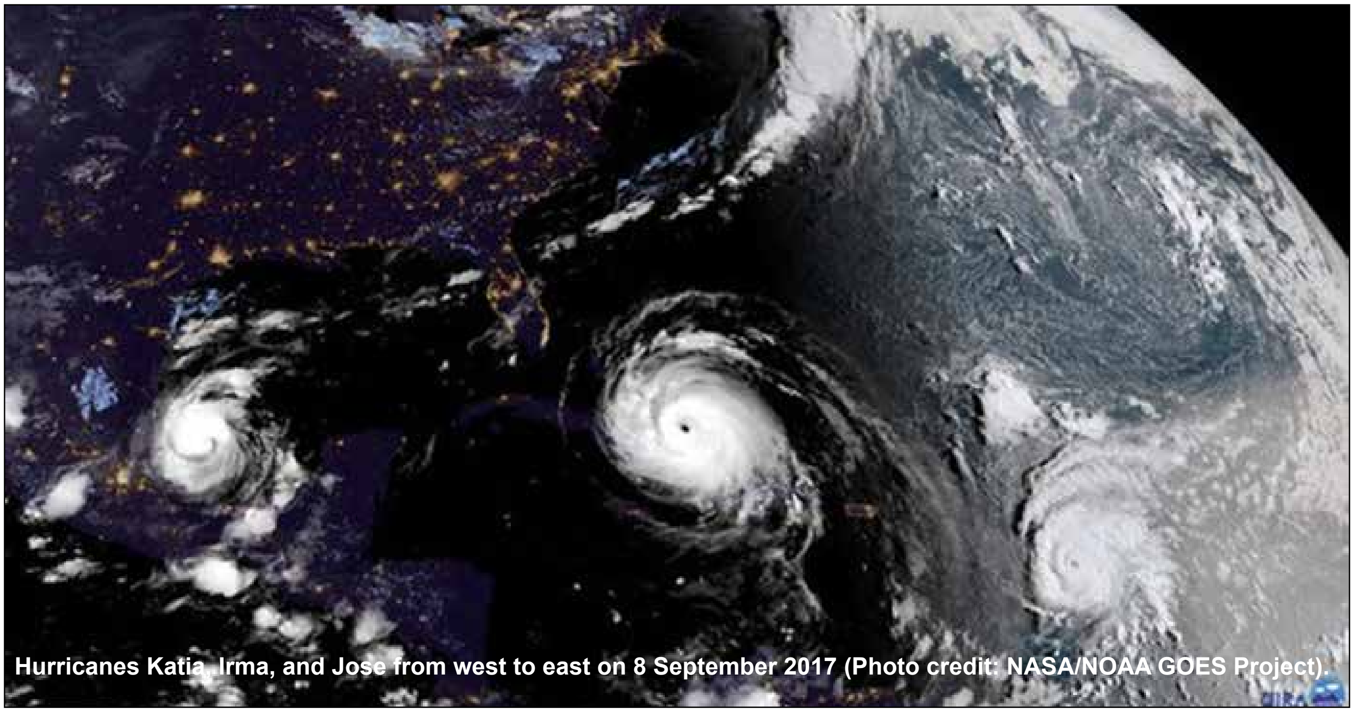

Hurricanes Katia, Irma, and Jose from west to east on 8 September 2017 (Photo credit: NASA/NOAA GOES Project).

U.S. Coastal Research Program

Advancing the understanding of storm processes and impacts

By

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In 2017, Hurricanes Harvey, Irma, and Maria caused more than $200 billion dollars of damage in the United States, as well as the incalculable cost of the loss of life and mental trauma associated with these disasters (Sullivan 2017). In a changing climate, sea level rise and the potential for increasing tropical cyclone intensity can result in even more devastating damages (IPCC 2013; Knutson *et al.* 2010). Therefore, engineers, community planners, and coastal residents need accurate, timely, and accessible forecasting of storm processes and their impact on coastal communities to bolster national resilience and reduce risk to life and property during these events. However, along with uncertainties in understanding and modeling of storm processes, there are complex challenges associated with determining and meeting the needs of end users who rely on these forecasts for emergency management decisions.

To determine needed advancements in storm forecasting, the U.S. Coastal Research Program (USCRP) hosted a Storm Processes and Impacts workshop for coastal stakeholders 16-18 April 2018, in St. Petersburg, Florida. The attendees included local coastal managers, emergency managers, state and regional agencies, federal agency scientists and engineers, academics, and private industry scientists and engineers. Workshop objectives were to synthesize present capabilities for modeling storm processes and forecasting impacts and to prioritize advancements. In addition, the workshop provided an opportunity to bridge the apparent gap between the research of coastal scientists and engineers and the information being distributed publicly and to emergency managers before, during, and after storm events. Finally, plans for a large-scale, extreme-event field experiment, DUNEX (During Nearshore Event eXperiment), anticipated in 2020-2021, were presented to encourage continued engagement of coastal researchers across disciplines.

This paper represents a synthesis of the forecasting challenges, research needs, infrastructure improvements, and communication challenges presented and discussed during the workshop. Each section includes a table of prioritized challenges or needs based on the workshop participants' feedback.

Three main research goals to address forecasting challenges and advance storm impact predictions were identified: (1) expand the understanding and representation of dynamic feedbacks between multiple time/length scales and processes (Represent Dynamic Feedbacks); (2) improve forecasting methodology and communicate inherent model uncertainty (Improve Forecasting Methods);

Table 1.
Prioritized forecasting challenges

1 — Integrate multiple hazards/processes over temporal & spatial scales	
2 — Valuate accuracy of meteorological conditions	
3 — Determine & propagate uncertainty	
4 — Predict timeline and level of impact	

and (3) quantify the role of nature-based and engineered shorelines in mitigating storm effects (Assess Hazard Mitigation). To advance these goals, improvements in observations and modeling (Infrastructure) are needed. A final challenge involves translating these processes, forecasts, and uncertainties to the end user (Communication).

FORECASTING CHALLENGES

Forecasting challenges prioritized by workshop participants are given in Table 1 and discussed below.

Extreme storms involve multiple hazards driven by a variety of coastal processes that operate on different temporal and spatial scales. Storm surge, dangerous surf, strong and damaging winds, tornadoes, and extreme rainfall can all contribute to the overall storm hazard. However, each of these hazards may impact a coastal community at a different time during a storm, and the state of the art of mapping and modeling these multiple hazards has not yet advanced to provide coupled forecasts about water-related hazards. Emergency managers may be utilizing discrete products to assess the impacts of large rainfall events and storm surge impacts. The integration of multiple hazards and processes over the course of an extreme event remains a significant forecasting challenge.

Furthermore, forecasting the impacts of these hazards requires accurate meteorological conditions that may not be available. Storm track errors increase 30-40 nautical miles per day prior to landfall, and errors in intensity forecasts increase for three days, then level off (hurricanes.gov/surge). Determining and propagating this uncertainty into storm models and then into forecasts poses a significant challenge, and thus it is difficult to predict the timeline and impact levels on the temporal scales required by emergency managers who are often expected to begin making decisions up to one week before storm impact.

Forecasting at adequate spatial resolution also presents a challenge. There is a discrepancy in the resolution of national-scale models like the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model, which have a typical grid cell resolution of 500 to 1,000 m in coastal regions, as compared to the parcel- to street-level resolution required for evacuation zone assignments (Kerr *et al.* 2013).

RESEARCH NEEDS

Workshop participants prioritized a number of specific research needs, ranging from fundamental science questions (e.g. better understanding sediment transport to improve morphologic change models) to practical questions about the timing of evacuation orders (Table 2).

Table 2.
Prioritized research challenges

1 — Quantify spatial/temporal resolution and accuracy required for users	
2 — Improve models to integrate relevant processes	
3 — Expand understanding of sediment transport – model improvements in morphology	
4 — Determine feedbacks between physical processes	
5 — Determine inputs for accurate coastal hazard forecasts in probabilistic models	
6 — Study mitigation solutions - how to mitigate hazards	
7 — Learn from model error to improve process understanding and models	
8 — Quantify the value of nature and nature-based features	
9 — Investigate beach and dune recovery	
10 — Understand variability of impacts depending on shoreline type – cliff, marsh, mangrove, ice	
11 — Assess impacts to structures (hydro, load, energy, surge)	
12 — Assess available statistical methods to best use limited model results	

The specific research needs (Table 2) were grouped into the following research themes or goals which are discussed in the sections below.

- Represent the dynamic feedbacks among storm-driven hydro- and morphodynamics (2, 3, 4, 9);
- Improve forecasting methods to better account for uncertainties (1, 5, 7, 12); and
- Assess the hazard mitigation capabilities of natural, nature-based, and built features (6, 8, 10, 11).

REPRESENT DYNAMIC FEEDBACKS

Workshop participants identified research needs related to the dynamic feedback between physical (hydrodynamic) processes and the system (morphologic) response during storm events. Four specific objectives identified were to: 1) better understand sediment transport to improve our ability to simulate morphologic change, 2) integrate relevant physics into numerical models, couple the models, and provide a feedback mechanism between models, 3) include the effects of vegetation and sedimentation on beach and dune response and recovery, and 4) incorporate rainfall runoff into the hydrodynamic and morphodynamic modeling capabilities. To represent these dynamic feedbacks during storms, research will require the integration of multiple processes over a range of spatial and temporal scales as discussed in the forecasting challenges section above.

The coupling between hydrodynamics and morphodynamics on a variety of spatial and temporal scales is needed to understand and predict the full range of coastal impacts from storms and the recovery of beaches that occurs between individual storms events. For instance, feedbacks (two-way coupling) between ocean waves, wave-driven currents, and geomorphology may result in offshore movement of sandbars during storms (Thornton and Humiston 1996, Gallagher *et al.* 1998) and onshore migration of the bar during small to moderate wave conditions (Hoefel and Elgar 2003). Similar coupling between oceanographic and geomorphologic processes affect the movement of other features in the beach profile such as the shoreline, berm, and dune. Alongshore variations in sandbar depth and location can affect the maximum elevation of ocean water levels and breaking wave heights and accompanying wave runup on the beach (Raubenheimer *et al.* 2001, Cohn and Ruggiero 2016), which in turn influences the potential for dune erosion (Overbeck *et al.* 2017) and the quantity of sediment transported back to the surf zone. Sediment transported from the dune to the surf zone can change the sandbar geometry, resulting in less (negative feedback) or more (positive) dune erosion. Although the offshore surf zone transport owing to mean flows may be understood reasonably well, the processes affecting onshore transport (including the recovery of beaches after storms) are less certain. Studies have shown that onshore transport may be driven by flow skewness (Trowbridge and Young 1989), flow accelerations under asymmetric waves (Hoefel and Elgar 2003), and boundary layer processes (Henderson *et al.* 2004), and is sensitive to near-bed turbulence and pick up functions, inter-granular stresses and fluid-granular interactions (Hsu and Liu 2004), stratification owing to the suspended sediment (Falchetti *et al.* 2010), and infiltration and exfiltration through the seafloor (Turner and Masselink 1989, Nielsen *et al.* 2001, Chardón-Maldonado *et al.* 2016). Wave-resolving models are required to accurately simulate these transport processes but are not always feasible to implement when considering the broad spatial extent of coastline that can be impacted by some extreme storms (*O*(1,000km)).

Storm-induced, large-scale (*O*(10,000 m)) subaerial sand erosion patterns can be reproduced fairly well with some existing models (0.35 < Brier skill score < 0.74, McCall *et al.* 2010, Harter and Figlus 2017, Overbeck *et al.* 2017). Empirical and semi-empirical models for dune erosion are efficient and have reasonable skill representing observations (Stockdon *et al.* 2007, Long *et al.* 2014, Overbeck *et al.* 2017), but some methods forecast the type of beach response (e.g. Sallenger 2000, Stockdon *et al.* 2007) instead of quantifying coastal change. In addition, empirical and semi-empirical methods cannot adequately represent the dynamic feedback between processes that occurs during storms. For instance, higher total water levels may not always result in higher magnitudes of dune elevation change suggesting that the transport of sediment from the dune is not linearly related to the maximum water level elevations during a storm (Long *et al.* 2014). Instead, process-based models are necessary to account for the timing, coupling of, and feedbacks between inner-shelf, surf zone, and beach processes (Roelvink *et al.* 2009, Palmsten and Holman 2012, Callaghan and Wainwright 2013, Dissanayake *et al.* 2014, Splinter *et al.* 2014).

Previous observations and model simulations suggest alongshore-variable dune erosion during wave collision events may be related to inhomogeneous along-coast inner-shelf bathymetry (shoals), spatial changes in the orientation of the coast relative to the (alongshore homogeneous) incident wave direction, timing of the largest waves with respect to high tide, the initial location of the dune toe and the initial dune topography and/or saturation (dune shape) (Bender and Dean 2003, Schupp *et al.* 2006, Claudino-Sales *et al.* 2008, Houser *et al.* 2008, Palmsten and Holman, 2011, Dissanyake *et al.* 2014, de Winter *et al.* 2015, Safak *et al.* 2017, Splinter *et al.* 2018). However, parameters in the models used to investigate these processes are usually calibrated and evaluated by comparison of simulated with observed topographic and bathymetric changes between pre- and post-storm surveys (McCall *et al.* 2010, Splinter and Palmsten 2012, Dissanyake *et al.* 2014, Harter and Figlus 2017) and the processes that occur during the storm may not be well-represented. In addition, in some cases the available pre-storm topography has not been updated for years before the event, which has been shown to impact model skill (e.g. Lindemer *et al.* 2010). The lack of model validation for these storm processes is, in large part, because there are few observations of the nearshore (surf, beach, dune) bathymetry and hydrodynamics before, during, and after extreme storms, and thus the importance of alongshore-variable surf zone bathymetry and waves and water levels in the geomorphological feedback process is uncertain.

Interactions between tidal, wind-driven, and wave-driven currents may amplify forces on the beach and increase transport of sediment (Mulligan *et al.* 2008). Exchange of sediments between the subaerial beach and surf zone, and between the shoreline and inner shelf likely are important during extreme events when dune and bluff erosion can be severe and strong rip currents (and undertow) may carry sediments into deep water. The net gain or loss of material to the outer surf zone during storms may be the determining factor for net shoreline movement, and the exchange processes may be closely coupled. Additionally, the large changes observed in erosional patterns over small alongshore spatial scales (*O*(100-1,000 m)) are not modeled well (de Winter *et al.* 2015), likely owing to the simplifications and parameterizations used in the models.

Feedbacks between hydrodynamic, morphologic, hydrogeologic, and Aeolian processes also may contribute to the observed alongshore inhomogeneity. Periodic dune erosion hotspots may have positive feedbacks with the growth of erosive beach cusps and rip currents that carry sediments offshore (Castelle *et al.* 2017). During beach recovery, wider cusp horns may be eroded by Aeolian sediment transport, whereas wind-blown sand is captured in dune scarps and low sections of the beach. Process-based models may be able to simulate many of these feedback mechanisms but because these processes occur on different temporal scales (hours to decades) a single model is not capable of simulating all of the relevant processes. Moreover, the simulations are sensitive to user-selected hydrodynamic and morphodynamic parameters (McCall *et al.* 2010, Splinter and Palmsten 2012, Dissanyake *et al.* 2014, Harter and Figlus 2017), which often are not well known and calibrated values from one area may not be directly applicable to another. In particular, understanding the effects of infiltration and exfiltration through the seafloor, sediment dynamics during and after dune slumping, Aeolian transport (including effects of rain, groundwater, and vegetation), and overland flows need to be improved.

Integrating relevant physics into numerical models, coupling models, and providing a feedback mechanism between models is another challenging area of research. Existing modeling systems have limitations, both for long-term coastal management and for real-time forecasting. For long-term management via the development of flood risk maps by FEMA and its contractors, erosion is considered after the larger-scale waves and flooding have been predicted. A coastal engineer uses a one-dimensional beach transect to manually update the primary frontal dune as necessary (Bellomo *et al.* 1999, FEMA 2003). The updated topography is then coupled back to the overland waves and flooding, but in a semi-automated way through the use of one-dimensional models for wave action landward of the dune (FEMA 1989, Divoky 2007, FEMA 2007). For real-time forecasting, the larger-scale wave and flooding models (e.g. SLOSH or ADCIRC) are used with a fixed ground surface. The wave and water-level predictions can then be used to predict the erosion regime, such as overwash or inundation, along the coast (e.g. the USGS Coastal Change Hazards Portal). None of these systems link the updated topography back to the larger-scale waves and flooding.

However, as topography erodes, waves and surge can progress further into regions that were protected previously. For storms impacting Long Island, New York, overwash and breaching increased the water levels in the back bay by as much as 1 m (Canizares and Irish 2008). Degradation of the Chandeleur Islands in Louisiana can increase the wave heights in coastal marshes by 1 m to 4 m and the surge levels near New Orleans by 0.5 m (Wamsley *et al.* 2009). Erosion on Bolivar Peninsula could increase the surge volume in Galveston Bay by 50% to 60% (Rego and Li 2010). However, these studies were conducted with flood models using fixed ground elevations. Even when erosion was simulated in a separate, process-based model (e.g. XBeach), the dune crests were lowered in the larger-scale circulation model before its simulation (Canizares and Irish 2008). Thus, these studies are overly conservative, in both magnitude and timing of the altered surge. There is a critical need to invest in model coupling to integrate the processes of storm-driven hydro- and morphodynamics over multiple scales, and to investigate questions about how the erosion of beaches and dunes can affect the magnitude, extent, and timing of flooding.

Including the effects of vegetation and sedimentation on beach and dune response and recovery is another portion of the storm processes feedback loop. Vegetation causes wave attenuation, thus exposing the landmass to lower wave forces and thereby reducing sediment loss to erosion on vegetated dunes during storms. In addition, vegetation reduces erosion from storm surge and waves by acting as surface cover thereby creating drag, reducing flow velocities, overtopping, and overwash (Tanaka *et al.* 2009, Kobayashi *et al.* 2013, Anderson *et al.* 2011, 2013). Storms have the potential to move large amounts of sediment causing erosion in some areas and deposition in others (Leatherman *et al.* 1977) creating a heterogenous dune environment varying in morphological parameters such as height and slope (Houser *et al.* 2008). Foredune stabilizing plants are capable of growing out of this deposition and surviving with as much as 1 m of burial (Maun 1994).

As previously mentioned, the height of the dune relative to the storm surge will affect the type of impact that results, with dunes higher than the surge experiencing swash or collision and lower dunes experiencing overwash and inundation (Sallenger 2000). The foredune is a defense line whereby any break in the crest will result in water flowing into and potentially through the entire system. The initial dune profile morphology affects uprush and overtopping potential (Silva *et al.* 2016, Figlus *et al.* 2011). In general, vegetation affects dune morphology by its ability to trap sediment and stabilize the dune (Hesp 1989, Murray *et al.* 2008), which creates differences in erosion potential because plant response to wave action and overwash is species-dependent (Charbonneau *et al.* 2017). A more complete understanding of the effects of waves and surge on sediment and vegetation requires a variety of data types (Moore 2000, Delgado-Fernandez *et al.* 2009), such as observational studies and modeling (Larson *et al.* 2004, Mull and Ruggiero 2014), both physical and numerical (Larson *et al.* 2004) to better determine morphologic change and ultimately categorize risk associated with storm impacts. Pre-event data, which is often lacking, is required to establish a baseline allowing for the determination of how and why local and broad topographic changes occurred (Charbonneau *et al.* 2017). Remote sensing can provide necessary data on dune elevation, plant species, and plant density (Timm *et al.* 2014, Brodie and Spore 2015), but these data should be supplemented with physical sampling to determine more specific details on the dune vegetation condition and verify mapping results (Simmons *et al.* 2017). Vegetation makes dunes serve as both habitat and flood protection features, both functions of which provide invaluable ecosystem services as a result of being able to withstand storm forces.

Many studies have focused on the beneficial reduction of storm waves and surge that vegetation provide (Costanza *et al.* 2008, Narayan *et al.* 2017) and the effect that such storms impose on marshes (Chabreck and Palmisano 1973, Stumpf 1983, Nyman *et al.* 1995). However, quantification of the feedbacks between waves and surge with sediment and vegetation is needed to fully forecast storm impacts and plan mitigation strategies. A broad approach including observational studies, physical modeling, and numerical modeling is required to better quantify these feedbacks and, ultimately, the risk associated with storm impacts. More observations of wave and surge interactions with mixed sediments (e.g. Roberts *et al.* 2013) are necessary to improve our ability to make risk-informed decisions. The non-uniform nature of vegetated shoreline response requires an understanding of variation in vegetation structure, cohesive sediment dynamics processes, erosive properties of vegetation, and mass failing (Priestas and Fagherazzi 2011). As green engineering solutions are increasingly applied in coastal protection, how nature-based features such as dunes and wetlands affect waves and surge need to be quantified (Gedan *et al.* 2011). Storms can be important events for import of sediment to coastal marshes (e.g. Cahoon *et al.* 1995; Moskalski and Sommerfield 2013) so the effects of such features on storm-induced sedimentation is equally important for long-term coastal protection. Pre-event data is requisite for determining the baseline in order to quantify storm effects. Remote sensing can provide necessary data on elevation and plant species and density but may need to be ground-truthed to determine specific characteristics (Klemas 2013). Ultimately, the valuation of storm risk reduction from natural and nature-based features (e.g. Narayan *et al.* 2017) is needed to justify future investment.

Incorporating rainfall runoff into the hydrodynamic and morphodynamic modeling dynamic feedback loop is another need highlighted by the 2017 and 2018 hurricane seasons. Flooding from rainfall-runoff in the riverine and coastal areas during tropical cyclones can be as devastating as the effects of storm surge and/or wind, depending on the location, drainage system, and intensity of the rainfall event. Flooding from both precipitation and storm surge is an increasing risk for most of the coastal areas within the U.S. (Wahl *et al.* 2015). During the 2017 and 2018 hurricane seasons, Hurricanes Harvey, Irma, and Florence produced significant flooding due to precipitation in both the riverine and coastal areas, along with flooding caused by storm surge. As mentioned in Blake and Zelinsky (2018), Hurricane Harvey produced the most precipitation of any tropical cyclone within the recorded rainfall records of the United States. The rainfall associated with this storm caused flooding within the city of Houston, TX, and regions of southeastern Texas, and in many cases exceeded the 100-year rainfall event for these areas. Furthermore, Hurricane Irma caused flooding in the Jacksonville, FL, area from the combined effect of rainfall-runoff and storm surge (Cangialosi *et al.* 2018). In the Jacksonville area, precipitation from the storm lead to peak riverine flows occurring at the same time as peak storm surge in the St. Johns River, which lead to historic flooding. Other tropical cyclones (e.g. Tropical Storm Allison, Hurricane Floyd) have also been associated with flooding due to rainfall-runoff. Thus, it is evident that to capture these combined effects it is necessary to have a predictive dynamic modeling capability. To capture both the upland riverine flows caused by the rainfall-runoff along with the coastal flooding, several coupled modeling systems have been developed or are under development to either utilize a hydrologic model (e.g. Tromble *et al.* 2011, Dresback *et al.* 2013), hydrologic and hydraulic model (e.g. Ray *et al.* 2011, Christian *et al.* 2015, Torres *et al.* 2015) or employ USGS gauge information (e.g. Flowerdew *et al.* 2010, Warner *et al.* 2010). In the case of coupling with the USGS gauge information, a real-time forecast can only extend outward on the order of hours due to the lack of future flows from the gauge information.

Modeling the compound flooding from rainfall-runoff and storm surge, requires several research areas to be explored and pursued, include determining: 1) the boundary location to couple a hydrologic model with a coastal hydrodynamic model; 2) the coupling (one-way or two-way) between models and the frequency of data exchanges; 3) methods to implement structures in the riverine areas (e.g. dams, bridges) into the model domain; 4) methods to address urban areas with these coupled modeling system, such as inclusion of a hydraulic model and fluid-structure interactions; 5) lateral inflows from the upland areas to the coastal zones. Lastly, uncertainty quantification and sensitivity analysis need to be considered for different forecast inputs (e.g. initial river stages, precipitation rates, storm track, storm size, and intensity) to formulate ensemble forecast.

IMPROVING METEOROLOGIC AND SURGE FORECASTING METHODS

During the last few decades, computational models to forecast hurricane winds and storm surge have improved significantly and led to reduced uncertainty. However, there are remaining challenges for current technologies when accurate and rapid predictions are needed by emergency management professionals. The top research need, as identified by the workshop participants, was to "quantify spatial and temporal resolution and accuracy for end users," which motivates research in two key areas. First, storm surge models and other forecasting technologies can provide rapid predictions with higher uncertainty or time-consuming predictions with higher accuracy. The National Hurricane Center (NHC) uses the former approach, by providing probabilistic guidance based on hundreds of relatively-coarse simulations, whereas academic researchers have pursued the latter approach, by providing deterministic guidance based on a small number of relatively-detailed simulations. There is a need to close this gap between probabilistic and deterministic predictions. Second, these models rely on input data that are highly uncertain; storm forecasts may have errors in parameters like track, size, and intensity, while flooding models may have errors in bathymetric and topographic elevations, surface and bottom roughness, and other processes. There is a need to account for and communicate these uncertainties to end users.

To balance timeliness and accuracy in forecasts of storm-driven hazards, researchers need to close the gap between high-resolution, deterministic guidance and large-ensemble, probabilistic guidance. Models for the prediction of coastal flooding and related impacts require the representation of a continuous domain (i.e. deep ocean, nearshore, and coastal floodplain) as discrete elements (Westerink *et al.* 1994, Hagen *et al.* 2004, Westerink *et al.* 2008). The level of spatial discretization is directly related to model resolution. Coarse resolution results in lower computational cost and allows for probabilistic guidance from suites of simulations, but sacrifices the model's accuracy in both its representation of the natural landscape (i.e. topography, bathymetry, and surface roughness) and its mathematical solution. Finer model resolution will result in higher computational cost, but it allows the model to better represent the natural landscape and yields more detailed and accurate hydrodynamic calculations, especially in the nearshore and across the coastal floodplain (Hagen *et al.* 2006, Bilskie and Hagen 2013, Bilskie *et al.* 2015).

Operational storm surge modeling systems have been developed with different approaches for resolution and accuracy, and thus with different implications for end users. The Tropical Cyclone Storm Surge Probabilities (P-Surge, http://slosh.nws.noaa.gov/psurge2.0), a SLOSH-based (Jelesnianski *et al.* 1992) product developed by the National Weather Service (NWS) in collaboration with the NHC, is an example of a technology that yields rapid but highly uncertain storm surge predictions. SLOSH must be fast, and so it is used with coarse representation of storm processes and coastal geography, and then hundreds of SLOSH simulations are combined statistically to provide a probabilistic forecast for each advisory. P-Surge provides 10% to 50% exceedance peak storm surge elevations for preparedness and general emergency management decision-making. The widespread of the 10% to 50% exceedance interval, often encompassing 10 or more feet, and lack of storm surge hydrograph estimation are of limited usefulness for the operation of flood gates, pumps, and other components of flood-protection systems.

The use of high-resolution, high-fidelity models is necessary when more accurate storm surge predictions are required. The ADvanced CIRCulation (ADCIRC) model can be implemented as the ADCIRC Surge Guidance System (ASGS) in high-performing computing environments to perform individual simulations and provide high-fidelity predictions. Individual forecast simulations can take from a half hour to a few hours to complete, depending on the capabilities of the computing environment. Alternatively, surrogate or meta-models (Jia *et al.* 2016; Taflanidis *et al.* 2017, Nadal-Caraballo *et al.* 2018) can be trained on existing high-fidelity ADCIRC databases, and subsequently executed to predict storm surge in a few seconds while conserving the fidelity of the underlying ADCIRC database. These meta-models can also be used to simulate ensembles of thousands of hurricanes in probabilistic frameworks and account for the uncertainties in meteorological forcing.

To reduce and communicate uncertainties in both model inputs and results, researchers need to better quantify these uncertainties and how they propagate through the forecast models. Workshop participants identified a key research need related to "inputs for accurate coastal hazard forecasts in probabilistic models." Storm surge forecasts are dependent on meteorological forcing, and are thus subject to the inherent uncertainties in hurricane forecasts. Regardless of the approach (i.e. deterministic or probabilistic), storm surge model simulations rely on cyclone vortex models that are constructed with a limited set of hurricane parameters, such as landfalling or bypassing location (x_0), central pressure deficit ($\Delta\rho$), radius of maximum winds (R_{max}), translational speed (V_f), and heading direction (θ). Torn and Snyder (2012) and Landsea and Franklin (2013) estimated the uncertainties for wind speed, central pressure, position, and gale, storm and hurricane wind radii. The uncertainty associated with the cyclone position, for example, can be expected to range from 9 km to 65 km depending on the intensity and organization of wind circulation. Wind speed uncertainty can vary from 9 km to 34 km/h; likewise, central pressure uncertainty can vary and from 1.5 hPa to 15 hPa. The gale (63 km/h), storm (93 km/h) and hurricane (119 km/h) wind radii uncertainties range from to 9 km to 111 km.

Meteorologists and other scientists are improving forecasting models and reducing uncertainty through ensembles and data assimilation techniques. The NHC forecast track errors have trended down during the past 40 or so years (NHC 2017). For unorganized tropical cyclones with weak eye structure, establishing the position of the vortex can be a challenge. Of particular concern, however, are the uncertainties in wind radii, which are often the basis for the estimation of R_{max}. Recent improvements in the estimation of R_{max} include the development of asymmetric vortex models. When using these vortex models, R_{max} can be estimated by quadrant typically by fitting a velocity profile model to match the velocity and distance of the highest isotach, as estimated by NHC forecasters. Other approaches include estimating R_{max} by averaging the wind profiles, and thus R_{max}, associated with all available isotachs. Moreover, R_{max} estimated by different reanalysis efforts have often produced inconsistent and conflictive results, with estimates off by up to a factor of two (Levinson *et al.* 2010). Given the sensitivity of storm surge predictions to meteorological forcing, improvements to the methods for estimation of hurricane forcing parameters are warranted. It is expected for forecasters to progressively shrink the uncertainty bands associated with hurricane intensity, position and projected trajectory, but the estimation of parameters that not are directly measured or observed, such as R_{max}, requires further investigation.

These uncertainties in atmospheric forecasts must then be translated into uncertainties in storm surge forecasts, leading to research needs in "assessing available statistical methods to best use limited model results" and "learning from model error to improve process understanding and models." In recent years, research efforts have attempted to better resolve uncertain physical processes that contribute to errors in storm surge forecasts (e.g. surface wind field representation, bottom friction, wind-driven waves, and rainfall). However, understanding and incorporating these physical processes into storm surge modeling remains a significant challenge. It is necessary that all of these uncertainties (i.e. those resulting from uncertain physical processes and meteorological forcing) as well as their impacts be quantified and accounted for effective storm surge forecasting.

Data assimilation methods offer an approach to this type of consideration and quantification of uncertainty. The methods combine observed data with numerical model output to improve the accuracy of modeled data. Statistical data assimilation methods, or Kalman filters, operate in two main steps, a forecast step and an analysis step. In the forecast step, an initial estimate of the model state (e.g. modeled water elevations) is forecasted to some later time using the numerical forecast model (e.g. a storm surge model). In the analysis step, observed data (i.e. observed water elevations) is used to update the forecasted model state. The model state generally does not lie in the same space as the observed data (e.g. data may be observed at a subset of the locations at which it is modeled). Thus, the model state is first projected into the observation space through an observation operator. The residual between the observed data and the projection of the forecasted state is then computed, weighted, and added to the forecasted state to form the updated state, or the analysis. The weight is known as the Kalman gain, which is defined in a way that minimizes the uncertainty of the update. The Kalman gain is also used to produce an estimate of the error variance of the update from that of the forecast.

These methods allow data to be assimilated sequentially, as data become available, making them particularly advantageous for real-time forecasting. This is a direct approach to reducing uncertainty in modeled data, as simulated storm surge heights are explicitly adjusted toward observed values in an optimal way. The methods also produce an estimate of uncertainty in the improved storm surge forecast. In meteorological forecasting, pressure data are often used to improve weather models of precipitation (Kalnay 2003). The same methods can be implemented for storm surge forecasting. Measurements of water elevations and currents can be used to better estimate storm surge model output, i.e. water elevations and currents, as well as their uncertainties (Butler *et al.* 2012). Additionally, they can be used to estimate uncertain model parameters, such as bottom friction (Mayo *et al.* 2014).

Ongoing research efforts should focus on closing the gap between probabilistic and deterministic guidance, but with emphases on meeting needs of and on communicating uncertainties to end users. Meta-model databases will be expanded to include simulations of storms with new combinations of parameters and to improve representation of the coastal zone with new geospatial data and higher model resolution. The development of new numerical algorithms and implementation of the latest computing technologies will reduce cost and wall-clock time of high-resolution models (Dietrich *et al.* 2011, Dietrich *et al.* 2013), thus leading to faster and more reliable predictions. Instead of ever-increasing model resolution, sub-mesh-scale processes can be parameterized in coarse-resolution models, and geospatial techniques can be used to downscale and extrapolate the flooding guidance to critical infrastructure. Increasing data availability will allow for increased use of data assimilation in real-time storm surge predictions. Research should continue to improve both accuracy and efficiency of model forecasts.

ASSESSING HAZARD MITIGATION

Coastal communities are continually challenged to adapt to the impact caused by storms and to prepare for future impacts caused by sea level change and increased storm activity. Essential to this adaptation is the understanding of the hydrodynamic forces impacting the beach, coastal dune system, and engineered structures, improving models of storm processes and coastal response, and ultimately refining our ability to forecast impacts to future events. Along the U.S. coastline, beaches, dunes, cliffs, wetlands, and, often, engineered structures provide a primary line of protection to landward infrastructure, habitat, and populations from elevated water levels caused by extreme tides, surge and wave runup. Understanding the variability of the processes and response of different types of shorelines, both natural and engineered, will better inform decisions for addressing risk on the coast and mitigating hazards.

Large stretches of the U.S. Pacific and Great Lakes coastlines are backed by cliffs and bluffs. Coastal cliff erosion and progressive landward retreat is caused by a complex and unique combination of subaerial and marine factors. These include direct and indirect wave impacts (Sunamura 1977; Emery and Kuhn 1982), rainfall and groundwater percolation (Young *et al.* 2009; Young 2015), permafrost thaw in Arctic environments, especially near remote native communities (Barnhart *et al.* 2014; Erikson *et al.* 2015), biochemical and biophysical rock erosion (Coombes *et al.* 2017), and, occasionally, seismic shaking (Hapke and Richmond 2002). These processes act to degrade the structural integrity of sea cliffs (Trenhaile 1987; Sunamura 1992), ultimately leading to sudden landslides that threaten cliff-top infrastructure. In many places, cliffs erode primarily during storm events, when elevated water levels (i.e. surge and set-up) allow large waves to impact the cliff with high frequency and intensity (e.g. Earlie *et al.* 2015). For example, sea cliffs near San Francisco, California retreated by up to 14 m during the high-energy 1997-1998 El Niño winter season (Sallenger *et al.* 2002). Although storm-driven coastal cliff erosion occurs globally and often accounts for the majority of observed cliff erosion, the process can be particularly difficult to measure in-situ during extreme storm wave conditions — limiting our overall knowledge of cliff evolution.

Recent advances in low-cost remote sensing technology, including Structure-from-Motion (SfM) topographic data collection (Ruzic et al. 2013; Warrick et al. 2016) and time lapse surf zone photography (e.g., Holman *et al.* 2013), as well as the growing use of seismometers to record the geomorphic response of cliffs to wave impacts in different environments (Adams *et al.* 2005; Dickson and Pentney 2012; Norman *et al.* 2013; Earlie *et al.* 2015; Young *et al.* 2016), are expanding our understanding of coastal cliff erosion. But our understanding could be expanded further by systematic pre-storm "rapid response" deployments – involving cost and instrument sharing between coastal scientists – to directly monitor storm impacts on cliffs. Additional research needs to improve forecasts of storm impacts to cliffs include, but are not limited to: (1) modeling and quantifying wave transformation across shore in different morphological settings to better understand the energy impacting cliffs; (2) relationship between rock strength and cliff behavior, such as microseismic fatigue, rapid retreat, sudden failure, over a range of time scales; and (3) development of automated approaches for observing cliff position and retreat from high resolution imagery.

Even along the highly studied dune-backed shorelines, models are not able to capture spatial variability in storm response or time evolution of the dune structure accurately or quickly enough to meaningfully inform decisions about mitigation. When water levels during storms reach these protective features, dunes can be eroded on the seaward face causing it to narrow, or the dune may be overwashed and inundated when water levels rise above the maximum dune height (Sallenger 2000, Long *et al.* 2014). Under these conditions, the elevation of the dune can be reduced significantly or breached completely and sand can be transported landward and away from the active beach system. As a result, when dunes become lower or narrower, the vulnerability of that section of coastline to the next storm increases. The time scale over which dunes re-grow (O(decades)) is much longer than the storm time scales (O(hours)) that cause them to lower and can be related to the frequency of storms that impact a particular region (Houser and Hamilton 2009, Houser *et al.* 2015).

Previous studies have used pre- and post-storm observations of dunes to characterize and quantify how sand dunes respond to storm forcing (e.g. McCall *et al.* 2010, Lindemer *et al.* 2010, Sherwood *et al.* 2014). Using these observations, process-based (Roelvink *et al.* 2009, Harter and Figlus 2017), statistical (Plant and Stockton 2012, Wahl *et al.* 2016), and empirical models (Long *et al.* 2014) of dune evolution have been developed and tested. While these models have been shown to be skillful at reproducing dune evolution for individual storms and specific locations, they have not been fully evaluated for a wide range of conditions. In addition, some models that are capable of predicting part of the storm-induced dune response (e.g. dune erosion; Larson *et al.* 2004, Palmsten and Holman 2012) are not able to capture the full range of processes, such as collision, overwash, and inundation. Due to the difficulty of measuring coastal processes and change during a storm event, only a few studies, typically based on laboratory observations, have assessed the accuracy of these models in predicting time-dependent dune evolution (Figlus *et al.* 2011, McCall *et al.* 2010, Palmsten and Splinter 2016). Novel observations of the oceanographic forcing, including wave run-up, and dune response during storms in a field setting are needed to increase understanding about how dunes erode (slumping, saturation [Palmsten and Holman 2011], overwash, etc.), while longer-term studies are needed to better quantify recovery processes and associated time scales. With these data, models of dune erosion and recovery can be combined, enhancing their power and usefulness, providing stakeholders with tools and actionable information to quantify vulnerability to future storm events as well as to evaluate viable restoration options of dune features (e.g. Mickey *et al.* 2017).

As mentioned in the dynamics feedback section above, nature-based features, such as sand dunes, have been identified as key elements on resilient coasts. A more complete understanding of the processes that control their growth and stability is necessary for evaluating options for use in mitigating future storm impacts. A major control on foredune growth and stability is vegetation (Bryant *et al.* 2017). Species-specific morphology, defined by form and structural characteristics, has been shown to affect dune system geomorphology in a biophysical feedback loop (Murray *et al.* 2008; Zarnetske *et al.* 2010; Duran and Moore 2013; Fei *et al.* 2014). Plant shoots catch aeolian sand but the efficiency of capture varies depending on species morphology, establishment, survival ability, and density (Hesp 1989; Zarnetske *et al.* 2010). Differences in plant community structure, transport potential, and sediment supply along a coast (Houser and Mathew 2011) create heterogeneous environments that lead to variability in the topography of the dune system (Hilton *et al.* 2006; Hacker *et al.* 2011). Shoots create drag and surface cover, thereby creating a bioshield that retards wind and wave erosion and increases dune stability (Tanaka *et al.* 2009). The above-ground biomass also serves to disrupt run-up, thus reducing erosion (Bryant *et al.* 2018).

Plant roots stabilize otherwise unstable sand particles (Maun 2009) by developing complicated root networks that bind sand, providing structural integrity (Forster and Nicolson 1981; Tanaka *et al.* 2009; Sigren *et al.* 2014). Laboratory tests have shown that the belowground biomass (plant root network) provides sediment stability and thus, reduces erosion (Bryant *et al.* 2018). Many foredune plants invest in symbiotic relationships with fungi that produce belowground hyphal networks that both directly and indirectly reduce soil erosion (Mardhiah *et al.* 2016). Similarly, microorganisms, like bacteria, living on roots increase sand aggregation thereby positively affecting stability (Forster and Nicolson 1981). Plants vary in their investment in roots versus shoots, which will then affect dune response to storm, as recently observed during Hurricane Sandy where erosion varied as a function of the species dominating foredunes (Charbonneau *et al.* 2016). Plants in coastal dune habitats can thus be considered ecosystem engineers as they initiate, build, and stabilize dunes. The biophysical feedback loop between vegetation and dune, or ecology and geology, has only recently begun to be explored (Stallins 2006; Murray *et al.* 2008). Understanding the role of vegetation for dune building and stabilization is important for understanding topographic heterogeneity and storm response which feedback on beach management.

Where beaches and dunes have not been able to recover naturally, engineered features are sometimes constructed to protect against future storm events. To determine structural response to storms, multiple processes (hazards) associated with coastal flooding — such as storm surge flooding, wave action, flow velocity — must be integrated. A current challenge is to understand the environmental load associated with storms and the impacts these loads have on coastal structures. Previous work has made use of observational, theoretical, physical, and computational models to investigate relationships between storm characteristics (storm surge elevations, significant wave heights, wind velocities), structural characteristics (elevation of lowest horizontal member, date of construction, building archetype) and damage in coastal communities. Fragility models, which predict the likelihood of exceeding a given damage threshold based on a hazard intensity measure, have made strides in evaluating storm impacts on structures. For example, Kennedy *et al.* (2011) assessed building damage on the Bolivar Peninsula, TX, after Hurricane Ike (2008); using these data and an ADCIRC+SWAN hindcast of the storm, Tomiczek *et al.* (2014) derived empirical fragility models predicting the probability of elevated, wood-framed structures on the peninsula experiencing collapse limit state failure. Environmental variables (e.g. significant wave height, storm surge elevation) showed more skill in predicting failure than standards-based force computations, suggesting that design equations must be refined to better represent physical processes associated with wave impacts. Design guidance from the American Society of Civil Engineers (2016) and FEMA (2011) do not explicitly include wave height in equations predicting the horizontal breaking wave-induced force, and guidance is limited for estimating the vertical wave uplift forces on elevated residential near-coast structures.

Some experimental work has measured these horizontal and vertical forces on structures in idealized settings. For example, Bea *et al.* (1999) proposed a method for estimating the total force on a bridge deck, and Bradner *et al.* (2011) similarly measured wave-induced forces and pressures on a large-scale model of a bridge superstructure. More recently, in a large-scale wave flume experiment examining forces on an idealized elevated coastal structure, Park *et al.* (2017) found that the vertical force was on the same order of magnitude as the horizontal force for some elevation-wave height combinations, reinforcing the need for additional research on vertical wave forces on coastal structures. Additional work is required to accurately characterize a structure's response to wave impacts and to identify scaling effects from laboratory to prototype structures and conditions. To bridge this knowledge gap, datasets providing full-scale measurements of wave-induced forces and structural response in a realistic environment are required, as are careful laboratory investigations of scaling effects and more generalized wave conditions. These data may inform computational fluid dynamics models, which can, in turn, inform community stakeholders about potential structural vulnerabilities and mitigation alternatives. Community robustness as a whole, depends on the impact on individual features, both natural and engineered coastal features, as well as successive and integrated impacts. A remaining research challenge for adequately understanding coastal response and mitigation will be to link these processes and develop the timeline of impacts and damage.

INFRASTRUCTURE NEEDS

The prior sections identified observational and modeling needs to better represent dynamic feedbacks, improve forecasting methods to better account for uncertainties, and assess the hazard mitigation capabilities of natural, nature-based, and built features. Here, we elaborate on needed observations, modeling advancements, and community efforts. Table 3 summarizes the infrastructure needs prioritized by workshop participants.

Better understanding storm processes and impacts will require improved observations of physical processes and responses during storm events. Researchers need real-time data before, during, and after storm events. These data may be collected with new arrays of instrumentation that have greater spatial resolution than is presently available or with high spatial- and temporal-resolution remote sensing data. This will help update the initial physical conditions, such as bathymetry, topography, and nearshore oceanographic conditions for more accurate model input. It may also lead to modeling advancements, for example predicting rapid morphologic change during storm events.

Collecting accurate source data, such as georeferenced aerial photographs, satellite imagery, and lidar surveys, and subsequently digitizing topographic features is a time-intensive process, especially for long stretches of coastline. Recent research has focused on developing automated feature position extraction routines from topographic Lidar data (Palaseanu-Lovejoy *et al.* 2016), but such routines do not exist for imagery. For beaches, Luijendijk *et al.* (2018) used automated shoreline detection and leveraged the wealth of publicly available, high-temporal-resolution satellite data on the Google Earth Engine to calculate global rates of shoreline change. Ideally, a similar approach could be developed for cliffs, allowing easy (and centralized) access to short-term (weekly) time series of cliff positions, which can then be used to monitor and predict storm impacts.

Improving forecasts of sediment transport and morphological changes during storms requires simultaneous observations of nearshore hydrodynamics, sediment fluxes, and bathymetric and topographic changes and improved models for coupled hydrodynamic, meteorologic, and sediment processes, including predictions of coastal inundation. Due to the difficulty of measuring coastal processes and change during a storm event, novel observations of the oceanographic forcing, including wave runup, and dune response during storms in a field setting are needed to increase understanding about how coastal features evolve.

In addition to morphologic observations, datasets providing full-scale measurements of wave-induced forces and structural response in a realistic environment are required, as are careful laboratory investigations of scaling effects and more generalized wave conditions. These data may inform computational fluid dynamics models, which can, in turn, inform community stakeholders about potential structural vulnerabilities and mitigation alternatives. Smart structures that can support instrumentation and the associated power and data storage requirements to measure storm impacts on the built environment are required. Finally, the research community is presently lacking the integration, coordination, and support of multidisciplinary field studies related to this type of work. The field studies should include stakeholder engagement and citizen science opportunities.

Once datasets of before, during, and after storm events have been collected, researchers would benefit from a mechanism to host a central repository that makes the data available in a common language. Such a mechanism (an online platform or other virtual hub) would provide a community of practice to not only serve data, but to also address a number of other infrastructure needs. Virtual and in-person meetings would provide regular interactions of like-minded researchers to share open source models, model results, data, instrumentation, challenges, best practices, lessons learned, and knowledge.

Table 3.
Prioritized infrastructure needs

1 — Community of Practice: Communication; sharing instruments; sharing of model results, data, and knowledge
2 — Focused, comprehensive process-based during storm observations (rapid response)
3 — Data:
    Available data sets in common language, central repository
    Real time data with adequate spatial coverage
    Updated initial conditions (topo, bathy, waves)
    Observations during storms
    High resolution remote sensing data
4 — Instrumentation of built environment for rapid response (smart structures)
5 — Integration, support, & coordination for field studies
6 — Community involvement (citizen science)
7 — Reliable fast predictions? New algorithms? Models? HPC?
8 — Novel instrumentation platforms for better observations of sediment & morpho-dynamics
9 — Pre-event funding pool

COMMUNICATION CHALLENGES

The discussion above focuses on scientific and engineering challenges that will be addressed by coastal researchers, ideally in partnership with national and regional government forecasters. The following discussion focuses on communicating this research to local forecasters and emergency managers. Table 4 summarizes the communication challenges prioritized by workshop participants.

For purposes of this paper, the role of direct communication with the public is assumed to be filled by the local emergency and coastal managers. They are

Table 4.
Prioritized communication challenges

1 — Communicate and manage uncertainty (temporal/spatial variability)
2 — Translate numerical output to relatable user products
3 — Educate (surge, impacts, post-storm conditions)
4 — Communicate economic benefits of mitigation
5 — Engage social scientists
6 — Tailor messaging
7 — Share best practices/data (see Infrastructure: Community of Practice)
8 — Consolidate and unify tools
9 — Help underserved communities access and deliver information

typically employed by a coastal county or municipality and may not have been trained in coastal science or engineering, but have the experience with, and access to, successful messaging techniques tailored to their local community. Local managers are best positioned to increase public risk salience through local, tailored messaging strategies to reduce the psychological distance to risk (e.g. Lorenzoni *et al.* 2007; O'Neill and Nicholson-Cole 2009). When coastal researchers communicate with local managers and/or the public, interactions are better with a two-way flow of information rather than a one-way flow from scientist to stakeholder (NASEM 2018).

Today's local coastal and emergency managers are experienced, knowledgeable, and capable of utilizing fairly complex model results to make risk-based decisions. However, during an emergency event, they are extremely limited by time. Unlike weather models, which periodically update using the latest observations, local emergency managers cannot iteratively change or update evacuation orders. Evacuation modifications result in a loss of public trust and apathy. In addition to the changing storm characteristics and the local geomorphology and urban setting, managers must navigate multilayered bureaucratic decision-making processes and sometimes complex social and economic factors within their communities.

The preceding sections have described differences in probabilistic and deterministic models to predict storm impacts. Many tools have been developed for emergency managers to utilize the output from these different models; however, managers appear to be overwhelmed by the number of models, tools, and information related to coastal risk assessment. There may be limitations on the usefulness of these products to support decision making. Managers acknowledge they end up relying on products that are intuitive and easy to use, rather than potentially more sophisticated but complicated tools (NASEM 2018). Emergency managers tend to use nationally approved tools – for example, the National Hurricane Program's HURREVAC and NHC's SLOSH. In order for managers to adopt new models and tools, they need consolidated, unified tools and user products that translate complex numerical model results.

Researchers aim to offer higher resolution models with less uncertainty. Local area forecasters are challenged to provide forecast guidance and descriptions of impacts that are comprehensive enough to be useful, yet do not imply greater precision than is justified. Local emergency managers sometimes have to make evacuation decisions based on high forecast uncertainty. In these cases, managers need to understand the worst-case scenario to manage risk. Thus, the challenge may not in reducing uncertainty but in communicating uncertainty to users. As one manager stated, "hurricane evacuation decision making is as much art as it is science, so the more practitioners understand the tools and the process, the better the art."

It is important for local emergency managers to understand and have information to educate residents about surge, impacts, and post-storm conditions. Rappaport (2014) identified storm surge and rising water to be the deadliest component of hurricanes, with water responsible for as many as 90% of all storm-related deaths and storm surge responsible for half of those. To increase public awareness of the risk from water-related deaths, creative communication methods are being employed around the nation. For example, in Pinellas County, FL, property owners receive information about their evacuation zone on monthly electric bills and on annual property tax statements. Educational signage has been installed at schools and parks to help residents visualize potential storm surge elevations.

It is also important for local building officials to have information about the economic benefits of mitigation to provide to their coastal residents. Local officials can communicate structural resilience/vulnerability to low-income and socially vulnerable populations in order to improve mitigation decisions and ensure life-safety during extreme events. An education tool is FEMA's "Evolution of Mitigation" video (https://www.fema.gov/media-library/assets/videos/153336), which describes how improved building codes have helped to reduce storm impacts on coastal homes over time, resulting in more resilient coastal communities.

SUMMARY

Storm processes and impacts research needs include

A) Represent the dynamic feedbacks among storm-driven hydro- and morphodynamics. The research objectives are to: 1) better understand sediment transport to improve our ability to simulate morphologic change, 2) integrate relevant physics into numerical models, couple the models, and provide a feedback mechanism between models, 3) include the effects of vegetation and sedimentation on beach and dune response and recovery, and 4) incorporate rainfall runoff into the hydrodynamic and morphodynamic modeling capabilities. Quantification of the feedback between hydrologic, hydraulic, sediment transport, morphologic, and vegetation conditions is needed to fully forecast storm impacts and plan mitigation strategies.

B) Improve forecasting methods to better account for uncertainties. The research goal is to close the gap between high-resolution, deterministic guidance and large-ensemble, probabilistic guidance. This research will require the development of better descriptions of coastal regions and faster models for storm-driven hazards, as well as a better understanding of uncertainties in model inputs and how they affect the model results.

C) Assess the hazard mitigation capabilities of natural, nature-based, and built features. The research goal is to help coastal communities adapt to the impact caused by storms and to prepare for future impacts caused by sea level change and increased storm activity. This involves an understanding of the hydrodynamic forces impacting the beach, coastal dune system, and engineered structures, improving models of storm processes and coastal response, and ultimately refining our ability to forecast impacts to future events.

Infrastructure needs include advancements to provide coastal data before, during, and after storms at high spatial and temporal resolution. Communication challenges include addressing the disconnect between the research needs to reduce the uncertainty and increase the resolution of model output and the emergency managers' need to make evacuation decisions based on an intuitive and easy-to-use model with high certainty several days to a week before landfall.

As discussed in the infrastructure needs section, the coastal research community should develop a storm processes and impacts community of practice to foster collaboration and provide a platform to share data, models, instrumentation, and knowledge. Emergency managers and local administrators should be included in the discussions to inform research investments and to help determine whether research advancements are useful to stakeholders.

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