa to 1008 hPa as it moved northeastward under the wind-speed maxima.

The position of the 850 hPa upper-level low in conjunction with a northward moving surface low in Blockbuster cases suggest that the cyclone became vertically stacked in the lower troposphere, especially by 6 hours after onset. This slows its progress relative to the upper-level flow, inducing an eastward drift south of New England found in 6 of 7 individual blockbuster cases. The isotherms have an "S" signature along the east coast in Blockbuster cases suggesting strong warm air advection ahead of the cyclone and with subfreezing 850 hPa air over Boston. These factors help in the development and strengthening of the cyclone and are part of the "self-development" process. In major cases warm air advection had intensified up the east coast during this time frame and the isotherms begin to take an orientation similar to that found 6 hours prior to snow in Blockbuster cases. This suggests that the advection patterns in Major cases were about 12 hours slower than the patterns found in Blockbuster cases. Slower Major case development explains the delayed vertically stacking of the low, permitting continual northeastward motion instead of stalling south of New England. The 850 hPa confluent stretching in the wind field (at onset) over the Atlantic southeast of Massachusetts suggest that an east-west oriented frontal boundary lay south of Boston, providing further advection over cold air over that area. The moisture profile between differed between storms; Blockbuster cases were much drier overall up the eastern seaboard with an area of peak moisture content (3.0 g/kg) extending northwest up the
central Atlantic coast at six hours after onset. Major cases had a higher moisture content extending up the east coast (6.0g/kg) originating from the Gulf of Mexico.
Figure 10. Same as Fig 6 but for T-0: A Blockbuster, B Major.
Figure 10 continued
Figure 10 continued
Figure 10 continued
Figure 11. Same as Fig 6 but for T+6: A Blockbuster, B Major.
Figure 11 continued
Figure 11 Continued
Figure 11 continued
Figures 12 and 13 depict surface and upper-level composites for both storm types covering 12 and 18 hours after snow onset. From twelve hours to eighteen hours the Blockbuster cases cyclone moved from a position a few hundred miles south of Nantucket to a similar distance just south-southeast of Cape Cod, moving slightly east-northeast but lingering just south of 40°N. The blockbuster cyclone maintained a minimum pressure of 1000 hPa. In major cases the 1004 hPa low centered just off the Virginia coast, developed more rapidly to a pressure of 996 hPa and moved to a closer position (than in Blockbuster cases) southeast of Cape Cod. The major case storm position to just west of the blockbuster case and had a more northerly track component over the period.

Twelve to eighteen hours after snowfall onset the Blockbuster cases trough axis had a clearly defined negatively tilted axis. At eighteen hours the upper level trough closed off over southeastern New York State up to the 500 hPa level. The closing off of the 500 hPa height contours in the blockbuster cases suggest that the cyclone was becoming vertically stacked with the upper-level low and caused the eastward storm motion to stall out. This provided an explanation to the eastward storm track pattern found in six of the seven blockbuster cases. Major cases had a neutral tilted trough axis extending from the Great Lakes region at twelve hours and became more amplified and changed to a negative tilt over the Appalachian region at eighteen hours. The negatively tilted trough has amplified and approached the east coast at this time. In contrast, in Major cases the negative tilted trough intensified and closed off west of Boston at
eighteen hours. The main difference between the two cases was that the upper-level low in blockbuster cases was positioned to the southeast of Boston. The upper-level low in blockbuster cases was almost vertically above the surface cyclone lying just to its northwest. The vertical stacking of the cyclone would slow the progression further and help enhance snowfall over southeast New England. The vorticity maximum in Blockbuster cases was centered over outer Cape Cod at twelve hours and east-northeast of Boston at eighteen hours. The Major cases vorticity maximum was centered over southeast Canada at twelve hours after onset and directly over eastern Massachusetts at eighteen hours. The maximum in 700 hPa vertical motions was just to its east at both times. The vorticity pathway in the composites up to eighteen hours had an eastward progression in Blockbuster cases and a northwest to southeast progression in the Major cases. Weak rising air is over Boston but the center of rising air moved well east and south of Boston in Blockbuster cases. The surface cyclone maintained a minimum pressure of 1000 hPa and was no longer intensifying. The distribution of rising air in Major cases remains uniform in shape and moves northeast along the coast from just south of Long Island at twelve hours to east-northeast of Boston at eighteen hours. The jet streak in blockbuster cases intensified and moves from the South Carolina Coast to just offshore and maintained its coverage area with a 60 m/s wind peak. Its eastward motion is in keeping with the vorticity max and omega maxima motions. The jet streak was well to the southeast of the surface cyclone suggesting that the diverging air associated with them was no longer influencing the development of the cyclone. The southern Major cases jet streak became more organized and strengthened to 45 m/s just
off the southeastern U.S. coast. Its PVA area, and that of the jet streak farther northeast, coincides with the 700 hPa upward motion maxima. The main difference in the 250 hPa field seen so far is (1) the left exit region of the jet streak plays an integral role in the development of Blockbuster cyclones as well as in some subsequent motion east by providing the necessary upper-level divergence and, (2) the cyclone develops later in major cases as a result of having late developing double jet streaks that dynamically interact.

The center of the 850 hPa low in Blockbuster cases remained to the southeast of Boston and none of the 7 cases included a changeover from snow to ice or rain. The 850 hPa cyclone intensification in Blockbuster cases deepens the temperature trough and easterly 850 hPa flow off the Atlantic advects warm moist air over Boston at 12 hours. This begins to weaken by 18 hours and cold air advection is beginning. The maximum moisture content covered eastern New England in both storm types at eighteen hours after onset. In contrast, Major cases continue under warm air advection up the east coast into New England. The thermal pattern was also much warmer in Major cases where the 0°C isotherm had moved from just south of Nantucket at twelve hours to directly over Cape Cod at eighteen hours. This advection of mid-level warm air explains why some of the Major cases included a changeover to ice and rain. At the same time the 0°C isotherm was several hundred miles to the southeast of New England in Blockbuster cases. The thermal patterns along the east coast in Major cases also exhibited a later development than Blockbuster cases. Major cases continued to be moister than Blockbuster cases.
Figure 12. Same as Fig 6 but for T+12: A Blockbuster, B Major.
Figure 12 continued
Figure 12 continued
Figure 12 continued
Figure 13. Same as Fig 6 but for T+18: A Blockbuster, B Major.

A Continued
Figure 13 continued
Figure 13 continued
Figures 14 and 15 depict surface and upper-level composites for both storm types covering twenty-four and thirty hours after snow onset. The Blockbuster cases cyclone stalled and maintained a position east-southeast of Cape Cod with the pressure slightly deepening from 1000 hPa to 996 hPa. Support for the pressure fall may have been continuing upward motion of 700 hPa. Overall, Blockbuster case had a closed low up to 500 hPa and was vertically stacked over southeast New England (i.e. Boston) extending just south and southeast of Cape Cod. The three-hourly precipitation amounts for blockbuster cases were nearly double the amount of major cases during this time frame. This suggests that heavier snow occurs when the upper-level low is positioned to the south and east of Boston in a vertically stacked system. The major case cyclone continued to slowly progress northeastward moving from just southeast of Cape Cod to the Gulf of Maine six hours later. The minimum pressure also deepened from 996 hPa to 992 hPa. The main differences seen between the two cases are (1) the Major storm cyclone continued moving northeastward passing north of Boston's latitude and (2) the Major cases had a lower cyclone pressure than the Blockbuster cases. The upward 700 hPa motions maximum also migrated northeast of Boston. These differences suggest that once the cyclone passed north of Boston's latitude the accumulating snowfall ceased. The accumulating snow composite ended at 29.1 hours for Major cases, but continued to 40.7 hours for the Blockbuster cases. The major cases negatively tilted trough became more amplified and approached the east coast during this time frame and may have provided support for the northward moving vertical motion maximum. The blockbuster jet streak is moving over the Atlantic, supporting the eastward drift of the surface cyclone over its
divergence area. The surface cyclone in Major cases moved from just southeast off the
New England coast to the Gulf of Maine, encouraged also by 250 hPa isohypse difluence
over this area. The trough at 250 hPa became more amplified in major cases and the jet
stream guided the surface cyclone on a more northerly track than Blockbuster cases.

The 850 hPa upper-level Blockbuster low remains to the southeast of Nantucket at
24 hours and east-southeast of Boston at 30 hours with cold air advection over Boston.
In contrast, the upper-level Major low moved from a position directly over southeast
Massachusetts to north of Boston's latitude in southeast Maine at thirty hours. The upper-
level low was also stronger in Major cases at both times suggesting that once the 850 hPa
low moved beyond Boston's latitude the snowfall would cease, as found in the composite
reports. Boston was much colder in Blockbuster cases, -6°C at 24 hours while the 0°C
isotherm was just east of Boston in Major cases. The warmer profile provides evidence as
to why a rain and/or ice changeover occurs in Major cases. The temperature gradient was
stronger in Major cases, running from north to south over eastern New England, whereas
Blockbuster cases had a cold pool of air covering the northeast U.S. At thirty-hours
Boston becomes colder in both Blockbuster and Major cases from six hours earlier. This
suggests that a northeast flow in relation to 850 hPa was necessary for snow to continue
for an extended time frame, as was seen in blockbuster cases from twelve to thirty hours
after onset of snow. Once the upper-level low had passed Boston's latitude the northeast
flow had ceased as well as the accumulating snow. Moisture in Blockbuster cases moves
northeast of Boston and into the Gulf of Maine. Major cases moisture content shrank in
size but moderately high moisture content continued extending over New England.
Figure 14. Same as Fig 6 but for T+24: A Blockbuster, B Major.
Figure 14 continued
Figure 14 continued
Figure 14 continued
Figure 15. Same as Fig 6 but for T+30: A Blockbuster, B Major.
Figure 15 continued

850 hPa Geopotential Height

850 hPa Temperature and Wind

850 hPa Specific Humidity [g/kg]
Figure 15 continued
Figure 15 continued
Figures 16, 17, and 18 depict surface and upper-level composites for both storm types covering 36 through 48 hours after snow onset. From T+36 to T+48 hours the blockbuster cyclone slowly drifts eastward east-southeast of Boston while the major case cyclone continues to move northeastward into Nova Scotia. A minimum pressure of 1000 hPa and 996 hPa is maintained for each, respectively. High pressure dominates much of the central-eastern U.S. in both cases. The Blockbuster cyclone maintained a position at or just south of Boston's latitude and accumulates snowfall until 40.7 hours after onset. It was no longer snowing for Major cases by this time.

The Blockbuster 700 and 500 hPa closed low lifted northward, weakened and the flow becomes northwesterly. The negatively tilted trough crossed New England and lifted northeast of Boston during this time frame. The major cases are characterized by a persistent negatively tilted upper level trough over the area which helps maintain the surface cyclone on a track along and up the coast. Pronounced northwesterly flow is not evident in these cases until 42 or 48 hours. The upper-level low was closed at 500 hPa in blockbuster cases but began to weaken in the final hours, while the trough remains negative tilted and intense through forty-eight hours in major cases. This suggests that a vertically stacked cyclone will provide a longer duration of accumulating snow than a cyclone that is negatively tilted. Even though the vertically stacked Blockbuster cyclone had weakened by T+30, accumulating snowfall persisted longer than the negative tilted flow in major cases. The 500 hPa vorticity maximum continues moving northeast for both cases. The core of rising air 700 hPa air has departed Boston by T+36 and the snowfall stops shortly thereafter. Major cases had relatively higher positive vorticity near
Boston during this time frame, but the precipitation had shut off sooner. Rising air had long departed the Boston area. The distribution of descending air took on a northwest to southeast pattern in Blockbuster cases (over the mid-Atlantic States) and a northeast to southwest pattern in Major cases. Sinking air can be associated with dry air and developing fair weather. The Blockbuster 250 hPa height pattern became zonal with weak wind speed maxima off the southeast U.S. coast.

Major cases had a more amplified negatively tilted trough and the jet streak a few hundred miles east of the North Carolina rapidly moved northeastward. The greater amplification and negative tilt of the Major cases isohypses supported the cyclone with divergence and difluence as it moved toward the Maine coast. Divergence and jet streak support in blockbuster cases in contrast migrated slowly off the east coast over the Atlantic. The surface low never made it north of 40° N latitude until T+42. The 850 hPa Blockbuster upper-level low lifted northeast, with a northwest flow developing at T+48. In contrast, Major cases upper-level low stalled out over eastern Maine during the final twelve hours. Slower development of the Major surface cyclone and upper-level low suggests why Boston did not experience Blockbuster-like snowfalls. Major case cyclones became vertically stacked later while northeast of Boston, providing instead "Blockbuster-like" snowfall accumulations over Maine and not Boston.

From 36 to 48 hours after onset cold air advection at 850 hPa takes over in both Blockbuster and Major cases. Major cases have much colder air move over Boston by T+48. Blockbuster and Major cases moisture content diminished in scope and size. Major cases had a higher moisture content at thirty-six hours than Blockbuster cases (as was
seen throughout each storm types development). As precipitation shut off in both cases so did the moisture content, as would be expected.
Figure 16. Same as Fig 6 but for T+36: A Blockbuster, B Major.
Figure 16 continued
Figure 16 continued
Figure 16 continued
Figure 17. Same as Fig 6 but for T+42: A Blockbuster, B Major.
Figure 17 continued

850 hPa Temperature and Wind

850 hPa Specific Humidity [g/kg]

A Continued
Figure 17 continued
Figure 17 continued
Figure 18. Same as Fig 6 but for T+48: A Blockbuster, B Major.

A Continued
Figure 18 continued
Figure 18 continued
Figure 18 continued
CHAPTER 5: DISCUSSION AND CONCLUSIONS

As discussed in Chapter 2, Brandes and Spar (1971) was the only study that attempted to define heavy snow along the east coast using a composite method. A similar conclusion to their findings in regard to the 850 hPa field was also found for Blockbuster cases. Brandes and Spar found that at T-0 (or snow onset), there tended to be a 850 hPa low center, a pool of high humidity spreading to the coast, and temperatures 0° to -5° C in the coastal plain of heavy snow. Blockbuster cases at T-0 had a 850 hPa low center over southeast New Jersey, -6° to + 4°C temperatures spread over the coastal plain, and specific humidity of 4-6 g/kg (Fig. 10). Major cases did not show the same pattern. Major cases had an 850 hPa low center located over the Ohio Valley and a temperature spread of -6° to 6° C but the temperature gradient did not follow the coastal plain. However, Major cases did have a larger defined pool of specific humidity of 5-7 g/kg spreading up the coast from the Gulf of Mexico to New England.

Bosart et al (1972) and Kocin & Uccellini (2004) discussed how enhancement of the baroclinic zone along the coast or "coastal frontogenesis" was a common signature in east coast snowstorms. Bosart and Bell (1989) described how an anticyclone north of the approaching cyclone acts as a positive feedback mechanism in that it enhances low level thermal fields by supplying cold air advection at the surface. An anticyclone was found in both Blockbuster and Major cases in southeastern Canada prior to snow onset. Sinking
700 hPa vertical motions was found underneath the anticyclone, T-24 through T-18 hours in Blockbuster cases (Fig 6-7) and T-12 though T+12 in Major cases (Fig. 8-12). A common characteristic of cold air damming is an inverted high pressure ridge extending southward along the coastal plain. Blockbuster cases showed subtle signs of a high pressure ridge extending southward along the coast at T-24 through T-12 hours (Fig. 6 through 8). 850 hPa cold air advection was also found over New England in Blockbuster cases T-24 through T-6 (Fig 6 through 9). Major cases did not have a high pressure ridge extending southward but did have cold air advection patterns in New England from T-12 to T+6 hours. This study also shows similar findings of the "S" pattern found along the coast that represented coastal frontogenesis. In Blockbuster cases the "S" pattern was subtle at T-6 (Fig 9) but became stronger at T-0 continuing through T+18 hours (Fig 10 through 13). Major cases did not show the "S" pattern till T+6 lasting through T+30 hours (Fig 11 through 15). Kocin and Uccelini (2004) discussed the development of a low level jet that helped transport moisture into the area of heaviest snow, as well as increase the baroclinicity along the coast, via warm air advection. The grid scale is rather coarse to be able to locate such a low level jet but in Blockbuster cases at T+18 through T+24 hours there are signs that suggest a low level jet formed southeast of New England. 700 hPa omega showed a pool of rising air extending from New England to southeast of Cape Cod (northwest to southeast). The 850 hPa specific humidity also showed a pattern similar to that of omega that suggests that warm moist air was being advected into the area of heaviest snow (Figs. 13 and 14).
One of the patterns that Kocin and Uccellini (2004) found in their examination of 30 Northeast snowstorms was an increase in amplitude and decreasing half-wavelength between the trough and downstream ridge during cyclogenesis, as well as an increase in diffluence downstream of the trough axis. These features would enhance upper-level divergence and provide a favorable environment for cyclogenesis. The evolution of the upper-level trough in both Blockbuster and Major cases (850 hPa through 250 hPa) also followed a similar pattern. The difference between the two cases was that the Blockbuster case trough amplified sooner than Major cases. Major cases also took on a negative tilt at T+18 hours (Fig. 13) which enhanced diffluence east of the trough axis. The earlier development of the ridge-trough amplification in Blockbuster cases also resulted in a surface cyclone developing sooner suggesting how important upper-level divergence and diffluence are in east coast cyclogenesis.

Palmen and Newton (1969) and Roebber (1993) discussed the three initial ingredients necessary for east coast cyclogenesis: (1) an upper level-trough and/or jet streak; (2) a low-level baroclinic zone; and (3) a pre-existing weak surface cyclone. All three of these ingredients were met in Blockbuster cases at T-12 hours (Fig. 8). An upper-level trough, jet streak, baroclinic zone, and a weak surface cyclone were all present in the southeast U.S. that later resulted in the Blockbuster cyclogenesis. Major cases did not meet all of the ingredients initially. The jet streak influence was a combination of double jet streak dynamics from T-6 to T+6 hours (Figs. 9-11) and the baroclinic zone did not intensify till T+0 hours (Fig. 10). The later production of these components also suggests why the cyclone developed later than Blockbuster cases.
Blockbuster cases had more snowfall accumulation (19.8 to 27.5 inches) than Major cases (8.1 to 13.3 inches of snow). The individual cases within the Blockbuster group had less track variability than the Major group. All seven of the Blockbuster group surface cyclone passed southeast of New England with six of the seven cases exhibiting an eastward progressing track south of New England. Major case individual storm tracks followed two patterns of (1) just southeast or west of Boston, and (2) well south of New England. Blockbuster cases remained in the form of snow for the entire duration of the each case, while Major cases had individual cases that included a changeover to ice and/or rain. The duration of accumulating snow was also longer than Major cases. Three hourly precipitation composites also showed the Blockbuster cases had heavier measureable precipitation in the majority of time intervals. The combination of a longer duration and intensity of snowfall in Blockbuster explains why more snowfall accumulated overall.

Blockbuster cases cyclone developed more rapidly than Major cases due to upper-level support more readily available. The upper-level trough at 250, 500, 700, and 850 hPa was more amplified and located further east prior to snow onset in Blockbuster cases. Divergence east of the Blockbuster upper-level trough was greater than Major cases, which was further increased with the addition of a jet streak entering the southeast U.S. T-12 to T-6 hours prior to snow onset. At T+6 hours Blockbuster cases also had larger amounts of 500 hPa vorticity advection and 700 hPa vertical motion maxima over the exit region of the 250 hPa jet streak, further intensifying the divergence aloft.
850 hPa cold air advection was stronger initially over New England prior to snow onset in Blockbuster cases. Warm air advection also developed up the eastern seaboard more rapidly in Blockbuster cases providing an intense baroclinic zone for the surface cyclone to intensify and track northeast along. The greater initial temperature contrast along the coast also provides an explanation to why the surface cyclone developed sooner.

Blockbuster storms became vertically stacked with the upper-level low up to the 500 hPa level at T+18 hours. Major cases did not become vertically stacked to 500 hPa till T+30 hours. The vertically stacking of the cyclone southeast of New England in Blockbuster cases provided an explanation for the stalling out and eastward progression track of the surface low. The later development of a negatively tilted diffluent trough T+12 to T+30 hours in Major cases provides an explanation for a more northward track than Blockbuster cases.

The slower and more southern track found in Blockbuster cases was a product of the surface and upper-level fields supporting each other earlier in the overall development of the “Blockbuster Type” east coast snowstorm. The vertical stacking of the Blockbuster cases allowed for the cyclone to stall out and slowly progress eastward, prolonging the duration of snow. The later development of upper-level divergence/diffluence and slower developing 850 hPa baroclinic zone in major cases resulted in the “Major Type” east coast snowstorm developing later and having a more northward track hugging the coast. The northward track allowed for some of the Major cases to include a changeover and for
the snowfall duration to be shorter. The combination of these features allowed for higher snowfall accumulations for “Blockbuster Type” snowstorms affecting Boston.
CHAPTER 6: FUTURE RESEARCH

Smaller scale factors that influence the evolution and development of east coast cyclogenesis were not analyzed due to the coarse grid size of the NCEP/NCAR Reanalysis 1 model data that was used in creating composites of the Blockbuster and Major composites. Future research could focus on the lower troposphere thermal fields showing where coastal fronts and cold air damming was occurring. Use of NCEP North American Regional Reanalysis (NARR) with 32 kilometer resolution would better depict these thermal fields over New England. A smaller grid scale would also better represent an inverted high pressure ridge signifying cold air damming between the Appalachian Mountains and the coast. Another area that could be examined with a smaller grid scale is the sensible and latent fluxes occurring up the eastern Atlantic. It would be interesting to see if there was a difference in the mesoscale features that could not be analyzed with a global model. NARR data are only available starting in 1979 and a new Blockbuster and Major case selection method would have to be developed to cover the available data.


