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SECTION A – Natural Hazards: Analysis, Vulnerability, Forecasting and Warning

1 CARIBBEAN TSUNAMIS: AN INITIAL HISTORY

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ABSTRACT

Reports of 50 tsunamis of varying certainty are listed for the Caribbean beginning with an event off the coast of Venezuela in 1530. Fifteen of these have reports of damage associated with them and six have reported fatalities. As a thoroughly researched history for the region has not been done, these numbers are approximate and probably low. The author has just learned of but not yet seen, a paper on Caribbean tsunamis by Myrtle Thorm and Compton Deane at the Civil Engineering Department, University of the West Indies, St. Augustine, Trinidad written in the late 1970's. Also, given the increase in coastal development, a repeat of these events today would cause much higher damage and fatalities. Although the history of the Caribbean area is the longest in the Western Hemisphere, the tsunami history has not been studied in detail. The varied colonial past and the number of political divisions make such a study difficult and needing local involvement. Tsunamis have affected the whole area from the northern coast of South America, Costa Rica and Panama, to the whole arc of the Antilles. It is subject to tsunamis of tectonic origin asssociated with the trench and with structures cutting the arc. Notable is the 1867 tsunami originating in the Anegada trough between St. Thomas and St. Croix, Virgin Islands, which caused 14 to 16 fatalities and was observed throughout the Caribbean. The 1918 tsunami off the northwestern corner of Puerto Rico caused about 40 fatalities and extensive damage. The Caribbean area is also subject to rare but destructive teletsunamis from Atlantic sources. The 1755 tsunami which affected Lisbon, North Africa and England put waves as high as 7 metres at Saba, and 3.7 metres at Antigua and Dominica. Waves reached the second story of buildings in Martinique. The Caribbean may also be subject to tsunamis generated by volcanic activity as seen by the 1690 landslide on Nevis Peak and an explosion of a mud volcano near Trinidad in 1911. Kick-em Jenny, a submarine volcano discovered in 1939, may have generated small, local tsunamis in the 1939 or 1990 eruptions (Sigurdsson, 1996) and may in the future produce a larger wave. Landslides are another source of tsunamis. Each type of source produces tsunamis with different characteristics. The risk should be thoroughly evaluated by a multi-national effort to improve the history and predict effects by using models.

INTRODUCTION

The tsunami hazard in the Caribbean is not as large as some other hazards, notably hurricanes. However, there is a history of destructive tsunamis which, when viewed against the current state of development in coastal areas and numbers of tourist visitors, would be disastrous if they occurred today. Tsunamis in the future can be expected to be at least as large as those in the past and more destructive. This initial history lists 50

can be expected to be at least as large as those in the past and more destructive. This initial history lists 50 reported tsunamis (Table 1) including 15 which caused damage and six which had reported fatalities.

Table 1.
Preliminary List of Caribbean Tsunamis

1530,	**Sep. 1**	**Venezuela.** Sea rose 7.3 m and sank again near coast of Paria and at Cumana and near Island of Cubagua. Ground opened emitting black salt water and asphalt. Mountain at the side of the Gulf of Cariaco was cleft (earthquake). A fort and many houses destroyed but not clear whether due to the wave, the earthquake or both. Berninghausen, 1968; Heck, 1947; Mallet, 1853; Milne, 1912; Robson, 1964.
1543,	**(no date)**	**Venezuela.** Waves noted. City of Cumana destroyed by earthquake? Berninghausen, 1968; Centeno-Grau, 1940; Heck, 1947.
1688,	**Mar. 1**	**Jamaica.** Shocks felt throughout the island and waves damaged ships in Port Royal. A ship at sea was damaged by a hurricane. Berninghausen, 1968; Mallet, 1853; Milne, 1912; Perry, 1847.
1690,	**Apr. 16**	**Leeward Is.** The sea withdrew from Charlotte Amalie, St. Thomas, 16.5 to 18.5m. Robson gives the date as April 5 for Nevis but this is the Julian date. Earthquake of intensity IX caused landslides on volcanic Nevis Peak which caused the sea to withdraw 201m from Charleston before returning in two minutes. Lander, et al., 1989; Mallet, 1853; Olsen, 1988; Robson, 1964, citing Calendar of State Papers, 1689-1692 (1901); Taylor, 1888.
1692,	**June 7**	**Jamaica,** Port Royal. Earthquake and subsidence destroyed the city. Ships overturned, frigate washed over tops of buildings. Along the coast of Liganee (possibly Liguanea Plain) the sea withdrew 183 or 274m, exposing the bottom; upon returning the water overflowed the greater part of the shore. At Yallhouse (possibly Yallahs) the sea is said to have retired about 1.6km. At Saint Anns Bay a large wave was reported. 2000 people killed by the earthquake and tsunami. Berninghausen, 1968; Heck, 1947; Mallet, 1853; Milne, 1912; Myles, 1985; Sloane 1809, Taber, 1920.
1751,	**Oct. 18**	**Haiti,** Azua de Compostela. The city was destroyed by an earthquake and overwhelmed by the resulting tsunami. Santo Domingo also reported wave damage. Berninghausen, 1968; Heck, 1947; Mallet, 1853; Perry, 1847; Taber, 1922.

Table 1 cont'd.

1755,	**Nov. 1**	**Teletsunami from the Lisbon, Portugal, earthquake.** Waves of amplitude 7m were observed at Saba, 3.6m at Antigua and Dominica, 4.5m at St. Martin, leaving a sloop anchored in 4.6 m of water laying broadside on the dry bottom, 1.5-1.8m at Barbados, where the wave had a period of 5 minutes and the water was black as ink. This could be a local landslide tsunami or seiche triggered by the Lisbon wave. At Martinique, at some places the water was reported to have withdrawn for 1.6 km and at other places it flowed into the upper level rooms of the houses. The lowlands on most of the other French Islands were inundated. There is a report of Santiago de Cuba being nearly inundated in 1755 but the month and day were not given. This is probably from the Lisbon tsunami. Affleck, 1809; Heck, 1947; Lander et al., 1989; Mallet, 1853; Robson, 1964; Scherer, 1912; Southey, 1827; Taber, 1922.
1761,	**Mar. 31**	**Teletsunami from the Lisbon, Portugal, earthquake.** A second earthquake near Lisbon, Portugal, caused an extraordinary flux and reflux of the sea at Barbados. Berninghausen, 1968; Davidson, 1936; Mallet, 1854.
1766,	**June 11**	**Jamaica.** An earthquake lasting 1 1/2 to 7 minutes hit Cuba. Ships at sea 7.2 km from the coast of Jamaica rolled so much that their gunwales were immersed in the water. Ships in deep water would not experience a tsunami. Either the ships were near the coast or in shoaling water or the wave was a storm wave but no storm was reported. Mallet, 1854.
1766,	**Aug. 21**	**Cumana, Venezuela.** Very violent shocks raised Cumana and caused the island of Orinoco to sink and disappear. In many places the water surface was disturbed. This is a possible tsunami report. Mallet, 1854.
1767,	**Apr. 24**	**Martinique and Barbados.** The sea was much agitated and ebbed and flowed in an unusual way. Berninghausen, 1968; Mallet, 1854; Robson, 1964.
1770,	**June 3**	**Haiti.** Waves noted at Golfe de la Gonave, and Arcahaie. La Saline Mountain foot partly submerged. The sea inundated 7.2km inland. Berninghausen also cites Mallet with a similar report dated 1769 but this is one event. Berninghausen, 1968; Heck, 1947; Mallet, 1854; Milne, 1912; Southey, 1827; Taber, 1922.
1775	**no date,**	**Hispaniola and Cuba.** Three earthquakes reported and waves did extensive damage. Berninghausen, 1968; Heck, 1947; Southey, 1827; Taber, 1922.

Table 1 cont'd.

1781,	**Oct. 2**	**Jamaica, Savanna La Mar.** An earthquake occurred during a hurricane. The sea rose to a height of 3m at 0.8 km from the beach and swept away a number of houses Ten people were killed by the wave and at least 40 more by the storm. All vessels in the bay were dashed to pieces or driven onshore. There is a problem with this date. Berninghausen, Heck and Milne all quote a date of October 2, 1880 for a similar report as reported by Perry. Berninghausen also gives a date of October 22 for this event, citing Mallet who gives the date as October 2. Berninghausen, 1968; Mallet, 1854; Perry, 1845-1846; Southey, 1827.
1787,	**Oct. 27**	**Jamaica.** A small local shock was felt at Montego Bay and the vessels in the harbour were agitated. Mallet reports earthquakes in Jamaica on Oct 1 and 21 at Kingston and Port Royal. This would be a low validity report as no wave was cited and the agitation may have been a report of a seaquake effect. Berninghausen, 1968; Mallet, 1854.
1802,	**Mar. 19**	**Antigua I., St. Christopher, and other West Indian Islands.** Earthquakes were reported in February and March with the largest on this date. It was accompanied by great agitation of the sea Intensity IV. Berninghausen, 1968; Heck, 1947; Mallet, 1855; Robson, 1964.
1802,	**May 5**	**Venezuela.** Earthquakes at Cumana caused the water of the Orinoco River to rise so high as to leave part of the bed dry. This could describe wave action near the mouth of the river, or bore action. Mallet, 1855.
1812,	**Nov. 11 or 12**	**Jamaica.** The sea was much agitated following an earthquake. This could describe wave action or seaquake action. Mallet, 1855.
1823,	**Nov. 30**	**Martinique.** At 3:10 P.M. a strong undulation (earthquake) was followed by a tidal wave which caused some damage in Saint-Pierre Harbor. Berninghausen, 1968; Heck, 1947; Mallet, 1855; Perry, 1847; Robinson, 1964.
1824,	**Sep. 13**	**Guadeloupe.** Earthquakes were felt at Basse-Terre on the 9th and on the 13th there was a remarkable rise and fall of the tide at Plymouth (Montserrat, British Virgin Islands?). There had been a terrible storm and heavy rain on September 7-9. Mallet, 1855.
1824,	**Nov. 30**	**Martinique.** Severe shock at St Pierre. A very high tide threw many ships upon the strand. Heavy rain followed lasting 10 days. Mallet, 1855.

Table 1 cont'd.

1825, Sep. 20

British Guiana, Demerara County.

Local earthquake and oscillations of the sea were noted. An earthquake was also noted at Trinidad, Tobago, St. Vincent and Barbados. Berninghausen, 1968; Mallet, 185; Milne, 1911; Perry, 1847.

1831, Dec. 3

Trinidad and St. Christopher.

An earthquake occurred. The sea was in a state of violent agitation. Note the large distance between reporting areas. An earthquake was also reported Grenada, St. Vincent, British Guiana. Berninghausen, 1968; Mallet, 1855; Perry, 1847; Robson, 1964.

1837, July 26

Martinique.

Several shocks accompanied by a large wave occurring during a hurricane. Source of wave uncertain. Berninghausen, 1968; Mallet, 1855; Perry, 1847.

1842, May 7

Guadeloupe.

A strong earthquake produced waves with heights reported as follows: Basse-Terre, 0.9m, Deshaies and Sainte Rose, 8.3m and a wave carried away all floatable objects at Gouyave, Grenada, (Charlotte Town). There was some damage, at Bequia I., 1.8m, at Haiti a destructive tsunami struck the north coast, at Mole Saint-Nicholas, Cap-Haitien there was extensive destruction caused by the earthquake and tsunami, at Port-de-Paix the sea receded 60m and the returning wave covered the city with 5m of water. About 200 of the city's 3,000 inhabitants were killed by the earthquake and tsunami. It was observed at Fort-Liberte, Mole-St.-Nicolas and Santiago de los Caballeros. At St. Johns, Virgin Is., the height was 3.1m. At Hispaniola there was destruction on north coast. Note the large area of this event which suggests a teletsunami, but the earthquake was felt at Haiti, Jamaica, Puerto Rico, and other islands. Note also the missing locations such as Puerto Rico for which no tsunami report is available although there are reports from Haiti and the Virgin Islands. Berninghausen, 1968; Heck, 1947; Mallet, 1855; Milne, 1912; Scherer, 1912; Taber, 1922.

1843, Feb. 8

Antigua.

An earthquake was felt at Pointe-a-Pitre, Guadeloupe, St. Lucia, St. Kitts, Monserrat, Martinique and other islands. The sea rose 1.2m but sank again immediately. Robson, 1964.

1853, July 15

Venezuela.

A violent earthquake in Cumana followed by a tsunami. Berninghausen, 1968; Centeno-Grau, 1940; Milne, 1912; Perry, 1847; Robson, 1964.

1860, Mar. 8

Hispaniola.

An earthquake was reported from Port-au-Prince and Anse-a-Veau. Waves were reported from Golfe de la Gonaves, Cayes, and Acquin. At Anse-a-Veau the sea withdrew and broke with a crash on the shore. Berninghausen, 1968; Heck, 1947; Milne, 1912; Taber, 1922.

Table 1 cont'd.

1867, Nov. 18

St. Thomas, Virgin Is.

At Charlotte Amalie the height was 2.4m at the wharf, and the lower part of city was flooded. The water receded nearly 100m and returned as a wave 4.5 to 6m high swamping small boast in the harbor. The wave penetrated 76m inland. The *USS De Soto* was damaged, 11-12 people were killed. At Altona, houses were washed far inland, and there was some damage at Hassel I. At Christensted, St. Croix, waves swept inland 91m, and at Gallows Bay, 20 houses were damaged. At Fredericksted the sea withdrew and returned as a wall of water 7.6m high leaving the *USS Monongahela* stranded. Five were killed, 3-4 injured, and 20 houses were damaged. At Puerto Rico, at San Juan, the river water rose 0.9-1.5m and at Vieques, high waves were observed. At Fajardo, a very small wave was reported, and at Yabucoa the sea retreated and inundated 137m on its return. In the British Virgin Islands, at Peter I., a wave was noted and people fled to Tortola. At Roadtown, Tortola, a 1.5m waves swept some houses away. At Saba, there was some damage. At St. Christopher the wave was also observed. At St. Martin and St. Barthelemy there was some damage. At St. Johns, Antigua, the wave had a height of 3.0m. At Basse-Terrre, Guadeloupe, the height was 1.0m with the sea retreated far from coast. At Deshailes, houses in village were destroyed. At Isles des Saintes there was a slight swell, and at Fond du Cure, houses inundated to a depth of 1m. At Pointe-a-Pitre there was a slight swell, and at Sainte-Rose, a 10m wave. The sea withdrew 100m and flooded and damaged houses on return. It was observed at Martinique and St.Vincent had unusually high water. At Grenada, Gouyave (Charlotte Town) the height was 3m and at St. George, 1.5m. At Becquia Island it was 1.8m. Deville, 1867; Lander et al., 1989; Milne, 1912; Paiwonsky, 1979; Reid and Taber, 1920; Robson, 1964.

1868, Mar. 17

Puerto Rico, Arroyo and Naguabo.

An earthquake and tsunami were observed. At St. Thomas, Charlotte Amalie, it was 0.6m, with a small recession and flooding. Berninghausen, 1968; Heck, 1964; Lander, et al., 1989; Milne, 1912; Robson, 1964; Taber, 1922.

1874, Mar. 11

Lesser Antilles.

A submarine shock to the southeast of St. Thomas shook the island and ships in the harbour. Simultaneously the water in the bay, then perfectly still, appeared turbid as though clouded by sand and mud. A little later strong ripples from the south agitated the water surface lasting some time. This probably was the tsunami and the earlier effects from the seismic waves agitating the bottom. At Dominica the steamer *Corsica* reported a series of heavy rollers in the harbor lasting half an hour and rendering communication with the shore impossible. They did not feel the earthquake. The reduced effects at Charlotte Amalie may indicate a source on the eastern side of the island. Berninghausen, 1968; Palgrave, 1874.

Table 1 cont'd.

1881, Aug. 12

Jamaica.

An earthquake was felt on the island and a wave was reported from the north coast. At Kingston Harbour the water rose about 46cm. Berninghausen felt that this wave was not caused by the earthquake but does not give any reason for his conclusion. Berninghausen, 1968, Hall, 1907; Taber, 1920.

1882, Sept. 7?

Northeastern Panama, San Bias Archipelago.

Milne reports an earthquake for this date observed in Colombia, Panama, Nicaragua, and Ecuador but does not mention a tsunami. Camacho reported the tsunami but did not give details or a date. Eduardo Camacho, 1993; Milne, 1912.

1887, Sept. 23

Haiti.

The epicenter was apparently near the Barlett Trough a short distance southwest from Mole Saint Nicholas. At Jeremie the sea withdrew 20m and returned with a rush. Waves were noted at Mole Saint Nicholas, Anse-D'Haiuault, Pointe Tiburon, and other ports. Heck mistakenly identified the area as in the Philippines. Milne reports the earthquake felt at Port-de-Paix, Haiti and Inagua Island, Bahama Islands. Berninghausen, 1968; Heck, 1947; Milne, 1912; Scherer, 1912, Taber, 1922.

1907, Jan. 14

Jamaica.

Earthquake damage at Kingston, and surrounding territory. Buff Bay was destroyed. Waves noted at Hope Bay, Orange Bay, Sheerness Bay, and Saint Anns Bay. At Annotto Bay, an observer reported the sea receded 73 to 93m, dropping 3 to 3.7m below normal sea level. The returning wave raised the water level 1.8 to 2.4m above normal, sweeping into the lower parts of town destroying houses. On the higher land it came up 7.6 to 9.1m. At Buff Bay the sea receded some distance from the land. At Port Maria the sea withdrew 25.6m. At Ocho Rios near St. Ann's Bay the sea withdrew 69m. At Port Antonio the wave moved a small building near the beach. Waves were also reported from the south coast of Jamaica and seiches were set up in Kingston Harbour. Berninghausen, 1968; Heck, 1946; Taber, 1920.

1911, Nov. 3

Trinidad.

Some extraordinary waves were noticed on the coast following an explosion of a mud volcano island. This is a volcanic-related tsunami. Arnald and Macready, 1956; Berninghausen, 1968.

1916, Apr. 25

Panama.

An earthquake was reported from Bocas del Toro and Almirante, and waves at Boca del Toro carried debris and canoes 198m inland Berninghausen, 1968; Heck, 1947; Kirkpatrick, 1920; Reid, 1917.

Table 1 cont'd.

1918,	**Oct. 11**	**Puerto Rico.** A magnitude 7.5 earthquake caused a wave of 2.4 to 3.3m above sea level at Aguadilla which destroyed 300 huts and drowned 34 people. At Cayo Cardona water rose 75 cm on the west side of the island. At El Boqueron the wave droppped 1.5m and rose 90cm above mean sea level. About 800m southeast near the entrance to the bay the water rose only 45cm. At Punta Borinquen Lighthouse the wave was 4.5m above sea level. In a low area just southwest of the lighthouse the wave penetrated 91m inland. Submarine cables were cut in several places. At Gaunica, 45cm waves observed. At Isabela the water rose 1.8m. At Isla Caja de Muertos water rose 1.5m covering 15m of the beach. At Isla Mona the receding water bared the reef and the returning wave was 3.6m above sea level washing a pier washed away, and flooding a cistern. At Mayaguez, a wave entered the first floors of buildings near the waterfront and destroyed a few native huts and a brick wall was overturned. Water levels reached 40 to 150cm above sea level. At Playa Ponce slight water movements were observed. At Puerto Arecido waves 30 to 60cm high were observed and a bore about 10cm went up the Rio Grande. At Punta Agujereada waves estimated at 5.5 to 6m uprooted several hundred palm trees and destroyed several small houses. Eight people drowned. At Punta Higuero Lighthouse waves uprooted coconut palms and crossed railroad tracks 4.9m above sea level while 800m southeast of the lighthouse the water rose 2.6 to 2.7m. At Rio Culebrinas 1000kg blocks of limestone were moved 46 to 76m slightly downhill. Waves were at least 3.7m high. At Rio Grande de Lioza, water receded and rose about 90cm. At St. Thomas, Virgin Islands, Charlotte Amalie the water rose 45cm and at Krum Bay, 1.2m. At Santo Domingo, Hispaniola water of the Rio Ozama fell and rose 60cm with a period of 40 minutes. Waves were noted at Tortola. Berninghausen, 1968; Lander, et al., 1989; Reid and Taber, 1919; Robson, 1964.
1918,	**Oct. 25**	**Puerto Rico, Mona Passage.** Submarine cables were cut again and a steamer rolled heavily. Waves were recorded on the tide gage at Galveston, Texas. Berninghausen, 1968; Heck, 1946; Lander, et al., 1989.
1922,	**May 2**	**Puerto Rico.** A wave was recorded on the Galvaston gage which has been associated with a small earthquake in Vieques, but the small earthquake does not seem likely to have produced a recordable tsunami. Lander, et al., 1989, Berninghausen, 1968; Parker, 1922; Campbell, 1991.
1929,	**Jan. 17**	**Cumana, Venezuela.** City was destroyed by an earthquake and a steamer off shore was endangered by a hugh wave. The tidal wave following the earthquake caused much damage. Many sailboats were wrecked. Berninghausen, 1968; Robson, 1964; Seismological Notes, 1946.

Table 1 cont'd.

1932,	**Feb. 3**	**Cuba.** Small waves were reported at the time of an earthquake at Santiago de Cuba. Berninghausen, 1968; Hess, 1932.
1946,	**Aug. 4**	**Dominican Republic, Matanzas.** The town was severely damaged and 100 people killed although the wave probably was only 2.4m. At Villa Julia Molina the wave was estimated to be 3.6 to 4.6m high but caused little damage. At Cabo Samana several ebbs and flows were observed. It was recorded at San Juan, Puerto Rico, 36 minutes after the earthquake. It was also recorded at Bermuda at 2:07 after the earthquake and at Daytona Beach, 3:59 and Atlantic City , 4:49. Berninghausen, 1968, Bodle and Murphy, 1948; Heck, 1947, Lynch and Bodle, 1948.
1946,	**Aug. 8**	**Puerto Rico, Aquadilla.** The sea retreated 24m and returned. At Mayaguez the sea retreated 76m and returned. At San Juan it was recorded on tide gage 35 minutes after the earthquake. It was an aftershock of the August 4 event. The wave was also recorded with travel times of Bermuda. 2:02. Daytna Beach, 4:02, and Atlantic City, 4:42. Berninghausen, 1968; Bodle and Murphy, 1948; Lander et al., 1989.
1953,	**May 31**	**Dominican Republic.** Recorded on the Puerto Plata tide gage at 6cm height. Murphy and Cloud, 1955.
1955,	**Jan. 18**	**Venezuela, La Vela.** A wave was reported and four ships were wrecked and four waterfront buildings damaged. No earthquake is listed for this time. Berninghausen, 1968; *Seismological Notes*, 1955.
1968,	**Sept. 20**	**Venezuela.** A report of a tsunami has not been verified. Coffman and Cloud, 1970.
1969,	**Dec .25**	**Leeward Is.** Recorded at Barbados, Antigua, and Dominica with a maximum amplitude of 14cm at Barbados. Von Hake and Cloud, 1971.
1989,	**Nov. 1**	**Puerto Rico, Cabo Rojo.** A small tsunami was reported. *Preliminary Determination of Epicenters*, 1989

Table 1 cont'd.

1991, Apr. 22

Costa Rica.

At Bocas del Toro, Panama, people reported that Las Delicias sand bank normally covered by 60 to 90cm of water emerged as the sea receded less than ten minutes after the earthquake and remained above water for five to seven minutes. Afterwards several waves entered the bay with great force flooding 50 to 100m in the flat northern part of the town. At Carenero Island violent waves destroyed dwellings. At San Cristobal Island the sea receded several meters for about 45 minutes. People went on the beach to catch trapped fish. It was also observed at Bastimento, Cristobal, 10cm, Puertobelo, W. Panama, 60cm and recorded at Colon. Eduardo Camacho, 1993.

These are plotted in Fig. 1. These have affected 22 countries and administrative groups of islands in Central and South America and the Caribbean Islands This list is undoubtedly incomplete both with respect to the number of events and affected localities.

Tsunamis are instantaneously generated gravity waves in water. In the older literature they may be referred to as tidal waves, or seismic sea waves, km. The great Lisbon, Portugal, earthquake and tsunami of 1755 sent waves in to the Caribbean with amplitudes of 7m at Saba, 3.6m at Antigua and Dominica, 4.5m at St. Martin, into the upper stories of waterfront buildings in Martinique, and 1.5-1.8m at Barbados. There are no known reports for their effects in other islands in the Caribbean, but with waves of these sizes, they probably affected most of the islands.

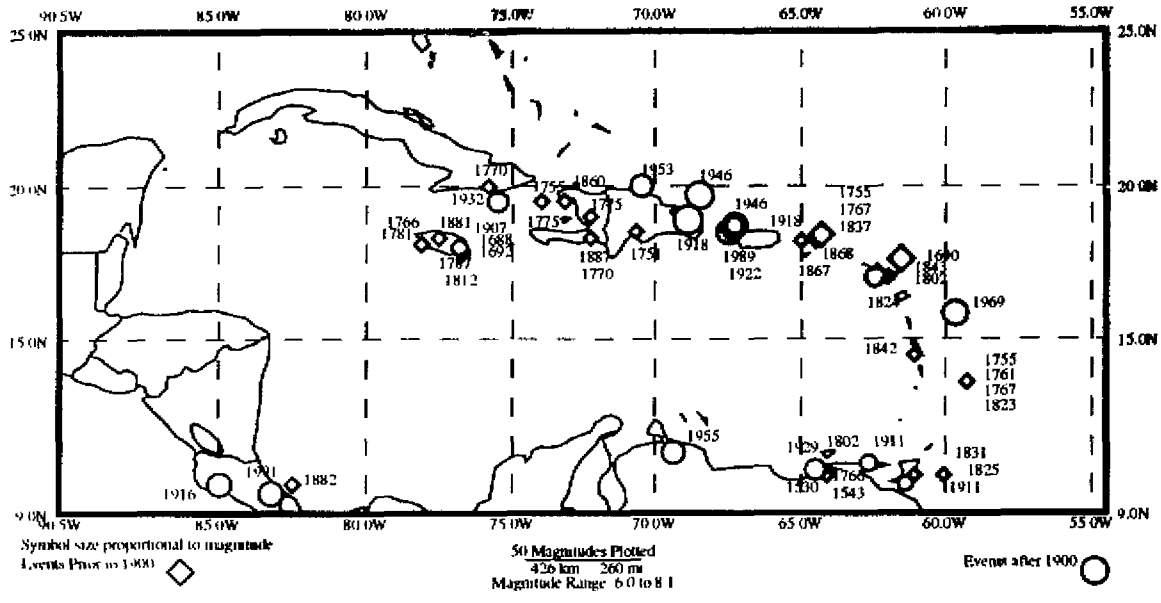

Fig. 1. Location of the source and date of tsunamis reported for the Caribbean except for the teletsunami generated near Portugal in 1755.

maremoto in Spanish, and raz de maree and vagues sismique in French. They are traveling waves whose velocity depends on the square root of the depth of the water such that they slow down and rise up on reaching shoaling depths. Like earthquakes, most are small and recorded mainly on tide gages. Tsunamis are caused by a number of agents and have different characteristics. Teletsunamis originate at distances greater than 1000

The return time for events in the Atlantic is not known, but the Portuguese are concerned enough to be setting up a warning system. Such tsunamis will have about eight hours of lead time before they arrive from the source of the Lisbon tsunami, and have long periods of up to an hour. The dangerous period may last for up to twelve hours. Tsunamis may also be caused by tectonic action in subduction zones. The mechanism is

probably thrusting of the overriding plate into the trench. This is a likely source for a number of Caribbean tsunamis in the history.

Other tectonic features, such as structures cutting the arc, are also sources as shown by the 1867 tsunami originating in the Anegada Trough and the 1918 tsunami originating in the Mona Passage. Most tsunamis in the Caribbean are associated with earthquakes.

Volcanoes are the source of tsunamis from several mechanisms including explosions, collapse of the crater edifice, material sliding off the cone during eruptions or at other times. Submarine and sub-aerial landslides can cause very large but local tsunamis with only a few minutes of warning time available. In Alaska, such tsunamis are the leading cause of damage and fatalities due to the extensive fiords there. On the U.S. west coast local tsunamis are associated with landslides down submarine canyons.

Each area has a unique hazard to tsunamis. An adequate history is needed both to get the magnitude of the problem and to learn of the local types of tsunamis. There is some evidence to suggest that hurricanes may trigger earthquakes and tsunamis. The destructive 1867 earthquake was followed within three weeks by a destructive tsunami and the 1927 Grand Banks earthquake and tsunami occurred simultaneously. The earthquake and tsunami of 1781 at Jamaica occurred during a hurricane. Some historical earthquakes associated with hurricanes are listed in Table 2. A recent study by Dunbar and Whiteside of five hurricane tracks showed that small earthquakes followed the storm track. (Figs. 2 and 3). The extreme low pressures possibly act as triggers for earthquakes at locations where the stress is already near the breaking point. Hurricane-generated tsunamis, if they exist, and if they occur near the time of the storm, may be hard to separate from the storm waves. Information on the time of occurrence, runup heights, damage, wave periods, duration, weather, volcanic activity, and earthquake occurrence should also be noted when compiling a tsunami history.

A problem in compiling a thorough catalogue of Caribbean tsunamis is the diversity of political divisions and of the colonial histories, necessitating a coordinated approach by local compilers for each island group or political division.

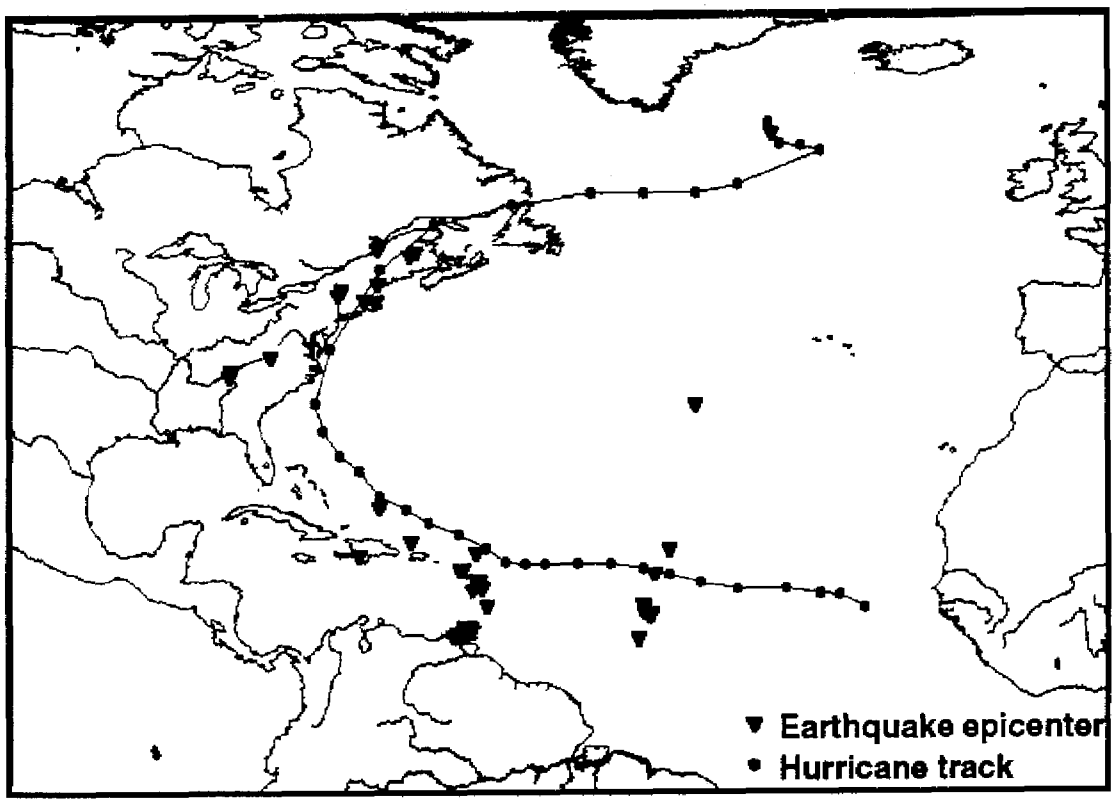

Fig. 2. Huricane Gloria Sept. 16-Oct. 2, 1985, and earthquakes Sept. 16-Oct. 8, 1985, from Dunbar and Whiteside (1994).

Table 2.

Examples of historical earthquakes in the Caribbean associated with hurricanes or storms prior to 1870

1766,	**Aug. 6**	**Martinique.** An earthquake occurred during a hurricane. Mallet, 1853.
1766,	**Oct. 6**	**St. Eustatius.** Earthquake acompanied by a hurricane. Mallet, 1853.
1771,	**Aug.**	**St. Eustatius.** Violent earthquakes were followed by a terrible storm. Mallet, 1854.
1775,	**Sept. 2-3**	**St. Thomas.** Two violent shocks followed by abundant rain for 24 hours. Mallet, 1854.
1781,	**Oct. 2**	**Jamaica.** Heck reports waves due to hurricane but Perry mentions an earthquake. Heck, 1946, Perry, 1845.
1785,	**May 20**	**Surinam.** Earthquake accompanied a tempest. Mallet, 1854.
1787,	**Sept. 23**	**St. Thomas.** Three feeble shocks followed next day by a severe storm. Mallet, 1854.
1813,	**July 28**	**Kingston, Jamaica.** Violent earthquake accompanied a dreadful tempest and heavy rain. Mallet, 1854.
1819,	**Oct. 16**	**Martinique and St. Lucia.** Shocks occurred during violent gale of wind. Mallet, 1854.
1819,	**Oct. 19**	**St. Thomas.** Three shocks during the hurricane. Mallet, 1854.
1821,	**June 8**	**Martinique.** Earthquake followed by sudden gale. Mallet, 1854.
1824,	**Sept. 7-8**	**Guadeloupe.** Terrible storm and heavy rain. More earthquakes on the 9th. Mallet, 1855.
1826,	**Aug. 18**	**Jamaica.** Two severe shocks and a violent tempest soon after. Mallet, 1855.
1827,	**Nov. 30**	**Martinique.** Earthquake predated in Guadeloupe by a violent squall. Mallet, 1855.
1831,	**Aug. 11**	**Barbados and Jamaica.** Large earthquake and violent hurricane. Mallet, 1855, Milne, 1911
1837,	**July 26**	**Martinique.** Several shocks acompanied by a large wave occurred during a hurricane. Berninghausen, 1968, Mallet, 1855, Perry, 1847.
1839,	**June 9**	**Antigua.** Violent earthquake followed by violent tempest. Mallet, 1855.
1867,	**Nov. 18**	**St. Thomas, St Croix and other locations.** Large earthquake and tsunami followed a hurricane by 20 days. Lander, et al., 1989.

METHODS

To compile a thorough historical catalogue, researchers must rely on all available records and especially contemporary records. These include government, company, and church records, ship logs, newspapers, marigrams (tide gage recordings) and other sources. As tsunamis often occur with other geophysical phenomena such as earthquakes, volcanic eruptions, landslides, and perhaps hurricanes, it is well to get lists of the occurrences of these events and check for possible mention of water disturbances in other records. Tsunamis rarely (if ever) occur as great breaking waves such as the famous Hokusai painting, Fig. 4, and more often are seen as rapidly changing tides, unusual currents in harbours, bores on rivers, and flooding. Tsunami-generated currents in relatively protected harbours at San Francisco Bay, Los Angeles and San Diego have caused over a million dollars in damage due principally to the failure of finger piers and setting adrift small craft.

Some records may have to be sought from national archives in colonial countries. The work involves close cooperation with local sources including university Departments of history and geophysics and libraries, local government archives, historical societies, libraries for newspapers, repositories for instrumental records, and archives. Coordinated work among political divisions is also useful.

OBSERVATIONS

It is clear from Fig. 1, a location map of source regions for tsunamis in the Caribbean, that the whole area is at risk. Some areas such as Jamaica, Hispaniola, Venezuela, and Puerto Rico seem to have more tsunamis but this may be the result of better reporting or previous studies in those areas.

Some events appear incomplete, such as 1831 with reports of wave action observed at Trinidad and St. Christopher, and 1842 with reports of of destructive waves at Haiti and 3.1m waves at the Virgin Islands but no report of waves at Puerto Rico. This event was also reported from Grenada, Bequia Island, and Guadeloupe. Such a large area suggests a teletsunami but there was a reported earthquake with the effects in Haiti, Jamaica, Puerto Rico, and other islands.

There are problems with calendars. Prior to 1582 the Julian calendar (adopted by Julius Caesar), was in effect. This calendar lost one day every 128 years and was 10 days off when Pope Gregory proposed a new calendar. This calendar was adopted sporadically in Europe and was not adopted by the English until 1752

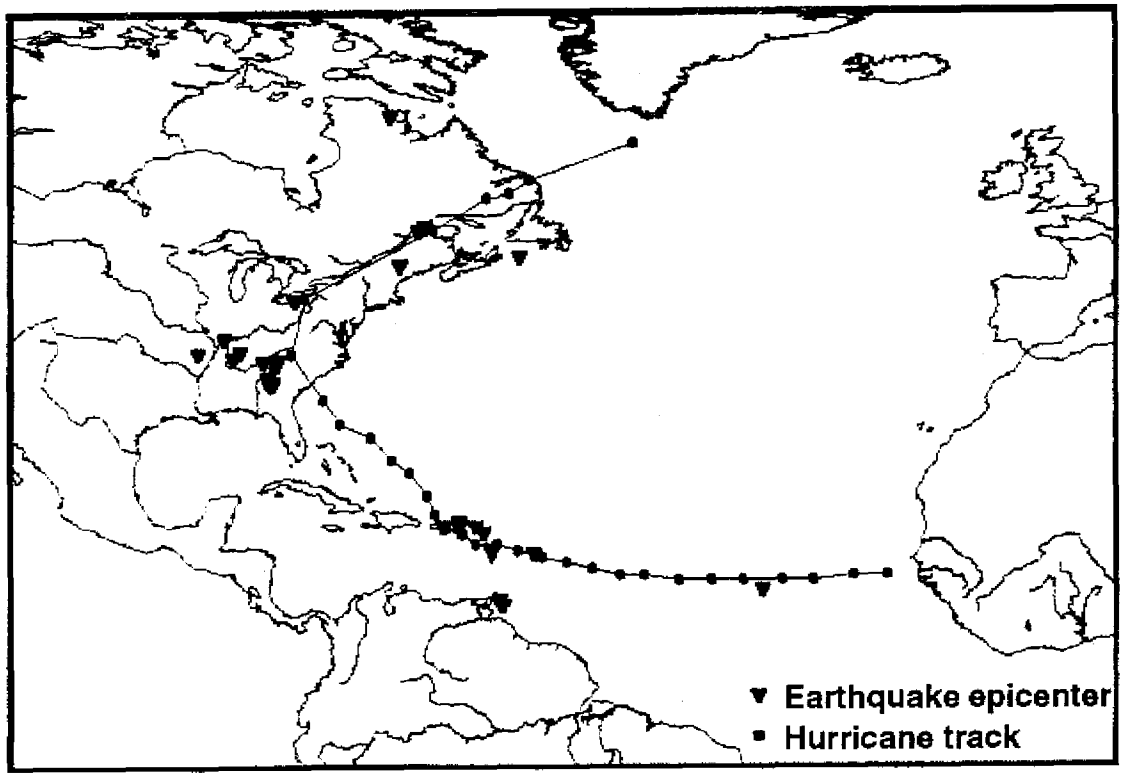

Fig. 3. Hurricane Hugo Sept. 10-25, 1989 and earthquakes Sept. 13-Oct. 2, 1989, from Dunbar and Whiteside (1994).

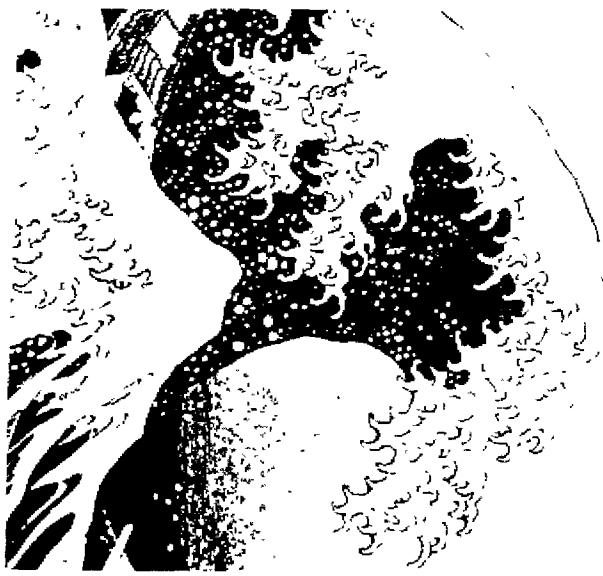

Fig. 4. Hokusai painting often used as a logo for tsunamis but large breaking waves are rarely seen in nature.

and applied to its American colonies. By then the correction was 11 days. Note that in the list of events that the event given as 1690, April 16, includes reports of effects for April 5, are the same event with two different calendars in use.

The events of 1946, August 4 and 8, illustrate that large aftershocks can also cause significant tsunamis.

In the preceding hundred years, 1891-1991, there were 16 reported tsunamis or one about every 6 years.

The 1867 tsunami was one of the most widely observed in the Caribbean It caused at least 11-12 fatalities at St. Thomas and 5 on St. Croix. Figure 5 shows a woodcut of the Royal Mail Steamer La Plata and coal barges which suffered most of the fatalities at St Thomas

Eleven or twelve crewmen on coaling barges were lost. Figure 6 shows the travel time from its source through the Caribbean. It shows there was about 90 minutes potential warning time for a tsunami from this source to Grenada where waves 3 meters high were reported. This is more than adequate for a regional warning to be effective. Such maps centered on each island or port would show the amount of time before a wave arrived from any given source and can be easily produced from digital bathymetric data.

The size of the wave is usually reported as the height, the full excursion from rise to fall of the water. It is often reported as the runup height which is the elevation on land of the maximum inundation of the wave above the water level at the time of the wave's arrival. This latter is more closely related to the amplitude, the amount of the rise or the fall of the water.

Table 3 lists the known fatality causing tsunamis.

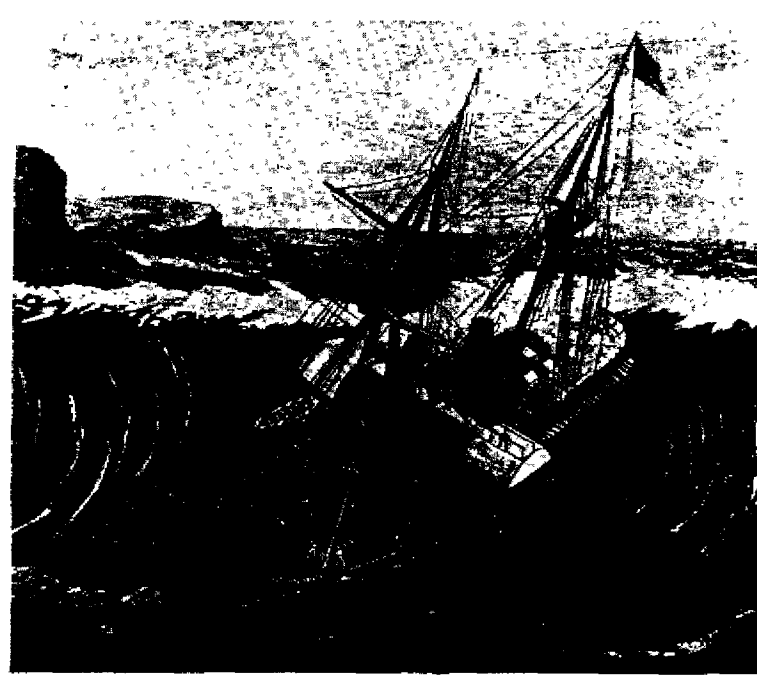

Fig. 5. The Royal Mail Steamer, La Plata, anchored near the southern point of Water Island about 4 km from Charlotte Amalie, St. Thomas Island engulfed by the tsunami of November, 18, 1867. Lithograph from Harpers Weekly, vol. XII, No. 578, Jan. 25, 1868).

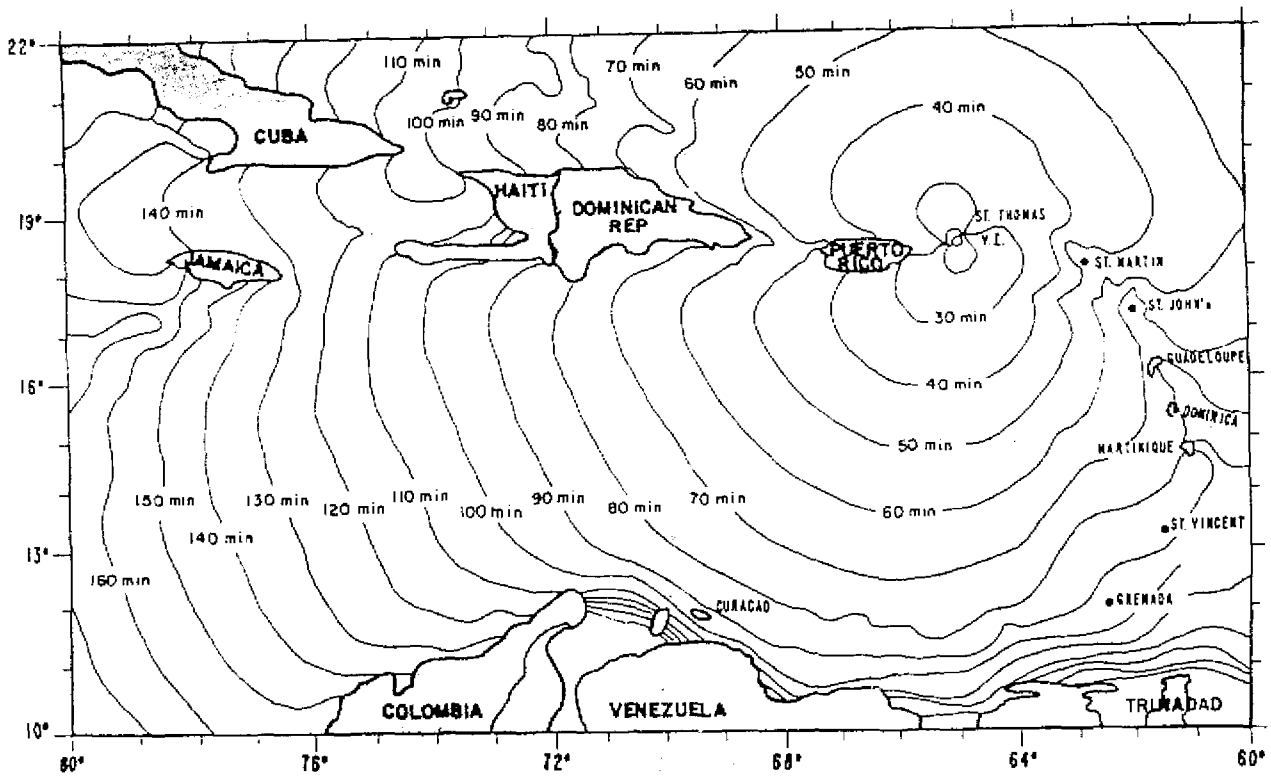

Fig. 6. A travel time chart showing the time a wave needs to reach Charlotte Amalie from locations around the Caribbean. For example, a tsunami generated near Grenada would take over 90 minutes to reach Charlotte Amalie.

Table 3.
Tsunamis causing fatalities

1692,	**Apr. 16**	**Port Royal, Jamaica.** Probable earthquake-generated landslide tsunami. An unknown part of the total of 2000 fatalities were due to the tsunami.
1781,	**Oct. 2**	**Jamaica.** 10 tsunami fatalities.
1842,	**July 26**	**Port-au-Prince, Haiti.** 200 killed by earthquake and tsunami.
1867,	**Nov. 18**	**US Virgin Islands.** 11-12 fatalities near Charlotte Amalie, St. Thomas and 5 at Frederiksted, St. Croix.
1918,	**Oct. 11**	**Puerto Rico.** 34 fatalities at Aguadilla, and 8 at Punta Agujereada.
1946,	**Aug. 8**	**Matanzes, Dominican Republic.** 100 fatalities.

As there is a degree of uncertainty with many historical reports of tsunamis a validity scale has been devised. Catalogued events are rated on a scale of 0 to 4, from validity 0, certainly an invalid report, to validity 4, a certainly valid report. Validity 0 events are those which have been shown to have been in error in date, or due to wave action of storms or other non-tsunamigenic type. These are usually left in the catalogue to prevent their being added back at a later time. Validity 1 reports are judged to have about a 25% chance of being valid and include such effects as waves seen at sea, waves continuing for more than 12 hours for a minor event, reports which could be seaquakes, etc. Validity 2 are judged to be about 50% likely to be valid and include single reports lacking detail, reports of the sea being disturbed, etc. Validity 3 has a 75% chance of being valid, and include reports of waves being observed, debris lines higher than normal high tide, known possible source of the tsunami such as an earthquake or landslide, etc. Validity 4 events may have been recorded on marigrams, and/or observed by a number of people or at a number of localities, have correct travel times from distant sources, etc.

DISCUSSION

A tsunami disaster is highly likely in the future as six damaging tsunamis have occurred in the last century. These are most likely to be more damaging than past events as the coastal areas are more developed. Teletsunamis with up to eight hours lead time are certainly amenable to mitigation by warnings. This takes a system to receive and process the warnings and plans for evacuation. Modelling may make it possible to project the expected runup; areas on the Atlantic coast may be more threatened. Boats may be evacuated as there is little danger to boats in deep water as the waves rise only on shoaling. A regional warning system could serve for these events and for regional tsunamis such as the 1867 tsunami but the response time for the latter is short. Local tsunamis have a short response time measured in minutes.

The population must learn to evacuate without a communicated warning whenever there is a sharp local earthquake or a longer lasting shake from a more distant earthquake. They should also evacuate whenever a peculiar activity of the ocean is observed such as a sudden withdrawal or rise, or the formation of turbulence Once evacuated, people should remain away from the coast until all activity has ceased.

This may be 12 hours for teletsunamis. Other actions which can mitigate the tsunami effects include land-use restrictions which keep critical facilities and hazardous materials above any likely flooding. Fires from ruptured petroleum storage tanks are a common secondary hazard. People in responsible positions such as harbour masters, beach resort managers, cruise ship captains, waterfront store owners, etc., should be aware of the potential for a tsunami and have plans of action for the safety of those in their area of responsibility.

In most cases, warning systems and mitigation actions were taken only after a disaster. The Pacific Tsunami Warning Center was established after the 1946 disaster in Hawaii, and the Alaskan Tsunami Warning Center was established after the 1964 disaster. The Caribbean is one of the last places with a significant hazard and no warning system. Mitigation actions should be taken before the next disaster.

CONCLUSIONS

1. The current history is sufficient to indicate that there is a significant hazard from future tsunamis but a comprehensive history using all available local and colonial sources would improve the understanding of the nature and frequency of the tsunami hazard.
2. Actions can be taken now to mitigate the effects of a future tsunami which could save lives and property.
3. Further research, including improved information on previous tsunamis, possible danger from volcanic, hurricane, and landslide sources and modeling for runup heights and travel times can aid the development of mitigation planning.
4. Such research and planning activity needs to be taken on a regional basis.

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