Coastal inundation research: an overview of the process

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Coastal inundation is the flooding of coastal zone resulting from increased river discharge, spring tides, severe storms, or generation of powerful waves from tectonic activity (tsunami). This article discusses the critical factors that contribute to coastal inundation. Among the probable factors that cause coastal flooding and destruction, storm surge is the most frequent, and hence this article provides a detailed evaluation of the progress made in storm inundation research. Recent advances in coastal inundation modelling include efforts to understand the nonlinear dynamic interaction of near-shore waves, wind and atmospheric pressure with still water sea level and coastal currents, and their combined effects on storm surge along the coast and interaction with coastal morphology. An advanced storm-surge model comprises different modules, viz. an atmospheric component, and two ocean components for surge and wave simulations; these modules are coupled with each other. The nesting of regional coastal model with an ocean-wide model captures the far-field boundary forcing of extreme events that usually originate from the warm open ocean. Even though significant advancements reported on the efficiency and accuracy of storm surge and inundation prediction, further studies are required to understand the nonlinear interaction of storm surge with coastal landforms and their vegetation (land cover). In the context of rising sea level, increased tropical cyclone activity and rapid shoreline change, it is pertinent to evaluate the future flooding risk associated with landfall of tropical cyclones in densely populated coastal cities.

Keywords: Coastal inundation, coupled models, storm surge, tropical cyclones.

THE coastal communities are exposed to natural hazards like acute beach erosion, tropical and extra-tropical storms, tsunamis, sea-level rise and inundation resulting in severe loss of life and property. Nearly 23% of the global population, i.e. close to 1.5 billion resides within 100 km of the coast, thus number will rise to 50% by 2030 (ref. 1). An estimate of more than US$ 3 trillion was invested in real estate development, infrastructure built-up and dwellings along the Atlantic and Gulf coast of the United States[2]. With rising sea level, the coastal zone is undergoing rapid changes worldwide. The rate of sea-level rise had increased over the past two centuries, as the average air and water temperatures have increased. Warm oceans have resulted in the formation of powerful tropical cyclones and hurricanes in the tropical ocean basins[3]. Recently, Sahoo and Bhaskaran[4,5] have reported on the synthesis and assessment of historical tropical cyclone tracks in a risk evaluation perspective for the east coast of India. Their study had led to the development of synthetic cyclone tracks for pre- and post-monsoon periods for the coastal states along the east coast of India, which is useful for the assessment of coastal and social vulnerability along the coastal belt of the country.

Tropical cyclones/hurricanes are one of the major categories of windstorms with wind speed reaching 220 km h^{-1}. The passage of these low-pressure systems causes a localized increase in sea level called 'storm surge'. The surge generated in the shallow continental shelf could penetrate the river and creek systems and tidal inlets, causing excessive flooding of the low-lying coastal zone[6]. In addition, intense rainfall associated with cyclonic storms can add to the disastrous effects on the coast. An estimated 10 million people would experience coastal flooding each year due to storm surges associated with landfall of cyclones/typhoons, and 50 million could be at risk by 2080 due to climate change and ever-increasing population densities along the coast[7].

Tsunamis, another cause of coastal flooding, are less frequent and mostly occur due to underwater earthquakes or abrupt seafloor slumping[8]. Tsunamis can result in the generation of waves reaching as high as 10–15 m, and inundating a wider swath of the coastal zone, causing total destruction of the coast, for example, the Indonesian tsunami of December 2004 wiped out vast tracts of land along the coasts of Indonesia, Thailand, Sri Lanka and India[9–11]. Sea-level rise is another major concern, albeit affecting slowly and steadily, which would result in large-scale submergence of low-lying coastal areas and flat islands; for example, Entire deltaic plains (Ganges–Brahmaputra Delta) of Bangladesh and adjoining coasts of India; Everglades along south Florida, USA; low-lying islands like Maldives and numerous tropical Pacific islands. Large-scale coastal erosion, especially due to nonlinear interaction of storm surge with high energetic waves, can evolve into a major hazard if the erosion rate exceeds a threshold level for future coastal restoration

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and management. Coastal erosion also results in the exposure of inland coastal region to waves and tides, causing flooding of inlands as well as widespread damage to low-lying freshwater marsh thriving behind the barrier islands[12].

The landfall of a tropical cyclone also results in inland flooding due to sustained rainfall and increased run-off from the upper reaches of the watershed. It is evident that the inland flooding can be an offshoot of coastal hazard; but this need not be the case always. However, it implies that threat from coastal hazards not only confined to coastal communities its effect could occur farther away from the coast. The devastation brought about by typhoon Hyan in 2013, the Indian Ocean tsunami in 2004, etc. are the most recent reminders on the enormous losses that coastal hazards could bring into thickly populated coastal areas[13]. The Indian coast experiences almost every year the impact of tropical cyclones that form over the Bay of Bengal or the Arabian Sea. The frequency of occurrence is higher over the Bay of Bengal compared to the Arabian Sea. In a hydro-meteorological perspective, the study by Mascarenhas[14] reports on the oceanographic validity of buffer zones for the east coast of India. It shows that in terms of landfall considering the severe cyclones over a century, the Andhra coast is most vulnerable (about 32% of cyclones that form over the Bay if Bengal makes landfall) followed by Odisha (about 27%), Tamil Nadu (26%) and West Bengal (15%). The 1989 Kavali cyclone that crossed the south Andhra Pradesh coast (30 km north of Kavali) on 8 November at 1900 UTC, resulted in a maximum surge (run-up height) of 4.0 m (ref. 15). The simulated maximum water level was about 2.6 m, and associated horizontal inundation varied from 1 to 3 km along the right of the cyclone landfall location. The November 1996 Andhra cyclone resulted in maximum surge of about 3 m near Kakinada, and the extent of coastal flooding reported was about 3.0 km (ref. 15). The November 2000 Cuddalore cyclone resulted in storm surge varying from 1.2 to 1.5 m, with no inundation reported. Mahadevan and Latha[16] studied the influence of coastal flooding on surge estimates along the east coast of India. Their study simulated the 1977 Andhra cyclone and illustrated that high surges confined to short coastal stretches. This cyclone generated storm surge of nearly 5 m along the Machilipatnam coast causing flooding extending to more than 15 km inland after its landfall.

Another study conducted for the Government of Andhra Pradesh as part of the World Bank project on cyclone mitigation indicates that storm-surge penetration can vary between 10% and 15% more distance through the riverine systems[17]. The increased penetration distance is limited to 10% for river systems having many meanders. In addition, Rao *et al.*[17] conducted a study on the penetration of storm surge through the Godavari, Krishna and Pennar river systems, both for the main stream and their tributaries. Results indicate that the widest surge inundation and wind-affected areas cover East Godavari to Guntur districts and the southern Nellore district. The coastal districts of Odisha have experienced severe flooding in the past not only due to storm surges associated with tropical cyclones that originate in the Bay of Bengal, but also due to flooding from rivers as well as from heavy precipitation associated with tropical cyclones and monsoon depressions[18]. The flooding events in the deltaic area of Odisha attributed to high complex and nonlinear interaction between storm surges, tides, coastal set-up due to wind-waves, and river discharge. Flooding also results from the additional river discharge due to heavy rainfall and direct flooding of deltaic land by intense rainfall that persists from several hours 2–3 days. The study provides a comprehensive database on the flooding events along the Odisha coast during the last two centuries[18]. The readers can refer to ref. 14 for more details. The recent studies on storm surge modelling and coastal flooding for the east coast of India include a coupled hydrodynamic modelling system for very severe cyclones such as Phailin[19,20], Thane[21,22], Aila[23].

Compared to storm-surge events, the extent of flooding and destruction is extremely higher for tsunami events. Tsunami waves can destroy the coastal infrastructure, geomorphology and coastal ecosystem. For the Indian coast, major research on tsunami modelling and observations, changes in coastal morphology, changes in coastal ecosystems and palaeo-tsunamis began after the 26 December 2004 event. Various workers studied on tsunamis of the Indian coast[9–11,24–29]. More details on tsunamis and their effects on coastal morphology and ecosystems are available in ref. 30. The present article evaluates the various coastal processes that may cause extensive coastal inundation, with a focus on one of the major natural hazards–tropical cyclones.

Coastal inundation and its causes

There are factors that cause long-term and short-term coastal inundation that could make the coast unstable and susceptible to further modifications in the future. Persistent sea-level rise, coastal erosion, geomorphologic alterations and anthropogenic activities are responsible for permanent flooding and retreat of the coast, and their effects are enduring; whereas other factors viz., landfall of tropical cyclones, tsunamis, extreme waves, tides, etc. cause short-term inundation leading to episodic flooding and widespread destruction of the coast. The cyclones/tropical storms originate over the open ocean and intensify while traversing over warm tropical and subtropical waters and finally, during landfall, much of its energy dissipates along the coastal zone. During the pre-landfall phase, persistent onshore wind along with low pressure associated with the approaching eye of the storm brings in large amount of sea water towards the coast, causing a sudden and inexorable rise in sea level much more than the normal range of sea-surface elevation, resulting in disastrous flooding along the coast. The subsequent section provides a detailed account on the impact of storm surge and the progress achieved over the last few decades in simulating coastal inundation due to tropical cyclones.

As mentioned above, another major catastrophic event that results in extensive flooding and destruction of coastal areas is the tsunami. The term 'tsunami' was coined in 1960s, but it gained attention after 2004, when many of the coastal communities along the Southeast Asia were devastated by huge waves and extensive inundation from a mega-tsunami, which itself spawned from a massive shift in the seafloor off the coast of Banda Ache (Sumatra Island coast of Indonesia). After the intensity of tectonic process that spawns a tsunami, wave height is the determinant for the danger posed by the tsunami wave. It is worth to note that not all underwater earthquakes would result in a tsunami generation. In order to produce a tsunami, there should be considerable vertical displacement of a portion in the seafloor due to an earthquake, or massive slumping of the seafloor. Once tsunami waves are generated, they propagate radially from the epicenter for thousands of kilometres, with a speed of 900–1000 km h^{-1} (comparable to the speed of a commercial jetliner). The inundation caused by a tsunami depends upon coastal relief, width, mean depth and slope of the continental shelf, tsunami height and its wavelength. The metrics for evaluating the destructive power of a tsunami depends on the run-up height, inundation height; onshore distance covered during run-up, etc. Monitoring of the inundation height and penetration distance is a highly complicated and daunting task. In the scientific literature, one can find tsunami inundation rarely compared with storm surge, but its destruction potential is much higher than storm surges.

Extreme waves are another cause of coastal flooding, which are usually triggered by far-away storms. The swells from remote storms travel thousands of kilometres, reaching the near-shore coastal waters. The interaction of these swells with local coastal currents results in modification of waves, leading to flooding of low-lying coastal areas. The term 'kallakkadal' used in the literature (confined to the Indian coast) refers to coastal flooding of this nature in Kerala, located in southwest India[31]. Published work in this area suggests that swells generated near Antarctica propagate into the north Indian Ocean, and while encountering southward-propagating coastal current, amplifies through the nonlinear interaction between waves and currents. There is no documentation of kallakkadal in the scientific literature, however, local fishermen claims that it occurs every year. One of the intense kallakkadal phenomena occurred during May 2005 was reported[32,33]. Another report stated its occurrence during late April 2007 and of low intensity during February 2008 (ref. 31). Elsewhere, Tintore *et al.*[34] reported large-scale sea-level oscillations with amplitudes up to 1 m and having 10 min period from various bays and harbours of the Mediterranean Sea. These oscillations results from a three-way resonant coupling between atmospheric gravity waves, coastally trapped edge waves and normal oscillation modes of the harbour (Seiches). Atmospheric pressure fluctuation is the energy source for these large-scale sea-level oscillations. In addition, 'extreme tides' also needs to be mentioned as a plausible cause of coastal inundation. It refers to comparatively higher high-tide occurring due to the complex alignment of sun, moon and earth system and thereby amplifying the tidal range during spring tides. Extreme tides only cause flooding in very shallow coastal regions, e.g. city of Venice in Italy. Extreme wave and tidal flooding are not frequent, but when combined with strong onshore winds and rainfall, the scenario of flooding could become severe.

The coastal geomorphology, coastal erosion and persistent sea-level rise are all contributing factors. The estimated current rate of global sea-level rise is about 3 mm yr^{-1}, with exceptions of some deltaic coasts experiencing rapid rise in sea level as high as 10 mm yr^{-1} (Mississippi Delta, Louisiana, USA and Ganges–Brahmaputra Delta, Bangladesh)[35]. Gornitz[36] states that 'accelerating sea level trends could seriously exacerbate erosion, inundation and salinization hazards, with increased risk to human life and property along low-lying coastal areas'. The rising sea level will also enhance the frequency of inundation events, resulting from storm surges, tsunamis and extreme waves.

Shen *et al.*[37] showed that coastal morphological features such as barrier islands, inlets, lagoons and shoreline configuration has a significant effect on the evaluation and prediction of coastal inundation. The slopes of the innershelf, beach geomorphology as well as characteristics of beach sediments are the critical parameters that govern the extent of inundation. In a mild slope beach, the wave run-up will be higher resulting in greater inundation landwards. Persistent coastal erosion is another major factor that exacerbates inundation of the coast and low-lying inland areas. The breaking waves and swift currents modify the coast by the process of erosion and accretion of sediments. The riverine engineering works like channel straightening and deepening; construction of dams, levees, etc. results in increased water level in the rivers. It would result in elevated water level in the river, causing additional pressure on the river banks and levees when a storm surge propagates upstream. Increased rainfall in the watershed of such heavily fortified river systems will lead to disastrous flooding scenario (the massive levee network of Lower Mississippi River amplified the storm surge in the New Orleans city, USA, during the landfall of Hurricane Katrina in 2005) . The ill-conceived design of coastal structures, viz. breakwaters, groins, jetties, seawalls, etc. is another contributing factor for inundation. Poorly designed coastal protection structures could result in acute coastal erosion and hence the loss of beach sediments. This could increase the wave run-up and overtopping potential in the coastal zone. The uncontrolled expansion of human settlements in low-lying coastal areas and delta plains could hinder the overland flow during the surge events. This may result in increased inundation depth and obviously will increase its severity in terms of loss of life and damage to property. Modification of the coastal boundaries by means of construction activities such as waterways, canals, marinas and boat ramps, and large-scale coastal reclamation may also adversely affect the coastal environment and thereby enhance the potential for flooding.

Tropical cyclones, storm surges and relative sea-level rise

Tropical cyclones are intense cyclonic storms that originate over warm tropical seas. In North America, the terminology used is 'hurricane' because cyclone refers to an intense, counterclockwise-rotating extra-tropical storm. In Japan and Southeast Asia, it is known by 'typhoons'[38]. Tropical cyclones also produce widespread torrential rain, sometimes in excess of 6 inches, which may result in devastating flooding and landslides along its path. Coastal flooding also results from nor'easters, extra-tropical storms formed along the polar front, which are cold-core low-pressure systems, whereas tropical cyclones are warm-core low-pressure systems. The common characteristics shared by these storms are low atmospheric pressure system packed with high whirling winds. These transient meteorological systems can elevate the water level and cause a storm surge along their tracks. Storm surge accounts for 90% of human loss during landfall of tropical cyclones[39]. Storm surges are further elevated by persistent onshore wind, especially where the continental shelf is shallow and wide as in the case of the Ganges–Brahmaputra Delta in Bangladesh. When neglecting the bottom friction and other localized external forcings; the wind generated storm surge is proportional to $U^2(W/h)$, where U is the wind speed, W the open ocean fetch, and h is the mean water depth over which the wind blows. Especially in deltaic environment, low-lying nature of the coast makes it vulnerable to enhanced tropical cyclone flooding[40].

Harris[41] observed that storm surge has a period of oscillation (cyclic) measured in hours and rarely exceed two or three significant cycles during a cyclone landfall. It has a wavelength of many kilometres, and along low-lying coasts and swampy inland areas, it may penetrate several kilometres onshore. Earlier studies on storm surge have been documented[42,43]. It was Cline[43] first coined the term 'storm tide' and explained that it results from the physical forces of the hurricane driving large waves forward and transferring the water from open-ocean in the same direction as the track of the hurricane. According to Cline, storm tide is probably not more than 5 ft in the open-ocean, but obstruction due to the coastline acts as a barrier and the water gradually banks up as it does against a dam across a stream. The concepts on storm surge were further modified by other researchers[41,44–46]. Harris[41] defined storm surge as the difference between the actual tide as influenced by the meteorological disturbance, and the astronomical tide that would have occurred in the absence of any meteorological disturbance. He also discussed five factors that can alter the water level in tide-controlled water bodies during the passage of a storm[47]. These five include pressure effect, direct wind effect, effect of the earth's rotation, effect of waves and rainfall. Heaps[48] defined storm surge as the raising or lowering of sea level produced by wind and by changes in atmospheric pressure over the sea associated with a storm. Very intense storms can generate large and devastating sea surges. Fritz *et al.*[49] have discussed the ravage and destruction due to levee failure brought by Hurricane Katrina in 2005, to the city of New Orleans[49]. The devastation potential of an intense tropical storm depends on factors such as coastal geometry; topography; individual characteristics of the tropical cyclone, viz. forward speed, radius of maximum wind, central pressure; shoreline configuration and the relative sea level of the affected coastline. Woodruff *et al.*[40] observed that densely populated regions affected by coastal flooding from tropical cyclones experience a rate of sea-level rise near or greater than the global average over the instrumental record. The probability of coastal flooding associated with landfalling tropical cyclones depends on the probability of tropical cyclone occurrence and the behaviour of relative sea level.

Numerical modelling of storm inundation

Numerical models are viable and effective tools to understand and predict the dynamics of the coastal environment. They provide an opportunity to understand and forecast the response of coastal environment to varying meteorological forcing conditions. Storm-surge models mainly focus on peak surge height and its spatial and temporal variability along the coast and immediate inland areas, arising from a cyclonic system. A review on the development and progress of storm-surge modelling mentioned about a 'geographical divide'[50]. As the storm surge results from tropical cyclones and the mid-latitude nor'easter storms, efforts of modelling groups were concentrated to a particular geographic region. Worldwide, numerous research groups and organizations have been working on storm-surge predictions since late 1950s. One can find the pioneering efforts by various workers[48,51–55] on storm-surge studies. The SPLASH model developed by Jelesnianski[56] performed real-time forecasting of hurricane-induced surge along the Gulf and Atlantic coast of the United States. During the 1990s, research communities and Government agencies used advanced storm-surge forecasting models such as SLOSH (NOAA) and ADCIRC[57]. The initial phase of model development for storm surge focused mainly on the evolution of surge height and location of peak surge. It did not consider coastal flooding due to onshore penetration of sea water. The resultant peak surge output from model computations was often times over-estimated. To address this issue, refinement of storm-surge models allowed flow across the coastline boundary, utilizing advanced numerical algorithms that consider spatially varying bottom friction imposed on the storm surge. The algorithm considers the effect of coastal geomorphology, including the effects of vegetation (land cover). The following section provides a review on the advancements in storm-surge inundation studies over the past two decades.

Development of drying and wetting algorithms

Hubbert and McInnes[58] developed a storm-surge model incorporating an inundation algorithm that allows wetting and drying of computational nodes, and constrained sea-level height and current speed. The flow rate used in the inundation algorithm provided model stability under reduced grid resolution. This algorithm was implemented in numerical models and case studies conducted for various coastal settings around Australia[59]. Cheung *et al.*[60] have discussed the critical need of coastal flood modelling for emergency management operations. Their study employed a system of four models to predict coastal flooding. The component models included an open-ocean storm-surge model, an open-ocean wave model, a coastal wave model, and a Bousinessq model to stimulate the surf-zone processes and wave run-up. A pre-processor drives these four models that generates the computational grids and input atmospheric conditions, manages the data exchange between component models, and finally automates the simulation process with minimal user intervention. Cheung *et al.*[60] validated the performance of this coupled modelling system for different case scenarios. The case study provided the wave and surge conditions simulated for hurricanes Ikini and Iwa that hit the Hawaiian Island of Kauai in 1982 and 1992 respectively. Their study highlighted that wave set-up can be a significant component of the storm-water level, while wave swashing is required in the evaluation of inundation. Xie *et al.*[61] conducted an exhaustive modelling study on coastal inundation for the Atlantic basin. They developed an integrated storm surge and inundation modelling system by modifying the inundation scheme referred as HM scheme[58]. The modified HM scheme incorporated mass conservation with flexibility to choose inundation speed, based on three-dimensional flow fields. Peng *et al.*[6] implemented this model to study the surge and inundation in Croatan–Albemarlee–Pamlico Estuary System in North Carolina, USA. The study evaluated surge and inundation from ten hypothetical storms of categories 2 and 3, and with varying minimum central pressure and radius of maximum winds. The storm surge and inundation showed a dependence on minimum central pressure, radius of maximum winds and translational speed of the storm. Rego and Li[62] also reported on the dependence of coastal storm-surge in Galveston Bay during hurricane Ike, to path of the storm as well geometric properties of the Bay.

Development of coupled models

Westerink *et al.*[63] performed an extensive study of storm surges using the ADCIRC model for the Louisiana coast, a region of complex coastal geometry with numerous hydraulic features. Their work highlights the incorporation of basin-scale domain in the coastal model to simplify the specification of open-ocean boundary conditions for tides and surges, and the modification of wind field in relation to land roughness. Their work stressed the need for coupling ADCIRC with wave models to represent realistic water-level variations due to wind-wave effects[63]. Another significant study discussed the vulnerability of New York City to coastal flooding by storm surges[64]. Dietrich *et al.*[65] reported on the tight coupling of ADCIRC with the SWAN model. Their work provides an elaborate discussion on the coupling mechanism, and its implementation at different coastal regions of the United States to study storm surge and associated inundation. Sheng *et al.*[66] conducted an extensive study on storm surges, waves, currents and inundation for the Chesapeake Bay during Hurricane Isabel (2003), using an integrated storm surge modelling system CH3D-SSMS. This integrated model comprises four components – coastal surge model (CH3D), coastal wave model (SWAN), region/basin-wide surge model (ADCIRC or UFDVM), and a regional/basin-wide wave model (WW3). Coupling local models with regional-scale models improved the accuracy of boundary conditions. The authors also performed a case study to evaluate the nonlinear wave–current interaction during a hurricane landfall. It highlights that during extreme events wave radiation stress has a major role than wave-induced stress in controlling the surge effect along shallow coastal waters. Condon and Sheng[67] carried out a detailed evaluation of coastal inundation in the present and future climate. Their study area covered the Florida coast using the integrated storm-surge model developed by Sheng *et al.*[66] with optimal storm ensemble and multivariate interpolation. This model computed coastal inundation due to sea-level rise with and without the effect of storm surge to understand the climate change effects. Kennedy *et al.*[68] used a two-way coupled ADCIRC-SWAN model to simulate the coastal inundation along with phase-resolving Bousinessq model for wave run-up.

Simulation studies cover storm inundation scenarios from Hurricane Iniki along the coast of Kauai compared with observations. In contrast to the observed run-up lines and marks along the beach, the surge inundation modelled by coupled SWAN–ADCIRC is much lower in many cases, and consistently under predicts inundation levels. This is because the phase-averaged computation does not account for the intra-wave and wave group-driven run-up that may intermittently add several metres to the spectrally averaged radiation stress-driven wave set-up. The authors also determined the peak surge for a hurricane case in the Louisiana coast, to compare the generated surge over the island and the mainland. Even though peak surge height over Louisiana coast is much higher than the Kauai coast, the inundation was high due to wave run-up over the steep beaches. The wave run-up contributes to a major part of the inundation for the Hawaiian coast.

Recent progress in inundation mapping from models

Yoon and Shim[69] employed the FVCOM model (developed by Chen *et al.*[70]) to evaluate the extent of inundation along the Korean coastal region for Typhoon Maemi. Their study investigated the inundation characteristics over the low-lying coastal area near Masan, Yeosu and Busan cites in South Korea. It provided inundation maps for the coastal zones for a return period of about 200 years. Burston *et al.*[71] developed a real-time forecasting system for storm-tide inundation. It comprised of three components, viz. (i) a method to select probabilistic ensemble of tropical cyclone events to simulate storm-tide based on cyclone intensity, scale and track (landfall location and time); (ii) extension of existing wind-field-generation techniques available in real-time and (iii) hydrodynamic model optimized for real-time forecasting with options for near-shore storm-tide or inundation modelling. The inundation mapping procedures suggested two approaches – bath-tub mapping and inundation modelling and the study was implemented for the Yasi cyclone (January 2011) which made landfall along the east Australian coast.

Progress in inundation modelling for the Indian subcontinent

The tropical cyclone frequency for the northern Indian Ocean is around 5–6% of the global annual average. The frequency is higher in the Bay of Bengal than in the Arabian Sea and the ratio is 4 : 1 (ref. 72).

The monthly frequency of tropical cyclone activity in the Bay of Bengal displays a bimodal character with a primary peak during November and a secondary peak in May. May and June as well as October and November produce cyclones of severe intensity. Around 16% of cyclones intensify to severe cyclones and about 7% intensify to very severe cyclonic storms. Figure 1 shows the composite tracks of cyclones and depressions in the north Indian Ocean for the past century (1913–2013). A total of 1185 cyclones and tropical depressions formed in the north Indian Ocean basin during this period. In 2013 alone, five cyclonic storms, viz. Mahasen, Phailin, Helen, Lehar and Madi, formed over the Bay of Bengal. The Phailin cyclone[19] prompted India's biggest coastal evacuation efforts in the past 23 years, displacing more than 550,000 people from the coasts of Odisha and Andhra Pradesh to safer locations. The same storm took away 45 lives along its destructive trail and the total estimated damage was more than 696 million USD. The Figure 2 *a* shows the extent of model-computed onshore inundation from Thane cyclone along various locations in the Tamil Nadu coast[22]. As seen from the figure the onshore inundation distance varies between 2 and 349 m, with a mean value of 47.45 m. The Cuddalore which is close to the landfall location shows highest value of 349 m. Figure 2 *b* shows the beach slope at various locations along the coastline of Tamil Nadu that has a direct bearing on the onshore inundation during extreme weather events such as tropical cyclones. The historical landfall data show that the northern Indian Ocean cyclones mostly affect the Indian and Bangladesh coasts with occasional landfall along the Burmese coast. It is obvious that most of these tropical cyclone landfalls results in widespread flooding of the low-lying deltaic coastal plains.

In the context of the Indian subcontinent, storm-surge studies started in earnest during early 1970s. Previous studies focused mainly on the Bay of Bengal region, as it is a well-known cyclone-generating basin. Das[73] pioneered the storm-surge modelling work by developing the first numerical model to predict storm surges in the Bay of Bengal for the east coast of India and Bangladesh. This model simulated a devastating storm that struck the northeastern Bay of Bengal coast near Chittagong on 12 and 13 November 1970. The numerical computation of storm surge provided a maximum surge of 3.2 m at a distance of 40 km southwest of Chittagong, higher than the observed tide gauge record of 1.5 m. Later, storm-surge prediction models were developed and implemented for the Bangladesh coastal plain, being a high-risk low-lying delta (Ganges–Brahmaputra Basin). The cyclones approaching this Basin would be intensified due to the conical shape of the water body and their forward motion slowing down significantly when the cyclonic system interacts with the wide and shallow deltaic shelf off Bangladesh[72,74]. The super cyclone of April 1991 resulted in a storm-surge height that ranged from 6 to 8 m. Around 138,000 people lost their lives in the devastating floods due to the cyclone. During 2007, the Sidr cyclone resulted in death toll reaching around 10,000 and estimated property loss of around 1.7 million USD. Cyclone-induced storm surge along the Bangladesh coast has been studied

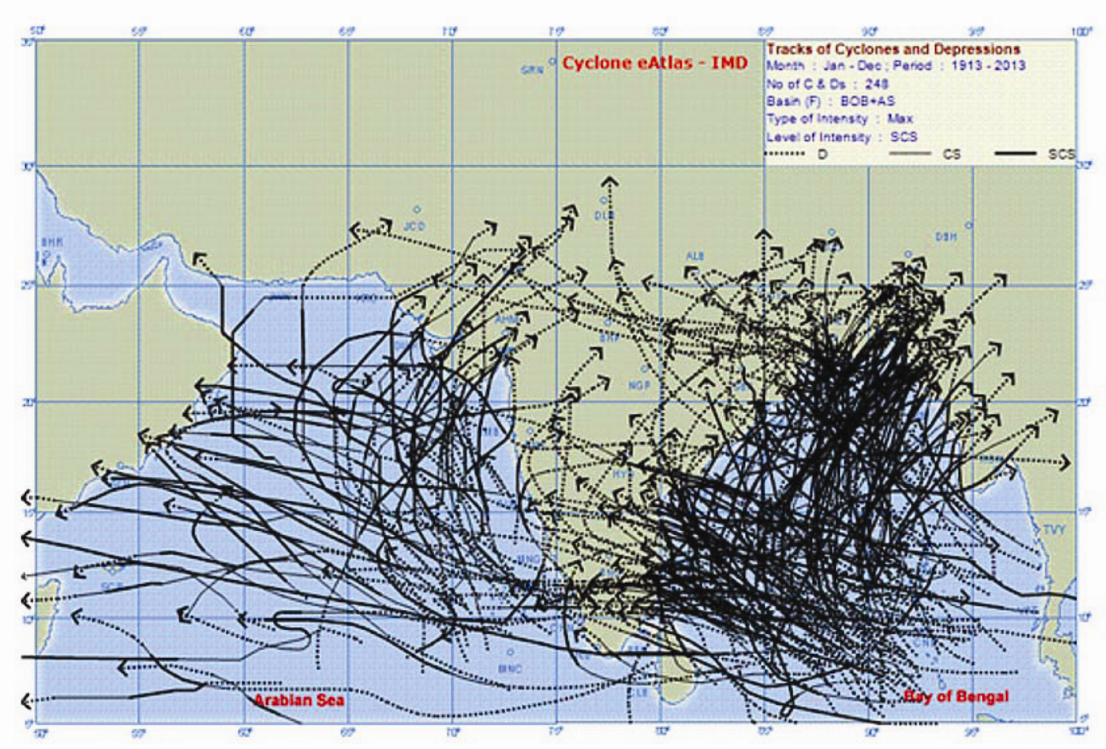

Figure 1. Cyclone tracks in the North Indian Ocean from 1913 to 2013. Source: Cyclone e-Atlas of India Meteorological Department.

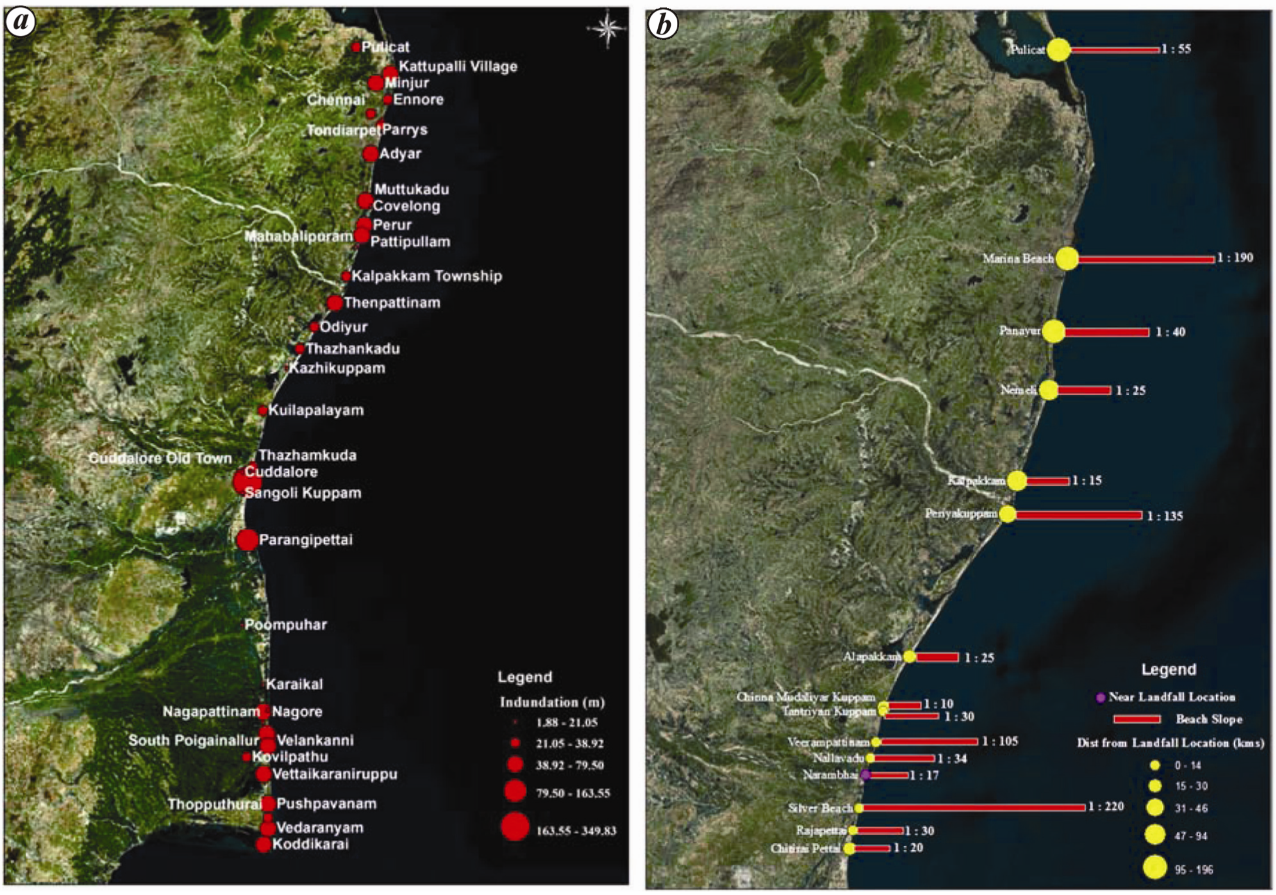

Figure 2. ***a***, Onshore coastal inundation (m) from numerical model. ***b***, Beach slopes along the Tamil Nadu coast for Thane cyclone. (Source: Bhaskaran *et al.*[22].)

by several researchers[75–81]. However, most of these studied failed to account for inundation of the low-lying inland areas that crisscross with numerous creeks and tidal channels with direct connection to open coastal waters. Madsen and Jokobsen[82] developed a forecast system for cyclonic surge and associated inundation along the Bangladesh coast. This model comprises three components: (i) statistical forecast models for cyclone track and maximum wind speed; (ii) analytical cyclone model for cyclone wind and pressure field generation, and (iii) data assimilation system that allows updating cyclone parameters based on air pressure and wind speed observations. The forecast model adopted MIKE 21 (DHI Water and Environment) to simulate the surge and inland flooding associated with the April 1991 super cyclone. The authors studied the flooding scenario using two cyclone tracks, one from JTWC (Joint Typhoon Warning Center) and other from BMD (Bangladesh Meteorological Department). The simulated storm-surge levels were in good agreement with *in situ* observations. Based on a sensitivity study involving two different cyclone tracks, the authors concluded that data assimilation in surge forecast modelling could significantly enhance the quality of storm surge and inundation prediction. Another breakthrough in inundation modelling for Bangladesh coast is by Lewis *et al.*[83]. The flood forecast model (LISFLOOD-FP) solves a local inertial approximation to the full shallow-water equations using a finite-difference technique. The study used topographic data from Shuttle Radar Topography Mission (SRTM) to generate DEM for the LISFLOOD-FP inundation model. Another highlight of inundation modelling is the incorporation of river run-off as a boundary forcing. The model investigated the surge and inland flooding associated with the 2007 Sidr cyclone. The performance of LISFLOOD-FP in simulating the flooded area from cyclone Sidr-induced storm surge was evaluated using data from ENVISAT Advanced Synthetic Aperture Radar (ASAR) image. The authors concluded that LISFLOOD_FP is a computationally inexpensive model that could use freely available data sources for flood-risk management. Fritz *et al.*[84] conducted an extensive modelling study for cyclone Gonu storm surge and inundation along Oman coast using ADCIRC. The study reported that flooding along the Oman coast was from a combination of cyclone-induced storm surge and intense rainfall. The necessity for coupling storm surge and wave models to better quantify their relative importance in simulating coastal-inundation during cyclone landfall are discussed by the auhors. Dube *et al.*[85] developed location-specific inundation models for the Andhra and Odisha coasts using finite difference approach, to evaluate the inland intrusion of the storm surge. The model formulation, boundary conditions and numerical procedures were similar to that of Johns *et al.*[86]. The peak surge height and inland intrusion caused by the 1977 the Andhra cyclone and the Andhra coast 1990 May cyclone were determined for 13 locations along from Mahabalipuram to Santapalli. The maximum peak surge was computed using both inundation model and fixed coastline model (see Johns *et al.*[86] for more details on these two approaches). Comparison of the results showed that the inundation model under-predicts the surge value with respect to the fixed coastline model. Johns *et al.*[86] concluded that under-prediction could be attribute to the inland intrusion of water in the inundation models. Even though the model under-predicts the peak surge, maximum inland inundation at Divi was in close comparison to the field survey reports. Rao *et al.*[87] implemented ADCIRC model for the east coast of India to evaluate extreme storm-surge scenarios along Kalpakkam coast, known for its nuclear power plant. They identified 11 very severe cyclonic storms that made landfall in coastal Tamil Nadu from 1971 to 2007. Using these actual and theoretical tracks, seven synthesized generated tracks provided a comprehensive geographical coverage of the coastal areas of Tamil Nadu. Based on the simulations using synthetic tracks, the authors concluded that Kalpakkam region is vulnerable to inland inundation that may cause significant damage to local development, if the cyclone-generated surges are more than 3.5 m. The Figures 3 *a* and *b* shows the respective spatial distribution of storm surge for Phailin cyclone using uncoupled (ADCIRC standalone) and coupled (ADCIRC + SWAN) model runs[19]. As seen from the figure, the storm surge affects vast stretches along Odisha coast with extreme water levels exceeding 1.5 m, with peak surge development in close vicinity of Ganjam, Odisha. The computed maximum storm-tide (combination of surge with tide) at Ganjam is 2.3 m with ADCIRC model run in standalone mode, whereas computation using a coupled model (ADCIRC + SWAN) gives a value of 2.8 m amsl. The Figure 3 *c* illustrates the enlarged view on the extent of maximum horizontal inundation with the Phailin cyclone. Sreenivasa Kumar *et al.*[20] reported that the maximum inundation extent of about 430 m occurred neared Ganjam for Phailin cyclone (Figure 3 *c*). Their study showed that the modelled inundation extent varied between 50 and 430 m, and increased over regions where the topographical slope was less than 1 : 100, and post-storm survey data at 29 coastal stations were used to validate the model-simulated inundation extent[20].

Wave-induced set-up also contributes to the extreme water-level elevation during cyclonic events. Figure 4 shows the water-level elevation produced from wave set-up, seen extending all along coastal Odisha and northern parts of Andhra Pradesh close to Vizianagaram.

Sudha Rani *et al.*[88] have provide a comprehensive review on coastal vulnerability assessment studies over India. Rajesh Kumar *et al.*[89] have studied the role of muddy beds on wave attenuation characteristics. Nayak *et al.*[90] and Nayak and Bhaskaran[91] have reported on the location-specific near-shore wave-induced set-up and

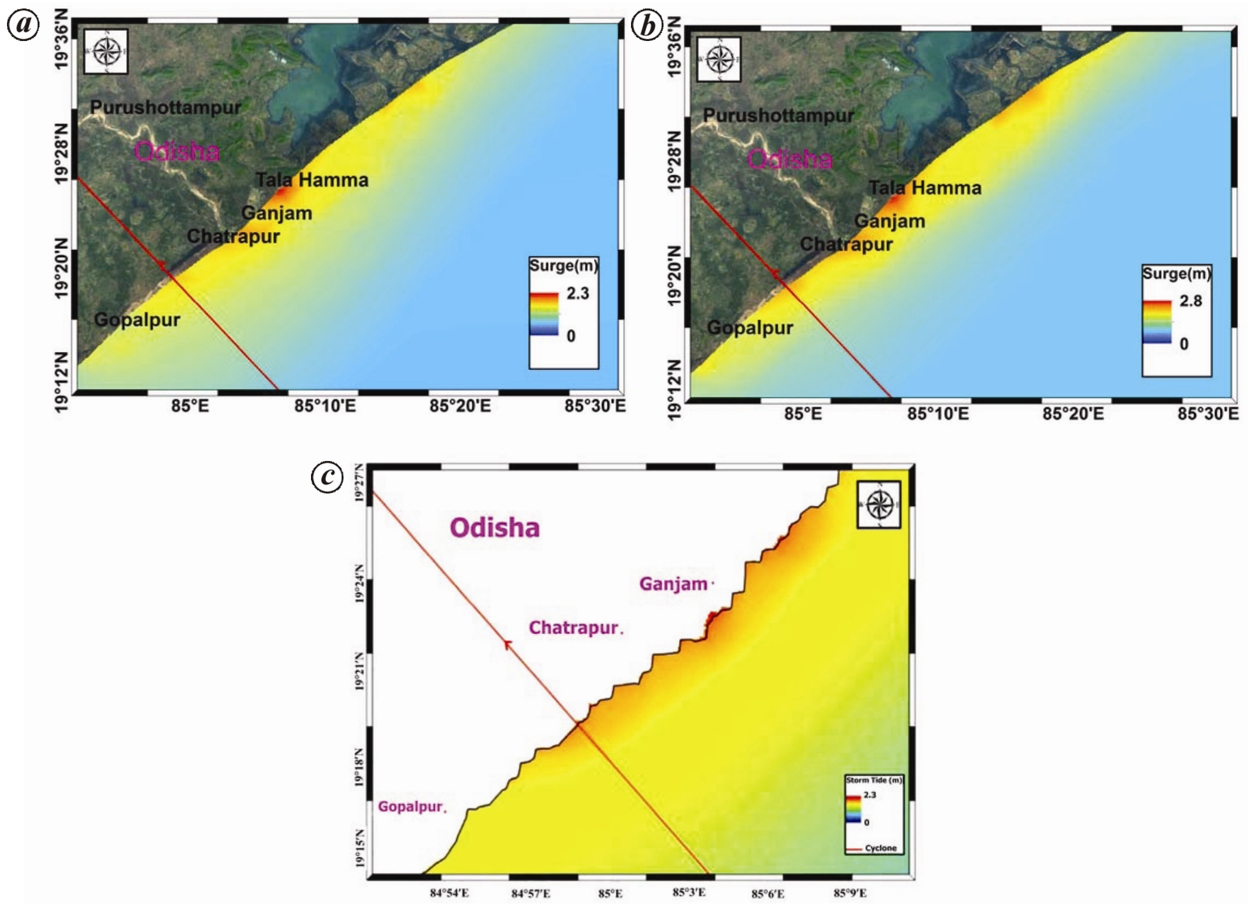

Figure 3. Spatial distribution of storm surge (m) obtained using (***a***) uncoupled (ADCIRC alone), and (***b***) coupled (ADCIRC + SWAN) model runs for Phailin cyclone (source: Murty *et al.*[19]). (***c***) Enlarged view of the spatial distribution of storm tide near Ganjam showing the inundation extent (source: Srinivasa Kumar *et al.*[20]).

coastal vulnerability from extreme waves considering historical tropical cyclones in the Bay of Bengal. Another interesting study by Nayak *et al.*[92] considered the role of remote forcing effects from distant swells in modifying the local wind-wave climate. Sandhya *et al.*[93] reported on the importance of an operational wave-forecasting system and its validation for a coastal location in India. Further progress in inland inundation modelling was made by Bhaskaran *et al.*[21,22] using a version of ADCIRC in a coupled wave-hydrodynamic model (ADCIRC + SWAN), that runs in a parallel computing architecture. This coupled model simulated peak surge and coastal inundation along Tamil Nadu coast due to a very severe tropical cyclone (Thane) in the Bay of Bengal. The study revealed that coastal zone located south of the cyclone track inundated significantly, attributed to low-lying topography and geomorphological features of that region. This work is unique in the Indian context, as it attempted to validate the simulated landward extent and intensity of inundation with field measurements. The study also illustrated that for steep slope beach, inundation is comparatively higher than flat slope beaches. It also highlighted the importance of an operational coastal inundation modelling system for the Indian coasts.

Summary and conclusion

The present study provided a review of coastal inundation involving various contributing factors and physical mechanisms. The main objective was to evaluate the progress achieved so far in tropical storm-induced storm surge and inundation modelling. Further, this work focused on the status of storm-surge research in the Indian subcontinent, which has recently seen an increase in both frequency and intensity of tropical cyclones generated in the Bay of Bengal. During the last few decades tremendous progress was achieved in coastal inundation research, particularly in hurricane/cyclone-induced storm surge and coastal flooding due to tsunamis. The latest reported studies on storm-surge research have utilized models like ADCIRC, FVCOM and CH3D-SSMS, which can be constrained using coastal geomorphologic features and the land use/land cover for additional friction. These advanced models adopted coupled model architecture for

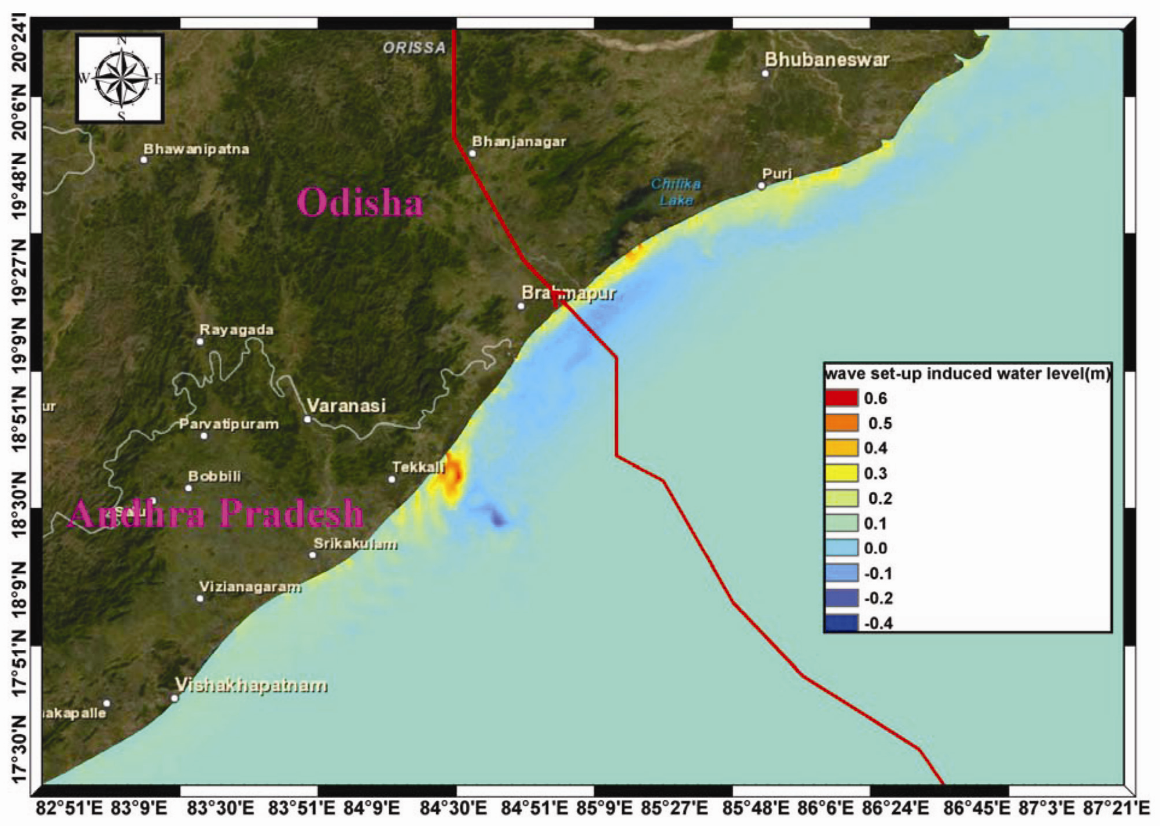

Figure 4. Model-computed wave induced set-up (m) for Phailin cyclone along the Odisha coast (source: Murty *et al.*[19]).

predictions that are more realistic and computationally optimized. Many factors need consideration to obtain realistic estimates of peak surge and onshore intrusion of the sea. The first and foremost factor is utilizing a high-resolution computational grid that well captures the coastline geometry and its complex bathymetry, particularly for complex coastal zones, viz. deltaic coasts of Bangladesh and eastern India coast. In addition, the GIS-enabled digital elevation models need blending with coastal survey data to enhance the overall quality of topographic and bathymetric data. In addition to the above measures, significant improvements are required in the meteorological forcing fields, viz. data on spatial and temporal evolution of wind field. Model-computed coastal inundation is sensitive to this forcing field, and uncertainties of input wind could adversely affect numerical predictions. Tuning of appropriate model physics needs to be adapted for the location of interest. Therefore, advancements in these aspects of modelling techniques can result in improving the capability of model prediction and its application for operational needs.

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Received 9 November 2015; revised accepted 25 August 2016

doi: 10.18520/cs/v112/i02/267-278