Wind Driven Setup in East Central Florida's Indian River Lagoon: Forcings and Pameterizations

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ABSTRACT

High resolution hydrodynamic models are computationally expensive to run – especially if ensemble forecasts are desired. This can be problematic within coastal estuaries which are not well resolved by today's operational meteorological forecast models. As an alternative, this paper evaluates the wind forcing for three setup parameterizations (based on the Zuiderzee, modified Zuiderzee, and long wave equations) using a combination of observed setup from in-situ water level gauges and local wind observations. In addition, three methods are explored for developing hourly time series of wind forcing from 5-minute observations: top of the hour, hourly mean, and wind run approach. The wind forcings, which are weighted by the length of two lagoon-oriented axes, are used to drive the setup parameterizations. The observed setup is used to tune each of the parameterizations via a least squares approach. The observation spread, linear model residuals, coefficient of determination (R^2), and root mean squared error (RMSE) indicate that the wind run out performs the other two methods. In terms of the three parameterizations, the modified Zuiderzee had consistently higher R^2 values, lower RMSE, and narrower 95% confidence intervals than the two other methods. This optimized parameterization is currently being used operationally to generate ensemble setup forecasts for the Indian River Lagoon, a restricted estuary on Florida's east-central coast. These simple ensemble forecasts are designed to guide the National Weather Service (NWS) in identifying potentially significant setup events that warrant high resolution hydrodynamic simulations.

1. Introduction

The National Weather Service (NWS) Nearshore Wave Prediction System (NWPS, van der Westhuysen et al. 2013), is designed to provide high resolution nearshore model guidance to coastal weather forecast offices. As a result, the NWPS does not include a hydrodynamic component and does not extend beyond the shoreline into coastal estuaries. Given the complex land-water mask and coastal geometry, hydrodynamic models require high spatial resolution (Weaver et al., 2016b), making them computationally expensive to run, particularly for ensemble forecasting. For example, the National Centers for Environmental Prediction (NCEP) has two operational atmospheric ensemble forecast systems including the Short Range Ensemble Forecast (SREF, Du and Tracton 2001) and the Global Ensemble Forecast System (GEFS, Toth and Kalnay 1993), both of which have more than 20 members. While it is not practical to run the full suite of hydrodynamic simulations on a high-resolution grid using wind forcing from each of the atmospheric ensemble members, a probabilistic approach that captures the magnitude and uncertainty associated with high impact wind events, remains attractive. An inexpensive setup parameterization can serve as a proxy to generate probabilities for setup and wave height inside the coastal zone. Use of parameterizations because of their computational efficiency is not uncommon (e.g., Apotsos et al. (2008) tested and calibrated several widely used wave parameterizations for coastal management). The objective here is to develop and tune a system that can be forced by ensemble wind forecasts. In addition, the probabilistic product can be used to determine whether resources for a high resolution hydrodynamic model run are warranted and in the subsequent selection of the relevant wind forcing (i.e., a particular ensemble member) for a deterministic water level forecast. The goal is not to replace hydrodynamic models but rather to facilitate their use.

For the most part, setup parameterizations are used for engineering design (structural) purposes with a focus on threshold exceedance, i.e., what magnitude of wind speed, fetch and depth produce critical setup (Mostertman, 1963). The approach here is somewhat different since the focus is geared towards ensemble forecasting and model guidance. As a result, effort is spent in the development and evaluation of representative wind forcing that accounts for the local geometry, i.e., the lagoon orientation. Three different averaging methods are applied to surface wind observations and then used to force three setup parameterizations.

The Indian River Lagoon (IRL), located in east-central Florida (Fig. 1), is long (195 km), shallow (1-3 m), narrow (2-4 km), and has five inlets that connect it with the ocean, making it a restricted lagoon system (Kjerfve, 1986). In general, water movement in estuaries is influenced by atmospheric forcing, tidal action, and freshwater runoff (Reynolds-Fleming and Luettich, 2004). However, because of the restricted nature and orientation of the lagoon, the effects of tidal forcing are reduced and thus the IRL is primarily wind driven (Smith, 1990). Given its narrow geometry, the IRL is extremely fetch limited with its orientation providing setup favorable conditions only in the presence of persistent southeast (or northwest) winds. These events can cause local flooding along the IRL, property damage, erosion, and impact water quality as a result of enhanced nutrient loading, resuspension, and sediment transport. In terms of the latter, Csanaday (1973) examined water motion forced by wind stress on long lakes (where the depth contours run parallel to the shores, similar to the IRL) and concluded that, in nearshore areas, the wind-forced component of the flow dominates. In fact, the wind-forced component was more important in transport than either seiching or oscillating movements, both of which are present in the IRL (Weaver et al., 2016a). Additionally, downwind-driven water level increases are able to support substantially higher wave heights given the depth-limited nature of the IRL. Our data show it is not uncommon to see water level increases on the order of 40-50 cm during frontal passages or approaching cyclones, yielding a near 50% increase in water levels in some locations along the IRL.

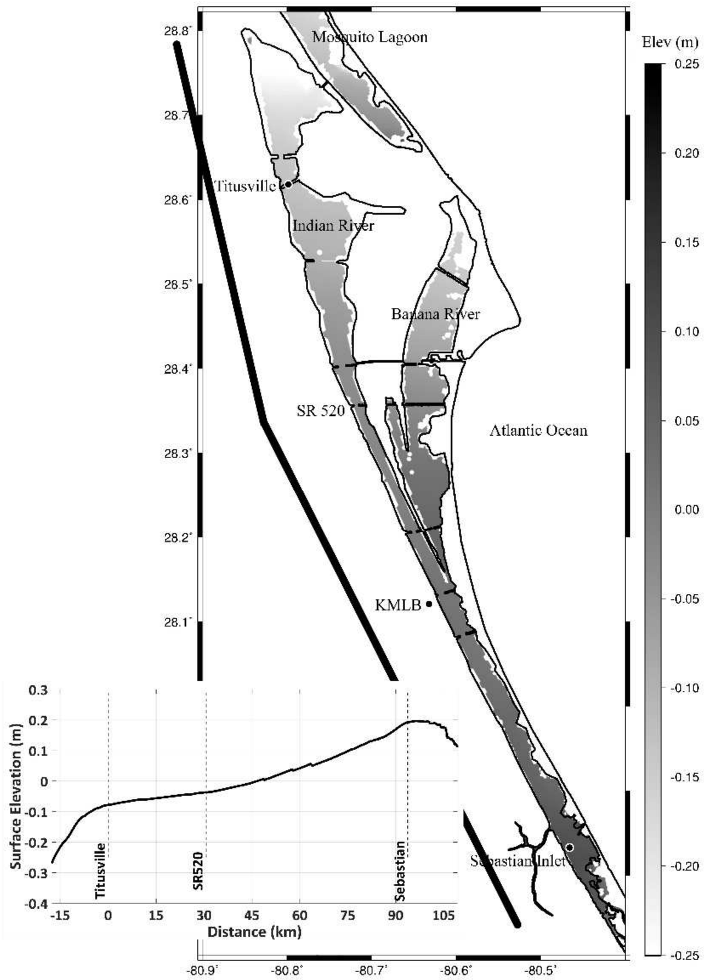

Fig. 1. The northern Indian River Lagoon (IRL) basin of study including: the sensor locations, (Titusville and Sebastian Inlet), and the Melbourne National Weather Service Automated Surface Observing Station, KMLB. The bold black line approximates the orientation of the two lagoon

axes (see text for details). Also shown are the water elevation anomalies (m, shaded) and a surface elevation transect (m, inset) from ADCIRC+SWAN during the peak setup on 7 March 2015.

A brief overview of the setup parameterizations is presented, followed by a description of the observational datasets (water level and winds). The wind averaging methodology, the identification of setup events, and a least squares approach that regresses the observed setup against the parameterized estimates for the different wind methods are then discussed. Finally, the wind forcing is evaluated using the best performing parameterization along with a brief summary and short discussion regarding potential forecast applications.

2. Methodology

2.1 Setup Parameterizations

2.1.1 The Zuiderzee Equation

The equilibrium condition between the wind stress on the water surface and the pressure gradient generated by the slope of the free surface is expressed as the ratio of the kinetic energy of the wind stress, $k\rho_a U^2$ (where k is the friction coefficient, ρ_a is the density of air, and U is the wind speed), and the potential energy of the water level increase, $\rho g d$ (where ρ is the density of water, g is the acceleration of gravity, and d is the water depth). This ratio, which represents the setup *S* over the fetch *F*, is defined as

$$\frac{S}{F} = 0.4\ x\ 10^{-6}\,\frac{U^2}{d}\,, \qquad (1)$$

where $k\rho_a/(\rho g) = 0.4\ x\ 10^{-6}$ (Mostertman, 1963). The friction coefficient *k (= 0.003)* was obtained from measurements on the Zuiderzee as well as other lakes in Holland. Eq. (1) can be transformed into the well-known Zuiderzee relationship by letting $a = k\rho_a/(\rho g)$ and expressing the setup as a function of wind speed, fetch, and water depth, i.e.,

$$S = a\frac{U^2 F}{d}\,. \qquad (2)$$

2.1.2 The Modified Zuiderzee

While many studies relate the setup to the square of the wind speed, Harris (1963) suggested that strong correlations can also be found using powers of the wind ranging from one to two. To examine this here, the Zuiderzee is modified by setting U^2 equal to U^N in Eq. (2). In order to determine the optimal power *N* in the modified Zuiderzee equation, wind forcing is inserted while systematically varying *N* from 0.5 to 2.5 in increments of 0.1. For each value of *N*, the predicted setup was regressed against the observed and the corresponding R^2 values were then used to identify the optimum power (=1.5, Fig. 2).

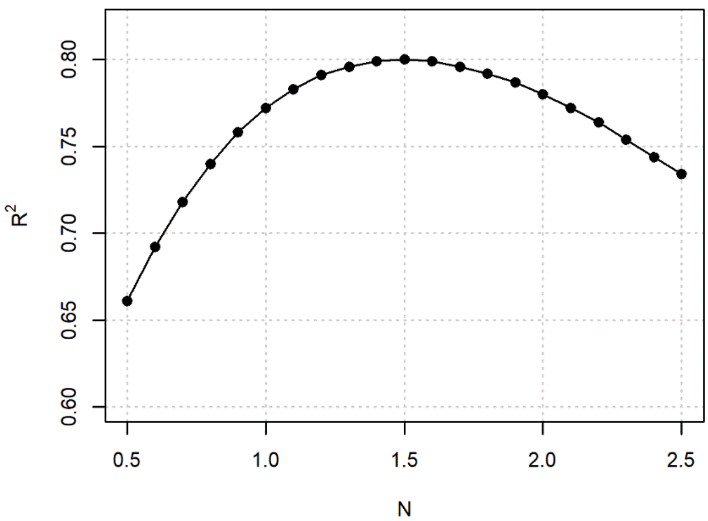

Fig. 2. R^2 values obtained from regressions of the observed versus parameterized setup for differing values of the wind speed exponent in the modified Zuiderzee parameterization (Eq. 2, with U^2 equal to U^N).

2.1.3 The Long Wave Equations

Water level changes induced by wind blowing over a water surface can also be described by the long wave equations (LWE) (Freeman et al., 1957). In this simple model, surface wind stress generates a current in the direction of the wind that, in turn, produces return flow in the opposite direction at the bottom of the water column. This counter current has a bottom stress associated with it that is usually unknown and not easily calculated (Sorensen, 2006). Both Saville (1952) and van Dorn (1953) found that the bottom stress was about 10% of the surface stress. Assuming steady state flow, the long wave equations simplify into a balance between the surface stress, bottom stress, and the pressure gradient of the sloping water surface (the addition of bottom stress distinguishes this approach from the Zuiderzee). The surface wind stress, τ_s, is given by

$$\tau_s = k_s \rho U^2, \tag{3}$$

where k_s is the friction coefficient and ρ the water density. While Eq. (3) can also been written in terms of air density (Wu, 1969), this study uses Van Dorn's (1953) approach because it is more useful for looking at wind setup. For wind speeds greater than or equal to 5.6 $m\ s^{-1}$, Van Dorn's (1953) expression for the friction coefficient is given by

$$k_s = 1.21\ x\ 10^{-6} + 2.25\ x\ 10^{-6}\left(1 - \frac{5.6}{U}\right)^2. \tag{4}$$

At wind speeds below 5.6 $m\ s^{-1}$, k_s is assumed to be constant ($= 1.21\ x\ 10^{-6}$), while for wind speeds greater than or equal to 5.6 $m\ s^{-1}$, k_s asymptotically increases (to $3.46\ x\ 10^{-6}$) to account for increased roughness as waves form on the surface.

The LWE setup as developed in Dean and Dalrymple (1990) and Sorensen (2006) is given by

$$S = d\left(\sqrt{\frac{2k_{sb}U^2F}{gd^2} + 1} - 1\right), \quad (5)$$

where k_{sb} is a combined surface/bottom stress coefficient. This study uses Eq. (4) to calculate the surface stress from the wind speed. This value is then multiplied by 1.1 to obtain an estimate of k_{sb} (Sorensen, 2006). The setup prediction from Eq. (5) is hereinafter referred to as the *long wave* method.

2.2 Water level

Two water level gauges, located near Sebastian Inlet to the south and Titusville to the north (about 100 km apart), were used to calculate water level differences and thus estimate the observed wind setup between the two locations (Fig. 1). A HOBO U20 titanium water level pressure sensor was deployed in a PVC tube stilling well near the Sebastian Inlet, while the northern sensor near Titusville is maintained by the St. Johns River Water Management District. Sensors at both locations provide hourly water level data. To correct for atmospheric effects on the water level, the hourly barometric pressure observations from the Melbourne (KMLB) National Weather Service Automated Surface Observing Station (ASOS, Fig. 1) were subtracted from the sensor pressure measurements. This approach is generally robust along the IRL as pressure variations are on the order of 1 mb or less between KMLB and the Titusville ASOS (KTIX, not shown). Assuming a hydrostatic pressure response, the adjusted pressure is converted to a relative water level (i.e., height above instrument). The data used for this investigation were collected from November 2014 to March 2015 and from November 2015 to March 2016. Frontal passages leading to significant setup events are common during these months. Additionally, the time period selected spans Florida's dry season, and thus, should lessen the impact of storm water runoff on water levels.

The relative water level is expressed in terms of anomalies, which are calculated by subtracting the hourly measurements from the seasonal (November to March) mean. Although some formulations reference setup from still water level, here it is defined to be consistent with its original interpretation (Mostertman, 1963) i.e., as the difference between the relative water levels on the downwind and upwind portions of the basin. A simple twelve-hour running mean was applied to filter the tidal signal at the sensor near Sebastian Inlet. This method produced results comparable to that of harmonic analysis software -- removing high frequency wind waves, boat wakes, etc. Because the water level at Titusville is subtracted from that of Sebastian, the observed setup is defined as positive for northerly flow (set down in Titusville, setup in Sebastian) and negative for southerly flow (set down in Sebastian, setup in Titusville) as shown in Figure 3.

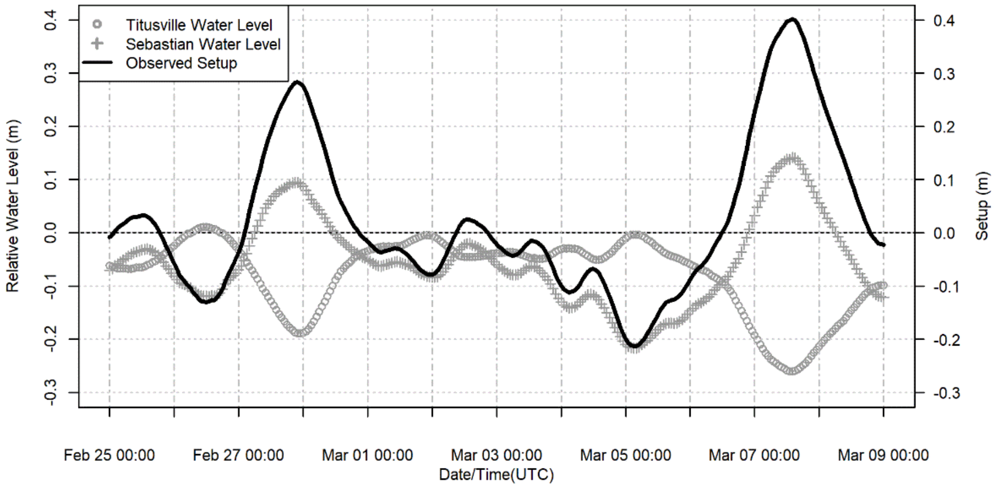

Fig. 3. Water level data for the Titusville station (open circles) and the Sebastian Inlet station (crosses) for 25 February - 9 March 2015. The observed setup is calculated by subtracting Titusville from Sebastian, yielding positive/negative setup for a northerly/southerly wind event (black line).

2.3 Wind

The wind from the KMLB ASOS is used to force the three setup parameterizations examined herein. Although the station is centrally located, it is inland, and thus may not be representative of the over water winds that drive setup in the IRL. This issue is addressed in more detail in the context of tuning the parameterizations presented in Section 2.4. Comparisons using in-situ open fetch winds from WeatherFlow station data within the IRL produced similar results (not shown), hence only KMLB winds are presented here.

The IRL is long and narrow and thus extremely fetch limited in most locations with fetch lengths, even for the most favorable flow directions, generally less than 10 km (Holman et al., 2017). While each of the setup parameterizations depend on the wind speed, it is the along-lagoon component of the wind that is ultimately responsible for setup. Furthermore, the constant direction assumption regarding fetch is complicated somewhat by the geometry of the portion of the IRL under consideration here. To account for a change in the orientation of the major axis of the lagoon, an along-estuary wind component is calculated by projecting the observed wind onto two distinct fetch-weighted segments (Fig. 1). The respective wind components for each section are then calculated separately by multiplying the KMLB wind speed by the cosine of the angle between the wind direction and the relevant lagoon axis. A single lagoon representative wind U_R is constructed by weighting each of the components (U_1 and U_2) by their respective fetch lengths (F_1 and F_2), i.e.,

$$U_R = \left(\frac{U_1F_1+U_2F_2}{F_1+F_2}\right). \tag{6}$$

The approach of breaking the estuary into two segments yielded slightly higher correlation values (between observed and predicted setup) than using just a single average angle and fetch length (not shown).

In order to match the temporal scale of the water level observations, three different averaging methods were used to generate hourly time series from the five-minute KMLB wind data. In addition, the hourly wind forcing is more consistent with respect to ensemble wind forecasts, which generally have a three or six-hour temporal resolution. The three wind averaging methods include: top of the hour, hourly mean, and wind run. The top of the hour method uses the wind speed and direction nearest to the beginning of the hour. The hourly mean method calculates a vector mean speed and direction for the prior hour. The wind run is comprised of a running average over a specified time period. In this study, an antecedent twelve-hour window is used (other intervals were explored but the 12 h performed best). The u and v components are averaged separately and then recombined to produce the wind run forcing. The wind run is the only method of the three explored that considers a wind duration longer than an hour.

2.4 Tuning the Setup Parameterizations

In order to identify setup events, a centered rolling extrema function with a temporal width of 9 h was applied to determine if the observed setup was a local maximum or minimum within the prescribed time window (i.e., +/– 4 h of the current observation time). The resulting extrema were initially selected using a subjective setup threshold of +/– 10 cm. However, this leaves a data gap with respect to low amplitude events (i.e., less than 10 cm) and inflates the R^2 values. As a result, a threshold of 1 cm is used instead. The addition of the low-end events produces robust regression statistics, with only slight changes the values of the slopes or intercepts. Overall, 350 events were identified, but eight were removed because either some or all of the wind speed data were missing prior to the setup time. Three distinct wind forcing time series, associated with the 342 events, were calculated by inserting the wind speeds from the – top of the hour, hourly mean, and wind run – into Eq. (6). Since setup response to the wind forcing is not instantaneous (see lag discussion in Section 4), the maximum wind speed is selected from a period prior to the observed peak setup for both the top of the hour and hourly mean methods. Time intervals ranging from 6 to 18 hours were evaluated, with a 12-hour period producing the best results (i.e., lowest RMSE between the predicted and observed setup). A similar approach is applied to obtain the optimal averaging time period for the wind run method -- also 12-hours.

Each of the setup parameterizations depends on the water depth, which is typically taken to be the average depth along the fetch. However, because this can be problematic for irregularly-shaped basins, Sorensen (2006) suggests using the average depth of the basin. This study uses the average depth ($d = 1.2\ m$) for the northern section of the IRL (Titusville to Sebastian). If depth and fetch (both constants) are incorporated into α, the setup parameterizations can be expressed as

Zuiderzee: $$S = \alpha U_R^2 + \beta, \tag{7}$$

Modified Zuiderzee: $$S = \alpha U_R^{1.5} + \beta, \text{ and} \tag{8}$$

Long Wave: $$S = \alpha\left(\sqrt{\frac{2k_{sb}U_R^2F}{gd^2} + 1} - 1\right) + \beta. \tag{9}$$

where α is the slope and β the intercept. The three wind forcings are then inserted into each of the setup parameterizations with the output regressed against the corresponding observed setup. The regression is straightforward and is accomplished by plotting the observed setup versus the forcing in equations (7-9). This results in 9 distinct regression equations - one for each combination of the individual wind forcings and parameterizations. The regression essentially tunes the setup parameterizations to the IRL with the values of α and β varying for each of the parameterization and wind forcing pairings.

Because the heights of the water level gauges are not referenced to a vertical datum, the setup is estimated using a local water level anomaly based on the seasonal mean at each gauge location.

Ideally, for each regression, the intercept, β, should be close to zero, i.e., no wind/no setup. However, the seasonal prevailing winds will likely contribute to some nominal wind setup between the two locations. A non-zero (positive) setup in the absence of wind forcing indicates that the seasonal mean water level at the Sebastian Inlet sensor is higher than that at Titusville. This systematic bias is evident, as a nonzero intercept (on the order of -3 cm), in the various regressions (Table 1). An unbiased estimate of the regression setup coefficients requires that the average difference between the observed and predicted setup over some time interval be close to zero. Therefore, a 3 cm bias correction, which is within one standard deviation of the mean observed setup with no wind forcing, is applied here. The bias corrected scatterplot and least-squares fit for the wind run forced modified Zuiderzee parameterization is shown in Figure 4. The regression parameters for each of the possible wind forcing/parameterization combinations are presented in Table 1.

Table 1

Summary of regressions (no bias correction) and RMSE for each wind forcing/parameterization pair. Highest R^2 and lowest RMSE are in bold.

Forcing	Parameterization	α (slope)	β (intercept)	R^2	RMSE (cm)
Top of Hour	Zuiderzee	0.0048	-0.0277	0.5256	4.94
	Mod. Zuiderzee	0.0122	-0.0286	**0.5790**	**4.46**
	Long Wave	0.2943	-0.0300	0.5415	6.39
Hourly Mean	Zuiderzee	0.0054	-0.0281	0.5762	4.74

	Mod. Zuiderzee	0.0130	-0.0287	**0.6170**	**4.34**
	Long Wave	0.3187	-0.0296	0.5810	6.27
Wind Run	Zuiderzee	0.0073	-0.0304	0.7800	3.85
	Mod. Zuiderzee	0.0164	-0.0311	**0.8001**	**3.59**
	Long Wave	0.7461	-0.0321	0.7582	5.98

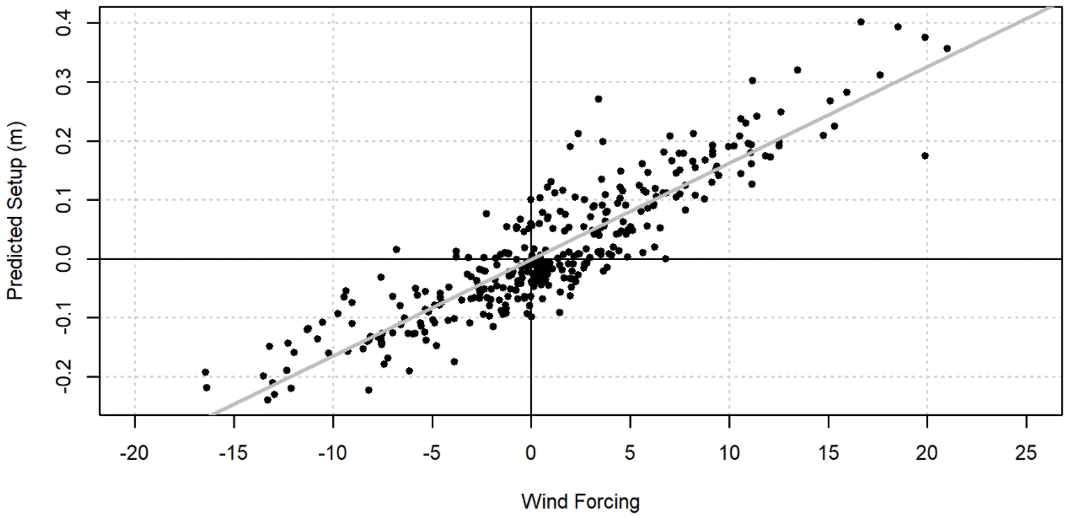

Fig. 4. Predicted set up (bias corrected) for the modified Zuiderzee with wind run forcing. The black dots represent the 342 events in the training dataset, and the gray line is the least squares fit.

3. Results

The tuning dataset is used to optimize the setup parameterizations using the different wind forcing methods. Performance is evaluated using the R^2 and RMSE statistical parameters.

3.1 Parameterization Performance

To evaluate the robustness of each regression, 5000 R^2 values were generated by bootstrapping the tuning data (i.e., the 342 events). The density histograms from the bootstrapping are shown in Figure 5. The 95% confidence interval (vertical lines) is tighter and the R^2 larger for the three wind run forced parameterizations. In addition to the significant increase in R^2 for all three parameterizations when forced with the wind run, a tighter confidence interval is also evident. The modified Zuiderzee performs slightly better than the Zuiderzee and the long wave methods. A bootstrapping approach was also applied by randomly subsampling our dataset to successively reduce the number of events and examining the change in the width of the 95% confidence intervals for the regression coefficients (i.e., slope and y-intercept) and R^2 for 5000 samples. The results (not shown) indicate that the widths of the confidence intervals decrease rapidly and then flatten out at around 250 events, suggesting that our dataset (342 events) is robust in defining the regression coefficients of our parameterizations.

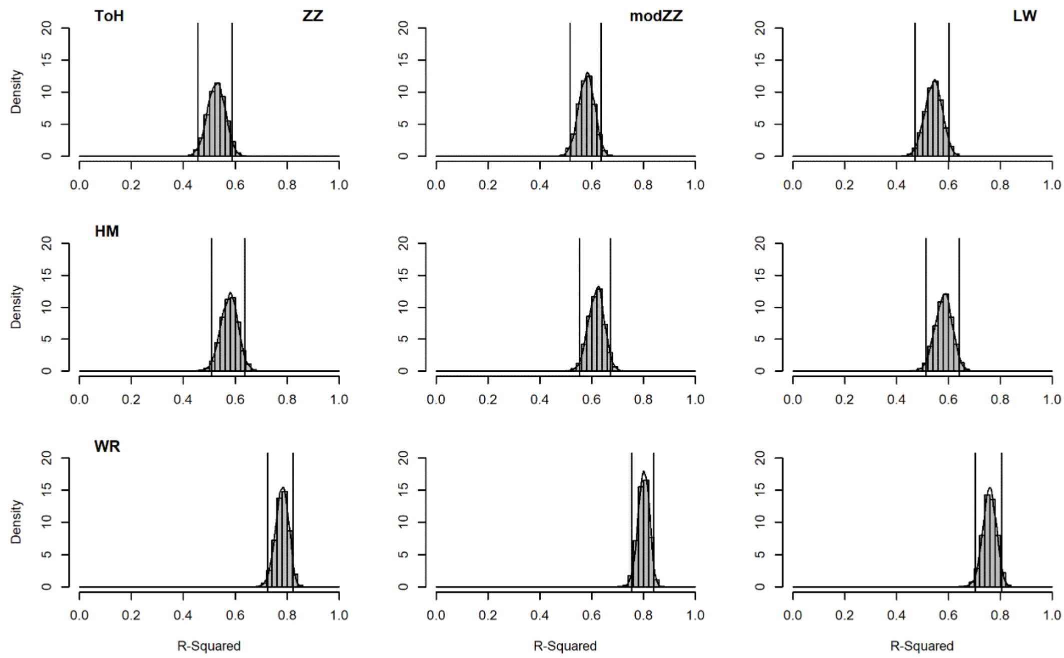

Fig. 5. Bootstrapped density histograms for the nine wind forcing/parameterization

combinations. Rows (from top-to-bottom) are the different wind forcing methods: top of the hour (ToH), hourly mean (HM), and wind run (WR). The columns (left-to-right) are the three setup parameterizations: Zuiderzee (ZZ), modified Zuiderzee (modZZ), and the long wave (LW). The vertical lines in each panel represent the 95% confidence intervals.

In addition to the regression statistics, a standard box plot of the predicted setup versus each of the wind run forced parameterizations is presented (Fig. 6). Here, each of the boxes has the same width and are populated with their respective predictions (open circles). The x-axes represent the independent variables for each parameterization (Eqs. 7-9). The outliers are depicted by the filled circles. The box plots indicate a degree of heteroscedasticity (e.g., a maximum variation in setup for low wind forcing in the Zuiderzee). The standard deviations of the box heights for each of the parameterizations, which represent the spread of the middle 50% of the forecast setup, vary from 1-to-5 cm, with the modified Zuiderzee exhibiting the lowest variability. In addition, of the three parameterizations, the modified Zuiderzee exhibits greater consistency along the x-axis (i.e., a more even distribution).

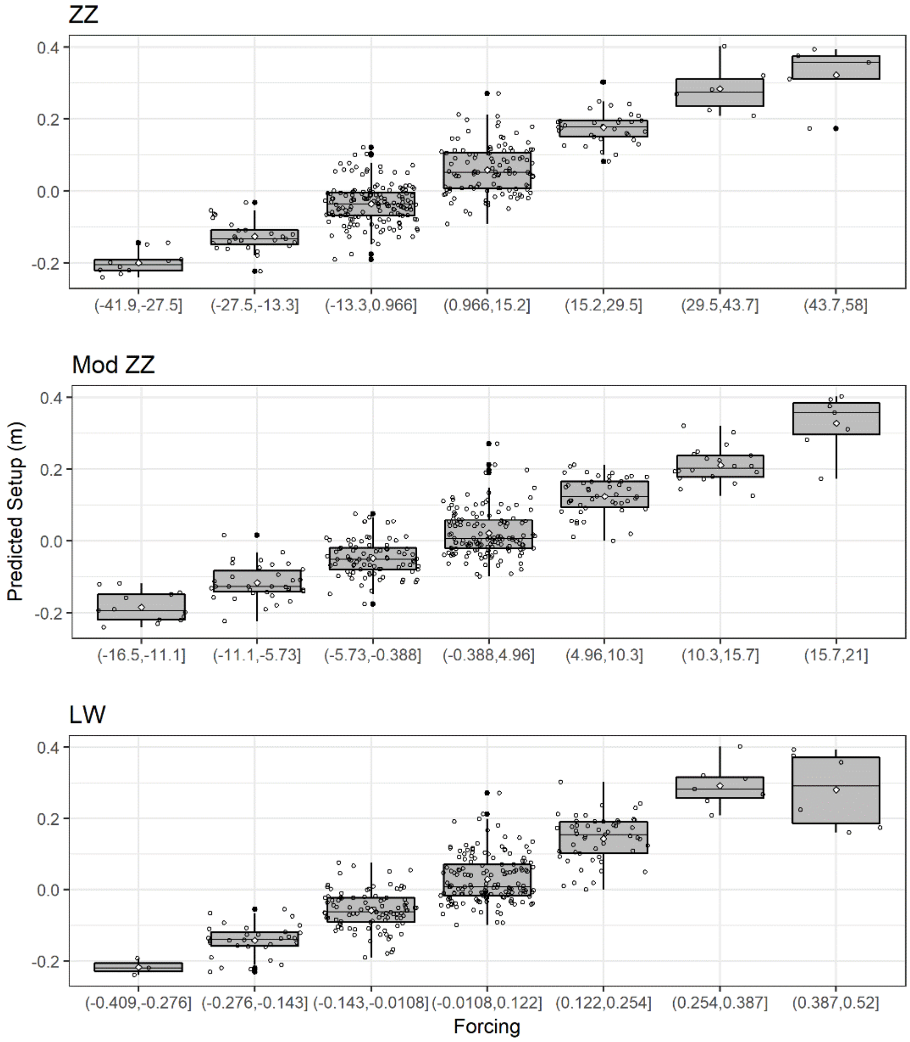

Fig. 6. Boxplots for the three wind run forced setup parametrizations (top-to-bottom): Zuiderzee (ZZ), modified Zuiderzee (modZZ), and long wave (LW). The shading represents the middle 50% of the data distribution (within equally-spaced intervals, x axis) and the whiskers depict the upper and lower quartiles. The intervals (x-axis) represent the independent variables in equations (7- 9). The median (mean) is given by the thin horizontal line (white diamond) within each box. Open circles depict the spread of the data within the given intervals and outliers are indicated by the solid black dots.

3.2 Evaluation

While for the tuning, the lag was accounted for by pairing the peak wind forcing with maximum setup for each of the events (see section 2.4), this will not be the case for the predicted setup. In terms of the latter, it would be advantageous to determine the wind forcing/water level response time scale for the IRL study region. Here, a standard cross-correlation technique is applied to estimate the lag. Our results indicate a peak correlation (on the order of 0.95) for a lag of 6 hours. This result is consistent for all three parameterizations and wind forcings – except for the wind run which does not require a lag adjustment (see Section 4). Ultimately, any inherent lag would need to be taken into account within a forecast environment.

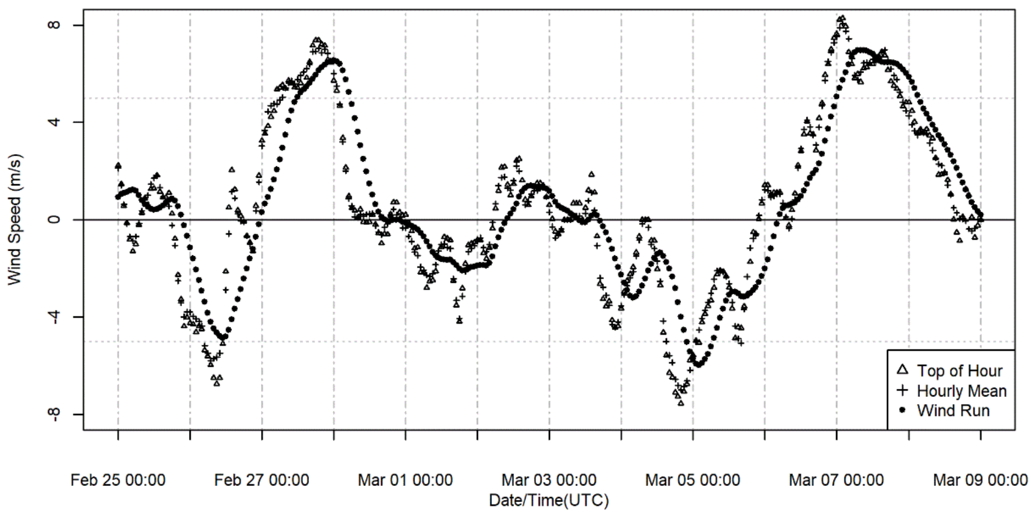

Fig. 7. Wind speeds (m/s) on 25 February - 9 March 2015 for the top of the hour (open triangles), the hourly mean (crosses) and the wind run (filled circles).

In order to gauge the impact of the wind forcing on the predicted setup, the best performing parameterization, the modified Zuiderzee, is applied to a time period from 25 February – 10 March 2015. This period is relatively active as it has four somewhat distinct setup events (i.e., setup > 10 cm). The wind speed time series computed using the three wind forcing methods is shown in Figure 7. The top of the hour and hourly mean winds behave similarly, with the latter showing a small reduction in the predicted peak wind speed. As expected the wind run method acts as a temporal filter on the wind speed, but it also takes the wind duration into account. In tandem, these two characteristics act to reduce the RMSE which is the lowest of the three forcings (Table 1). The observed and predicted setup for each of the wind run forced parameterizations is shown in Figure 8.

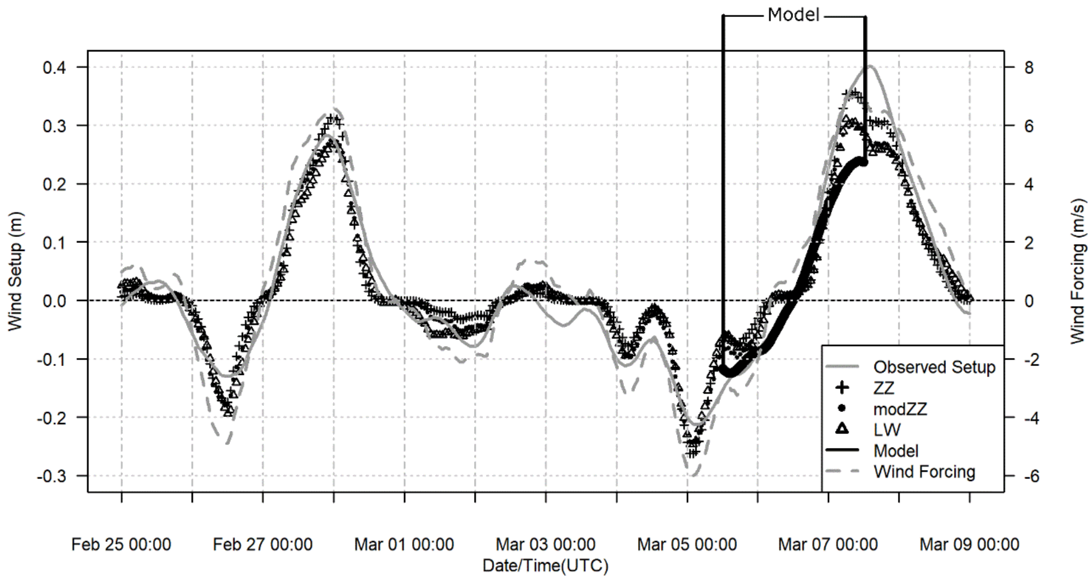

Fig. 8. Setup from the three wind run forced parameterizations including the Zuiderzee (crosses), modified Zuiderzee (filled circles), and the long wave (open triangles). Also shown are the observed setup (solid gray line) the wind run forcing (dashed gray line, right axis) for 25 February - 9 March 2015, and the predicted setup from the ADCIRC + SWAN for 12 UTC 5 March - 12 UTC 7 March (thick black line).

In order to relate the predicted setup to water levels throughout the lagoon, results from a coupled ADCIRC + SWAN (Booij et al., 1999; Luettich, R.A., Jr., J.J. Westerink, 1992) hydrodynamic/wave model simulation are briefly presented here. The event period 5-7 March 2015, captures a strong frontal passage. ADCIRC + SWAN was forced using a four member ensemble of winds with various spatial and temporal resolutions, generated from the Weather Research and Forecasting (WRF) model (see Weaver et al. 2016b for more details). As a direct comparison with the three parameterizations, ADCIRC water levels are mined at the Titusville and Sebastian gauge locations and their difference (setup) is shown in Figure 8, (bold black line labeled model). The phase (timing) of the model predicted setup is coeval with that of the parameterizations. The amplitudes of the modeled and the parameterized setup vary between 25 and 35 cm, all of which under forecast the observed peak near 40 cm.

IRL water level anomalies during the peak setup (12 UTC 7 March) associated with post-frontal northerly flow is shown in Figure 1 (shaded). Water levels change somewhat gradually with maximum set down north of Titusville and peak setup in the flow constricted area southeast of Sebastian. In particular, the fetch favorable (northeast to southwest) orientation of the Banana River exhibits water level variations between 10-15 cm, while in northwest-to-southeast oriented Mosquito Lagoon the differences are on the order of 5 cm or less. Maximum setup in these portions of the estuary likely occurs at different times during the course of the wind event. The response in other regions of the IRL during the peak setup (as defined by our two locations) is somewhat less and depends on the respective fetch.

An ADCIRC+SWAN transect of water levels on the Indian River is shown in Figure 1 (inset). This transect extends beyond the boundaries of the Titusville and Sebastian Inlet gauges used to calculate the observed setup for the parameterizations. The two fetch segments (Section 2.3) are divided by route 520 which crosses the Indian River about 30 km south of the Titusville gauge location. As evident by the slope, the change in water levels from Titusville to SR520, a somewhat wider section of the Indian River, occurs more slowly than the change between SR520 and Sebastian Inlet. A relatively large decrease in the water level occurs north of Titusville. This shallow portion of the lagoon is often blown down during periods of extended northerly flow.

4. Discussion and Conclusion

The performance of the modified Zuiderzee parameterization was somewhat unexpected given that it does not directly account for bottom stress. However the LWE, which takes into account the effects of friction at the lower boundary (it is approximated assuming that it is 10% of the surface stress, i.e. $k_{sb} = 1.1k_s$, Eq. (4)), has slightly degraded results. A stress approximation similar to that of the LWE can be applied to the Zuiderzee methods. This would result in a trivial modification of the coefficient *a* in Eq. (2) by a constant multiplicative factor. While this would have an impact on the regression parameters, it would not affect the statistics (i.e., R^2). In this sense, the bottom stress is implicit in the Zuiderzee formulations.

The Zuiderzee was originally formulated to assess the impact of wind driven setup on structures using an exceedance value or some maximum expected wind speed (Ahrens, 1976; Mostertman, 1963). In contrast, the approach here is predictive rather than diagnostic, i.e., input a forecast wind speed time series and output setup. As previously discussed, the relationship between the wind and setup may not be quadratic (Section 2.1.2). Here, this was examined using variable forcing in the form of setting U^2 to U^N in Eq. (2). The best results (i.e., the highest R^2) were achieved for N=1.5. This non-standard formulation relating wind setup to $U^{1.5}$ was referred to as the modified Zuiderzee herein. Why the modified Zuiderzee performs slightly better is not clear. As previously mentioned, the Zuiderzee has been used only as an exceedance tool (i.e., as a maximum setup threshold for coastal construction), while here it is applied in a predictive capacity and thus is not a traditional application of the parameterization.

The hysteresis associated with maximum wind speed and peak setup was investigated for all three wind forcing methods (Section 2.4). Cross correlation revealed that the peak setup lagged the maximum wind speed by 6 hours for both the top of the hour and the hourly mean methods while indicating little or no lag for the wind run method. This latter result is consistent with the averaging methodology of this approach which is based on a non-centered running mean that shifts the wind forcing forward in time and thus has an intrinsic lag.

While all of the parameterizations generally perform quite well in predicting the setup between the two locations, a hydrodynamic model simulation is necessary in order to provide context with respect to the lagoon-wide impact. The coupled ADCIRC + SWAN simulation indicates that the water level response is relatively uniform between Titusville and Sebastian Inlet (Fig. 1), and produced comparable results, in terms of timing, to those of the parameterizations. However, the model also underpredicted the peak setup for the event, which was attributed to the WRF generated wind forcing (Weaver et al., 2016b).

An examination of some of the poorly predicted setup events indicates that these cases may, in part, be related to relatively large air-water temperature differences. While the near surface atmospheric stability will impact the surface stress, it has not been considered here. A follow-up study regarding the role of stability in the generation of estuary setup would likely improve the forecasts.

The goal of this study was the development of a setup parameterization, along with an appropriate wind forcing, in support of real time water level forecasting on a coastal estuary. This work is part of a larger effort to integrate NCEP ensemble model output (winds) within the NWPS. After accounting for bias correction, downscaled wind forecasts from the SREF or GEFS can be used to force a setup parameterization. In addition to providing an inexpensive water level ensemble, the results would serve as a guide for the NWS in terms of allocating resources for a high resolution (deterministic) hydrodynamic model simulation for high impact events.

Acknowledgements

Funding: The work in this paper was supported with funds from NOAA and the National Weather Service Program Office (NWSPO), Collaborative Science, Technology, and Applied Research (CSTAR) Award: NA14NWS4680014, *"An Ensemble-based Approach to Forecasting Surf, Set-Up and Surge in the Coastal Zone"*.

Water level data from pressure gauges installed in the IRL by the Florida Institute of Technology were supplemented with data from gauges managed by the Saint John's River Water Management District (SJRWMD).

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