Timescales of Global Tidal Flooding

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TIMESCALES OF GLOBAL TIDAL FLOODING

by

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ABSTRACT

Millions of people in low-lying areas are already affected by flooding, and the number will increase substantially in the future. Tidal flooding, the form of flooding caused by a combination of high tides and sea level rise to overcome protection levels, can cause damage and inconveniences such as road closures, overwhelmed drainage systems, and infrastructure deterioration from water damage. Tidal flooding already occurs annually in cities along the U.S. east coast, most notably Miami. However, the time it will take for other regions globally to begin to experience tidal flooding has not yet been assessed. Therefore, there is a limited understanding of how and when human populations will be exposed to this type of flooding. Tide gauge data from the GESLA-2 data base are used to obtain information about the highest astronomical tide (HAT) and extreme value statistics for 571 locations globally. For a complete spatial analysis, modelled water levels from the Global Tide and Surge Reanalysis (GTSR) are also used. Estimated protection levels are extracted from the DIVA database and translated to absolute heights based on the extreme value statistics of high water levels. This analysis is based on calculating the difference between the existing protection level and HAT, which indicates how much sea levels can rise before tidal flooding occurs, and evaluating in what decade this is expected to happen under different sea-level rise (SLR) scenarios. Tidal trends from the nodal and perigean are also taken account and used to modify 1000 different sea level rise scenarios to provide a more comprehensive analysis of possible tidal flooding years. Our results indicate that tidal flooding may occur within a few decades in many locations (under the assumption that no adaptation will take place), and therefore awareness should be heightened so that actions can be taken to minimize the impacts.
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INTRODUCTION

Flooding that is caused by high tides alone is often referred to as “nuisance flooding”, and by definition, it causes moderate damage and inconveniences. The effects of this form of flooding will continue to worsen and affect millions more people as sea levels rise. Increases in flooding caused by high tides are due primarily to increases in regional sea level rather than storm characteristics (Sweet et al. 2018). These “minor” flooding incidences have been occurring in some places along the U.S. East and Gulf Coasts, in cities such as Miami and Norfolk. However, the time it will take for other regions globally to begin to experience this type of flooding has not yet been assessed, and therefore, there is a limited understanding of how and when human populations will be exposed to it. Moftakhari et al. (2018) defines nuisance flooding as having a depth >3 cm and <10 cm, regardless of the source. An important distinction between tidal and nuisance flooding in this analysis is that tidal flooding considers protection level, so the amount of flooding will be greater than in nuisance flooding because the protection level is intended to protect people and infrastructure. When it is exceeded, there will be a more significant amount of flooding. The definition used in this analysis varies from this as we are considering the tidal flooding level to be any level that exceeds the calculated freeboard, which in this context is the difference between the protection level and the combined height of sea level and high tides.

With a continuation and acceleration of the rate of sea level rise, due to the continuous feedback loop of ocean warming and land-ice melt, the likelihood and frequency of tidal flooding will increase. In 2010, 39% of the U.S. population lived in counties directly along the coastline, and this number is expected to increase by 8% before 2020 (US Department of
Because regional sea level changes deviate from the global mean sea level, increases in flood risk will not be uniform in every coastal area. Thermal expansion and land ice changes are the greatest contributors to future projections of sea level rise, causing regional coastal sea level rise to vary from the global average (Carson et al. 2015). Therefore, the global mean sea level will not provide enough information about how local areas should adapt (Kopp et al. 2015). This analysis will identify how mean sea level in different areas combined with high tides in those places will contribute to tidal flooding. As sea level continues to rise, areas already experiencing tidal flooding will be more vulnerable to catastrophic flooding and land loss. Smaller storm surges will begin to have the same negative impacts as extreme flood events (NOAA 2015).

Previously, no study has been done to identify the tidal flooding year of different coastal locations on a global scale. However, nuisance flooding has been studied using other criteria. One similar study included the use of 18 tide gauges in the United States, using generalized linear models (GLM) and Gaussian Process (GP) models to estimate the changed frequency of nuisance flooding as well as the uncertainties from this approach. This study also considered sea level rise projections under two representative concentration pathways, RCP2.6 and RCP8.5, with an overall goal of determining flooding in 2030. The results indicated an increase of about 400% of hours of nuisance flooding occurrences (Vandenberg-Rodes et al. 2016). Additionally, a 2015 study found that under the RCP8.5 scenario, an 80 ± 10% local sea level rise causes the median of the nuisance flooding distribution to increase by 55 ± 35% in 2050 (Moftakhari et al. 2015). The economic effects of minor flooding are likely to result in high-cost impacts eventually, and Moftakhari et al. (2015) use a Cumulative Hazard Index (CHI) to identify how
cumulative costs of more frequent minor events relate to the cost of less frequent extreme events. For example, Miami Beach has over 11 billion USD of properties on land that is less than 3 feet above mean higher high water. This study identifies how local problems such as infectious diseases, small-scale Internet crimes, and minor natural hazards can aggregate into national and global high-cost outcomes. However, if action is taken before it is necessary, public trust may be broken (Moftakhari et al. 2017). With knowledge of the time period in which flooding is predicted to occur, it is more likely that action will be taken before severe damage occurs.

This study creates tangible results that highlight the time period in which tidal flooding will begin in different regions globally. The goal is to identify during which decade sea level rise will lead to elevated base water levels so that the highest tides in the year exceed the protection level, causing tidal flooding in the area to become a regular occurrence. This analysis will identify areas that are most at risk for tidal flooding, as well as when this flooding is likely to occur, in order to prepare for the impact of these flooding events.
BACKGROUND

Sea Level Rise

Increasing sea levels globally are the major cause of increased tidal flooding, because while high tides will continue to occur during different time periods, an increase in sea levels will result in these tides causing flooding if coastal areas do not have adequate protection. Slangen et al. (2017) uses twelve climate models to evaluate the global mean sea level change. Slangen showed that global sea level changes will result from processes such as thermal expansion, which accounts for 46% of total mean simulated sea level change, as well as other factors such as changes in land water storage due to human usage. Slangen also notes other factors that will result in changes on regional and local levels, such as gravitational effects, vertical land movement, and seasonal as well as decadal variability. Additionally, the rise in sea level would continue even with a reduction in greenhouse gas emissions due to the delayed response of ice sheets and in the deep ocean. Through artificially extending sea level records as well as utilizing individual tide gauge records, a coastal mean time series, and a global sea level reconstruction, there was found to be significant evidence that the rate of sea level rise over the past century has experienced a sustained increase (Haigh et al. 2014).

Nicholls et al. (2010) addresses rising sea levels by recommending monitoring for accelerations in sea level rise, improving understanding of climate-induced processes that contribute to sea level rise (such as the two major ice sheets) for better modeling, and responses through climate mitigation to reduce sea level rise and adapt to it. Long-term strategies are preferable and are especially relevant to those places that have been identified as unlikely to implement protection, such as small islands, Africa, and parts of Asia. The Warming
Acidification and Sea Level Projector Earth systems model was utilized to predict that pH and temperature changes will likely stabilize by the year 2300 with an unmitigated RCP8.5 scenario; however, sea level rise will continue past that year regardless of which stabilization scenario (1.5°C or 2.0°C) is considered. Therefore, adaptation is essential to reduce the risk of this unavoidable rise (Nicholls et al. 2018).

Additionally, an assessment that determines when tidal flooding will occur in different areas is necessary because sea level does not change uniformly, and “over 80% of local sea level projections differ from the projected global mean by up to ±20 cm”, with the northeast coast of North America and New York City projected to experience the greatest regional sea level change of densely populated areas and therefore vulnerable to a considerable amount of damage (Carson et al. 2015).

**Losses from Flooding**

Many cities globally have already experienced levels of flooding resulting in billions of dollars of damage and thousands of deaths, due to events such as Hurricane Katrina, Cyclone Nargis, Hurricane Sandy, Typhoon Haiyan, Hurricane Matthew (Haigh et al. 2016). Tidal flooding will become more severe and may result in similar losses as sea levels continue to rise. Through an evaluation of the 136 largest coastal cities globally, it was found that due to sea level rise as a result of climate change and subsidence, current protection levels will not be sufficient to avoid significant financial losses that may be as much as U.S. $1 trillion a year or more by 2050, with both optimistic and pessimistic projected sea level rise scenarios (Hallegatte et al. 2013). Additionally, even if the present flood risk is maintained by increasing protection levels, the losses will still rise to about U.S. $60 to $63 billion every year, as the floods will cause more
damage when protection is breached. The cities from developing countries are most vulnerable, as well as those in the United States such as New Orleans, Miami, and Tampa—Saint-Petersburg. Cities with high wealth and low protection levels result in the greatest amount of aggregate losses, and Miami, New York City, and New Orleans account for 31% of the global losses in the 136 largest coastal cities. Guangzhou has the greatest losses of any city. Hallegatte considered four scenarios with socioeconomic and environmental changes and found that without adaptation, environmental change had a much more significant effect than socioeconomic change on global losses.

**Tidal Flooding**

In order to appropriately adapt to increases in sea level, coastal communities should take into consideration both the frequent damages from minor flooding and less frequent losses from major flooding (Ghanbari et al. 2019). This necessitates an analysis outside of extreme value analysis because as these flooding events occur more frequently, they will not remain in the upper tail of the distribution and will instead shift towards the middle. While many places will experience a higher frequency of major flooding due to sea level rise, the Gulf and northeast Atlantic coastal regions will most likely be exposed to a greater amount of minor flooding.

NOAA defines minor nuisance flooding based upon elevations at specific locations determined from the NOAA National Weather Service Weather Forecasting Offices for 45 coastal water level gauges. Minor flooding events will cause minimal damage that threatens public property and will result in inconveniences. The great diurnal tidal datum, defined by NOAA as the height difference between the mean higher high water tidal datum and the mean lower low water tidal datum, are the local tide ranges and are used to determine the flood
thresholds based upon heights. A pattern between these thresholds shows that for many locations, minor flooding will start at about 0.5 m above this local tide range, while moderate and major flooding will start at about 0.8 m and 1.2 m, respectively (Sweet et al. 2018).

At the majority of these gauges, the number of nuisance flooding days has been accelerating over the past fifty years, even though the relative sea level rise in these locations may or may not be accelerating. Those areas with a high number of nuisance flood days are coastal areas along the Mid-Atlantic, in the Chesapeake Bay, North and South Carolina, and southern Texas. These areas experienced more than twenty nuisance flood days over three years (NOAA 2015).

Besides resulting in damages, high tide flooding can have economic impacts by reducing visits to businesses. In a study of the historic downtown of Annapolis, Maryland, it was found that current visits are reduced by 1.7% due to high tide flooding, and this number will increase to 3.6% with 3 inches of sea level rise and 24% with 12 inches of sea level rise (Hino et al. 2019).

It was found that the frequencies of nuisance flooding have been increasing along the U.S. East and Gulf Coasts, and regardless of the amount of sea level rise, other locations will soon follow (NOAA 2014).
DATA

We obtain extreme value analysis results using the Global Extreme Sea Level Analysis Version 2 (GESLA-2) tide gauge data (Woodworth et al. 2017). This data has 571 tide gauges with long enough data sets to be used for this analysis, located in different areas globally.

The Global Tide and Surge Reanalysis (GTSR) data set covers the world’s coastlines and includes hydrodynamic modeling of tides, surges, and estimates of extreme sea levels (Muis et al. 2016). It will be used to obtain a larger quantity of data for flooding year predictions in different areas, in addition to the tide gauge locations. These data sets are shown in Figure 1.

![Figure 1: Data sets used for tide gauges (length) and GTSR (100-year return levels) data](image)

The protection levels, as well as population data, are obtained from the Dynamic Interactive Vulnerability Assessment (DIVA) database (Vafeidis et al. 2008). The data from the representative concentration pathways (RCP2.6, RCP4.5, and RCP8.5) were projected by Slangen et al. (2017). The tide change data used to determine how tides will change as sea level changes come from Pickering et al. (2017). This study uses the tidal modal ATISmpi to simulate the response of four different tidal constituents to various sea level rise scenarios. The influence of the nodal and perigean cycles was taken into account by creating a time series from the TPXO7.2 global tidal model (Haigh 2011).
METHODOLOGY

The main goal of this analysis is to determine when tidal flooding (i.e., high tide exceeds protection levels) occurrences will begin in coastal areas globally. It is predicted that tidal flooding will increase in frequency and severity in those areas where it is already occurring, such as the U.S. East and Gulf Coasts.

Tide gauge data from the GESLA-2 database are used to obtain information about extreme value statistics and the highest astronomical tide (HAT) for 571 locations globally (GESLA 2019). The HAT is the highest predicted astronomical tide expected to occur at a specific location and is based upon average meteorological combined with astronomical conditions (Highest Astronomical Tide 2019). For a complete spatial analysis, modeled water levels from the GTSR data are also used. These components are shown in Section 1 of Figure 2. Estimated protection levels are extracted from the DIVA database (shown in Section 2) and translated to absolute heights based on the extreme value statistics of high water levels. This analysis is based on calculating the difference between the existing protection level and HAT, which indicates how much sea levels can rise before tidal flooding occurs and evaluating in what decade this is expected to happen under different sea level rise (SLR) scenarios.

In this analysis, the GESLA-2 dataset used was composed of 571 tide gauges that had enough data to determine HAT. The HAT at each of these tide gauges was found by determining the maximum tide over an approximately 19-year period to account for the nodal cycle. Then, the protection level closest to each tide gauge was found by calculating the shortest distance to one of the location IDs from the DIVA database (using longitude and latitude coordinates of the tide gauges and the DIVA locations) and finding the protection level at this location. The
protection levels from the DIVA database are given as return periods, indicating what type of flooding event each location is protected from. For example, a location with a protection level of 100 is protected from a 100-year event, that happens on average once every 100 years, and has a 1% (or 1/100), chance of occurring in any given year.

In order to evaluate high tides, the Gumbel distribution was fit to a time series of either annual maxima water levels and the Generalized Pareto distribution (GPD) was used with a peak-over-threshold approach. A Gumbel distribution uses two parameters, location and scale, while more flexible distributions such as Generalized Extreme Value or Generalized Pareto distribution (GPD) use a third parameter of shape and are more able to represent extreme events (Wahl et al. 2017). In this case, Gumbel and Generalized Pareto were ideal for determining when tidal flooding will occur. The number of exceedances (for GPD), distribution parameters, and protection level were used at each tide gauge to determine the absolute height of protection, demonstrated in Section 3 of Figure 2. This resulted in two sets of protection level data for the tide gauges. Because there were no GPD parameters for some of the tide gauge locations, these locations were removed from the data set, leaving 510 tide gauge locations. After the distributions were used, those locations that had protection levels of 0, meaning that they are not protected from any flooding event, had return levels of NaN. Therefore, these return levels had to be replaced with estimated absolute heights from which these locations would be protected. It was determined that these locations would either be given a return level equaling that of the HAT or that they would be protected from a 2-year event. Therefore, four sets of data were obtained, with those locations with 0 protection having two possible outcomes for each of the two distributions used.
The sea level rise scenarios for three different representative concentration pathways (RCP2.6, RCP4.5, and RCP8.5) were determined from Slangen et al. (2017), which provided the sea level rise at each longitude and latitude coordinate. This is shown in Section 4 of Figure 2. The closest ocean coordinate to the longitude and latitude of each tide gauge was determined, and the data at this point was obtained for 94 years (2007 to 2100). With this data, the tidal flooding year, seen in Section 5, could be determined by finding the year in which the sea level rise exceeded the difference between the absolute height of the protection level and the HAT. This is because, when sea level rise exceeds this difference due to the HAT, the protection level will be unable to protect from the combined sea level rise and high tide. Additionally, because sea level rise in a particular year could be an anomaly, and the goal is to determine the year in which tidal flooding will begin to occur regularly, the fifth year, not necessarily consecutively, in which sea level rise exceeded the difference between protection height and HAT was determined to be the tidal flooding year. Lastly, those locations where sea level was falling rather than rising were not considered to be tidal flooding locations. At the locations where sea level rise would not exceed the protection height, the year was identified as 2101 and outside of the scope of this study. World maps were created demonstrating the flooding year for the tide gauge locations, grouped by the decade in which tidal flooding was expected to begin. At this point, sets of data were created excluding those locations with a protection level of 0 because this correlates to a very low population. This data set was used for the rest of the analysis. Additionally, delta maps were created to show the difference in flooding years between different sea level rise scenarios as well as between the data determined by the Gumbel and Generalized Pareto distributions.
Section 4 shows that tide changes were also taken into account as a percentage of sea level rise for each scenario, with data from Pickering et al. (2017). The GTSR data, which includes over 16,000 gridpoints, was also considered by repeating the process and finding the HAT for each GTSR point, finding the closest DIVA data point and using the protection level at that location, and determining the absolute height for the protection level through the Gumbel distribution. The tidal flooding year was determined for GTSR data again by finding the difference between the protection level and HAT, then determining when sea level rise will be greater than this value. A comparison between the GTSR and GESLA-2 tide gauge data was performed by finding the closest GTSR grid point to each tide gauge. The GTSR flooding year was subtracted from the tide gauge flooding year, which was found using the Gumbel distribution, finding how close the GTSR model was to the tide gauge predictions. The locations with a protection level of 0 were removed from this set of data as well.

Geographic information system (GIS) was used to construct maps displaying the average flooding year for each country. To find out how many people would be affected by tidal flooding in each decade, histograms were created using the population data from the DIVA database. The database shows the number of people living under every meter of elevation at each grid point, and the closest grid point to each tide gauge was used to find how many people were affected based on the protection level at each location and when that protection would be overcome. For example, at a location with a protection level of 2 meters, no one would be affected at that location until tidal flooding occurred, and it would then affect every person living at an elevation of 2 meters or lower, for that year and every year after that.
Additionally, tide predictions were also taken into account using the 18.61-year nodal tide cycle and the 4.4-year lunar perigean cycle, shown in Section 4 of Figure 2. The closest data point with information on these tidal cycles to each tide gauge or GTSR grid point was found. This data was used to adjust the sea level at each location by creating an hourly time series from 2007 to 2100. Bathymetry data from TPX0 (which provides information on elevation, longitude, and latitude) was used to determine grid points that were over water, which would have tidal information. This hourly tidal prediction was used to determine the 4.4- and 18.6-year cycles based on the standard deviation and percentiles, which are exemplified in Figure 10.

1000 different mean sea level simulations were used for each tide gauge to account for the interannual variability of the RCP4.5 and RCP8.5 scenarios. The tide change as a percentage, demonstrated in Figure 11, was multiplied by the sea level rise and then added to the sea level rise, and the tide trends from the 4.4- and 18.6-year cycles were added as well. This resulted in 1000 different sea level rise projections for each of the 510 tide gauges, and flooding years were found using this data.

With the 1000 flooding years for each tide gauge, boxplots were created for 59 major cities by finding the tide gauge closest to these cities and creating boxplots in Matlab with the 1000 flood years, then arranging the 59 boxplots by protection level. Additionally, the maximum and minimum flood year for each of the 510 tide gauge locations was identified, and the range of these years was found, then plotted on a map using a color bar to show the range.
Figure 2: Diagram of methodology
RESULTS

The results in Figure 3 show the mean flooding year for each country under the RCP4.5 SLR projection for the GTSR results, with the average flooding year in the United States being around 2050. Figure 30 and Figure 31 show similar results for the RCP2.6 and RCP8.5 scenarios, with the RCP8.5 scenario showing the United States flooding year to be a decade sooner.

Figure 3: Average flooding year for RCP4.5 SLR projections derived from GTSR grid points belonging to individual coastal countries

Figure 12 and Figure 13 show the difference between replacing a protection level of 0 with the HAT or with 2 for the Generalized Pareto distribution, while Figure 14 and Figure 15 show the same for the Gumbel distribution. The different replacements do not result in a significant change in most locations, except a few tide gauges in Western Europe.

Additionally, the results show that, on average, flooding years are 25 years closer to present-day under RCP8.5 SLR projections compared to RCP2.6. By 2030, 9% of GTSR grid
points (where protection exists) will experience tidal flooding under RCP2.6 and 8.5 scenarios (SLR projections do not diverge much in the near future). For 2070 it increases to 56% and 73%. This is shown in Figure 4. For the tide gauges, Figure 16 compares the tidal flooding year for tide gauges for the RCP2.6 and RCP4.5 scenarios, while Figure 17 compares the RCP4.5 and RCP8.5 flooding years.

![Map showing global flooding years](image)

*Figure 4: Difference between flooding years calculated from RCP2.6 and RCP8.5 sea level rise projections for GESLA-2 tide gauges*

As seen in Figure 5, on average, protection levels estimated from GTSR are 5 cm lower as derived from GESLA-2 (25 cm average absolute difference), but tidal flooding occurs on average 9 years later (because HAT is also different).
Figure 5: Difference between flooding years calculated from GTSR and GESLA-2 for RCP4.5 sea level rise projections

The high-frequency tidal predictions do not have a significant effect on the tidal flooding year, which can be seen by comparing Figure 18 and Figure 19.

Figure 20 demonstrates the tidal flooding year for every GTSR gridpoint, while Figure 21 does not include those gridpoints with protection levels of 0, because there would be little to no population in those locations. Because of this, those places with no protection have tidal flooding years closer to the present.

Inset maps, shown in Figures 22-29, more clearly demonstrate the tidal flooding years of different regions, including Western Europe, Southeast Asia, the U.S. East Coast, and Japan.

Figure 6 shows that every decade, beginning in 2021, more people will be affected by tidal flooding than have ever been affected before. Millions of people in new regions will be affected every decade, with over 5 million people being affected beginning in the upcoming decade alone. Figure 7 demonstrates that the total population affected by tidal flooding will continue to increase dramatically.
Figure 6: Incremental increase in population affected by tidal flooding each decade under RCP4.5

Figure 7: Total population affected by tidal flooding each decade under RCP4.5
The 1000 different SLR projections demonstrate the likely range of time during which tidal flooding will begin to occur. Those cities with lower protection levels are more likely to experience tidal flooding in this century. This is true under both the RCP4.5 and RCP8.5 scenarios, shown in Figures 8 and 32.

Figure 8: Boxplots showing flood years for 1000 different SLR projections for 59 major cities arranged by increasing protection level for RCP4.5

Figure 33 shows the average flooding years at each of the tide gauges that are found using 1000 SLR projections for the RCP4.5 scenario. The range of these flooding years for the 1000 scenarios, shown in Figure 9, shows that while some locations show a great range of flooding years for the different SLR projections, particularly those tide gauges near the Nordic countries, due to interannual variability.
Figure 9: Flooding year range for each GESLA-2 Tide Gauge for 1000 different sea level rise projections for RCP4.5
CONCLUSION

Tidal flooding will continue (and become more frequent) in areas along the U.S. East and Gulf Coasts, where it already happens today. It will also become an issue throughout this century in many other coastal regions globally, including Western Europe, Australia, and the Pacific Islands. Of 510 tide gauges, under the RCP4.5 scenario, 460 are expected to experience tidal flooding before the end of the century. With knowledge of the average flooding year for a country, that country will be able to adapt appropriately to prepare for the possible outcomes of this flooding. With the GESLA-2 tide gauge data as opposed to the data from GTSR grid points, flooding is, on average, nine years closer to the present. As expected, for both data sets, flooding years are much closer under the RCP8.5 SLR projection than under the RCP2.6 SLR projection. While there is not much of a difference in tidal flooding locations before 2030, there is a much more significant difference by 2070.

Considering additional changes in tides associated with SLR as a percentage will only have a small effect. However, the 18.61-year lunar nodal cycle and the 8.85-year cycle of lunar perigee make larger contributions in some regions, depending on the tidal range of that region (Haigh et al. 2011). Accounting for these tide trends lowers the tidal flooding year in most locations when considered with the 1000 different SLR projections. These projections show that for most of the tide gauges, there is not a great amount of variability, with the exception of the Nordic countries.

The protection level data in this analysis was taken from the DIVA database, based primarily on population data and GDP values that may or may not accurately represent the actual
protection in that area. Therefore, it would be beneficial to obtain more accurate information on
these levels in further studies to accurately determine the tidal flooding years.

The current results indicate that tidal flooding may occur within a few decades in many
locations (under the assumption that no adaptation will take place), and therefore awareness
should be heightened so that actions can be taken to minimize the impacts. While under 2 million
people are affected by tidal flooding now, over 55 million people will be affected by the year
2100 if no action is taken to increase the protection level. An increase in protection level may
require sea walls or changes in zoning regulations and building codes (Ghanbari et al. 2019).
While these adaptations may come at a high expense, they are much less than the risk involved if
no modifications are made to protect tens of millions of people and billions of dollars of property
that would be affected by these increases in flooding.
APPENDIX A: ADDITIONAL FIGURES
Figure 10: Tide trend accounting for nodal and perigean cycles over 94 years for GESLA-2 Tide Gauge #1 (Abashiri, Japan)

Figure 11: Tide change over 94 years under RCP4.5 for GESLA-2 Tide Gauge #1 (Abashiri, Japan)
Figure 12: Tidal flooding years found using GPD and replacing protection levels of 0 with HAT for RCP4.5 SLR projections at GESLA-2 tide gauges (not including tide changes)

Figure 13: Tidal flooding years found using GPD and replacing protection levels of 0 with 2 meters for RCP4.5 SLR projections at GESLA-2 tide gauges (not including tide changes)
Figure 14: Tidal flooding years found using Gumbel distribution and replacing protection levels of 0 with HAT for RCP4.5 SLR projections at GESLA-2 tide gauges (not including tide changes)

Figure 15: Tidal flooding years found using Gumbel distribution and replacing protection levels of 0 with 2 meters for RCP4.5 SLR projections at GESLA-2 tide gauges (not including tide changes)
Figure 16: Difference between flooding years calculated from RCP2.6 and RCP4.5 sea level rise projections for GESLA-2 tide gauges.

Figure 17: Difference between flooding years calculated from RCP4.5 and RCP8.5 sea level rise projections for GESLA-2 tide gauges.
Figure 18: Tidal flooding years found using GPD for RCP4.5 SLR projections at GESLA-2 tide gauges (not including tide changes and excluding locations with no protection)

Figure 19: Tidal flooding years found using GPD for RCP4.5 SLR projections at GESLA-2 tide gauges (including tide changes and excluding locations with no protection)
Figure 20: Tidal flooding years found using RCP4.5 SLR projections at GTSR grid points (not including tide changes and including locations with no protection)

Figure 21: Tidal flooding years found using RCP4.5 SLR projections at GTSR grid points (not including tide changes and excluding locations with no protection)
Figure 22: Tidal flooding years in Japan found using Gumbel distribution for RCP4.5 SLR projections at GESLA-2 tide gauges (not including tide changes and excluding locations with no protection)

Figure 23: Tidal flooding years in Southeast Asia found using Gumbel distribution for RCP4.5 SLR projections at GESLA-2 tide gauges (not including tide changes and excluding locations with no protection)
Figure 24: Tidal flooding years along U.S. East Coast found using Gumbel distribution for RCP4.5 SLR projections at GESLA-2 tide gauges (not including tide changes and excluding locations with no protection)

Figure 25: Tidal flooding years in Western Europe found using Gumbel distribution for RCP4.5 SLR projections at GESLA-2 tide gauges (not including tide changes and excluding locations with no protection)
Figure 26: Tidal flooding years in Japan found using RCP4.5 SLR projections at GTSR grid points (not including tide changes and excluding locations with no protection)
Figure 27: Tidal flooding years in Southeast Asia found using RCP4.5 SLR projections at GTSR grid points (not including tide changes and excluding locations with no protection)

Figure 28: Tidal flooding years along U.S. East Coast found using RCP4.5 SLR projections at GTSR grid points (not including tide changes and excluding locations with no protection)
Figure 29: Tidal flooding years in Western Europe found using RCP4.5 SLR projections at GTSR grid points (not including tide changes and excluding locations with no protection)

Figure 30: Average flooding year for RCP2.6 SLR projections derived from GTSR grid points belonging to individual coastal countries
Figure 31: Average flooding year for RCP8.5 SLR projections derived from GTSR grid points belonging to individual coastal countries
Figure 32: plots showing flood years for 1000 different SLR projections for 59 major cities arranged by increasing latitude for RCP8.5

Figure 33: Average flooding years found using 1000 SLR projections for the RCP4.5 scenario at GESLA-2 tide gauges (including tide changes and excluding locations with no protection)
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