ELEVATED SEA LEVELS, COASTAL FLOODING, AND TIDAL GAUGES

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Abstract

In the scientific literature that analyzes tidal gauge records in order to determine the extent of historic coastal flooding, it is traditionally assumed that in order for a given storm event to have caused coastal flooding, it is necessary for that storm event to have produced a greatly elevated sea level on the relevant tidal gauge. In this paper, I examined this assumption by looking at an independent record for measuring storms and compared that record with the sea levels recorded on the tidal gauges. This comparison was made for the period of 1992-2012 in the cities of Boston, New York, and Atlantic City. I used the daily newspapers of these cities as an independent, qualitative record of whether or not there was flooding for a given storm, which I then compared to the tidal gauge of that city's harbor. I found that for Boston and New York, elevated sea levels proved necessary and sufficient to "predict" coastal flooding for most storms, but not all, while I found that elevated sea levels were only sufficient, but not necessary to "predict" coastal flooding for all storms in Atlantic City. Furthermore, I found that there were storms in Boston, New York, and Atlantic City that the newspapers recorded as causing massive amounts of flooding, yet barely registered an elevated sea level at all on the relevant tidal gauges. This suggests that attempting to perform frequency analysis for past coastal flooding based on elevated sea levels is a mistake, as such frequency analysis will underestimate the number of floods that have occurred, as well as miss some of the most devastating floods of the time period examined.

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Introduction

The relation of the sea level recorded on a tidal gauge to coastal flooding is much more complex than most studies that deal with tidal gauges assume. Most studies of this type tend to assume that a greater recorded sea level will result in a greater chance of coastal flooding (Mciness et al., 2003),(Ali, 1996), (Araujo & Pugh, 2008). That is, if the maximum sea level for a particular storm is recorded at 5000 mm on the relevant tidal gauge, and there is no flooding for that storm, then there will be no flooding for a storm in which the maximum sea level is 4000 mm. Some studies even use this assumption as a basis for determining the extent and extance of historic coastal flooding by defining a sea level as the threshold for coastal flooding, and then assuming that any storm which produces a sea level greater than the threshold can not only be viewed as a historic coastal flood, but can be relatively ranked by how much over the threshold its maximum sea level was (Kirshen et al., 2008), (Pirazzoli, 2000). Other studies use a related method, and count the number of storms in a certain time period by the number of recorded sea levels that are over a threshold (Zhang et al., 2000), (Menendez & Woodworth, 2010), (Bromirski et al., 2003).

However, strangely, no study has actually directly tested this assumption. One that came close was Ruocco et al. (2011), which found seemingly contradictory results. As the authors state in the study: "Interestingly, the 100 highest sea levels [at the tidal gauges tested] are not simply related to the occurrence of a coastal flood, or the severity of the flood, or the number of locations affected," (Ruocco et al., 2011). One possibility as to why this assumption has never been tested is that in order to test the accuracy and precision of tidal gauges with regards to measuring coastal flooding, it is necessary to have an independent record of coastal flooding. Unfortunately, no such scientific record exists. So, in order to test this assumption in this study, an independent, non-scientific measure of coastal flooding was used: newspaper records. This method has been used in the past for similar, although not identical purposes (Ruocco et al., 2011).

Methods

First, a comprehensive record of twice-a-day, maximum sea levels was gathered for tidal gauges in three major coastal cities in the American Northeast: The Battery, NYC, Boston, MA, and Atlantic City, NJ for the period of January 1, 1992 to January 1, 2012. Care was taken to make sure that these sea levels were each separated by periods of at least 3 days, to ensure that these sea levels did not result from the same storm. The highest sea levels were gathered for each city until a threshold value for flooding was found (or confirmed to be non-existent, in the case of Atlantic City). Then, a second list was gathered for each city of tropical storms or hurricanes that impacted the city over the time period of 1992-2012.

This list was gathered from an online source, and then crosschecked for veracity and the precise date using the newspapers of record mentioned below. Each storm on this second list was also checked to make sure that it caused flooding according to the relevant newspaper records. If the relevant newspaper record did not record flooding for a storm on the second list, the storm was discarded. After all storms on the second list that did not cause flooding were discarded, the maximum sea level for each storm was gathered from the relevant tidal gauge. The storms from the first list were then labeled “normal” storms, while the storms from the second list were labeled “abnormal” storms. Due to the selection process, the normal storm list included both flooding and non-flooding storms, while the abnormal storm list included only flooding storms.

The tidal gauges that were chosen to be tested using a few criteria. First, they needed to have complete records of both their actual sea levels and their predicted (to calculate the storm surge) for the time period looked at on the NOAA Seas and Tides website with as few missing dates as possible. Second, the tidal gauges needed to have daily newspapers that covered the relevant area for the relevant time period, and reliably reported when and where flooding occurred, as well as when it did not occur and was expected to. The daily newspapers also needed to be easily accessible online, as searching through newspapers by hand is prohibitively time-consuming.

Finally, the tidal gauges needed to cover a wide-enough geographic range that they were more or less independent (of any purely local phenomena), but needed to be similar enough that they were comparable. For this study, it was decided that three tidal gauges in the American Northeast were best suited for these criteria. On a related note, the time period itself was chosen as a substantial time period that represented the latest and presumably most accurate tidal gauge technology.

The process for determing whether or not a given storm caused coastal flooding was as follows. For each maximum sea level date and for the list of dates of when tropical storms or hurricanes impacted each city, the local newspaper of record (Boston Herald, Press of Atlantic City, and New York Times, respectively) was examined for mention of flooding. This involved accessing online databases containing the newspapers and searching for articles that contained relevant key terms such as "storm" or "flood" in their titles or content. For each date the following 2 days were examined for mention of flooding as well, to allow for time delay in reporting. If flooding was reported, the type of storm, location of flooding, and extent of flooding was recorded as well to the greatest detail allowed by the newspaper, in order to make sure only the relevant areas were being checked for flooding, as well as to allow for qualitative comparison of storms.

Finally, for each abnormal storm, and for a representative sample of normal storms (6 from each city, both flooding and non-flooding storms), a storm surge graph was constructed, using the predicted and actual sea levels previously gathered from the NOAA Seas and Tides website. For abnormal storms, this storm surge graph involved the 48 hours around the relevant time of coastal flooding. For the normal storms, this graph involved the 72 hours around the relevant time of coastal flooding, to allow for the generally longer storm surge of non-tropical storms (which, due to selection methods, were included in the normal storm list but not in the abnormal storms).

Results

As can be seen in Figure 1, Boston and New York both have relatively clear thresholds for their normal storms (that is, there is an almost exact threshold above which there is only coastal flooding, and below which there is no flooding for normal storms). This threshold lies between .01 and .1 percent of sea levels in Boston and New York. Atlantic City has no clear threshold, and has non-flooding normal storms and flooding normal storms throughout the range of maximum sea levels sampled. As can also be seen in Figure 1, however, Boston, New York, and Atlantic City all have storms that flooded far below the threshold. For New York, flooding storms ranged from in the .5 percent of sea levels to close to 10 percent of sea levels, while both Boston and Atlantic City had flooding storms at much closer to the 50 percent mark.

Discussion

Defense of methods

Preliminarily, it is necessary for me to defend some of my methods. As the hypothesis that was attempted to be proved and explained was that it is possible for the sea level as recorded on a tidal gauge at the time of coastal flooding to be significantly lower than the sea level at a time of no coastal flooding, it was not necessary to establish a record of every time this was true or false. Indeed, it would have been impossible to do so, given that checking a daily newspaper for every day for a period of 20 years would be time prohibitive for one city, let alone three. Some of the reasons for why sea level recorded on a tidal gauge would not be a reliable predictor of coastal flooding are given below, though, which should provide adequate proof that my methods of choosing dates likely captured the majority of dates in which my hypothesis was proven true, if not all. There are also two other possible criticisms of my methodology, both related to the idea that the issue at stake is the range of tidal gauges (how large a geographic area a given tidal gauge records accurate sea levels for), rather than the accuracy of tidal gauges. That is, the instances for which I find there to be flooding with no commensurate elevated sea level (abnormal

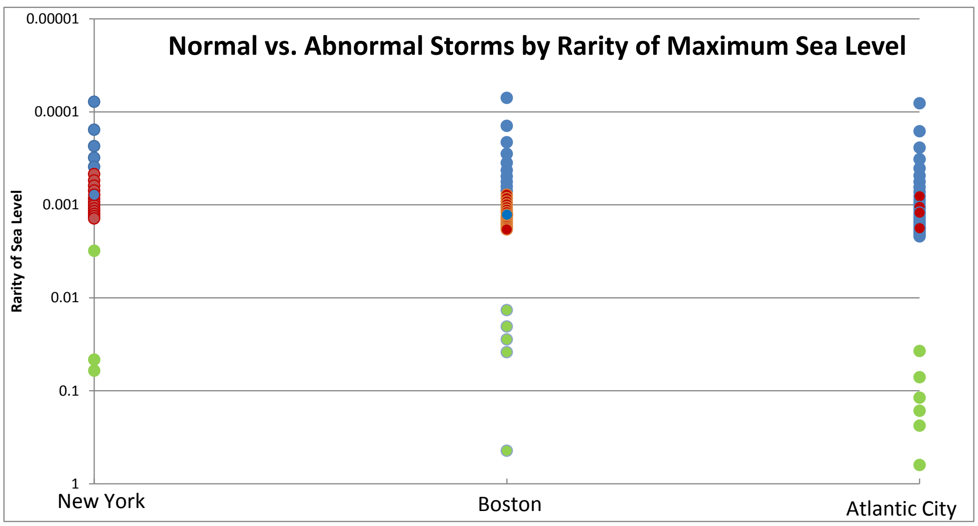

Figure 1: Normal flooding (blue), normal non-flooding (red), and abnormal (green) storms plotted by rarity of maximum sea level recorded by local tide gauge of storm at 6 minute interval. Rarity calculated by $\frac{\text{sea levels greater than or equal to maximum sea level}}{\text{total number of sea levels recorded}}$. For example, the top value for each city is roughly 7.8E-5, because that is approximately equal to $\frac{1}{(365)(2)(20)}$

storms) are merely instances where flooding is not occurring near enough the tidal gauge for an elevated sea level to be recorded. In order to address these criticisms, I further analyzed the tidal gauge data as well as the newspaper records. In order to determine the range of tidal gauges, I examined the sea level values for the maximum sea levels for all tidal gauges in the New York area. I found that all of the maximum sea levels are within 50 mm of each other in a range as broad as the Battery tidal gauge to the Bergen Point West Reach tidal gauge, which is a distance of 35 miles. This information is shown in Table 1 (note that Table 1 uses the difference between different sea levels as a way for accounting for differing station datums). Tide gauges have a range, but it is not limited to simply the harbor in which they are situated. Then, in order to see if flooding occurred in different places for normal and abnormal storms (which would support the idea that, for abnormal storms, flooding was occurring in areas where the tidal gauge could not record the sea level accurately), I analyzed the newspaper records. I found that, for the instances in which the newspaper did record where exactly was flooded, it was frequently the same areas and even the same streets that were flooded for both normal and abnormal storms. In New York, for instance, the Jamaica Bay area in Queens was flooded in both Hurricane Floyd in 1999 (an abnormal storm), and in a blizzard that occurred in 1992 (a normal storm).

The utility of flooding thresholds and implications

According to my results, sea level thresholds may be applied to Boston and New York in order to predict only certain types of coastal flooding. That is, it is both sufficient and necessary to have an elevated sea level in order to "predict" coastal flooding for normal storms (that is, storms that produce abnormally elevated sea levels). A weaker threshold for flooding may also be applied in Atlantic City, namely that there is a sea level below which there is no flooding, but no level above which there is guaranteed to be flooding for storms. It is sufficient, but not necessary, to have elevated sea level to "predict" coastal flooding. It is worth noting that the statistical threshold, however, changes for each city. The sufficient and necessary thresholds for Boston and New York City are much closer to each other than they are to the sufficient threshold for Atlantic City. The other main result I found is that thereâs a small but significant (in terms of impact) number of storms that are below any “sufficient” threshold for Boston, New York, and Atlantic, yet still caused coastal flooding. These abnormal storms included some of the most severe storms of the past 20 years, including the so-called “Perfect Storm” of 1990, which devastated the East Coast. The abnormal storms in general frequently caused more devastating flooding than the normal storms, inundating the same areas (even the same streets) as the normal storms as well as additional area.

Using arbitrary thresholds to indicate coastal flooding for normal storms

With regards to thresholds found for normal storms (storms that resulted in elevated sea level), my results indicate that the areas that separate tidal gauges cover are different enough that no general statistical threshold can be applied to all cities (such as the top 1% of sea level values or two standard deviations above the mean for sea level values) to come up with a threshold for flooding for normal storms. This also means that the common practice of describing sea level values or coastal floods by their level of rarity (i.e. the 100 year flood) is not particularly meaningful, as a flood or sea level value of a given frequency can have very different effects for different cities (e.g. a 1 in 1000 days sea level value for Atlantic City might result in flooding, while it would not matter for Boston). Rather, it is worth describing floods by their relative intensity, or by their geographical coverage, as has been proposed by many authors in the floodplain management field over the years (Platt, 2004), (D.Smith, 2004) . Similarly, it is worth describing sea levels by comparison of them to sea levels which have in the past resulted or caused flooding in that area, rather than describing them in an abstract statistical sense.

Explanations

While it is beyond the scope of this paper to fully explore the physics of why the phenomena discussed in this paper take place, it is possible to begin to explore them . Essentially, there are two possibilities as to why the relationship between tidal gauges and coastal flooding is more complicated than traditionally assumed (as mentioned in the Introduction). The first is that the

Date (year/month,day)	The Battery	Bergen Point West Reach	Montauk
201210301	NA	NA	NA
199212112	1306	NA	428
201108282	86	NA	173
201003141	177	NA	302
199303141	154	NA	-115
199603201	10	NA	204
201104171	66	11	-165
200212252	117	158	-8
199802241	12	-20	-144
200704161	11	-28	-120
201206051	1	51	156
200601312	2	-22	NA
200805122	10	45	NA
200704191	1	-15	-223
200301032	1	51	186
200910162	22	26	-240
201109292	1	11	251
200304181	7	-17	86

Table 1: This table shows 3 tidal gauges in New York and their recorded maximum sea level for 18 storms that resulted in greatly elevated sea levels. The storms are arranged by descending maximum sea level as recorded at the Battery. In order to account for differing station datums, the difference between one storm's sea level and the above storm's sea level is shown, rather than the sea level itself. So, the first value is not available (NA) for every location, because there is no sea level that is above the first sea level. As can be seen, the values of the Battery and Bergen Point West Reach are generally similar (within 50 mm), while the values of the Battery and Montauk are very different (up to 800 mm). This suggests that there is a range to tidal gauges, and that 35 miles (the distance between the Battery and Montauk) is within that range.

tidal gauge is recording inaccurately (i.e. equipment failure). The second is that the tidal gauge is recording accurately, but that our assumptions about what it's recording and what its recordings mean are ill-founded. The only formal means of diagnosing equipment failure from the tidal gauge readings themselves are if there appears in the storm surge an unexplained spike (Pugh, 1996) or "large tidelike fluctuating residuals" (Zhang et al., 2000). In the absence of either of those two errors, we therefore must assume that the tidal gauge is recording accurately. In order to help the exploration of the explanation, the following storm surge figures are organized into normal and abnormal storms which share what I consider a defining characteristic. Each category contains a number of storms across the time period examined and across the three cities surveyed.

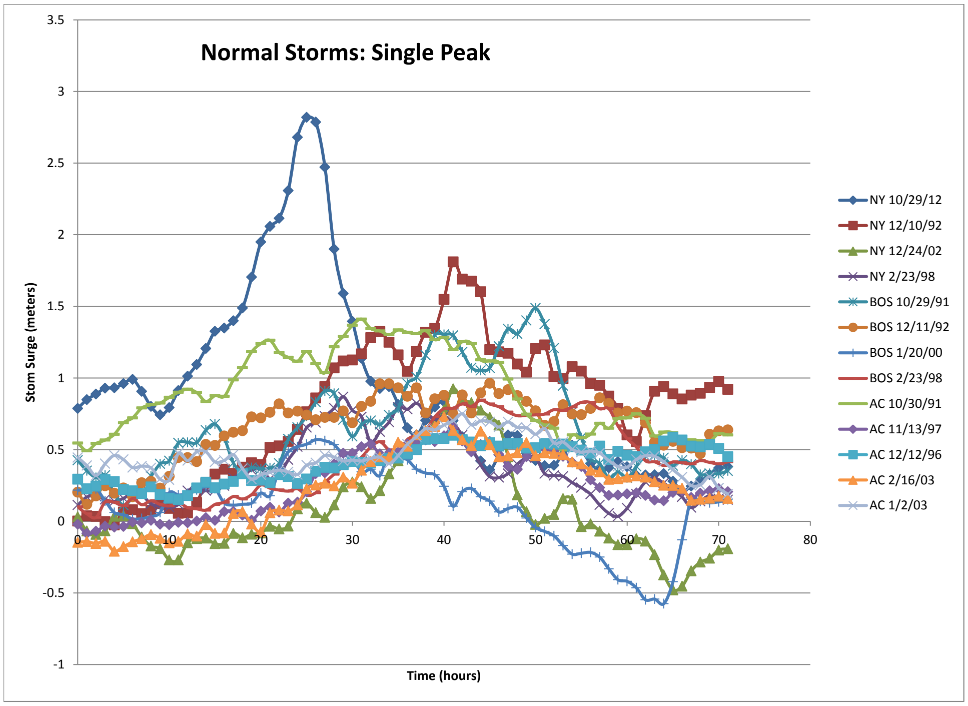

Figure 2: This figure shows the time series for what I call "single peak" normal storms. Those are normal storms that reach one highest storm surge, and, once coming down from that storm surge, do not reach that level again. These storms are storms that act as we expect them to: they come into the coast, raise the local sea level through a storm surge, and a combination of the storm surge and wind causes flooding in the coastal area. Predictably, most of these storms are the normal storms that cause flooding.

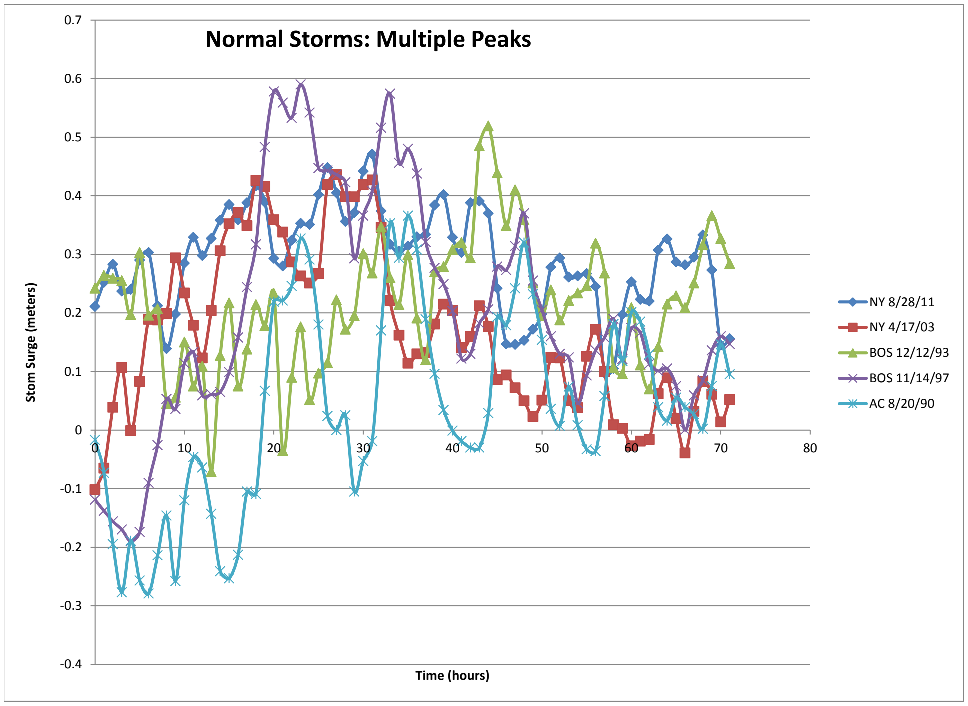

Figure 3: This figure shows the time series for "multiple peak" normal storms. These are normal storms that reach a maximum storm surge multiple times. Because of the cyclicality of their storm surges (as well as the relatively low maximum sea level), they generally do not result in elevated sea level long enough for coastal flooding to occur. Predictably, most of these storms are the normal storms that do not cause flooding.

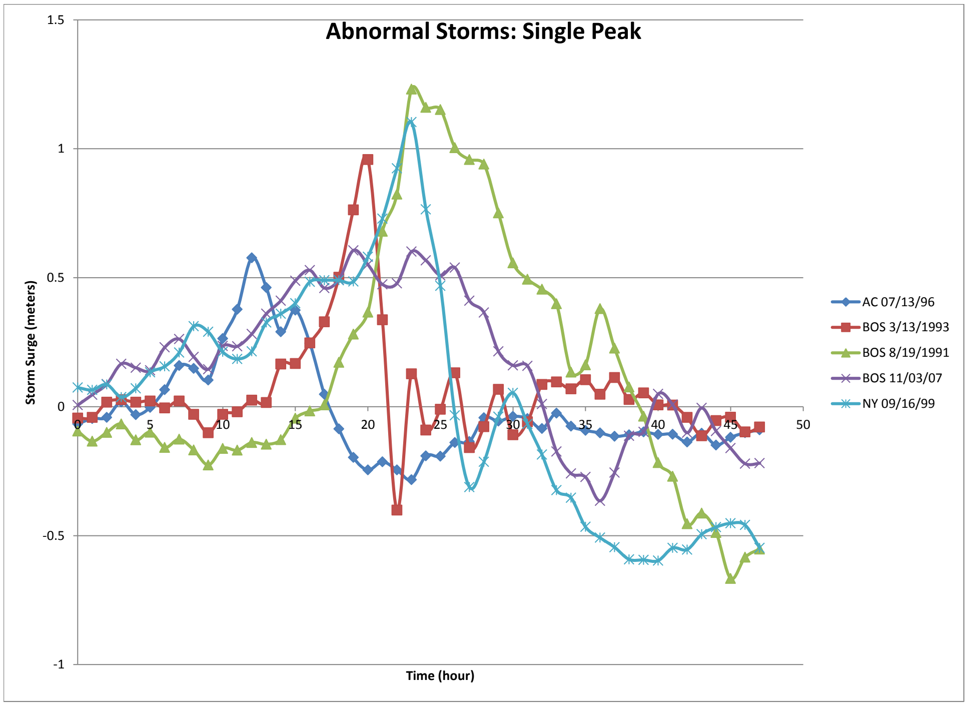

Figure 4: This figure shows the time series for single peak abnormal storms. Unlike the single peak normal storms, it is interesting that the single peak abnormal storms do not have a sustained storm surge. Their storm surge levels decline very rapidly after reaching their peak. This is especially interesting as many of these abnormal storms were recorded as causing a huge amount of flooding in the newspaper, such as “Storm of the Century” in March, 1993. This suggests that these peaks are caused either by equipment failure (i.e. the storm surge remains high or climbs even higher after the recorded peak, but the tidal gauge malfunctions and records the storm surge as crashing), or that there is a physical means by which the storm surge increases rapidly, causes massive flooding, and then decreases just as rapidly. With regards to the latter, it is possible that if a storm is moving particularly rapidly inland, it could cause flooding by rapidly moving a huge amount of water into the coast, overwhelming natural and artificial defenses. Then, once the storm had moved on land from the water, the sea level could just as rapidly die down without the storm to sustain it.

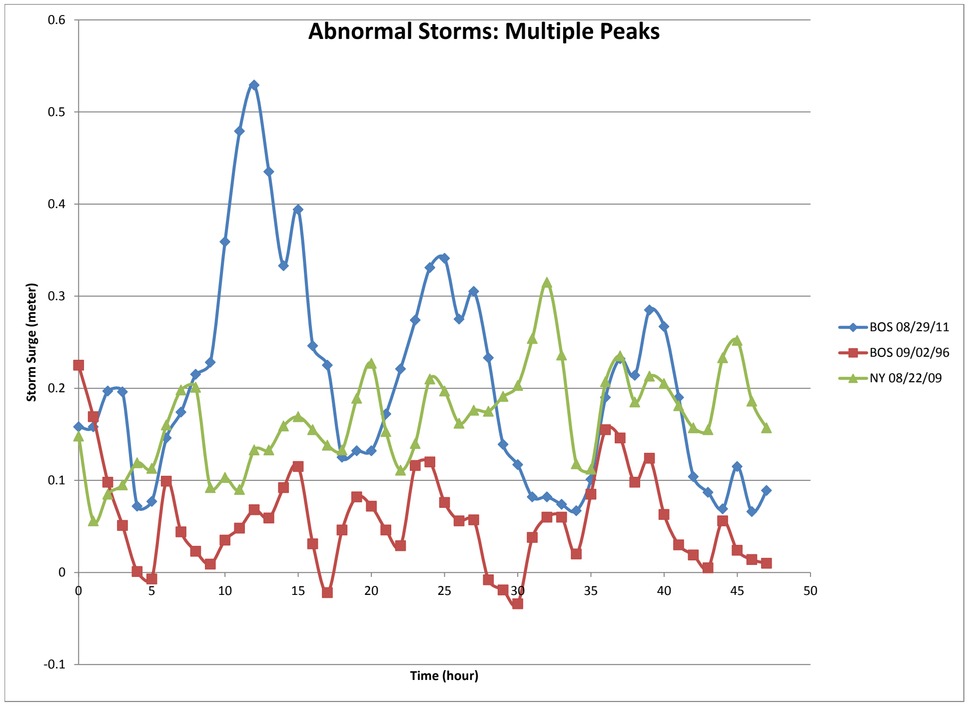

Figure 5: This graph shows abnormal storms with multiple peaks, which means that they reached a similar storm surge magnitude multiple times. Considering that these storms, despite causing impressive flooding, have weirdly low magnitude throughout their time series, and also look like tides in their time series, it seems likely that these are examples of the equipment failures that Zhang mentions.

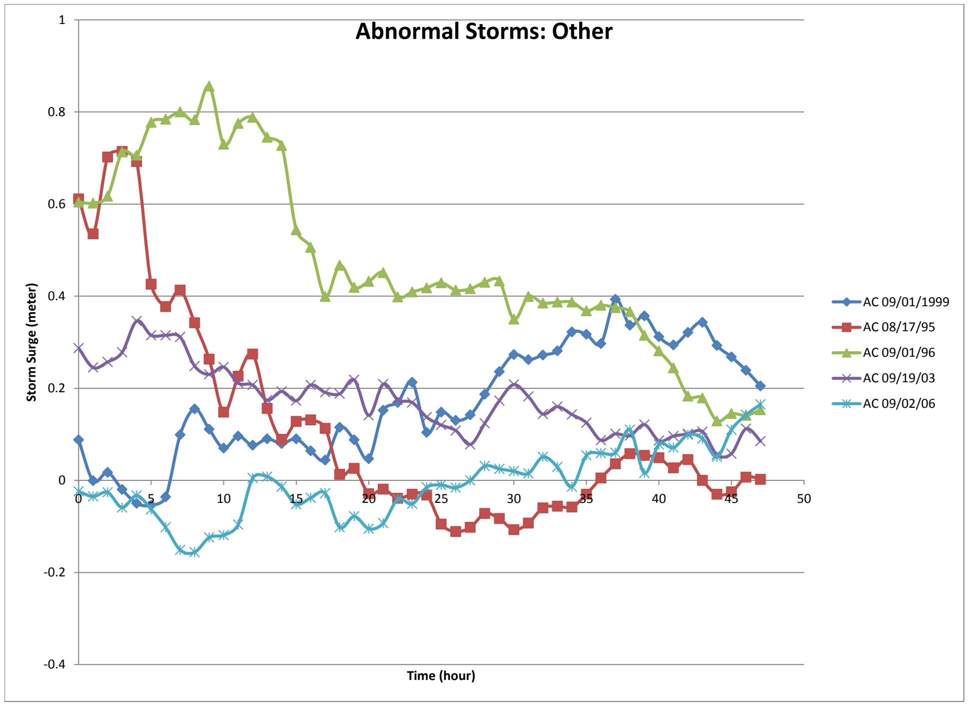

Figure 6: This last category contains storms that I do not have a convenient way of describing. Although they are technically single peak storms by my definition, they look much more like single peak normal storms than single peak abnormal storms. Considering that they are all Atlantic City storms, and that I failed to find a threshold for normal storms for Atlantic City, it seems likely that the time series for these storms are oddly shaped because of something in the way that the tidal gauge records storms in Atlantic City, rather than anything intrinsic about the storms themselves.

Conclusions

It is ill-advised for a study to assume that there is an obvious and direct correlation between a given coastal storm and its maximum sea level recorded on a tidal gauge. Although there may be actual correlation of unusually elevated sea level with storms or coastal flooding, there is no necessary instrumental correlation. Studies which attempt to rank historic storms or floods by their recorded tidal gauge levels will likely fail, and studies which attempt to count the number of floods or storms in the past by counting how many storms surpassed a threshold will necessarily underestimate the number of storms that occurred. This issue especially presents a challenge to those studies which would want to use past correlation of storminess or flooding with sea level to the future likelihood of storminess or flooding with rising sea level, a challenge which may prove fatal to this technique entirely.

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