Evaluation of storms through the lens of erosion potential along the New Jersey, USA coast

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Abstract: Coastal erosion is driven by both a storm's erosion potential and by an area's vulnerability. Therefore, the problem of estimating impacts can be approached in two-step. The first includes an assessment of erosion potential based on readily available storm parameters, while the second combines this information with highly localized parameters, describing vulnerability, to more directly predict local impacts. The work presented in this paper focuses on this first step, where a storm erosion potential climatology is developed by analyzing historical storms and is then utilized to identify historic patterns. Specifically, storms which have impacted the New Jersey coast over the past several decades are reevaluated using the Storm Erosion Index (SEI), developed by Miller and Livermont (2008), which considers the three primary storm-related drivers of coastal erosion (wave height, water level, and storm duration). These storms are assessed at thirteen shoreline segments defined along New Jersey's Atlantic coast from a 34 year-period (1980 – 2013) when concurrent wave and water level data is available. Approximately 130 unique storms are identified with the top three being the December 1992 nor'easter, the November 2009 Veteran's Day Storm, and Hurricane Sandy in October 2012, each having an estimated return period of greater than 15 years. The resulting climatology is found to exhibit several interesting spatial and temporal trends. Both portions of the state as well as months of the year that have historically experienced more storms and/or higher cumulative SEI (over the 34 years) are identified. While analysis of the climatology has also identified periods of reduced storm activity and those of intensified conditions, future monitoring is suggested to assess whether these patterns are persistent or related to climactic variations with cycles longer than can be captured by the thirty years included in this study.

Key words: *coastal storm; erosion potential; storm intensity; New Jersey*

1 INTRODUCTION

While the impact of tropical storms (e.g. Hurricane Ike, Sandy, Michael, etc.) are well documented, the impacts of extratropical storms (i.e. nor'easters), especially the cumulative effects of smaller magnitude, lower return period storms, are less well documented and understood. Exemplifying the potential hazards, four sequential storms in March 2018 cumulatively resulted in 10 fatalities and approximately $3 billion (USD) in damages in southern New Jersey (Aon Benfield, 2018). To mitigate such damages, coastal communities require reliable information about an oncoming storm in order to anticipate its impacts and make preparatory decisions. Beach scraping (McNinch and Wells, 1992) is an example of a practice commonly used by communities to mitigate the effects of oncoming storms; however this preparation diverts resources from other potentially more valuable efforts. Thus, there exists a need to properly estimate a storm's severity in terms of erosion potential prior to its impact.

Traditionally, storm intensity has been quantified by one or more of a storm's properties. For tropical storms this includes meteorological properties such as barometric pressure, maximum wind speed, or storm surge potential. The most well-known example of this in the United States is the Saffir-Simpson Hurricane Wind Scale (SSHWS) which classifies hurricanes on a scale from 1 through 5 based on their one-minute maximum sustained wind speed (Schott et al., 2012). The categories are often used, sometimes inappropriately, to infer potential property damage and flooding due to storm surge. There have been several criticisms of this scale as it relies solely on wind speed and does not consider other parameters such as measured storm surge, waves, or precipitation (Kantha, 2006). Several recent storms that have highlighted shortcomings of the SSHWS include Tropical Storm Debby and Hurricane Sandy in 2012. Neither Tropical Storm Debby nor Hurricane Sandy were classified as a hurricane according to the SSHWS at landfall, yet both caused extreme erosion and significant damage (Blake et al., 2013; Wehof et al., 2014). Over the years, there have been several suggestions to modify the SSHWS scale, including the addition of parameters such as storm size and forward speed (Done et al., 2015; Hebert et al., 2010; Kantha, 2006; Powell and Reinhold, 2007).

Extratropical storms are fundamentally different from tropical storms in terms of how they form and draw their energy (Davis and Dolan, 1993) and therefore cannot be categorized by wind speed the same way tropical storms typically are (Herrington and Miller, 2010). Understanding the intensity of these storms is important however, particularly in the mid-Atlantic region, where they routinely cause significant beach erosion and property damage along the coast. Although these storms are often less intense than their tropical counterparts, they impact this area of the coast more frequently, resulting in extreme cumulative damage. Traditionally, a stage frequency analysis of either water level or wave height has been used to estimate storm severity of extratropical storms. However, this approach, while suitable for predicting or assessing flood potential, does not adequately estimate the erosion potential of a storm, as a combination of parameters are involved in this process.

Beach erosion, which is one of the common impacts associated with both tropical and extratropical storms is driven by a combination of storm and beach state parameters. The three primary storm parameters which include wave conditions, total water level, and storm duration, essentially define the erosion potential of the storm, while the beach state parameters impact how much of that potential is realized. The wave conditions relate to how much energy is available to generate sediment movement and to what direction that sediment will move. The total water level, which includes the tide level and storm surge, determines how high on the beach the water rises and thereby what portion of the beach is subject to wave action. Storm duration describes how long the beach is subjected to intensified wave conditions and elevated water levels. The storm duration is therefore associated with how much erosion is accumulated over the duration of the storm.

The Veteran's Day Storm which impacted New Jersey in November 2009 demonstrates how stage frequency analysis of water levels does not adequately indicate severity in terms of erosion. The Veteran's Day storm resulted in severe beach erosion along much of the New Jersey coast and is considered one of the most damaging storms in New Jersey in recent history (Herrington and Miller, 2010) despite barely exceeding the moderate flood threshold set by the National Weather Service (2.13 m above MLLW at Atlantic City). This can be attributed to the large waves (H_s > 8m at NDBC buoy 44009) generated by the storm that persisted over several tidal cycles. The importance of storm duration has also been acknowledged by Dohner et al. (2016) who found that Hurricane Sandy and Hurricane Joaquin (October 2015) resulted in more erosion at Lewes, Delaware than Winter Storm Jonas (January 2016) despite Jonas having larger wave heights. This was attributed to the relatively short duration of Jonas in comparison to the other two storms.

The aforementioned storms emphasize the difficulty of assessing a storm based on a single parameter. Several more robust indices have been developed which take multiple parameters into account. Dolan and Davis (1992) derived an index specifically for extratropical storms based on maximum wave energy and storm duration. This index places a storm into one of five classes with expected storm impacts (e.g. beach and dune erosion, overwash, and property damage) associated with each class based on the researcher's experience in the mid-Atlantic. Mendoza et al. (2011) modified this scale where storms were classified by wave energy content integrated over the duration of the storm. This modification aims to eliminate possible overestimation in the Dolan and Davis scale which arises by describing the storm by a single wave energy value. Kriebel et al. (1996) also developed an index aimed to classify extratropical storms considering wave height, storm duration, and storm surge which was missing from the previously described index. Although the study's focus was on Delaware, it is noted that the methodology can be applied to other locations. Additional parameters that have been use to represent storm intensity focus on storm surge and tide (Balsillie, 1986; Zhang et al., 2001), cumulative wave energy (Splinter et al., 2014), total horizontal momentum (Basco and Mahmoudpour, 2012; Basco and Walker, 2010), and wave run-up (Kraus and Wise, 1993). A table of several of the parameters used as a measure of storm intensity is provided to serve as a source of comparison (Table 1).

Miller and Livermont (2008) developed the Storm Erosion Index (SEI) which evaluates storms based on their erosion potential and includes the three primary drivers of coastal erosion: wave height, total water level, and storm duration. This index makes no distinction between tropical and extratropical storms. It has been successfully applied to a number of locations including but not limited to the Gulf of Mexico and Atlantic coasts of Florida (Janssen et al., 2019; Miller and Wehof, 2013; Wehof et al., 2014), North and South Carolina (Miller, 2015), New Jersey (Miller and Livermont, 2008), and Spain (Villatoro et al., 2014) and has been shown to be more closely related to observed erosion than more traditional indices (Miller and Livermont, 2008).

The purpose of the research presented here is to reevaluate storms that have impacted the coast of New Jersey over the past several decades in terms of their erosion potential. The intent is to utilize the resulting erosion potential climatology to evaluate historic trends (presented here) and provide input to a more comprehensive coastal storm impacts model (ongoing work) that takes into account localized beach state parameters. To assess the erosion potential of the historical storms, the Storm Erosion Index (SEI), developed by Miller and Livermont (2008) is applied. SEI is chosen because it considers the three primary storm-based drivers of beach erosion (wave height, water level, and duration) and is applicable to both tropical and extratropical storms, both of which impact the New Jersey coast. The following sections review the Storm Erosion Index, describe the development of the climatology, and highlight some of the more interesting trends contained within the climatology.

2 METHODS

2.1 Storm Erosion Index

The foundation of the Storm Erosion Index (SEI) is the physical response of a beach profile due to increased water levels. The simplest form of this response is the well-known Bruun Rule (Bruun, 1962). SEI is based on a form of this rule modified by Dean and Dalrymple (2002) to predict the equilibrium shoreline recession (Δy) due to an increase in water level, S, and cross-shore varying wave set-up, η, due to breaking waves (Figure 1):

$$\Delta y = -W_* \left[\frac{0.068H_b + S}{B + 1.28H_b} \right] \quad \text{Eq. 1}$$

In Equation 1 H_b is the depth-limited breaking wave height ($H_b = 0.8\ h_b$), W_* is the width of the active surfzone, and B is the berm height. W_* can be approximated as the distance to the breakpoint, and using equilibrium beach profile theory, can be determined as:

$$W_* = (Ah_b)^{3/2} \quad \text{Eq. 2}$$

where h_b is the water depth at the breakpoint and A is the sediment scale parameter which has been shown to be related to the median grain size (Dean et al., 2001; Moore, 1982).

Miller and Dean (2004) utilized a time-varying form of this modified Bruun Rule to predict equilibrium shoreline change based on wave height, water level, and storm duration. Miller and Livermont (2008) suggested that the time varying form could be interpreted as the Instantaneous Erosion Intensity (IEI):

$$IEI(t_i) = W_*(t_i) \left[\frac{0.068H_b(t_i) + S(t_i)}{B + 1.28H_b(t_i)} \right] \quad \text{Eq. 3}$$

where t_i is a time index and the negative sign is dropped for convenience. IEI is representative of the intensity of a storm at a given point in time based on its instantaneous breaking wave height and surge. In the time varying version, the surge is taken as the instantaneous water level with respect to mean sea level. Two parameters based on IEI that can be used to characterize the erosion potential of a storm are the Peak Erosion Intensity (PEI) and the Storm Erosion Index (SEI). PEI is the maximum value of the IEI over the duration of a storm, t_d, and represents the erosive power at the peak of the storm. SEI is the sum of the IEI over t_d, and represents the cumulative erosion potential:

$$SEI = \sum_{t_d} IEI(t_i) = \sum_{t_d} \left\{ W_*(t_i) \left[\frac{0.068H_b(t_i) + S(t_i)}{B + 1.28H_b(t_i)} \right] \right\} \quad \text{Eq. 4}$$

Further details regarding the application of the index are provided in the following section.

Although SEI estimates the potential for erosion based on storm parameters rather than actual storm impacts, Miller and Livermont (2008) found that storms with higher SEI values typically caused greater erosion. They also found that the time-lag between storm occurrence and typically seasonal beach profile and shoreline measurements made direct comparisons difficult due to the propensity for the beach to recover between surveys. To supplement the comparisons between SEI and the measured shoreline changes at Wildwood, NJ, comparisons between qualitative post-storm erosion reports collected by the New Jersey Department of Environmental Protection (NJDEP) and SEI were also considered. The results confirmed that events where the erosion was described as moderate to severe typically had higher SEI values than those with erosion described as slight or minor.

Here, storms are classified by their SEI and PEI by two methods to facilitate comparison and identify trends. First, an extreme value analysis (EVA) is performed to determine the return period associated with an individual storm based on its SEI and PEI. The Peak-Over-Threshold (POT) method is used where all exceedances above a specified threshold are assumed to be represented by a Generalized Pareto Distribution (GPD). Thresholds are selected with consideration of optimization techniques described in Palutikof et al. (1999) and Lang et al. (1999) as well as visual fit. The advantage of this method over other EVA methods such as the Annual Maximum Series (AMS) is that it allows for multiple large events during the same year to be captured rather than limiting the analysis to just one event per year. This is useful given the possibility to have multiple large storms during a single year.

Second, a simplified classification is made by applying a categorization procedure that mimics the Saffir-Simpson Hurricane Wind Scale. This procedure categorizes storms as 1 through 5 and may be useful for relaying storm severity to the public. This categorization is site specific and provides a general measure of erosion potential. In this procedure, the storm with the lowest SEI value at a given site is assigned a Category 1 and that with the highest is assigned Category 5. Linear interpolation is used to assign categories to the remaining storms in the site's record according to:

$$Cat = 5 \times \left[\frac{SEI - SEI_{min}}{SEI_{max} - SEI_{min}} \right] \qquad \text{Eq. 5}$$

where this value is rounded up to the nearest whole integer. The same categorization procedure is applied for PEI.

2.2 New Jersey Climatology Development

2.2.1 Site Description and Data Aggregation

As discussed, the purpose of this research is to produce a historical record of storms which have occurred over the last several decades in New Jersey and to classify them based on their erosion potential using the Storm Erosion Index. As both storm conditions and beach characteristics vary spatially, the Atlantic coast of New Jersey is divided into thirteen smaller segments and a historical record is developed for each. The shoreline segments are depicted in Figure 2.

The Atlantic coastline of New Jersey consists of several distinct features and the shoreline segments in this study are defined to reflect some of these features. North of Shark River Inlet (the northernmost inlet along New Jersey's Atlantic coast), the shoreline consists of the barrier-spit system of Sandy Hook and the coastal bluffs of central Monmouth County. With no inlets to define distinct regions, Shoreline Segments 1 through 3 are defined by changes in shoreline orientation. Shoreline Segment 1 includes the Sandy Hook spit which connects to the mainland at Monmouth Beach, located in the middle of Shoreline Segment 2. Monitoring of the spit has shown elongation towards the north indicating northward longshore transport in that part of the state (Messaros et al., 2018). The northernmost 8 km of Shoreline Segment 1 are generally unpopulated, made up of the Gateway National Recreation Area. Most structures in this area are government and educational facilities. The remaining area north of Shark River Inlet is developed.

South of Shark River Inlet, shoreline segments are defined by the location of inlets. While shoreline Segments 4 and 13 are coastal bluffs, the remaining area consists of barrier beaches. Unlike some other parts of the country, many of the barrier islands are highly developed and storms impacting the system put many property owners at risk. Based on the 2000 census New Jersey was ranked fourth by barrier island population (158,320) and second by population density (915/km^2) among states along the U.S. Atlantic and Gulf coasts (Zhang and Leatherman, 2011). Shoreline Segment 5 is the longest shoreline segment with the southernmost 16 km being a natural beach (Island Beach State Park).

Representative beach properties for each shoreline segment are summarized in Table 2. Shoreline orientation is provided as the shore-normal angle, measured with respect to north. Berm height and sediment size are assumed constant over the period of the analysis. These values are obtained from information collected by Richard Stockton's Coastal Research Center. Twice a year, this group surveys profiles along the New Jersey coast. Approximate berm heights are determined at each of the profiles based on seasonal profiles measured from 1986 to 2013 (Farrell et al., 2017). The median berm height of the profiles at each shoreline segment is taken as the representative berm height. Similarly, the representative median grain size is determined for each segment based on samples collected and analyzed by Richard Stockton at each profile in 2011 (Flynn). Generally, sediment sizes are coarser in northern New Jersey and are finer in the southern portion of the state with the exception being Shoreline Segment 13, which has the coarsest sediment. For the development of this climatology, instead of using the site-specific information, a representative grain size and berm elevation is used for the entire state. Doing so allows for a true comparison between individual shoreline segments as only the storm characteristics (wave properties and water level) and shoreline orientation will vary from segment to segment. The representative median grain size for New Jersey is 0.4 mm and the representative berm height is 2.5 m.

Wave and water level information for the past several decades are required to identify historical storms and to calculate the IEI. This information is obtained from available hindcast sources. Offshore directional wave information is obtained from the United States Army Corps of Engineers' (USACE) Wave Information Studies (WIS) Hindcast (USACE, 2015). USACE uses a discrete spectral wave model with wind-forcing to generate a spatially and temporally varying wave field for coasts of the US and its territories for 1980 – 2014. Time series of wave properties are provided at virtual buoys located in 15 to 20 meters of water approximately every 10 km along the coast. Wave information from the virtual buoy located closest to the center of each shoreline segment is used in the analysis. Each virtual buoy is shown in Figure 2 and listed in Table 2.

A corresponding time series of water levels is extracted for each shoreline segment from the 1979 – 2013 hindcast developed by researchers at Stevens Institute of Technology using the New York Harbor

Observing and Prediction System's (NYHOPS) three-dimensional hydrodynamic model (Georgas et al., 2016). This model applies surface meteorological and hydrologic forcings to reanalyze total water level conditions in the domain covering Massachusetts through Maryland and has been shown to match local observations. The combination of the wave and water level data sets yields a study period of 34 years (1980-2013).

2.2.2 Storm Erosion Index Application

Prior to the calculation of the IEI using Equation 3, the wave record is assessed to ensure the waves considered in the analysis are both erosional and directed onshore. Offshore directed waves are considered to be those with a wave angle of greater than 90 degrees relative to shore-normal and are removed from the data set. A wave steepness threshold is used to distinguish between waves that are considered to be erosional (those exceeding the threshold) and those considered to be accretional (those below the threshold). Laboratory and field experiments have shown the threshold to lie in the range between 0.01 and 0.03 (Kana, 1977; King, 1953; King and Williams, 1949; Masselink et al., 2010; Saville, 1957). Although 0.025 is the most commonly used value (Johnson, 1949; Waters, 1939), Wehof et al. (2014) when using SEI to reevaluate Hurricane Isaac found that using this threshold seemed to be too restrictive and eliminated some portions of the storm from the calculation. In this study, a lower value within the accepted range (0.02) is chosen to ensure important storms are not excluded while also eliminating waves that are clearly accretional, particularly on the tail of the storm which contributes to recovery. This value acts as a coarse filter before a second more selective filter, described below, is applied to further reduce the wave record and remove any waves not considered to be part of a storm. Waves meeting both the steepness and directional requirements are shoaled and refracted to the breakpoint using linear wave theory. The instantaneous erosion intensity (IEI) is calculated hourly based on the hourly breaking wave heights and water levels remaining in the record.

Individual storms are identified by setting objective criteria. Previous studies have defined storms by periods when offshore wave heights and/or water levels exceed a particular threshold. These particular thresholds can be very site specific and open to interpretation. A number of studies have used an offshore wave height threshold defined as either a singular value ranging from 1.5 m to 3 m depending on location (Callaghan et al., 2008; Dolan and Davis, 1992; Splinter et al., 2014; USACE, 2018; You and Lord, 2008) or as a percent exceedance level (Héquette et al., 2019), with a manual assessment that individual storm events are not separated. Additional information used to identify storm events have included minimum required storm duration and/or minimum gap length between separate storm events (Mendoza and Jiménez, 2006; Shand et al., 2011; USACE, 2018). Those studies looking at elevated water levels have defined storms by when the storm surge exceeds a pre-determined value dependent on the location (Munger and Kraus, 2010; Zhang et al., 2001).

Previous applications of the Storm Erosion Index have used wave height and water level thresholds of two standard deviations above the mean to define a storm (Miller and Livermont, 2008). The present work adopts the threshold exceedance approach, and defines a storm as a period of time during which either the wave height exceeds the 95% threshold, or the water level exceeds the 99.9% threshold. Both parameters are considered so as not to exclude storms for which there is a large storm surge and only moderate waves or vice versa. The water level threshold is optimized to capture storm events and ignore spring high tides with slight anomalies. Storm duration, t_d, is defined as the time between the first and last exceedances of one of the thresholds. If two storm events are separated by less than 48 hours, they are considered to be part of the same storm. This accounts for cases where the storm conditions temporarily subside and fall below the defined criteria, but then pick up again in intensity. An example is shown in Figure 3 for Hurricane Sandy. Here, water levels exceed the threshold between 11 PM 10/28/2012 and 2 AM 10/30/2012 with conditions falling below the defined criteria during low tides. Because the high tides that exceed the threshold are separated by less than 48 hours, by definition they are all considered as part of the same storm. For this storm the waves exceed the threshold between 8 PM 10/28/2012 and 2 PM 10/30/2012. Because this range exceeds that for the water level, on both the rise and fall of the storm, the wave exceedances define the overall storm duration.

The SEI of an individual storm event is calculated by summing the hourly IEI values over the storm duration. This includes all time steps between the start and end point of the storm, whether or not the individual time steps themselves meet the wave and water level threshold criteria. The PEI is determined for each storm by taking the highest value of the IEI within the storm duration, as depicted in Figure 3. SEI and PEI values are determined for each identified storm in the record. This procedure is performed for each shoreline segment. Storms are then classified in terms of SEI and PEI based on the categorization analyses described above. One classification system is developed for all of New Jersey scaled using the minimum and maximum SEI and PEI across all the shoreline segments. Return periods associated with each storm are determined using the POT method at each shoreline segment separately. Therefore, while the storm classes (Categories 1 through 5) are consistent across all shoreline segments in New Jersey, return periods are specific to the individual segment. This approach is consistent with that currently used for hurricanes where the classifications (Categories 1 through 5) are uniform nationally, as they are simply based on wind speed, and the return period associated with it can vary from one location to another.

3 RESULTS & DISCUSSION

3.1 Identification of Major Storms

The Storm Erosion Index is applied here to establish a historical record of storms for each region in New Jersey where storms are ranked based on erosion potential. Individual records exist for all thirteen shoreline segments and contain the SEI, PEI, and associated return periods and categories for each storm identified. In this paper, the top five storms for four representative shoreline segments are presented (Table 3). Shoreline Segments 3 and 5 are within the northern half of the state (Figure 2), north of Barnegat Inlet. The other two, Shoreline Segments 8 and 11, are within the southern half. The top three storms identified across all shoreline segments are the December 1992 nor'easter, the Veteran's Day Storm (November 2009), and Hurricane Sandy (October 2012); however, their order varies by location. The three storms are typically categorized as either Category 4 or 5 based on their SEI with return periods of at least 15 years. Each of the top three identified storms are known to have resulted in major erosion of the New Jersey coast.

At the time, the December 1992 nor'easter produced coastal flooding that was the worst the state had seen in forty years. Sustained wind speeds were 15 to 20 m/s and at times gusts were hurricane force (NOAA, 1992). The combination of large waves with elevated water levels, resulted in considerable beach and dune erosion throughout New Jersey. It was estimated that damage to the beaches and other property was over $100 million USD.

The Veteran's Day Storm (November 2009) formed from the remnants of Hurricane Ida as it collided with another low pressure system developing off the coast of North Carolina. It is most notable for its long duration, lasing about four days. Damage sustained in Ocean, Atlantic, and Cape May counties prompted a Presidential Disaster Declaration. Due to the nature of the storm, the southern portions of New Jersey fared worse than those in the north, particularly areas such as Atlantic City, Ocean City, and Avalon which are located within Shoreline Segments 8, 10, and 11 respectively (Farrell et al., 2010).

Hurricane Sandy (October 2012) is to date the costliest natural disaster in the state, resulting in nearly $30 billion USD worth of damages including but not limited to the damage of 346,000 housing units with 22,000 of those uninhabitable (Blake et al., 2013; NJOEM, 2014). The late-season hurricane made landfall as a post-tropical cyclone in Brigantine, New Jersey, which is located at the midway point of Shoreline Segment 7 (Figure 2). Sustained wind speeds were approximately 25 m/s and waves measured a maximum of 9.6 m at the offshore NDBC buoy 44025 located 70 km off the coast of northern New Jersey. Combined with a record-breaking storm surge, measuring 2.6 m at the Sandy Hook NOAA tide station, the storm resulted in massive damage to the coastline and beaches both north and south of its landfall. In general, however, beaches towards the south were impacted less severely than those in the north due to the shift in wind direction as the storm made landfall (Barone et al., 2014).

Figure 4 (top) shows the SEI and PEI values for the three storms at each shoreline segment. As a reference, the thresholds that define Category 3, 4, and 5 storms based on SEI and PEI are plotted as horizontal lines. As shown, there is much variability in the calculated erosion potential of these three storms spatially. Hurricane Sandy tends to have its highest values between Shoreline Segments 4 through 7, where it is also categorized as a Category 5. A maximum of 3540 occurs at Shoreline Segment 6. While ranked first a number of the northern shoreline segments, it falls behind both the Veteran's Day storm at the December 1992 nor'easter in the southern shoreline segments. Although SEI is not a direct predictor of beach impacts this increased intensity towards the north corresponds well with the general observations that the storm tended to cause more coastal erosion in parts of northern New Jersey than it did south of the landfall (Farrell et al., 2010). This trend is stark contrast to the Veteran's Day storm whose highest SEI values occur between Shoreline Segments 5 and 11. The maximum value of 3520 occurs at Shoreline Segment 6, with another local peak of 3360 occurring at Shoreline Segment 9. This too coincides with observations that the Veteran's Day storm impacted southern New Jersey more severely than it did the northern portion of the state (Farrell et al., 2010). A split in these trends appears to occur at Shoreline Segment 6. Shoreline Segment 6 is also where the shoreline orientation of New Jersey's Atlantic coastline shifts reinforcing that the orientation of the shoreline relative to the storm waves plays an important role in determining erosion potential.

Based on PEI, Hurricane Sandy is ranked first among all shoreline segments. Of the three storms discussed thus far, the December 1992 nor'easter is second followed by the Veteran's Day Storm. However, it should be noted that other storms including "The Perfect Storm" in October 1991 and Hurricane Irene in August 2011 exceed the Veteran's Day Storm in terms of PEI at several shoreline segments further south. Although Hurricane Sandy remains the highest ranked storm based on PEI across all shoreline segments, the intensity decreases relative to the other storms. The PEI value of Hurricane Sandy decreases from a maximum value of 163 at Shoreline Segments 2 and 4 to a minimum value of 78 at Shoreline Segment 13. North of Shoreline Segment 6 it is generally classified as a Category 5 storm by PEI and is the only storm to have this classification at any shoreline segment. At Shoreline Segment 7 through 9 it is classified as Category 4 and at the remaining shoreline segments it is classified as Category 3. The return periods based on PEI decrease from well over 100 years at Shoreline Segment 1 to around 60 years at Shoreline Segment 13. The December 1992 nor'easter is classified as Category 4 in northern New Jersey and as Category 3 in southern New Jersey. It has return periods between 15 and 30 years. The Veteran's Day Storm is classified as Category 3 at all shoreline segments and has return periods between 6 and 10 years.

3.2 Role of Shoreline Erosion Drivers in PEI and SEI

As the two parameters discussed in this study (SEI/PEI) describe different aspects of storm intensity it is reasonable that each shoreline erosion driver may influence the two parameters differently. To begin to understand how the three erosion drivers influence these two parameters, the three major storms identified from the climatology are discussed in further detail.

PEI reflects the maximum instantaneous erosion potential during the storm and is influenced by the breaking wave height, water level, and the timing of the two maxima in relation to one another. An example time series of breaking wave height and water level for the three storms is shown in Figure 5 for Shoreline Segment 8. It should be noted that breaking wave heights are only shown for those waves which meet the criteria described in the earlier section and is shown as 0 at all other timesteps. A list of selected parameters is provided in Table 4. The maximum breaking wave height of 7.0 m and maximum water level of 2.0 m MSL for Hurricane Sandy exceed that of the other storms and the two appear to occur simultaneously. This leads to Hurricane Sandy having the highest PEI of any storm in the record at 98. Of the three discussed storms, the December 1992 nor'easter has the next highest PEI of 81. This is a result of its nearly simultaneous large maximum breaking wave height and maximum water level (6.4 m and 1.8 m MSL, respectively), though neither as large as that for Hurricane Sandy. The Veteran's Day Storm, though having a similar maximum breaking wave height to the December 1992 nor'easter, has lower water levels and the combination of the two leads to a smaller PEI of 70.

While PEI reflects the peak erosion intensity, SEI reflects cumulative erosion potential by considering storm duration and summing of the instantaneous erosion intensity over that duration. The storm duration defines the length of the time storm conditions act on the beach. Even if a storm has elevated wave heights and water levels, if it moves quickly it has a less time to act on the beach and accumulate effects. The example of Hurricane Sandy in particular helps illustrate the importance of storm duration. Although Hurricane Sandy exceeds all other storms at each shoreline segment in terms of PEI, which is a response to its simultaneously high wave heights and water levels, it does not always rank first in terms of SEI, which is a response to its intensity over the storm duration.

Shoreline Segment 8 is one of the locations where the December 1992 nor'easter and the Veteran's Day Storm have a lower PEI than Hurricane Sandy as discussed above, yet are similar or higher in terms of SEI. This is attributed to the long durations of relatively high intensity of the two storms. The December 1992 nor'easter and Veteran's Day Storm have durations based on the thresholds described above of 105 and 89 hours, more than a day longer than Hurricane Sandy which has a duration of 62 hours. In terms of the average intensity ($\overline{IEI}$ = SEI/t_d) the Veteran's Storm and December 1992 nor'easter are similar and both below that of Hurricane Sandy (Table 4).

3.3 Distributions of Storms

3.3.1 SEI and PEI Categories

A median of 131 storms are identified at each shoreline segment using the methodology described above. For the thirteen shoreline segments, the range is 92 to 138 storms with an interquartile range of 14 storms. The distribution of storms among the Categories 1 through 5 based on SEI is presented in Figure 6. The values represent the median percentage of storms in each category taken across all thirteen shoreline segments. A median of 79% of the storms are classified as Category 1 based on SEI (IQR = 10%). 16% (IQR = 8%) are classified as Category 2, and the remaining 5% are classified as Category 3 or higher. These percentages vary from one shoreline segment to another but are consistent with one another in that a majority of the storms are Category 1, a majority of the remaining are Category 2, and the rest are spread out among the highest 3 categories. Each shoreline segment has at least 1 category 5 storm, with the exception of the three northernmost and one southernmost segments (1 – 3; 13). The range of SEI values associated with each category is presented in Table 5, along with the typical values of some of the contributing factors. Because of the small number of storms classified as either Category 4 or 5, these two are combined. The medians and interquartile ranges provided are based on the data from all thirteen shoreline segments. As expected increased typical values for PEI, average intensity ($\overline{\mathrm{IEI}}$), maximum breaking wave height during the storm ($H_{b,max}$), maximum total water level during the storm (WL_{max}), and storm duration (t_d) are associated with increased SEI values and category. The return periods associated with the thresholds of each SEI category for the each shoreline segment is listed below (Table 6). Typically, storms that are classified as a Category 2 based on SEI have return periods between 1 and 4 years; Category 3 storms have return periods of between 4 and 14 years; Category 4 storms have return periods between 14 and 30 years; Category 5 storms have return periods of greater than 30 years. Exceptions to this are some of the middle shoreline segments (Shoreline Segments 4 through 7) where the SEI values tend to be higher. Here, Category 4 storms have return periods between 8 and 12 years and Category 5 storms have return periods of greater than 20 years.

Figure 6 also presents the distribution of storms among the Categories 1 through 5 based on PEI. A median of 17% of the storms are classified as Category 1 based on SEI (IQR = 6%). 74% (IQR = 5%) are classified as Category 2, 9% (IQR=4%) are classified as Category 3, and the remaining storms are classified as Category 4 or Category 5. As discussed earlier, the PEI value of Hurricane Sandy greatly exceeds the PEI values of the other storms in the northern shoreline segments; therefore, when the thresholds are developed for the five categories based on Equation 5, very large values are required for a storm be classified into one of the higher categories. The range of values associated with each category is presented in Table 6. Only Hurricane Sandy is classified as Category 5 at Shoreline Segments 1 through 4 and Shoreline Segment 6. At the remaining shoreline segments, no storms are classified as Category 5. At Shoreline Segments 10 through 13, no storms are classified as Category 4 either, illustrating the lower peak intensity of storms experienced at the southernmost shoreline segments. Because of the wide range of the PEI values experienced at each shoreline segment, there is a wide range in the return levels associated with each category for the thirteen shoreline segments (Table 6). For example, at Shoreline Segment 4 a Category 4 storm has a return period between 14 and 60 years whereas at Shoreline Segment 13 it has a return period well over 100 years. While values between 93 and 128 (Category 4) have already occurred over the last 34 years at Shoreline Segment 4 (PEI_{max} = 163), they have not yet occurred at Shoreline Segment 13 (PEI_{max} = 77). The values associated with a Category 4 storm are 20% to 70% higher than the maximum PEI value ever experienced at Shoreline Segment 13.

In Table 6, any return periods associated with the thresholds that are greater than 100 years are simply recorded as such due to the uncertainty with projecting longer return periods with a relatively short data set.

3.3.2 Spatial patterns

The developed climatology is utilized to determine if there are any differences between the shoreline segments in terms of the frequency or intensity of storms. Parameters that are analyzed include the number of storms, the number of higher intensity storms classified (i.e. Category 2 or higher based on SEI), and the cumulative SEI. Each parameter is accumulated across the entire 34-year record and is presented in Figure 7, along with the median value presented as horizontal dotted lines.

Based on the data presented, the northernmost shoreline segments tend to have less storms, less intense storms, and a smaller cumulative SEI than the rest of New Jersey. Shoreline segments towards the middle of New Jersey (ie. Shoreline Segment 6) tend to have more intense storms and a higher cumulative SEI. Shoreline Segment 1 has the lowest total number of storms at 92 which is significantly lower than the median of 131 (30% lower). The remaining segments are much closer together, within 10 storms (or 8%), of the median of 131. This difference between the northern shoreline segments and the rest equates to an average difference of up to 1 storm less per year (median of 3 storms per year versus 4). When only considering the higher classified storms over the 34 years, the three northernmost shoreline segments along with Shoreline Segment 13 have the lowest number at around 15. The remaining segments are near or above the median of 27 storms. A maximum of 33 storms occurs at Shoreline Segment 7. In terms of cumulative SEI the northernmost and southernmost shoreline segments (Shoreline Segments 1 – 3; 13) have the smallest values, all falling below the median value of 61,600, with a maximum departure of 27% at Shoreline Segment 1. Shoreline Segments 4 through 11 are closer together with the maximum value occurring at Shoreline Segment 6.

The disparities in the three parameters described above between the northernmost shoreline segments and the rest of New Jersey is likely related to the sheltering effect of Long Island. The influence of this sheltering effect on the direction of longshore sediment transport has been well documented (Messaros et al., 2018). Generally, in New Jersey the net longshore sediment transport tends to be directed towards the south due to the winter nor'easters. However, for the New Jersey coast north of Mantoloking (located at the northern end of Shoreline Segment 5) net transport tends to be directed towards the north. This is due to Long Island blocking a portion of the large but relatively infrequent waves during nor'easters that drive the net transport towards the south.

The potential influence of the sheltering effect of Long Island was evaluated by examining the percentage of time that the waves are both directed onshore as well as met the wave steepness threshold. While 31% of the total waves in the record meet these requirements at Shoreline Segment 6, just 20% of the total waves in the record meet them at Shoreline Segment 1. This 10% difference results in a difference of on average 37 days/year. In general, the northernmost shoreline segment sees less large waves directed onshore per year contributing to less storms, less intense storms, and a smaller cumulative SEI whereas those in the middle are exposed to waves coming from both directions (north and south).

For the remainder of the state, variation in cumulative SEI appears to be driven more by the increased erosion potential of the storms versus a change in the number of storms. Shoreline Segment 6 has one of the highest number of storms with a Category 2 or higher by SEI as well as the highest cumulative SEI. On the other hand, Shoreline Segment 13 has a similar number of storms, but 55% less storms categorized as 2 or higher, and a 37% smaller cumulative SEI. The average storm intensity per hour ($\sum \mathrm{SEI} / \sum \mathrm{t}$) and per storm ($\sum \mathrm{SEI} / \mathrm{n}_{\mathrm{orm}}$) at Shoreline Segment 6 is 25/hr and 535/storm whereas that at Shoreline Segment 13 is 17/hr and 338/storm.

3.3.3 Yearly patterns

A similar analysis is performed to determine which years are associated with the most storms, the most higher intensity storms (i.e. Category 2 or higher based on SEI), as well as the highest cumulative SEI. For this analysis a year is defined from the start of hurricane season on June 1st until May 31st of the following year. Defining a year as such keeps most of the erosional events (tropical in the summer to fall and extratropical during the winter to early spring) together and provides a better representation of seasonal erosion. For this analysis only full years are looked at. This includes 1980 (6/1/1980 – 5/31/1981) through 2012 (6/1/2012 – 5/31/2013).

The median number of storms per year is calculated across the thirteen shoreline segments and is presented in Figure 8. 2009 (6/1/2009 – 5/31/2010) accounts for the highest median number of storms at 8 which corresponds to about 6% of the 34-year total. Another year of note is 1997 (6/1/1997 – 5/31/1998) which has a median of 7 storms (5.4% of the total). 2009 accounts for the most storms when only considering those that are a Category 2 or higher based on SEI. This includes the Veteran's Day Storm in November 2009, one smaller storm earlier that year in September, and a nor'easter in March 2010. The Friedman test procedure is applied to confirm that there are significant differences between the years in the record based on the percentage of total storms well as the percentage of the higher intensity storms. This is a nonparametric test procedure to assess the plausibility that the groups of interest, in this case the years, are indistinguishable in a randomized block design (Friedman, 1937). For each shoreline segment, each year is ranked 1 through 33 based on a single parameter, with 1 being the lowest and 33 the highest. In this case, the test is performed for each of the parameters discussed above. For each test, the rank is averaged across all shoreline segments to determine an average rank for each year. The assessment of plausibility is based on how close the rank averages ($\bar{\mathrm{r}}_{\mathrm{i}}$) are to the average expected rank value (in this case 16). If the average rank for each shoreline segment is close to the average expected value, then no significant differences (i.e. spatiality) is detected in the data. This test indicates that there are some spatial differences associated with each parameter as the p-value is sufficiently low. 2009 has the highest average rank for both parameters at about 33 indicating at nearly all of the shoreline segments, 2009 exceeds all other years.

To further assess each year, a cumulative SEI for each year is determined by summing the SEI of the storms occurring within each year. The median yearly cumulative SEI is shown in Figure 8. 2009, again, is the year associated with the highest cumulative SEI of 6671 (11% of the total). The severity of this winter storm season in New Jersey in terms of the frequency of storms and their collected impacts have been well-documented (Farrell et al., 2010). This year is followed by 1992 and 2012, with yearly values of 4353 and 3465 (each accounting for about 6% of the total) respectively. Large contributors of these two values are the December 1992 nor'easter and Hurricane Sandy in October 2012. Because of the spatial variation in intensity of these two storms, the yearly SEI value for 1992 and 2012 varies by shoreline segment. As the two storms were more intense in northern New Jersey than in southern New Jersey, the value tend to be higher in the northern segments (accounting for 10% of the cumulative SEI) and lower in the southern segments (accounting for just about 6% of the cumulative SEI).

The available data reflects a lull in storm activity in the late 1980s and late 1990s. Between the years 1985 and 1989 (6/1/1985 – 5/31/1990) and the years 1998 and 2001 (6/1/1998 – 5/31/2002) not a single Category 2 or higher storm occurred. Total storm counts and cumulative SEI tend to be lower with most years accounting for a median of 2 storms or less and each with a median yearly SEI of 1100 or less (less than 2% of the respective total). Average ranks derived when performing the Friedman test procedure range from 2 to 18 based on storm count and from 2 to 14 based on cumulative SEI for these years. These ranks are generally below the average expected rank of 16.

The yearly data suggests that there may be some trend in terms of the frequency and intensity of storms over time. The yearly totals discussed above are summed into five year periods starting from 1983 and extending to the end of the record in 2013. The median values across all shoreline segments for each of the parameters is presented in Figure 9. A Friedman test is performed to confirm there are significant differences within the periods in the dataset for the three parameters discussed. Based on the median number of storms accounted for by each five-year period there does not seem to be a strong trend of an increase in the number of storms over time with values fairly stagnant over the last twenty years. A median of 15 storms (13% of the total) occurred in the earliest period of the record (6/1/1983 – 5/31/1988) whereas 23 storms (20% of the total) occurred in the latest period (6/1/2008 – 5/31/2013) with variation in the periods in between. On the other hand, there appears to be an increase in the cumulative SEI. Between the first and last period, the medians of the parameter more than doubles with SEI summed over the five-year interval increases from 6300 to 15,500. These changes are associated with increases of 11% to 28% of the thirty-year totals. Based on these observations, it appears that the increase in SEI over time may not be due to an increase in the number of storms but to an increase in the intensity of those storms. SEI per storm increases from 420/storm in the first 5-year interval to 673/storm in the most recent 5-year interval. However, continued monitoring of is suggested to assess whether the trends observed are maintained or are related to climatic variations only evident over periods longer than the thirty years included in this study.

3.3.4 Monthly patterns

The developed climatology was also analyzed to determine if there are any patterns in the seasonal distribution of storm occurrences. At each shoreline segment, the number of storms occurring within each month (January – December), regardless of year, are identified by start date. The same is performed for storms classified as Category 2 or higher based on SEI value. The SEI values for each storm identified for each month are also summed to determine a cumulative SEI for each month over the length of the climatology. Figure 10 shows the medians of each of these values determined using the information derived for all thirteen shoreline segments. The error bars show the 95% confidence interval for the median. The Friedman test procedure is applied to confirm that there are significant differences between the months in the record based on all three parameters.

As expected, a majority of storms occur during the fall and winter months. The average ranks calculated as part of the Friedman test and presented in Table 7 show that the months that are ranked above the average expected rank of 6.5 include January through March and September through December. With the exception of February, these months exceed the average expected rank for all three parameters. All other months which include those in the spring and summer fall below the average expected rank. These observations are shown in Figure 10 where median values for April through August are smaller than the rest of the months for each of the parameters discussed.

By individual month, March and October have the highest occurrence of storms with 17 storms each over the 34 years of the climatology. This corresponds to each accounting for 14% of the total. The average rank for these months is about 11 indicating that these months are generally the top two ranked months though there is some variation across the shoreline segments. However, when considering only the storms that are Category 2 or higher based on SEI, October is the stormiest month accounting for a median of 8 of those storms. This equates to 31% of the total number of the higher intensity storms over the 34 years. One of these storms is Hurricane Sandy, which occurred at the end of October 2012 and is classified as Category 4 or 5 at all shoreline segments. Other October storms of note include the October 13, 2005 storm, the "Perfect Storm" which occurred in October 1991, and Hurricane Josephine in October 1984. October also accounts for the highest average percentage of cumulative SEI for the 34-year period with a median of 22%. Based on these two parameters, October is followed by several other fall and winter months which are all fairly similar to each other based both on median values and average rank. The average rank for October is 12 based on both the percentage of storms classified as Category 2 or higher and cumulative SEI confirming that at all of the shoreline segments October has the highest value for these two parameters.

4 CONCLUSIONS

In this study, 34 years (1980 – 2013) of New Jersey storms were reanalyzed on the basis of their erosion potential according to the Storm Erosion Index (SEI). The resulting SEI-based climatology identifies approximately 130 storms at each of thirteen shoreline segments. SEI considers the three main storm related drivers of coastal erosion, wave intensity, total water level and storm duration, and has previously been shown to be capable of ranking both tropical and extra-tropical storms on a single, physically meaningful scale. One of the key advantages of SEI compared to other measures of storm intensity, is that it accounts for storm duration which has been identified as a critical factor related to beach erosion in previous studies (Dohner et al., 2016; Herrington and Miller, 2010).

The results presented in this paper illustrate that SEI is capable of identifying and classifying the major storms that have impacted the New Jersey coast, including the December 1992 nor'easter, the November 2009 Veteran's Day Storm, and Hurricane Sandy in October 2012. Spatial variations of each storm's intensity (SEI/PEI) have also been identified. The importance of storm duration is highlighted by the Veteran's Day Storm (November 2009), a well-known coastal event in New Jersey that resulted in significant erosion particularly in the southern part of the state. This otherwise ordinary storm resulted in extraordinary impacts due to the extreme waves, which persisted over 3.5 days. At Shoreline Segment 8, using more typical means of classifying storm intensity such as maximum wave height or water level, this storm would be ranked sixth and have a return period on the order of 5 years. When SEI is considered however, this storm is ranked first with a return period of approximately 40 years.

The developed 34-yr storm SEI climatology is further used to identify spatial and temporal patterns in storm erosion potential for the state. For example, in New Jersey more storms, and more intense storms are identified at the shoreline segments towards the middle of the state versus those towards the northernmost end, which may be partially due to the sheltering of waves during nor'easters by Long Island to the northeast. Additionally, the climatology shows that the most storms occur during the fall and winter months, as expected, with the most storms individually occurring during March and October. However, more of the storms with higher erosion potential tend to occur during October as October accounts individually for the highest percentage of higher classified storms and cumulative SEI (each about one-quarter of their respective totals). Analyzing erosion potential by year, New Jersey is shown to have periods of reduced storm activity as well as those of intensified conditions. As more data is collected it is suggested to monitor trends to see if there is any increase in storminess or if anything can be related to longer-cycle climatic variations.

The methodology presented in this paper demonstrates the usefulness of SEI for evaluating erosion potential on the basis of readily available storm parameters. Here, SEI was applied in a hindcast sense to evaluate temporal and spatial patterns in erosion potential; however, because the calculation is computationally efficient, and only relies on simple input parameters, extension to short-range forecasts, or long-term climate studies is possible. It is also possible to combine the storm information captured by SEI with typically less readily available, and potentially more spatially and temporally variable beach state information such as profile geometry (Cheng and Wang, 2019; Splinter et al., 2014; Splinter et al., 2018), offshore bathymetry (Mahabot et al., 2017), nearshore structures (Plant and Griggs, 1992), offshore and nearshore wave direction (Harley et al., 2017), and storm sequencing (Callaghan et al., 2009), to more directly estimate beach impacts. Both extensions are the focus of ongoing research.

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6 REFERENCES

Aon Benfield, 2018. Global catastrophe recap March 2018.

Balsillie, J.H., 1986. Beach and coast erosion due to extreme event impact. Shore & Beach, 54(4): 22-37.

Barone, D., McKenna, K. and Farrell, S., 2014. Hurricane Sandy: Beach-dune performance at New Jersey Beach Profile Network sites. Shore & Beach, 82: 13-23.

Basco, D.R. and Mahmoudpour, N., 2012. The modified Coastal Storm Impulse (COSI) parameter and quantification of fragility curves for coastal design. Coastal Engineering Proceedings, 1(33): 66.

Basco, D.R. and Walker, R.A., 2010. Application of Coastal Storm Impulse (COSI) parameter to predict coastal erosion. Coastal Engineering Proceedings, 1(32): 23.

Blake, E.S., Kimberlain, T.B., Berg, R.J., Cangialosi, J.P. and Beven, J.L., 2013. Tropical cyclone report: Hurricane Sandy, National Hurricane Center.

Bruun, P., 1962. Sea-level rise as a cause of shore erosion. J Waterw Port Coast, 88(1): 117-132.

Callaghan, D.P., Nielsen, P., Short, A. and Ranasinghe, R., 2008. Statistical simulation of wave climate and extreme beach erosion. Coast Eng, 55(5): 375-390.

Callaghan, D.P., Ranasinghe, R. and Short, A., 2009. Quantifying the storm erosion hazard for coastal planning. Coast Eng, 56(1): 90-93.

Cheng, J. and Wang, P., 2019. Unusual Beach Changes Induced by Hurricane Irma with a Negative Storm Surge and Poststorm Recovery. J Coastal Res, 35(6): 1185-1199.

Davis, R.E. and Dolan, R., 1993. Nor'easters. American Scientist, 81(5): 428-439.

Dean, R.G. and Dalrymple, R.A., 2002. Coastal processes with engineering applications. Cambridge University Press, New York, NY, 475 pp.

Dean, R.G., Walton, T.L. and Kriebel, D.L., 2001. Cross-shore sediment transport. Coastal Engineering Manual. US Army Coastal & Hydarulics Laboratory.

Dohner, S.M., Trembanis, A.C. and Miller, D.C., 2016. A tale of three storms: Morphologic response of Broadkill Beach, Delaware, following Superstorm Sandy, Hurricane Joaquin, and Winter Storm Jonas. Shore & Beach, 84: 3-9.

Dolan, R. and Davis, R.E., 1992. An intensity scale for Atlantic coast northeast storms. J Coastal Res, 8(4): 840-853.

Done, J.M., Paimazumder, D., Towler, E. and Kishtawal, C.M., 2015. Estimating impacts of North Atlantic tropical cyclones using an index of damage potential. Climatic Change, 146(3-4): 561-573.

Farrell, S. et al., 2017. An analysis of thirty years' study of sand redistribution and shoreline changes in New Jersey's four coastal counties Raritan Bay, the Atlantic Ocean coast, and Delaware Bay fall 1986 through fall 2016, The Stockton University Coastal Research Center.

Farrell, S.C. et al., 2010. New Jersey Beach Profile Network 2009 annual report on shoreline changes in New Jersey coastal reaches one through fifteen Raritan Bay to Delaware Bay, The Richard Stockton Coastal Research Center.

Flynn, M.J., Sediment characterization of the New Jersey shoreline: Comparison of median grain size distribution from 1950 to 2011, The Richard Stocton College Coastal Research Center.

Friedman, M., 1937. The use of ranks to avoid the assumption of normality implicit in the analysis of variance. Journal of the american statistical association, 32(200): 675-701.

Georgas, N. et al., 2016. An open-access, multi-decadal, three-dimensional, hydrodynamic hindcast dataset for the Long Island Sound and New York/New Jersey Harbor estuaries. J Mar Sci Eng, 4(3).

Harley, M.D. et al., 2017. Extreme coastal erosion enhanced by anomalous extratropical storm wave direction. Scientific Reports, 7(1): 6033.

Hebert, C.G., Weinzapfel, R.A. and Chambers, M.A., 2010. Hurricane Severity Index: A new way of estimating a tropical cyclones destructive potential. 29th Conference on Hurricanes and Tropical Meteorology, p.^pp.
Héquette, A. et al., 2019. Alongshore Variability in Coastal Dune Erosion and Post-Storm Recovery, Northern Coast of France. J Coastal Res, 88(sp1): 25-45.
Herrington, T.O. and Miller, J.K., 2010. A comparison of methods used to calculate northeaster damage potential. Shore & Beach, 78(2): 20-25.
Janssen, M.S., Lemke, L. and Miller, J.K., 2019. Application of Storm Erosion Index (SEI) to paramterize spatial storm intensity and impacts from Hurricane Michael. Shore & Beach, 87(4): 41-50.
Johnson, J.W., 1949. Scale effects in hydarulic models involving wave motion. Transactions of the American Geophysical Union, 30(4): 517-525.
Kana, T.W., 1977. Beach erosion during minor storm. Journal of the Waterway, Port, Coastal and Ocean Division, 103(4): 505-518.
Kantha, L., 2006. Time to replace the Saffir- Simpson Hurricane Scale? Eos, Transactions American Geophysical Union, 87(1): 3-6.
King, C.A.M., 1953. The relationship between wave incidence, wind direction, and beach changes at Marsden Bay, County Durham. Transactions and Papers (Institute of British Geographers), 19: 13-23.
King, C.A.M. and Williams, W.W., 1949. The formation and movement of sand bars by wave action. The Geographical Journal, 113: 70-85.
Kraus, N.C. and Wise, R.A., 1993. Simulation of January 4, 1992 storm erosion at Ocean City, Maryland. Shore & Beach, 61(1): 34-41.
Kriebel, D., Dalrymple, R., Pratt, A. and Sakovich, V., 1996. Shoreline risk index for northeasters. Proceedings of the 1996 Conference on Natural Disaster Reduction, p.^pp. 251-252.
Lang, M., Ouarda, T.B.M.J. and Bobee, B., 1999. Towards operational guidelines for over-threshold modeling. J Hydrol, 225(3-4): 103-117.
Mahabot, M.M., Pennober, G., Suanez, S., Troadec, R. and Delacourt, C., 2017. Effect of Tropical Cyclones on Short-Term Evolution of Carbonate Sandy Beaches on Reunion Island, Indian Ocean. J Coastal Res, 33(4): 839-853.
Masselink, G., Russell, P., Blenkinsopp, C. and Turner, I., 2010. Swash zone sediment transport, step dynamics and morphological response on a gravel beach. Mar Geol, 274(1-4): 50-68.
McNinch, J.E. and Wells, J.T., 1992. Effectiveness of beach scraping as a method of erosion control. Shore and Beach, 60(1): 13-20.
Mendoza, E.T. and Jiménez, J.A., 2006. A storm classification based on the beach erosion potential in the Catalonian coast. J Coastal Res, SI 48: 81-88.
Mendoza, E.T., Jimenez, J.A. and Mateo, J., 2011. A coastal storms intensity scale for the Catalan sea (NW Mediterranean). Nat Hazard Earth Sys, 11(9): 2453-2462.
Messaros, R.C. et al., 2018. Assessing the coastal resilience of Manasquan Inlet to Sea Bright, New Jersey: Regional sediment budget 1992–2003. J Coastal Res, 34(4): 955-967.
Miller, J.K., 2015. Evaluation of storm severity based on the Storm Erosion Index along the Atlantic Coasts of North Carolina and South Carolina. Technical report prepared for the Charleston District of the USACE., Stevens Insitute of Technology, Davidson Laboratory.
Miller, J.K. and Dean, R.G., 2004. A simple new shoreline change model. Coast Eng, 51(7): 531-556.
Miller, J.K. and Livermont, E., 2008. A predictive index for wave and storm surge induced erosion. Proceedings of the 31st International Conference on Coastal Engineering, Hamburg, Germany, p.^pp. 4143-4153.

Miller, J.K. and Wehof, J., 2013. Evaluation of storm severity based on the Storm Erosion Index along the Southeast Atlantic Coast of Florida in the wake of Hurricane Sandy. Technical report prepared for the Jacksonville District of the USACE., Stevens Insitute of Technology, Davidson Laboratory.

Moore, B.D., 1982. Beach profile evolution in response to changes in water level and wave height. MCE Thesis, Department of Civil Engineering, University of Delaware, 164 pp.

Munger, S. and Kraus, N.C., 2010. Frequency of extreme storms based on beach erosion at Northern Assateague Island, Maryland. Shore & Beach, 78(2): 3-11.

NJOEM, 2014. 2014 New Jersey state hazard mitigation plan.

NOAA, 1992. Storm data with annual summaries and unusual weather phenomena with late reports and corrections. Volume 34. No. 12., National Oceanic and Atmospheric Administration.

Palutikof, J.P., Brabson, B.B., Lister, D.H. and Adcock, S.T., 1999. A review of methods to calculate extreme wind speeds. Meteorol Appl, 6(2): 119-132.

Plant, N.G. and Griggs, G.B., 1992. Interactions between nearshore processes and beach morphology near a seawall. J Coastal Res: 183-200.

Powell, M.D. and Reinhold, T.A., 2007. Tropical cyclone destructive potential by integrated kinetic energy. B Am Meteorol Soc, 88(4): 513-526.

Saville, T., 1957. Scale effects in two dimensional beach studies. Transactions from the 7th General Meeting of the International Association of Hydraulic Research, p.^pp.

Schott, T. et al., 2012. The Saffir-Simpson Hurricane Wind Scale, NOAA/National Weather Service.

Shand, T. et al., 2011. NSW coastal inundation hazard study: coastal storms and extreme waves. UNSW Australia Water Research Laboratory Technical Report, 16.

Splinter, K.D., Carley, J.T., Golshani, A. and Tomlinson, R., 2014. A relationship to describe the cumulative impact of storm clusters on beach erosion. Coast Eng, 83: 49-55.

Splinter, K.D., Kearney, E.T. and Turner, I.L., 2018. Drivers of alongshore variable dune erosion during a storm event: Observations and modelling. Coast Eng, 131: 31-41.

USACE, 2015. Wave infomation studies.

USACE, 2018. Storms at the FRF.

Villatoro, M. et al., 2014. An approach to assess flooding and erosion risk for open beaches in a changing climate. Coast Eng, 87: 50-76.

Waters, C.H., 1939. Equilibrium slopes of sea beaches, University of California, Berkeley, CA.

Wehof, J., Miller, J.K. and Engle, J., 2014. Application of the Storm Erosion Index (SEI) to three unique storms. Proceedings of the 34th International Conference on Coastal Engineering, Seoul, Korea, p.^pp.

You, Z.J. and Lord, D., 2008. Influence of the El Nino-Southern Oscillation on NSW coastal storm severity. J Coastal Res, 24(2b): 203-207.

Zhang, K.Q., Douglas, B.C. and Leatherman, S.P., 2001. Beach erosion potential for severe nor'easters. J Coastal Res, 17(2): 309-321.

Zhang, K.Q. and Leatherman, S., 2011. Barrier island population along the U.S. Atlantic and Gulf coasts. J Coastal Res, 27(2): 356-363.

Table 1: Characteristics of indices & other common parameters used to estimate storm intensity

Index/Parameter	Type of Storm	Parameters Considered	Source
Saffir-Simpson Hurricane Wind Scale (SSHWS)	Tropical	Wind speed	Schott et al. (2012)
Hurricane Intensity Index (HII) & Hurricane Hazard Index (HHI)	Tropical	Wind speed, radius, translation speed	Kantha (2006)
Integrated Kinetic Energy (IKE)	Tropical	Wind speed, storm volume	Powell and Reinhold (2007)
Hurricane Severity Index (HIS)	Tropical	Wind speed, radius	Hebert et al. (2010)
Cyclone Damage Potential (CDP) Index	Tropical	Wind speed, radius, forward speed	Done et al. (2015)
Dolan and Davis Scale	Extratropical	Energy (wave height, duration)	Dolan and Davis (1992); Mendoza et al. (2011)
Shoreline Risk Index	Extratropical	Wave height, surge, duration	Kriebel et al. (1996)
Storm Erosion Potential Index (SEPI)	Extratropical	Storm surge, tide, duration	Zhang et al. (2001)
Balsillie regression analysis	Tropical & Extratropical	Water level, duration	Balsillie (1986)
Maximum wave run-up	Tropical & Extratropical	Wave run-up (wave height, water level)	Kraus and Wise (1993)
Storm Erosion Index (SEI)	Tropical & Extratropical	Equilibrium beach response (wave height, total water level, duration)	Miller and Livermont (2008)
Coastal Storm Impulse (COSI) Parameter	Tropical & Extratropical	Total horizontal momentum (wave height, surge, duration)	Basco and Mahmoudpour (2012); Basco and Walker (2010)
Cumulative wave energy	Tropical & Extratropical	Energy (wave height, duration)	Splinter et al. (2014)

Table 2: New Jersey shoreline segments

ID	Northern Bound	Southern Bound	Length (km)	Median d50 (mm)	Median Berm Elev. (m NAVD88)	Shore-normal Angle	Local WIS Station
1	Sandy Hook	Sea Bright	11.7	0.39	2.4	83	63126
2	Sea Bright	Long Branch	7.2	0.50	3.0	95	63127
3	Long Branch	Shark River Inlet	13.0	0.49	3.0	102	63128
4	Shark River Inlet	Manasquan Inlet	9.5	0.51	3.0	102	63130
5	Manasquan Inlet	Barnegat Inlet	37.0	0.51	2.6	100	63133
6	Barnegat Inlet	Little Egg Inlet	33.6	0.41	2.4	120	63138
7	Little Egg Inlet	Absecon Inlet	13.4	0.28	1.5	132	63140
8	Absecon Inlet	Great Egg Harbor Inlet	12.9	0.28	1.8	145	63142
9	Great Egg Harbor Inlet	Corson Inlet	12.6	0.25	2.4	130	63143
10	Corson Inlet	Townsends Inlet	10.6	0.27	1.8	119	63145
11	Townsends Inlet	Hereford Inlet	11.9	0.22	1.5	126	63147
12	Hereford Inlet	Cape May Inlet	9.8	0.17	1.5	135	63149
13	Cape May Inlet	Delaware Bay	7.9	0.62	2.4	163	63151

Table 3: Top five storms based on SEI for four representative shoreline segments in New Jersey

Rank	Date	SEI	SEI Return Period (yr)	SEI Category	PEI	PEI Return Period (yr)	PEI Category
Shoreline Segment 3: Long Branch to Shark River Inlet							
1	10/2012	2932	38	4	155	140	5
2	12/1992	2601	30	4	100	30	4
3	11/2009	1850	16	3	69	19	3
4	10/2005	1812	15	3	53	2.4	2
5	10/2009	1200	7.0	2	42	1	2
Shoreline Segment 5: Manasquan Inlet to Barnegat Inlet							
Rank	Date	SEI	SEI Return Period (yr)	SEI Category	PEI	PEI Return Period (yr)	PEI Category
1	12/1992	3238	37	5	98	31	4
2	10/2012	3204	36	5	124	180	4
3	11/2009	3128	33	5	79	8.4	3
4	10/2005	2166	11	3	58	2	2
5	09/2008	1855	7.0	3	56	1.8	2
Shoreline Segment 8: Absecon Inlet to Great Egg Harbor Inlet							
Rank	Date	SEI	SEI Return Period (yr)	SEI Category	PEI	PEI Return Period (yr)	PEI Category
1	12/1992	3366	41	5	81	23	3
2	11/2009	3090	32	5	70	7.7	3
3	10/2012	2961	28	4	98	160	4
4	09/2008	2077	10	3	55	2.3	2
5	10/1984	1927	8.7	3	61	3.6	3
Shoreline Segment 11: Townsends Inlet to Hereford Inlet							
Rank	Date	SEI	SEI Return Period (yr)	SEI Category	PEI	PEI Return Period (yr)	PEI Category
1	12/1992	3672	38	5	79	21	3
2	11/2009	3193	25	5	71	8.5	3
3	10/2012	2846	18	4	90	100	3
4	10/1991	2305	10	4	75	14	3
5	09/2008	1897	6.5	3	54	1.9	2

Table 4: Characteristics of the top five storms based on SEI at a representative shoreline segment in New Jersey

Shoreline Segment 8: Absecon Inlet to Great Egg Harbor Inlet							
Rank	Date	SEI	PEI	Max H_b (m)	Max WL (mMSL)	Duration (hr)	$\overline{\text{IEI}}$
1	12/1992	3366	81	6.4	1.8	105	32
2	11/2009	3090	70	6.5	1.6	89	35
3	10/2012	2961	98	7.0	2.0	62	48
4	09/2008	2077	55	6.1	1.3	101	21
5	10/1984	1927	61	6.4	1.4	69	28

Table 5: Median values and interquartile ranges (25% to 75%) for select variables associated with each storm classification based on SEI

Variable		CAT 1	CAT 2	CAT 3	CAT 4 & 5
Defined SEI Range		< 730	730 - 1510	1510 - 2300	> 2300
No. storms	Median	103	21	3	3
SEI	Median (IQR)	194 (80 – 366)	971 (845 – 1119)	1874 (1769 – 2035)	3026 (2741 – 3330)
PEI	Median (IQR)	33 (25 – 40)	53 (45 – 60)	60 (55 – 68)	83 (74 – 101)
$\overline{\mathrm{IEI}}$	Median (IQR)	18 (12 – 23)	29 (23 – 33)	29 (21 – 35)	39 (35 – 48)
$H_{b,max}$ (m)	Median (IQR)	4.5 (4.1 – 4.9)	5.5 (5.1 – 6.1)	6.0 (5.6 – 6.4)	6.8 (6.4 – 7.5)
WL_{max} (m MSL)	Median (IQR)	1.1 (0.8 – 1.3)	1.4 (1.2 – 1.5)	1.5 (1.3 – 1.6)	1.9 (1.7 – 2.1)
t_d (hr)	Median (IQR)	12 (6 – 18)	35 (30 – 46)	65 (61 – 88)	74 (62 – 90)

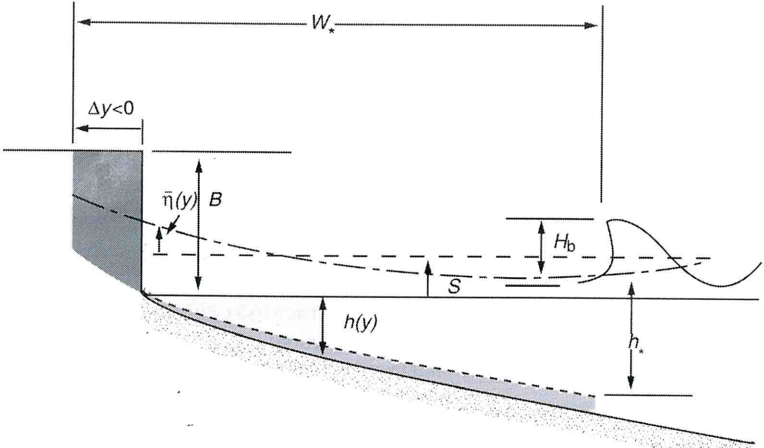
Table 6: Value and return period ranges associated with storm classifications based on SEI and PEI value

	Minimum values and return periods (yr) for SEI Categories 1 through 5				Minimum values and return periods (yr) for PEI Categories 1 through 5			
	CAT 2	CAT 3	CAT 4	CAT 5	CAT 2	CAT 3	CAT 4	CAT 5
ID	730	1510	2300	3080	23	58	93	128
1	2.6	9.3	22	40	0.7	3.8	27	> 100
2	2.4	9.5	22	40	0.8	3.1	19	70
3	2.6	11	24	41	0.6	3.7	23	70
4	1.5	6.3	17	35	0.7	2.1	14	60
5	1.2	4.3	13	31	0.6	2.0	22	> 100
6	1.1	3.5	9	18	0.6	1.7	16	> 100
7	1.1	3.9	11	25	0.6	2.2	39	> 100
8	1.3	4.9	14	31	0.6	2.8	80	> 100
9	1.2	4.4	12	26	0.7	2.9	50	> 100
10	1.0	4.4	12	27	0.6	2.7	> 100	> 100
11	1.2	4.0	10	23	0.6	2.6	> 100	> 100
12	1.3	5.0	15	35	0.7	3.4	> 100	> 100
13	2.0	8.7	26	60	0.5	5.8	> 100	> 100
Median	1.3	4.9	14	32	0.6	2.8	39	> 100
IQR	1.0	4.7	10	14	0.1	1.3	> 100	> 100

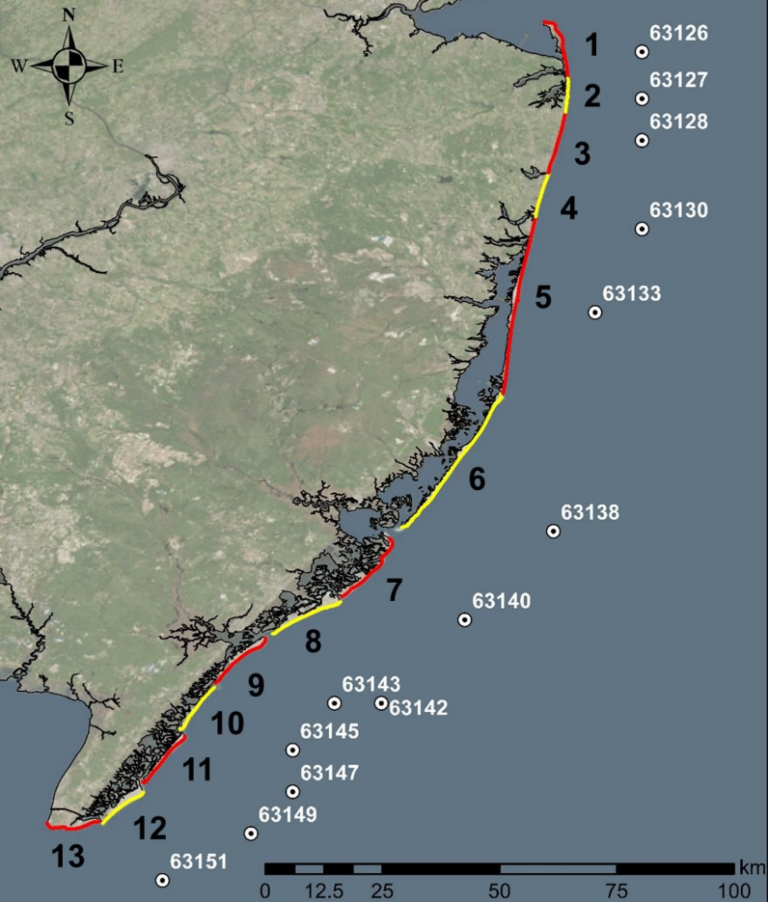
Table 7: Average rank ($\bar{r}_i$) for each month determined via the Friedman test procedure based three parameters

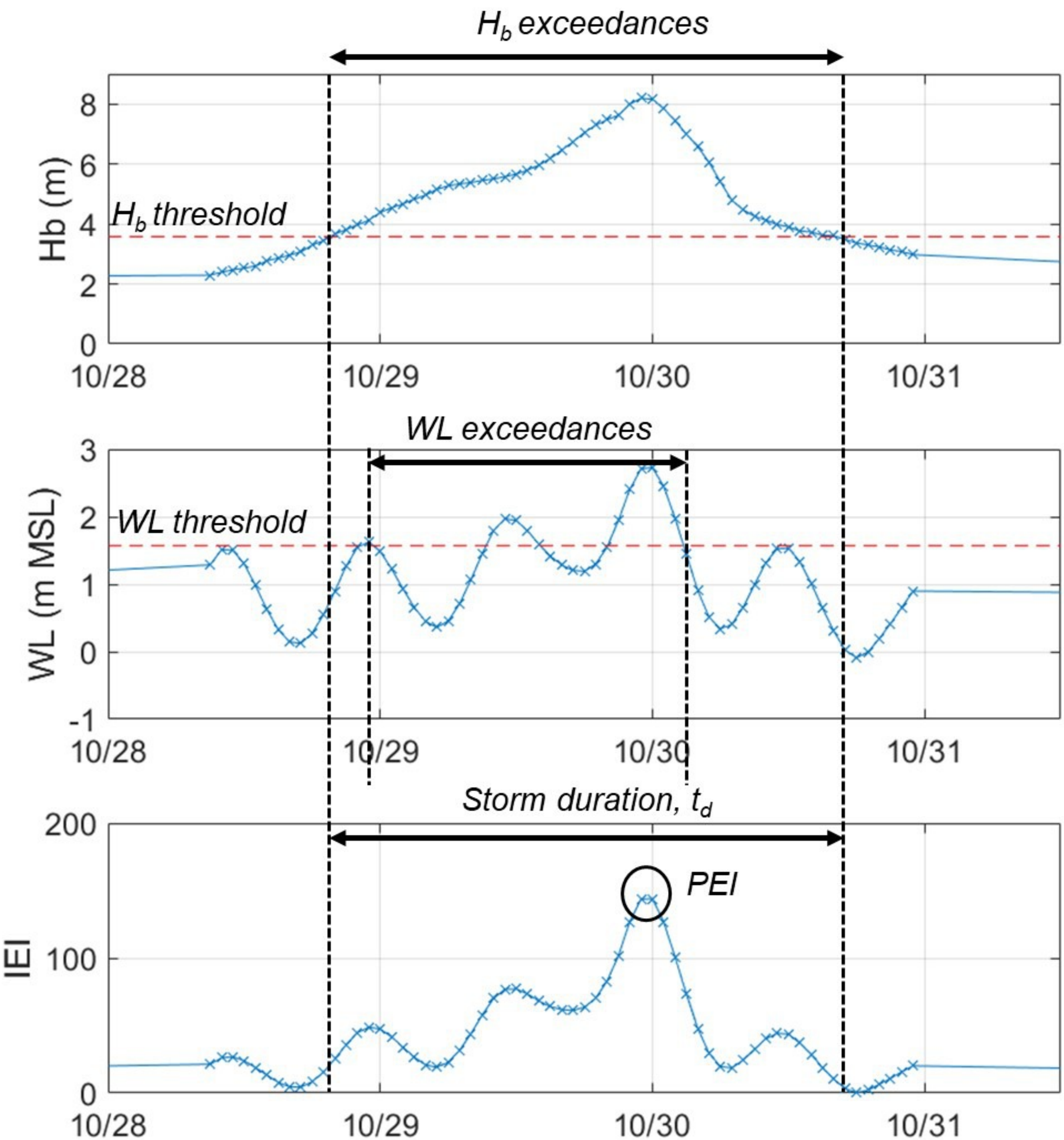
Month	$\bar{r}_i$ Number of storms	$\bar{r}_i$ Number of storms > Category 2 (SEI)	$\bar{r}_i$ Total SEI
Jun	1.5	2.3	1.2
Jul	1.6	2.3	1.8
Aug	4.5	5.2	4.7
Sep	9.3	10.1	9.2
Oct	10.6	11.8	12.0
Nov	8.2	9.9	10.8
Dec	7.0	8.6	9.5
Jan	8.7	7.8	7.5
Feb	8.3	5.7	5.9
Mar	10.9	7.1	8.1
Apr	4.3	2.3	3.4
May	3.2	4.8	4.0

List of figures

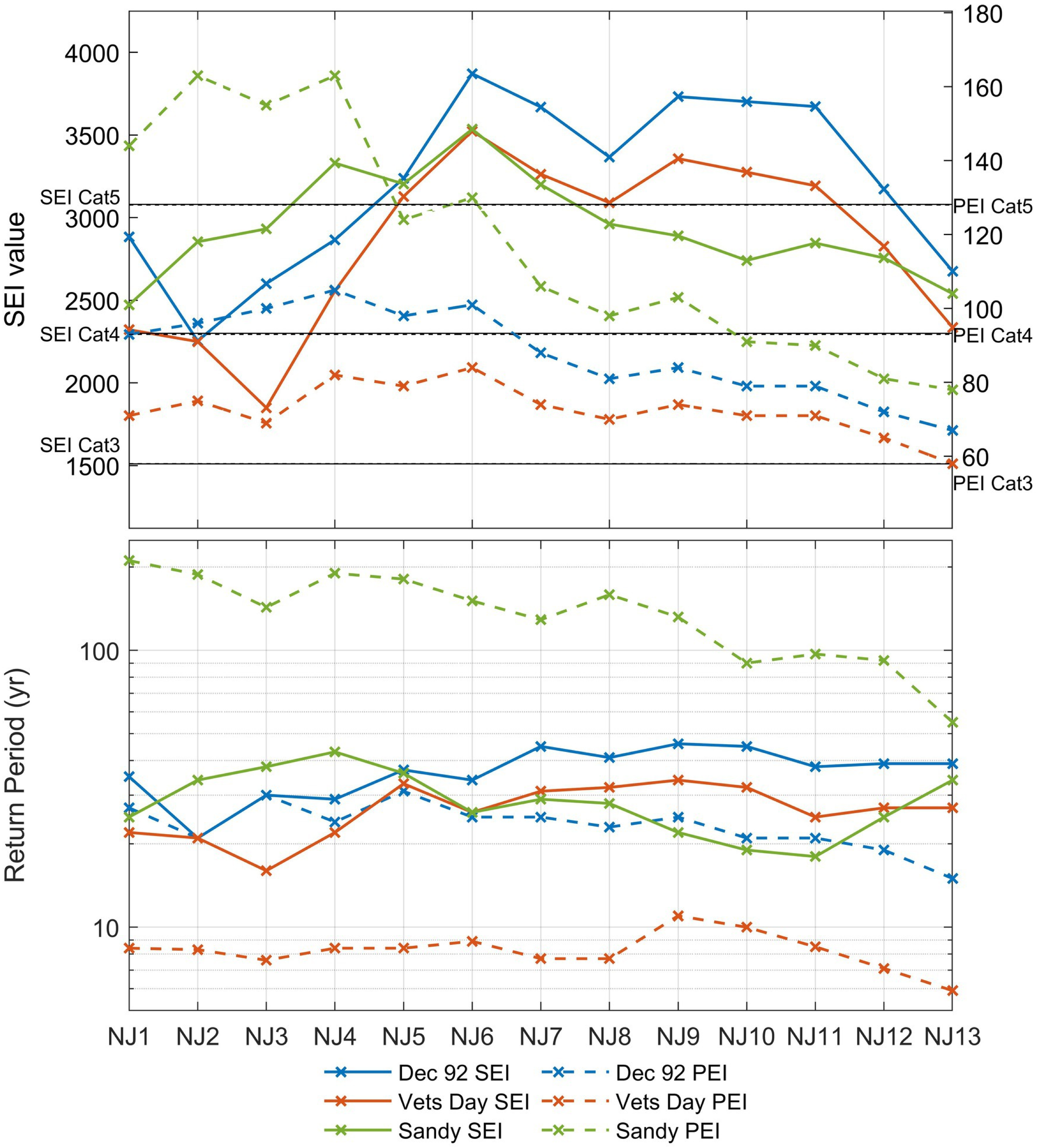


W_*
$\Delta y<0$
$\bar{\eta}(y)$
B
H_b
S
$h(y)$
h_*

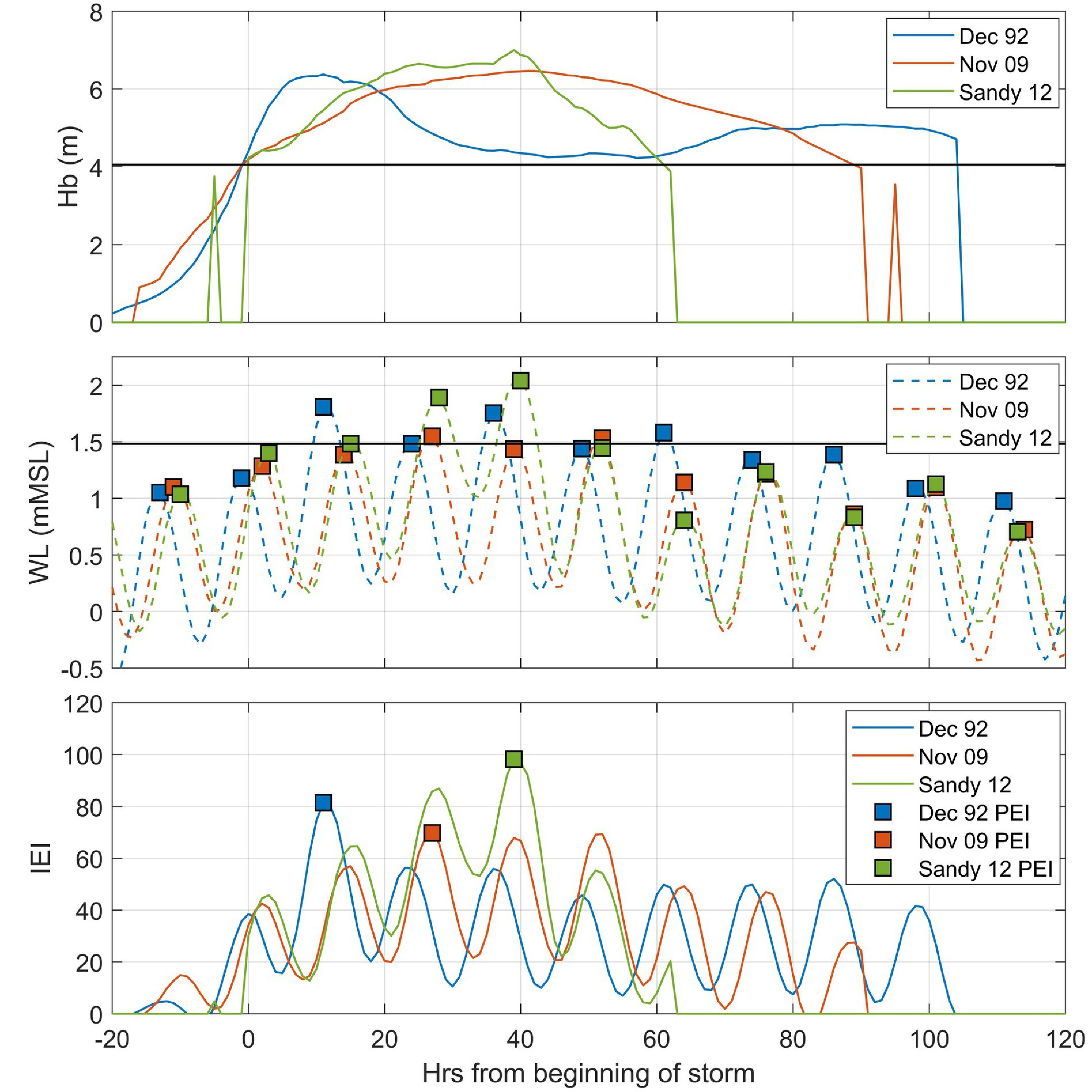

N
S
W
E
1
2
3
4
5
6
7
8
9
10
11
12
13
63126
63127
63128
63130
63133
63138
63140
63143
63142
63145
63147
63149
63151
0
12.5
25
50
75
100
km



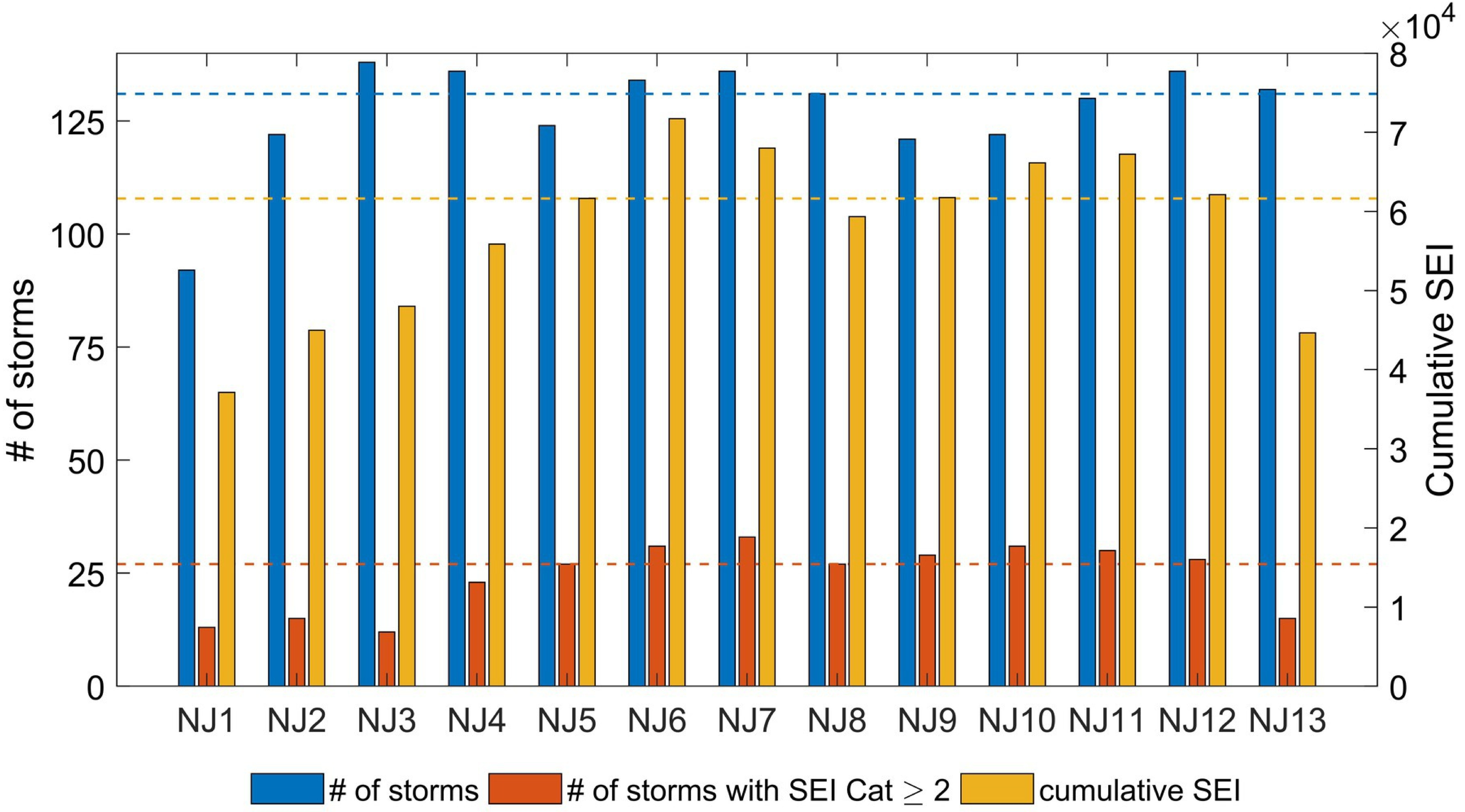
H_b exceedances
Hb (m)
H_b threshold
8
6
4
2
0
10/28
10/29
10/30
10/31
WL exceedances
WL (m MSL)
WL threshold
3
2
1
0
-1
10/28
10/29
10/30
10/31
Storm duration, t_d
IEI
PEI
200
100
0
10/28
10/29
10/30
10/31



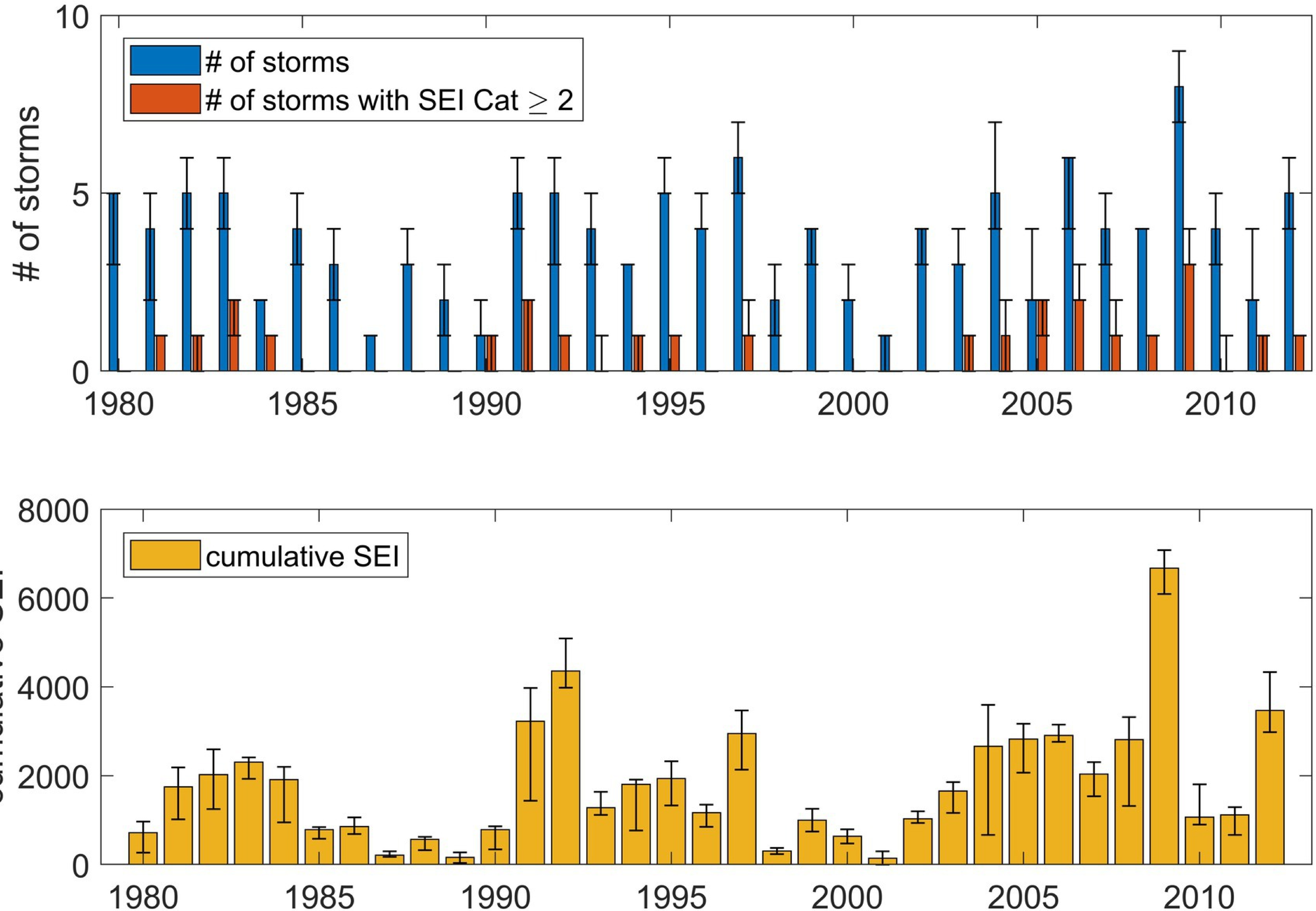
SEI value
PEI value
SEI Cat5
SEI Cat4
SEI Cat3
PEI Cat5
PEI Cat4
PEI Cat3
4000
3500
3000
2500
2000
1500
180
160
140
120
100
80
60
Return Period (yr)
100
10
NJ1
NJ2
NJ3
NJ4
NJ5
NJ6
NJ7
NJ8
NJ9
NJ10
NJ11
NJ12
NJ13
Dec 92 SEI
Dec 92 PEI
Vets Day SEI
Vets Day PEI
Sandy SEI
Sandy PEI


Hb (m)
Dec 92
Nov 09
Sandy 12
WL (mMSL)
Dec 92
Nov 09
Sandy 12
IEI
Dec 92
Nov 09
Sandy 12
Dec 92 PEI
Nov 09 PEI
Sandy 12 PEI
Hrs from beginning of storm

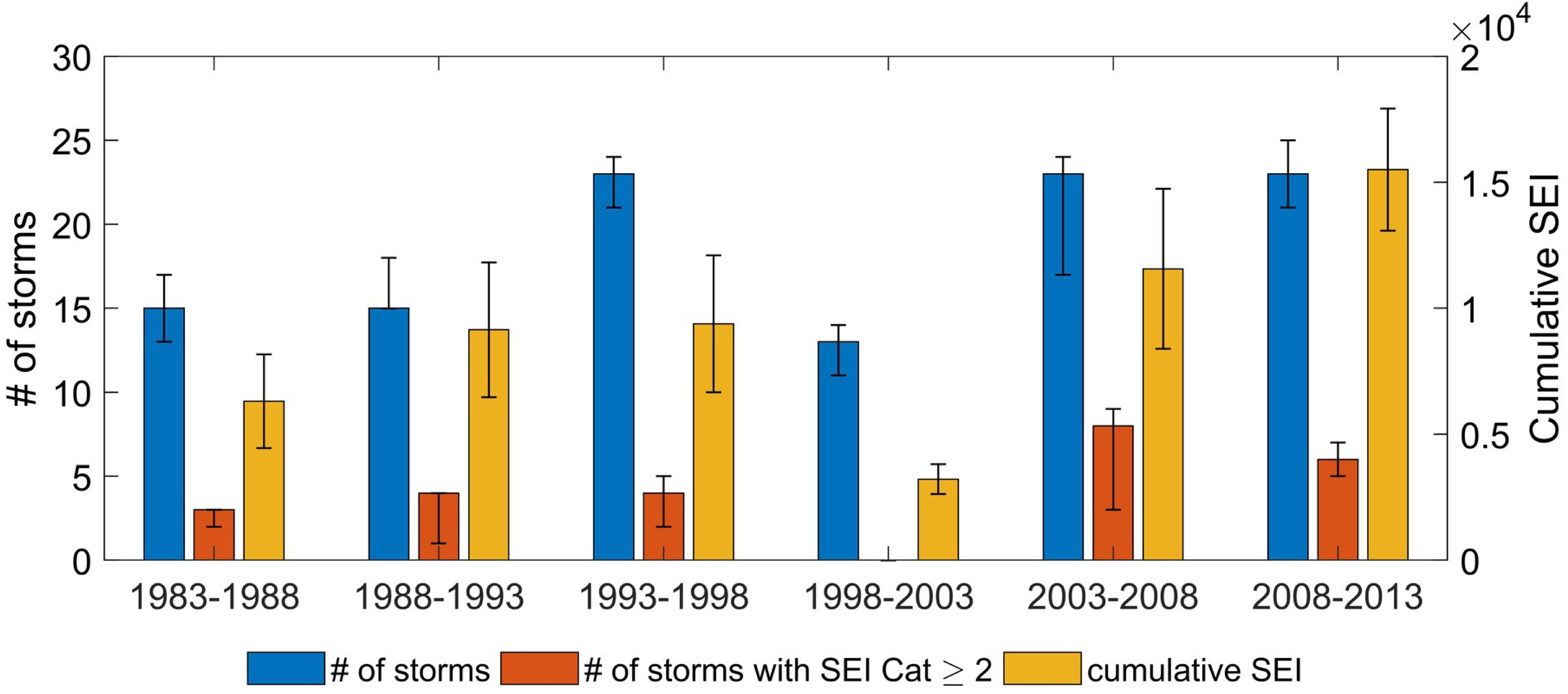
120
100
80
60
40
20
0
% of total number of storms
Median SEI
Median PEI
Cat 1
Cat 2
Cat 3
Cat 4
Cat 5

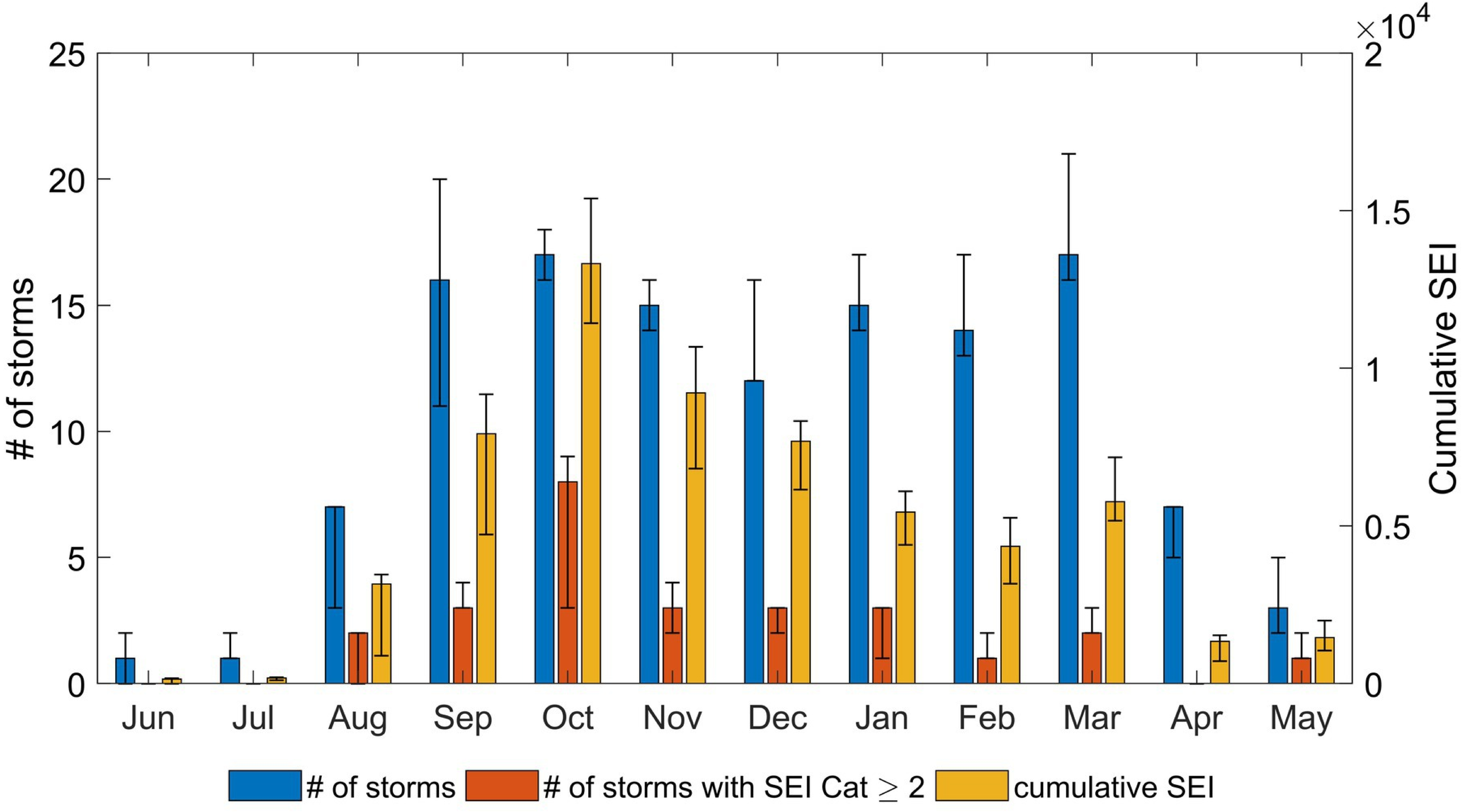


×10^4
125
100
75
50
25
0
# of storms
8
7
6
5
4
3
2
1
0
Cumulative SEI
NJ1
NJ2
NJ3
NJ4
NJ5
NJ6
NJ7
NJ8
NJ9
NJ10
NJ11
NJ12
NJ13
# of storms
# of storms with SEI Cat ≥ 2
cumulative SEI



# of storms
# of storms with SEI Cat ≥ 2
10
5
0
1980
1985
1990
1995
2000
2005
2010
cumulative SEI
8000
6000
4000
2000
0


×10^4
30
25
20
15
10
5
0
# of storms
2
1.5
1
0.5
0
Cumulative SEI
1983-1988
1988-1993
1993-1998
1998-2003
2003-2008
2008-2013
# of storms
# of storms with SEI Cat ≥ 2
cumulative SEI


×10^4
25
20
15
10
5
0
2
1.5
1
0.5
0
# of storms
Cumulative SEI
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
# of storms
# of storms with SEI Cat ≥ 2
cumulative SEI