Impacts and responses

This information has been summarised from the Introduction to Tropical Meteorology (2nd Edition) which can be accessed, free of charge, on the MetEd/ COMET website (requires free registration).

Introduction

Tropical cyclones are the most hazardous tropical weather systems. Their hazards include:

- strong winds
- storm surge
- wind-driven waves
- heavy rainfall & flooding
- tornadoes
- lightning

Their Impacts fall into two categories:

- **Direct** impacts result directly from the storm itself, and include coastal erosion by storm surge and loss of infrastructure from wind stress.
- **Indirect** impacts occur as a consequence of direct impacts, and include diseases associated with water contamination, oil price increases when drilling platforms and refineries are damaged or closed, and fires started by live, downed power lines.

Furthermore, some indirect impacts are **longer term**, including economic loss from damage to crops and fisheries where livelihoods are dependent on agriculture, post disaster stress, and insurance rate increases.

The hazards created by tropical cyclones have a variety of impacts that vary spatially and temporally.

Societal and Environmental Impacts

Storm Surge and Wind-driven Waves

Whenever there was a large loss of life from tropical cyclones, the predominant cause of death was drowning, not wind or windblown objects or structural failures.

Globally, storm surge is the deadliest direct TC hazard. A storm surge is a large dome of water, 50 to 100 miles wide, that sweeps across the coast near where a hurricane makes landfall. It can be more than 5 metres deep at its peak (Fig. 1).

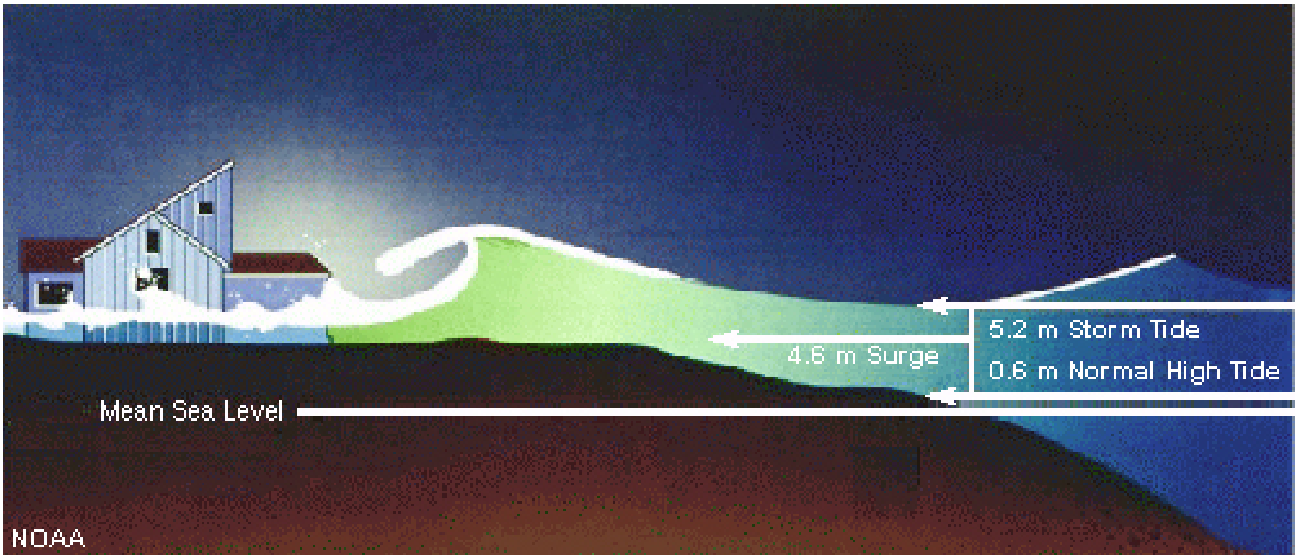


Figure 1 *A conceptual model of storm surge. NOAA*

The storm surge is created by wind-driven waves resulting from the low-pressure at the centre of the cyclone. The surge is strongest where the winds are enhanced by the motion of the cyclone, therefore, the right (left) forward quadrant of the storm is the most dangerous storm surge region as the forward motion of the cyclone and direct of the wind are added together.

While the waves may be relatively low in the open ocean, they gain height as they approach the coast, and are aggravated by a high tide (consequently the timing of landfall in relation to lunar tides directly influences the potential hazard and associated impacts). The surge can move coastal structures and soil several miles inland. Geological studies have revealed layers of sediment in an Alabama lakebed believed to have been brought inland by storm surges as many as 3000 years ago.

Coastal flood models, such as NOAA's 'SLOSH' model (Sea, Lake, and Overland Surges from Hurricanes) are used to predict the storm surge. Further information, and access to SLOSH mapping is available from https://www.nhc.noaa.gov/surge/slosh.php.

Extratropical transition (ET) (when the cyclone moves from the tropics into the mid-latitudes (30-60° latitude) of tropical cyclones can cause extreme waves.

For example, waves of over 30 meters were generated during the ET of Hurricane Luis (1995) causing extensive damage to the Queen Elizabeth II ocean liner. The extreme waves arrived only shortly before the main centre of the storm.

The growth of these waves has been explained in terms of "trapped fetch" in which the rapid forward motion of the cyclone means that the storm moves for a long time with the fastest growing waves (Fig. 2). As a result, waves generated during ET can be much larger than the waves generated by a tropical cyclone while it remains in the tropics.

Enhancement in wave growth occurs only in the fastest wind region of the ET storm (where the storm winds and its forward motion are additive).

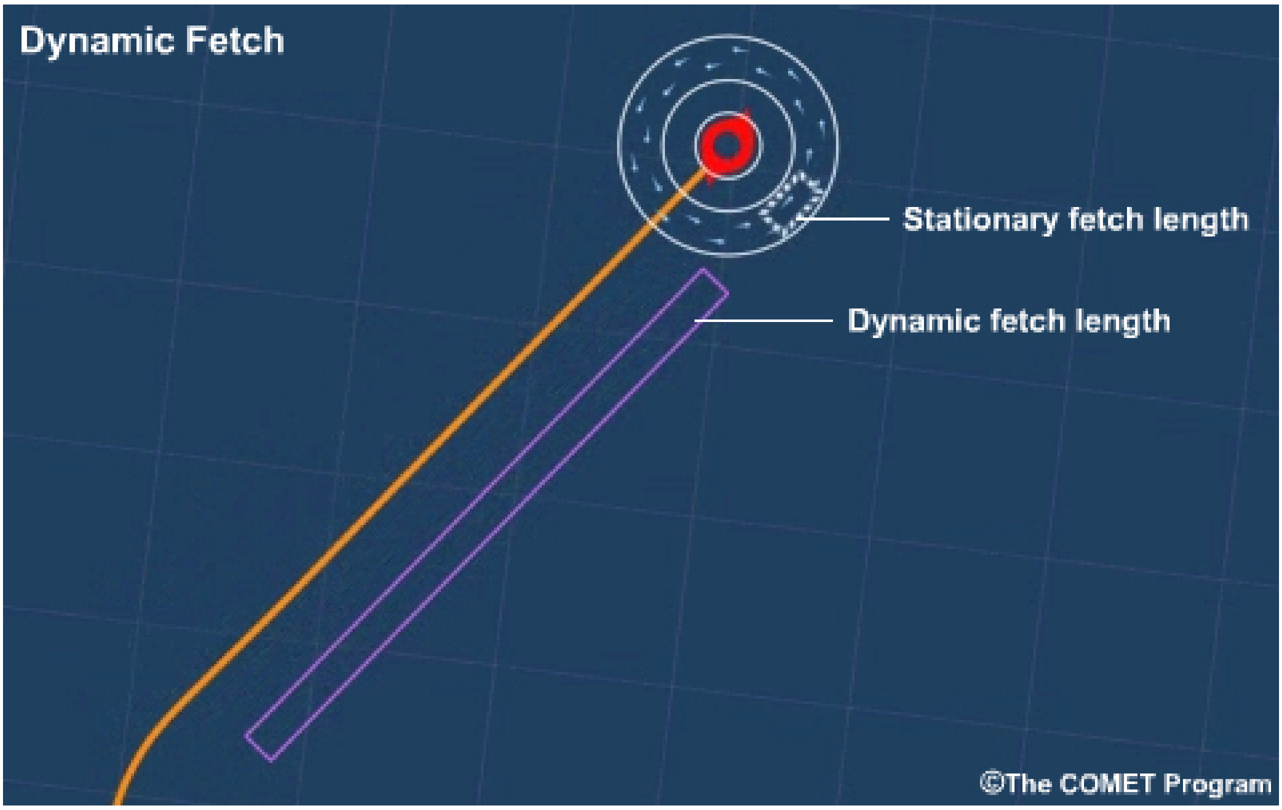
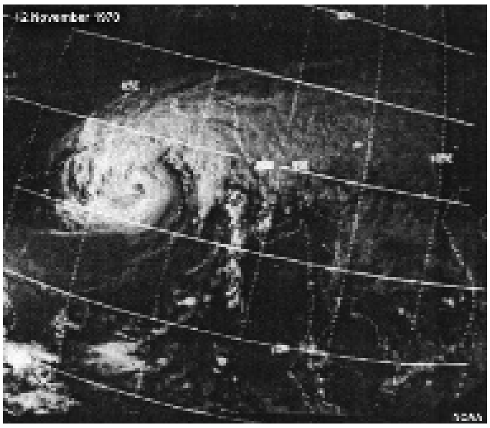


Figure 2 *Conceptual model of a tropical cyclone with a straight storm path and a fetch in the right of track (outlined with a dotted white line), Waves within the dotted line experience a longer period of wind forcing; the distance over which they grow is called*

Case studies – Bangladesh

Bangladesh is particularly vulnerable to storm-surge, wind-driven waves and coastal inundation as much of the south of the country is essentially at sea-level.

The Bhola Cyclone, 1970



On the 12 November 1970 Cyclone Bhola made landfall after dark in Bangladesh, killing between 300,000 – 500,000 people.

The cyclone formed over the central Bay of Bengal on 8 November and intensified as it moved North, reaching its peak 10-minute sustained wind speed of 50 m s^{-1} (185 km h^{-1}; Category 3 on the Saffir-Simpson scale) with minimum central pressure of 966 hPa on 12 Nov 1970.

That night of 12 November 1970 the storm made landfall on the coast of East Pakistan (now Bangladesh). Many of the offshore islands were devastated by storm surge. The city of Tazumuddin (in the Bhola district of Bangladesh) was the most severely affected, with over 45% of the population of

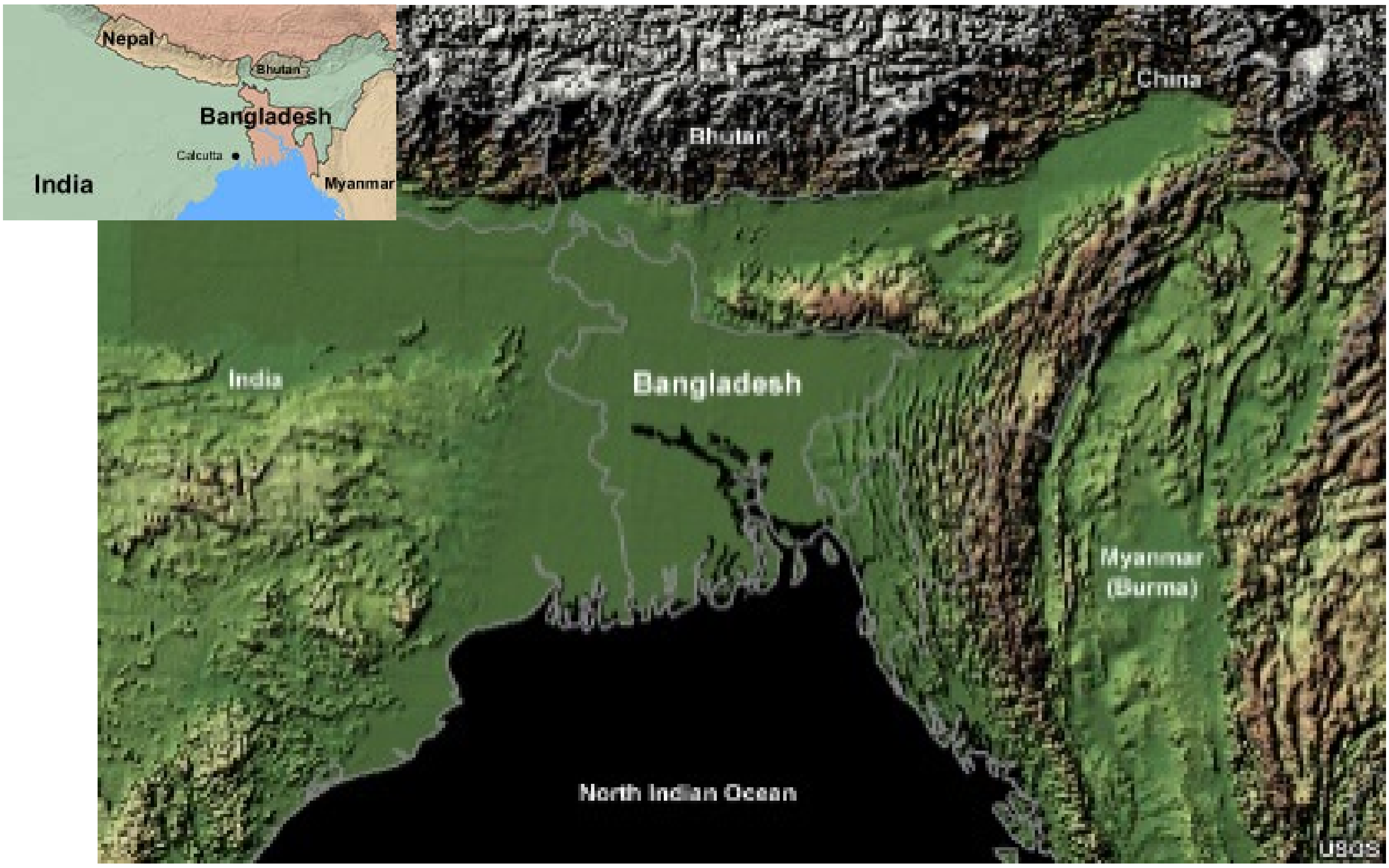


Figure 3 *A topographical map showing the location of Bangladesh in a low-lying delta region (dark green) surrounded by higher terrain.*

167,000 killed by the storm. Orographically enhanced rainfall and storm surge made a devastating and deadly combination in the low-lying areas in the northern reaches of the Bay of Bengal (Fig. 3).

The Chittagong Cyclone, 1991

Tropical Cyclone 02B made landfall in Chittagong, Bangladesh on 29 April 1991 at about 1900 UTC. The official death toll from this storm was 138,000 people. Estimated damage was in excess of US $2.8 billion (in 2019 dollars). The coastal region was devastated by peak 1-minute averaged surface winds in excess of 72 m s^{-1} (260 km h^{-1}), 898 hPa minimum pressure (Saffir-Simpson Category 5), and a 6.1 metre storm surge.

Figure 4 Tropical Cyclone 02B at ~ 1900 UTC, 29 April 1991.

However, as the 1970 Bhola storm demonstrated, the death toll could have been much higher. Evacuations of 2-3 million coastal residents were effective in reducing the fatalities, although the storm was still the largest natural disaster globally in 1991. The value of evacuation and shelter was demonstrated even more dramatically when powerful Category 4 Cyclone Sidr made landfall on 15 November 2007. The death toll was estimated at just over 3000 persons compared with the hundreds of thousands from the past cyclones. Although the damage was still costly and the destruction affected approximately 8.9 million people, better planning reduced fatalities by two orders of magnitude.

Relative success in Bangladesh stands in contrast to tremendous loss of life in Burma (Myanmar) due to storm surge and flooding from Cyclone Nargis, May 2008 which killed c138,000.

Further information

- UN Report on TC Nargis, July 2008
  http://www.reliefweb.int/rw/rwb.nsf/db900SID/ONIN-7GRR3J?OpenDocument&rc=3&cc=mmr
- Global storm surge forecast and inundation modelling – Nargis case study (page 29).
  http://www.gdacs.org/Public/download.aspx?type=DC&id=169

Flooding and Landslides

Tropical cyclones produce large amounts of precipitation and can cause flash floods, river floods, urban floods, and landslides, dependent on the land response. For example, hurricane Mitch (1998) killed more than 11,000 people in Central America when a week of rain caused landslides that covered entire villages; the storm struck near the end of the rainy season when soil was saturated.

Major flooding is not limited to hurricanes, nor to less-developed regions. Weak tropical storms can cause deaths and catastrophic damage, for example tropical Storm Allison (2001) produced more than 915 mm of rainfall over five days, caused 22 deaths, damage to over 48,000 homes, and exceeded $5.15 billion dollars in total damage in Texas and neighbouring states.

The amount, extent, and impact of TC flooding depend on the following:

- **Antecedent precipitation**
  Saturated soil has greater flood potential than dry soil. An example of this is the case of Jamaica in 2002 (Fig. 5). The island received heavy rainfall as the eye of Tropical Storm Isidore passed to the south, 17-24 September. Only three days later, Tropical Storm Lili passed to the north and brought more heavy rain from 27-30 September. From the two storms many rainfall records were broken; many places received more than 600% of their September normal rainfall.

Figure 5 *Tracks of Tropical Storms Isidore and Lili (2002) (left), flooding in Maggotty, southwestern Jamaica, 30 Sep 2002 (right).*

- **Speed of movement of the cyclone**
  Slower movement leads to greater flooding.
- **Orographic enhancement**
  Additional lifting of moist air by high terrain produces more precipitation.
- **Intensification due to synoptic forcing**
  Interaction of the cyclone with midlatitude synoptic systems can sometimes enhance the low pressure and increase precipitation. A prime example is Hurricane Agnes (1972), which produced widespread river flooding in the north-eastern US and associated property loss from the inland flooding of $3.5 billion dollars despite causing only $10 million of losses from its landfall in Florida.
- **Hydrology**
  Narrow river basins are easier to flood than flat, broad river basins. Confluence of multiple rivers can also aggravate flooding. Bangladesh is one of the most vulnerable places for flooding because it is the confluence of major rivers and at the mouth of the Bay of Bengal.

- **Land use**
  Urban landscapes are more prone to flash floods because of increased runoff and channelling which causes acceleration of surface water. Denuded hillsides are more prone to landslides as plant roots and vegetation cover help to stabilize the soil. Vegetation also intercepts precipitation and slows soil through-flow further reducing river flows.
- **Other geographical influences**
  Flooding is also influenced by soil type and condition. Soils with slow infiltration due to composition, or compaction and poor structure due to intensive agricultural use lead to greater runoff and flooding.

Strong Winds and Tornadoes

The wind velocity is a defining parameter for TCs because of the deadly and damaging impact of strong winds. The Saffir-Simpson scale was created to provide guidance on the effects of strong winds.

In addition to the strong winds associated with the landfalling tropical cyclone, extremely strong winds are generated in tornadoes that sometimes also accompany a TC. As a tropical cyclone makes landfall, the surface winds decrease faster than winds above, creating vertical wind shear which allows for tornadoes to develop.

In general, tornadoes develop in the right-forward (left-forward) quadrant of the cyclone in the northern (southern) hemisphere, in the outer rain-band where vertical wind shear is favourable. Tornadoes that form in the intense inner core are produced by eyewall mesovortices (which occur over a relatively small area)

In the US, hurricanes recurving to the northeast are more likely to produce tornadoes than those moving westward, possibly due to enhancement of low-level shear.

Lightning

Lightning in TCs is a small percentage of total global lightning. When lightning does occur in TCs, it most often happens in the convective outer rainbands. The highest density of flashes is frequently on the eastern side of storms (Fig. 6).

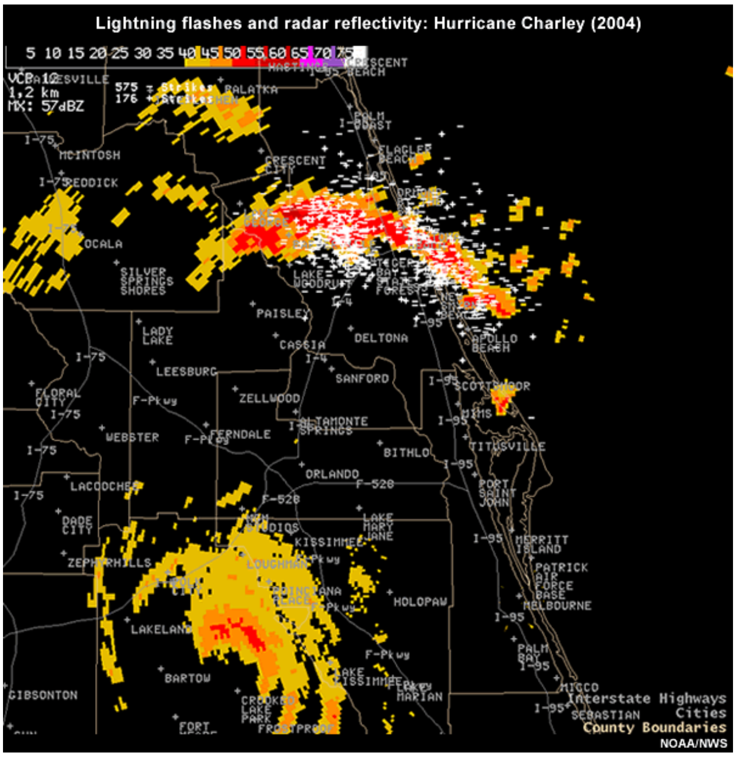


Figure 6 Lightning flashes and radar reflectivity of Hurricane Charley (2004). Maximum flashes are occurring in rainbands to the northeast of the eye, which is over central Florida. (Image courtesy of NOAA/NWS Melbourne, Florida).

Lightning flashes and radar reflectivity of Hurricane Charley (2004). Maximum flashes are occurring in rainbands to the northeast of the eye, which is over central Florida.

A more recent example is found in this NOAA video of Hurricane Harvey which shows the same effect over a period spanning 36 hours, during which the hurricane makes landfall.

Further information

https://www.youtube.com/watch?v=wG6jXYOxKPE

GOES-16 captured this animation of Hurricane Harvey showing cloud cover and optical lightning emissions on August 25-26, 2017. This loop was created by combining infrared imagery from GOES-16's Advanced Baseline Imager, which is useful for determining the cloud features both day and night, with imagery from the satellite's Geostationary Lightning Mapper, which observes total lightning (both in-cloud and cloud-to-ground) day and night across the Western Hemisphere. Forecasters can use this kind of imagery depicting both cloud cover and lightning flashes to get a better sense of storm intensification and thunderstorm severity during dangerous weather conditions.

Source: https://www.nesdis.noaa.gov/content/hurricane-harvey-august-2017

Impacts of Extratropical Transition

Tropical cyclones undergoing extratropical transition may initially weaken as they move into the extratropics (30-60^{o} latitude), but they can re-intensify into midlatitude storms that are occasionally more intense than their tropical selves (e.g. Hurricane Sandy in 2012), often traveling at forward speeds of 15-20 m s^{-1}(54-72kph, 33-45mph).

These intense weather phenomena can exist long after their "tropical storm" status has been discontinued. The remnant tropical storm can also provide a source of enhanced thermal contrast for the later development of an intense midlatitude storm. The rapid forward speed, large area of gale force winds, intense asymmetric precipitation zone, and potential for extreme ocean waves associated with ET events make these systems difficult to forecast.

The changing structure of the ET system compared to its "parent" tropical cyclone means that the area of damaging winds is much larger and typically confined to the right (left) of a Northern Hemisphere (Southern Hemisphere) cyclone looking towards its direction of motion. The rain region is also larger and is located on the **opposite** side to the strongest winds.

Hazard Mitigation

Catastrophes such as the Bangladesh cyclones, TC Nargis, and Hurricanes Katrina and Harvey highlight the need for mitigation measures that take into consideration both the physical and social aspects of tropical cyclones.

Hazard mitigation is multi-faceted, involving long-term planning (education, building codes and zoning) and short-term planning (responding to an individual event and its immediate aftermath).

Mitigation against tropical cyclone impacts includes:

- improvements in TC forecasting
- understanding the sources and distribution of societal vulnerability
- understanding the long-term impact of coastal environmental change (e.g., removal of marshes)
- up-to-date floodplain maps
- land use planning and building codes
- warning systems tailored to reach all populations

One of the challenges of mitigation for tropical cyclones is that the responsibilities for the various aspects (warnings, education, zoning, recovery, etc.) are spread across a range of levels and departments of government, varying by country and region; no single tropical cyclone strategy operates.

Education

The success of TC hazard mitigation by public education on the dangers of storm surge was demonstrated during the landfall of Cyclone Sidr in Bangladesh on 15 November 2007. Cyclone Sidr was a category 4 cyclone, yet deaths numbered a few thousands instead of the hundreds of thousands during past cyclones of similar magnitude.

Unfortunately, mitigation against deaths from storm surge remains uneven around the Bay of Bengal, as demonstrated by the tremendous loss of life when Tropical Cyclone Nargis made landfall in Burma (Myanmar) on 2 May 2008.

In the US, public education on inland flooding was jumpstarted when it was reported that freshwater flooding from tropical cyclones was the largest single cause of hurricane-related deaths in the United States between 1970 and 1999.

Evacuation

Timely evacuation from storm surge has been successful in reducing loss of life from tropical cyclones. However, evacuation is a complex issue for officials and the general population. Can you think of some issues that need to be considered? For example, think of situations in which evacuation may not be possible or advisable.

Issues associated with evacuation include, but are not limited to the following:

- On small islands, residents must shelter in place, unlike continental regions where coastal residents can move far inland.
- Evacuation is costly and the cost will not be replaced if there is no impact.
- It is not advisable to evacuate when the evacuation time is longer than the forecast lead time or when the evacuation route is impassable.
- Maps of evacuation boundaries often do not recognize the difference between discomfort (standing, shallow water) and deadly harm (moving water and drowning).
- Assessment of those differences could reduce the number of unnecessary evacuees.
- Uncertainty in the forecast makes evacuation decisions more difficult.

Warning and evacuation declarations are the mitigation strategies employed immediately prior to a tropical cyclone impacting a location.

Effective warning systems require the integration of monitoring technology, evacuation plans and procedures, and personnel. Sorensen (2000) reviewed twenty years of warning systems and found several major factors that affect the desired response to a warning or evacuation declaration. Response was most affected by:

- physical cues (e.g., images of the size and intensity of the storm)
- proximity to the threat
- experience with hazards
- social cues (e.g., trusted neighbours evacuating).

It should be understood that mitigation is a continuous process of adjustment and improvement. For example, experience with Hurricane Camille led some coastal residents to flee from Hurricane Katrina while others stayed because they had survived Camille.

Further information

- NOAA NWS, Turn Around Don't Drown, http://www.srh.noaa.gov/tadd/
  World Bank Report, TC Sidr,
  http://reliefweb.int/report/bangladesh/bangladesh-planning-and-implementation-post-sidr-housing-recovery-practice-lessons
- NASA, TC Nargis,
  http://www.nasa.gov/mission_pages/hurricanes/archives/2008/h2008_nargis.html
- UN Report, TC Nargis,
  http://www.reliefweb.int/rw/rwb.nsf/db900SID/ONIN-7GRR3J?OpenDocument&rc=3&cc=mmr
- WMO Links to Active National Warnings of Tropical Cyclones,
  http://www.wmo.int/pages/prog/www/tcp/National%20Warnings.html
- United Nations Stop Disasters game, http://www.stopdisastersgame.org/stop_disasters/