E History of Sandy and Hurricanes in the Northeast

This appendix provides material that is supplementary to Chapter 1.

E.1 Timeline and History of Hurricane Sandy

Like many tropical systems, Hurricane Sandy originated as a tropical wave that emerged off the west coast of Africa on October 11, 2012.[1] Most tropical waves are harmless and bring vital precipitation to island nations of the Caribbean, but some tropical waves evolve into tropical disturbances, then tropical depressions, tropical storms, and eventually hurricanes. Once a storm achieves depression status it is officially termed a tropical cyclone.

One week later on October 18, the tropical wave that would become Hurricane Sandy was disorganized in the eastern Caribbean Sea, in an environment with too much wind shear present to allow it to develop. Computer models continued to show the potential for development, and on October 20, deep convection increased, with a broad area of low pressure forming and drifting toward the southwestern Caribbean Sea. The reduced shear environment there was conducive for hurricane development, and on October 22 a tropical depression was formed approximately 305 nautical miles south-southwest of Kingston, Jamaica; Tropical Storm Sandy formed 6 hours later.

The southwestern Caribbean is a common place for tropical cyclone formation in late October, and Sandy initially followed the typical north and northeast motion at this time of year toward Jamaica. On the morning of October 24, Sandy became a hurricane with an eye about 80 nautical

1 All information about the life cycle and evolution of Hurricane Sandy was obtained from *The Hurricane Sandy Tropical Cyclone Report* from the National Hurricane Center (NHC 2013b).

miles south of Kingston and made landfall later that day with winds of approximately 86 miles per hour (mph) as a Category 1 hurricane (refer to Table B-1). Sandy rapidly intensified after briefly crossing Jamaica over the warm waters between Jamaica and Cuba. In the early morning hours of October 25, Sandy made landfall as a Category 3 hurricane near Santiago de Cuba with winds estimated at 115 mph.

TERMINOLOGY

Extratropical cyclone: A larger than average storm system with established fronts, a cold core, and a shape resembling a comma instead of the roughly circular shape of tropical cyclones.

Post-tropical storm: A type of extratropical storm that was once tropical.

Tropical cyclone: A storm with a concentric circulation, tropical convection near the center, and a core of warm air near the center.

Tropical wave: A roughly linear-shaped feature of lower pressure, clouds, and showers embedded within the flow of the tropical trade winds moving from east to west.

Wind shear: The change in wind speed and/or wind direction with increasing height in the atmosphere. Excessive wind shear disrupts tropical cyclone formation and can also destroy well-developed hurricanes.

Sandy rapidly weakened after crossing Cuba and began to undergo extratropical transition, resulting in a rapid increase in the size of the storm. On October 25 and 26, Sandy entered a dry autumn air mass over the Bahamas, and was also influenced by an upper-level trough to the west (lower heights in the atmosphere and colder temperatures). The combination of these two factors initiated the tropical to extratropical transition. The maximum winds of Sandy began to decrease, but the size of the storm rapidly expanded as a warm front formed on the northeastern side of the storm, well removed from the center of circulation, and a stationary front formed on the northwestern side. The deep convection near the center, a trademark of tropical cyclones, dissipated for a short time. At this point, Sandy was a hybrid storm, but more tropical than extratropical.

The extratropical transition stalled on October 27 as Sandy moved northeast away from the negative influence of the upper-level trough and the lower atmosphere also became more humid. Since the water was still above 80 degrees near the Gulf Stream, Sandy redeveloped a tropical convective core and achieved hurricane status again while still maintaining the extratropical cyclone frontal structures on the periphery of the storm. At this time, the radius of maximum winds extended over 100 nautical miles from the center, making Sandy one of the largest hurricanes ever recorded in the Atlantic.

On October 28, Sandy passed over the Gulf Stream southeast of North Carolina, and initial evidence suggested the formation of a tropical eye once again. Normally, before arriving at this latitude, late October tropical cyclones are swept out into the Atlantic by the mid-latitude westerly winds. Sandy began to turn northward off the North Carolina coast on October 29 due to a peculiar atmospheric pattern over the Atlantic. The northward turn brought Sandy directly over the warm Gulf Stream, while the upper level atmospheric pattern to the west of the storm reduced the wind shear. The combination of reduced wind shear and warm water allowed Sandy to intensify to a Category 2 hurricane with approximately 98 mph wind speeds on the morning of October 29 approximately 220 nautical miles southeast of Atlantic City, NJ.

A rapid northwest turn ensued toward the New Jersey coast, and Sandy's forward speed accelerated to over 20 knots. Structural changes from tropical to extratropical began to occur on the afternoon of October 29 as Sandy began to ingest drier and cooler Canadian air on its western side while also moving over cooler waters closer to the New Jersey coast. Temperatures near the ocean surface at the center of the storm dropped 46.4°F during the day on October 29, and by 5 p.m. Eastern Daylight Time, about 45 nautical miles southeast of Atlantic City, Sandy was declared post-tropical. The center of post-tropical cyclone Sandy made landfall at Brigantine, NJ, with estimated sustained winds of 80 mph and a minimum pressure of 945 millibars. The pressure at landfall was typical of Category 3 hurricanes (refer to Table B-1), but the observed wind speed was on the lower end of Category 1 hurricane intensity.

Although Sandy no longer possessed the technical characteristics of a hurricane at the time of landfall, it still had a large radius of maximum wind that extended 1,000 miles (three times that of a typical hurricane). These winds, along with the storm's low pressure, were responsible for significant storm surge. Furthermore, the perpendicular angle of approach and its counterclockwise onshore winds drove the surge directly into the New York and New Jersey metropolitan area.

After landfall, Sandy moved through southern New Jersey, northern Delaware, and southern Pennsylvania. It lost its defined center passing over northeastern Ohio on October 31, and what remained of the storm continued over Ontario, Canada, before merging with a low pressure area over eastern Canada.

Hurricane Sandy Track

The track of Hurricane Sandy was unique for an East Coast storm. Hurricane tracks are controlled by pressure patterns. Normally the subtropical high pressure zone occupies much of the Atlantic Basin between the latitudes of 20 and 40°N during the peak months of hurricane season, July to October. When the subtropical high is farther east, many tropical cyclones will dissipate over the ocean and never make landfall in the United States.

If the subtropical high is in a more neutral position, it is common for tropical cyclones to take a track that parallels the eastern coast of the United States before turning into the Atlantic. In this scenario, the North Carolina coast is commonly hit because it is the easternmost prominence of the continent in the southeastern United States. Likewise, the edges of the Massachusetts coast including Cape Cod, Martha's Vineyard, and Nantucket are often struck by a parallel track for the same reason. Occasionally storms skirt the East Coast on a northward track, making an initial landfall in North Carolina and then traversing the Chesapeake region followed by New Jersey and eastern Pennsylvania.

Hurricane Sandy initially followed the typical path of tropical cyclones originating in the Caribbean in late October (NHC 2013a). Sandy was disrupted after passing over eastern Cuba, and atmospheric steering pushed it north. Sandy then resumed a typical track northeastward toward the open Atlantic and away from the coastline until reaching 35°N latitude. At this point, Sandy encountered a strong blocking ridge over the mid- and higher latitudes of the Atlantic. This blocking ridge was so strong that it completely altered the atmospheric flow throughout the northern hemisphere. The normal west to east progression of weather systems and fronts in the mid-latitudes was disrupted so that systems were forced up and over the top of the ridge, but not before considerable blockage was produced. A hydrological analogy would be a large dam on a reservoir with a side spillway. The strong atmospheric ridge that produced the blocking pattern also caused a trough of cold air from Canada to deepen because the trough was not able to climb over the top of the ridge. Once the trough deepened into the southeastern United States, it also tilted negatively (backwards), causing atmospheric flow over the Mid-Atlantic States to anomalously flow toward the northwest. This sequence of events turned Sandy from a northeasterly track to a northerly track, then northwest, and ultimately almost due west before landfall. This series of meteorological events resulted in an unusual landfall orientation nearly perpendicular to the New Jersey coast.

E.2 Northeastern Storm History

The northeastern region of the United States has had powerful storms make landfall in the past. These have included Tropical Storm Irene and the three nor'easters described in the sections that follow. Additional information on coastal flood and wind events that occurred between 1900 and 2010 and that affected the northeastern United States can be found in Volume 1 of FEMA P-55, *Coastal Construction Manual* (2011a).

E.2.1 March 5–9, 1962 Nor'easter

Known as "The Great Atlantic Coast Storm" or "Ash Wednesday Storm," this nor'easter affected almost the entire eastern seaboard of the United States and caused extreme damage in the mid-Atlantic region. As the storm intensified on March 5 and moved up the eastern seaboard, it was slowed by a high-pressure system over Canada on March 6. As the storm slowly moved up the U.S. East Coast on March 7 and 8, it was elongated by the southward-moving high-pressure system. This caused a deep pressure gradient on the north side of the storm, creating north-easterly winds and a long fetch, which produced high storm surge and large waves (Zhang et al. 2001). As documented by Wood (1976), the high winds associated with this slow-moving storm included peak gusts of up to 84 mph, and the high winds continued for 65 hours. In many locations, waves 20 to 30 feet high were reported. Compared to the diameter of an average hurricane (600 to 700 miles), this nor'easter was much bigger, with a diameter of 1,500 miles. It also lasted longer than most hurricanes—the nor'easter lasted through five successive high tides. The size and length of the storm, combined with its occurrence at the peak of the spring tides, combined to cause large amounts of damage (O'Brien and Johnson 1963). Flooding caused severe beachfront erosion, inundated subdivisions and coastal industrial facilities, and toppled beachfront houses, sweeping them out to sea. It required the evacuation of coastal areas, destroyed large sections of coastal roads, and interrupted rail transportation in many areas. In all, property damage was estimated at half a billion dollars (in 1962 dollars) (FEMA 2011a) and took 33 lives (Cooperman and Rosendal 1962).

E.2.2 Halloween 1991 Nor'easter

The Halloween 1991 Nor'easter, also known as the "Perfect Storm," formed on October 28. At the same time it formed, a hurricane named Hurricane Grace moved northward; the two merged on October 29. The nor'easter moved west-southwestward from October 29 to 31, then northward on November 1. The broad scope of the storm and long duration resulted in erosion and considerable property damage, in excess of $168 million (in 1991 dollars), and 12 deaths along the East Coast. The Halloween 1991 Nor'easter was similar to the nor'easter of March 1962 in that the long fetch generated large waves, some over 40 feet in height, it had wind gusts near 80 mph, and it lasted for several tidal cycles (National Weather Service 1991).

A FEMA *Flood Damage Assessment Report* (FEMA 1992) documented damage to buildings along the south shore of Long Island, NY, and in the Boston, MA, area, and noted the following:

- Pre-FIRM at-grade buildings were generally subject to erosion and collapse; at least one was partially buried by several feet of sand overwash.
- Some buildings were damaged by flood-borne debris from other damaged structures.
- Some pile-supported buildings sustained damage because of inadequate pile embedment; some settled unevenly due to loss of bearing capacity; and some were damaged by collapse of the *landward* portion of the foundation (the landward failure was attributed to original piles that were less deeply embedded than the seaward portions of the foundation, which had been repaired after recent storms).
- In areas subject to long-term erosion, buildings were more vulnerable to damage or collapse.
- Although erosion control structures protected many buildings, some buildings landward of revetments or bulkheads were damaged by wave overtopping and erosion behind the erosion control structures.
- Buildings on continuous cast-in-place concrete foundations performed better than those on continuous masonry block foundations (such as those permitted in Zone A), and were generally more resistant to wave and flood damage; however, some continuous cast-in-place concrete foundations were damaged when footings were undermined by erosion and localized scour.

E.2.3 January 4, 1992 Nor'easter

The January 4, 1992 Nor'easter occurred only a few months after the Halloween 1991 Nor'easter; in comparison it was relatively short lived and small. It developed rapidly and moved fast. Landfall occurred right around high tide during the highest tide of the month along the Delaware Coast, with wind gusts reported up to 50 mph (Delaware Geological Survey 1992).

The January 4, 1992 Nor'easter was the most intense and damaging in coastal Delaware and Maryland since the March 5–9, 1962 Nor'easter. A FEMA Building Performance Assessment Team (BPAT) inspected damage in six Delaware and Maryland communities. The resulting report documented the following conclusions (FEMA 1992):

- Damage was principally due to storm surge, wave action, and erosion. Beaches affected by the January 4, 1992 Nor'easter had not fully recovered from the Halloween 1991 Nor'easter, which left coastal areas vulnerable to further damage.
- Buildings constructed to NFIP requirements fared well during the January 4, 1992 Nor'easter. For those buildings damaged, a combination of ineffective construction techniques and insufficient building elevation appeared to be the major causes of damage.

- For some pile-supported buildings, inadequate connection of floor joists to beams led to building damage or failure. Obliquely incident waves were believed to have produced non-uniform loads and deflections on pile foundations, causing non-uniform beam deflections and failure of inadequate joist-to-beam connections. The report recommends three possible techniques to correct this problem.

- Some buildings had poorly located or inadequately fastened utility lines. For example, some sewer stacks and sewer laterals failed as a result of erosion and flood forces. The report provides guidance on locating and fastening sewer connections to minimize vulnerability.

- Many pile-supported buildings were observed to have sustained damage to at-grade or inadequately elevated mechanical equipment, including air conditioning compressors, heat pumps, furnaces, ductwork, and hot water heaters. The report provides guidance on proper elevation of these units.