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LETTER

Comparing hurricane and extratropical storm surge for the Mid-Atlantic and Northeast Coast of the United States for 1979–2013

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Abstract

This letter examines the magnitude, spatial footprint, and paths of hurricanes and extratropical cyclones (ETCs) that caused strong surge along the east coast of the US between 1979 and 2013. Lagrangian cyclone track information, for hurricanes and ETCs, is used to associate surge events with individual storms. First, hurricane influence is examined using ranked surged events per site. The fraction of hurricanes among storms associated with surge decreases from 20%–60% for the top 10 events to 10%–30% for the top 50 events, and a clear latitudinal gradient of hurricane influence emerges for larger sets of events. Secondly, surges on larger spatial domains are examined by focusing on storms that cause exceedance of the probabilistic 1-year surge return level at multiple stations. Results show that if the strongest events in terms of surge amplitude and spatial extent are considered, then hurricanes are most likely to create the hazards. However, when slightly less strong events that still impact multiple areas during the storm life cycle are considered, the relative importance of hurricanes shrinks as that of ETCs grows. Furthermore we find distinct paths for ETCs causing multi-site surge at individual segments of the US east coast.

1. Introduction

Coastal flooding caused by storms is often associated with storm surge, which is defined as the difference between the observed and predicted tidal water level at the coast. Coastal flooding in the Mid-Atlantic and Northeast US has received extensive attention in the recent literature, because of the extreme nature of Hurricane Sandy (Hall and Sobel 2013, Georgas *et al* 2014, Lopeman *et al* 2015), as well as regional surge projections (Lin *et al* 2012, Little *et al* 2015), and flooding trends (Talke *et al* 2014, Reed *et al* 2015). The atmospheric storm type of focus in these studies was mainly hurricanes, with the exception of Talke *et al* (2014) who examined the influence of the North Atlantic Oscillation (NAO), which is known to correlate with the distribution of extratropical cyclone (ETC) paths (Serreze *et al* 1997).

Nevertheless, the most common storms creating hazards in the Northeast US are ETCs, and studies have investigated surge(s) associated with these storms. DeGaetano (2008) examined ETC surge near New York City (NYC) and focused on seasonal predictors in sea surface temperature anomalies and atmospheric teleconnections. Salmun *et al* (2011) developed a surge prediction model for NYC based on buoy wind data. Colle *et al* (2010) used sea level data from the Battery, NYC to create a climatology of storms that cause surge for the region. The study also examined the path of hurricanes and ETCs creating surge in NYC, but did not compare the impact of the two storm types. Roberts *et al* (2015) studied the importance of wind direction and shear in generating coastal impacts for NYC, as did Warner *et al* (2012) for Long Bay, South Carolina. The role of storms in surge has also been examined north of NYC, as seen in

Butman *et al* (2008), who ranked storms by wave-generated bottom stress observed in Massachusetts Bay.

While hurricanes clearly have a major impact on the Northeast US (e.g., Hurricane Sandy), it is also the case that ETCs generate storm surge in regions as far south as North Carolina (Dolan and Davis 1992, Davis *et al* 1993). Despite active research on both individual storm types and storm surge, the relative influences of hurricanes and ETCs remains rarely analyzed. Studies in the literature are Scileppy and Donnelly (2007) who provide a limited comparison of storm strength for hurricanes and ETCs in the context of ocean sediment transport; the aforementioned Colle *et al* (2010), and Zervas (2013), who examined storm tide, with a focus on the top percentages per station and 10- to 50-year return levels with and without Sandy.

Here we examine hurricane and ETC related surge and expand on previous work by: (1) focusing on events occurring regularly on shorter time scales (i.e., 1- and 3-year storm events), and (2) considering surge events that occur concurrently at multiple stations (i.e. multi-site events). These two details are motivated by the fact that there is little guidance in the present literature regarding the relative roles of hurricanes versus ETCs for strong surge on shorter time scales. Yet these events are important to hazard management, because they have the potential to create frequent expensive disasters (Sweet and Park 2014, Sweet *et al* 2014). Additionally, to our knowledge only DeGaetano (2008) and Grinsted *et al* (2012) approached the issue of concomitant, multi-site surge, in which the former study only focused on the region close to NYC and the latter focusing solely on hurricanes.

This letter examines storm surge throughout the year for the US east coast. The goal of the work is to compare the magnitude, spatial footprint, and paths of hurricanes and ETCs for the region spanning from Duck, North Carolina to Portland, Maine and that occurred during the years 1979–2013. To this aim, we utilize Lagrangian cyclone tracking and probabilistic return levels (RLs), and develop a multi-site analysis.

2. Data and methods

The water level data used in this analysis is provided by the NOAA Center for Operational Oceanographic Products and Services (http://tidesandcurrents.noaa.gov). The time period considered is 1979–2013, with the start year chosen to correspond with that of the ERA-Interim (Dee *et al* 2011) reanalysis dataset used in this study. NOAA provides hourly measured water levels, from which we remove the astronomical tide (note that a low-frequency seasonal cycle is included in the predicted tide data distributed by NOAA (Gill and Schultz 2001)) and extract daily maxima of the non-tidal component of the water level. We also remove the long-term trend, which is most likely associated with global sea level rise and not storms (Talke *et al* 2014), by subtracting the trend in surge for each station from the data (as is done in Colle *et al* 2010). Thus, the target variable of this study is the daily maximum storm surge with the linear, long-term trend removed (hereinafter referred to simply as the surge data). Clearly, storm surge as defined here is not the best metric to assess actual flood damage because peak surge at low astronomical tide might cause weak flooding compared to when it occurs during high tide. However, since storms can occur at arbitrary astronomical tide states, it is a key metric for attributing potential flood damage to them in a statistical study based on historical data. We also note that for assessing local flooding potential, tide and surge as well as their interaction need to be considered (Horsburgh and Wilson 2007).

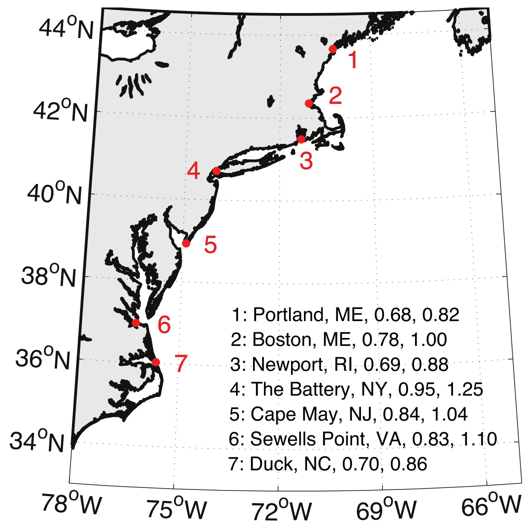

Figure 1. Location of the sea level stations used in the study. The legend gives the names of the stations and the 1-, and 3-year return levels (in meters) per station.

We consider data from seven sea level gauges spanning from Duck, North Carolina to Portland, Maine (figure 1). The region is selected for being influenced by both ETCs and hurricanes, as discussed in the introduction. Only stations with at least 90% data coverage over the study period were considered for analysis. The spacing between stations is not equidistant, but it is as close to equidistant as possible given the available record of stations in our study domain and our adopted constraint on the percentage of data available. The distance between stations ranges between 99–250 km, using great circles, with an average of 180 km and the shortest distance occurs between two stations that are separated by Cape Cod. For completeness and as a sensitivity check we analyzed a denser set of stations for the region between New Jersey and Rhode Island (supplementary figure 1). We also analyze strong surge events that occur concurrently at multiple stations. This work focuses on the interior five stations in our set (i.e., from Sewells Point, Virginia to Boston, Massachusetts), to avoid issues caused by storms that only impact the southernmost or northernmost parts of our study domain.

Rather than focusing on specific/individual seasons, we consider storm surge events during any time of the year. This allows a direct comparison of surge events caused by hurricanes and ETCs. To identify strong events, a peak-over threshold approach (e.g., Coles 2001) is applied, in which the top 3% of surge data (per station) is fit with a Generalized Pareto Distribution (GPD). Then, at each site, surge levels coinciding with 1- and 3-year return levels (RL) are determined from the fitted GPD. After we find dates that exceed the 1- and 3-year RLs, we reduce the set of dates to events. To do this, we identify any cluster of successive dates that exceed the RL values and retain only the date of maximum exceedance within each cluster. This is because we are focused on associating surge events with storms, and so we do not want to double count a storm. The 1-year RLs (listed in figure 1(a)) exceed the flood nuisance levels per station as listed in Sweet *et al* (2014), noting that nuisance level flood in Sweet *et al* (2014) is calculated as water level minus mean high higher water (MHHW), so it is a different metric than storm surge.

We explicitly focus on short-term (1- to 3-year) RLs because those are well constrained for the length of the time period that we consider. The robustness of short-term RL estimates on site levels was tested at The Battery, New York and Newport, Rhode Island. To do so, we calculated RLs on surge data for a longer record (1930–2013), as well as for various subsets of the data. The results show that 1- to 3-yr return level estimates are well constrained, i.e., agreeing within ± 0.05 m when estimated for different time periods. These RLs minimally change if we remove Hurricane Sandy from the analysis. Furthermore, our choice to focus on a relatively short return periods is motivated in part by the existence of a large body of literature regarding the return period of extreme surge such as caused by Hurricane Sandy (Lin *et al* 2012, Hall and Sobel 2013, Zervas 2013, Lopeman *et al* 2015, Georgas *et al* 2014). Notably, the RL estimates for Sandy vary substantially among these studies, most likely because the observational record is not long enough to robustly constrain the most extreme events (see also: Dangendorf *et al* 2016 for the influence of a single extreme event on longer RLs).

Information on the time evolution of the location of cyclones' centers (i.e., Lagrangian track information) is used to associate the surge events with hurricanes and ETCs. For the hurricanes, the NOAA Atlantic hurricane database (HURDAT2, Landsea and Franklin 2013) is used. We consider all tracks in HURDAT2, regardless as to whether they were full hurricanes or just tropical storms when they were in proximity of our region. This approach gives a conservative account of all possible hurricane influence in the Mid-Atlantic and Northeast region. For the ETCs, the NASA Modeling Analysis Program (MAP) Climatology for Midlatitude Storminess (MCMS) tracking algorithm (Bauer *et al* 2016) is applied to ERA-Interim reanalysis to identify cyclone tracks. The MCMS algorithm identifies all mobile low-pressure systems and therefore it identifies both hurricanes and ETCs. To remove hurricanes from the MCMS set we isolate the identical storms in both the HURDAT and MCMS cyclone catalogs. We note that studies have used sea level data to identify storminess (Zhang *et al* 2000, Thompson *et al* 2013). We, instead, focus on Lagrangian tracks to allow the separation of hurricanes and ETCs.

To focus on storms that impact the region of interest, we identify the cyclone centers that pass within 750 km of the station of interest. If multiple stations are considered, we use the arithmetic mean of the latitudes and longitudes of the considered water level gauges to evaluate the search radius. If a storm caused surge at multiple stations spread over two days, we calculate the storm center distance on both days and retain the minimum distance. We note that 750 km is a small search radius for ETC association (e.g., Nissen *et al* 2010 used 1200 km), however as TCs tend to be smaller than ETCs, we opted for a smaller search radius. For the multi-station surge events discussed in this paper, no storm center was located more than 600 km from the search center and most of the centers passed within 300 km of the search center. Therefore, we tested the results using 300 km and found only minor differences. However, as seen below, using 300 km excludes one of the largest hurricane associated events, therefore we chose the 750 km search radius. The cyclone track data is available in 6-hourly resolution, and therefore the query checks the track location at 00Z, 06Z, 12Z, and 18Z on the date of the surge event. The track association is based on the proximity of the cyclone center, however, if multiple cyclones are close to the target region, we determine the most likely storm of influence based on the direction of the 925 hPa geopotential winds (from ERA-Interim) over the region (for further details see, Booth *et al* 2015).

3. Results

The first part of our analysis focuses on the local spatial scale by ranking the surge events separately at each station. We then calculate the percentage of events associated with hurricanes per station for the top 5 events and repeat this for incrementally larger sets of events, up to the top 100. (figure 2). When the strongest 10 surge events per gauge are considered, the percentage of hurricanes causing surge ranges from 20% to 60%. The role of hurricanes decreases as more events are considered, even though the surge events are still large. For example, all of the top 50 surge events per station exceed nuisance flooding (Sweet

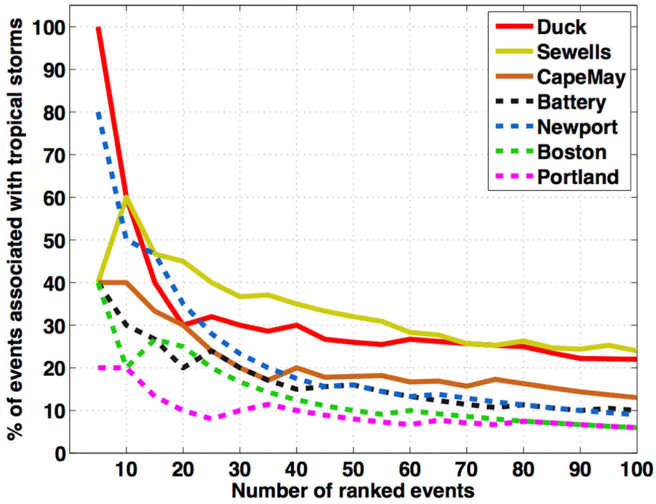

Figure 2. Percentage of surge events that are caused by hurricanes versus number of ranked events considered, per station. The solid lines indicate stations in this study located south of New York City. The dashed lines indicate those north of New York City. The percentages are calculated starting with the top 5 events at an interval of 5, up to the top 100.

et al 2014), and the majority of these events are associated with ETCs (figure 2).

Next we examine the importance of the latitude of the stations for storm type influence. For the top 10 events per station, the influence of hurricanes on surge does not show a latitudinal gradient (figure 2). In fact, hurricane influence for the top 10 surge events is equal at Newport, RI and Duck, NC. This appears to be related to the orientation of the coast of Newport, an issue that will re-appear later in the paper. When considering a larger set of events (e.g., the top 50) per station, a clear latitudinal gradient emerges, which matches ones expectations that at the southernmost stations 30% of the strongest surge events are associated with hurricanes and that the influence of hurricanes decreases by 10% for the central stations and another 10% for the northern most stations (figure 2).

The second part of our analysis is concerned with surge impacts of the cyclones on larger spatial scale. To this aim we develop a multi-site analysis of the surge events. Here, one has to consider that surge statistics might differ from station to station, based on coastline orientation, local bathymetry, tides, and as illustrated above, the latitude of the station. Therefore, our multi-site analysis utilizes an approach in which we consider events that have exceeded a specific return level (e.g. the 1-year RL) at multiple sites, where RLs are calculated separately for each station (figure 1). We begin by providing cumulative statistics related to the return levels. For the 7 stations, a total of 255 exceedances of the 1-year RL are found (as discussed in section 2, if multiple days in a row exceed the RL at the same station we only keep the date of the largest exceedance). Of these events, about 20% are associated with hurricanes. The 1-year RL corresponds roughly to the top 40 events per station, and therefore the 20% hurricane association is consistent with the results in figure 2. Furthermore, we find 84 exceedances of the 3-year RL, and nearly 30% of these are associated with hurricanes. The increase in hurricane influence for stronger surge events also agrees with results in figure 2. As discussed in section 2, for stations with longer records, the 1- and 3-year RLs only change by ± 0.05 m if longer records are used. Additionally, hurricane association was carried out using data at The Battery for 1935–2013 and the relative frequency of surge associated with hurricanes changed by less than 5 percent (it decreased relative to 1979–2013).

We begin the multi-site analysis by examining the surge events in which the 1-year RL is exceeded at three geographically consecutive stations. To this aim, we form groups of three stations (using the 7 stations shown in figure 1) and moving north along the coast, i.e., Duck–Sewells Point–Cape May, is one group, Sewells Point–Cape May–The Battery is another, etc. For each group, we find all surge events that exceed the 1-year RL at all three stations. Because of the spatial distance among stations, we allow the RL exceedances to occur within a range of 3 consecutive days when creating multi-site events. The use of 3-stations to define multi-site events also removes issues regarding cyclones that might impact only the southern and northern edges of our study region. We performed a sensitivity analysis for the region between Cape May and Newport using a denser network of stations (supplementary figure S1). In a comparison of the dense multi-site events with those using three stations we found very similar results, in terms of storm ranking and hurricane influence.

In figure 3 we show the 3-station surge events ranked using a simple average of surge at the three stations involved. However, we also computed the ranking after calculating anomalies at each station by subtracting the station's 1-year RL value from the

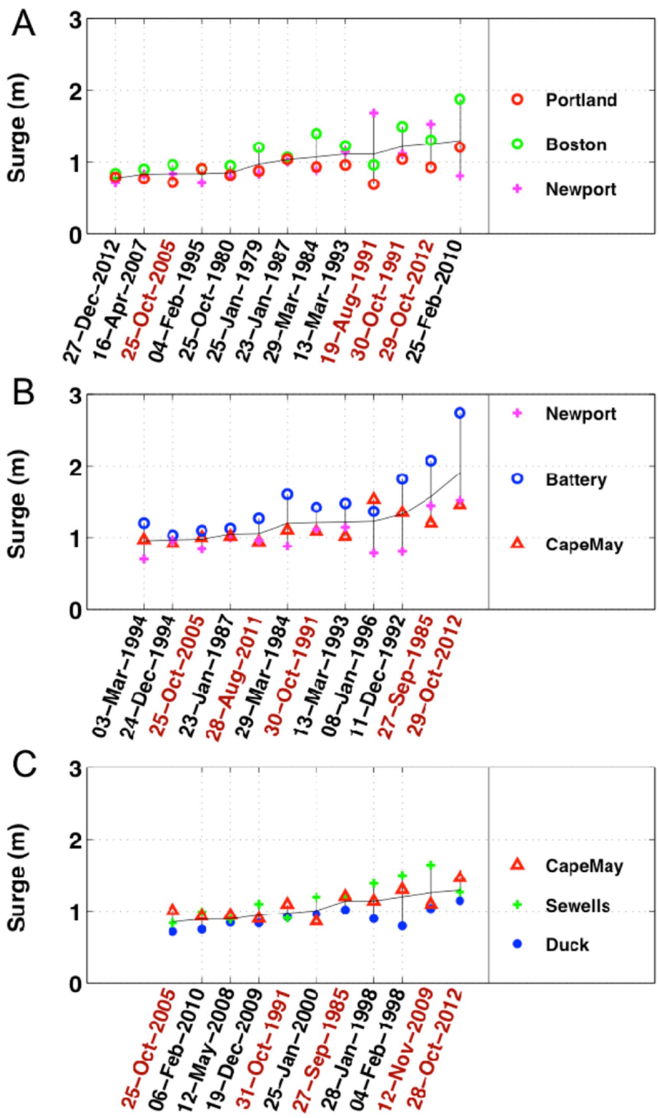

Figure 3. Surge values and dates for the storms that caused surge to exceed the 1-year RL at three consecutive stations, ranked largest to smallest from right to left, based on the multi-site average of the surge amplitudes. Panel (a) shows results for Portland, ME—Boston, MA—Newport, RI; (b) shows Newport, RI—The Battery, NY—Cape May, NJ; (c) shows Cape May, NJ—Sewells Point, VA—Duck, NC. Color-coding of dates indicates storm association: hurricanes (red) and ETCs (black). The thin black line indicates the multi-station mean value for each event.

surge time-series and then averaging the anomalies on the date of the events. For the two ranking methods, the results are very similar (not shown).

Figure 3 shows the surge events exceeding the 1-year RL at three consecutive stations, ranked based on the 3-station average, with the largest event on the right. For Portland–Boston–Newport, there are 13 events that exceed the 1-year RL at all 3 stations, of which, 30% are associated with hurricanes. We find 12 such events (42% associated with hurricanes) for Newport–Battery–Cape May and 11 for Cape May–Sewells–Duck (45% associated with hurricanes). As expected, the relative influence of hurricanes decreases with latitude, though this decrease is not statistically significant (following a X^2-test; p-value $= 0.74$). The decrease in hurricane influence is mainly attributable to an increase in the frequency of multi-site ETC surge. Figure 3(b) shows that Sandy's surge level exceeds by far all the other extreme cases we identified. However, if Hurricane Sandy is excluded from figure 3(b), the surge strengths of the remaining hurricanes and ETCs are comparable. We note in passing that the results for the groups Sewells–Cape May–Battery and Battery–Newport–Boston, not shown in figure 3, are consistent with the results for the other groups.

Some storms affected all or most of the study region, and therefore the storms listed per station group in figure 3 are not mutually exclusive. Table 1 shows the exact number of stations at which the 1-year RL is simultaneously exceeded, separated by storm association. For the years we studied, only hurricanes created coincident surge exceedances of 1-year RL's at all seven stations: the 'Perfect Storm' (30 October 1991; Cardone *et al* 1996), Hurricane Wilma (25 October 2005), and Hurricane Sandy (29 October 2012).

Table 1. Counts of hurricanes and extratropical cyclones per number of stations exceeding 1-year RL.

	Exact number of stations exceeding 1-year RL per storm event				
Storm type	3	4	5	6	7
Hurricanes	2	1	1	—	3
Extratropical cyclones	20	7	3	—	0
Total	22	8	4	0	3

Meanwhile, the ETCs show a much larger influence for smaller multi-site events. As stated above, by considering events that impact at least 3 stations, we avoid the issue of cyclones that only impact the edge stations (Duck NC and Portland ME), however, it also means that our multi-site analysis is focused on the region from Sewells Point, VA to Boston, MA. Based on climatologies of cyclone tracks this is the region in which the dual influence of hurricanes and ETCs is markedly large (e.g. compare Hall and Yonekura (2013) for hurricanes with Hirsch *et al* (2001) for ETCs).

Of course, storms do not always impact consecutive stations, and therefore we also analyzed events that exceeded the 1-year RL at 3 or more non-consecutive stations. There were eight storms in this category, only one of which was a hurricane (it affected Sewells Point, VA, The Battery, NY and Newport, RI). Of the remaining events, six impacted Cape May, NJ plus two stations to its north, without creating a 1-year RL exceedance at Newport, RI. Thus it appears Newport, RI is susceptible to a somewhat different set of storms as compared to the surrounding stations in this study.

Next we define multi-site events as those in which surge exceeded the 1-year RLs for three or more stations (regardless of geographical location) and examine cyclone tracks for storms associated with these events (figure 4). Eight hurricanes caused multi-site surge for our time period. Four of the storms take similar paths, hugging the coastline (figure 4(a)). These storms' centers all passed within 130 km of the stations at which exceedances occurred. The four other hurricane tracks are each unique: (1) the 'Perfect Storm' (30–31 October 1991) which started as an ETC then became a hurricane; (2) Hurricane Wilma (25 October 2005) whose center was the farthest from the stations for all hurricanes and ETCs in the multi-site set (590 km); (3) Hurricane Ida (12 November 2010), which merged with an ETC (Egan *et al* 2010); the track shown for Ida is from MCMS not HURDAT2; and (4) Hurricane Sandy (28–29 October 2012) which took an extremely rare path (Hall and Sobel 2013).

For the ETCs' tracks, the maximum distance of any low-pressure center to the stations at which it caused surge was 360 km. We separate the multi-site ETC tracks into three sets: (1) southETC (6 storms), those that exceeded the 1-year RL at Duck, NC (figures 4(b)), (2) northETC (12 storms), those that exceeded the 1-year RL at Portland, ME, and midETC (10 storms) those that did not effect Duck or Portland (figure 4(d)). If we focus on the coastline, we see a latitudinal separation of the storms per set, consistent with the fact that the low center traveled very close to the stations at which they caused surge. Additionally, there are multiple tracks in northETC with a strong meridional trajectory, and this is not the case for the other sets. The circulation for the two tracks in the midETC which move east and then south were further examined, and we find a strong stationary anticyclone to the north, suggesting the presence of an atmospheric block (supplementary figure S2 shows the sea level pressure maps for these cases).

For one of the multi-site surge events, no track was identified using the automated tracker. We manually analyzed sea level pressure for this storm and found there was an ETC that the tracker missed (21 December 2012). The issue for the tracker failing was the initial development of two separate low-centers, which led to the initial track of this cyclone being discarded. For more details on tracking algorithms and issues of tracks selection, see Bauer *et al* (2016). Figure 4 also shows that hurricane tracks associated with multi-site surge are much smoother (and similar to one another) in appearance than those of the ETCs. This is due in part to the hurricane tracks being created by manual analysis at the National Hurricane Center while automatic algorithm identifies the ETCs. The very crooked nature of some of the ETC tracks may be related to downstream atmospheric blocking.

4. Discussion and conclusions

The analysis presented here uses a mixture of Lagrangian tracking and probabilistic ranking of surge events to understand the relative influence of hurricanes and ETCs in causing strong surge on the US east coast. Stations were selected based on the region in which hurricanes and ETCS create surge hazards, as well as data availability. A comparative analysis of a set of more closely spaced stations for one region of our study shows similar results.

Overall, the results show that hurricanes create the strongest events, in terms of surge magnitude and spatial extent. However, when we consider slightly less strong events that still impact multiple areas during the storm life cycle, the relative importance of hurricanes is reduced and that of ETCs increases. Thus, on a per site basis and for 1- to 3-year timescales, ETCs are equally important as hurricanes and should be considered when planning for the dangerous, while not most extreme, storm surge events.

The relative influence of hurricanes, in terms of local and multi-site surge, decreases for stations at the north end of the domain. This decrease is more related to an increase in strong surge occurrence due to ETCs, rather than a decrease in the occurrence of strong

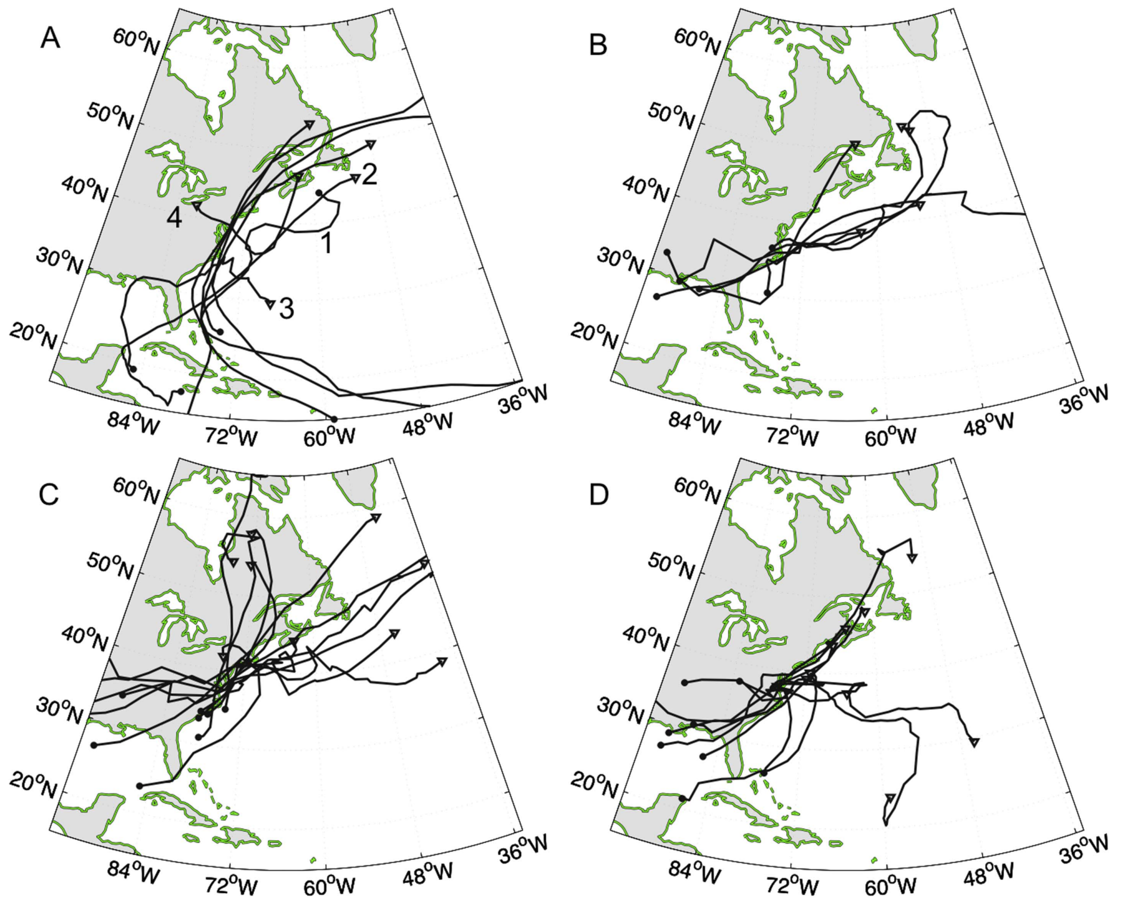

Figure 4. Cyclone tracks for multi-site surge events that created 1-year RL exceedances at three or more stations. (a) shows hurricanes (8 tracks shown), with the numbered tracks discussed in the text. (b)–(d) show ETC tracks for multi-site surge: (b) tracks for events that include a 1-yr RL exceedance at Duck, NC (6 tracks shown). (c) as (b) but for Portland, ME (12 tracks shown). (d) tracks for ETCs that created multi-site events but did not exceed the 1-year RL at either Duck or Portland (10 tracks shown). For all panels circles on the track lines indicate the storm genesis location while triangles indicate the lysis locations.

surge causing hurricanes. If we examine the regional footprints of storms, by considering 1-yr RL exceedance at 3 adjacent stations, we find an equal importance of ETCs and hurricanes. However, for our time period only hurricanes create 1-year exceedances concurrently over the entire region.

Although Hurricane Sandy caused the strongest surge (by a multi-site average criterion) in the region during 1979–2013, our analysis highlights the importance of ETCs as contributors of strong surge events. Interestingly, for the time and date of the surge events caused by Sandy for the stations in the north of our domain, the storm was dynamically more similar to an ETC than a hurricane (Galarneau *et al* 2013). Here we refer to hurricanes as any storm that was classified as a hurricane at some time in its life cycle, however the scale of impacts of Sandy and 'the Perfect Storm' show the need for more analysis of hybrid storms.

Newport, RI stands out because hurricanes cause a large portion of its strong surge events despite its high latitude (figure 2). Half of the 3-year RL exceedances at Newport were caused by hurricanes, the largest value of all the stations. This relates to both a high number of hurricanes creating surge for Newport and a small number of ETCs. Both of these facts are most likely related to its coastal orientation.

A potential caveat of our work is that it does not consider interannual sea level variability, which can be important for the region (Sweet and Zervas 2011, Goddard *et al* 2015, Hamlington *et al* 2015, Wahl and Chambers 2015). However, establishing the existence of interannual variability would be difficult given that the record is short and our set of surge events is small. The possible influence of the tides is another factor that will require a longer data set. Following Horsburgh and Wilson (2007), we examined the timing of our surge events relative to the timing of high tide (supplementary figure S3). For Cape May and Boston, there is a tendency for the surge events to occur when the tide is near its lowest point. However, for the current analysis period no robust statistical assessment can be made given the small number of events considered and the large variability in the timing of the surge relative to high tide. Therefore future analysis (including longer records) will need to focus on this question.

In closing we note that we investigated trends in the occurrence frequency of multi-site surge, and found no such pattern for our events. As we removed the long-term linear trend for all of the daily maximum data, any remaining surge trend would be attributable to a change in storminess, rather than sea level rise. However, no such signal is found, consistent with previous studies documenting no evidence for long-term trends in storminess (Marcos *et al* 2015 and references therein). On the other hand, as global warming continues to cause sea level rise, even if there are no trends in the storms' themselves, future surges will happen in respect to an enhanced base level, which could lead to even more frequent (and more severe) flooding (Woodruff *et al* 2013).

The significance of this work is the novel multi-station analysis for surge. The presented approach opens the door for similar analyses of the footprint of surge events and is applicable to any coastal region that experiences storm surge. Additionally, the comparison of hurricane and ETC influence on surge, emphasizing the need to plan for both storm types, provides a timely reminder to hazard management planning. Especially on the US east coast, where Hurricane Sandy's impact might draw attention away from ETCs. As outlined in this study through spatial analysis (figure 3 and table 1), ETCs are capable of creating more than just nuisance flooding across a wide region. The physical qualities of the storms discussed here are also of immediate use, as track analysis shows that both ETC and hurricane centers travel very close to the impacted regions during multi-site events. These results are applicable to any other region in which surge is created by both ETCs and tropical cyclones (e.g., south-east Asia).

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