= Storm surge =

A storm surge is a coastal flood or tsunami @-@ like phenomenon of rising water commonly associated with low pressure weather systems (such as tropical cyclones and strong extratropical cyclones) , the severity of which is affected by the shallowness and orientation of the water body relative to storm path , and the timing of tides . Most casualties during tropical cyclones occur as the result of storm surges .

The two main meteorological factors contributing to a storm surge are a long fetch of winds spiraling inward toward the storm , and a low @-@ pressure @-@ induced dome of water drawn up under and trailing the storm 's center .

= = Historic storm surges = =

The deadliest storm surge on record was the 1970 Bhola cyclone , which killed up to 500 @,@ 000 people in the area of the Bay of Bengal . The low @-@ lying coast of the Bay of Bengal is particularly vulnerable to surges caused by tropical cyclones . The deadliest storm surge in the twenty @-@ first century was caused by the Cyclone Nargis , which killed more than 138 @,@ 000 people in Myanmar in May 2008 . The next deadliest in this century was caused by the Typhoon Haiyan (Yolanda) , which killed more than 6 @,@ 000 people in the central Philippines in 2013 and resulted in economic losses estimated at $ 14 billion (USD) .

The Galveston Hurricane of 1900 , a Category 4 hurricane that struck Galveston , Texas , drove a devastating surge ashore ; between 6 @,@ 000 and 12 @,@ 000 lives were lost , making it the deadliest natural disaster ever to strike the United States .

The highest storm tide noted in historical accounts was produced by the 1899 Cyclone Mahina , estimated at almost 44 ft (13 metres) at Bathurst Bay , Australia , but research published in 2000 saw the majority of this was likely wave run @-@ up , due to the steep coastal topography . In the United States , one of the greatest recorded storm surges was generated by 2005 's Hurricane Katrina , which produced a maximum storm surge of more than 25 ft (8 metres) in the communities of Waveland (41 @.@ 5 ft) , Bay St. Louis (38 ft) , Diamondhead (30 ft) and Pass Christian (35 ft) in Mississippi . Another record storm surge occurred in this same area from Hurricane Camille in August 1969 , with the highest storm tide of record noted from a high water mark as 24 @.@ 6 ft (7 @.@ 5 m) , also found in Pass Christian (the back side of St. Louis Bay got up to 35 ft) . A high storm surge occurred in New York City from Hurricane Sandy in October 2012 , with a high tide of 14 ft (4 @.@ 2 m) .

= = Mechanics = =

At least five processes can be involved in altering tide levels during storms : the pressure effect , the direct wind effect , the effect of the Earth 's rotation , the effect of waves , and the rainfall effect . The pressure effects of a tropical cyclone will cause the water level in the open ocean to rise in regions of low atmospheric pressure and fall in regions of high atmospheric pressure . The rising water level will counteract the low atmospheric pressure such that the total pressure at some plane beneath the water surface remains constant . This effect is estimated at a 10 mm (0 @.@ 39 in) increase in sea level for every millibar (hPa) drop in atmospheric pressure .

Strong surface winds cause surface currents at a 45 degree angle to the wind direction , by an effect known as the Ekman Spiral . Wind stresses cause a phenomenon referred to as " wind set @-@ up " , which is the tendency for water levels to increase at the downwind shore , and to decrease at the upwind shore . Intuitively , this is caused by the storm simply blowing the water towards one side of the basin in the direction of its winds . Because the Ekman Spiral effects spread vertically through the water , the effect is inversely proportional to depth . The pressure effect and the wind set @-@ up on an open coast will be driven into bays in the same way as the astronomical tide .

The Earth 's rotation causes the Coriolis effect , which bends currents to the right in the Northern

Hemisphere and to the left in the Southern Hemisphere . When this bend brings the currents into more perpendicular contact with the shore it can amplify the surge , and when it bends the current away from the shore it has the effect of lessening the surge .

The effect of waves , while directly powered by the wind , is distinct from a storm 's wind @-@ powered currents . Powerful wind whips up large , strong waves in the direction of its movement . Although these surface waves are responsible for very little water transport in open water , they may be responsible for significant transport near the shore . When waves are breaking on a line more or less parallel to the beach , they carry considerable water shoreward . As they break , the water particles moving toward the shore have considerable momentum and may run up a sloping beach to an elevation above the mean water line which may exceed twice the wave height before breaking .

The rainfall effect is experienced predominantly in estuaries . Hurricanes may dump as much as 12 in (300 mm) of rainfall in 24 hours over large areas , and higher rainfall densities in localized areas . As a result , watersheds can quickly surge water into the rivers that drain them . This can increase the water level near the head of tidal estuaries as storm @-@ driven waters surging in from the ocean meet rainfall flowing from the estuary .

Surge and wave heights on shore are affected by the configuration and bathymetry of the ocean bottom . A narrow shelf , or one that has a steep drop from the shoreline and subsequently produces deep water in proximity to the shoreline tends to produce a lower surge , but a higher and more powerful wave . This situation well exemplified by the southeast coast of Florida . The edge of the Floridian Plateau , where the water depths reach 91 metres (299 ft) , lies just 3 @,@ 000 m (9 @,@ 800 ft) offshore of Palm Beach , Florida ; just 7 @,@ 000 m (23 @,@ 000 ft) offshore , the depth increases to over 180 m (590 ft) . The 180 m (590 ft) depth contour followed southward from Palm Beach County lies more than 30 @,@ 000 m (98 @,@ 000 ft) to the east of the upper Keys .

Conversely , coastlines along North America such as those along the Gulf of Mexico coast from Texas to Florida , and Asia such as the Bay of Bengal , have long , gently sloping shelves and shallow water depths . On the Gulf side of Florida , the edge of the Floridian Plateau lies more than 160 kilometres (99 mi) offshore of Marco Island in Collier County . Florida Bay , lying between the Florida Keys and the mainland , is also very shallow ; depths typically vary between 0 @.@ 3 m (0 @.@ 98 ft) and 2 m (6 @.@ 6 ft) . These areas are subject to higher storm surges , but smaller waves . This difference is because in deeper water , a surge can be dispersed down and away from the hurricane . However , upon entering a shallow , gently sloping shelf , the surge cannot be dispersed , but is driven ashore by the wind stresses of the hurricane . Topography of the land surface is another important element in storm surge extent . Areas where the land lies less than a few meters above sea level are at particular risk from storm surge inundation .

For a given topography and bathymetry the surge height is not solely affected by peak wind speed ; the size of the storm also affects the peak surge . With any storm the piled up water has an exit path to the sides and this escape mechanism is reduced in proportion to the surge force (for the same peak wind speed) as the storm covers more area .

In the Asian region , the Philippines are one of the most affected by storm surges of typhoons as it lies in the path of tradewinds @-@ entrained typhoons heading toward Japan , Taiwan , China , Vietnam , and Cambodia .

= = = Extratropical storms = = =

Similar to tropical cyclones , extra @-@ tropical storms cause an offshore rise of water . However , unlike most tropical cyclone storm surge , extra @-@ tropical storms can cause higher water levels across a large area for longer periods of time , depending on the system . This is due to many factors , such as storm size and different steering winds , which could keep a system in a storm @-@ surge prone area for longer periods of time .

Another component of extra @-@ tropical storm surge is the phenomenon of negative water levels . If strong winds are blowing offshore , situations can arise where mean water levels in a bay fall significantly , which poses a serious threat for ships tied up at piers . If negative water levels are

severe enough , ships tied up at docks can actually sit on the seafloor , preventing them from leaving port .

In North America , extra @-@ tropical storm surges may occur on the Pacific and Alaska coasts , and north of 31 ° N on the Atlantic Coast . Extra @-@ tropical storm surges may be possible for the Gulf coast mostly during the wintertime , when extra @-@ tropical cyclones affect the coast , such as in the March 1993 Storm of the Century .

November 9 ? 13 , 2009 marked a significant extratropical storm surge event on the US east coast when the remnants of Hurricane Ida developed into a Nor 'easter off the Southeast US coast . During the event , storm force winds from the east were present along the northern periphery of the low pressure center for a number of days , forcing water into locations such as Chesapeake Bay . Water levels rose significantly , and remained as high as 8 feet (2 @.@ 4 m) above normal in numerous locations throughout the Chesapeake for a number of days as water was continually built @-@ up inside the estuary from the onshore winds and freshwater rains flowing into the bay . In many locations , water levels were shy of records by only 0 @.@ 1 feet (3 cm) .

= = Measuring surge = =

Surge can be measured directly at coastal tidal stations as the difference between the forecast tide and the observed rise of water . Another method of measuring surge is by the deployment of pressure transducers along the coastline just ahead of an approaching tropical cyclone . This was first tested for Hurricane Rita in 2005 . These types of sensors can be placed in locations that will be submerged , and can accurately measure the height of water above them .

After surge from a cyclone has receded , teams of surveyors map high @-@ water marks (HWM) on land , in a rigorous and detailed process that includes photos and written descriptions of the marks . HWMs denote the location and elevation of flood waters from a storm event . When HWMs are analyzed , if the various components of the water height can be broken out so that the portion attributable to surge can be identified , then that mark can be classified as storm surge . Otherwise , it is classified as storm tide . HWMs on land are referenced to a vertical datum (a reference coordinate system) . During evaluation , HWMs are divided into four categories based on the confidence in the mark ; only HWMs evaluated as " excellent " are used by NHC in post storm analysis of the surge .

Two different measures are used for storm tide and storm surge measurements . Storm tide is measured using a geodetic vertical datum (NGVD 29 or NAVD 88) . Since storm surge is defined as the rise of water beyond what would be expected by the normal movement due to tides , storm surge is measured using tidal predictions , with the assumption that the tide prediction is well @-@ known and only slowly varying in the region subject to the surge . Since tides are a localized phenomenon , storm surge can only be measured in relationship to a nearby tidal station . Tidal bench mark information at a station provides a translation from the geodetic vertical datum to mean sea level (MSL) at that location , then subtracting the tidal prediction yields a surge height above the normal water height .

= = SLOSH = =

The National Hurricane Center in the US , forecasts storm surge using the SLOSH model , which stands for Sea , Lake and Overland Surges from Hurricanes . The model is accurate to within 20 percent . SLOSH inputs include the central pressure of a tropical cyclone , storm size , the cyclone 's forward motion , its track , and maximum sustained winds . Local topography , bay and river orientation , depth of the sea bottom , astronomical tides , as well as other physical features are taken into account , in a predefined grid referred to as a SLOSH basin . Overlapping SLOSH basins are defined for the southern and eastern coastline of the continental U.S. Some storm simulations use more than one SLOSH basin ; for instance , Katrina SLOSH model runs used both the Lake Ponchartrain / New Orleans basin , and the Mississippi Sound basin , for the northern Gulf of Mexico landfall . The final output from the model run will display the maximum envelope of water , or MEOW

, that occurred at each location . To allow for track or forecast uncertainties , usually several model runs with varying input parameters are generated to create a map of MOMs , or Maximum of Maximums . And for hurricane evacuation studies , a family of storms with representative tracks for the region , and varying intensity , eye diameter , and speed , are modeled to produce worst @-@ case water heights for any tropical cyclone occurrence . The results of these studies are typically generated from several thousand SLOSH runs . These studies have been completed by USACE , under contract to the Federal Emergency Management Agency , for several states and are available on their Hurricane Evacuation Studies (HES) website . They include coastal county maps , shaded to identify the minimum SSHS category of hurricane that will result in flooding , in each area of the county .

= = Mitigation = =

Although meteorological surveys alert about hurricanes or severe storms , in the areas where the risk of coastal flooding is particularly high , there are specific storm surge warnings . These have been implemented , for instance , in the Netherlands , Spain , the United States , and the United Kingdom .

A prophylactic method introduced after the North Sea Flood of 1953 is the construction of dams and floodgates (storm surge barriers) . They are open and allow free passage but close when the land is under threat of a storm surge . Major storm surge barriers are the Oosterscheldekering and Maeslantkering in the Netherlands which are part of the Delta Works project , the Thames Barrier protecting London and the Saint Petersburg Dam in Russia .

Another modern development (in use in the Netherlands) is the creation of housing communities at the edges of wetlands with floating structures , restrained in position by vertical pylons . Such wetlands can then be used to accommodate runoff and surges without causing damage to the structures while also protecting conventional structures at somewhat higher low @-@ lying elevations , provided that dikes prevent major surge intrusion .

For mainland areas , storm surge is more of a threat when the storm strikes land from seaward , rather than approaching from landwards .