Synoptic Analysis of Heavy Snowfalls over Central New England, 1996-2007

ABSTRACT

Forecasting snowfall totals for central New England can be a difficult task as slight synoptic and topographical changes can enhance or inhibit precipitation across mesoscale distances. The goal of this research project is to determine differences and similarities between the synoptic setup of storms that produce significant snowfall in Plymouth, NH, and the setup of systems that do not. Using archived climatological, METAR, and surface data, cases were selected and snowfall initialization times were utilized for NCEP/NCAR composites. The composites were split into three different sets: 44 cases where one of three selected sites (Plymouth NH, Concord NH, St. Johnsbury VT) received more than the local NWS-defined winter storm warning criteria of 7 or more inches of snowfall, of which 25 cases where Plymouth received warning criteria, and 19 cases where Plymouth received less than the warning criteria. Subjective analysis shows that while there are multiple similarities, subtle differences can be the deciding factor in whether Plymouth does or does not receive substantial snowfall.

1. Introduction and Objectives

Forecasting snowfall in central New England can be a difficult task. Slight synoptic changes and topographic influences can cause large variations in snowfall amount from location to location. There have been many cases in recent times where the town of Plymouth, New Hampshire receives little or no snowfall, while the surrounding areas in central New England receive enough snow to shut down schools and businesses. This can become troublesome for not only the forecasters for the region, but also members of the community who prepare for large snowfall totals and see results much different than what was forecast.

This research project concerns itself with the synoptic differences between cases where Plymouth receives significant snowfall and cases where little or no snowfall was recorded while area cities received significant accumulations. We will discover that slight changes in flow direction, low and mid-level temperature advection and cyclone track can produce a storm with either heavy or light snowfall for Plymouth, NH. The primary objective of this study is to determine whether or not simple pattern recognition schemes can be utilized to forecast snowfall totals in Plymouth, NH, and whether accumulations will be less than surrounding locations.

2. Data and Methodology

Using F6 monthly climatological data during the winter seasons of 1996 through 2007 from Plymouth NH, Concord NH and St. Johnsbury VT, events were defined as when any one of the three cities received seven or more inches of snow during a single storm. Surface analyses were then analyzed to determine classify storm type and evolution. For example, it was prudent to discover whether the storm underwent coastal redevelopment or traversed the country from the lee of the Rockies. Cases where multiple storms over a few days generated seven inches were eliminated to maintain the initial goal of analyzing single storm snowfall totals. Through this analysis, it should be noted that most of the cases used in this study were storms that underwent some form of coastal redevelopment.

In order to classify a criteria storm versus a non-criteria storm, the National Weather Service standard for a winter storm warning was utilized. This definition of a winter storm warning is classified as an area receiving seven inches or more from a single storm (NOAA 2005). Of the 44 cases, twenty-five were found to satisfy this criteria in Plymouth, while nineteen did not. These three case sets were labeled as the control, criteria and non-criteria events, respectively. Using surface maps and METAR data for each storm for each city the time of snowfall initialization was determined for each selected case. The initialization times were then implemented into the 12-hourly NCEP/NCAR Reanalysis Data and composites were created. Two grids domains were utilized: an outer grid (260-310° longitude, 25-60°N latitude) and an inner grid (275-300° longitude, 35-50°N latitude). The former is centered on the East Coast, with the latter being centered on New England. Composites were generated for data every twelve hours (T-24, T-12, T-0, T+12, T+24) of 250-hPa winds, 500-hPa heights, 700-hPa omega, 850-hPa vector winds and temperatures, sea level pressure and surface winds for all three case sets.

3. Results

a) Setup of All Events (control).

Composite analysis reveals the mean distribution of the characteristics of all storms that resulted in at least seven inches of snow at one of the three previously defined locations. These composites show that the typical storm track begins with the primary low entering the Ohio

River Valley from the southwest and then transferring its energy over the Appalachian Mountains and forms a secondary coastal storm off the mid-Atlantic coastline. Specific storm evolution at various time steps and pressure levels is defined below.

Twenty four hours prior to event onset (Fig. 1) a surface high pressure is centered over Quebec, Canada, with a surface low pressure centered in the Canadian Maritimes. Northwest flow between these systems pushes colder temperatures into the Northeast. Temperatures at 850-hPa are generally very cold at this time, with the 0°C line over northern West Virginia and Delaware. At this same time a polar jet streak is centered over the Northeastern United States, with an area of 45 ms^{-1} extending from New York State to the Gulf of Maine and as far south as Southern New Jersey. At 500-hPa, the main shortwave trough is positively tilted with the trough axis centered over northern Minnesota into Iowa. The surface low moves east into the Ohio River Valley over the next twelve hours (Fig. 2), with warm air advection occurring from south to north across the Northeast. Warm air advection at 850-hPa helps to build the ridge at 500-hPa over the Northeast and deepen the surface cyclone slightly. Even with warm air advection at 850-hPa, the temperatures across the area of interest remain cold enough to support frozen precipitation.

By the time of event onset (Fig. 3) a secondary low has developed along the East Coast, with a central pressure of 1009 hPa. Flow into the Northeast at the surface is primarily southeast as the low begins developing. 850-hPa temperatures have moderated further, with the 0°C line now located over the southern coastline of New England. The thermal pattern is amplifying rapidly, with isotherms oriented more southwest to northeast with time, indicating stronger meridional warm air advection occurring downstream and cold air advection upstream as the storm develops and the precipitation develops over central New England. The jet at 250-hPa has progressed eastward with the highest winds now centered over the Gulf of Maine. This would place the developing low pressure system in the equatorward entrance region of this jet streak. There is also a hint of a developing subtropical jet stream at 250-hPa at this time. The 500-hPa trough is now neutrally tilted and centered over the eastern Great Lakes, with mid-level heights beginning to lower across New York, western Vermont, and western Massachusetts .

Twelve hours after the event begins (Fig. 4), the surface low is centered off of Cape Cod and has deepened to a central pressure of 1001 hPa. 850-hPa temperatures have risen across all of New England, with the 0°C line oriented northeast to southwest through eastern Massachusetts, Rhode Island, and Connecticut. At 250-hPa a dual jet streak signature, involving the subtropical and polar jet streams, has developed. The low pressure system is now placed in the poleward exit and equatorward entrance regions of the jet streaks, both lending upper-level support via divergence aloft. At 500-hPa, the trough is now negatively tilted and oriented from Ontario southeastward to New York City. Mid-level heights are now falling across Vermont and Northern New Hampshire. Twenty-four hours after onset (Fig. 5), the surface low pressure system lifts out toward Nova Scotia. At 850-hPa, the Northeast is experiencing strong cold air advection with the 0°C line now well out over the Atlantic Ocean. The dual jet streak setup breaks down after twenty four hours with the polar jet weakening over the region and a subtropical jet much stronger off the Carolina coastline. The 500-hPa trough has developed a strongly negative tilt centered over the Gulf of Maine.

b) Synoptic Aspects of criteria vs. non-criteria snowfall composites.

Analysis of the evolution of these two storm sets shows significant differences as far as 24 hours prior to the event onset (Figs 6 & 7). A study of criteria and non-criteria event composites shows us many characteristics that are similar between the two storms. However, it is the subtle differences that compose this storm into a heavy snow-maker for Plymouth, NH.

At T-24 significant yet subtle differences can already be seen at several levels. In composite, the non-criteria events have a stronger shortwave at mid-levels associated with a deeper thermal trough just upstream over south-central Canada. The intense northern jet stream moving over New England is aiding the inverted surface trough over the central Mississippi Valley via divergence aloft. However in criteria events the jet stream is slightly further north, keeping the surface trough in the Mississippi Valley out of the equatorward entrance region and not enhancing upper-level divergence. The shortwave trough embedded in the northern stream is weaker with a flat thermal pattern at 850-hPa. Over New England a large storm has wrapped itself up in the Canadian Maritimes with a strong surface high pressure building in over the Northeast. The pressure gradient between these two features is much stronger in criteria cases, which has brought much colder air into New England at low levels on northwesterly flow.

Leading up to onset both criteria (Fig. 8) and non-criteria (Fig. 9) composites have some important similarities. 12 hours prior to the event a shortwave is evident near Lake Michigan with colder low-level air trailing behind. A surface cyclone is developing in the Ohio Valley and transferring its energy to a coastal low near the Carolina coast. The subtropical jet begins entering the picture at 250-hPa, while the northern jet core is bending poleward as the heights rise over the Northeast in response to increasing low-level warm advection.

The subtle differences between the two classes are what really make the criteria versus non-criteria begin to stand out. For instance, the shortwave trough over the Midwest is digging much further south in non-criteria cases. This is a result of stronger low-level cold advection flowing southeast behind the weakening primary cyclone over the Midwest and the strengthening secondary cyclone on the coast. The latter cyclone in turn is being aided by a strong northern jet and its associated divergence in its equatorward entrance region. However, the criteria composites show a much weaker and less amplified pattern, with a weaker primary and secondary cyclone, less cold advection behind the cyclone, and not quite located in the best region for upper-level divergence associated with the northern jet stream.

The surface high weakens and moves east much quicker in the non-criteria events. This lack of blocking allows the surface low to deepen and move northeast, bringing copious warm air northward toward New England. This same feature remains intact and resists movement in criteria events, forcing a more blocked pattern to develop. 500-hPa heights begin to build over the Northeast in both situations leading up to event onset due to the warm advection at lower levels. In non-criteria events the shortwave trough deepens further, becoming neutrally-tilted due to intense cold advection behind the rapidly intensifying cyclone. The jet stream strengthens slightly as well, with rapid parcel accelerations heading into the jet streak from the southeast likely enhancing divergence aloft. The jet in criteria cases begins to place the surface low beneath the equatorward entrance region only in the 12 hours prior to onset, leading to a slower development of the cyclone than in non-criteria cases.

By event onset (Figs. 10 & 11) both situations are developing the secondary low pressure center rapidly near the Delmarva Peninsula in composite. The shortwave trough at 500-hPa is moving into the western Appalachian Mountains, with the non-criteria trough remaining the stronger of the two. Cold advection at 850-hPa is beginning to intensify somewhat in the criteria cases, with strong advection continuing in the non-criteria events. The surface cyclone is well-developed in non-criteria cases by onset, strengthening beneath the best area of upper divergence. Since the non-criteria storms are stronger at this point, the warm advection downstream is also stronger. The 0°C isotherm at 850-hPa has moved northward into the south coast of New England and across southeast MA. In criteria storms the advection is not as pronounced, therefore the low-level thermal pattern has not been deformed a great magnitude. The freezing line at 850-hPa is only just reaching New York City and is still south of Long Island by onset. In these storms the jet is nearing its peak intensity, with the divergence region becoming situated on top of the area of low pressure. This begins to enhance central pressure falls for criteria cyclones rapidly over the following hours.

12 hours after onset, the criteria storm (Fig. 12) is undergoing rapid intensification, deepening 7 hPa in 12 hours to a central pressure of 1001 hPa. Surface winds are blowing out of the east-northeast over central New England, which is a favorable direction for heavy snows in Plymouth NH (Fig. 18). In non-criteria events (Fig. 13) the cyclone has strengthened to its most intense (1000 hPa), with a northeast flow at low levels, which is not desirable for heavy snows in Plymouth (due to terrain blocking from the White Mountains, Fig. 18). Both scenarios have the surface cyclone in a region of dual jet streak divergence aloft, being in both the equatorward entrance and poleward exit regions simultaneously.

The low-level thermal pattern amplifies further in both scenarios, with the more extreme amplification being in the non-criteria cases with strong temperature advections both up and downstream of the cyclone center. Warm advection has pushed the 0°C 850-hPa isotherm across all of southeast New England and into southern Nova Scotia, while criteria cases observe less low-level warm advection and the 0°C isotherm only moving north across Cape Cod. This pattern is reflected in the surface temperature, with the 0°C isotherm extending from New York City through the north shore of Boston in criteria cases while the 0°C isotherm extends from

New York City towards the seacoast of New Hampshire in non-criteria cases (Fig. 14). The surface wind at this time shows the stronger low-level jet ahead of the cyclone center, implying stronger warm advection downstream of a non-criteria cyclone. The upstream shortwave trough is becoming negatively tilted at 500-hPa for criteria cases, with a deep and strongly negative shortwave in non-criteria events. The downstream ridging is pushing much further northward in criteria cases, with 500-hPa heights becoming as much as 100 meters higher than in non-criteria systems across Nova Scotia. Mid-level heights are crashing in both scenarios across the Northeast as the cyclone wraps itself up offshore.

In criteria cases the surface cyclone is tracking from the Delmarva Peninsula to a position approximately 50 miles south of Nantucket, very close to the benchmark (40°N 70°W). The benchmark is an important location, since surface cyclones that track along or just outside of the benchmark tend to keep colder temperatures locked in place at all levels, maintaining snow as the dominant precipitation type. Storms that track inside the benchmark bring a stronger southerly to southeasterly flow at low and mid levels, enhancing warm advection north of the cyclone center and bringing a mix of ice and/or rain to the region.

As the system moves away at T+24 (Figs. 15, 16) there is still a significant difference in the evolution. The surface winds in criteria cases, which had been east-northeasterly at the surface at T+12, is now due north (Fig. 17). This flow direction, while not topographically ideal for heavy snow in Plymouth, could continue transporting wrap-around moisture northwest of the cyclone across Maine and into New Hampshire. In non-criteria cases, however, cold advection at low levels behind the storm has taken over, with west-northwest winds at the surface implying downsloping and drying for the Plymouth area. These winds are not wrapping moisture around the storm, but rather are associated with descending dry air wrapping into the low pressure system from southeastern Canada. With downsloping and drying working its way in at low levels, snow production shuts off in the lee of the mountains and upslope (given enough residual moisture) will become the primary mode of precipitation formation.

The surface cyclone is reaching its most intense in criteria events by T+24 just southwest of Nova Scotia (999 hPa). The support from upper-level divergence is still present, with a strong southern jet racing out of the southwest to place the system in its poleward exit region. Shortwave energy associated with the trough's vorticity advection is slowing, as the trough axis has nearly caught up to the surface storm center. Cold advection has taken over in force across the Northeast, digging the mid-level shortwave further southeast with time. Warm advection continues across the Canadian Maritimes. In non-criteria events the cyclone is weakening slightly, with the entire system becoming vertically stacked through 250-hPa. Cold advection to the south has ceased, cutting off any further deepening of the mid-level trough. Warm advection continues across the Maritimes, with the 0°C 850-hPa isotherm pushing much further north.

4. Conclusions

This research project has found the existence of several crucial differences in storm evolution within the 24 hours surrounding event onset. Low level temperatures during cases where Plymouth receives locally-defined NWS winter storm warning criteria are generally colder over the Northeast prior to and during an event. Cyclone development also shows important differences: cases with criteria snowfall in Plymouth tend be weaker initially, deepening more rapidly and taking a track slightly outside of the benchmark (40°N 70°W). Cases where Plymouth did not receive the 7-inch criteria were stronger initially, tracking closer to the coast with warmer air ahead of the system. Isotherms at the surface as well as 850-hPa tend to be more amplified, with warmer temperatures invading New England from the southeast during non-criteria events. This may cause Plymouth to change to either a wet snow or a mix of ice and/or rain.

Low-level flow is also critical in determining snowfall for Plymouth, NH. In criteria cases the near-surface flow is easterly at event onset, where terrain blocking is minimized and no shadowing effects occur. In non-criteria events this flow tends to be northeasterly, which places Plymouth in an unfavorable location for heavy snows due to terrain blocking. Since non-criteria events deepen earlier than criteria storms, the northwesterly flow causes stronger cold advection as the cyclone moves beyond Plymouth's latitude. This, in effect, causes further terrain blocking, cutting off precipitation as Plymouth is affected by dry, downsloping flow from the Green and White Mountains. Criteria cases, however, maintain a northerly to northeasterly component, leaving Plymouth with wrap-around moisture and a chance of continuing snowfall. These differences may be sufficient to account for the higher *vs*. lower snowfall totals in Plymouth, NH.

5. References and Acknowledgements

HPC, cited 2007: Surface Analysis Archive. [available online at http://www.hpc.ncep.noaa.gov/html/sfc_archive.shtml]

Kocin, Paul J and Uccellini, Louis W, 2004: *Northeast Snowstorm: Volume I: Overview, Volume II: The Cases*. Meteorological Monograph Series, 818 pp.

NCDC, cited 2007: Unedited Local Climatological Data. [available online at http://cdo.ncdc.noaa.gov/ulcd/ULCD]

NCEP/NCAR, cited 2006: 6-Hourly Reanalysis Data Composites. [available online at http://www.cdc.noaa.gov/Composites/Hour/]

NWS Gray, Maine Climate Data, cited 2007: Monthly F6 Climate Statistics. [available online at http://www.erh.noaa.gov/er/gyx/climate_f6.shtml]

PSU Vortex, cited 2007: Product Generator for Archive Data. [available online at http://vortex.plymouth.edu]

Unisys Weather, cited 2007: Image and Map Archive. [available online at http://weather.unisys.com/archive/index.html]