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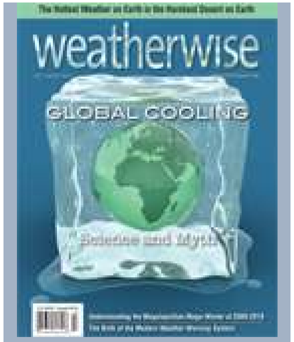

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Mega-Snow in the Megalopolis: The Mid-Atlantic's Blockbuster Winter of 2009–2010

by Jeffrey B. Halverson and Thomas D. Rabenhorst

If you examine the long-term variability of snowfall along the densely populated East Coast, you'll find that the Northeastern Megalopolis (the region stretching from Richmond, Virginia, to Boston, Massachusetts) typically experiences several light- to moderate-intensity snowfalls each winter season. Exceptionally heavy snowstorms are infrequent. The average return interval of a major “snowmaker,” defined as a nor'easter-type coastal storm producing 10-inch or greater snowfall, is on the order of two to three years for Washington, D.C., Baltimore, Philadelphia, and New York City, while Boston is visited once every one to two years.

Now, imagine what sounds like a worst-case scenario: Four crippling storms, each producing widespread 10- to 20-inch swaths of snow across the mid-Atlantic, arrive back-to-back within a *single season*. One produces wet thundersnow at a rate of two to three inches per hour, several contain regions of 36-inch snow accumulation, and two rapidly intensify into destructive windstorms creating blizzard conditions and enormous drifts. The deep snow cover doesn't melt between storms, thanks to a prolonged stretch of sub-freezing days. Such a winter season would be unprecedented. And, indeed, it was—until this past winter. The unforgettable “Megalopolitan Mega-Winter” of 2009–2010 is without equal.

The annual snow-removal budgets of the megalopolis, its socioeconomic infrastructure, and the psyche of its denizens are geared toward the more frequent and lighter mode of snowfall. The excitement (for snow-lovers) or dread (for snow-haters) of a really big storm comes only once every few years. Twenty inches or so is about par for seasonal snow totals in Washington, D.C., Baltimore, and Philadelphia. But during the winter of 2009–2010, 55–80 inches of snow topped the measurement scale, an all-time record for these three cities.

For those living downwind of the Great Lakes or along the Sierra Nevada mountain range, seasonal snow totals of 80 inches barely raise an eyebrow. What truly crippled the mid-Atlantic was the frequency of the big snow storms; most arrived back-to-back, with little time to recover in between events. To make matters worse, this winter was preceded by a snow drought lasting three to four years. With the region out of practice for dealing with a major snowstorm, perhaps there was a collective sense of “snow amnesia.” The end result of this unrelenting snow and wind was a great cumulative strain—physical, economic, and psychological—placed on millions.

Perhaps the best way to begin to understand the winter of 2009–2010 is to place the season into a historical and geographic context based on snow accumulation and population density. Even more interesting for those who study meteorology are the climatological cycles and complex meteorology that may have contributed to the season's wintery parade of frequent storms. Paradoxically, one possible connection is a tropical-based oscillation, El Niño, although that one factor alone doesn't tell the whole story.

Table 1: 2009–2010 Mid-Atlantic Snowfall By The Numbers

City	**Dec 19–20**	**Jan 30–31**	**Feb 5–6**	**Feb 9–10**	**Season Total**	**Previous Seasonal Record**	**Average Seasonal Total**
Richmond, VA	7.4	10.0	6.6	2.8	28.0	21.6	11.9
Washington, DC	16.4	6.4	17.8	10.8	56.0	46.0	15.2
Baltimore, MD	21.1	5.0	24.8	19.5	77.0	62.5	18.2
Philadelphia, PA	22.5	2.1	28.5	15.8	78.7	65.5	20.5
New York city	10.9	0	0	10.0	51.4	75.6	23.6

Table 1 Notes: ***(1) Individual storm totals are based on preliminary NWS data; (2) seasonal total for 2009–2010 includes snowfall from storms not shown in this table; (3)***

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previous seasonal record based on data extending backto the late 1880's; (4) average seasonal snow total based on official records from 1971–2009; (5) all values forsnowfall are shown in inches.

A New Seasonal Snowfall Record

Table 1 shows the dates of each major storm, the mid-Atlantic cities impacted, and the 2009–2010 season-total snowfall. The first significant storm came on December 19–20, as a nor'easter intensified off Cape Hatteras, North Carolina. A swath of heavy snow fell from Washington, D.C., to New York City but was heaviest in the Baltimore-Philadelphia corridor. The next major storm arrived on January 30–31, as a low over the Gulf Coast moved northeastward and intensified off the Carolinas. The storm took more of a southern track, confining the heavy snow band to the Richmond-Petersburg metro area, where localized amounts of 14-plus inches fell across the northern suburbs.

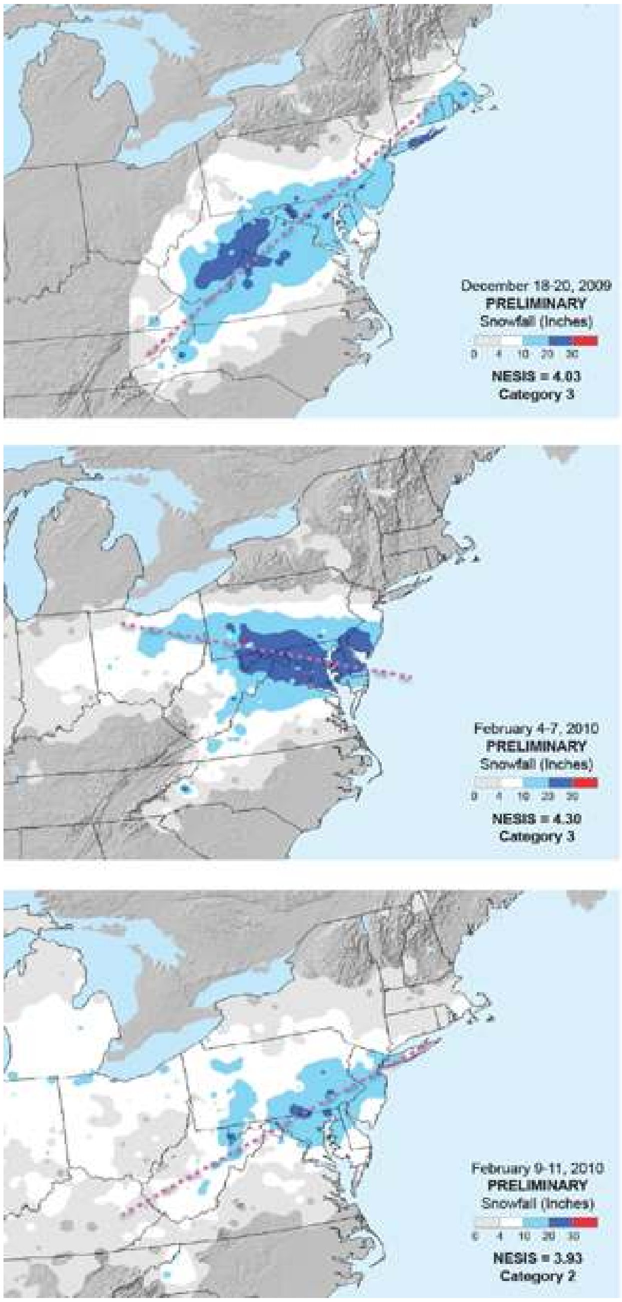
Only a few days later, a much larger and more complex area of low pressure tracked up the East Coast and intensified, producing a narrow but impressive swath of 25–30 inches snow through the Baltimore-Philadelphia region. The vortex had two distinct parts. The first part was a coastal piece of energy that rapidly intensified, drawing in a river of atmospheric moisture from as far away as the equator. This rich conveyor of tropical moisture produced exceptionally wet, heavy snow, falling at rates of several inches an hour, and accompanied by lightning. The rapid rate of wet snow accumulation on tree limbs, combined with high winds from the deepening vortex, led to 300,000 power outages across northern Virginia and Maryland. The second piece of energy arrived after a brief respite. An additional foot of wind-blown snow accumulated from a weakening upper-level vortex moving out of the Ohio Valley.

The final major mid-Atlantic storm arrived very soon thereafter, on February 9–10, adding an additional 15–20 inches of snow to Baltimore-Philadelphia's already prodigious total. This snow was much drier and powdery, but the rapidly intensifying nor'easter from which it fell created sustained winds in the 35–45 mph range. For the first time ever, the entire state of Maryland was placed under a blizzard warning. Whiteout conditions prevailed for hours, and the drifts were exceptional, stranding hundreds of vehicles on several major interstates. Widespread power outages occurred across the Baltimore metro region and further northeast. The nor'easter, while offshore, moved sluggishly—if at all—leading to a prolonged wind and heavy snow event. Three of these storms repeatedly assaulted the Washington, D. C.-Philadelphia urban corridor, impacting the lives of an estimated 15 million people. The effects were nothing short of crippling, considering the shut-down of commercial aviation and ground travel, shipping, and the local economy. Many school systems were closed for more than a week, and the federal government was shuttered for four consecutive days. A great many people endured endless days and nights in freezing homes without power, literally stranded while waiting as many days for the snowplows to clear residential streets. And once the roads were cleared, the fallen trees removed, and the power restored, there were rebound effects: Roofs collapsed under the weight of snow, gutters fell from homes on drippy ice dams, and mountains of plowed snow made parking and routine driving dangerous.

The seasonal snow totals shown in Table 1 indicate new all-time records for Richmond, Washington, D.C., Baltimore, and Philadelphia. Richmond broke its last record set in 1939–1940, while the rest of the cities topped the very snowy winter season of 1995–1996, which featured several back-to-back major snowstorms, much like this past winter. The stretch of years from 2006 through early 2009 saw significantly below-average snow accumulation. These alternating periods of snowy “feast or famine” highlight the episodic nature of heavy snow events in the mid-Atlantic. Such swings make advance prediction of an entire season's worth of snow activity difficult.

Geographical Impact of the Mid-Atlantic's Big Storms

But what about the geographical impact of the storms that struck the mid-Atlantic and Northeast this past winter? The Northeast Snowfall Intensity Scale (NESIS) is a new tool used by NOAA to assign a categorical rating to a storm, based on its snow accumulation and the number of people impacted by the storm's snow footprint. Designed in 2004 by meteorologists Paul Kocin, currently a forecaster at NOAA's Hydrometeorological Prediction Center, and Louis Uccellini, currently director of the NWS, National Centers for Environmental Prediction, it quantifies the area and depth of snowfall and relates these to population density derived from the U.S. census. The resulting NESIS Value ranges from 1 to 10 and is divided among five impact categories (Category 1 through Category 5), with Category 5 being labeled "Extreme." In addition to computing snow impact, NESIS can also be used to order storms according to historical significance. Figure 1 (right) shows the preliminary NESIS ratings of the three major storms that struck the Washington, D.C.-Philadelphia corridor. Based on a database of 40 high-impact snowstorms dating back to 1950, these three storms rank in the middle of the pack, as Category 2 and 3 events (the highest-ranked storm on the scale was the Category 5 March 12–14, 1993 nor'easter).



NOAA

From these diagrams, we can discern some key differences and similarities between events. All three storms were narrowly confined to the mid-Atlantic. This clustering of storm tracks reflects a similar course to the upper-level jet stream, which propels winter storms from southwest to northeast. The December 19–20 storm features a 20- to 30-inch snow footprint trending from southwest to northeast, along the spine of the Appalachians—a very "classic" pattern that parallels the nor'easter's track up the coastline. The fact that the heaviest snow was confined to a relatively sparsely populated mountain region reduced the storm's overall NESIS category.

The February 5–6 heavy snow swath is oriented much differently, from northwest to southeast. This pattern reflects the large and complicated structure of the low-pressure region, which was split into two separate vortices. It scores a higher NESIS value by virtue of the heavy snow region (20–30 inches) that is shifted eastward into denser population centers. The band of 20- to 30-inch snow with spotty locations exceeding 30 inches is very broad and consistent with the storm's high tropical moisture content. Finally, the February 9–10 snowstorm reflects a more general southwest-northeast orientation, but the region of heaviest accumulation (20–30 inches) is small. While the snow footprint was centered over big cities, significantly lower snow totals reduced this storm's overall NESIS value to Category 2.

Why Was the 2009–2010 Winter So Extreme?

Major snowstorms along the East Coast are created when vigorous waves in the westerly jet stream move over strong temperature contrasts along the coastline (cold land and warm ocean). An initial low-pressure disturbance along the coast may amplify under these circumstances, deriving energy from the thermal gradient, intensifying into a coastal low or nor'easter. During the 2009–2010 winter, the subtropical branch of the jet stream was unusually active—meaning the jet contained high winds with a large number of waves or "ripples" passing through. The subtropical jet remained over the Gulf Coast and southeastern United States for much of the season. As Figure 2A illustrates, this type of persistent pattern is often a hallmark of El Niño. While El Niño is a type of coupled air-sea interaction that takes place across the equatorial (tropical) Pacific, it can cause the subtropical jet stream to strengthen over North America and shift northward. The linkage between climate patterns in the tropics and mid-latitude circulation patterns is called an atmospheric "teleconnection." Data from NOAA's Climate Prediction Center revealed that this winter's persistent El Niño pattern first developed in May of 2009 and gradually strengthened into a moderate to strong event through the winter season (Figure 2B). During 2009–2010, an unusually large number of wave disturbances in the subtropical jet developed into coastal lows along the U.S. Gulf Coast. As many of these moved up the Eastern Seaboard, they rapidly developed into nor'easters. It is ironic that climate patterns across the tropical Pacific helped trigger a series of potent snowstorms along the U.S. East Coast. But atmospheric circulations such as these are inextricably linked. Many meteorologists reported during their coverage of the storms this past winter that exceptionally snowy winter seasons tend to come in “cycles” that are controlled by El Niño, and there is certainly truth to this statement. But El Niño was not the only cycle to blame for the excessive snows.

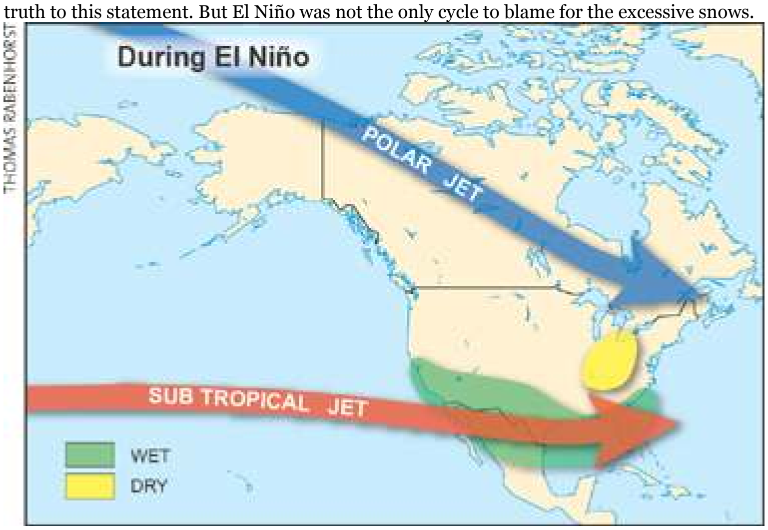


Figure 2A

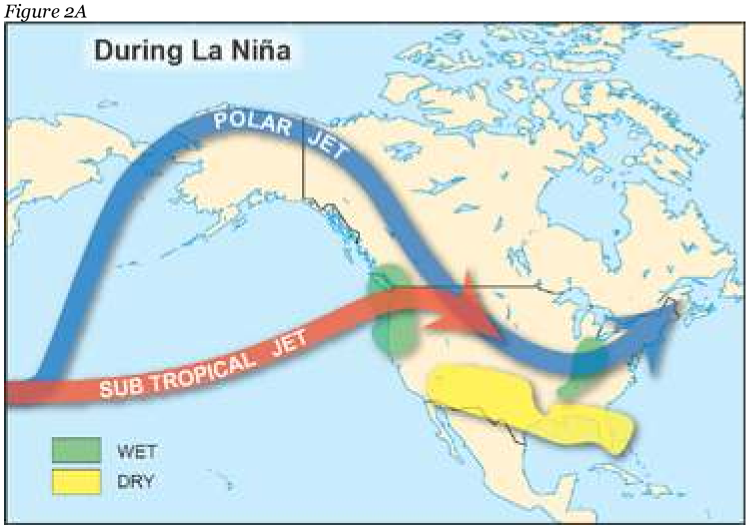


Figure 2B

A 2004 study conducted by Kocin and Uccellini found that, statistically, the predictive relationship between El Niño and above-average seasonal snow across the mid-Atlantic and New England was not very strong. This is because an active subtropical jet stream may generate frequent coastal storms, but cold air masses are often lacking, or storms track farther inland, so heavy rain, not snow, falls across the mid-Atlantic and coastal New England. While El Niño may supply the storminess and moisture, without cold air to support heavy snow, the winter just as easily could end up wet rather than snowy.

There is another important cyclic variation in northern hemisphere climate called the North Atlantic Oscillation (NAO) and its closely-related, larger scale cousin, the Arctic Oscillation (AO). While these cycles are less well-known to the general public, they profoundly influence the winter weather of both Europe and the Eastern Seaboard. Figure 3A illustrates the characteristic atmospheric circulation pattern during a cold or “negative” NAO phase. While El Niño's strength is based on the east-west sea level pressure difference across the tropical Pacific, the measure of the NAO is defined by pressure differences between the Azores and Iceland, along a north-south line. The NAO can also change signs or phases, from positive to negative and vice versa, very rapidly, over a matter of days, while a fully developed El Niño tends to show persistence over many months.

Figure 3A

The NAO/AO, when in its negative phase, generates sizeable shifts in atmospheric circulation patterns across the North Atlantic. These include conditions that favor the formation of polar anticyclones, which push the polar jet stream south of normal in mid-latitudes, leading to cold air outbreaks across the Northeast and Mid-Atlantic. Additionally, the polar branch of the jet stream often develops a “blocking pattern”, particularly downstream over Greenland, meaning nor'easters often move slowly or not at all – prolonging of cold, high wind, and snow accumulation. When Kocin and Uccellini examined the relationship between the NAO's negative phase and seasonal snowfall across the Northeastern Megalopolis, they found that the NAO is a much stronger predictor of above-average seasonal snow. And the 2009–2010 winter saw the most negative AO since records began in 1950.

Figure 3B shows the variation of NAO's index from mid-November through mid-March. The 2009–2010 winter featured several weeks-long stretches of negative NAO anomaly, and that anomaly was rated moderate to strong. When one looks for climatological factors controlling seasonal snow along the East Coast, a useful analogy may be to think of the gears in a car transmission. Each set of meshing gears is defined by a particular climate cycle. To shift the weather into a cold and snowy mode, you have to select the proper gear sets. The 2009–2010 record snow season seems to have required both copious moisture and storminess (supplied by El Niño) and cold air (supplied by the AO). Lacking one or the other condition, the season may have fallen short of historical proportions. The number-two snowiest season of 1995–1996 was also characterized by a moderately warm El Niño-Southern Oscillation (ENSO) and moderately cold NAO. While the analogy seems to work for some seasons, it breaks down for others. For instance, when we examine the past 60 winter seasons, other headliners such as 1963–1964 or 2002–2003 were dominated either by a neutral or slightly cold ENSO, and a neutral or moderately cold NAO. One reason for the apparent breakdown may be the extent to which mid-latitude teleconnections become fully expressed, which depends on factors other than ENSO strength. Additionally, there are a host of factors that influence storm track along the Eastern Seaboard. Small shifts in the rain-snow line, which depend on storm track, make all the difference between an inch of rain or a foot of snow.

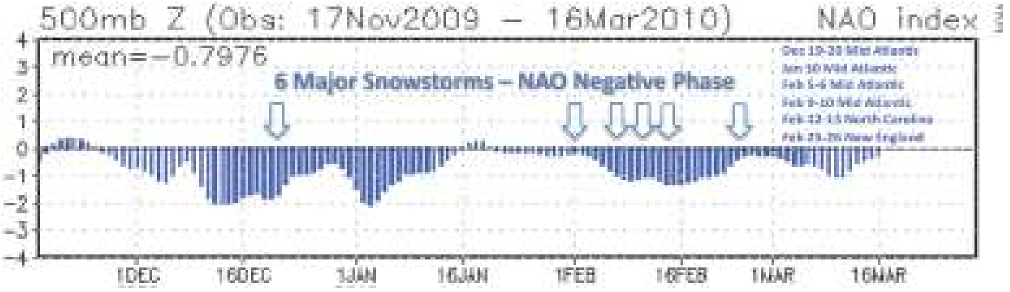
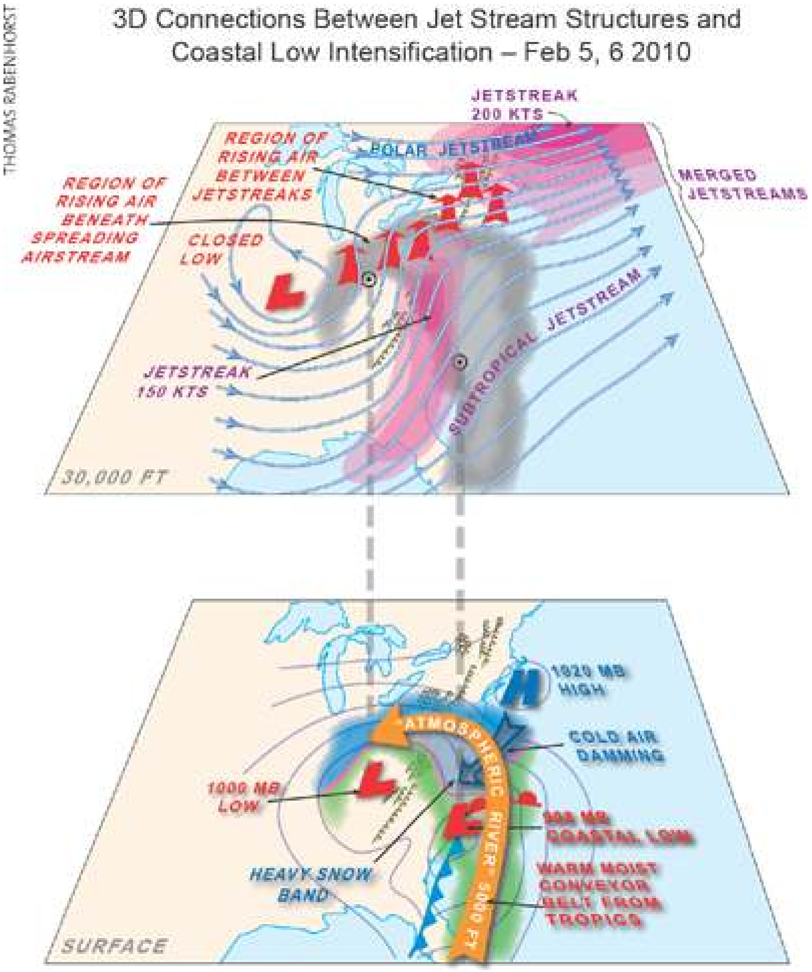


Figure 3B

The 3-D Meteorology of East-Coast Snowmakers

To understand the meteorology of a snowstorm, one must think in terms of the atmosphere's vertical structure. Powerful cyclonic vortices such as nor'easters, while fueled by low-level temperature contrasts between land and sea, ultimately are created and sustained by regions of rising air. Those regions are controlled from the jet stream level, located approximately 30,000 feet above the surface during the winter season. In Figures 4 and 5, we sketch the salient features of the February 5–6 and 9–10 storms, respectively, showing the surface and jet stream interactions. Heavy snow typically falls in one or more bands displaced to the northwest of the storm's center by 100–200 miles. A deep cold air layer must be in place at the surface, as must an abundant source of moisture, either of Gulf or Atlantic origins. In the February 5–6 storm, the cold influx was substantially aided by a wedge of cold air dammed up against the Appalachians, channeled southward by high pressure over New England. In the February 9–10 storm, cold air arrived in the lowest 5,000 feet from the west, with some contribution from the north.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3D Connections Between Jet Stream Structures and Coastal Low Intensification – Feb 5, 6 2010
JETSTREAK
200 KTS
POLAR JETSTREAM
MERGED
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REGION OF
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L
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SUBTROPICAL JETSTREAM
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HIGH
"ATMOSPHERIC RIVER" 5000 FT
COLD AIR
DAMMING
L
1000 MB
LOW
L
COASTAL LOW
HEAVY SNOW
BAND
WARM MOIST
CONVEYOR
BELT FROM
TROPICS
SURFACE

Figure 4

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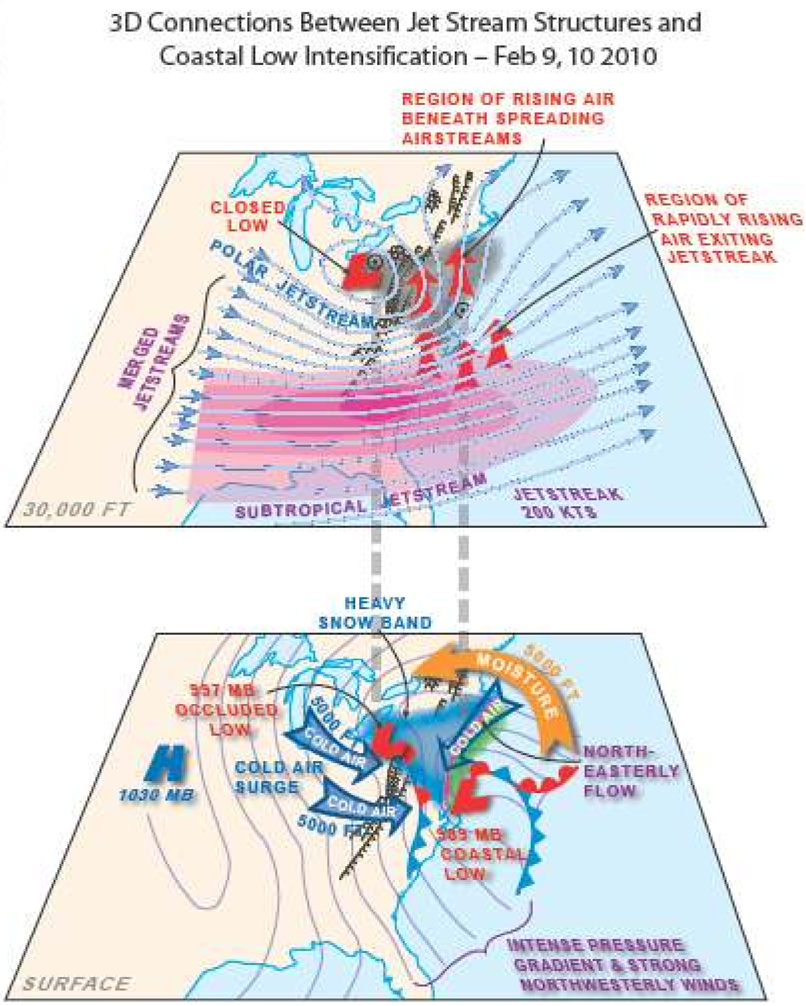

Figure 5

Both snowstorms featured a large and complex surface cyclone, consisting of multiple vortices. Both evolved over the southeastern United States, as a low over the Ohio Valley merged with a new region of low pressure forming along the coast. In both systems, energy was transferred from the inland to the coastal vortex, which began to draw in copious amounts of oceanic moisture. It's important to note that as these storms began condensing and freezing oceanic moisture, heat energy was released within clouds, which essentially “turbocharged” the cyclone's engine and contributed to its intensification.

In both storms, the subtropical jet stream coursed across the southeastern United States, and became phased with the northern (polar) branch of the jet stream. Phasing of jet streams is a hallmark of major East Coast snowstorms, causing otherwise separate waves (troughs) to combine and amplify into a single giant vortex. In both storms, air movement around the vortex then created pockets of rapidly rising air that resulted in separate areas of sustained heavy snow and even thundersnow across the mid-Atlantic.

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