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Winter storm intensity, hazards, and property losses in the New York tristate area

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Winter storms pose numerous hazards to the Northeast United States, including rain, snow, strong wind, and flooding. These hazards can cause millions of dollars in damages from one storm alone. This study investigates meteorological intensity and impacts of winter storms from 2001 to 2014 on coastal counties in Connecticut, New Jersey, and New York and underscores the consequences of winter storms. The study selected 70 winter storms on the basis of station observations of surface wind strength, heavy precipitation, high storm tide, and snow extremes. Storm rankings differed between measures, suggesting that 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.

Keywords: winter storms; property damage; hazards; meteorological intensity

Introduction

The Northeast United States coast is among the most densely populated regions 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 tristate 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., one or two 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, 10

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winter storms in the United States caused 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 focused on meteorological features of winter storms to devise a classification scheme for evaluating storm intensity and aiding in impact prediction.[8] However, he did not take losses into account for his categorization. Instead, he concentrated on physical intensity and duration, and discussed 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 affected 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 they hit 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, and other factors. Although Rooney did not directly assess costs, his theory followed that first-order storms would cause greater economic consequences, since a paralyzing storm would halt travel, trade, and other economic factors while simultaneously causing damage, requiring snow removal funds, and other consequences.[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, as well as how this intersection might change in the future, we devised a ranking of storm intensities on the basis of meteorological parameters and then bridged those storm characteristics to their financial impact and the locations where they are concentrated. We designated wind, precipitation, storm tide, and snow depth as four measures of winter storm intensity and developed a ranking to identify the 20 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.* 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 that the “most important driver of future economic disaster damage” is the location of assets in vulnerable regions.[16] Thus, the 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.

Materials and methods: storm selection

Winds, precipitation, and snowfall

This study uses the Daily Summary Data from the 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 data set is a quality-controlled subset of the ISD provided by the NOAA. The key variables we examine are total 24-h precipitation, sustained wind maximum, and 24-h snowfall. The NOAA defines sustained wind maximum as the maximum of the 2-min 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 former data are 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 are provided with 0.1-in accuracy. The list of stations used is provided in Table S1 and depicted in Figure S1.

Water level

The study uses the NOAA Tides and Currents database (https://tidesandcurrents.noaa.gov/). The data have been quality controlled and are 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 are provided at hourly intervals. We calculate daily averages for our analysis, because we are interested in identifying the events that create a high water for a sustained period. 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 vs. 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 Table S2 and depicted in Figure S1.

Identification of extreme storms for all categories

Station data for each of the four variables (precipitation, surface wind speed, snowfall, and tide) were averaged across all stations at each time step to create a single time series, and the strongest 20 events were 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 were crosschecked with National Weather Service (NWS) archives to ensure that they encompass the full length of an event for the entire study area.[18,19] Next, we assessed 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 1 day before the storm and 3 days after to capture all storm impacts. In the case of successive storms, the search range was adjusted to avoid duplication.

The Storm Events Database provides information on reported hazards or "events" for each storm, such as coastal flooding or heavy rain. The study's storm categories represent a particular hazard that we focused on as a measure of overall storm intensity, and the presence of a storm in a category means that 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.

On the basis of data from the NCEI Storm Events Database and documentation instructions from the NWS, 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 NWS forecast zones/counties.[20] Event types reported for the Storm Events Database are defined in NWS 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, when a hazard occurs for a certain length of time, or when conditions meet warning criteria,[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.

Results

Meteorological characteristics

Extreme storms by category. The study focuses on ranking of winter storms into categories on the basis of four features of extratropical cyclones: precipitation, surface wind speed, storm tide, and snowfall amount in the period from 2001 to 2014, for the months November–April. The November–April months were chosen to focus on cold-season extratropical storms; any hazards associated with storms of 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 20 storm dates was identified for each of the four storm feature categories (precipitation, surface wind speed, storm tide, and snowfall amount) using the methods outlined above.

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 nine 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 class, one storm was among the top 20 in three categories, and the other eight were among 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 Table S3.

There are a few notable patterns in the distribution of storm category occurrence per month (as displayed in Fig. S2). About 45% of ranked storm tide storms occurred in December and, owing to the prevalence of storm tide in the multiple-category class, the greatest portion (44.44%) of its storms also occurred 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 that this uptick in December storm tide events was unique for the epoch that we analyzed (2001–2014). Additional information can be found in Table S4. The highest percentage of snowfall storms occurred in February (38.10%), which is consistent with the results of Kocin and Uccellini for snowfall events exceeding 10 in (their figs. 2–11).[7] March and April experienced the highest incidence of precipitation storms (30% and 25%, respectively), while none 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 three and four 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.

Analysis of typical weather metrics. A storm's 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 Figure 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 × 57.5W and 55N × 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 class. 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 with those in the precipitation and storm tide classes. However, the differences are not statistically significant, on the basis of a Student's 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 class as well.

While the multiple-category designation appears to denote an intense storm given the measures of

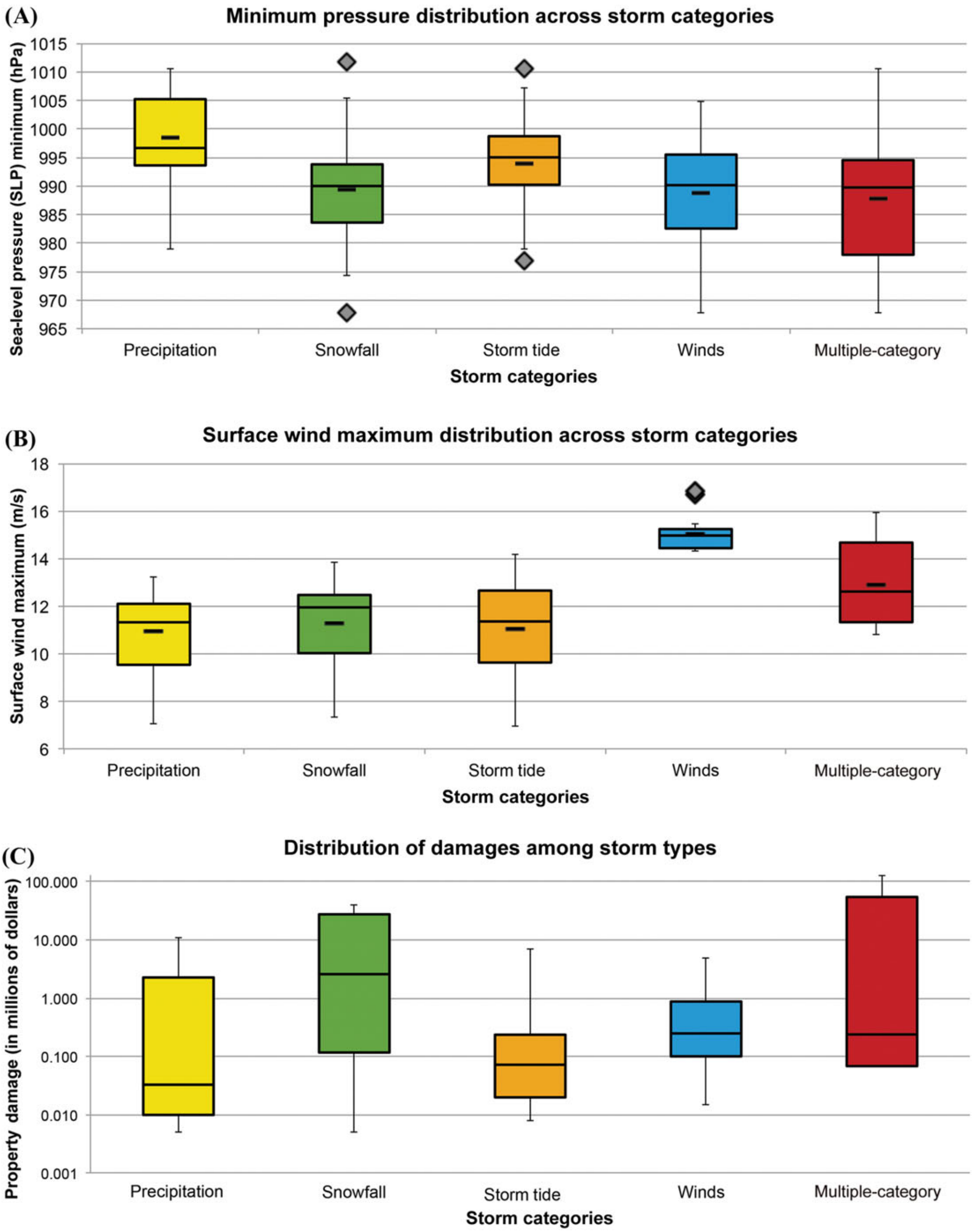


Figure 1. Box plots depicting (A) sea-level pressure (SLP) minimum (hPa) distributions, (B) surface (SFC) wind maximum (m/s) distributions, and (C) property damage distributions (in millions of dollars) for storms with damage above $0 using a logarithmic scale. The middle line represents the median, the 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) The multiple-category class exhibits the lowest mean (987.7 hPa) but the widest distribution. Snowfall, winds, and multiple-category storms share the lowest minimum for December 26–28, 2010. (B) Wind contains the highest mean (15.04 m/s) and shortest distribution. The multiple-category class demonstrates much variability, with a wide interquartile range, and the remaining classes have a large spread of weaker values. (C) The multiple-category class has the widest distribution and damage above $100M, while a few snowfall storms led to damages above $10M.

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 class 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 class. The wind metric is based on the multistation 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 class 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.

Property damage characteristics

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 the 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 the multiple-category and snowfall classes exhibit the widest distributions and are composed of storms with the highest losses. Multiple-category storm 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) (Fig. 1C). The multiple-category class 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 minimum SLP, for example. Snowfall storm costs followed multiple-category storms, but its wind distribution in Figure 1B is similar to the precipitation and storm tide categories, which caused little damage in the study. On the basis of these findings, wind intensity alone is not always a fitting parameter to extrapolate damage.

It is important to note that the damages archived by the NCEI and the damages described in this study focus on direct physical property damage and do not reflect the full economic losses caused by storms. The NCEI data include 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 class, which consists of nine 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 April 15–16, 2007 to 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

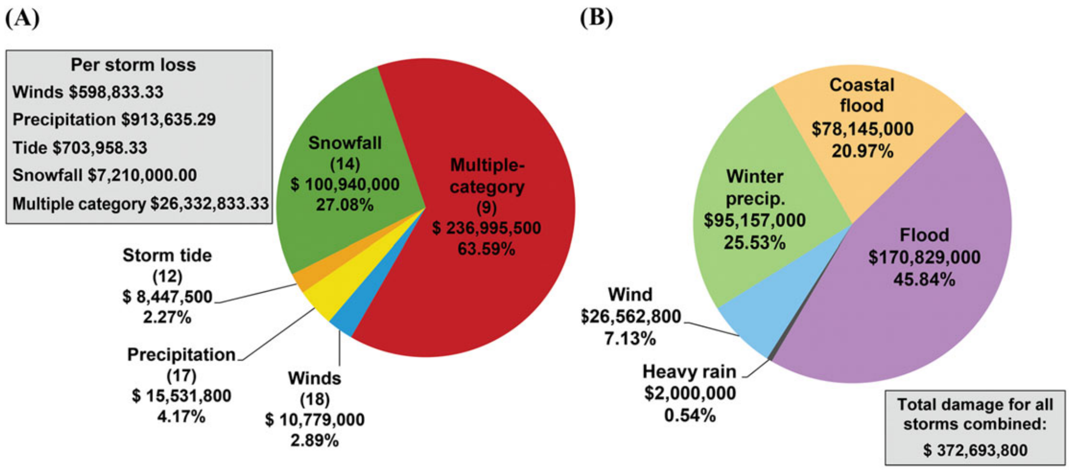


Figure 2. (A) The damage amount per storm type and percentage of total damage for all storms combined. Numbers in parentheses indicate the total number of storms that fell in that category. Multiple-category storms and snowfall storms caused the most damage by far. Precipitation and wind storms had the most storms but caused less than 10% of the damage combined. Overlapping storms were placed in a new class called multiple-category storms. (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, 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.

multiple-category storms fell into two classes. The fact that such a large percentage of the storm losses came from a 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. Figure 2B displays the breakdown of damage amounts for winter storm hazards for all storms combined. A single hazard type, inland flooding, accounted for more than 40% (\$170,829,000) of the property damages associated with winter storms in the tristate 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 (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 flooding, 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 that of December 5–7, 2003, caused 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 brunt of the losses from the April 2007 to March 2010 storms was caused by inland and coastal 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) that flood losses are among the costliest, if not the costliest, hazard plaguing the United States[23–25] and (2) suggestions that flood losses are on the rise,[15,23,25] albeit perhaps owing to social forces.[15,23] Interestingly,

Table 1. **Loss percentages for each hazard per storm category**

	Winds	Precipitation	Storm tide	Snowfall	Multiple-category storms
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%

Note: Bold values highlight the hazard with the greatest loss total within each storm category.

after flooding, the costliest hazard type was winter precipitation, which encompasses several intense hazards, such as snow and wind, suggesting again that greater impacts often transpire when storms are intense in multiple 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 class primarily comprises winter precipitation, wind, and coastal flood. This pattern is logical, since these hazards correspond to our storm categories at large (i.e., snowfall, wind, and storm tide), and the multiple-category class groups the storms that exhibit several of the intensity metrics we designated.

Spatial distribution of damages. Figure 4A illustrates the damage for each county within the study area for all 70 storms combined. Losses are unevenly distributed spatially. The 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 with 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 the most damage from multiple-category storms. Connecticut's low damages therefore support the notion that storms possessing several physical intense characteristics are stronger and more costly.

The two costliest storms, which occurred on 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

Table 2. **Hazard damages per multiple-category storm (USD)**

	December 5–7, 2003	February 11–14, 2006	April 15–16, 2007	December 19–21, 2009	March 12–15, 2010	December 26–28, 2010	March 6–9, 2013	January 2–4, 2014	December 9–10, 2014
Coastal flood	0	900,000	26,000,000	0	36,000,000	0	745,000	0	0
Flood	0	0	99,200,000	0	60,800,000	0	0	0	0
Heavy rain	0	0	0	0	0	0	0	0	0
Wind	0	367,000	775,000	90,000	11,295,000	66,000	370,000	27,500	110,000
Winter precipitation	0	0	0	150,000	0	100,000	0	0	0

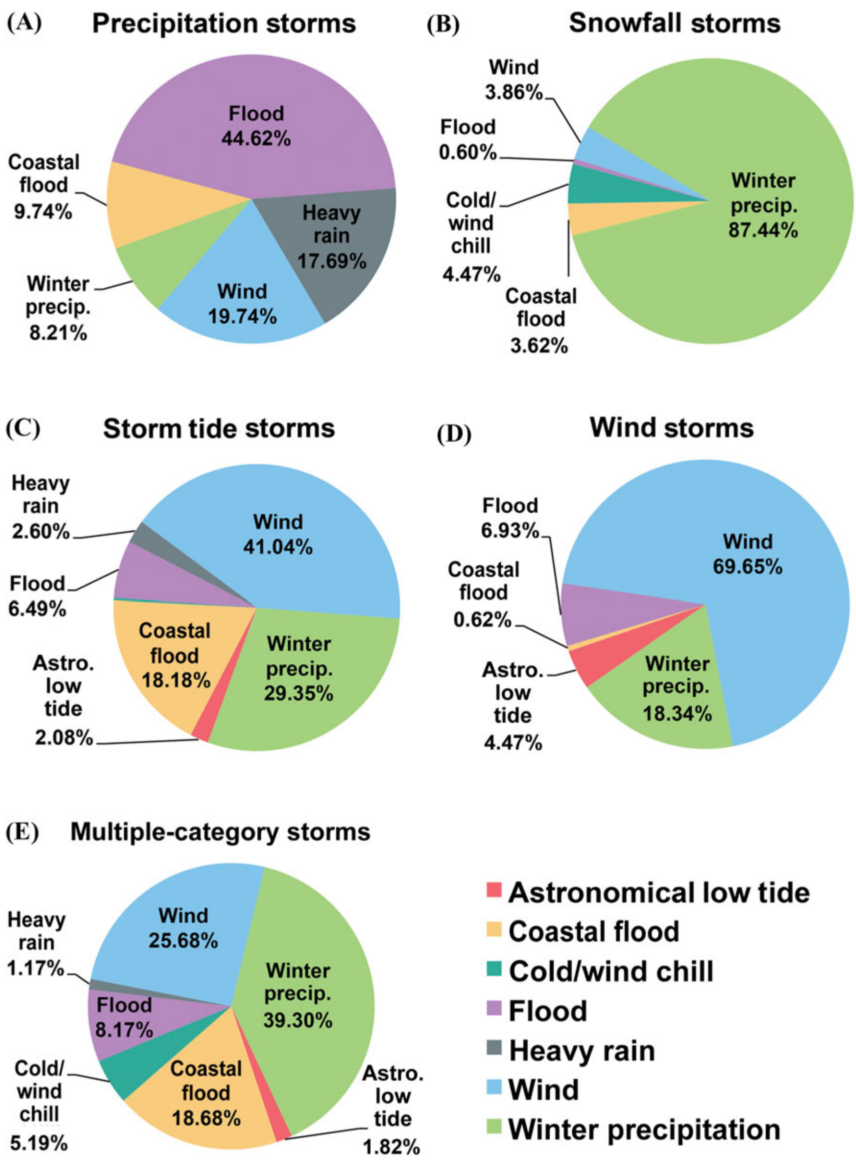
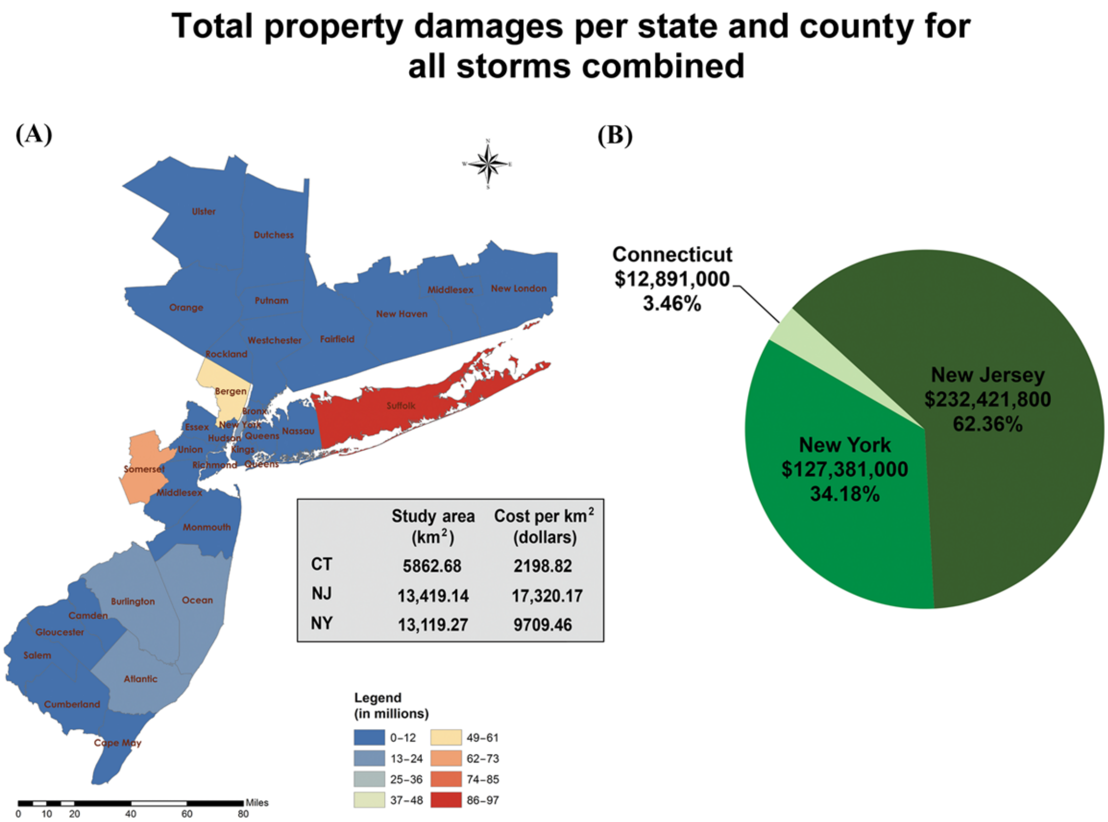


Figure 3. Distribution of reported hazards in the Storm Events Database per storm category. Related hazards types are combined, including ice storm with winter precipitation and flash flood with inland flooding. Reports with and without damage for the above hazards are included. Winter precipitation 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 storms have roughly similar breakdowns concentrated on wind and winter precipitation. The snowfall and wind predominantly sustain their particular hazards (i.e., winter precipitation and wind, respectively).

sustained \$63M and \$52.4M, respectively, in damages from inland flooding (please refer to Fig. 4A for county locations). 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, is rising.[27,28]

We cannot speak of whether the greatest driver of inland flood damage is a physical parameter (e.g., precipitation or storm surge) or social and infrastructural vulnerabilities. Therefore, future research is needed on the relationship between



	Study area (km^2)	Cost per km^2 (dollars)
CT	5862.68	2198.82
NJ	13,419.14	17,320.17
NY	13,119.27	9709.46

Figure 4. (A) Map of the distribution of the total damages per county for all storms combined. Somerset, Suffolk, and Bergen counties experienced more than $50 million in losses, while New York, Atlantic, and Burlington counties faced more than $15 million in damages. Fifteen of the remaining 26 counties had damages in the $1–15 million range. Land area values were 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 the percentage of total damage for all storms combined are listed.

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]

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 further examine the meteorological and damage characteristics of each costly storm in this section. Figure 5 shows the precipitation (TRMM-3B42) in mm/day,[29] SLP (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-h 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 costliest 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 costliest storms, only two (January 22–23, 2005 and February 8–10, 2013) possessed a relatively deep low-pressure center, and 100% of their damages resulted from winter precipitation. However, they also sustained the least damages of the six, which suggests that pressure

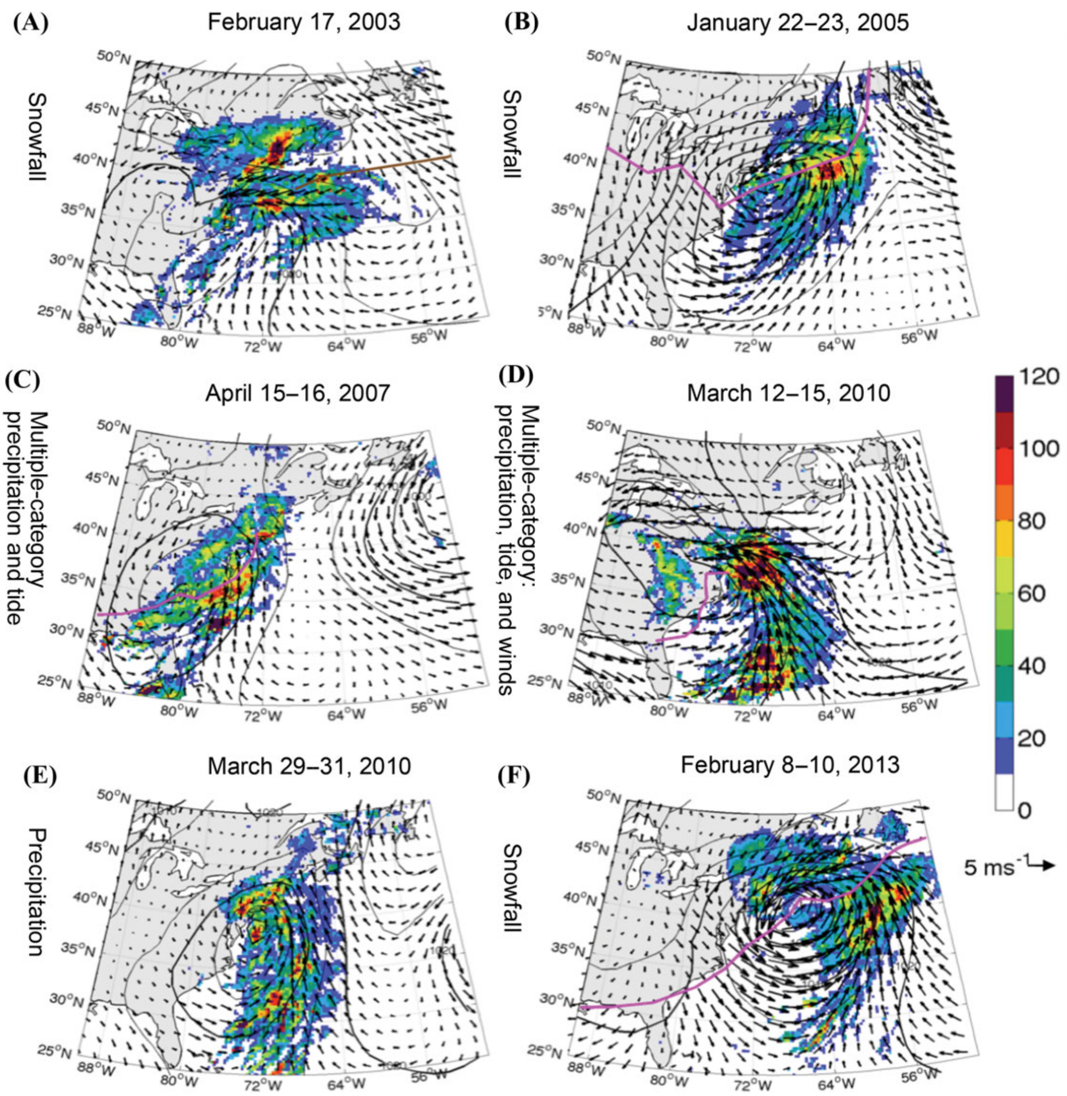


Figure 5. Plots of daily average precipitation in mm/day, sea-level pressure in hPa, and storm tracks and wind vectors in m/s centered on 12Z on the date of interest for the costliest storms. Storm tracks are found by applying the Hodges cyclone tracking algorithm[31] to the 6-h SLP fields from the ERA-Interim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

is not the best indicator of 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 (not statistically significant at the 95th percentile) exists between the 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 that 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. 6D), which is classified as a multiple-category

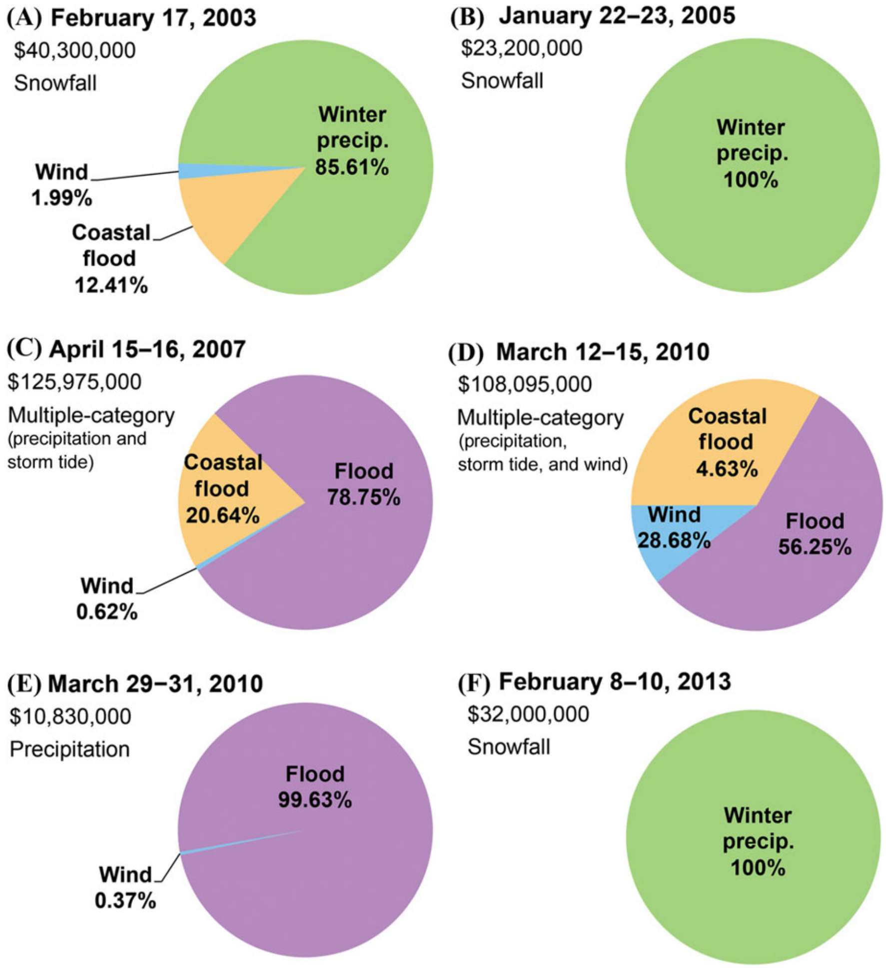


Figure 6. Breakdown of damages per storm for the six costliest storms. The snowfall storm category boasts the greatest representation, while the storm tide and wind category are not represented individually, just through the multiple-category class. Inland flood and winter precipitation led to the most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

storm, with extremes in precipitation and storm tide, in addition to wind. All of the other storms that fell into the wind category caused less than $5M in losses, and the percentage of wind damage among the costliest storms was less than 4%. However, studies often discuss wind as impactful when it occurs simultaneously with another winter storm hazard,[8,14,32] which seems to be consistent with the March 12–15, 2010 storm and to support the notion that the most 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 an important consideration 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 shown in Figure 5D. The winds directed onshore toward the study area are ideally oriented for creating a storm surge in the New York City region.[22] Additionally, 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 toward 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 those on March 12–15, 2010, but winds are blowing offshore. The onshore winds in the vicinity of New York City 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 surges in the New York City 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 began over land and then hooked toward the north (Fig. 5B and F). The same is true of the path for the two costly storms that generated multiple-category extremes (Fig. 5C and 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 (Fig. 5C and D) vs. winter weather-related damages (Fig. 5B and F)) on the basis of our analysis. This would be consistent with the results of previous work on storm surge[4] and wind storms.[33]

Limitations

A few caveats regarding the NCEI's Storm Events Database and the property damages analysis should be discussed. 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, the 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 the NCEI's database. Gall e*t 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.*[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 (e.g., Hurricane Sandy) or specified time periods, counties, and/or hazards. Property damage data are uploaded by the NWS about 75 days after a month concludes.[20] Although the accuracy of the information provided is not always confirmed,[38] we used these data owing to availability, since data access was a major obstacle in our investigation. Another draw to the NCEI data is that they are 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, the NCEI data were useful for our goals of determining areas where hazards are concentrated under varying storm characteristics as identified by our ranking method.

Discussion

In this study, we developed a list of 70 intense storms measured by wind strength, precipitation amount, storm tide, and 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 storms.

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 to 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 thus the measure of financial impacts will vary as well. We 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 from the other extremes) overall caused the least damage, but, since it is so widely present in the multiple-category class, storm tide may inflict damage primarily when exacerbated by another intensity metric.

Nevertheless, the evidence of impacts provided here 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 storms). However, a more in-depth analysis of 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 tristate 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 lead to damage, where they are concentrated, and what sort of societal changes have and will influence those values.

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Supporting Information

Additional supporting information may be found in the online version of this article.

Figure S1. Map of stations used to identify precipitation, snowfall, and wind storms (Table S1) and stations used to identify storm tide storms (Table S2).

Figure S2. 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, and April) also saw more precipitation storms, which were absent or minimal during the winter months.

Table S1. Stations used to identify precipitation, snowfall, and wind storms.

Table S2. Stations used to identify storm tide storms.

Table S3. List of 70 storms included in the study and their associated search ranges.

Table S4. Distribution by month for the top 20 storm tide events.

Competing interests

The authors declare no competing interests.

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