Annapolis's Hurricane History: A study of the Sensitivity to Storm Intensity and Approach Vector

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RESEARCH OBJECTIVES:

1. **Identify the most common direction of tropical cyclone (TC) approach to Annapolis, Maryland**
2. **Understand the mean TC wind and surge impacts for each approach direction**
3. **Use a leading tool in the Emergency Management community (HURREVAC) to simulate the impacts from those TCs in an operational setting**

BACKGROUND AND MOTIVATION

Annapolis, Maryland is vulnerable to flooding and tropical storms. Increased flooding in Annapolis is in part a result of sea level rise (Maryland Climate Change Commission, 2018). But, TC winds can cause a surge of water that damages critical commercial, governmental and residential interests in the city. An extreme case occurred in 2003, when the combined storm tide from Hurricane Isabel was over 2 m in Downtown Annapolis (Whitney, 2011). ***Figure 1*** shows the flooding from Hurricane Isabel in downtown Annapolis, whereby the maximum envelope of water (MEOW) was modeled to be between 1 to 2 m (***Figure 2***; Sheng et al, 2010).

Figure 1*: Dock Street, Annapolis, MD, one of the most prominent and commercial streets in Annapolis, as it is inundate by flood waters during Hurricane Isabel. (Capital Gazette, Capital File Photo)*

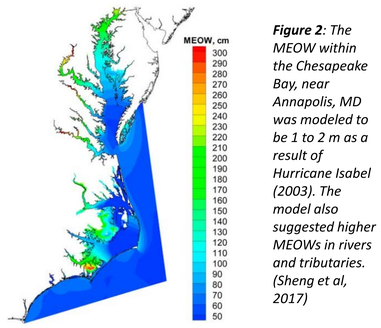

Figure 2*: The MEOW within the Chesapeake Bay, near Annapolis, MD was modeled to be 1 to 2 m as a result of Hurricane Isabel (2003). The model also suggested higher MEOWs in rivers and tributaries. (Sheng et al, 2017)*

HURREVAC AND EMERGENCY MANAGERS

Emergency managers are employed by a community to mitigate the effects of a disaster. Prior to a TC, city and state offices of emergency management are charged with keeping citizens updated on the potential for impacts. Hurricane Evacuation (HURREVAC) is a tool created jointly by the National Oceanographic and Atmospheric Association (NOAA), the Army Corps of Engineers (ACE) and the Federal Emergency Management Agency (FEMA) in 1987 that has been constantly updated to aid emergency managers in planning for and implementing hurricane response policies. HURREVAC supports decision making by helping to assess evacuation times and the potential for wind and storm surge (HURREVAC Support).

DATA AND METHODS

TC location and intensity were taken from the publicly available HURDAT data set (Landsea, 2013)

- Track and intensity are provided every 6 hours for every TC in the Atlantic region from 1851 to 2017.
- Only TCs that passed within a 5° longitude x 5° latitude box, centered on Annapolis, MD, were retained.
- Those TCs were binned into 30° groups by their approximate direction of approach to Annapolis (SW, S, SE, E, or W).
- Mean intensity and track were then calculated for each directional bin for 78 hours prior to landfall and 18 hours after landfall.
- Each mean track and intensity was entered into the HURREVAC (v.1.8.1) and HVX Beta (v.2.1.0) determine surge and clearance times.

Southwest				South			
Year	Name	Year	Name	Year	Name	Year	Name
1854	-	1949	-	1856	-	1971	Doria
1859	-	1952	Able	1861	-	1979	David
1874	-	1955	Diane	1861	-	1985	Gloria
1879	-	1959	Cindy	1863	-	1985	Henri
1881	-	1960	Brenda	1866	-	2011	Irene
1882	-	1960	Donna	1872	-	**Southeast**	
1886	-	1961	-	1876	-	Year	Name
1886	-	1986	Charley	1878	-	1893	-
1888	-	1988	Chris	1882	-	1933	-
1889	-	1994	Beryl	1883	-	1943	-
1893	-	1996	Bertha	1893	-	1983	Dean
1893	-	1999	Dennis	1893	-	1992	Danielle
1894	-	1999	Floyd	1897	-	2003	Isabel
1894	-	2001	Allison	1903	-	2012	Sandy
1904	-	2004	Bonnie	1934	-		
1915	-	2004	Gaston	1944	-		
1935	-	2004	Jeanne	1953	Barbara		
1944	-	2008	Hannah	1954	Hazel		
1945	-	2015	Ana	1955	Connie		

Table 1: *A list of all of the storms and year of occurrence that were considered in this study from the top 3 binned directions*

References

2018 Annual Report: Maryland Commission on Climate Change

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Acknowledgements

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RESULT 1: TROPICAL CYCLONES APPROACH ANNAPOLIS FROM THREE DIRECTIONS

- From 1851 to 2017, seventy- two (72) TCs passed within 5° lat-lon of Annapolis (***Figure 3***) with origins from the Gulf of Mexico to the western shore of Africa (***Figure 4a-c***).
- The TCs clustered into three dominant approach directions: southwest, south, and southeast (***Figure 3***).
- More than half (53%) of all the TCs that passed within 5° of Annapolis approached from the southwest (***Figure 3***).

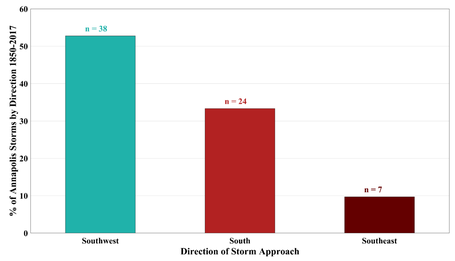


Figure 3*: Percent of TCs passing within a 5° x 5° lat-lon box around Annapolis, MD from 1851 to 2017, binned by direction of approach. The percent total includes 3 additional storms from the East and West.*

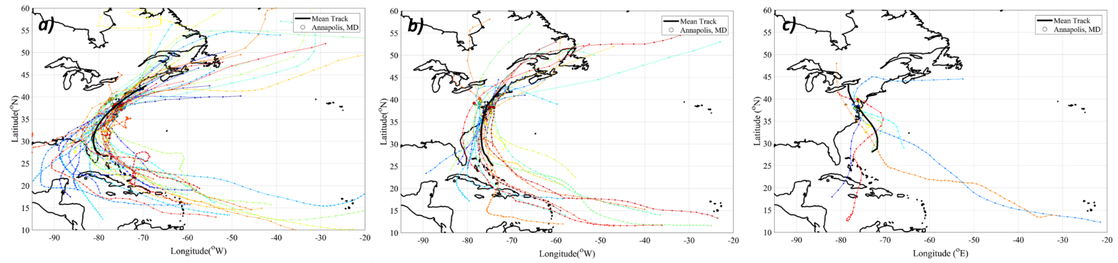
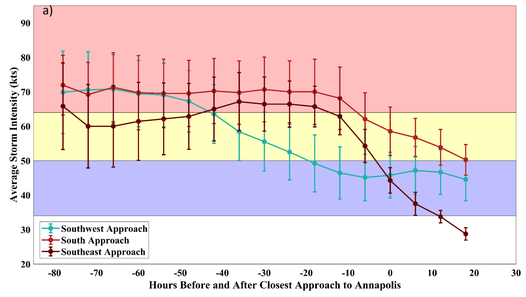


Figure 4a-c*: Track of all TC's that approach Annapolis (white circle) from 1851 to 2017, clustered by direction of approach* ***a)*** *Southwest,* ***b)*** *South,* ***c)*** *Southeast. Each 6 hours interval is represented by a dot on the track with enlarged dots representing the point of closest approach. The mean track of each respective direction is characterized by a solid black line.*

RESULT 2: ON AVERAGE, STORMS THAT APPROACH FROM THE SOUTH ARE STRONGEST

- Within 24 hours of landfall TCs generally approach from the southwest as tropical storms (34 to 63 kts) and the south and southeast as hurricanes (64+kts) (***Figure 5a***). TC wind speed variability decreases for each approach direction as the storm approaches Annapolis. The intensity also generally decreases as the storm interacts with land.
- TCs approaching from the south retain a higher intensity through Annapolis because their circulation does not interact with land (***Figure 5b***).



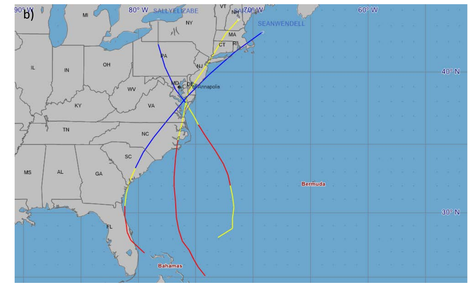
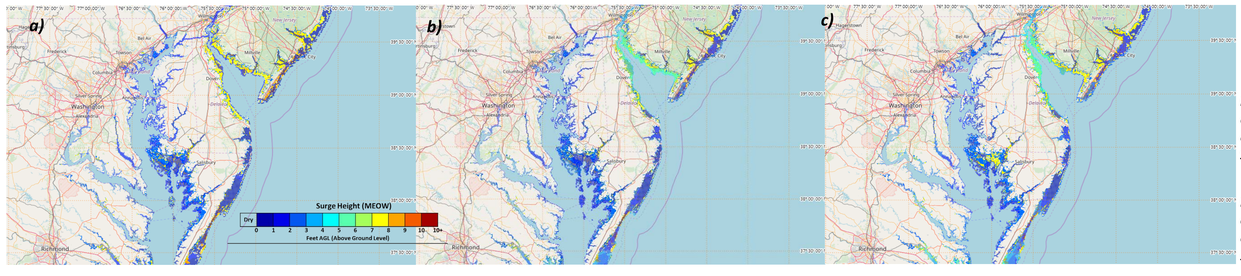


Figure 5a-b*: Mean intensity (colored lines) and standard error (bars in panel a) for TCS within 5° x 5° lat-lon of Annapolis. Line colors in both panels represent TC intensity: white, under 34kts; blue, 34kts to 50kts, tropical storm; yellow, 50kts – 64kts, strong tropical storm; red, above 64kts, hurricane. Both figures show intensity* ***a)*** *and track* ***b)*** *for the 78 hours leading up to landfall and the 18 hours after landfall.*

RESULT 3: HURREVAC SURGE & EVACUATION TIMES PROJECTS VARY WITH APPROACH

- Storm surge, as predicted by HURREVAC (which incorporates static sea, lake, and over-land surges from hurricanes (SLOSH) model conditions), does not vary much by storm approach vector over the Severn River or Annapolis areas (***Figure 6***). However, surge differences are seen by approach vectors throughout the Chesapeake Bay, Delaware Bay, Delmarva coast, and New Jersey Coast.
- HURREVAC suggests the evacuation clearance times for Annapolis will vary based on storm intensity and population density (***Figure 7***)



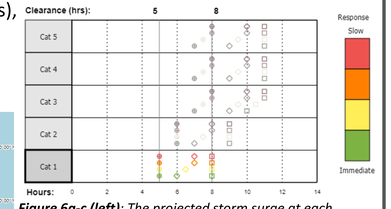


Figure 6a-c (left)*: The projected storm surge at each direction of approach in ft above the maximum envelope of water (MEOW) at each direction of approach* ***a)*** *Southwest,* ***b)*** *South, and* ***c)*** *Southeast.*

Figure 7a-c (top)*: Mean evacuation times for Annapolis categorized by intensity, response time, and tourist occupancy (+: low; circle: medium; diamond: high; square: worst).*

DISCUSION AND FUTURE WORK

- Although TCs frequently impact the Annapolis area, **the majority of the storms approach from the southwest**, which does not cause as many negative consequences. However, should the TC **approach from the south or southeast**, Annapolis may see **more flooding and impacts**.
- While HURREVAC is a proven tool for disaster planning, training, and emergency management, the interface likely **lacks the detailed physics** associated with specific storm training scenarios (***Figure 8***).
- Further work using HURREVAC is needed to clarify the consequences of specific hurricane surges based on wind direction and intensity.
- Further investigation into impacts of the East and West direction and their impact on surge and clearance times.
- More work is needed to determine the frequency and significance of the most impactful storms in the Annapolis area, such as Isabel, Sandy or Agnes.

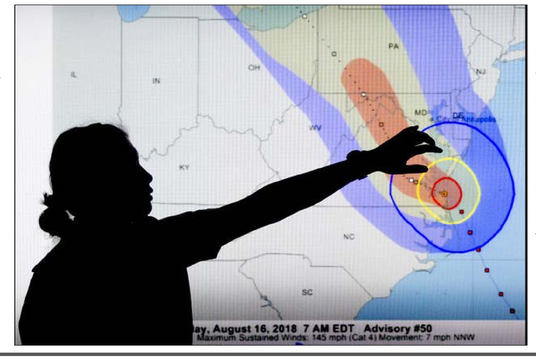


Figure 8*: The city of Annapolis Emergency Management Office recently used HURREVAC to reevaluate their current hurricane policy in a hurricane simulation exercise (Capital Gazette, Jen Rynda)*