The Need and Rationale for a Coastal Flood Risk Index

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***Abstract*—There is need for an index for estimating and communicating the potential storm surge and inundation caused by land-falling hurricanes. In 2003, the U.S. Congress passed a law which was signed by the Administration that funded the creation of such an index which would be in keeping with the well-known Saffir-Simpson Hurricane Wind Index. We propose a formula for such an index by simplifying the Navier-Stokes momentum and conservation equations configured for a hurricane about to make landfall onto a coast. Two mechanisms, one by the alongshore, and the other by the cross-shore wind stress are formulated and their relative role are discussed. The formula used the information of, besides the main driving force of hurricane wind stress, hurricane translation speed, water depth, hurricane size (fetch), and topographic slope. Other factors that affect the surge height, such as the Sea Level Rise, tidal, surface air pressure and others, can be easily added to the estimated surge height and therefore to the estimate of the inundation potential. An example is given in which the surge height calculated using the proposed formula matched the observed values for Hurricane Andrew. The impact of Sea Level Rise on the inundated area estimated using the proposed formula are compared against the ones obtained with full dynamic models.**

***Index Terms*—storm surge, inundation, flood, modeling.**

I. Introduction

Tropical cyclones (TC) and their storm surge and inundation are a major threat to lives and properties in coastal communities worldwide. Successful hazard mitigation requires quick risk identification and effective communication between emergency agencies and the general public. Indices have been used to aid communication of complex hazard risk information to the general public who dont have the science background or have difficulty reading detailed forecast advisories, such as the Saffir-Simpson (SS) hurricane categories[1]. The general public can easily understand the 1-to-5 classes of an incoming hurricane defined in SS and they do response to a higher category hurricane more than a lower one. However, it is now well known that more hurricane damage is caused by storm surge and inundation than by the wind in coastal and inland environs. Although wind is the major driving force, storm surge and inundation are affected by many more factors than just maximum wind. In the early years SS was also used to categorize storm surge height, but this function was removed later as storm surge and inundation predicted using only wind are typically not accurate. There have been multiple efforts to study the relationships between tropical cyclone (TC) winds and the storm surge heights and found that, although a regression relation can be established between TC winds and surge heights, the uncertainty is too large for the regression relation to be used for prediction purpose. For example[2] , the residual standard error (RSE) can be greater than 1 m, which is on the same order of magnitude as the surge height itself; and a 100 knot wind speed event can result in surge heights ranging from less than 1 m to more than 6 m, making the regression relation of very limited practical usefulness for predicting storm surge height and inundation area. Pietrafesa et al (2012) pointed this out at the 2012 American Meteorological Society (AMS) Annual meeting on an AMS Panel Session, and the academic and emergency management communities responded favorably.

A method is needed to quantify TC-induced storm surge and inundation risk with the ability for quick communication to the public. The method must be simplified so that emergency managers can carry out the calculations without having to rely on super computers and complex numerical computer models. More factors must be considered in addition to maximum wind speed. The goal of this study is to propose a methodology. We use the simplified shallow water equations and the continuity equation to derive a formula to estimate the storm surge height and inundated area that considers a wide range of parameters, including the incoming hurricanes wind speed, wind size, its translation speed, coastal water depth, coastal land slope, existing water level variation, and atmospheric sea level pressure.

II. Methods

We consider a simple scenario where a TC over coastal water approaches the land (see Fig.1). The shallow water equations describe such a scenario are [3]:

$$\frac{\partial u}{\partial t} - fv = -g\frac{\partial \eta}{\partial x} + \frac{1}{\rho_w}\frac{\tau_x}{h} \tag{1}$$

$$\frac{\partial v}{\partial t} + fu = \frac{1}{\rho_w}\frac{\tau_y}{h} \tag{2}$$

$$\frac{\partial (hu)}{\partial x} = -\frac{\partial \eta}{\partial t} \tag{3}$$

where u and v are ocean currents in the x and y directions respectively. f is the local Coriolis parameter,η is water level, τ_x and τ_y are surface wind stress in x and y directions, respectively, and h is the water depth. In this configuration, the ocean is open-ended in the alongshore or y direction. In the x direction, perpendicular to the coast, the land acts as a solid boundary with the non-slip condition (no erosion at the

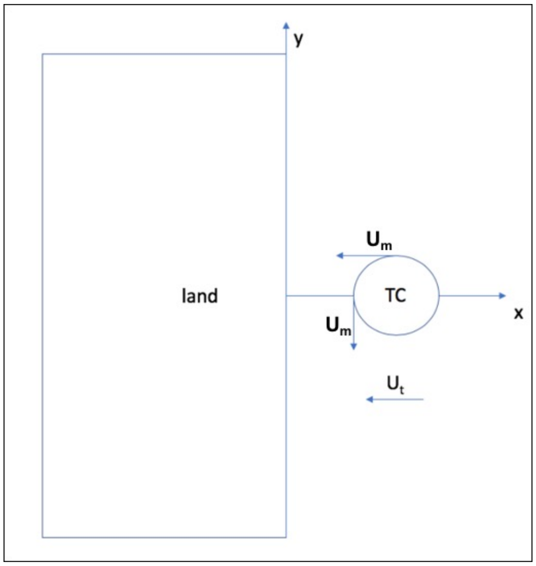

Fig. 1. A conceptual diagram of an TC over coastal water with maximum wind speed of U_m approaching land with the translation speed of U_t

coast) under which the ocean current components, u and v, are both zero on the solid boundary when x=0. The wind stress is calculated as $\tau_x = \rho_a C_d U_m^2$ and $\tau_y = \rho_a C_d V_m^2$ where ρ_a is the air density, C_d is a dimensionless drag coefficient and U_m and V_m are the surface wind speed in the x (cross-shore) and y (along-shore) directions, respectively. For simplicity, bottom stress is not considered in this study.

Storm surge is the water level change due to the wind stress, which can have two possible mechanisms, one due to the alongshore wind and the other cross-shore.

A. alongshore

Assume the wind and flow fields have reached a steady state, then in the y direction, from Eq.2, we have $u = \frac{\tau_y}{hf} = \frac{\rho_a C_d V_m^2}{\rho_w hf}$. Therefore under the wind stress and Coriolis force, there is a water flow toward the land. On solid land condition, however, both u and v are zero. Thus the flow u creates a convergence of water toward the coast and from Eq.3, this convergence cause water to pile up against the coast, leading to the equation below.

$$\Delta\eta = \frac{\rho_a C_d V_m^2}{\rho_w f \Delta x}\Delta t = \frac{\rho_a C_d V_m^2}{\rho_w f U_t} \tag{4}$$

B. cross-shore

For cross-shore wind, the wind stress τ_x is balanced by the pressure gradient force, so in Eq.1, we have [4], [5], [6]

$$\Delta\eta = \frac{\rho_a C_d U_m^2 L}{\rho_w h g} \tag{5}$$

For example, assume $\rho_a = 1kg/m^3, Cd = 0.002$, L is the fetch of the wind field=100km, $\rho_w = 10^3 kg/m^3$, h is water depth, g=9.8, then the storm surge height $\Delta\eta = 0.02U_m^2/h$. For a wind speed of $20ms^-1$ and a coastal water depth of 10m, the surge height will be $0.02 * 20^2/10 = 0.8$m

In theory, both the alongshore and cross-shore winds should be considered, because the Rossby number is 0.1 for an ocean current of $1ms^{-1}$ and a spatial scale of 100 km at the mid-latitude. However the estimation of the storm surge height caused by the alongshore wind, as in section II-A, has large uncertainties. In section II-A, the alongshore wind stress τ_y causes onshore flow u and that causes water to pile against the land and thus affecting the storm surge. From Eq.1, in the x direction, the pressure gradient force due to the water slope is balanced by the alongshore flow. A faster alongshore flow speed v is needed for a higher surge height. However, in reality, bottom friction, a function of flow speed, limits the alongshore flow speed and thus also limits the surge height. Therefore, the storm surges height will be overestimated using section II-A without considering the bottom friction. In addition, the near shore areas are often too shallow, much less than the theoretical Ekman depth required for Ekman transport to fully-develop, so the assumption of Ekman transport of water to the right of the wind often does not hold for very shallow near-shore areas. [7]

Due to the uncertainty in estimating the surge height caused by alongshore wind stress, in this study we will focus on the surge height due to cross-shore wind stress as described in section II-B. The storm surge caused by five past storms are estimated using Eq.5, and the results in Table I showed that the estimation agrees well with the observations. Thus, a simple calculation using the National Weather Service (NWS) hurricane maximum wind forecast and the local coastal water depth, which can be carried out by emergency managers without having to rely on sophisticated full physics computer models, can give us estimated storm surge height accurate enough for estimating flooded areas.

It should be noted that the storm surge heights listed in Table I,both estimated and observed, are those caused by wind stress only, known as storm surge, to be distinguished with the total water level variations caused by other factors, such as the astronomical tides. To estimate the flooding extent, the total surge height, including the effect of not only storm wind stress, but also those by, among others, tides, rainfall, sea level rise (SLR), and relatively lower atmospheric sea surface pressure. The advantage of this proposed method is that these effects can be linearly added to the storm surge height estimated using Eq.5 to compute the total storm surge. Presently the astronomical tide height can be accurately predicted for the time and location of an incoming landfall TC. The SLR can also be known in advance. For a general estimation, for each mm of forecast rainfall amount, the estimated storm surge height should increase by 6mm, and for each ± 1 hPa change in the atmospheric surface pressure, the storm surge should change by ∓ 24 mm ([8]).

After the storm surge height estimate is obtained, it can be used to calculate the inundation area. The distance that the water can inundate is given by

$$I = \frac{\Delta\eta}{\alpha} \tag{6}$$

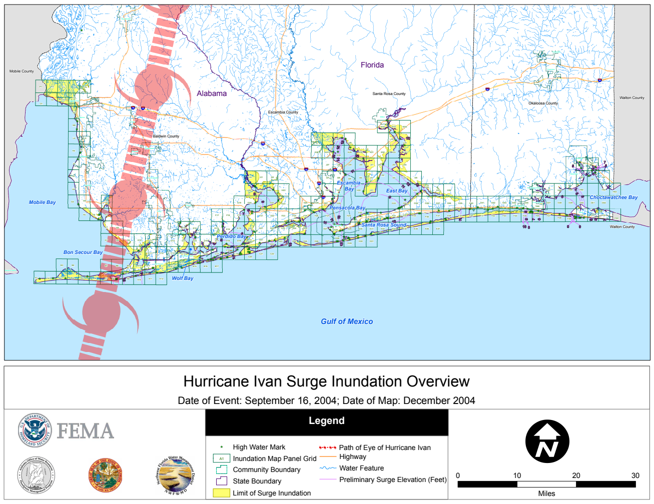

Fig. 2. Hurricane Ivan Surge Inundation Overview Map (data source: FEMA)

TABLE I
EXAMPLES OF STORM SURGE ESTIMATION USING EQ.5. STORM SURGE DATA ARE FROM HTTP://SURGE.SRCC.LSU.EDU/, HURRICANE WIND DATA ARE FROM NATIONAL HURRICANE CENTER (NHC) OF NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA)

TC	year	wind m/s	h (m)	$\Delta\eta$ obs.(m)	$\Delta\eta$ est.(m)	location
Andrew	1992	62	15	4.88	5.12	25.49 -76.63
Floyd	1999	40	15	2.04	2.17	33.91 -78.16
Kyle	2002	15	10	0.6	0.5	32.78 -79.92
Ivan	2004	50	10	4.57	5.00	30.34 -87.31
Irene	2011	33	10	2.16	2.17	40.58 -73.65

where α is the slope $\frac{\Delta y}{\Delta x}$ of the coastal topography. The inundation area, assuming a semi-circle shape, is given by

$$A = I^2 \frac{\pi}{2} \tag{7}$$

For example, when a total storm surge is estimated to be 5m for a coastal region with topographic slopes of 0.0001,0.0005 and 0.001 (respectively 1m,5m and 10m above sea level at 10km inland), the inundation distance will be 50km,10km and 5km, and the flooded area can reach 3925km^2 157km^2 and 40km^2 ,respectively. It is clear that the topography slope of the considered coastal region is a key factor affecting the flooded area caused by storm surge. As a practical example, for hurricane Ivan in 2004, the topography slope near the landfall location is around 0.0013, so the inundated distance would only be around 4km. From the Federal Emergency Management Agency (FEMA)'s hurricane Ivan inundation overview, the flooded area was indeed limited to only a few kilometers from the water bodies of Perdido Bay, Escambia Bay, East Bay and Pensacola Bay, due to the relatively steep topography. In a hypothetical scenario, if the same storm surge had occurred in a coast with a low-lying flat topography, the inundation area would have been larger, as discussed above.

III. DISCUSSION

A. Limitations

The Shallow Water equations, Eqs.3,6 and 7, have been used to estimate the storm surge height, inundation distance and lateral area. Bottom shear stress is not considered. The role of Coriolis force, and thus that of the alongshore wind stress, is also not taken into account. On the other hand, the use of these highly simplified equations is a strategy by design, so that all the calculations are simple and easy that can be carried out quickly by emergency managers using calculators, and as it occurs, the estimation can still be quite accurate, as can be seen from Table I.

It should be noted that our estimation did not consider socio-economic and vulnerability factors such as population, household income, household possessions, young and elderly populations, and so on [9]. For an example, if storm surge and inundation occurred in an uninhabited area, its risk and potential damage to human life and property would be much less than if the same hazard took place in a densely populated area with many young and elderly people (the earthquake in the desert scenario). In the future, those factors could and should be incorporated into this proposed method. Further, when applying this method for flood mitigation practices, emergency managers need to consider them.

B. Assessing the impact of SLR

The Intergovernmental Panel on Climate Change [10], the IPCC, and more recently Pietrafesa et al [11] have shown that SLR is It is a consensus that SLR has been ongoing and will continue so until at least the end of this century [10]. It is important to answer the question concerning what would the hazard caused by storm surge and inundation be different in the future climate change scenario with SLR, assume the storm's wind-field remains same. Jisan et al [12] simulated the impact of SLR (0.26 m for mid-of-century, and 0.54 for end-of-century) on the inundated area (Table 5 in [12]). Assuming a slope of 0.0005 near the flat low-lying coast topography of Bangladesh coast, Eq.3,6 and 7 yields inundated areas of 1445 km^2 and 1724 km^2 for TC ALia under the mid-21st century and end-21st century scenarios, respectively. And for TC Sidr, the estimated inundated area would be 2151 km^2 and 2489 km^2 respectively. Overall, the estimation using the proposed method in this paper is generally quite consistent with the results calculated using the hydrodynamic model DELFT [13] and realistic topography. Thus, the proposed methods can be applied to study the impact of climate change on future storm surge and inundation hazards.

IV. CONCLUSION

We describe the need and rationale for a flood risk index that allows for an easy and quick estimation of the potential storm surge height and inundation area due to incoming landfall hurricanes. Simplified 2-D shallow water equations are used to derive such a method. The effects of the alongshore and cross-shore wind stress on affecting the storm surge height

SLR scenario	TC Sidr		TC Aila	
	Inundated area (km^2)	Increase (%)	Inundated area (km^2)	Increase (%)
Present day	1860	n/a	1208	n/a
Mid-21st century	2437	31 %	1550	28 %
End-21st century	2846	53 %	1770	47 %

Fig. 3. Comparison for the inundated area between present-day and future SLR scenarios and calculated change in percentage with respect to the present-day scenario using the hydrodynamic model Delft-3D. In Mansur et.al. 2018 (cite) with authors' permission.

and their relative roles are discussed. The method was applied to five historical storm surge cases and the results agreed well with observations. Besides the effect of wind stress, the coastal water level change due to other factors, such as tides, atmospheric pressure, SLR and rainfall, can be easily added to get the total surge height. A simple procedure to use the total storm surge height to estimate inundation area is proposed. This method can also be applied to study the impact of future climate change such as SLR on storm surge and inundation hazards. Future work will incorporate socio-economic and population vulnerability factors.

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