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Building resilience to coastal hazards using tide gauges

Angela Hibbert describes the instrumentation that helps to warn of tsunamis and tidal surges.

The loss of life and physical devastation caused by the Indian Ocean tsunami of 2004 demonstrated that while large tsunamis may be infrequent, their impact can be disproportionately high when compared to other natural hazards. Tsunamis are a type of long wave, whose speed is proportional to the square root of water depth, meaning that they can rapidly propagate through the deep ocean. On reaching shallower coastal areas, the wave slows down and its kinetic energy is converted to potential energy, heightening the wave crest, sometimes by several tens of metres. So, while tsunamis may be barely detectable in the open ocean, they are highly destructive at the coast – indeed the Indian Ocean tsunami attained heights of up to 30 m and, in some places, extended 3 km inland.[1] This notable event galvanised governmental cooperation to mitigate such disasters in the future. Under the coordination of the Intergovernmental Oceanographic Commission (IOC), dedicated tsunami warning systems soon developed in the Indian Ocean, north-east Atlantic, Mediterranean and Caribbean regions.

TIDE GAUGES IN EARLY-WARNING SYSTEMS

Today, these warning systems generally comprise an array of seismic sensors to detect earthquakes, together with computer models that calculate the likely magnitude, direction of travel and arrival time of tsunamis that might be generated by these seismic disturbances. Within minutes of a seismic event, model-based tsunami alerts are released to member states. The authorities invoke emergency measures, so the reliability of these alerts is vital. Unnecessary evacuations are costly and can reduce the credibility of tsunami alerts, causing them to be largely ignored.

Therefore a network of sea-level monitoring stations is a third vital component of a tsunami warning system and mainly comprises tide gauges (although there are also open-ocean tsunami-detection moorings, known as DART (Deep-ocean Assessment and Reporting of Tsunamis) buoys. These tides gauges are coastal instruments that continuously monitor the height of the sea surface at a particular location (see **Box 1**). Their observations are transmitted in near-real time to warning centres where they are used to either confirm an alert or cancel it when the danger has passed. Their data are also used to improve numerical tsunami models, and thereby minimise the number of false alerts.

It is important to note that tsunamis can also be generated by processes other than submarine earthquakes – the three Storegga landslides that occurred in the Norwegian Sea around 8,200 years ago induced such large tsunamis in the North Atlantic Ocean that they are believed to have deposited oceanic sediments many kilometres inland.[2] Tsunamis caused by volcanic eruptions, such as Anak Krakatau, Indonesia in 2018, can also have devastating impacts. These days, tide gauges are likely to be the first means of detecting landslide and volcano-driven tsunamis (since seismic networks are not geared to their detection), so tide gauges are doubly important to tsunami mitigation efforts. Consequently, since 2004, the development of resilient tsunami-capable tide gauge networks was a central focus of programmes such as the IOC's ODINAfrica (Ocean Data and Information Network for Africa),[3] which installed and upgraded tide gauges around Africa.

While the Sumatra tsunami may have provided the impetus to enhance and expand tide gauge networks, these are also used increasingly for storm surge early-warning purposes, via real-time monitoring of individual surge events and validation of storm surge model alerts. In the hurricane-prone Caribbean region, for instance, the operational role of tide gauges is clearly implied by the name of the regional network: the Intergovernmental Coordination Group for Tsunamis and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (ICG/CARIBE-EWS). Although they are slower-moving than tsunamis and therefore allow for greater preparedness, storm surges are persistent and often as destructive as tsunamis – tropical cyclone Bhola, for example, led to the loss of an estimated 500,000 lives on the northern Indian Ocean coast in 1970.[4]

BOX 1. TIDE GAUGE TECHNOLOGY

Automatic tide gauges have been around in one form or another for 200 years. Earlier mechanical models were known as float gauges and consisted of a disc-shaped float contained within a large vertical tube (the stilling well) with an opening to the sea. The stilling well removed much of the wave action, and the float would rise and fall with the tide, its movements being recorded on a paper chart on a clock-driven chart recorder by a pen that was connected to the float via a pulley system.

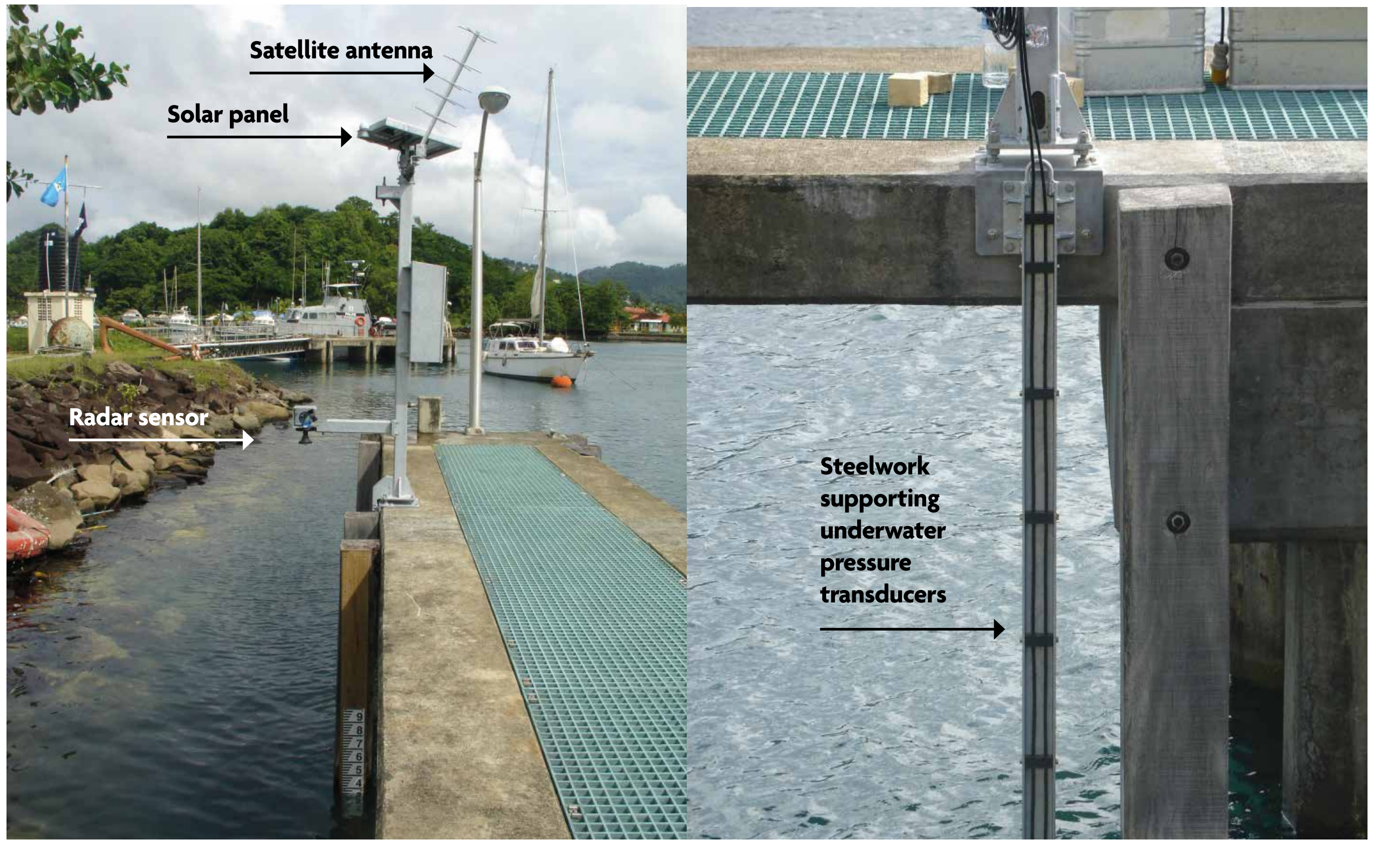
Although some float gauges remain in place, modern sensors are predominantly underwater pressure transducers (which measure sea-level height from the hydrostatic pressure of the overlying water column) or above-water systems such as radar or acoustic sensors (which calculate the distance to the sea surface using reflected radar or acoustic pulses). Tsunami-capable tide gauges often use a combination of the two technologies (see **Figure 1**) for added resilience: while surface-mounted systems are easier to maintain and therefore less likely to fall into disrepair, underwater systems cannot be overtopped during extreme events such as tsunamis.

MULTI-HAZARD TIDE GAUGE SYSTEMS

Sadly, while the value of tide gauges to early-warning systems is now well established, their scientific importance is often overlooked. If sea-level monitoring is sustained over several decades, these records become even more useful, for example, in evaluating the combined statistics of the probability of both extreme tides and storm surges to improve predictability. These statistics, in turn, inform coastal engineers in the design of sea defences and, of course, lengthy tide gauge records allow scientists to estimate the long-term trends in mean sea level that are associated with climate change. Long-term change is particularly important, as coastal inundation becomes increasingly likely if hazards such as storm surges and high tides are superimposed upon increased mean sea levels, meaning that short-term hazards become exacerbated by long-term trends.[5] So these days, tide gauge networks are increasingly viewed as multi-hazard warning systems.

However, a good understanding of *all* sea-level hazards demands high-quality sustained observations. This can only be assured through dedicated long-term funding and skilled local operators to maintain instruments and fully use data. These are key challenges even for well-established tide gauge networks, let alone for small island developing states and lesser developed countries, which, coincidentally, are so often vulnerable to coastal hazards, due to low elevation, hurricane activity or tsunami threat. As a result, fledgling tide gauge networks risk falling into disrepair or may be little used beyond satisfying their international early-warning obligations. National activities, such as the provision of basic tidal information to assist in port operations and safety at sea, are often ignored.

The Intergovernmental Coordination Groups of the IOC, such as ICG/CARIBE-EWS, have sought to address these challenges by identifying funding gaps and lobbying governments accordingly for financial support. For example, since 2005, ICG/CARIBE-EWS has worked with international and regional partners, donors and



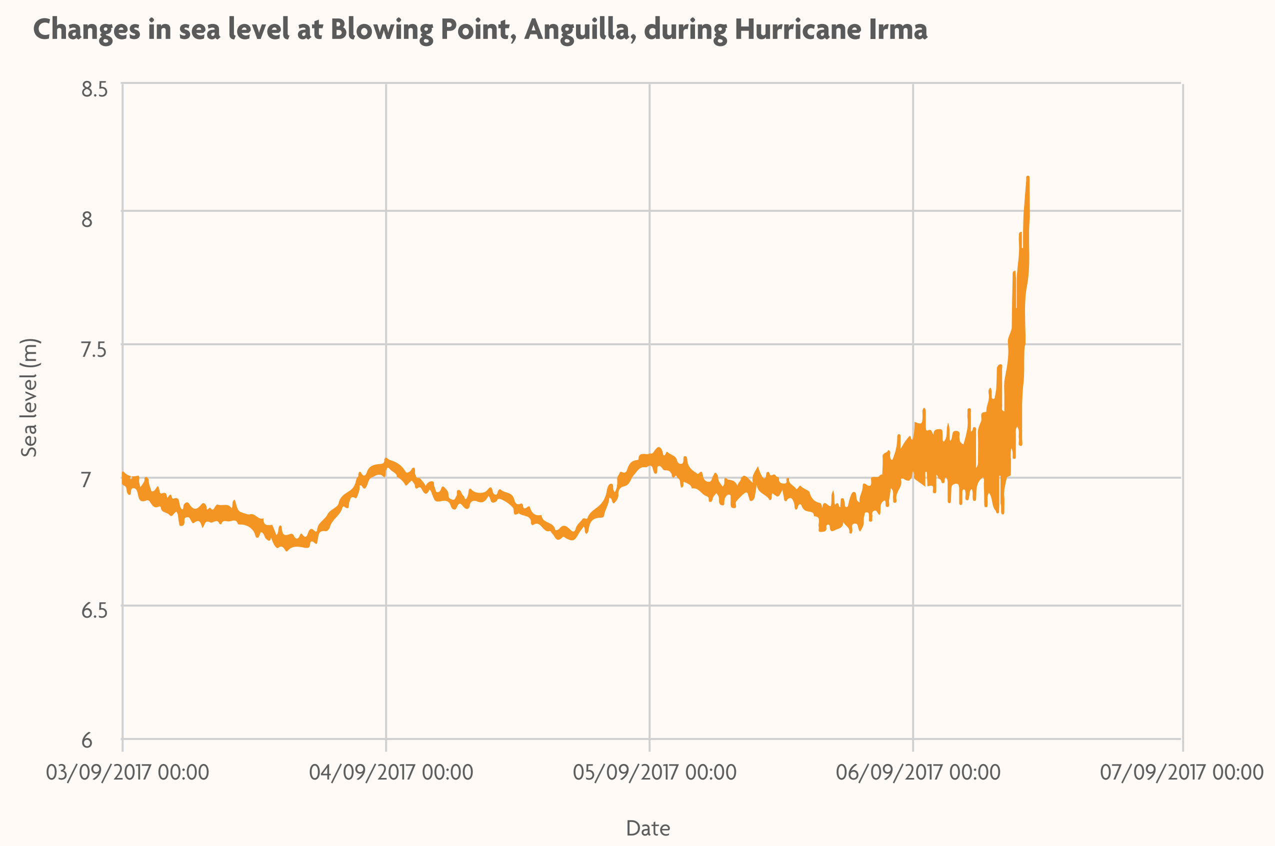
▲ **Figure 1. A solar-powered tsunami-capable tide gauge at Ganters Bay, St Lucia, with dual measurement technologies (radar and pressure sensors) and satellite telecommunications. The right-hand panel shows a side view of the supporting steelwork and power lines to the underwater pressure transducers. The gauge was installed by the NOC through the Commonwealth Marine Economies Programme. (© Jeff Pugh, NOC)**

▲ **Figure 2. Delegates and trainers at the 6th ICG/CARIBE-EWS Short Course on Sea Level Station Installation, Maintenance and Levelling, Quality Control and Data Analysis 26 February–2 March 2018, Mexico City. The author is seated third from left. (© IOC)** its 48 member states and territories and succeeded in increasing the number of tide gauges sharing data in real time from a handful in 2005 to 80 prior to the 2017 hurricane season. Even so, funding often remains sporadic, prompting the development of tide gauge technology that is low maintenance and has minimal operating costs, while still offering the resilience required to withstand harsh hurricane conditions. Tide gauges such as those installed by the National Oceanography Centre (NOC) in St Lucia, Belize (see **Box 2**) and Dominica between 2016 and 2018 have combined solar-powered technology and free-to-use geostationary satellite communications systems in order to minimise utility costs to local operators, while robust marine-grade steel stanchions have been used to mount tide gauge sensors and supporting electronics (**Figure 1**).

At the same time, ICG/CARIBE-EWS (alongside international partners) has promoted the longevity of the regional tide gauge network by delivering annual or biennial training courses to local tide gauge operators in tide gauge maintenance and early-warning systems (**Figure 2**). More recently, this capacity-building work has been extended to upskilling local tide gauge operators to quality control tide gauge records and produce tidal information, which is a significant step along the path to increasing local capacity to use these data to address their scientific and societal needs.

Autumn 2017 saw the arrival of two powerful hurricanes, Irma and Maria, which swept through the north-eastern Caribbean. Hurricane Irma developed in the Western Tropical Atlantic in late August, intensified as it moved westwards and attained category 5 status by the time it arrived in the Leeward Islands and Virgin Islands on 5 September. The tide gauge at Blowing Point, Anguilla recorded a 1 m surge before it was obliterated (**Figure 3**). Irma continued westwards in the three days that followed, causing inundation in Cuba, Haiti and the Dominican Republic, before making landfall over Florida. Just two weeks later, the category 5 Hurricane Maria hit Dominica, damaging or destroying 90 per cent of the buildings on the island before moving through the Leeward Islands and arriving in Puerto Rico as a category 4 event.

In all, hurricanes Irma and Maria were recorded by 30 and 32, respectively, of the ICG/CARIBE-EWS tide gauges. While the majority withstood the hurricane conditions, nine tide gauges were damaged or destroyed, serving as a timely reminder that work to improve tide gauge resilience is by no means complete. For ICG/CARIBE-EWS, 'hardening' their stations has now become a key priority and a number of their members and supporters have worked to develop and install more robust tide gauge equipment (**Figure 4**).



▲ **Figure 3. Data from the tide gauge at Blowing Point, Anguilla, during Hurricane Irma. The time series ended when the tide gauge was swept into the sea. (Courtesy of Jerard Jardin, Jardin Sea Level Systems)**

BOX 2. BELIZE – A CASE STUDY

Coastal inundation poses a significant threat to Belize, as around 40 per cent of the population resides in the coastal zone and offshore reef areas, while the population centre, Belize City, has an elevation of only about 50 cm above sea level. The combination of Belize's low elevation, together with its location in a region of both hurricane and seismic activity, means that it is particularly vulnerable to coastal hazards such as tsunamis, storm surges and the longer-term impacts of sea-level rise associated with climate change. This was exemplified by the impact of Hurricane Hattie in 1961, which destroyed about 75 per cent of buildings in Belize City, leaving more than 300 people dead and 10,000 homeless, and leading to the relocation of the Capital City 80 km inland to Belmopan.[8]

An acoustic tide gauge was installed in 1998 in Belize City and was upgraded in 2007, but by 2011 it had fallen into disrepair. A donor organisation had subsequently supplied the local meteorological service with radar sensors but they lacked the capacity and supporting equipment to install these. In late 2017, funded by Commonwealth Marine Economies Programme (which is funded by the UK government), the NOC installed a low-cost, low-maintenance radar-based tide gauge, training local operators in installation and maintenance procedures. Ongoing technical support is provided jointly by the NOC and ICG/CARIBE-EWS.

▲ **Dual radar sensors installed by the NOC at Belize City beneath a jetty walkway, where they are safe from damage by shipping. (© Jeff Pugh, NOC)**

TECHNOLOGY INNOVATIONS

One potential route to improving tide gauge resilience harnesses global navigation satellite system (GNSS) technology to monitor the sea surface from buildings and higher ground, thus minimising the risk of damage to the tide gauge. GNSS receivers (**Figure 5**) are more conventionally used to measure changes in land elevation by the detection of positioning and timing information from a constellation of navigational satellites such as GPS (USA), GLONASS (Russia), BeiDou (China) and GALILEO (Europe). Their observations are a valuable means of detecting land motion trends to help understand the long-term sea-level trends derived from tide gauge records, so they are often sited alongside tide gauges.

Over the last decade, it has become apparent that the strength of the GNSS signal at a receiver (and therefore the quality of the positions) can be affected by the local surroundings as a direct GNSS signal and its reflection off a nearby object will interfere. It turns out that where the signal is reflected off a relatively flat surface, such

▲ **Figure 4. Post-hurricane remains of the Blowing Point tide gauge shown alongside the newly installed 'hardened' replacement system. (© Jerard Jardin, Jardin Sea Level Systems)**

▲ **Figure 5. A GNSS receiver installed at Ruperts Bay, St Helena. (© Alan Hudson)**

as the sea, the combination of the direct and reflected signal (the signal-to-noise ratio) will exhibit a periodic variation, with a frequency that varies according to the elevation of the satellite and the level of the sea surface; this allows sea-level height to be inferred. Currently, this emerging technology, known as GNSS interferometric reflectometry (GNSS-IR) does not afford the frequency of sampling (<1 minute) or latency of communications (<6 minutes) that is ideal for tsunami-capable systems, but it is a promising technique for locations where conventional tide gauges might be unsuitable or where the tsunami risk is lower. GNSS-IR is also currently being incorporated into a number of prototype European tide gauge systems as a secondary technology.

It is important to emphasise that funding challenges are not peculiar to newly emerged tide gauge networks such as ICG/CARIBE-EWS. Some British Overseas Territories, including Montserrat and Pitcairn Island, lack any form of sea-level monitoring,[6] while a 2016 survey of European tide gauge operators by the European Global Ocean Observing System (EuroGOOS) indicated that 23 of the 40 respondents faced an uncertain funding scenario.[7] This has led some institutions to adapt to their own needs the low-cost, low-maintenance technology solutions that were originally designed for developing countries. However, such technology upgrades themselves demand significant investment.

It is unsurprising, then, that the United Nation's Decade of Ocean Science for Sustainable Development aims, as one of its key challenges (challenge 6) to 'Enhance multi-hazard early warning services for all geophysical, ecological, biological, weather, climate and anthropogenic related ocean and coastal hazards, and mainstream community preparedness and resilience'. This is a most welcome and timely development for those working in the coastal hazards community towards achieving the Ocean Decade outcome of 'a safe ocean'.

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