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Storm Surge Causes and Different Variations

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Abstract

A storm surge, storm flood or storm tide is a coastal flood or tsunami-like phenomenon of rising water commonly associated with low pressure weather systems (such as tropical cyclones and strong extra-tropical cyclones), the severity of which is affected by the shallowness and orientation of the water body relative to storm path, as well as the timing of tides. Most casualties during tropical cyclones occur as the result of storm surges. It is a measure of the rise of water beyond what would be expected by the normal movement related to tides.

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.

Keywords: Extra Tropical Storms; Measuring Surge; SLOSH; Mitigation; Reverse Storm Surge.

1. Introduction

A storm surge is a rise in sea level that occurs during tropical cyclones, intense storms also known as typhoons or hurricanes. The storms produce strong winds that push the water into shore, which can lead to flooding. This makes storm surges very dangerous for coastal regions.

2. Historic Storm Surges

Total destruction of the Bolivar Peninsula by Hurricane Ike's storm surge in 2008.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 meters) at Bathurst Bay, Australia, but research published in 2000 concluded that the majority of this likely was wave run-up because of the steep coastal topography. In the United States, one of the greatest recorded storm surges was generated by Hurricane Katrina in 2005, which produced a maximum storm surge of more than 25 ft. (8 meters) in southern Mississippi, with a storm surge height of 27.8 ft. (8.5 m) in Pass Christian. Another record storm surge occurred in this same area from Hurricane Camille in 1969, with a storm tide of 24.6 ft. (7.5 m), also at Pass Christian. A storm surge of 14 ft. (4.2 m) occurred in New York City during Hurricane Sandy in October 2012.

At least five processes can be involved in altering tide levels during storms

a) The atmospheric pressure effect
b) The direct wind effect
c) The effect of the Earth's rotation
d) The effect of waves near the shore
e) The rainfall effect.

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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 because surface currents at a 45° angle to the wind direction, by an effect known as the Ekman Spiral. Wind stresses because 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 blowing the water toward one side of the basin in the direction of its winds. Because the Ekman Spiral effects spread vertically through the water, the effect is 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, surface runoff can quickly flood Streams and rivers. This can increase the water level near the head of tidal estuaries as storm-driven waters surging in from the ocean meet rainfall flowing downstream into the estuary.

3. Other Processes

In addition to the above processes, surge and wave heights on shore are also affected by the flow of water over the underlying topography, i.e. the configuration and bathymetry of the ocean bottom and affected coastal area.

A narrow shelf, for example, 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 is well exemplified by the southeast coast of Florida. The edge of the Floridian Plateau, where the water depths reach 91 meters (299 ft.), lies just 3,000 m (9,800 ft.) offshore of Palm Beach; 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 Florida 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 kilometers (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 with 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 disperse, 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 area of piled up water can flow out of the storm perimeter, and this escape mechanism is reduced in proportion to the surge force (for the same peak wind speed) when the storm covers more area (storm perimeter length per area is inversely proportional to a circular storm's diameter).

4. Extra Tropical Storms

Similar to tropical cyclones, extra tropical cyclones cause an offshore rise of water. However, unlike most tropical cyclone storm surges, extra tropical cyclones can cause higher water levels across a large area for longer periods of time, depending on the system.

In North America, extra tropical storm surges may occur on the Pacific and Alaska coasts, and north of 31°N on the Atlantic Coast. Coasts with sea ice may experience an "ice tsunami" causing significant damage inland. Extra tropical storm surges may be possible further south for the Gulf coast mostly during the wintertime, when extra tropical cyclones affect the coast, such as in the 1993 Storm of the Century.

November 9–13, 2009, marked a significant extra tropical storm surge event on the United States east coast when the remnants of Hurricane Ida developed into a Nor'easter off the southeast U.S. coast. During the event, 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).

5. 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 photographs 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 National Hurricane Center 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 caused by 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.

6. SLOSH

The National Hurricane Center forecasts storm surge using the SLOSH model, which is an abbreviation 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, Hurricane 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. 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 the United States Army Corps of Engineers, 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 category of hurricane that will result in flooding, in each area of the county.

7. 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 storm-surge barriers (flood 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 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 landward.

8. Reverse Storm Surge

Water can also be sucked away from shore prior to a storm surge. This was the case on the western Florida coast in 2017, just before Hurricane Irma made landfall, uncovering land usually underwater. This phenomenon is known as a reverse storm surge, or a negative storm surge.

9. First Scientific and Technical Symposium on Storm Surges

The First Scientific and Technical Symposium on Storm Surges was organized in October 2007 by the WMO-IOC Joint Technical Commission JCOMM i.e. "Joint Commission for Oceanography and Marine Meteorology" in Seoul, Republic of Korea, hosted by the Korean Government. This symposium was the first such scientific event devoted solely to storm surges in at least the past 3 decades. It aimed to support the development of marine multi-hazard warning systems, by

1) Providing a forum for the exchange of ideas and information related to storm surge modelling, forecasting and hind casting;

2) Coordinating ongoing and planning future R&D initiatives in these fields; and

3) Providing guidance/technical support for National Meteorological Services and other national agencies providing storm surge forecasting and warning services.

Results from the Symposium are to contribute to the JCOMM Guide to Storm Surge Forecasting which was under finalization. It will set the stage for advances in forecasting of these events and reduction of their impacts. Overall, the symposium was a great success, and all participants were appreciative of this initiative at the present time. The quality of the presentations was excellent, which would facilitate the selection of a subset of them for peer review and publication in the planned special edition of the journal “Natural Hazards – Journal of the International Society for the Prevention and Mitigation of Natural Hazards” (Springer). This same subset would also form the “dynamic” part of the new Guide to Storm Surge Forecasting. A key component of the symposium was the panel discussion session on the last day, designed to draw conclusions and point the way forward in storm surge modeling and forecasting. The agreed set of recommendations and actions are addressed to researchers, WMO/IOC/JCOMM, and Member States.

10. Conclusion

Storm surge is the rise in seawater level caused solely by a storm. This example illustrates water level differences for storm surge, storm tide, and a normal (predicted) high tide as compared to sea level. Storm surge is the rise in seawater level caused solely by a storm.

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