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A new approach to using wind speed for prediction of tropical cyclone generated storm surge

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[1] We examine the best track wind speed data for all U.S. landfalling hurricanes between 1986 and 2007 to determine the relationship between wind speed and observed maximum storm surge heights at the coast. We show that pre-landfall intensity correlates significantly better with observed maximum surge heights than landfall intensity does. This outcome is not a result of outliers skewing the data, but is representative of a more definitive trend. We anticipate that our findings will lead to a reconsideration of the way wind is used as a surge predictor, and we believe that our findings provide a possible explanation for why some tropical cyclones' storm surges tend to over/under perform with respect to official storm surge forecasts.
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[2] When a tropical cyclone makes landfall, storm surge is generated primarily due to high winds blowing over the ocean's surface [*Harris*, 1963]. Storm surge indices and models have been created for more accurate prediction of potential storm surge height [*Jarvinen and Neumann*, 1985; *Graber et al.*, 2006; *Kantha*, 2006; *Russo*, 1998]. These indices and models account for different combinations of various factors, including maximum sustained winds at landfall, radius of maximum winds, translation speed, pressure, bathymetry, and coastline shape [*Jarvinen and Neumann*, 1985; *Graber et al.*, 2006; *Kantha*, 2006; *Russo*, 1998]. However, one factor that has not been included in any of these indices or models is the effect of pre-landfall intensity and oceanic response time on realized surge at the coast. An evaluation of available storm surge information along with landfall and pre-landfall intensity for corresponding tropical cyclones indicates that there exists a strong link between a tropical cyclone's intensity prior to landfall and the maximum storm surge that is produced at the coast due to that tropical cyclone.

[3] Before comparisons between wind speeds and observed storm surge heights could be conducted, it was necessary to derive a general relationship between wind speed and storm surge. A version of the Princeton Ocean Model [*Blumberg and Mellor*, 1987; *Clayson and Luneva*, 2006] with adjustable wind speed, radius of maximum winds, translation speed, and bathymetry was used to determine the relationship between wind speed and storm surge under widely varying conditions. Through power law analysis, it was determined that storm surge scaled like $V^{1.63}$, and this scaling factor is used for all subsequent calculations in this letter. It is important to note that some may object to this particular power and would prefer a V^2 relationship since wind stress is directly proportional to the square of the wind speed. All experiments in this paper were concurrently conducted using the V^2 relationship, and while those results are not presented in this letter, using V^2 does not appreciably change the results presented in this letter. However, it is reasonable to expect that the scaling factor in this scenario would not be two because that scaling factor only describes the initial transfer of momentum from the air to the sea. No proof exists that the scaling factor describing how that momentum is used in storm surge production should be two also. For instance, some portion of the momentum flux is used for wave-field maturation [*Moon et al.*, 2004]. Logically, then, the resultant scaling factor describing the relationship between storm surge and wind speed should be less than two. Subsequently, a database of wind speeds and observed storm surge heights for all U.S. landfalling hurricanes between 1986 and 2007 was compiled from information provided by the National Hurricane Center. No reliable storm surge information was available for three landfalling hurricanes, and these storms were excluded from the database. 39 landfall events are employed in all correlation analyses in this study. Table S1[1] provides a complete list of storms, wind speeds, and observed surge heights.

[4] The first correlation analysis performed involved using landfall wind speed for the database storms. A dimensionless quantity was obtained for all storms using the expression $(V_{landfall}/V_o)^{1.63}$, where $V_{landfall}$ is the landfall intensity, and V_o is 33 ms^{-1} [*Kantha*, 2006]. Correlating these dimensionless quantities and their corresponding maximum storm surge heights gives a Pearson correlation [*Johnson*, 2000] of 0.61. Next, for each storm an average wind speed was calculated using the intensity at landfall and at 6, 12, 18, and 24 hours prior to landfall ($V^{1.63}{}_{avg}$). Each component of the average was raised to the 1.63 power, and the average was subsequently non-dimensionalized through division by $V_o^{1.63}$, where V_o is 33 ms^{-1}. Correlating these dimensionless quantities and their corresponding maximum storm surge heights gives a Pearson correlation of 0.80. Therefore, using $V^{1.63}{}_{avg}$ explains approximately 27 percent more of the surge variance in this sample than using solely a landfall wind speed. Calculating a Spearman rank correlation [*Johnson*, 2000]

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for both scenarios gives correlations of 0.70 and 0.79, respectively.

[5] Next, in an attempt to make sure that outliers were not skewing the previous Pearson correlations, the three storms with the highest observed storm surge (Hugo, Andrew, and Katrina) were removed from the database, resulting in 36 samples. The same dimensionless quantities were obtained using $V_{landfall}$ and $V^{1.63}{}_{avg}$, and the resulting Pearson correlations are 0.55 and 0.76, respectively. Therefore, even though both correlations decreased by removing extreme outliers, strong evidence exists that it is $V^{1.63}{}_{avg}$, not $V_{landfall}$, that provides a better estimate of observed maximum storm surge. In fact, as is the case when the outliers are included, 27 percent more of the surge variance is explained using $V^{1.63}{}_{avg}$ as compared to $V_{landfall}$.

[6] Finally, other correlations were performed to determine whether another pre-landfall wind speed average would correlate better than the scaled, 24-hour, pre-landfall wind speed average. Furthermore, instantaneous wind speeds from 6 to 36 hours prior to landfall were also correlated with observed surges to determine whether the averages were masking a higher correlation with one of the instantaneous wind speeds. First, scaled 12-hour and 36-hour pre-landfall wind speed averages were correlated with observed storm surges. Pearson correlations for these scenarios are 0.76 and 0.73, respectively. Therefore, it appears that the scaled, 24-hour, pre-landfall wind speed average best represents the potential maximum storm surge with a landfalling tropical cyclone. Pearson correlations of instantaneous cyclone intensity at 6-hour intervals from 6 to 36 hours prior to landfall and observed storm surges indicate that the 12-hour pre-landfall instantaneous wind speed has the highest correlation at 0.8. Therefore, this sample of landfalling U.S. hurricanes indicates that using cyclone intensity 12 hours before landfall is just as good of an indicator of maximum storm surge as using a scaled, 24-hour, pre-landfall intensity average.

[7] Storm surge forecasts for many previous landfalling tropical cyclones could have been improved through consideration of pre-landfall intensity. For simplicity, we will consider the 12-hour, pre-landfall intensity instead of the 24-hour, pre-landfall average intensity since the usefulness of both methods has already been demonstrated. Hurricane Wilma (2005) rapidly strengthened from a moderate, Category 2 hurricane to a strong, Category 3 hurricane in the 12 hours prior to landfall in Southwest Florida. The actual intensity 12 hours prior to landfall was 47 m/s. The NHC, 12-hour intensity forecast was 49 m/s, and the corresponding storm surge forecast was for 2.8 meters to 5.2 meters of storm surge at landfall. Just before the center of the storm crossed the coast, the NHC forecasted storm surge heights to be between 3.7 meters and 5.5 meters at landfall since Wilma had strengthened to 56 m/s. The actual maximum observed storm surge from Hurricane Wilma was only 2.1 meters, much closer to the 12-hour forecast. Thus, the 12-hour storm surge forecast was more accurate, as it did not include the final, relatively short-lived strengthening. On the other hand, Hurricane Katrina (2005) provides an example of a system that weakened dramatically just prior to landfall. 12 hours prior to landfall on the Mississippi coast, Katrina's maximum sustained winds were 72 m/s. The NHC's 12-hour, forecast intensity for the time Katrina made landfall was 67 m/s, and the corresponding storm surge forecast was for surge heights of 5.5 meters to 6.7 meters, with localized surge heights as high as 8.5 meters. At the time of landfall on the Mississippi coast, Katrina's maximum winds had decreased to 56 m/s, and the NHC had lowered its surge forecast to between 4.6 meters and 6.1 meters. Katrina's actual maximum storm surge was 8.5 meters. Both of these examples show that using a 12-hour, pre-landfall intensity would have resulted in a better storm surge forecast.

[8] These results show that tropical cyclone landfall intensity is ultimately the worst predictor of maximum storm surge heights of the predictors considered here. In fact, even though 12-hour pre-landfall instantaneous wind speed and a scaled, 24-hour, pre-landfall intensity average appear to be the best predictors, the addition of any pre-landfall wind speed information improves correlations with observed surge values. These findings would be most beneficial in two main areas. First, meteorologists and oceanographers could provide overall better surge forecasts since some clarification has been provided as to the approximate time scales on which wind speed affects coastal storm surge. For decades, forecasters have been focused on trying to accurately predict landfall intensity, believing that parameter is most important in storm surge prediction. These results cast significant doubt on that theory. Overall, forecasts should be improved most in cases where tropical cyclones rapidly weaken or strengthen within a few hours of landfall. Second, tropical cyclone prone locations around the world with no access to sophisticated surge models could use observational information to estimate maximum surge heights with impending tropical cyclones. Such information could save lives and property.

[9] Finally, these results also indicate that there is a certain amount time that the ocean takes to respond to increases or decreases in wind stress, similar to the lag in time for the ocean wave field to respond to changes in the winds. In other words, although a tropical cyclone's maximum intensity may increase 20 ms^{-1} over three hours, the associated storm surge does not necessarily respond in tandem with the large change in intensity. More research needs to be conducted to quantify the nature of the lag time between increases/decreases in intensity and observed surge heights. An extension of this idea, particularly for areas away from the point of landfall, would involve examination of changes in radius of maximum winds since this factor would affect the distribution of storm surge observed around the point of landfall.

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References

Blumberg, A. F., and G. L. Mellor (1987), A description of a three-dimensional coastal ocean circulation model, in *Three-Dimensional Coastal Ocean Models*, *Coastal Estuarine Sci.*, vol. 4, pp. 1–16, AGU, Washington, D. C.

Clayson, C. A., and M. Luneva (2006), Preconditioning for deep convection in the Sea of Japan: Results of a numerical model, *J. Phys. Oceanogr.*, in press.

Graber, H. C., V. J. Cardone, R. E. Jensen, D. N. Slinn, S. C. Hagen, A. T. Cox, M. D. Powell, and C. Grassl (2006), Coastal forecasts and storm surge predictions for tropical cyclones: A timely partnership program, *Oceanography*, *19*, 130–141.

Harris, D. L. (1963), Characteristics of the hurricane storm surge, *Tech. Pap. 48*, U. S. Weather Bur., Washington, D. C., 139 pp.
Jarvinen, B. J., and C. J. Neumann (1985), An evaluation of the SLOSH storm surge model, *Bull. Am. Meteorol. Soc.*, *66*, 1408–1411.
Johnson, R. (2000), *Miller and Freund*'s *Probability and Statistics for Engineering*, Prentice Hall, Upper Saddle River, N. J.
Kantha, L. H. (2006), Time to replace the Saffir-Simpson hurricane scale?, *Eos Trans. AGU*, *87*, 3–6.
Moon, I.-J., T. Hara, I. Ginis, S. E. Belcher, and H. Tolman (2004), Effect of surface waves on air-sea momentum exchange: I. Effect of mature and growing seas, *J. Atmos. Sci.*, *61*(19), 2321–2333.
Russo, E. (1998), Estimating hurricane storm surge amplitudes for the Gulf of Mexico and Atlantic coastlines of the United States, paper presented at Oceans '98, Inst. of Electr. and Electron. Eng., Nice, France.

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