A SYNOPTIC CLIMATOLOGY FOR HEAVY SNOWFALL EVENTS SPANNING THE EAST COAST MEGALOPOLIS: INSIGHTS FROM *NORTHEAST SNOWSTORMS*

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Abstract

Analysis of the historical major snowfall events for the East Coast Megalopolis (Washington D.C. through Boston) reveals an interesting pattern. While storms bringing 10 inches or more to parts of the region have involved numerous combinations of features, those bringing that much snowfall to all of the major cities in the region were remarkably similar. This paper discusses those similarities with a view towards providing forecasters and emergency managers with insights into which storm types are capable of crippling the entire East Coast Megalopolis.

Five of the six historical storms that have brought 10 inches of snow to Washington D.C., Baltimore, Philadelphia, New York City, and Boston have followed similar tracks: along the Gulf Coast and then up the Atlantic Seaboard. The sixth storm exhibited coastal redevelopment and then followed a similar track. Three of these storms remained close to the coast while three angled farther offshore after passing Cape Hatteras, North Carolina. All six cyclones caused the steady progression of an onshore 850 mb jet northeastward across the entire Megalopolis, and five of the six storms interacted with an anticyclone of the same type.

1. Introduction

Heavy snowfall in the East Coast Megalopolis of the United States can have a major economic impact on the entire nation as it disrupts industry, commerce, and transportation on a national and international scale. Mitigating these effects by rerouting shipments, etc., becomes much more difficult when the entire Megalopolis has been crippled. Thus, storms that blanket Washington D.C., Baltimore, Philadelphia, New York City, and Boston have a qualitatively different impact than those which impact only a few of those cities.

For the purposes of this study we will define a "Megalopolitan blanketing snowstorm" as one that brings 10 inches (25.4 cm) or more of accumulation to all five of these cities. The 10-inch threshold was selected both because it approximates the breakdown threshold for real time urban snow removal, and because it corresponds to the first contour level in the published snowfall analyses (Kocin and Uccellini 2004b). The Megalopolis is defined as Washington D.C., Baltimore, Philadelphia, New York City, and Boston because these five cities represent a tightly interconnected "travelshed" serving as the European portal for most of the nation.

Kocin and Uccellini (2004a,b) provide a landmark discussion of those winter storms bringing heavy snowfall to the Megalopolis during the period of 1950 through 2003. Their analysis not only provides the data for the investigation described below, but also documents the broad range of synoptic features that can contribute to East Coast heavy snowfall.

Kocin and Uccellini (2004a) were able to separate the Northeast heavy snowstorms into two cyclone classes. In the *Atlantic Coastal Redevelopment* class (Fig. 3-5 of Kocin and Uccellini 2004a), a surface cyclone tracks from the Plains (Texas through the Dakotas) into the Ohio Valley (West Virginia and western Pennsylvania) only to dissipate there and redevelop along the Southeast coast (Florida through Virginia). These cyclones subsequently track east or northeast from the Delaware region bringing heavy snowfall to part of the Megalopolis. The second class of cyclones involves no redevelopment across the Appalachians, but instead track along the Gulf and Atlantic coasts from Texas to Georgia, and then northeast to New England or its offshore waters (Fig. 3-4 of Kocin and Uccellini 2004a). These *Gulf of Mexico - Atlantic Coast* storms often remain closer to the Megalopolis than do the *Atlantic Coastal Redevelopment* storms.

The anticyclones associated with Megalopolitan heavy snowfall are even more diverse (Kocin and Uccellini 2004a). While some form of polar continental air mass is required to prevent a premature transition from snow to rain, numerous variations have been reported. The two most common patterns involve strong anticyclones moving out of the Canadian prairie provinces of Alberta and Saskatchewan. In the first pattern, the anticyclone tracks east across Ontario and Quebec, reaching a point north of the Megalopolis just as the surface cyclone passes Cape Hatteras, North Carolina (Fig. 3-12 of Kocin and Uccellini 2004a). In the second pattern, the antiey-

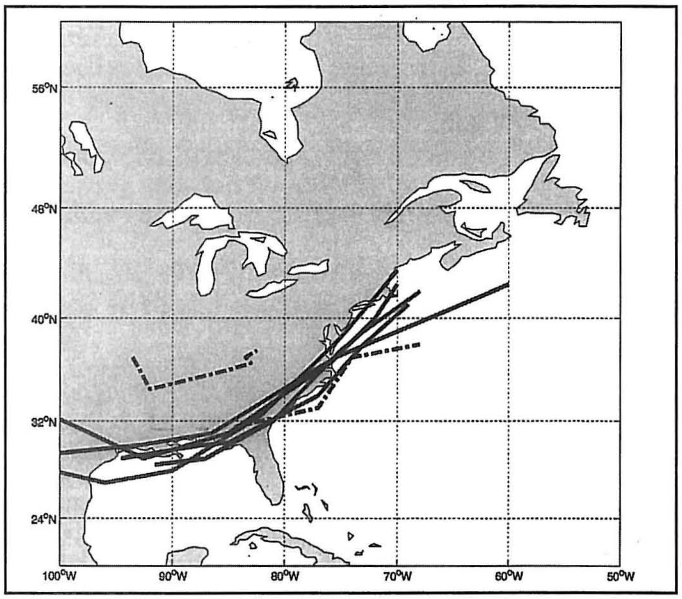

Fig. 1. Surface cyclone tracks for the six historical storms that blanketed the East Coast Megalopolis in 10 inches or more of snowfall. The tracks for the five storms of the *Gulf of Mexico - Atlantic Coast* cyclone class are shown as solid lines while the track for the one storm of the *Atlantic Coastal Redevelopment* class is shown as a dot-dash line. Compiled from the case study surface charts in Kocin and Uccellini (2004b).

clone tracks south into the central Plains (centered roughly on Omaha, Nebraska), but extends a surface ridge eastward along the United States – Canadian border (Fig. 3-12 of Kocin and Uccellini 2004a). A second ridge extends south from the high into Texas. Because the surface cyclone nestles between these two ridges, the anticyclone takes on a bent shape reminiscent of a banana, hence, the common name "banana high". Cold air damming east of the Appalachians can occur with either of these two patterns.

Upper level features associated with Megalopolitan heavy snowstorms show even less consistency, with the antecedent 500 mb vorticity maxima tracking anywhere across the lower 48 states (Fig. 4-4 of Kocin and Uccellini 2004a). Subsequent evolution can involve self-development, open waves, and cutoff lows (Fig. 4-3 of Kocin and Uccellini 2004a). Low-level (850 mb) onshore jets are, however, a common feature of Megalopolitan heavy snowstorms (Kocin and Ucellini 2004a,b). However, the track and evolution of these jets varies widely from storm to storm.

Thus, Kocin and Uccellini (2004a,b) demonstrate that 10-inch snowfalls occur in portions of the Megalopolitan region under virtually any synoptic pattern that provides a strong surface cyclone, an 850 mb onshore jet, upper air support via positive vorticity advection at 500 mb, and a sufficiently deep subfreezing layer adjacent to the surface. The remarkable finding of the current study is that only a small range of variation has been observed in those storms that blanketed the entire Megalopolis. Because Kocin and Uccellini (2004a) provide a detailed review of the dynamics involved in East Coast heavy snowfall events, the discussion below will focus on the synoptic pattern required to achieve a Megalopolitan blanketing 10-inch snowfall.

2. Data

The bulk of the data analyzed for this study are taken directly from the figures of Kocin and Uccellini (2004a,b). Their book represents a monumental effort to provide consistent documentation for each of the Northeast heavy storms between 1950 and 2003. These data were supplemented as necessary with the surface and upper air analyses produced by the NOAA/National Centers for Environmental Prediction and archived at the NOAA/National Climatic Data Center and the NOAA-CIRES Climate Diagnostics Center.

Of the 32 snowstorms documented by Kocin and Uccellini (2004b), only six brought 10 inches or more of snowfall to all five cities of the Megalopolitan region: 14-17 February 1958; 6-8 February 1967; 10-12 February 1983; 12-14 March 1993; 6-9 January 1996; and 15-18 February 2003. The 10-inch criterion was applied to the contoured snowfall maps in Kocin and Uccellini (2004b). Point measurements at some of the official urban recording sites were a fraction of an inch below this threshold for one of the events.

3. Synoptic Pattern

In contrast to the diverse conditions that can bring 10 inches of snow to one part or another of the Megalopolis, a very repeatable pattern occurs with those storms that bring 10 inches to the entire Megalopolis. This storm-to-storm consistency includes the behavior of the surface cyclone and surface anticyclone, as well as the existence of a cold-air outbreak over warm water, and an 850 mb onshore jet. Other features commonly associated with strong mid-latitude cyclones are often present with Megalopolis snowstorms, but with lesser degrees of consistency. These occasional features include a period of rapid deepening of the surface cyclone and development of a negative tilt in the associated 500 mb trough. Merger of multiple shortwave vorticity centers prior to the onset of the Megalopolis snowfall also occurred in some cases.

The most striking similarity between these six storms occurs in the track of the surface cyclone as shown in Fig. 1. Five of the six storms passed along the Gulf Coast of Texas in the early stages of their development, subsequently tracking east along the Gulf Coast to cross Georgia, and thence, proceed northward to the vicinity of Cape Hatteras. Thus, they are all members of the *Gulf of Mexico - Atlantic Coast* cyclone class defined by Kocin and Uccellini (2004a). Interestingly, these same five storms all accelerated as they tracked from the Gulf Coast to the Atlantic, with speed increases of 50 to 100 percent from one 12-hour period to the next for four of the five storms. Thus, even the *Gulf of Mexico - Atlantic Coast* cyclone class appears to exhibit a tendency towards redevelopment along the Atlantic coast. Only four of the six storms tracked along the Megalopolitan coast from Delaware to Cape Cod, Massachusetts. The other two angled farther offshore after passing Cape Hatteras. Thus, their tracks past the Megalopolis spanned the range observed by Kocin and Uccellini (2004a) for the *Gulf of Mexico - Atlantic Coast* cyclone class.

The sixth storm, the February 2003 "Superstorm", exhibited features of both the *Gulf Coast – Atlantic* and *Atlantic Coastal Redevelopment* cyclone classes. Its surface cyclone tracked east from Oklahoma to Tennessee before undergoing coastal redevelopment, but unlike the usual cyclone following this track, the February 2003 storm redeveloped with two centers: one along the Gulf Coast and the other in the usual position offshore from the Carolinas. This hybrid behavior pushed the cyclone track somewhat south of that usually seen for the *Atlantic Coastal Redevelopment* class, allowing the 10-inch snowfall line to extend south past Washington D.C. by a few scant miles. The few other historical storms to exhibit Gulf Coast redevelopment did not blanket the entire Megalopolitan region (Kocin and Uccellini 2004b). Thus, the February 2003 event was a marginal case by our criterion despite its "superstorm" status.

The intense lower tropospheric geopotential height gradients north and east of each cyclone resulted in strong 850 mb onshore jets, a key element in providing moisture convergence over the Megalopolis (Kocin and Uccellini 2004a). These conveyor belts are low-level flows driven by the strong pressure gradients associated with the cyclones' fronts. The warm conveyor belt lies on the warm side of the cold front and brings tropical maritime air northward into the storm where it overruns the warm front, leading to intense precipitation. The cold conveyor belt lies on the cool side of the warm front, sandwiched between the front and the sea surface. Thus, it feeds cooler, but still moist, maritime polar air westward into the storm. Lifting near the storm center can allow this moisture to condense and precipitate as well. Contact of the lower edge of both of these low-level jets with the sea surface, particularly the warm Gulf Stream, can enhance surface moisture fluxes, and further increase the storm's moisture supply. The warm conveyor exceeded 20 m s^{-1} in all six cases, while the cold conveyor belt exceeded this threshold in five of the six. In all six cases the warm conveyor belt passed over the Gulf Stream as the storm was progressing up the East Coast, often doing so for an extended period of time at the height of the storm, thus adding to the moisture supply and baroclinicity. As one would expect given the storm track northeastward from Cape Hatteras, the terminus of these low-level jets progressed from one end of the Megalopolis to the other during the passage of the storm.

The synoptic scale source of low-level cooling was the same in five of the six cases, a dual-ridge "banana" high (e.g., Fig. 2). The highs were centered between the Dakotas and Ontario at the time each cyclone passed Cape Hatteras. As is usual with this class of anticyclone (Kocin and Uccellini 2004a), one ridge extended south into Texas and the other east along the United States – Canada border. The sixth case exhibited the other anticyclone class, a single high pushing east along this northern axis with a southward ridge developing only late in its evolution.

Other features of these six storms showed much greater case-to-case variation. For example, the 500 mb

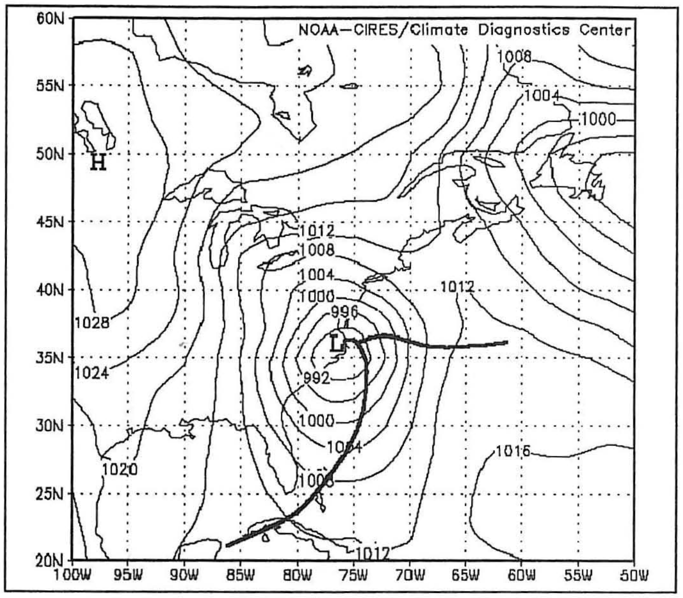

Fig. 2. Surface chart for 0000 UTC 16 February 1958. Adapted from the NOAA/National Centers for Environmental Prediction surface analysis (contours shown are in mb, fronts are depicted as dark black lines). While the reanalysis captures the fronts, cyclone, and anticyclone in close agreement with the surface charts in Fig. 10.2-2 of Kocin and Uccellini (2004b), it does not resolve the mesoscale kinking of the isobars along the fronts which those authors sketched in on theoretical grounds.

wave evolution spanned the full range of variability documented by Kocin and Uccellini (2004a,b). Three of the six cases developed negatively tilted troughs in association with periods of rapid deepening of the surface cyclone, while another of the storms partially cut off during a period of rapid deepening. In contrast, two of the storms exhibited nearly constant central pressures during their transit of the Gulf and Atlantic coasts. Likewise, there was no consistent pattern linking periods of rapid deepening or the development of negative tilt to slowing of the cyclones' northeastward progress. While three of the six storms slowed while passing the Megalopolis, allowing more time for snowfall accumulation, three did not.

Rapid deepening, when it did occur, began along the Gulf Coast and terminated along or off the Atlantic Coast. All four rapidly deepening cyclones had cold air outbreaks, reaching the warm waters of the Gulf or Gulf Stream just as deepening began in two of the cases, and within 12 hours thereafter, in the other two cases. In both of the lagged cases deepening began when the storm started to track along the Southeast coast immediately adjacent to the Gulf Stream. Thus, when deepening was present, it appeared to be linked to cold air outbreaks, land-sea temperature contrast, and perhaps the interaction of the two. The link to cold air outbreaks is fundamental in the basic theory of baroclinic instability (Kocin and Uccellini 2004a), so it comes as no surprise. Likewise, coastal baroclinicity, especially when enhanced by the presence of the Gulf Stream close offshore, has long been known to contribute to cyclone intensification (Kocin and Uccellini 2004a). The contribution of cold air outbreaks over warm water is potentially more complex. On the one hand, the resulting enhancement of surface heat flux in the cold air mass decreases cross-frontal baroclinicity, reducing that contribution to cyclone development. On the other hand, this warming of the polar air mass reduces the degree to which static stability can dampen the cyclone's vertical motion and thus, continued development. Interestingly, rapid deepening ended in all four cases when the cold air advection over warm water ceased to occur in the immediate rear of the cyclone.

Cold air damming east of the Appalachians has also been shown to affect the behavior of East Coast cyclones (Kocin and Uccellini 2004a), but it is not essential to those storms responsible for Megalopolis snowstorms. For these six cases, the number of 12-hour periods with cold air damming ranged from zero to four.

Thus, it is the surface cyclone track and the extent and shape of the anticyclone that sets apart those storms that can bring 10 inches of snowfall to all of the East Coast Megalopolis.

4. Conclusions

While Kocin and Uccellini (2004a,b) have demonstrated that two major storm types with a wide range of variations can bring heavy snowfall to portions of the East Coast Megalopolis, those storms which blanket the entire Megalopolis follow a much narrower range of synoptic patterns.

- Five of the six historical storms were of one cyclone class, the *Gulf of Mexico - Atlantic Coast*. The sixth was a hybrid with redevelopment along both the Gulf and Atlantic coasts.
- The five *Gulf of Mexico - Atlantic Coast* storms followed similar tracks along the Gulf Coast and then along the Atlantic Seaboard. The sixth storm took a different route in its initial stages, but followed this track from Georgia northeastward. Only four of the six storms tracked along the Megalopolitan coast from Delaware to Cape Cod, however. The other two angled farther offshore after passing Cape Hatteras. The five storms that tracked from the Gulf Coast to the Atlantic Seaboard accelerated while making the land crossing of the Southeast, suggesting some contribution of Atlantic Coast redevelopment, even along this track.
- All six cyclones caused the steady progression of an onshore 850 mb jet northeastward across the entire Megalopolis – not surprising given the storm tracks. The nature of the jet varied from case to case, however, with the warm conveyor belt reaching 20 m s^{-1} in all six cases, but the cold conveyor belt did so in only five of the six cases. In all six cases the warm conveyor belt remained over the Gulf Stream for extended periods of time, providing an ongoing mechanism for transporting moisture into the storm.
- Five of the six storms interacted with the same anticyclone type – the dual-ridge "banana" high.

This consistency can provide the basis for identifying potential cases in the medium-range numerical weather forecasts. Early identification is particularly important for these Megalopolis-spanning storms because their extent and track eliminates many mitigation strategies involving alternative routing for both ground and air travel.

Acknowledgments

The authors would like to thank Sam Perugini, Brad Herold, Anthony Lupo, and Mary Cairns for their painstaking critiques of this manuscript.

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