WINTER STORM INTENSITY, HAZARDS AND PROPERTY LOSSES IN THE NEW YORK TRI-STATE AREA

Cari E. Shimkus[1], Mingfang Ting[1], James F. Booth[2], Susana B. Adamo[3], Malgosia Madajewicz[4], Yochanan Kushnir[1], Harald E. Rieder[5,1]

1) Lamont-Doherty Earth Observatory, Columbia University; 2) City University of New York, City College; 3) Center for International Earth Science Information Network, Columbia University; 4) Center for Climate Systems Research, Columbia University; 5) Wegener Center for Climate and Global Change and IGAM/Department of Physics, University of Graz, Austria

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Corresponding author address: Mingfang Ting, Lamont-Doherty Earth Observatory, 61 Route 9w, Palisades, NY 10964. E-mail: ting@ldeo.columbia.edu

ABSTRACT

Winter storms pose numerous hazards to the U.S. Northeast including rain, snow, strong wind, and flooding. These hazards cause millions in damages from one storm alone. This study investigates meteorological intensity and impacts of winter storms from 2001–2014 on coastal counties in Connecticut, New Jersey, and New York, and underscores the consequences of winter storms.

The study selected seventy winter storms based on station observations of surface wind strength, heavy precipitation, high storm tide, and snow extremes. Storm rankings differed between measures, suggesting intensity is not easily defined with a single metric. Several storms fell into two or more categories ("multiple-category storms"). Following storm selection, property damages were examined to determine which types lead to high losses. The analysis of hazards (or events) and associated damages using the Storm Events Database of the National Centers for Environmental Information indicates that "multiple-category storms" were responsible for a greater portion of the damage.

Flooding was responsible for the highest losses, but no discernible connection exists between the number of storms that afflict a county and the damage it faces. These results imply that losses may rely more on the incidence of specific hazards, infrastructure types and property values, which vary throughout the region.

1. Introduction

The US Northeast coast is among the most densely populated in the country, hosting an array of urban centers with extensive built infrastructure and economic activity that spans the globe. The populations and interconnected infrastructure of communities located on the Atlantic and nearby riverine coasts are exposed to assorted hazards associated with winter storms, which are exacerbated by rising sea levels.[1 – 3]

The New York tri-state area, which here refers to the coastal areas of New York, New Jersey, and Connecticut, is exposed to warm season tropical cyclones and cold season extratropical cyclones. These storms exhibit similar coastal impacts in terms of storm surge if the rare (i.e. 1 or 2 events in the past 40 years), most extreme events are excluded.[4] Given the high frequency of extratropical cyclones, it is important to capture the distinct social and infrastructure vulnerabilities to winter storm hazards in the region, especially because extratropical storms are variable in terms of their intensity, frequency, path, precipitation types and temperature characteristics. Extratropical cyclones generate multiple impacts, including inland and coastal flooding, wind damage, and snow inundation. The hazards that cause these impacts are the focus of our study.

Snowstorms lead to billions of dollars in damages and send facets of society into disarray, claiming lives and undercutting the transportation sector.[5- 8] Smith and Katz found that from 1980 to 2011, ten winter storms in the U.S. sustained over $1B in losses each (in 2011 dollars).[9] More recently, several winter storms struck the Northeast during winter 2015 with near or record-breaking snowfall, crippling cold, and intense winds leading to school closures, business shutdowns, power outages, and serious travel disruptions.[10 – 12]

Zielinski focuses on meteorological features of winter storms to devise a classification scheme for evaluating storm intensity and aiding in impact prediction.[8] However, he does not take losses into account for his categorization. Instead, he concentrates on physical intensity and duration, and discusses possible social disruptions in general terms and the constraints in corresponding them to the categories.[8] Alternatively, Kocin and Uccellini incorporated snow totals, snowfall area, and population impacted into their classification instead of relying on meteorological or social facets alone.[13] Their classification suggests that storms causing comparable snowfall accumulations in various regions are more severe when hitting regions with higher populations.[5, 13]

Rooney discussed social "disruptions" that result from winter storms.[14] He characterized snowstorms on the level of disruption they inflict on social sectors (e.g. first order-paralyzing, second order-crippling), including transportation, communication systems, etc. Although Rooney did not directly assess costs, his theory followed that first order storms would boast greater economic consequences since a paralyzing storm would halt travel, trade, etc. while simultaneously causing damage, require snow removal funds, etc.[14] For example, a slow-moving storm may lead to the same amount of snow as a fast-moving storm, but the snowfall rates will vary greatly, which is an important distinction when considering the social response.[8]

To enhance our knowledge of winter storm hazards and the susceptibility of human systems to their impacts, and how this intersection might change in the future, this study devises a ranking of storm intensities based on meteorological parameters, and then bridges those storm characteristics to their financial impact and locations where they are concentrated. We designate wind, precipitation, storm tide, and snow depth as four measures of winter storm intensity and develop a ranking to identify the twenty strongest storms in each category. We subsequently compile the physical property damage costs (not economic losses) for the storms selected to determine if storm damages correlate with the meteorological measures of intensity, which serves as a foundation for extrapolating future impacts.

Coastal communities face numerous uncertainties concerning future storm intensity and related impacts, which partially stem from a disparity between social and physical causes. Kunkel et al.'s examination of winter storm catastrophes from 1949 into the 1990s hinted at a potential increase in east coast winter storms, but stressed the influence of heightened vulnerability on the uptick in damage.[15] Barthel and Neumayer studied loss patterns from 1973 to 2008 and argued that there is no perceptible surge in winter storm losses and posited the "most important driver of future economic disaster damage" is the location of assets in vulnerable regions.[16] Thus, we deduce that existing literature disagrees about trends and causes of changes in winter weather hazards.

The uncertainties in the trends of intensity and societal impacts highlight the need to better quantify present day winter storm intensity measures and the damage they inflict on the built environment. This study begins uncovering this relationship and our results aim to inform adaptation measures established by local decision-makers to prepare coastal communities for the perils of winter storms and enhance their resiliency in the aftermath.

2. Materials And Methods: Storm Selection

2.1 Winds, Precipitation, and Snowfall

This study uses the Daily Summary Data from National Oceanic and Atmospheric Administration (NOAA) Integrated Surface Database (ISD).[17] The ISD consists of synoptic observations from surface weather observation stations, ranging from airports to military bases.

The Daily Summary dataset is a quality-controlled subset of the ISD provided by NOAA. The key variables we examine are total 24-hour precipitation, sustained wind maximum, and 24-hour snowfall. NOAA defines sustained wind maximum as the maximum of the 2-minute averages from each hourly observation reported for the day (personal communication, Mark Lackey, NOAA). We focus the analysis on the sustained wind maximum rather than the wind gust because the data is more frequently available for our study period and region. For snowfall, we use the daily snow depth data in the ISD and calculate daily differences in depth to estimate the daily snowfall amount. The ISD snow depth data is provided with 0.1 inch accuracy. The list of stations used is provided in S1.

2. 2 Water Level

The study uses the NOAA Tides and Currents database (https://tidesandcurrents.noaa.gov/). The data has been quality controlled and is provided as anomalies to mean datum relative to the National Tidal Datum Epoch (NTDE). The NTDE in this study is 1981 – 2001, and the mean used is the mean higher high water (MHHW). The NOAA website provides the measured water level (relative to the MHHW) and the predicted water level (relative to zero). Therefore, we add the MHHW for each station to the retrieved water level data to compile the storm tide values that we analyze. The water level data is provided at an hourly interval. We calculate daily averages for our analysis. This is because we are interested in identifying the events that create a high water for a sustained period of time. Storm tide is distinct from storm surge in that storm surge captures only a portion of the full water level experienced during a storm (surge at high tide versus surge at low tide, for instance). Therefore, we utilize storm tide as our water level metric since it better indicates events that might lead to flooding and damage. The list of stations is included in S2.

2.3 Identification of Extreme Storms for All Categories

Station data for each of the 4 variables (precipitation, surface wind speed, snowfall, and tide) are averaged across all stations at each time step to create a single time-series, and then the strongest 20 events are identified. We require that events occur at least 2 days apart to guarantee that each is associated with a separate extratropical cyclone. For events occurring within 5 days, the sea level pressure (SLP) fields from reanalysis were analyzed visually to check whether separate, closed low-pressure systems caused the extreme events.

Storm dates are crosschecked with National Weather Service archives to ensure they encompass the full length of an event for the entire study area.[18, 19] Then we assess the relationship between the meteorological intensity metrics and losses by searching storm dates in the National Centers for Environmental Information (NCEI) Storm Events Database to collect information on the identified hazards and property damages for each storm.[20] We examined the database for all counties and hazards for one day before the storm and three days after to capture all storm impacts. In the case of successive storms, the search range is adjusted to avoid duplication.

The Storm Events Database provides information on reported hazards or ‘events’ for each storm, such as coastal flooding, heavy rain etc. The study’s storm categories represent a particular hazard that we focus on as a measure of overall storm intensity and the presence of a storm in a category means it ranks among the strongest for that specific hazard (i.e., precipitation, winds, storm tide, or snowfall). However, our rankings do not represent all possible winter storm hazards, and all storms, regardless of category, can experience a variety of hazards (or events in the Storm Events Database) simultaneously, from winds and snowfall to flooding. Therefore, in the remainder of the paper we use the term “category” or “class” to refer to the four characteristics that we used to rank and identify the extreme storms, and use “hazard” or “event” to refer to the reported damage types in individual storms in the Storm Events Database. In the present discussion, the terms hazard and events are used synonymously.

Based on data from the National Centers for Environmental Information Storm Events Database and documentation instructions from the National Weather Service, the term event refers to the occurrence of a hazard in a specific location.[20, 21] Reports can include the names of individual cities affected, but the official locations listed in the reports must refer to National Weather Service forecast zones/counties.[20] Event types reported for the Storm Events Database are defined in the National Weather Service Directive 10-1605 and include single hazards like high wind and coastal flooding or complex events like blizzard and winter weather. The latter two are similar event types that the Database distinguishes for various reasons, including when multiple hazards are present, a hazard occurs for a certain length of time, conditions meet warning criteria, etc.,[21] but we synthesize similar event types in the present study to streamline our comparisons of hazards and associated damages. For example, winter precipitation denotes blizzard, winter storm, winter weather, and/or heavy snow, wind refers to strong and/or high wind events, and coastal flood encapsulates any reports of coastal flooding, high surf, and/or storm surge/tide.

3. Results: Meteorological Characteristics

3.1 Extreme Storms by Category

The study focuses on a ranking of winter storms in categories based on four features of extratropical cyclones, precipitation, surface wind speed, storm tide, and snowfall amount in the period from 2001 – 2014, for the months November – April. The November – April months are chosen to focus on the cold season extratropical storms; any hazard associated with storms with tropical cyclone origin are excluded from the analysis (see Ref. 4 for details on how events are associated with tropical cyclone origins). A list of twenty storm dates is identified for each of the four storm feature categories (precipitation, surface wind speed, storm tide and snowfall amount) using the methods outlined in section 2.

We compared the top 20 events in each of the four storm ranking categories to identify any storm that fell into more than one category. This yielded 9 storms that were placed in a new group, which we termed multiple-category storms. The dates of these storms were then removed from the individual categories, leaving 18 wind, 17 precipitation, 12 storm tide, and 14 snowfall storms. In the multiple-category, one storm was in the top 20 in three categories, and the other 8 were in the top 20 in two categories. The low number for individual storm tide and snowfall events indicates that their strongest storms often occurred simultaneously. It is important to note that the precipitation category includes all precipitation types, liquid and solid. However, even though precipitation encompasses snowfall, the two categories contain no overlapping storms, indicating that the precipitation metrics capture snow reaching the ground far less for the heaviest precipitation events. All storms included in this study are listed in S3.

There are a few notable patterns in the distribution of storm category occurrence per month (as displayed in S4). About 45% of ranked storm tide storms occurred in December and due to the prevalence of storm tide in the multiple-category, the greatest portion (44.44%) of its storms also happened in December. The predominance of storm tide storms in December is somewhat unexpected (Colle et al. found an equal number of moderately strong surge events in December and January[22]), but further investigation found this uptick in December storm tide events was unique for the epoch that we analyzed (2001 – 2014). Additional information can be found in S5.

The largest percentage of snowfall storms occurred in February (38.10%), which is consistent with the results of Kocin and Uccellini for snowfall events exceeding 10 inches (their Fig. 2-11).[7] March and April experienced the highest incidence of precipitation storms (30% and 25%, respectively), while not one of the top 20 precipitation events occurred in January. As with the storm tide analysis, this result is unique to the time period used for the study. A subsequent analysis of 1981 – 1996 and 1991 – 2006 found 3 and 4 storms in January, respectively. However, for each of the 16-year epochs, there is a local minimum in precipitation events in the cold months (not shown). Wind storms have a more even distribution across months, except April which did not have any storms in this category.

3.2 Analysis of Typical Weather Metrics

A storm's sea level pressure (SLP) minimum is one common metric used to provide an estimate of its' strength. Therefore, we investigated the minimum SLP for each of the selected storms in Table 1, using the daily mean SLP on the date that the extreme weather event occurred. For each storm date, the SLP field is determined and the minimum SLP value is identified within the region bounded by 92.5W x 57.5W and 55N x 32.5N, which is a region centered on our study area. Figure 1a shows the distributions of the SLP minimum (in hPa) for each storm class including the multiple-category. We did not exclude the multiple-category storms from the individual categories, which allows the plot to show the entire range of the pressure distribution for each storm class and how it compared to the multiple-category storms. The wind and snowfall storms have lower mean values for central pressure minima, as compared to those in the precipitation and storm tide classes. However, the differences are not statistically significant based on a student t-test. The December 26 – 28, 2010 storm had the lowest pressure of all storms in the study (967.7 hPa), and as this storm created both wind and snowfall extremes, it appears in the multiple-category as well.

While the multiple-category designation appears to denote an intense storm given the measures of the mean (987.7 hPa) SLP minimum, the category also boasts great variability and has one of the highest central pressure values. As a result, it is difficult to draw deeper conclusions about the nature of its intensity, and SLP in general may not be an illuminative measure of storm strength. One possible reason for large SLP minimum variability in the multiple-category may be due to the fact that its greatest contributor is the storm tide class, whose distribution of SLP minima is at the higher end of all the storm classes.

Another reasonable measure of winter storm intensity is the maximum surface wind. Figure 1b shows the distribution of maximum surface winds (m/s) per storm class including the multiple-category. The wind metric is based on the multi-station average on the date of the event, which is the same metric used to identify the strong wind events. As we expect, the wind storm category has the strongest winds and smallest spread among all storms with a mean of 15.04 m/s. The multiple-category holds the second strongest winds in the study, indicating that the overlapping storms in each storm class tend to be biased toward the higher surface wind end. The precipitation, snowfall, and storm tide categories all have a similar distribution of wind maxima that is much less intense than the strong wind and multiple classes. As a result, surface wind maximum, like the SLP minimum, is not by itself a good indication of strong storms in general.

4. Results: Property Damage Characteristics

4.1 Damages by Storm Rankings

To link the storm strength to possible storm damages, Figure 1c shows the distribution of the storm losses as collected by NCEI for each storm class. In this case, the multiple-category storms are excluded from the single storm class to avoid overlap in damage depictions. It is clear that multiple-category and snowfall class exhibit the widest distributions and are comprised of storms with the highest losses. Multiple-category is the only class with events that caused storm damage above $100M and snowfall contains a few storms with costs surpassing $10M. The precipitation, storm tide, and wind categories sustained much lower damages overall. Several storms in the precipitation and snowfall classes caused no damage. The precipitation category experienced a higher damage total than the storm tide and wind classes while the storm tide class has the lowest total, but a greater portion of its storms led to some damage.

Even though the wind category has the most storms and demonstrates the strongest surface winds (Fig. 1b), it contains the smallest individual storm damage maximum value ($ 4,820,000) in Figure 1c. The multiple-category is the costliest class and contains the strongest winds after the wind category, suggesting that wind speed may be a better measure of storm impacts than, say, minimum sea level pressure, for instance. Snowfall storm costs followed multiple-category, but its wind distribution in Figure 1b is similar to the precipitation and storm tide categories, which had little damage in the study. Based on these findings, wind intensity alone is not always a fitting parameter to extrapolate damage.

It is important to note that the damages archived by NCEI and the damages described in this study focus on the direct physical property damage and do not reflect the full economic losses caused by storms. NCEI's data includes damage to both public and private property, but reported damage totals exclude items like overtime, debris cleanup, and snow removal.[21]

The sum of the damage for all states and storms (70 total) is $ 372,693,800. Figure 2a illustrates the total damage amount for each category and their relative contribution. Numbers in parentheses denote the number of storms in the category. The multiple-category, which consists of 9 storms, contributed 63.59% of the total cost for the storms in this study (Fig. 2a). The remaining four storm classes together led to $135,698,300 in total losses from 61 storms. The snowfall category was the second costliest, making up 27.08% of the overall damage while storm tide was the least damaging category (2.27% of the overall costs). Because there are an uneven number of storms in each category, the per storm loss was also estimated in Figure 2a for each category, with multiple-category storms showing the largest per storm loss with over $26M per storm, followed by snowfall.

Furthermore, 98.77% of the damage for the multiple-category storms, and 62.80% of the total damage for all storms, came from the April 15 – 16, 2007 and March 12 – 15, 2010 storms with their losses totaling $234,070,000 combined. March 12 – 15, 2010 was the only storm to qualify for three classes (precipitation, storm tide, and wind) while all other multiple-category storms fell into two classes. The fact that such a large percentage of the storm losses came from few storms is consistent with Changnon and Changnon, who compared the national peak loss phases and peak snowstorm frequencies for storms between 1949 and 2000 causing more than $35M in damages.[5] They found that the two peaks do not coincide, which suggests that the greatest national losses did not necessarily correspond to a higher number of storms.[5]

Each winter storm, whether it is classified as a strong wind storm or heavy snowfall storm, may incur damages in assorted hazard forms (i.e. those reported by the NWS), such as coastal or inland flooding, snow, or wind. Displayed in the pie chart in Figure 2b is the breakdown of damage amounts for winter storm hazards for all storms combined. One single hazard type, inland flooding, accounted for more than 40% ($170,829,000) of the property damages associated with winter storms in the tri-state area. Many other hazards are present such as various forms of winter precipitation leading to 25.5% of the total damages, coastal flood causing just over 20% and wind driving as little as 7% of the overall losses. Within each storm category, however, the dominant losses are from the particular hazards as seen in Table 1, which illustrates the loss percentages for each hazard per class of storm. The wind and snowfall class losses are overwhelmingly driven by wind and winter precipitation, respectively. The majority of the storm tide damages are caused by coastal flood with smaller amounts from wind and winter precipitation. Most multiple-category and precipitation losses result from inland and coastal flooding.

For the multiple-category class in particular, Table 2 illustrates the breakdown of damages per hazard for each storm. All storms except December 5-7, 2003 faced some level of wind damage. Even though the total loss from winter precipitation for all storms combined was considerable, only two multiple-category storms sustained winter precipitation damage and it was minimal. The April 2007 and March 2010 storm experienced the brunt of the losses from inland and costal flooding, and only four of the nine storms had damages above $1M.

The predominance of flood losses may be consistent with previous studies that found: (1) flood losses are among the costliest, if not the costliest, hazard plaguing the U.S.,[23 – 25] and (2) suggestions that flood losses have been on the rise,[15, 23, 25] albeit perhaps due to social forces.[15, 23] Interestingly, after flooding, the costliest hazard type was winter precipitation, which encompasses several intense hazards, such as snow and wind, suggesting again greater impacts often transpire when storms are intense in many respects.

When looking at the distribution of reported hazards with and without damage per storm category (Fig. 3), wind and winter precipitation are the most widely reported hazards across all storm types. Coastal and inland flood reports appear common but are less prevalent. In general, the storm classification we employed is fairly consistent with the reported hazards, i.e., more flooding and heavy rain events associated with precipitation storms, more winter precipitation events for snowfall class storms, and greater numbers of wind events associated with wind storms. For the strong tide storms, the most frequently reported events are strong winds, indicating a link between storm surges and coastal floods with onshore wind. The multiple-category is comprised primarily of winter precipitation, wind, and coastal flood. This pattern is logical since these hazards correspond to our storm categories at large (i.e., snowfall, wind, storm tide) and the multiple-category groups the storms that exhibit several of the intensity metrics we designated.

4.2 Spatial Distribution of Damages

To determine which geographic location in the study area tends to incur the most storm damage, Figure 4a illustrates the damage for each county within the study area for all seventy storms combined. Losses are unevenly distributed spatially. New Jersey counties with the highest damages, Bergen and Somerset, are not located directly on the coast. In New York, high losses occurred in Suffolk, a coastal county on Long Island, and New York, which is Manhattan island of New York City. These four counties incurred greater than $20M in reported losses.

New Jersey incurred the highest damage with $ 232,421,800 or 62.36% of the overall damage (Fig. 4b). Considering the large land area under examination in New Jersey in comparison to the other states, we also calculated the damages per unit area (land area values provided by the U.S. Census Bureau as square miles and converted to square kilometers).[26] The average cost per km^2 in New Jersey was $17,320.17. Connecticut endured the lowest damage total of $12,891,000, which originated primarily from the precipitation storms while New Jersey and New York suffered most damage from the multiple-category. Connecticut's low damages therefore support the notion that storms possessing several physical intense characteristics are stronger and more costly.

The two costliest storms, April 15 – 16, 2007 and March 12 – 15, 2010, spurred significant inland flood losses, followed by March 29 – 31, 2010. In general, inland flood losses are higher and more widespread. Somerset and Bergen counties sustained $63M and $52.4M, respectively, in damages from inland flooding (please refer to Figure 4a for county location). Much lower were county coastal flood losses amounting to less than $5M except for Suffolk's $64M. Even though coastal flood costs were much less than inland flood losses, Suffolk County's stark damage value necessitates adaptive action by local communities since the sea level, and thus coastal flood threats, are rising.[27, 28]

We cannot speak to whether the greatest driver of inland flood damage is a physical parameter (such as precipitation or storm surge) or social and infrastructural vulnerabilities. Therefore, future research is needed on the relationship between the meteorological storm properties and social conditions that contribute to flooding so that appropriate adaptation measures can be established to address the current vulnerabilities and the consequences of habitual flood events expected with climate change, especially when taking into account enhanced precipitation predictions.[28]

5. Results: Case Studies

While it is interesting to examine the general characteristics of the storm damages and the associated hazards, it is clear that these characteristics are storm dependent. In particular, a few of the costliest storms account for the majority of the total damages reported in this study. This motivates us to examine further the meteorological and damage characteristics of each costly storm in this section. Figure 5 shows precipitation (TRMM-3B42) in mm/day,[29] sea level pressure (hPa), surface winds in m/s from ERA-Interim reanalysis,[30] and cyclone tracks based on the Hodges cyclone-tracking algorithm[31] applied to 6-hourly SLP fields from ERA-Interim for each of the six costliest storms. To determine how meteorological conditions and damage amounts correspond, we compared the distribution of damage between hazard types for each of the costly storms (all storms with damages above $10M) in Figure 6.

Consistent with Figure 1a, Figure 5 indicates that center pressure appears to be a weak indicator of storm intensity or damage amount for the winter storms. Among the six costly storms, only two of them (January 22 – 23, 2005 and February 8 – 10, 2013) possessed a relatively deep low pressure center and 100% of their damage resulted from winter precipitation. However, they also sustained the lowest damages of the six, which suggests pressure is not the best indicator for damage amount. For example, the SLP for April 15 – 16, 2007 (Fig. 5c) shows that the low pressure center was relatively weak, yet it was the most damaging storm by far, mainly through inland and coastal flooding (Fig. 6c). Overall, a very weak relationship (and not statistically significant at the 95th percentile) exists between the sea level pressure (SLP) minimum (hPa) for each storm in the study and their corresponding total damages (not shown). The connection between the costs of each storm and their associated SLP anomaly (defined with respect to a daily climatology for 1979-2014) is a bit stronger, but overall, both comparisons indicate pressure intensity is not a strong parameter for predicting damage intensity.

There is an absence of wind storms among the costliest storms, except for March 12 – 15, 2010 (Fig. 6e), which is classified as multiple-category with extremes in precipitation and storm tide storms, in addition to wind. All the other storms that fell into the wind category caused less than $5M in losses and the percentage of wind damage among the costly storms was less than 4%. However, studies often discuss wind as impactful when it occurs with another winter storm hazard simultaneously,[8, 14, 32] which seems to be consistent with the March 12 – 15, 2010 storm and support the notion that the damaging storms incorporate multiple intensity metrics.

Even if wind intensity is not a strong individual parameter for damage, wind direction, in conjunction with a cyclone's track, is important to consider in assessing damages.[33] The March 12 – 15, 2010 storm led to costly flooding and generated intense precipitation, with the heavy rainfall along the coast in Figure 5d. The winds directed onshore towards the study area, are ideally oriented for creating storm surge in the NYC region.[22] Also the wind speeds in this region for this storm are among the strongest for all the storms listed, and although the coastal flooding is a smaller percentage of the storm's losses, the inland flooding costs, attributed to overwhelmed rivers, were sizable. Finally, the storm stalled off the coast (as indicated by the abrupt end to the storm track), allowing the winds to blow towards the study region for a prolonged duration. This finding is in line with Zielinksi, who noted that the duration of onshore winds could lead to high levels of flooding and erosion, particularly if a storm lingers long enough for more than one high tide.[8]

The station-measured wind speeds for January 22 – 23, 2005 (Fig. 5b) are just as strong as March 12 – 15, 2010, but winds are blowing offshore. The onshore winds in the vicinity of NYC that occurred earlier in the storm life cycle were weaker (not shown), and the path of the storm is not typical of those that cause strong storm surge in the NYC region.[4] Consistent with this, the 2005 storm did not lead to any flood losses.

For the February 2013 and January 2005 storms, the cyclones' centers begin over land and then hook towards the north (Figs 5b, f). The same is true of the path for the two costly storms that generated multiple-category extremes (Figs 5c, d). Although the sample size is small, it raises the possibility that the tracks of the winter storms along with the costal wind direction may be the best indicator of type of storm damages (flooding (Figs 5c, d) versus winter weather-related damages Figs 5b, f)) based on our analysis. This would be consistent with the results of previous work on storm surge[4] and wind storms.[33]

6. Limitations

A few caveats regarding the National Centers for Environmental Information's Storm Events Database and the property damages analysis should be discussed. The NWS Directive 10-1605 advocates that documenters enter damage amounts for all events where possible, but the only events specifically mentioned as requiring a monetary value in the documentation process are floods per a U.S. Army Corps of Engineers mandate.[21] However, Downton et al. argue that even the flood damage information captured by *Storm Data* is still imperfect since estimates are processed quickly and published without much verification.[34] Interestingly, 86.6% of the reported floods (coastal and inland) in our study still reported $0 in damage. The information in the database can come from a variety of sources, including the U.S. Army Corps of Engineers, emergency managers, U.S. Geological Survey, media, utility companies, or insurance companies, if available.[21]

To give credence to the data, it is important to note that quality concerns are not unique to NCEI's database. Gall et al. reviewed several data sources, including the NCEI data, the Spatial Hazard Events and Losses Database for the United States, the Natural Hazards Assessment Network, and the Emergency Events Database, detailing their assorted constraints and biases.[35] Restricted access, inconsistent reporting procedures across sources, and disparities in coverage for certain impacts are a few of the many conditions that make examining extreme event damages difficult.[36] Mentioning winter storms specifically, Kocin et al. (referenced by Kunkel et al., see Ref. 15), concur that our ability to assess and establish firm results concerning winter storm damages is constricted by irregular recordkeeping.[37]

The NCEI database does boast some benefits. Dixon et al. contend that NCEI data are readily available since they offer a frequently updated record of weather events within a searchable, online catalog.[38] The database also allows users to search by storm names (such as Hurricane Sandy) or specified time periods, counties and/or hazards. Property damage data are uploaded by the National Weather Service (NWS) about seventy-five days after a month concludes.[20] Although the accuracy of the information provided is not always confirmed,[38] we used this data due to its availability since data access was a major obstacle in our investigation. Another draw to NCEI data is that it is offered at the county/forecast zone level, thereby allowing us to conduct a more localized study. Changnon and Creech stated that although data like NCEI's may not be appropriate "for climatological assessments of the time or space dimensions of ice storms," it might be helpful "to identify locales with damaging conditions for use in case studies."[32] Thus, despite apparent drawbacks, NCEI data was useful for our goals of determining areas where hazards are concentrated under varying storm characteristics as identified by our ranking method.

7. Discussion

This study developed a list of seventy intense storms measured by wind strength, precipitation amount, storm tide, snow depth, and collected their corresponding losses as reported in the NCEI Storm Events Database. The analysis executed a distinct research approach by incorporating meteorological thresholds as opposed to a damage limit for inclusion in the analysis. The ranking method employed led to overlap in the categories, and therefore we created a fifth class designated as multiple-category.

Our investigation discovered that wind and multiple-category storms exhibited the lowest SLP minimum and mean values. However, center pressure and wind strength did not consistently relate to damage magnitude. The multiple-category class led to the highest total and per storm damages, with the greatest losses resulting from the April 15 – 16, 2007 and March 12 – 15, 2010 storms. The snowfall category was the second costliest. Overall, inland floods led to the highest damages, followed by winter precipitation. New Jersey experienced the highest losses total, but the level of damage varied geographically throughout the study region. It is also unclear what combination of factors led to the high incidence of inland flood costs.

It is important to note that this study does not capture the strain (financial, resources, and other) placed on coastal communities as a result of recurring winter storms within a season and how that corresponds to vulnerability and resilience. Analyzing the impacts of storms in close succession, in conjunction with duration and frequency, could illuminate certain vulnerabilities of locations given the stress on society and infrastructure. As Kunkel et al. state "the impact of individual snowstorms is often immediate and dramatic, but the cumulative effects of all snowstorms in a season can also be costly and disruptive."[39] Klawa and Ulbrich uncovered that substantial losses can result from an aggregate of weaker, recurrent events as they examined insured storm losses in Germany from 1970-1997.[40]

Overall, our results demonstrate that devising a single definition or classification of storm intensity and associated impacts proves difficult. The uneven breakdown of storms between categories and the disparity in damages between categories demonstrates that intensity is not uniform across physical characteristics and so the measure of financial impacts will vary as well. The study found that storms inflicting the greatest financial impact are those that are meteorologically intense in several respects. This result appears logical, but it is important to pay attention to the common characteristics of these intense storms to get a sense of what specific commonalities translate to high losses. As an individual parameter, the snowfall class was the second costliest; containing three of the six costliest storms, thereby demonstrating that snowfall intensity is directly related to high costs. On the other hand, the storm tide category (i.e., storm tide extremes that occur in isolation of the other extremes) overall caused the least damage, but since it as so widely present in the multiple-category, storm tide may inflict damage primarily when exacerbated by another intensity metric.

Nevertheless, evidence of impacts provided in this paper can serve as a baseline for the effects of certain storm strength characteristics, such as significant damages transpiring from a storm that exceeds intensity criteria for several hazards (i.e. multiple-category). However, a more in-depth analysis on the relationship between storm strength and social characteristics is needed to determine what parameters or conditions influence winter storm damages the most, particularly costly flood losses. Depending on when and where extreme winter storms occur, damages will result if the infrastructure or community is not capable of withstanding specific hazards. Knowledge and perception of the risks and how they influence preparations must be taken into account with the meteorological parameters to predict and assess impacts; precipitation amount or other physical parameters alone do not denote a specific level of "disruption."[8, 14]

The 2015 winter season brought numerous intense storm systems to the Northeast that traveled through the area over the span of several weeks, causing damages and outages, and interrupting transportation, business, and education.[10 – 12] We need to think creatively about which adaptation measures addressing infrastructure and resources will enable communities in the tri-state region to reduce future winter storm damages in the face of increasing climate-related risks, and prevent any standstills when a flurry of storms travels up the coast. Society can mitigate its own hazard losses, but decision-makers need to understand the sources of vulnerability, resilience, and the costliest or riskiest storm characteristics to make appropriate and effective policy decisions. Continued interdisciplinary research will prove indispensable for sustainable planning since it relies on knowing what meteorological parameters are leading to damage, where they are concentrated, and what sort of societal changes have been and will influence those values.

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Malgosia Madajewicz provided expertise on social vulnerability and resiliency
Yochanan Kushnir provided expertise on winter storm tracking and meteorological characteristics of storms
Harald E. Rieder assisted with storm intensity ranking

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FIGURE LEGENDS

Fig. 1 Box plots depicting sea level pressure (SLP) minimum (hPa) distributions **(a)**, surface (SFC) wind maximum (m/s) distributions **(b)**, and property damage distributions (in millions of dollars) for storms with damage above $0 using a logarithmic scale **(c)**. The middle line represents the median, dashed line is the mean, box bottoms and tops represent the first and third quartiles, edges of the whiskers denote the minima and maxima, and diamond markers signify outliers. **(a)** Multiple-category exhibits the lowest mean (987.7 hPa) but widest distribution. Snowfall, winds, and multiple-category share the lowest minimum from December 26 – 28, 2010. **(b)** Wind contains the highest mean (15.04 m/s) and shortest distribution. Multiple-category demonstrates much variability with a wide inter-quartile range and the remaining classes have a large spread of weaker values. **(c)** The multiple-category has the widest distribution and damage above $100M while a few snowfall storms led to damages above $10M

Fig. 2 **(a)** The damage amount per storm type and percentage of total damage for all storms combined. Numbers in parentheses indicate the total storms that fell in that category. Multiple-category and snowfall storms caused the most damage by far. Precipitation and wind storms had the most storms but less than 10 percent of the damage combined. Overlapping storms were placed in a new class called multiple-category. **(b)** Damage per hazard contributing to the winter storm losses total for Connecticut, New Jersey and New York combined. Hazard refers to those reported and defined by the National Weather Service in the Storm Events Database. A number of related hazards are reported separately, such as blizzard and heavy snow etc. but we have combined them here to streamline comparisons. Each hazard type's percent and damage dollar amount are listed. Inland flood losses account for most of the damages, but winter precipitation is also costly

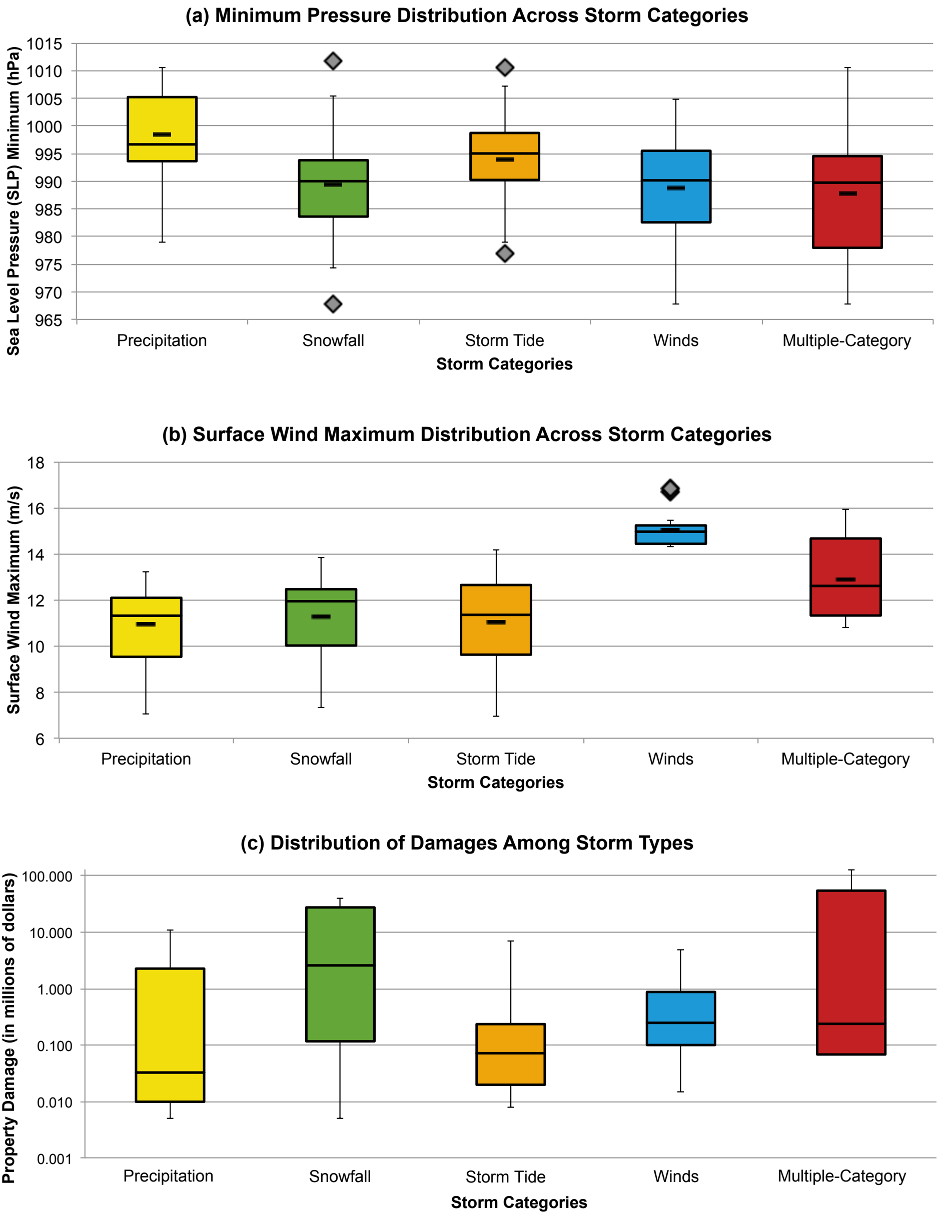
Fig. 3 **(a-e)** Distribution of reported hazards in the Storm Events Database per storm category. Related hazards types are combined, including ice storm with winter precipitation and flash flood with inland flooding. Reports with and without damage for the above hazards are included. Winter precipitation and wind are prevalent, and coastal and inland flood reports are also common. Flood events dominate the precipitation category, while the storm tide and multiple-category have a roughly similar breakdown concentrated on wind and winter precipitation. The snowfall and wind predominantly sustain their particular hazards (i.e. winter precipitation and wind, respectively)

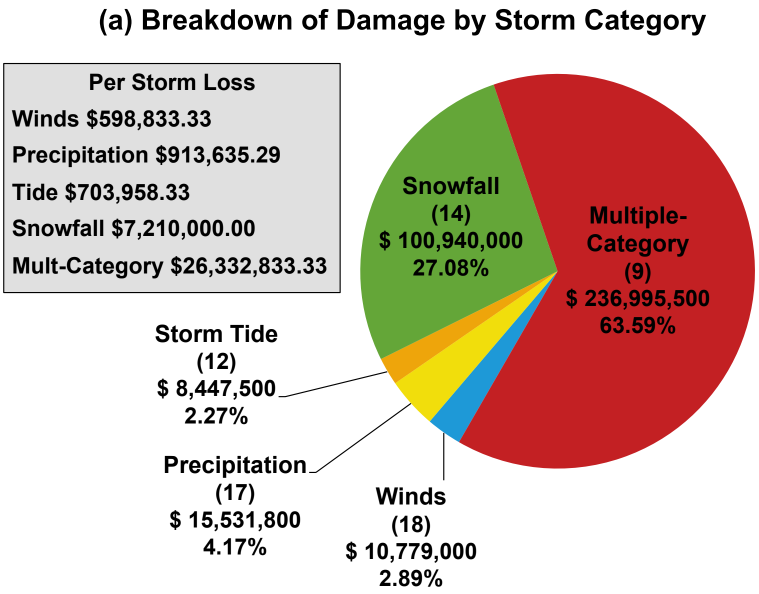
Fig. 4 (a) Map of the distribution of the total damages per county for all storms combined. Somerset, Suffolk and Bergen experienced more than $50 million in losses while New York, Atlantic, and Burlington faced more than $15 million in damages. Fifteen of the remaining twenty-six counties had damages in the $1 - $15 million range. Land area values provided by the U.S. Census Bureau (2014) as square miles and converted to square kilometers. **(b)** Breakdown of total property damage per state for all storms combined. The damage amount per state and percentage of total damage for all storms combined are listed

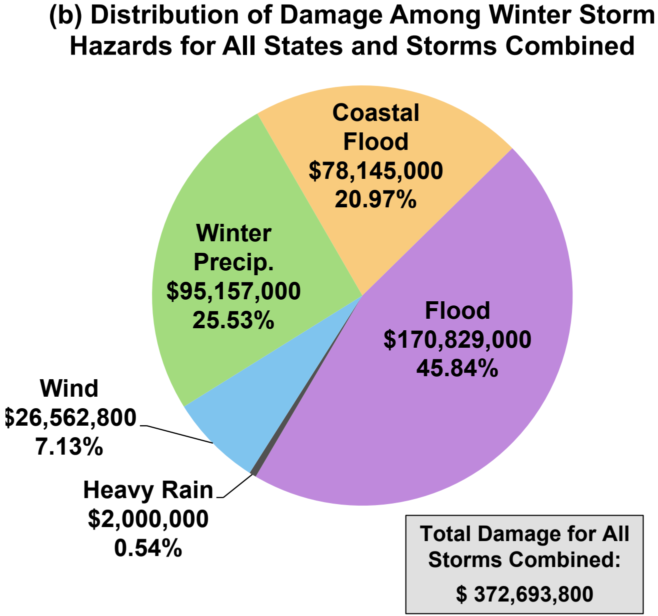
Fig. 5 Plots of daily average precipitation in mm/day, sea level pressure in hPa, storm tracks and wind vectors in m/s from centered on 12Z on the date of interest for the costliest storms. Storm tracks are found by applying the Hodges cyclone tracking algorithm (Hodges 1999) to the 6-hourly SLP fields from the ERA-Interim reanalysis. Tracks are magenta with the exception of the February 17, 2003, which has a brown storm track line. There is no track data for the March 29 – 31, 2010 storm. The contour interval is 5 hPa and the bold contours indicate 1010 hPa and 1020 hPa

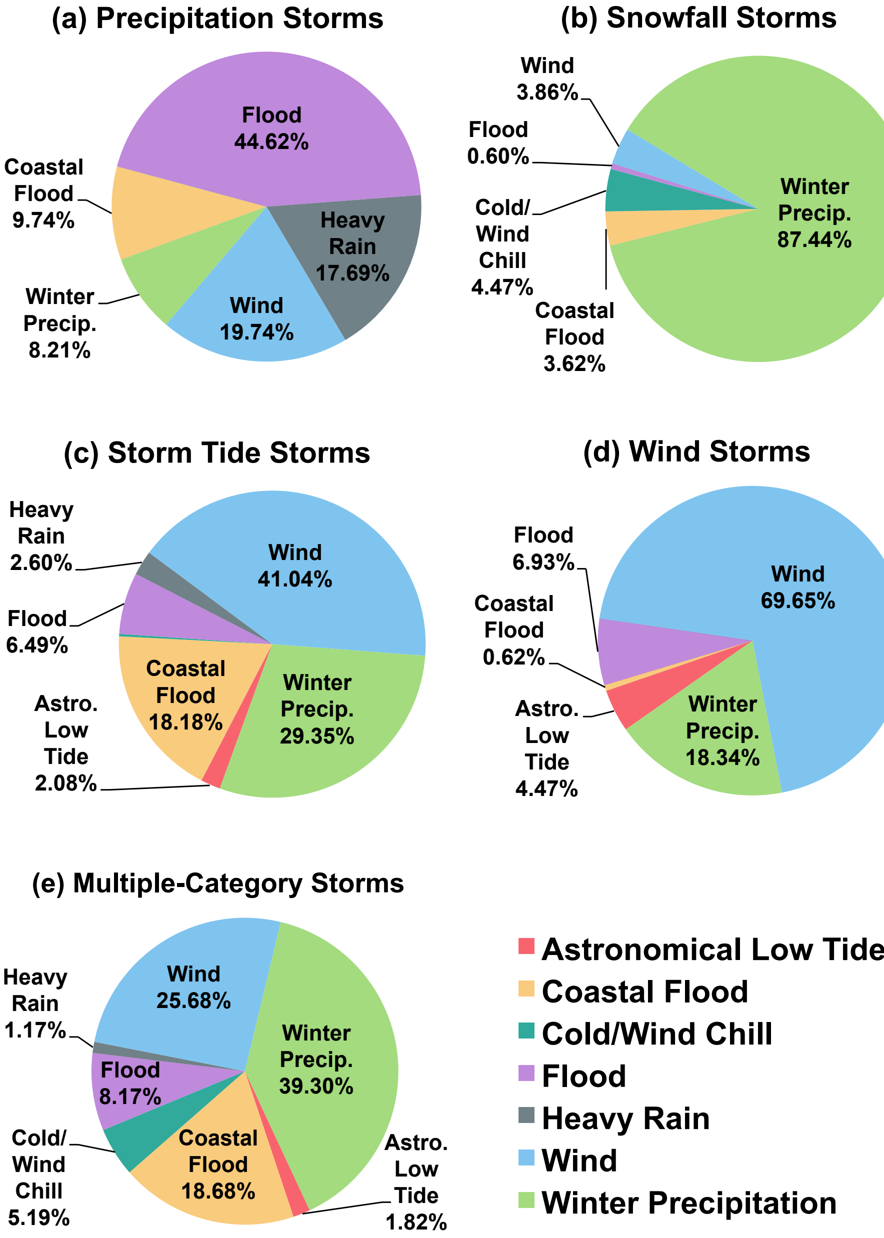
Fig. 6 Breakdown of damages per storm for the six costliest storms. The snowfall storm category boasts the greatest representation, while the storm tide and wind category are not represented individually, just through the multiple-category. Inland flood and winter precipitation lead to the most damages among these storms, while coastal flood and wind events are present but less damaging

S4 Breakdown of storm type incidence per month. December experienced the most storms in total, with the greatest number of storm tide, wind, and multiple-category storms. January, February, and March also saw an equal number of wind storms. Snowfall storms were by far more prevalent in February followed by January. Seasonal transition/spring months (November, March, April) also saw more precipitation storms, which were absent or minimal during the winter months


(a) Minimum Pressure Distribution Across Storm Categories
Sea Level Pressure (SLP) Minimum (hPa)
1015
1010
1005
1000
995
990
985
980
975
970
965
Precipitation
Snowfall
Storm Tide
Winds
Multiple-Category
Storm Categories
(b) Surface Wind Maximum Distribution Across Storm Categories
Surface Wind Maximum (m/s)
18
16
14
12
10
8
6
Precipitation
Snowfall
Storm Tide
Winds
Multiple-Category
Storm Categories
(c) Distribution of Damages Among Storm Types
Property Damage (in millions of dollars)
100.000
10.000
1.000
0.100
0.010
0.001
Precipitation
Snowfall
Storm Tide
Winds
Multiple-Category
Storm Categories

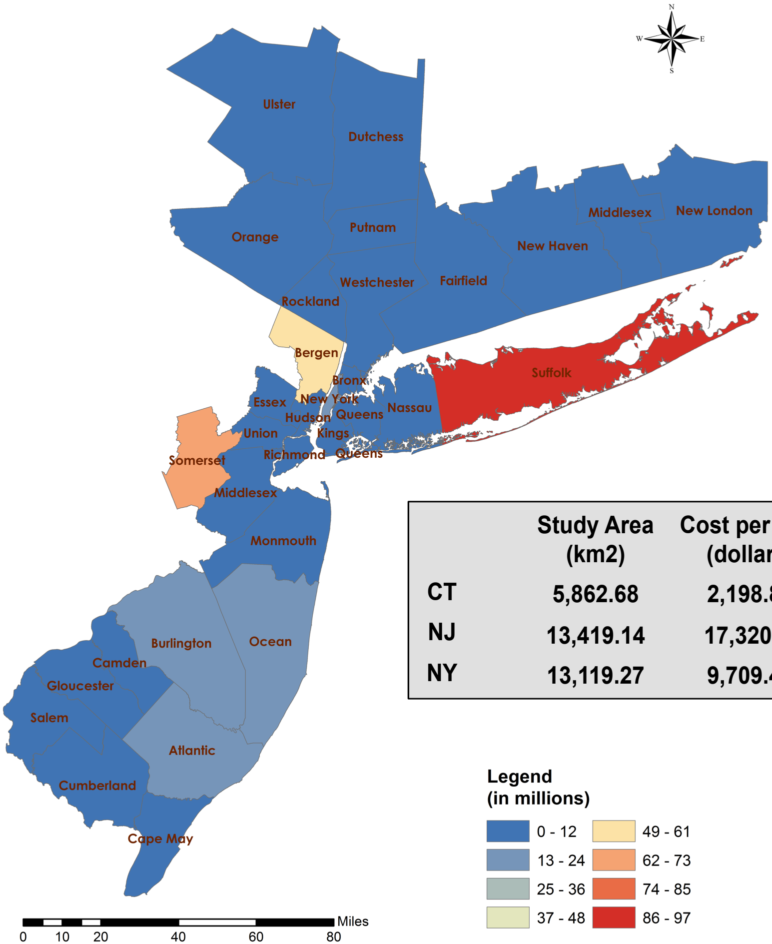

(a) Breakdown of Damage by Storm Category
Per Storm Loss
Winds $598,833.33
Precipitation $913,635.29
Tide $703,958.33
Snowfall $7,210,000.00
Mult-Category $26,332,833.33
Snowfall (14) $ 100,940,000 27.08%
Multiple-Category (9) $ 236,995,500 63.59%
Storm Tide (12) $ 8,447,500 2.27%
Precipitation (17) $ 15,531,800 4.17%
Winds (18) $ 10,779,000 2.89%


(b) Distribution of Damage Among Winter Storm Hazards for All States and Storms Combined
Coastal Flood $78,145,000 20.97%
Winter Precip. $95,157,000 25.53%
Flood $170,829,000 45.84%
Wind $26,562,800 7.13%
Heavy Rain $2,000,000 0.54%
Total Damage for All Storms Combined:
$ 372,693,800


(a) Precipitation Storms
Flood 44.62%
Coastal Flood 9.74%
Heavy Rain 17.69%
Winter Precip. 8.21%
Wind 19.74%
(b) Snowfall Storms
Wind 3.86%
Flood 0.60%
Cold/ Wind Chill 4.47%
Coastal Flood 3.62%
Winter Precip. 87.44%
(c) Storm Tide Storms
Heavy Rain 2.60%
Wind 41.04%
Flood 6.49%
Coastal Flood 18.18%
Winter Precip. 29.35%
Astro. Low Tide 2.08%
(d) Wind Storms
Flood 6.93%
Wind 69.65%
Coastal Flood 0.62%
Astro. Low Tide 4.47%
Winter Precip. 18.34%
(e) Multiple-Category Storms
Heavy Rain 1.17%
Wind 25.68%
Winter Precip. 39.30%
Flood 8.17%
Cold/ Wind Chill 5.19%
Coastal Flood 18.68%
Astro. Low Tide 1.82%
Astronomical Low Tide
Coastal Flood
Cold/Wind Chill
Flood
Heavy Rain
Wind
Winter Precipitation

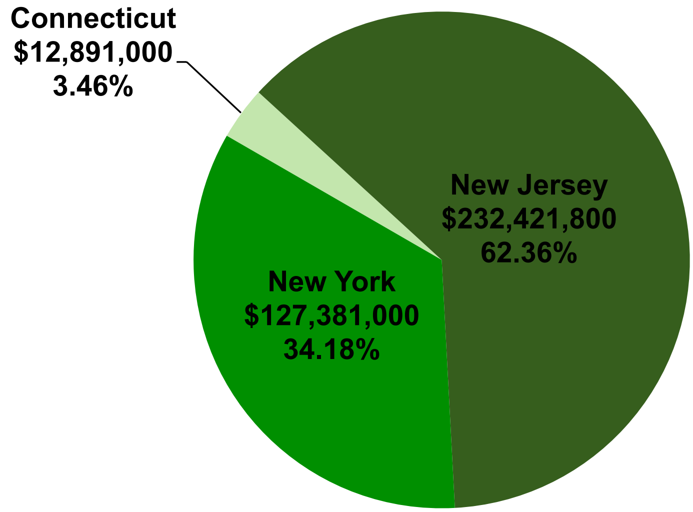
Total Property Damages per State and County for All Storms Combined

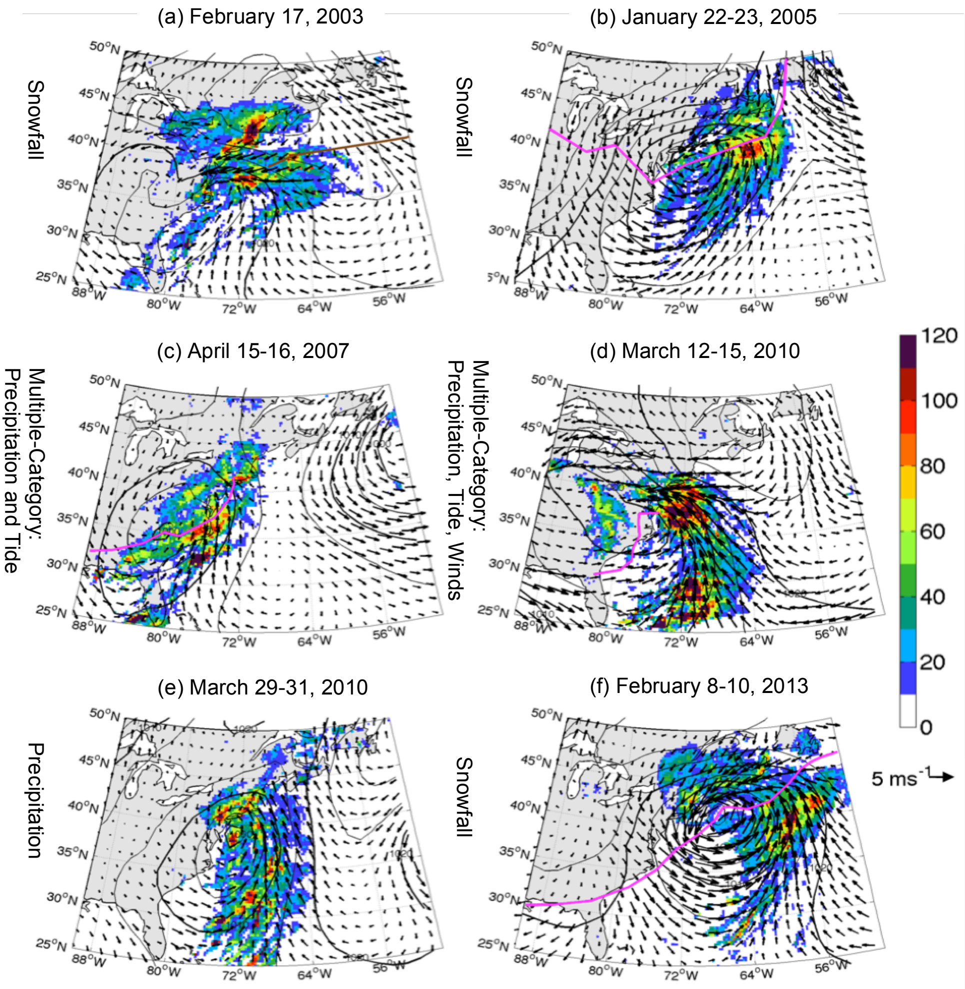
(a)



	Study Area (km2)	Cost per km2 (dollars)
CT	5,862.68	2,198.82
NJ	13,419.14	17,320.17
NY	13,119.27	9,709.46

(b)




(a) February 17, 2003
Snowfall
(b) January 22-23, 2005
Snowfall
(c) April 15-16, 2007
Multiple-Category: Precipitation and Tide
(d) March 12-15, 2010
Multiple-Category: Precipitation, Tide, Winds
(e) March 29-31, 2010
Precipitation
(f) February 8-10, 2013
Snowfall
50°N
45°N
40°N
35°N
30°N
25°N
88°W
80°W
72°W
64°W
56°W
120
100
80
60
40
20
0
5 ms-1

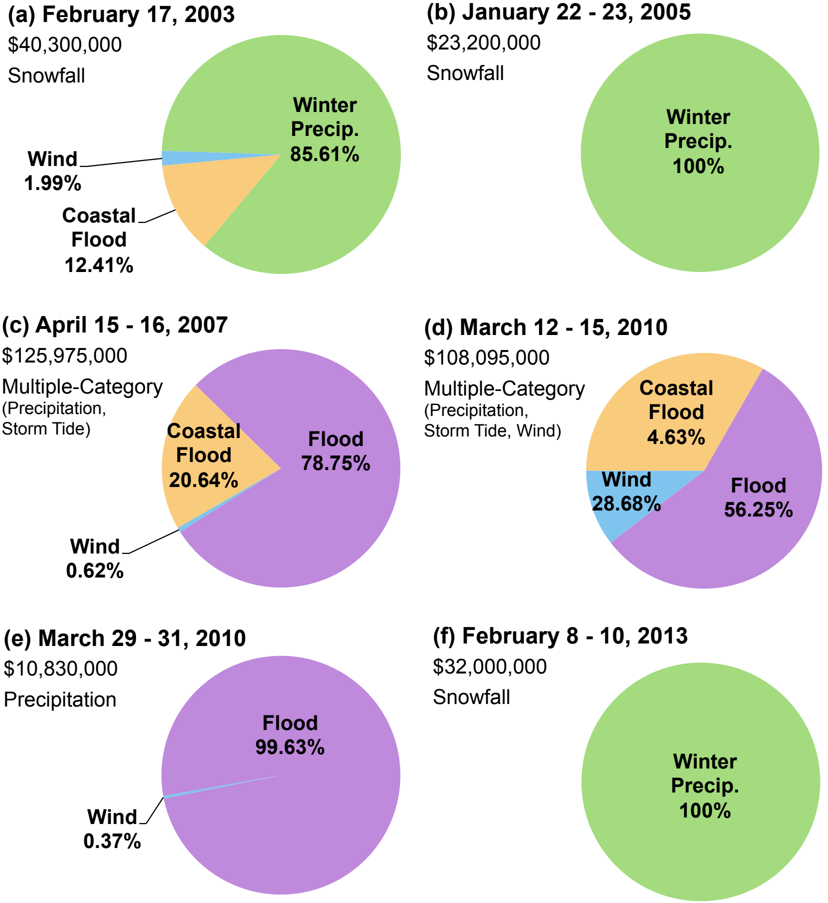

(a) February 17, 2003
$40,300,000
Snowfall
Winter Precip. 85.61%
Wind 1.99%
Coastal Flood 12.41%
(b) January 22 - 23, 2005
$23,200,000
Snowfall
Winter Precip. 100%
(c) April 15 - 16, 2007
$125,975,000
Multiple-Category (Precipitation, Storm Tide)
Coastal Flood 20.64%
Flood 78.75%
Wind 0.62%
(d) March 12 - 15, 2010
$108,095,000
Multiple-Category (Precipitation, Storm Tide, Wind)
Coastal Flood 4.63%
Wind 28.68%
Flood 56.25%
(e) March 29 - 31, 2010
$10,830,000
Precipitation
Flood 99.63%
Wind 0.37%
(f) February 8 - 10, 2013
$32,000,000
Snowfall
Winter Precip. 100%

Table 1: ***Loss Percentages for each hazard per storm category***					
	Winds	*Precipitation*	*Storm Tide*	*Snowfall*	*Multiple-Category*
Coastal Flood	0.00%	16.10%	**82.86%**	4.95%	26.85%
Flood	0.19%	**69.59%**	0.00%	0.00%	**67.51%**
Heavy Rain	0.00%	12.88%	0.00%	0.00%	0.00%
Wind	**99.81%**	1.44%	17.05%	1.03%	5.53%
Winter Precipitation	0.00%	0.00%	0.08%	**94.02%**	0.11%

S1: ***Stations used to identify precipitation, snowfall, and wind storms***			
State	*Station Name*	*Longitude*	*Latitude*
New Jersey	'MCGUIREAFB'	74.6W	40.017N
New Jersey	'NEWARKINTLAIRPORT'	74.169W	40.683N
New Jersey	'TETERBORO'	74.061W	40.85N
New York	'NEWYORK/LAGUARDIA'	73.88W	40.779N
New York	'WESTCHESTERCO'	73.708W	40.067N
New York	'STEWARTINTL'	74.1W	41.5N
New York	'NEWYORK/JOHNF.KE'	73.762W	40.639N
Connecticut	'BRIDGEPORT/IGORI.'	73.129W	41.158N
Connecticut	'TWEEDNEWHAVEN'	72.887W	41.264N
Connecticut	'GROTONNEWLONDON'	72.049W	41.328N

S2: *Stations used to identify storm tide storms*			
State	*Station Name*	*Longitude*	*Latitude*
New Jersey	Cape May	-74.9	38.93
New Jersey	Atlantic City	-74.42	39.36
New Jersey	Sandy Hook	-74	40.3
New York	Bergen Point West Reach	-74.12	40.66
New York	The Battery	-74.01	40.7
New York	Willets Point	-73.8	40.76
New York	Kingspoint	-73.73	40.81
New York	Montauk	-71.95	41.03
Connecticut	Bridgeport	-73.19	41.18
Connecticut	New Haven	-72.9	41.3

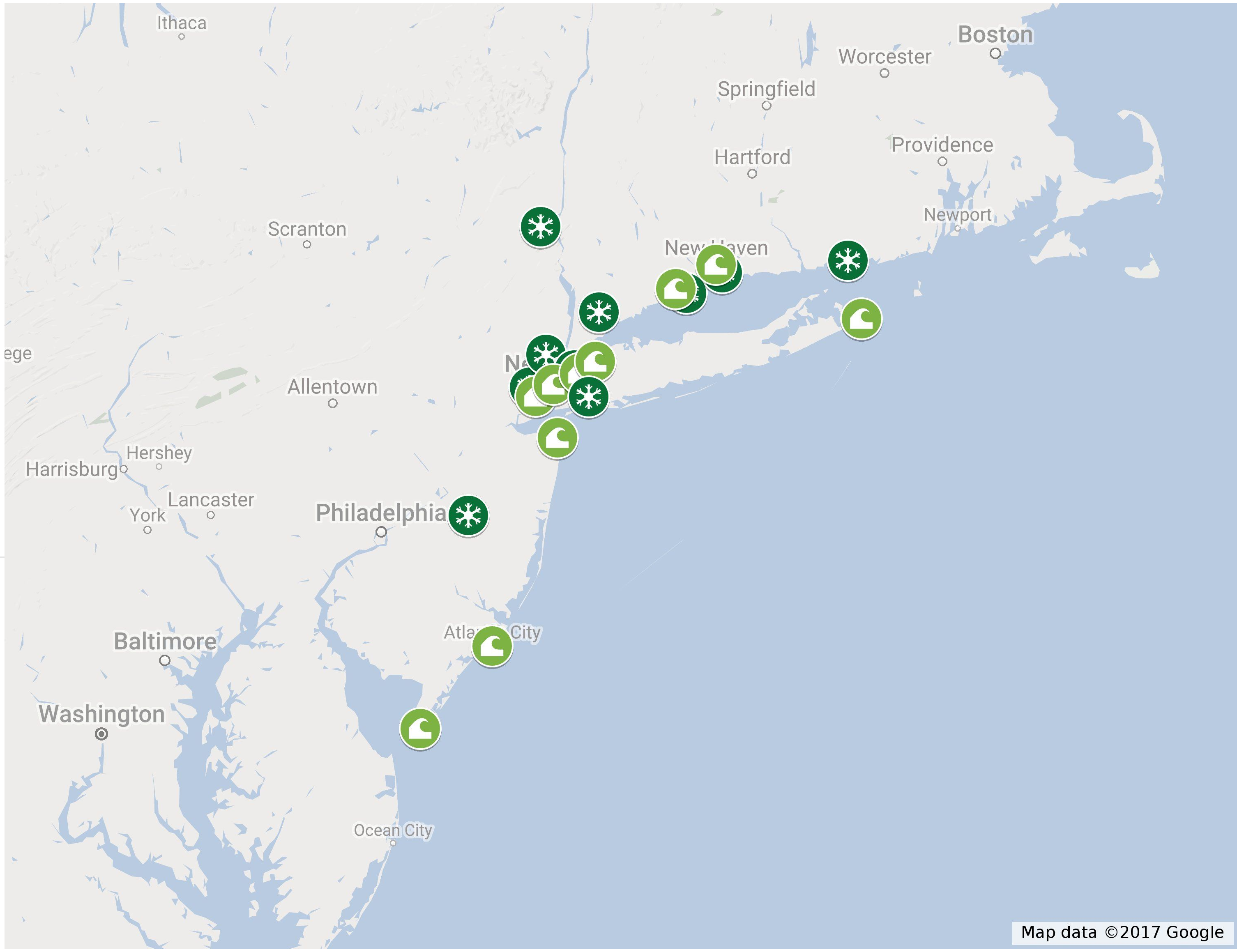
Winter Storms Supplementary Material

S1: Stations used to identify precipitation, snowfall, and wind storms

- McGuire Air Force Base
- Newark Liberty Int'l Airport
- Teterboro Airport
- LaGuardia Airport
- Westchester County Airport
- Stewart International Airport
- John F. Kennedy Int'l Airport
- Sikorsky Memorial Airport
- Tweed New Haven Airport
- Groton-New London Airport

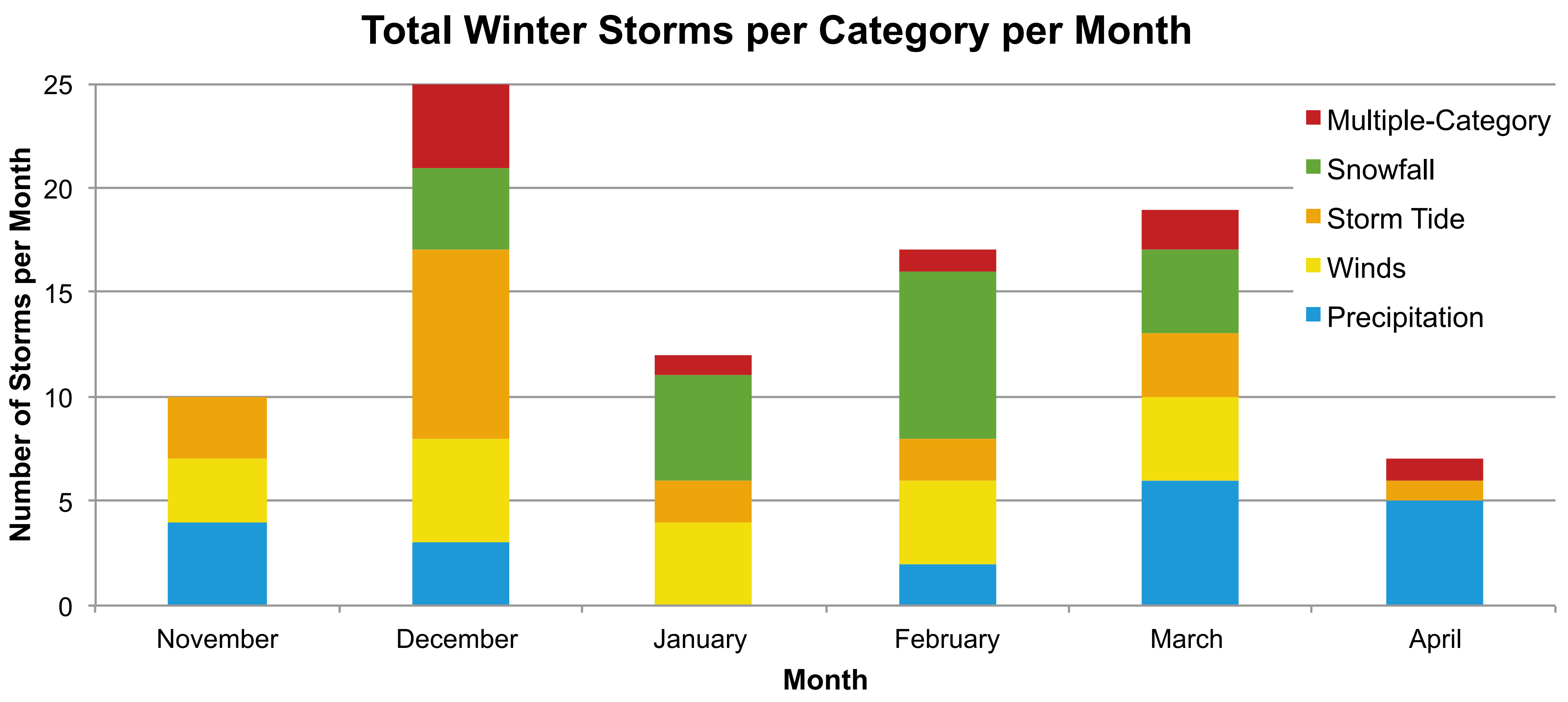
S2: Stations used to identify storm tide storms

- Cape May
- Atlantic City
- Sandy Hook
- Bergen Point West Reach
- The Battery
- Willets Point
- Kings Point
- Montauk
- Bridgeport
- New Haven



S3: ***List of seventy storms included in the study and their associated search ranges***					
Storm	*Search Range (* indicates adjusted range)*	*Storm Type*	*Storm*	*Search Range (* indicates adjusted range)*	*Storm Type*
February 17, 2001	February 16–20, 2001	W	December 29, 2009	December 28–January 1, 2010	W
March 7, 2001	March 6–10, 2001	T	January 25, 2010	January 24 – 28, 2010	W
January 13, 2002	January 12–16, 2002	W	February 9–12, 2010	February 8–15, 2010	S
March 10, 2002	March 9–13, 2002	W	February 25–28, 2010	February 24–March 3, 2010	S
November 23, 2002	November 22–26, 2002	W	**March 12–15, 2010**	**March 11 – 18, 2010**	**M** (P, T, W)
February 17, 2003	February 16–20, 2003	T	March 29–31, 2010	March 28 – April 3, 2010	P
February 23, 2003	February 22–26, 2003	P	November 11, 2010	November 10 – 14, 2010	T
November 14, 2003	November 13–17, 2003	W	December 1–2, 2010	November 30 –December 5, 2010	W
November 20, 2003	November 19–23, 2003	P	**December 26–28, 2010**	**December 25–December 31, 2010**	**M** (S, W)
November 29, 2003	November 28–December 2, 2003	W	January 11–14, 2011	January 10–17, 2011	S
December 5–7, 2003	**December 4–9, 2003***	**M** (S, T)	January 26–28, 2011	January 25–31, 2011	S
December 11, 2003	December 10–14, 2003	T	February 19, 2011	February 18–22, 2011	W
March 16–18, 2004	March 15–21, 2004	S	March 6–7, 2011	March 5–8, 2011*	P
April 12–13, 2004	April 11–16, 2004	P	March 10–13, 2011	March 9–16, 2011	P
December 1, 2004	November 30–December 4, 2004	W	April 16–17, 2011	April 15–20, 2011	P
January 22–23, 2005	January 21–26, 2005	S	November 22–23, 2011	November 21–26, 2011	P
February 28–March 1, 2005	February 27–March 4, 2005	S	December 7–8, 2011	December 6–11, 2011	P
March 9, 2005	March 8–12, 2005	W	December 28, 2011	December 27–31, 2011	W
March 28–29, 2005	March 27–April 1, 2005	P	January 12, 2012	January 11–15, 2012	T
January 18, 2006	January 17–21, 2006	W	April 22–23, 2012	April 21–26, 2012	P
February 11–14, 2006	**February 10–17, 2006**	**M** (S, T)	November 7–8, 2012	November 6–11, 2012	T
April 22–23, 2006	April 21–26, 2006	P	December 21, 2012	December 20–24, 2012	T
November 9, 2006	November 8–12, 2006	P	December 26–27, 2012	December 25–30, 2012	T
November 23–24, 2006	November 22–27, 2006	T	January 31, 2013	January 30–February 3, 2013	W
April 15–16, 2007	**April 14–19, 2007**	**M** (P, T)	February 8–10, 2013	February 7–13, 2013	S
December 15–16, 2007	December 14–19, 2007	T	February 26–27, 2013	February 25–March 2, 2013	T
February 2, 2008	February 1–5, 2008	P	**March 6–9, 2013**	**March 5–12, 2013**	**M** (S, T)
February 10, 2008	February 9–13, 2008	W	November 27, 2013	November 26–30, 2013	P
March 7–9, 2008	March 6–12, 2008	W	December 14–17, 2013	December 13–20, 2013	S
December 11–12, 2008	December 10–15, 2008	P	**January 2–4, 2014**	**January 1–7, 2014**	**M** (S, T)
December 21, 2008	December 20–24, 2008	T	January 21–23, 2014	January 20–26, 2014	S
February 12, 2009	February 11–15, 2009	W	March 30, 2014	March 29–April 2, 2014	P
March 1–4, 2009	February 28–March 7, 2009	S	February 3–6, 2014	February 2–9, 2014	S
December 8–9, 2009	December 7–2, 2009	T	February 13–18, 2014	February 12–21, 2014	S
December 19 – 21, 2009	**December 18–24, 2009**	**M** (S, T)	**December 9–10, 2014**	**December 8–13, 2014**	**M** (P, T)

Storm dates determined through station averages and crosschecking dates with National Weather Service archives.
Search ranges were the days included in the NCEI Storm Events Database hazards and damages analysis
M: Multiple-Category; P: Precipitation; S: Snowfall; T: Storm Tide; W: Wind



Total Winter Storms per Category per Month
Number of Storms per Month
25
20
15
10
5
0
Multiple-Category
Snowfall
Storm Tide
Winds
Precipitation
November
December
January
February
March
April
Month

S5: ***Distribution by months for the 20 storm tide events***

			NOV	DEC	JAN	FEB	MAR	APR	
1971-1984	*All Stations*	top 20	5	4	2	3	4	2	20
	Battery Only	top 20	5	4	1	3	4	3	20
1981-1994	*All Stations*	top 20	6	4	3	2	4	1	20
	Battery Only	top 20	5	6	3	1	4	1	20
1991-2004	*All Stations*	top 20	4	4	4	3	4	1	20
	Battery Only	top 20	3	6	4	3	4	0	20
2001-2014	*All Stations*	top 20	3	9	2	2	3	1	20
	Battery Only	top 20	3	8	0	2	4	3	20