The US Military on the Front Lines of Rising Seas:

Methodology and Key Caveats

The Union of Concerned Scientists' report "The US Military on the Front Lines of Rising Seas" assesses the potential exposure of coastal military installations to increased coastal flooding due to sea level rise. Specifically, we evaluated the effect of sea level rise on the severity and extent of storm surge inundation, the frequency and extent of tidal flooding, and the timing and extent of permanent inundation.

This document outlines the methods, tools, and data used.

Methodology

Storm Surge

The storm surge model: We have analyzed storm surge depth and extent using the SLOSH model, developed by the National Oceanic and Atmospheric Administration (NOAA), which is used to by the National Hurricane Center to issue storm surge alerts when a hurricane is approaching the coast and is routinely used by emergency managers. SLOSH forecasts were used, for example, as guidance by the New York City Emergency Management Department as Hurricane Sandy approached the city (NYC Emergency Management 2014).

NOAA has developed different composite storm surge predictions for each category of hurricane by running the SLOSH model several thousand times with hypothetical storms. We utilized a product of these composite runs known as the MOM, or the Maximum of the Maximum Envelopes of Water, which is considered a worst-case scenario for each particular storm category. The SLOSH model was chosen over other possible storm surge models such as ADCIRC because of its familiarity to emergency managers, its low computational cost, the ease of analysis for a wide range of storms, and its complete, consistent basin coverage of the East and Gulf coasts. Despite some studies finding that SLOSH may underperform in some situations due to its level of resolution and location-specific conditions (e.g. Kerr et al 2013), it is found to be adequate for our type of comparative analysis of various locations under similar storm conditions, i.e. storm categories (see key caveats, below).

The elevation data: Determining the extent and depth of inundation requires an elevation model. We obtained high-resolution elevation data primarily from the USGS 3DEP Program, which is regularly updated with the best available data. In most coastal locations, we have been able to obtain 1/9 arc-second data – approximately 3 m spatial resolution – derived from Lidar surveys. For Eglin Air Force Base, FL, we used data from both 3DEP and NOAA Digital Coast. We have interpolated the SLOSH results to the resolution of the elevation model. The vertical accuracy of the elevation data is typically less than 10 cm (USGS 2014).

The future scenarios: To assess the combined effects of sea level rise and storm surge, we have used locally specific sea level rise projections at three future time points – 2050, 2070, and 2100. These projections, provided by Climate Central (n.d.), are based on the widely utilized Intermediate-High and Highest global sea level rise projections developed for the 2013 National Climate Assessment (see Parris et al. 2012). We chose to use these projections rather than the Representative Concentration Pathways (RCPs) developed by the IPCC in its 5th Assessment Report (2014) based on input from a panel of military experts. The Highest scenario is recommended by the NCA for use when planning for areas that have a low risk tolerance.

To produce localized sea level rise projections, Climate Central first assessed the difference between the local rate of sea level rise at a set of tide gauges along the East and Gulf Coasts. Using the historical difference between the local and global rates of sea level rise, they developed a "local component" of sea level rise for each tide gauge. This local component does not quantitatively differentiate factors such as subsidence or groundwater withdrawal. Rather, all of these factors are lumped together to reflect the sum total of locally-relevant factors. For future projections, the local component for each tide gauge is held constant and used to adjust the global projection. The projections do not account for any changes in the rate of anthropogenic subsidence.

To assess the combined effect of sea level rise and storm surge, we have added the projected sea level rise linearly to the storm surge from the SLOSH model to define a future storm surge surface. For each surface, we performed a region group analysis and extracted only areas that were hydrologically connected to the ocean. This methodology is outlined in NOAA's Coastal Inundation Primer (2012).

For each of the time points (plus 2012 as a baseline for current conditions) and sea level rise projections, we evaluated surge for Category 1 to 5 storms for bases in the Gulf and East Coast up to Virginia, and Category 1 to 4 for bases north of (and including) Virginia, where Category 5 storms are extremely unlikely to occur.

The area statistics: Our analysis of the area of each base inundated at different depth intervals utilizes standard area statistics and other tools within ESRI's ArcGIS products. To determine base area overall, we have used the U.S. Census Bureau's latest spatial dataset of U.S. military installations. Note that the area of each base and the area inundated by storm surge may include natural bodies of water.

Tidal flooding

In addition to analyzing the combined effects of sea level rise and storm surge, we have analyzed how the frequency and extent of tidal flooding—often called minor coastal flooding or nuisance flooding—are affected by sea level rise in the years 2050, 2070 and 2100. As with our storm surge analysis, we utilized localized versions of both the Intermediate-High and Highest scenarios from the 2013 National Climate Assessment, provided by Climate Central (n.d.).

The method: To assess the frequency of tidal flooding today and in the future, we used NOAA's online Inundation Analysis tool. Tide gauges maintained by NOAA's National Ocean Service form the basis of our analysis. To be included in the analysis, a gauge must have a defined flooding threshold for minor coastal flooding defined by local Weather Forecast Offices (WFOs) and be available within the tool (NOAA Tides and Currents 2013). It is important to note that the results of the Inundation Analysis are tide gauge-specific and may have limited applicability to the surrounding areas. We have assessed the applicability of each tide gauge to the county containing the military base by evaluating the correlation between flood events--as determined by the Inundation Analysis tool--and the issuance of Coastal Flood Advisories by the National Weather Service for those flood events. And for Camp Lejeune, we could not confirm that the nearby Wrightsville Beach tide gauge reflects flooding in Onslow County, NC. For all other installations, the issuance of CFAs correlated well with the flood events identified through the Inundation Analysis. For more details on this method, see the Technical Appendix in Spanger-Siegfried, Fitzpatrick and Dahl 2014.

As reported by the Inundation Analysis tool, the errors associated with using tide gauge data to assess flood frequency include uncertainty in the tide gauge datum (approximately 1 to 5 cm) and tidal level measurements errors (1 to 2 cm).

Minor coastal flooding is typically associated with the issuance of a Coastal Flood Advisory, which alerts residents to minor, or nuisance, level flooding conditions that do not pose a serious risk to life and property (NWS 2009). For each military base, we have chosen the nearest available tide gauge with those properties. We have then calculated the average number of minor coastal floods annually using the five-year average for the 2009-2013 period. To assess future flood frequency, we effectively lowered the flooding threshold by subtracting the projected amount of sea level rise, then recalculated the annual average using the same 2009-2013 baseline. We report tidal flooding frequency as the mean for the 2009-2013 period and include error bars for +/- one standard deviation. For more detailed information, see the Technical Appendix in Spanger-Siegfried, Fitzpatrick and Dahl 2014.

It is important to note that the frequency of future tidal flooding applies only to the area currently affected by tidal flooding – the area shown in the lightest purple in our reports' maps. The areas that are currently exposed to tidal flooding tend to be limited and, in many cases, primarily wetlands. Our future tidal flooding frequency statistics apply to these areas. Our maps of the future extent of tidal flooding show the reach of extra-high tides as sea level rises. The newly exposed areas would experience tidal flooding with the same frequency as today. For example, if an area experiences 10 tidal floods per year today, the area mapped for 2100 would experience 10 tidal floods by that year.

In order to characterize the areas of each base that are currently exposed to tidal flooding, we visually assessed the overlap between wetland/marsh areas and areas that experience minor coastal flooding using the NOAA Sea Level Rise Viewer. We utilized this visual assessment to determine whether the areas exposed to tidal flooding are primarily wetlands or whether developed land is exposed as well.

To map the current and future extents of tidal flooding, we have again utilized the WFO-defined flooding threshold. For future extent, we have added the projected amount of sea level rise to that threshold and mapped the elevations that fall below the combined level. For each tidal flooding surface, we performed a region group analysis and extracted only areas that were hydrologically connected to the ocean. As with our storm surge analysis, we used standard area statistics tools within ESRI's ArcGIS products to determine the area of each base that would be inundated during a tidal flooding event. From this area, we have subtracted the area that is currently below the Mean Higher High Water (MHHW) level to ensure that the reported tidal flooding area does not include areas already below high tide today.

Permanent inundation

To assess the exposure of each base to permanent inundation, we have analyzed the changing extent of MHHW level as sea level rises. As with the other analyses for this report, we utilized localized versions of both the Intermediate-High and Highest scenarios from the 2013 National Climate Assessment, provided by Climate Central (n.d.).

The method: We obtained MHHW levels from tide gauge-specific pages within NOAA's Tides and Currents website. For each military base, we used the nearest available tide gauge maintained by the National Ocean Service. We performed a spatial analysis to create water surfaces for the present-day MHHW level at each base. We then added the projected amounts of sea level rise to the MHHW level and created a water surface for each sea level rise future. For each surface, we performed a region group analysis and extracted only areas that were hydrologically connected to the ocean. As with our other analyses, we used standard area statistics tools within ESRI's ArcGIS products to determine the area of each base that would be inundated at MHHW today and in the future. We have used the area inundated by MHHW today to determine the "currently dry land" area of each base by subtracting the MHHW area from the total base area. We report the future percentage of the base that would lie below the MHHW level as the percentage of the currently dry land area that would be inundated. In our products, we refer to this as the area that would be under water during high tide or the area that would become part of the tidal zone.

Uncertainty

This analysis is subject to a range of uncertainties. The elevation data we have used is primarily from Lidar and other high-resolution sources, but its vertical accuracy is only accurate to within about 10 cm (USGS 2014). The SLOSH MOMs are lower in resolution than the elevation data by an order of magnitude or more. Interpolating the SLOSH data as we have done may result in false precision. As higher-resolution SLOSH and elevation data become available, the areas we understand to be exposed to coastal flooding should be refined (NRC 2009).

As discuss below in the Key Caveats section, flooding simulated by SLOSH is limited only to that which is storm surge-induced. Sea level rise projections are highly dependent on the future trajectory of human emissions of heat-trapping gases as well as the Earth system response to those emissions. Both of those factors are uncertain, particularly in the latter half of the century. In addition, we assume that the effect of sea level rise on storm surge height will be linearly additive, while there is some evidence that this is not the case (e.g. ARCADIS 2013; Zhang et al. 2013). Our projections of tidal flooding frequency represent averages over a five-year period and thus incorporate some year-to-year variability.

We assume that tidal range and coastal morphology will not change substantially in the future, although there is evidence to suggest that this may not be the case (Flick, Murray, and Ewing 2003; FitzGerald et al. 2008; Lentz et al. 2016). Shoreline erosion, for example, and sea level rise can exacerbate one another. And beach nourishment projects and protective measures such as groins can have the unintended consequence of increasing coastal erosion in adjacent areas.

Key Caveats

It is important to highlight certain caveats of our analysis, mainly related to what it does and does not include, and our main objectives.

1. This study is not meant to be comprehensive. The military sites we analyzed are intended to provide snapshots of possible storm surge and sea level rise exposure and effects at points along the East and Gulf Coasts. They were chosen in consultation with military experts and do not include all existing bases on those areas.

2. The results of this study are intended to be illustrative of each military installation's potential exposure to flooding. Infrastructural planning and decision-making would require more detailed analysis.

3. This study does not address the probability of any particular category of storm hitting any particular stretch of coast. Nor does it address the return period of either major or minor coastal flooding. Planners at each military installation may want to consider conducting probability-based assessments of coastal flooding to better quantify risk.

4. The SLOSH model does not include rainfall-induced flooding or riverine flooding. It also does not include wave setup or run-up. We are aware that in many cases flooding is intensified by accompanying

precipitation due to the storm itself, but that is a separate, additional factor that we did not evaluate. Because of these factors, our results may underestimate the extent and severity of flooding at a given location.

5. Hurricanes are categorized on the Saffir-Simpson scale by wind speed, and storm surge levels are not tied directly or always proportionately to storm category. There are many factors that contribute to storm surge height, including storm size and angle of approach. The categories described in this report are based on thousands of simulations of hypothetical storms with wind speeds defined by the Saffir-Simpson scale. In this analysis, we use storm categories as a way of defining different strengths of storm independent of each hurricane's specific conditions. Therefore, it is important to note that not every storm of a given category will produce equal storm surge heights for a given location. It is also important to note that storms weaker than hurricane strength—e.g. nor'easters—often produce damaging levels of storm surge.

6. We are utilizing the SLOSH maximum of maximums, or MOMs, which represent a worst case scenario for a given storm category for every location within the SLOSH area. No one storm would be likely to produce the exact pattern of flooding depicted in each map.

7. We focus on "exposure" to storm surge rather than risk. A more technical definition of risk would include an assessment of probability, which we did not address.

8. We have assessed error on our tidal flooding frequency projections by capturing both the mean and standard deviation in the number of flood events over a 5-year period. However, the choice of a different 5-year baseline period (e.g. 2004-2008) could affect the future and projected frequency of tidal flooding. Aside from this, we have not quantitatively assessed uncertainty for this study.

9. The statistics for base area and storm surge area may include natural bodies of water. Moreover, we define "currently dry land area" as the area above the MHHW level. It is possible, however, that this area could contain natural bodies of water or wetlands that, in practice, are not usable, developable land.

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