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.

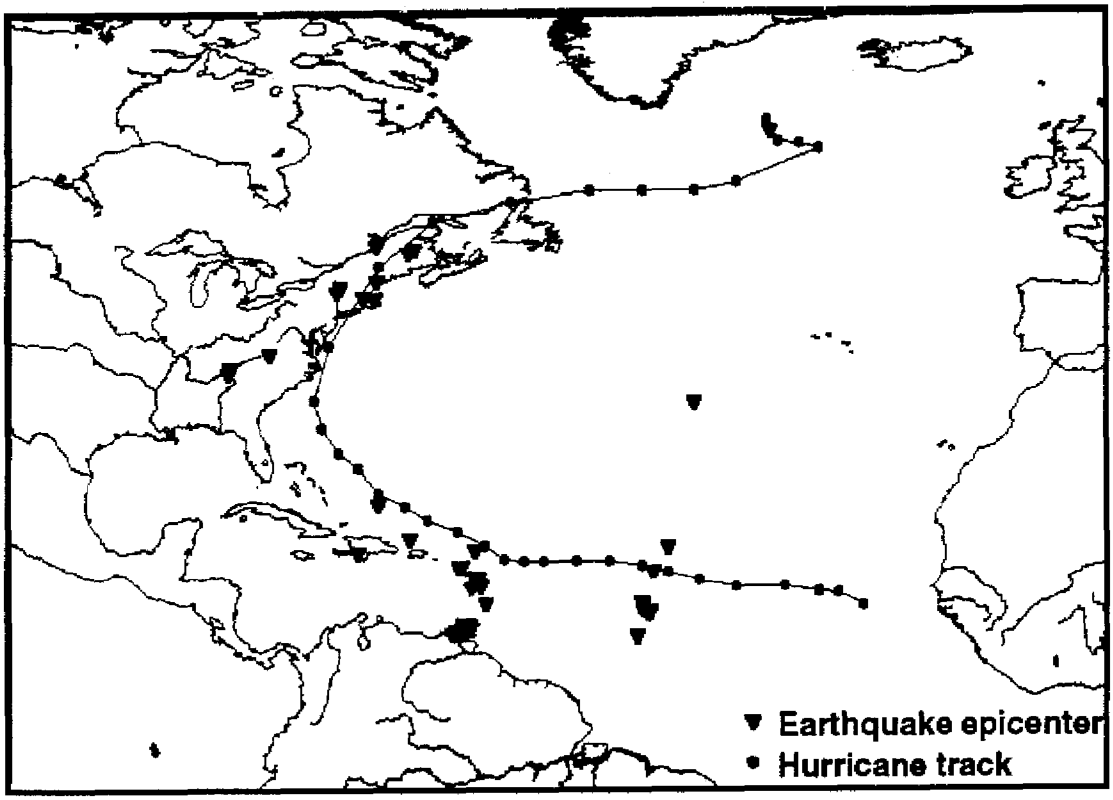

Fig. 2. Huricane Gloria Sept. 16-Oct. 2, 1985, and earthquakes Sept. 16-Oct. 8, 1985, from Dunbar and Whiteside (1994).

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

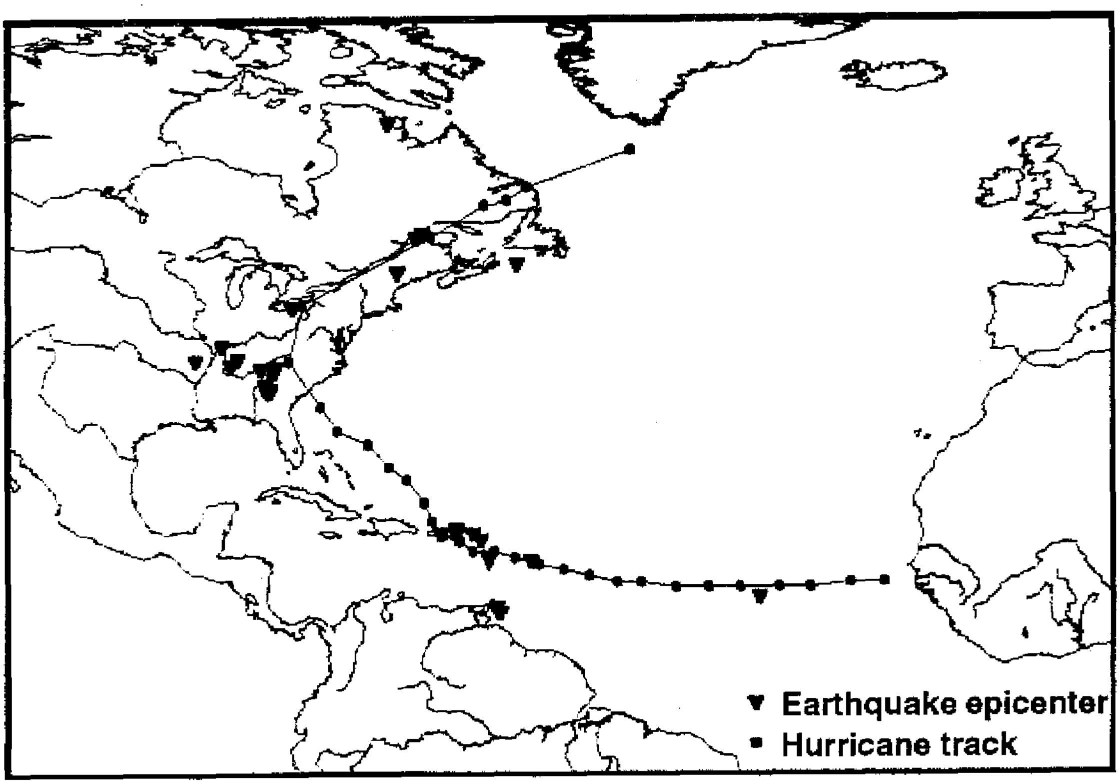

Fig. 3. Hurricane Hugo Sept. 10-25, 1989 and earthquakes Sept. 13-Oct. 2, 1989, from Dunbar and Whiteside (1994).

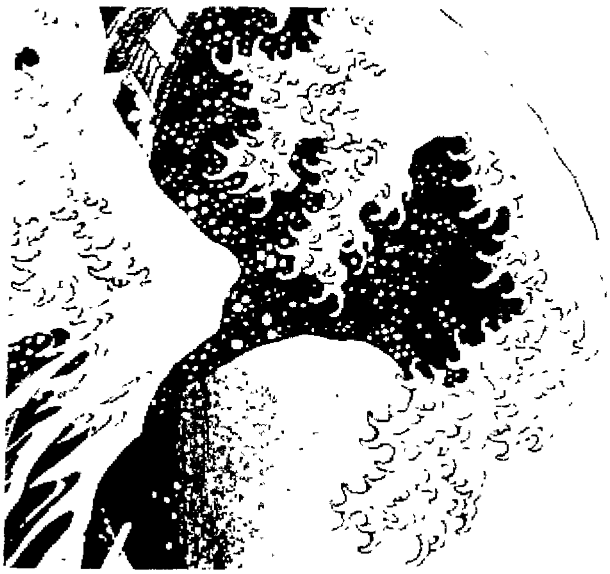

Fig. 4. Hokusai painting often used as a logo for tsunamis but large breaking waves are rarely seen in nature.

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.

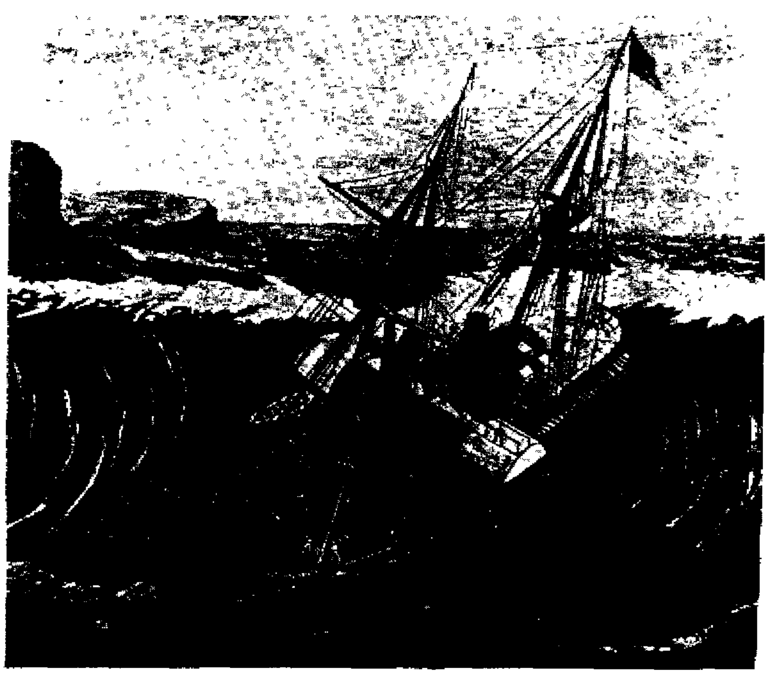

Fig. 5. The Royal Mail Steamer, La Plata, anchored near the southern point of Water Island about 4 km from Charlotte Amalie, St. Thomas Island engulfed by the tsunami of November, 18, 1867. Lithograph from Harpers Weekly, vol. XII, No. 578, Jan. 25, 1868).

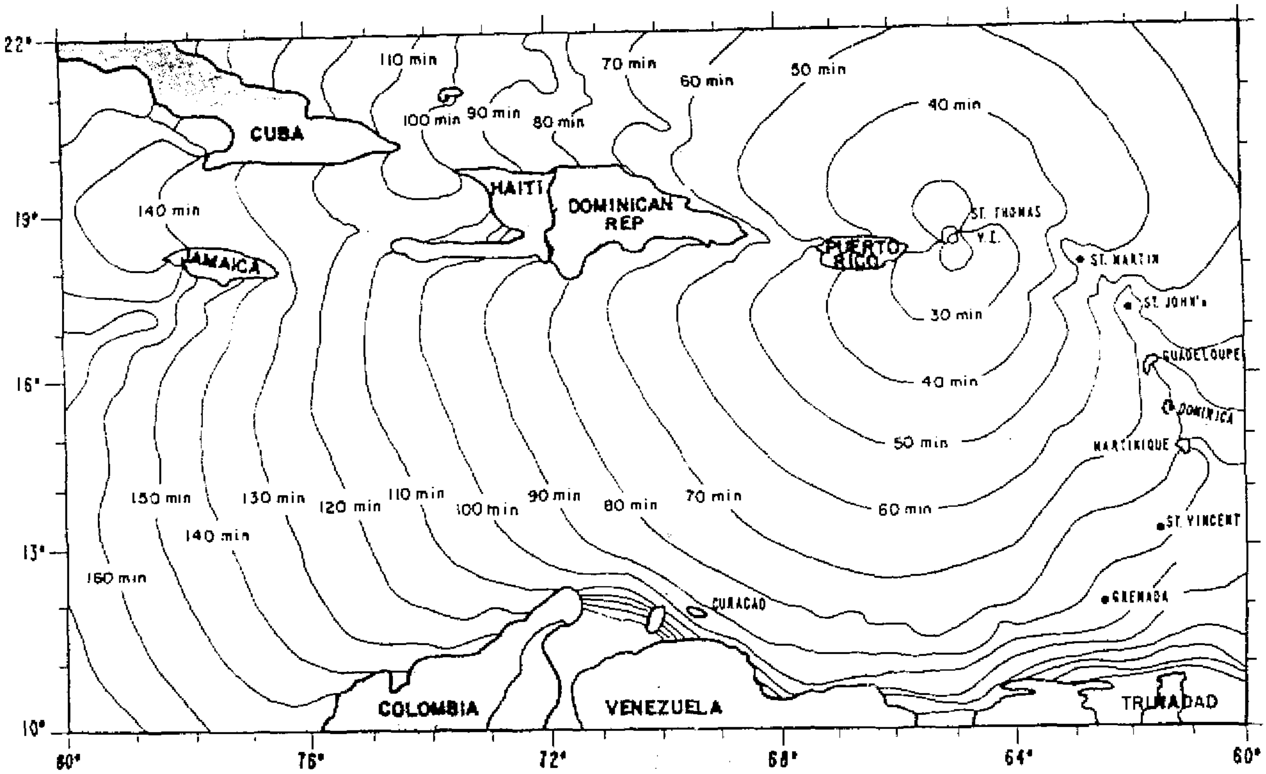

Fig. 6. A travel time chart showing the time a wave needs to reach Charlotte Amalie from locations around the Caribbean. For example, a tsunami generated near Grenada would take over 90 minutes to reach Charlotte Amalie.

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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