

Operational forecasts of wave-driven water levels and coastal hazards for US Gulf and Atlantic coasts

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Predictions of total water levels, the elevation of combined tides, surge, and wave runup at the shoreline, are necessary to provide guidance on potential coastal erosion and flooding. Despite the importance of early warning systems for these hazards, existing real-time meteorological and oceanographic forecast systems at regional and national scales, until now, have lacked estimates of runup necessary to predict wave-driven overwash and erosion. To address this need, we present an approach that includes wave runup in an operational, national-scale modeling system. Using this system, we quantify the contribution of waves to potential dune erosion events along 4,700 km of U.S. Atlantic and Gulf of Mexico sandy coastlines for a one-year period. Dune erosion events were predicted to occur at over 80% of coastal locations, where waves dominated shoreline total water levels, representing 73% of the signal. This shows that models that neglect the wave component underestimate the hazard. This new, national-scale operational modeling system provides communities with timely, local-scale (0.5 km resolution) coastal hazard warnings for all wave conditions, allowing for rapid decision-making related to safety and emergency management. The modeling system also enables continued research into wave-driven processes at a broad range of coastal areas.

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The impacts of climate change are already being experienced worldwide¹. On our coastlines, changes are manifest through increased flooding and coastal erosion brought on by extreme sea levels and more intense storms^{2–6}. The frequency of wave overwash and inundation of coastal environments is increasing as storm waves, combined with rising sea levels, push water levels higher on beaches, threatening infrastructure, businesses, transportation, and, in the most extreme events, public safety^{7–11}. While preparing for and adapting to future climates and building long-term coastal resilience, local officials are also responding to shorter term – weather- or storm-scale – coastal hazards and the implications for local communities and ecosystems^{12,13}. Public and private sectors have an increasing need for timely, decisional, and scientifically valid data to address erosion and flooding challenges faced when living and working along the coast^{14–17}.

Assessments of above-ground flooding, infrastructure impacts, and coastal geomorphic change can be made by comparing high-water levels to land elevations. Most large-scale, near-term advisories and vulnerability assessments rely on forecasts of high-water levels that only include modeled tide and wind- and pressure-driven surge, despite total water level at the shoreline being a combination of tides, surge, and a wave-driven component, termed wave runup (Fig. 1). Including wave runup is particularly important during storm events when waves significantly increase total water levels¹⁸. Without inclusion of wave runup, models of total water levels used to produce large scale guidance on coastal flooding and erosion are underestimating the occurrence and severity of the hazard¹⁹.

Process-based, numerical models have been used to hindcast time-varying wave runup and the associated flooding and erosion impacts, but they are typically focused on specific storm events and limited to local scales^{20–24}. These approaches have demonstrated skill for specific locations and times; however, attaining this level of accuracy requires frequent measurements of water depth, beach topography, and spectral wave characteristics for model inputs and detailed site-specific calibration of the models. Additionally, they are not computationally viable for application at alongshore scales spanning thousands of kilometers, which is required by national forecasting agencies^{21,25}. Worldwide, there is a need to develop continuously operating models that describe wave-driven, storm-induced water levels, the potential for flooding and erosion impacts, and associated coastal hazards^{20–22,26–33}.

Empirical parameterizations offer an alternative way of estimating wave runup and can support operational approaches to providing rapidly available total water level elevation and coastal change information at high spatial resolution ($O(100\text{ m})$) over very large scales ($O(1000\text{ km})$). These parameterizations have been extensively tested and are broadly applicable (see comprehensive reference list provided in ref. ²⁵), thus making them ideal to implement over a large scale to provide reliable information about weather-scale coastal erosion and flooding hazards. This approach is analogous to the use of parameterized sub-grid scale processes in operational weather prediction systems and climate modeling³⁴ and can be used to provide consistent guidance, highlight uncertainties, inform decisions, and prioritize research efforts³⁵. Runup parameterizations can also be used in

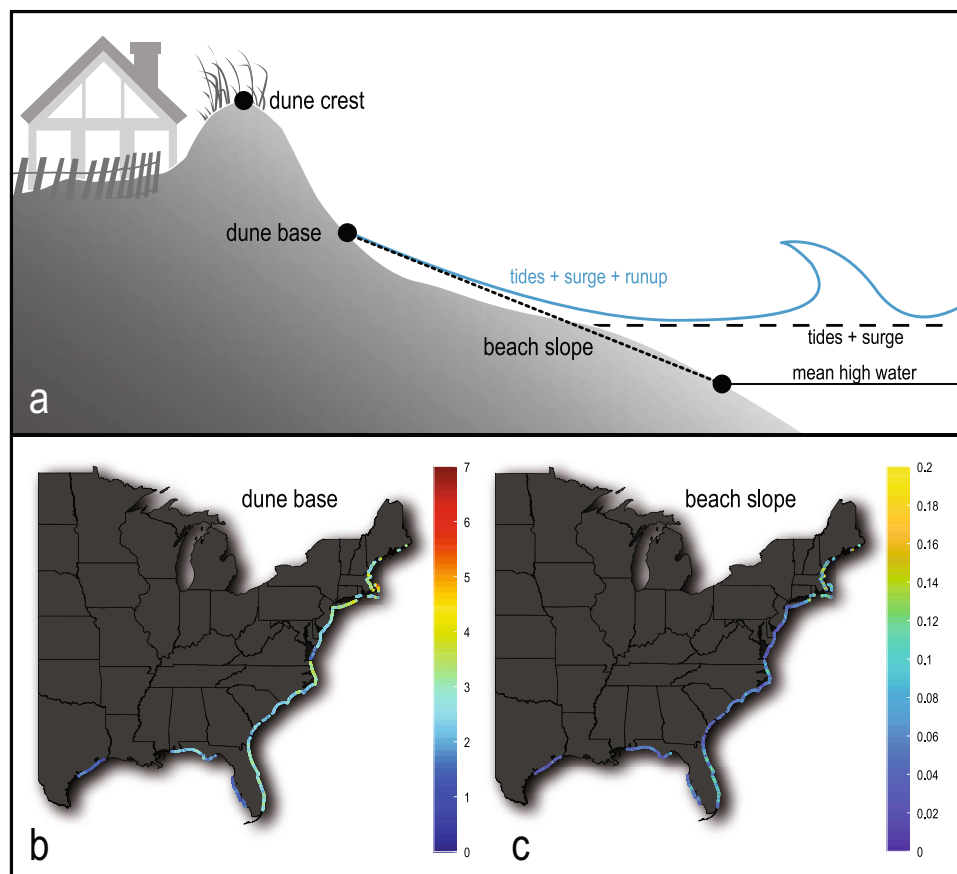


Fig. 1 Total water level components and geomorphic features used in predicting dune erosion events. Total water level (a) is modeled as the sum of tide, storm surge, and wave runup. Local morphology is represented by dune base elevations in meters (b) and beach slope (c), both derived from airborne lidar measurements.

combination with site-specific early warning systems in areas where data are available to use high fidelity process-based models and highlight areas where site-specific model development is needed.

By leveraging federal investments in research, observations, and modeling of coastal processes and landscapes, we have developed a real-time, operational model for total water levels, including wave runup, and coastal change that extends over 1000s of kilometers. Here, we quantify the contribution and importance of waves to shoreline total water levels and to potential impacts to coastal dunes, which often serve as protection between the ocean and coastal communities. Spatial variability over regional scales demonstrates the need for these high-resolution results to address user requirements. The use of a simple parameterization for wave runup³⁶, in combination with high-resolution predictions of offshore wave conditions and observations of beach morphology, allows for nationally consistent, local-scale, continuously operating forecasts of near-term threats of dune erosion, overwash, and flooding that can be used to assess vulnerability and inform actions to ensure safety.

Results

A newly developed operational model for wave runup (combination of wave setup and an extreme-value statistic for time-varying swash) and potential coastal change (see Methods), enabled a large-scale assessment of the temporal and spatial variability in total water level and quantification of the relative importance of wave runup to shoreline water levels for a one-year period. The model provides hourly predictions for a 6-day forecast window and is updated with meteorological forecasts produced and used by local National Weather Service (NWS) forecast offices every 6–12 h. Nowcasts of total water level from January 1 to December 31, 2020 were compared to the elevation of the base of the primary sand dune for sandy beaches along the U.S. Atlantic and northern Gulf of Mexico coastlines. Dune erosion events were defined as times when nowcast total water level was predicted to reach or exceed the base elevation of the primary sand dune (Fig. 1). Nowcast dune erosion events provide a proxy for potential geomorphic change associated with processes like dune narrowing and elevation loss and indicate increased risk of damage to infrastructure or transportation corridors behind the dunes. A total of 3157 coastal locations covering 4700 km were included in the analysis. Over the twelve-month period, dune erosion was predicted to occur for at least one hour at 81.0% of the locations. The average total number of hours of dune erosion predicted at each location during the year was 99.3 h with a maximum of 3655 h at a location in coastal Massachusetts (Fig. 2, right).

Over the study period, dune erosion events exhibit distinctive regional spatial patterns associated with coastal geomorphology and temporal patterns associated with weather systems (Fig. 2). Spatial variability along the vertical axis can be also attributed, in part, to alongshore variations in sand dunes as the models are dependent on local beach slope and the elevations of the dune base and crest (see Methods). Variability in the timing and duration of dune erosion events along the horizontal axis is related to changing oceanographic conditions, including both near- and far-field tropical and extratropical storms. Across all locations a total of 150,563 dune erosion hours were predicted from June 1 – November 30 (United States hurricane season) compared to 103,313 dune erosion hours from December 1 – May 31 when winter storms are more prominent in many locations.

The relative contribution of runup to total water level indicates the role that waves play in erosion hazards compared to storm

surge and tides alone. During times when dune erosion was predicted, wave runup accounts for an average of 72.9% of the total water level elevation (Fig. 3). For 98.2% of locations where dune erosion was predicted, wave runup, on average, contributed more than half of the total water level elevation during all dune erosion events at that location. This indicates that existing models of total water level using only combined tides and surge will underestimate possible coastal change hazards.

Discussion

The development and application of an operational model for total water levels that includes the wave component of shoreline water levels enables estimates of both the spatial and temporal variability in wave runup and resulting dune erosion events during a one-year period along the entire U.S. Atlantic and Gulf of Mexico sandy coastlines. This assessment of wave-driven coastal change variability, a first of its kind, indicates that the contribution of wave runup to total water levels during dune erosion events is as important (magnitude greater than 50%) as the combination of tides and surge at over 98% of nowcast locations. While previous literature has evaluated the contribution of wave runup during tropical storms in storm-impact areas¹⁸, this analysis illustrates the importance at the national level, especially as dunes along sandy beaches act as protection for coastal communities and infrastructure.

This study showed that not only are local coastal change and flooding hazards expected throughout the year, they are also ubiquitous along the U.S. Atlantic and Gulf of Mexico sandy coastlines. In 2020, dune erosion was predicted to occur at most of the sandy beach locations studied. Areas expected to experience more dune erosion (Fig. 2) identify places along the coast that are more vulnerable to coastal change. Variability in beach and dune morphology occurs over smaller spatial scales than variations in wave climate. Locations with low dunes or steep beach slopes are more likely to experience dune erosion events that will put critical infrastructure on or near the dunes at risk during high wave events. For example, the frequent wave interactions with dunes predicted in New Hampshire (Fig. 2) are related to the steeper beach (Fig. 1) that results in higher wave runup. Similarly, regions along undeveloped coastline with extremely low dune base elevations in Maine and Virginia experience frequent interaction with waves. In some locations forecast to have many hours of dune erosion, shoreline protection measures have already been taken to mitigate against constant wave attack, such as St. Simons Island, Georgia, where riprap was placed on the beach near the dune base location to maintain low-lying dunes and protect inland structures.

Dune erosion and coastal change are likely under a broad range of weather conditions. Times when there were a larger number of erosion event locations (Fig. 2) indicate when coastal erosion and increased risk of damage to infrastructure were expected over large areas of the coastline. These include extratropical storms that can generate large waves persisting for many tidal cycles and tropical storms. The potential for coastal change and flooding is not limited to landfalling hurricanes. For example, the dune erosion events predicted in mid-September 2020 (Fig. 2) are associated with the offshore passage of Hurricane Teddy, a strong, far-field storm that reached peak winds of 120 knots but maintained a northward track and did not approach the U.S. Atlantic coastline. Large waves from Hurricane Teddy arrived at the coast coincident with spring tides, resulting in elevated total water levels and widespread predictions of dune erosion along much of the coastline for multiple days. In some areas in North Carolina, high water levels and extensive dune erosion allowed waves to wash over roads, creating hazardous conditions for communities

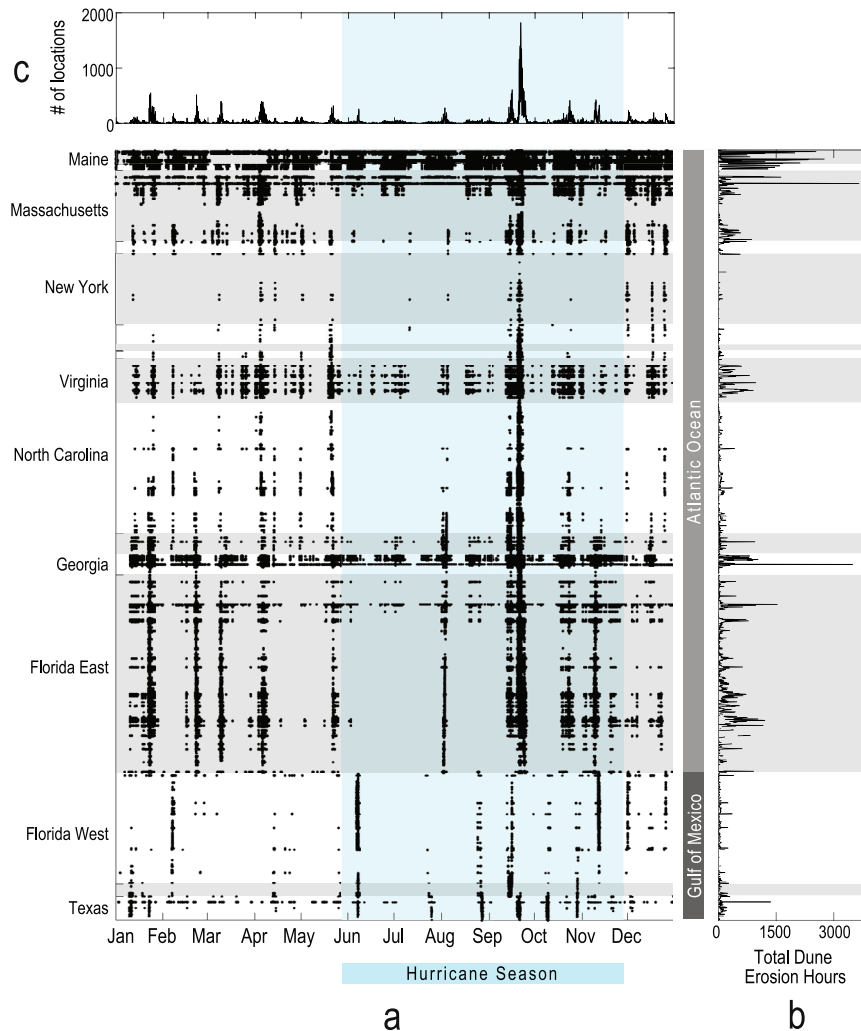


Fig. 2 Temporal and spatial patterns of potential dune erosion events in 2020 at 3157 nowcast locations spanning 4700 km of sandy coastline. Dots (a) indicate times when the predicted elevation of total water level (tide + surge + wave runup) is above the dune base. Tick marks on the y-axis represent state boundaries; only some state labels have been included for reference. Total hours of predicted dune erosion for each location (b) and number of locations with potential dune erosion throughout the year (c) are also shown. 253,876 h of dune erosion were nowcast across all locations.

(Fig. 4c). A coastal water level model that includes wave runup and operates continuously for all weather conditions provides information needed to anticipate when coincident high waves, tides, and surge increase local hazards - information that is not available when waves are neglected, or forecasts are only triggered for the potential landfall of major storms.

Here, we have shown that wave-driven water levels and associated dune erosion are not limited to a few locations along the U.S. coast or to the largest, landfalling storm events. They are triggered by a variety of weather conditions in all U.S. Atlantic and Gulf of Mexico states. This can lead to localized coastal hazards, such as erosion and flooding, disrupting how people work and live. The operational prediction and dissemination of wave-driven coastal total water levels, developed by the U.S. Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA), provide the public with nationally consistent and reliable guidance on coastal total water levels and advance notice of potential near-term impacts. The modeling system seamlessly connects national, operational hydrodynamic models³⁷ and decades of observed coastal morphology³⁸ with a widely applied empirical model for wave runup³⁶ to provide previously unavailable guidance on coastal hazards that informs official NOAA National Weather Service

(NWS) forecasts³⁷ (see Methods). Hourly, six-day estimates of total water level information and potential for coastal erosion (Fig. 4, right panel) are centrally computed and disseminated through different pathways to a variety of users. Model forecasts are directly integrated in internal NWS Weather Forecast Office display and analysis software package (Advanced Weather Interactive Processing System; AWIPS). NWS forecasters, building on existing relationships and lines of communication with emergency managers, issue water level and coastal change guidance in forecasts of coastal conditions for the nation and, using their local expertise, determine where and when to issue related watches and warnings. The model forecast is also provided through a public-facing visualization, and an application programming interface (API) allows the forecast to be downloaded by researchers or other stakeholders. Output is currently available for the U.S. Atlantic and Gulf of Mexico coasts and under development for sandy coastlines for U.S. locations on the Pacific coast. The modeling framework is designed to be flexible and promote on-going research that will incorporate improved modeling components (e.g., runup parameterizations on non-sandy beaches) and new observations (e.g., updated dune elevations). With the development of this model and continued refinements, sandy beach communities will have access to a

consistent level of guidance to prepare for and anticipate weather-scale, wave-driven coastal hazards that will continue to increase due to climate change and rising sea levels. This framework can be applied to other sandy coastlines around the world, helping to predict wave-driven coastal impacts, guide emergency management decisions, and reduce hazards.

Methods

The Total Water Level and Coastal Change Forecast (Fig. 5), a collaborative operational modeling effort between the USGS and NOAA/NWS/National Centers for Environmental Prediction (NCEP), is a post-processing component of the Nearshore Wave Prediction System (NWPS). NWPS, implemented by NCEP, is a centralized approach to forecast coastal waves on unstructured grids, resolving spatial scales down to 100 m in the inner coastal zone. The effects of tide and surge are incorporated via one-way coupling to surge models. This system (<https://coastal.er.usgs.gov/hurricanes/research/twlvviewer/>) produces hourly, six-day

forecasts of total water level on open-coast, sandy beaches, which, when compared with the elevation of beach morphologic features, are used to determine the potential for coastal change, defined as dune erosion, overwash, or inundation of the beach system. Forecasts are updated two to three times per day by local weather forecasters; more often when storms are approaching.

The total water level, η_{98} , is defined as the 98th probability of occurrence of the combined elevation of tide (η_{tide}), surge (η_{surge}), and an extreme-value statistic for wave runup (R_2). The choice of surge model implemented by the NWPS is dependent on weather conditions and is determined by the expertise of local NWS forecasters. During non-tropical systems, η_{tide} and η_{surge} are forecast with the NOAA Extratropical Surge and Tide Operational Forecast System (ESTOFS), a deterministic, ADCIRC-based model^{39–41}. For tropical events, the National Hurricane Center’s Probabilistic Surge (P-Surge), a probabilistic model that uses the Sea, Lake, and Overland Surges and Hurricanes (SLOSH) model to build composite surge level fields, provides η_{tide} and η_{surge} ^{42,43}. Because P-Surge is a probabilistic model, an exceedance level is chosen to provide a single surge elevation for the NWPS. The exceedance level is set in real-time by local weather forecasters, with more extreme exceedance levels far ahead of landfall (e.g., 10% exceedance), and less extreme exceedance as the storm approaches landfall (e.g., 50% exceedance³⁷). Regardless of model choice, η_{tide} and η_{surge} are extracted at the 20-m isobath for each coastal location. This reduces complications related to the shoreline boundary in operational surge predictions.

Wave runup, which includes time-averaged wave setup (η_{setup}) and time varying wave swash (S) is calculated using an empirical parameterization of the 2% exceedance level: $R_2 = 1.1[\eta_{setup} + S/2]$ ³⁶. In the parameterization, $\eta_{setup} = 0.35\beta_m(H_0L_0)^{1/2}$, where H_0 is the deep-water wave significant wave height, $L_0 = gT_p^2/2\pi$ is the deep-water wavelength, and T_p is the peak wave period. Wave swash, the time varying component of water level at the shoreline, is defined as $S = [H_0L_0(0.563\beta_m^2 + 0.004)]^{1/2}$. β_m is the foreshore beach slope between the dune base, z_b , and the Mean High Water contour⁴⁴ (Fig. 1). The parameterization, a representation of runup based on observations from a wide range of beach types, profile shapes, and wave conditions, does not require specific knowledge of the bathymetry, thus allowing for broad use and national application where detailed and current observations of nearshore water depths are not available.

The wave runup parameterization requires local wave and beach slope information. Wave information comes from the NWPS, an operational implementation of the Simulating Waves Nearshore Model (SWAN⁴⁵; by NCEP³⁷). The NWPS coastal grids receive offshore boundary forcing from NCEP’s global wave model, WAVEWATCH III⁴⁶. Effects of wind generation are included using wind forcing developed by NWS forecasters at local Weather Forecasting Offices (WFOs). The effects of time-varying water level due to tides and storm surge (described above) on wave transformation are incorporated. Bathymetry for wave simulations comes from the National Geophysical Data Center Digital Elevation Models. Wave information is extracted from the NWPS at ~500 m resolution along the 20-m isobath to provide estimates of H_0 and L_0 . β_m is estimated from all available airborne lidar surveys by averaging beach slope estimates obtained every 10 m alongshore within a 400 m wide Hanning window. A 95% uncertainty estimate representing spatial and temporal variability in β_m is defined as two standard deviations about the mean β_m ⁴⁷ and propagated through the calculations of runup.



Fig. 3 Average contribution of wave runup to the predicted total water level for all dune erosion events in 2020. Note the lower limit of the color scale represents wave runup contributing one-half of the total water level elevation.

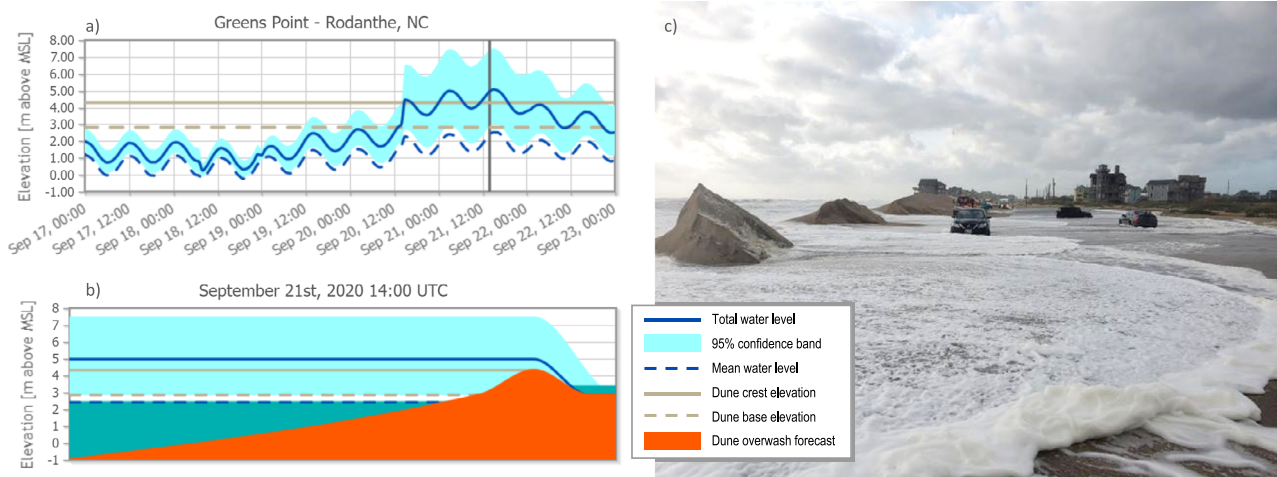


Fig. 4 Example total water level and coastal change guidance from USGS and NOAA NWS. **a** Time series of total water level and coastal change model guidance in Rodanthe, North Carolina, USA in September 2020 (thick vertical gray line indicates time of the forecast and photo in panels **b** and **c**). **b** Water levels forecasted on September 21, 2020, at 14:00 UTC indicated that dune erosion and overwash were likely due to far field waves from Hurricane Teddy. **c** Photo from Rodanthe, North Carolina, USA, taken on September 21, 2020, at 13:00 UTC, shows waves overwashing the only transportation corridor along the island, stranding vehicles and blocking traffic. Road elevation is 1.5 m above local mean sea level (Photo courtesy of Donnie Bowers and used with permission).

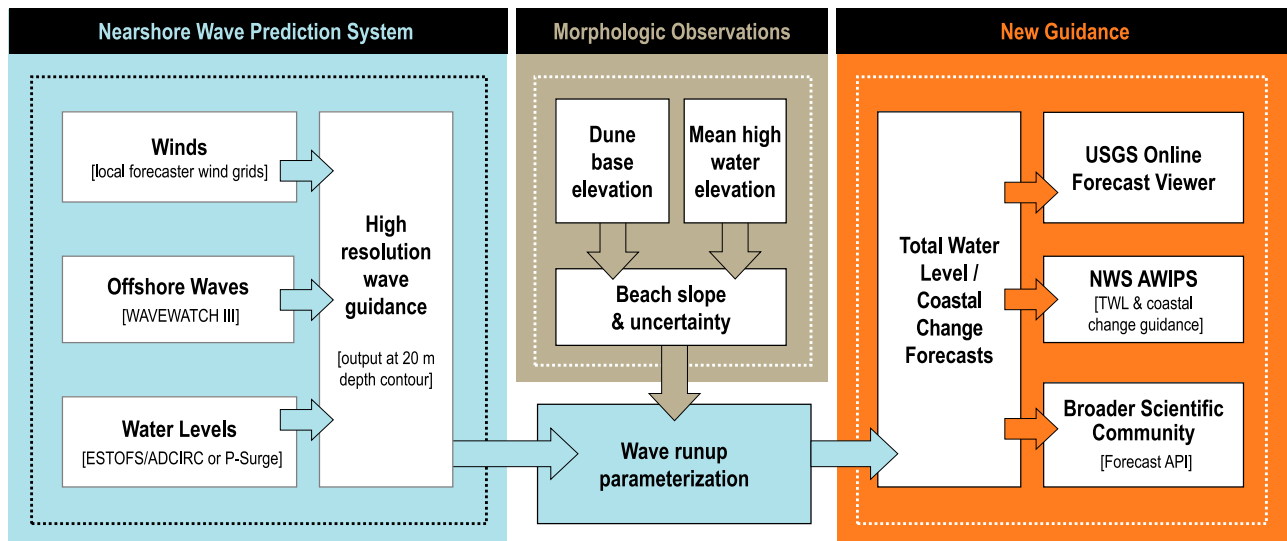


Fig. 5 Components of the total water level and coastal change modeling framework. Orange boxes indicate model output and guidance available to forecasters; brown boxes show morphology inputs derived from measurements of beach topography; blue boxes show modeled hydrodynamic modeling elements. National Weather Service (NWS) forecasters initiate model updates that are run on a central computing system. The Nearshore Wave Prediction System (NWPS) is based on the Simulating Waves Nearshore (SWAN) model and obtains boundary conditions from global WaveWatch III (WW3) model simulations. Water levels are derived from large-scale simulations using either the Extratropical Surge and Tide Operational Forecast System (ESTOFS) or National Hurricane Center’s Probabilistic Surge (P-Surge) model. Forecasters have discretion over the water level model depending on weather conditions.

The coastal change component of the forecast is based on the conceptual storm scaling model⁴⁸, which has been demonstrated to reproduce observed coastal changes¹⁸. In this work, we focus on the potential for dune erosion, defined in the storm scaling model as times when η_{98} exceeds the elevation of z_b . Stockdon et al. (2007) found that the storm scaling model accurately estimated 50–60% of dune erosion events as opposed to 33% accuracy by random chance. Observations of dune elevations are derived from lidar data⁴⁹, every 10 m along the coast. Dune crest, z_c is the maximum elevation of the seaward most dune. z_b is defined as the location of maximum slope change between the shoreline and the dune crest. An automated algorithm identifies these features in the lidar data, and the results are manually quality controlled⁴⁹. While the coastline will evolve at temporal scales shorter than data availability at national scales, regular updates to the morphology occur when new data are available and help prioritize data collection at local, regional, and national scales based on the time since last update or predictions of where the most frequent dune impacts occur.

Each of the total water level model components (wave height, wave period, tides, surge, beach slope, dune feature elevation, and shoreline position) contains uncertainty. Uncertainty of wave and water level components are well-known through ongoing near-real-time validation efforts. Estimates of NWPS model performance compared to NOAA National Data Buoy Center observations for July 2019 through June 2020 indicate the relative bias and scatter index of H_0 within the ranges of 0.03 m to -0.06 m and 0.27 to 0.30, respectively, at a 24 h lead time. Those errors increase to -0.08 m to -1.4 m and 0.45 to 0.48, respectively at 144 h lead time. This analysis is based on nowcasts, which will have the lowest level of uncertainty in wave parameters. Estimates of water levels from tides and surge from ESTOFS are routinely compared to NOAA National Ocean Service observations and updated in real time (e.g., <https://polar.ncep.noaa.gov/estofs/autoval/estofs.glo/index.htm>). At the time of writing, ESTOFS bias was 0.04 m and root mean square difference was 0.18 m.

A recent assessment of the Stockdon et al. (2006) runup parameterization found a root mean square error of 0.49 m and that the parameterization explained 60% of observed variance in wave runup for the cases tested²⁵. The largest source of uncertainty in the model framework is likely the static representation of coastal morphology (beach slope) in the empirical runup parameterization, a necessary operational limitation as daily measuring or modeling coastal morphology at the national scale is unrealistic. This is similar to the use of static bathymetry in most operational wave and circulation models. Spatial and temporal variability in observed local beach slope is used to define a 95% confidence interval on the runup contribution to total water level, providing an uncertainty estimate that enables decision making (Fig. 4, cyan band).

A national-scale, operational forecast for coastal hazards requires understanding model skill and decreasing uncertainty. Given the scale of the total water level and coastal change model, these efforts rely on partnerships, similar to those necessary for model development. USGS and NOAA, working with academic groups, are developing a complimentary set of coastal video imaging stations to observe total water level at the shoreline at different locations over long periods (hours to decades)⁵⁰. Images obtained through community science efforts are another

potential source of total water level and coastal change observations⁵¹. These networks, combined with the deployment of water level sensors in advance of extreme storms and pre-post imagery from aircraft or satellites, are components of an ongoing validation approach. Model results are accessible not only to weather forecasters but also to the broader scientific community for independent skill assessment at individual beaches. This promotes additional research that will lead to model improvements or the potential for assimilation of water level data in real-time.

Data availability

Beach slopes and dune elevations for all regions are available at: <https://coastal.er.usgs.gov/data-release/doi-F7GF0S0Z/>. Total Water Level and Coastal Change Forecasts are viewable at <https://coastal.er.usgs.gov/hurricanes/research/twviewer/>. Data are accessible via a user interface (UI) to allow users to download archived forecasts and nowcasts for their area of interest directly from the website. An accompanying application programming interface (API) allows users to programmatically download large quantities of data across multiple sites and times (<https://coastal.er.usgs.gov/hurricanes/research/twviewer/apidocumentation.html>).

Code availability

All methods and procedures are fully described in the “Methods” section. The Nearshore Wave Prediction System (NWPS) is run on a centralized high-performance computer and fully described at <https://polar.ncep.noaa.gov/nwps/>. Links to the source code for the model components that comprise NWPS are available at the same link.

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Author contributions

H.F.S. developed the methodology associated with the USGS portion of the model and established the interagency partnership with NOAA. J.W.L. and A.V.D.W. were responsible for the first operational implementation, and expansion across Atlantic coastline. A.V.D.W. was responsible for the NOAA-led model and development (NWPS). K.S.D. developed inputs needed to link agency models and maintains the USGS elements of the operational model. M.L.P. is responsible for ongoing model skill assessment strategy and continued model development. R.J.S. developed the online tool for displaying results and Application Programming Interface (API). H.F.S., J.W.L. and M.L.P. equally contributed to writing the manuscript. A.V.D.W., K.S.D. and R.J.S. provided editorial revisions.

Competing interests

The authors declare no competing interests.

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