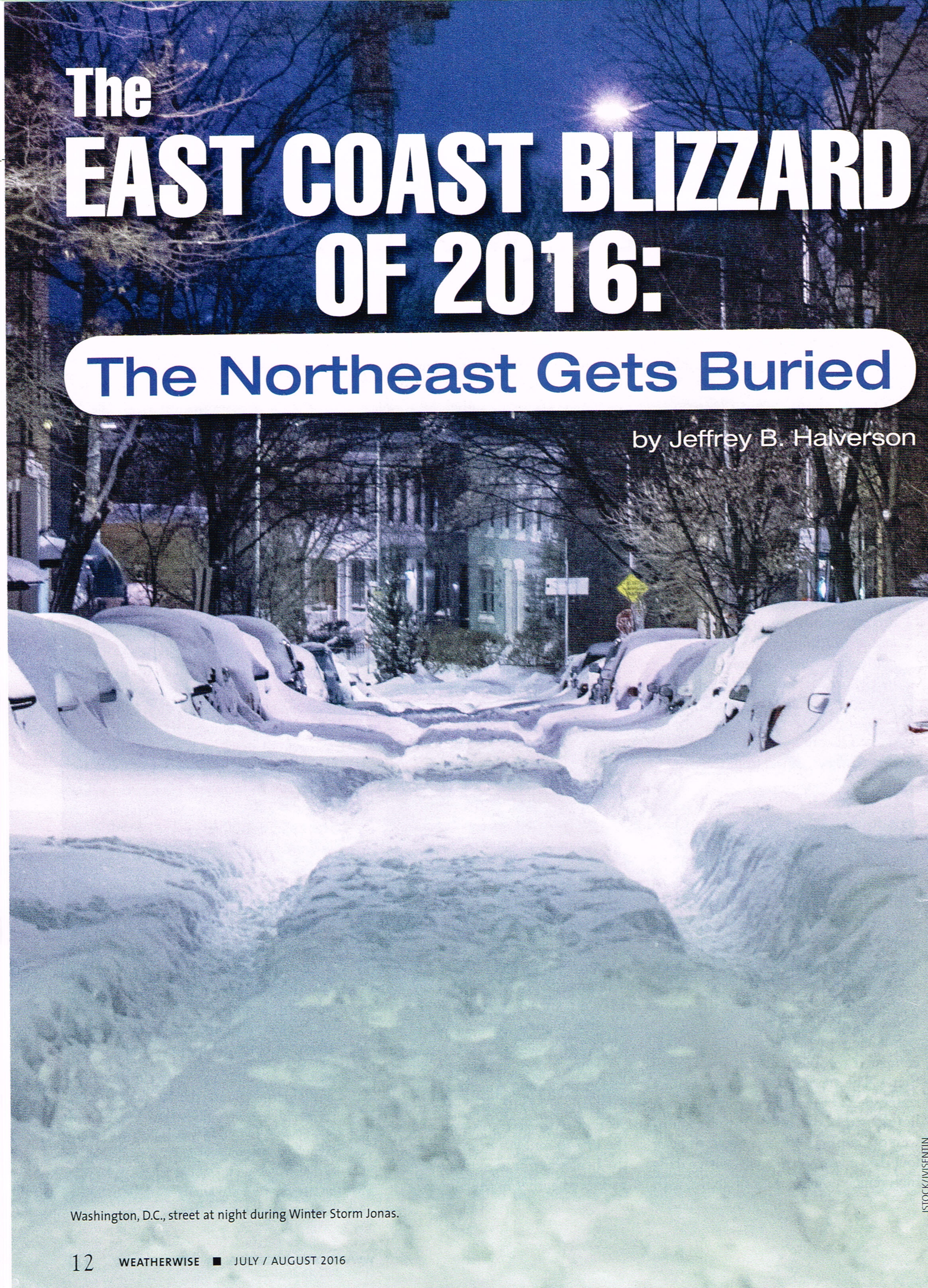
The EAST COAST BLIZZARD OF 2016:

The Northeast Gets Buried

by Jeffrey B. Halverson



Washington, D.C., street at night during Winter Storm Jonas.

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From January 22–23, 2016, a potent snowstorm and blizzard visited the United States East Coast, setting new snowfall records in several locations and paralyzing the vast Northeastern Megalopolis. Nearly 50 million people along the Eastern Seaboard experienced direct or indirect effects (Figure 1). This type of storm, called a Nor'easter, was called various other names by media outlets, including "Winter Storm Jonas" at The Weather Channel and "Snowzilla" by the *Washington Post's* Capital Weather Gang. Snow accumulations topped three feet in several major cities, garnering an impact rating of fourth highest since 1900, per the Northeast Snowstorm Impact Scale (NESIS). Forecasting the storm was an unprecedented achievement, with a remarkable eight days of lead time provided from the medium-range forecast models (both the European and the American models).

In this story, we review the meteorology behind this historical event, and explore its diverse impacts. As a coastal Nor'easter, disruption came not just from heavy snow, but also intense coastal winds and a powerful storm tide. We also discuss the outstanding forecast that enabled multi-day preparation for epic disruptions.

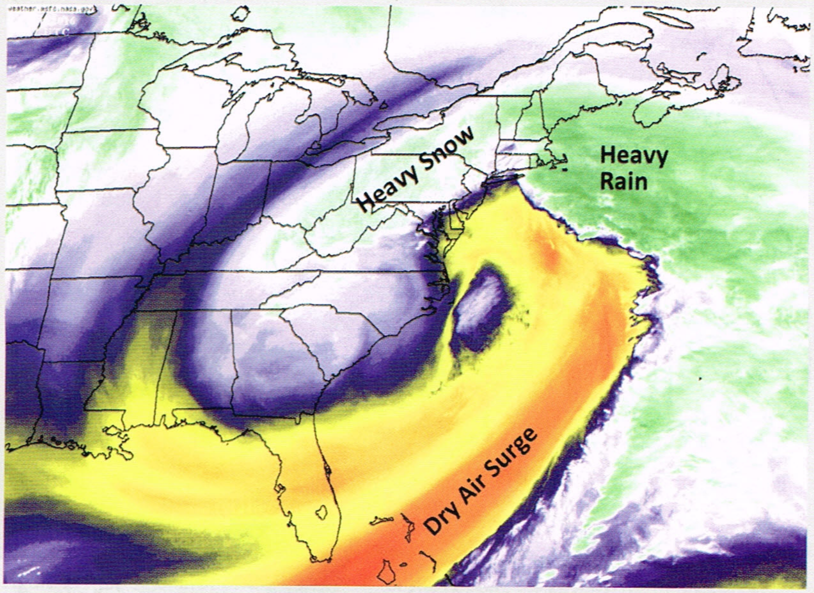

Figure 1. Like a giant fist, this satellite image of the January 23 Nor'easter reveals a massive surge of dry air slamming into a deep, moist air mass producing heavy snow over the Appalachians and New England. The dry air current was being pulled into the intense cyclonic circulation of the parent storm system, which became stationary along the New Jersey coast.

What Are Nor'easters?

Nor'easters occur regularly along the East Coast during winter. These are large, cyclonic storms associated with low pressure and fronts that demarcate contrasting air masses. They are creatures of the mid-latitude, westerly jet stream, but also draw heat energy out of the Atlantic ocean. Land-based cyclones over the United States develop ahead of giant waves in the jet stream, but Nor'easters also have a hurricane-like quality. Nor'easters often develop thunderstorms offshore and can even form an eye. Their central pressure, along with their rapid rate of pressure fall (a process called "bombing"), make them more intense than purely land-based cyclones. Winds over the ocean and along the coast can actually reach hurricane-force (> 74 mph sustained). Thus Nor'easters are a *hybrid-type* storm system, i.e., a blend of extratropical cyclone- and tropical cyclone-type influences. The cumulative damage of several wintertime Nor'easters along the shoreline can exceed that from a single landfalling hurricane during the late summer and fall.

The Meteorology Behind the Blizzard

The January 23 blizzard got its start in a round-about way, over Texas, as an area of low pressure located near Dallas early on January 22 (Figure 2). The track of this initial disturbance is shown by the series of black "Ls" and the dashed black line. By January 23, the inland low reached the southern Appalachians and began to dissipate. At the same time, a new low pressure center developed over the ocean off Charleston, South Carolina. This type of "center jump" is a common pattern that gives rise to Nor'easters. It occurs when low-level spin is weakened on the west side of the Appalachians and then re-amplified on the east side. The emerging coastal low is called a "secondary low" and becomes the nucleus of the Nor'easter.

Meanwhile, as the storm system was reorganizing, strong high pressure over eastern Canada was nosing down the Eastern Seaboard. A brisk, cold wind near the surface surged southward, down the east side of the Appalachians, ushering in a deep layer of sub-freezing air. The dense, chilly air mass became "locked in" over the Piedmont and Coastal Plain, unable to surmount the mountains. This process is called Appalachian cold air damming, and it is a common precursor to significant snowstorms along the East Coast—priming the entire region with freezer-like cold.

Figure 2 shows the full-blown Nor'easter late on January 23. This is a surface weather map illustrating the location of the low pressure (red "L"), principal fronts, isobars (lines of constant pressure, thin black lines), and the precipitation shield (dark blue = heavy snow, green = rain, purple = rain/snow mix, orange = sleet/freezing rain). The Nor'easter's intensity was at 992

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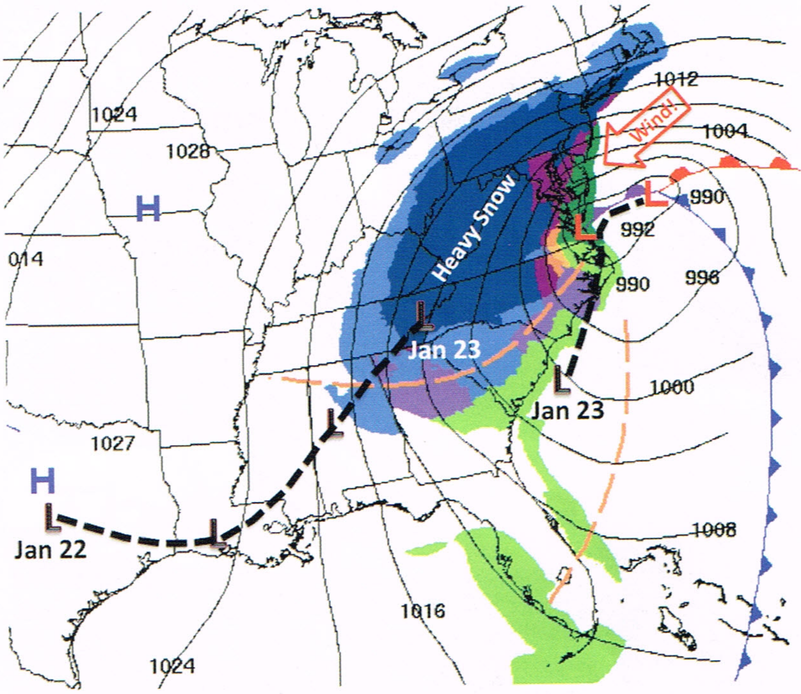

Figure 2. Surface weather map showing the Nor'easter (red "L"), fronts, and location of the heavy snow band (dark blue region) late in the day on January 23. Earlier track of the storm is shown by black "Ls" and black dotted line.

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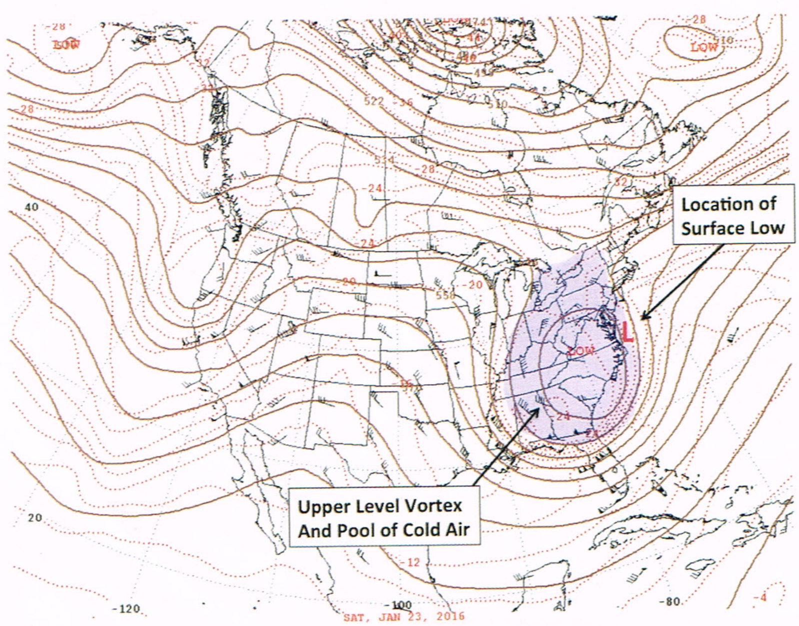


Figure 3. Upper air analysis of the blizzard on Saturday, January 23, showing the airflow at 18,000 feet as measured by weather balloons. Note the large pool of cold air, trapped inside a vortex or low pressure center.

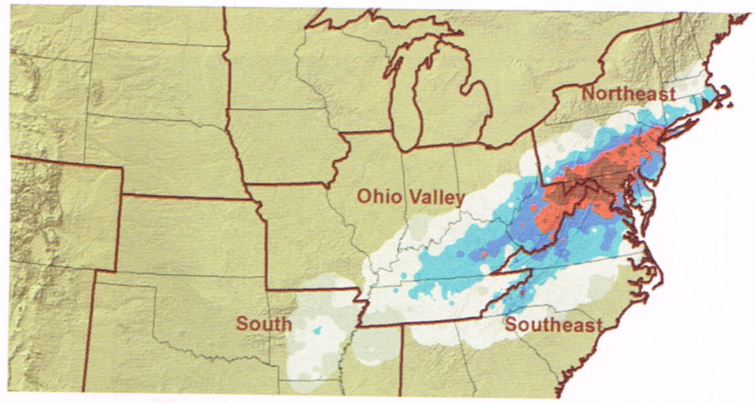
mb and rapidly deepening. Within the heavy snowband, snowfall rates approached two to three inches per hour, at times accompanied by lightning and thundersnow. What was causing the thundersnow? The answer: unusually warm ocean water. Courtesy of the Gulf Stream current, the water was four to five degrees warmer than average for this time of year. The air mass over the Gulf Stream destabilized (became warm and humid), and as this plume was drawn into the storm center, it energized snowburst-type thunderstorms over the mid-Atlantic.

Another key feature was the tight pressure gradient to the north of the low's center—essentially a crowding together of isobars, signifying a large change in pressure over distance. Low central pressure in the storm, combined with strong high pressure over Canada, contributed to this pressure gradient. The air responded by accelerating from the northeast (this is how Nor'easters get their name), reaching hurricane-force over the vast, low-friction surface of the North Atlantic. Like a fist, these high winds slammed into the coastline of Delmarva and New Jersey (large red arrow in Figure 2). The long-duration fetch of high wind heaved the seas into enormous waves, causing beach erosion and property damage. The winds whipped heavy snow into the white-out of true blizzard proportions for some locations. (By definition, a blizzard requires winds greater than 35 mph for more than three hours in the presence of snowfall, reducing visibility to less than one-quarter mile.)

The surface chart for this storm is busy, but betrays significant activity occurring in the upper atmosphere that contributed to the storm's violence. The upper-air chart at 18,000 feet altitude is shown in Figure 3. This is the level where westerly winds in the jet stream begin to intensify (increasing speed at higher altitudes), and it also reveals the position of wave-like features in the undulating jet stream. The major feature of interest is a pronounced trough or "dip" in the jet stream over the entire eastern United States. It is labeled "LOW" in Figure 3, and became so amplified that it pinched off into a closed vortex. Within this vortex was trapped a pool of extremely cold air. Cut off from the rest of the jet stream, the vortex began to slow and meander, essentially becoming stationary over the Appalachians. The surface-level Nor'easter was located along the eastern margin of the huge vortex, along the coast (large red "L"). The surface low and upper vortex were connected by vigorously rising air, and in fact dynamic motions in the vortex are what *caused* the air to rise, leading to a drop in surface pressure.

Normally the storm and its upper-level wave are progressive, moving to the northeast. But when a closed upper-level vortex forms, it slows, and the surface low migrates westward into it. The Nor'easter thus stalled off the Delmarva, contributing to very deep snow accumulation. The heavy snow band shown in Figure 2 was essentially "parked" across the mid-Atlantic and New England for 12–18 hours.

Not shown are additional, important processes even higher up, at the 30,000-foot level. At these heights, the jet stream screams along at high speed. It takes on the broad, meandering curves reflected at 18,000 feet, but also develops small pockets of super-fast winds, called jet streaks, entering the base of the vortex (southwest corner) and exiting along its northeastern side. Airflow in these jet streaks is highly unbalanced, and in an attempt to restore equilibrium, air rises rapidly over the center of the Nor'easter. This causes the surface pressure to drop even more rapidly, further intensifying the storm. These so-called "dual jet streaks" are a hallmark of the most intense East Coast snowstorms. In addition to deepening the storm, they also pump in more low-level moisture off the ocean and draw down additional cold air from the north. The result: For an extended period, the Nor'easter becomes "supercharged" with the very ingredients it needs to manufacture prodigious quantities of snow.



Region	RSI	Category
Northeast	20.138	5
Southeast	13.776	4
Ohio Valley	9.959	3
South	0.382	0

Figure 4. The Regional Snowfall Index (RSI) for the January 22–23 snowstorm rated at a phenomenally high Category 5 or Extreme category, in terms of total population impacted by the widespread, heavy snow.

Record Snowfall and Societal Impact

The Nor'easter dumped extreme amounts of snow on several major cities, including Richmond, Virginia; Washington, D.C.; Baltimore, Maryland; Philadelphia, Pennsylvania; Newark, New Jersey; and New York City, New York. An accumulation map is shown in Figure 4. The band of 18 inches or more stretched from eastern West Virginia to Long Island. Within this band, large regions exceeded two feet, and several pockets approached the three-foot mark. NOAA's Regional Snowfall Index (RSI) is designed to rank storms in terms of societal impact, and place them in historical context. It is based on an earlier measure called the Northeast Snowfall Intensity Scale (NESIS). Both RSI and NESIS use GIS-mapping techniques to examine the correlation between population density and amount of snow. Population-dense regions that coincide with heavy snowfall garner high intensity scale scores. The RSI geographically breaks down according to sub-regions. The storm of January 22–23, 2016, in the Northeast was rated a Category 5, the highest possible ranking with a verbal description of "extreme," which is one step beyond a "crippling" (Cat 4) storm. Very few storms of the past are in the same league as that of January 22–23, 2016.

Extreme snow totals for this event included 66 inches atop Mount Mitchell in North Caorlina; 42 inches in Glengary, West Virginia; 39 inches in Philomont, Virginia; 38 inches in Red House, Maryland; and 38 inches in Greencastle, Pennsylvania. New all-time event accumulation records were set at the following major air terminals: Newark, New Jersey, and LaGuardia, New York (28 Inches); Baltimore Washington International Airport (29 inches); Harrisburg, Pennsylvania (30 inches); JFK airport, New York (31 inches); and Allentown, Pennsylvania (32 inches).

Additional societal impacts include 55 storm-wide fatalities (many of them due to heart attacks and motor vehicle accidents), over 10,000 cancelled flights, and nearly 480,000 power outages. Many of the outages occurred across North Carolina, due to a crippling (0.5–0.75 of an inch) coating of freezing rain. Preliminary estimates place economic losses at $850 million, but this is likely to exceed $1 billion dollars; some estimates trend as high as $3–4 billion.

Coastal Impacts

Powerful Nor'easters deal a crippling blow to coastal zones and pose a deadly hazard to commercial ships (fishing, shipping, and cruise liners). These threats are under-appreciated, due to all the attention on heavy snow in the major cities. NOAA's Ocean Prediction Center, located in College Park, Maryland, routinely monitors marine storms and issues warnings for high seas and strong winds. Satellites have become an important tool in the Weather Prediction Center's arsenal. Microwave radiometers ping the ocean's surface with short bursts of energy. Able to penetrate thick clouds, the returned signals provide

NOAA

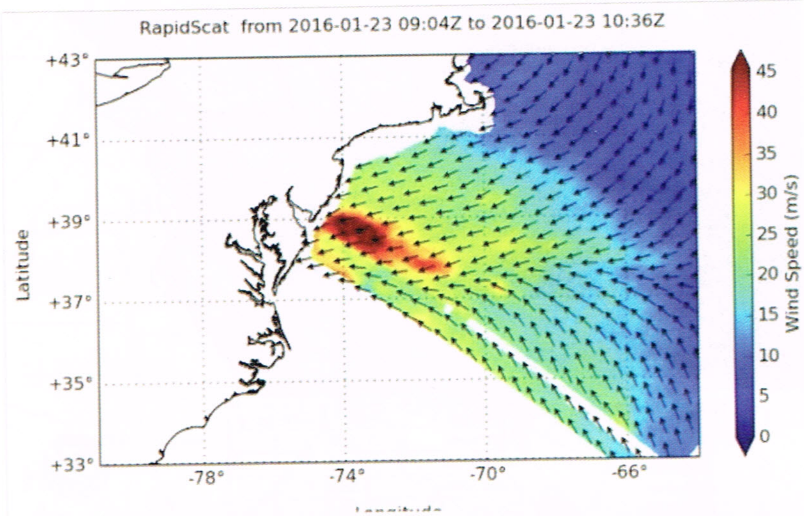


Figure 5. RapidScat overpass at 4 a.m., January 23 showing a large footprint of tropical-storm force (> 39 mph) winds off the East Coast (light green color), with en embedded region of hurricane-force (> 74 mph) wind (dark red) near the mouth of Delaware Bay.

an accurate assessment of peak wind speed and direction over large areas. An overpass from the RapidScat satellite sensor on January 23 is shown in Figure 5. Revealed is a region of hurricane-force winds off the Delaware Bay, sufficient to raise 30- to 40-foot waves in the open ocean. The satellite technology, which has matured over the past decade, is revealing a higher frequency of hurricane-level winds in wintertime ocean storms than previously thought.

Strong wind gusts blasted the East Coast from Tidewater, Virginia, to Maine. The highest gusts occurred along the shoreline. Some peak gust values are as follows: 85 mph, Assateague, Maryland; 75 mph, Dewey Beach, Delaware; 73 mph, Siasconsett, Massachusetts; and 68 mph, Tuckerton, New Jersey. Maximum sustained winds along the shore fell in the 53–57 mph range from Tidewater, Virginia, to Delaware.

Forecasting the Storm

Forecasting the January 22–23 Nor'easter marks a major success for the medium-range forecast models. A five-day lead time for a "crippling storm" and one of "historic significance" for the mid-Atlantic (Washington, D.C./Baltimore region) was generated by all the major models (including the American and European). The fact that the models arrived at such an early consensus, and remained locked on a single solution so far in advance, gave forecasters an unusually large dose of confidence. This confidence even prompted the issuance of a rare "Blizzard Watch" two days in advance for portions of the mid-Atlantic. This stands out in stark contrast, because the history of predicting these big, high-impact storms is marked by notable successes *and* failures. The infamous President's Day Snowstorm of 1979 was a major forecast "bust," back when medium-range forecasting was in its infancy. In contrast, the March 13–15, 1993, Superstorm—which brought heavy snow and high wind from Alabama to Maine—was an unprecedented forecasting success, with four to five days lead time and unusual concurrence among competing models.

While the historical snow forecast was a dead-ringer for the Nor'easter's bull's-eye over Washington, D.C., and Baltimore, locations on the northern fringe of the snow shield posed a serious forecast challenge. The NWS forecast office in Binghamton, New York, highlighted this extreme northern gradient, with 32 inches falling over Allentown, Pennsylvania, and only two inches over Scranton, Pennsylvania—a

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Snow depth in Montgomery County, Maryland.

distance of just under 50 miles. The forecast for New York City, New York, was for six to 12 inches, but the region received double to triple this amount. The medium-range models advertised that heavy snow would remain south of New York City, while a higher-resolution, short-term model called the North American Model (NAM) suggested much higher amounts for the big city. Thus, there was major uncertainty as to where the sharp northern cutoff to heavy snow would set up. Per a detailed analysis by Steve Gregory of Weather Underground, the major, heavy snow band on the northwest side of the storm advanced further north than predicted by the medium range models.

There has been much discussion pitting the American Global Forecast System (GFS) model against its rival, the European Center for Medium Range Forecasting (ECMWF) model. Both models nailed the January 22–23 storm. But statistically, over many years, the ECMWF has out-performed the GFS. During Superstorm Sandy, the ECMWF was the only model that predicted the infamous "left turn" of the storm into New Jersey six to seven days out, while the GFS model kept the storm out to sea. But the ECWMF is not always the top performer. During February 2015, a crippling New England snowstorm missed New York City, despite warnings for two- to three-foot snows. Preparations prompted the unnecessary closure of the New York subway—unprecedented in advance of a snowstorm. The forecast error stemmed from over-reliance on the European model, which predicted a direct hit on New York City, when in fact the GFS was more on target, shifting the heavy snow band eastward, over Long Island. The current director of the National Weather Service, Dr. Louis Ucellini, recently announced several key improvements that will be made to the GFS. These include a better way to initialize the model, allowing observations to be pulled in sequentially, over time, as opposed to lumping them all at the model's start time. Additionally, a new mathematical technique will be employed to better filter out bad data that would otherwise cause model errors to grow over time.

One can argue that the seeds for the January 22–23, 2016 storm were sown weeks in advance. Insights provided by Dr. Michael Ventrice of Weather Service International (as discussed by the *Washington Post's* Capital Weather Gang) implicate a potent tropical precursor, called the Madden Julian Oscillation (MJO), among other favorable large-scale patterns. The MJO is a massive disturbance containing thunderstorms that repeatedly moves eastward out of the Indian Ocean and into the tropical Pacific. The confluence of this region with warm El Niño waters,

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Street flooding in Ocean City, New Jersey, on January 23.

near the International Dateline, flared up a large area of tropical thunderstorms. These thunderstorms, in turn, heated mid-levels of the atmosphere, causing the mid-latitude jet stream to develop strong north–south undulations. Strong undulations are tied to especially intense low and high pressure regions at the surface, over North America. Add to this a phase of the North Atlantic Oscillation (NAO) that enabled unusually chilly air to spill southward down the East Coast, and ingredients over the broad environment converged for a classic, intense Nor'easter. This is *not* the same as saying that the MJO or NAO directly triggered the January 22–23 storm, but rather led to a series of tropical-mid latitude adjustments in the general circulation—a type of pre-conditioning that increased the odds of a big East Coast snow storm.

But these tropical, mid-latitude connections are not easily recognized in real-time practice, and often require the benefit of hindsight to sort out. For instance, we now know that the record cold wave over North America during the winter of 2014–2015 may have been in part triggered (or at least set up) by a super typhoon over the western Pacific! The "fuzzy" boundary between tropical, mid-latitude weather interactions, *upstream* of North America (to the far west), and the generation of extreme weather events over the United States is a relatively novel field, but one that is sure to generate some interesting surprises in the future. W

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