

NOAA/WEST COAST AND ALASKA TSUNAMI WARNING CENTER ATLANTIC OCEAN RESPONSE CRITERIA

Paul Whitmore - NOAA/West Coast/Alaska Tsunami Warning Center - Palmer, Alaska
Uri ten Brink – United States Geological Survey – Woods Hole, Massachusetts
Michael Caropolo – NOAA/National Weather Service – Wilmington, North Carolina
Victor Huerfano-Moreno – Puerto Rico Seismic Network – Mayaguez, Puerto Rico
William Knight - NOAA/West Coast/Alaska Tsunami Warning Center - Palmer, Alaska
William Sammler – NOAA/National Weather Service – Wakefield, Virginia
Al Sandrik – NOAA/National Weather Service – Jacksonville, Florida

ABSTRACT

West Coast/Alaska Tsunami Warning Center (WCATWC) response criteria for earthquakes occurring in the Atlantic and Caribbean basins are presented. Initial warning center decisions are based on an earthquake's location, magnitude, depth, distance from coastal locations, and pre-computed threat estimates based on tsunami models computed from similar events. The new criteria will help limit the geographical extent of warnings and advisories to threatened regions, and complement the new operational tsunami product suite. Criteria are set for tsunamis generated by earthquakes, which are by far the main cause of tsunami generation (either directly through sea floor displacement or indirectly by triggering of sub-sea landslides).

The new criteria require development of a threat data base which sets warning or advisory zones based on location, magnitude, and pre-computed tsunami models. The models determine coastal tsunami amplitudes based on likely tsunami source parameters for a given event. Based on the computed amplitude, warning and advisory zones are pre-set.

INTRODUCTION

In 2005 the U.S. National Oceanic and Atmospheric Administration (NOAA) extended its tsunami warning system coverage to the U.S. Atlantic and Gulf of Mexico coasts as well as to eastern Canada. A rudimentary system was already in place for Puerto Rico and the Virgin Islands (PR/VI) thanks to a cooperative effort between the NOAA/Pacific Tsunami Warning Center and the Puerto Rico Seismic Network (PRSN) that started in 2003. In 2005, warning criteria for the North American Atlantic coast were based on the little available historical data, and by extrapolation from criteria used in the Pacific basin.

Prior to 2005, no tsunami warning system was in place for U.S. Atlantic coasts outside of PR/VI due to the assumption that the tsunami hazard was low for that region. Dunbar and Weaver (2008) confirmed this characterization by ranking the U.S. Atlantic and Gulf of Mexico tsunami threat level as low to very low. This compares with their ranking of PR/VI and the U.S. west coast as high, and Alaska and Hawaii as very high. One lesson learned from the 2004 Indian Ocean tsunami and resultant loss of life was that the impact of just a single major tsunami to areas with low tsunami threat justifies the establishment of a tsunami warning system. While some of the areas greatly impacted by the 2004 tsunami were known to be at risk, several of the countries had no previous history of any tsunami impact (such as Maldives and Kenya).

The purpose of this report is to refine criteria the WCATWC uses to issue tsunami messages in its Atlantic area-of-responsibility (AOR – Figure 1). This AOR consists of the coasts of eastern Canada, U.S. Atlantic states, U.S. Gulf of Mexico states, and Puerto Rico/Virgin Islands. Criteria are proposed for tsunamis generated both inside and outside the AOR. The criteria address when alerts are issued, to which areas, and what level of alert is sent. The term “alert” refers to tsunami warning, watch, and advisory which are defined later.

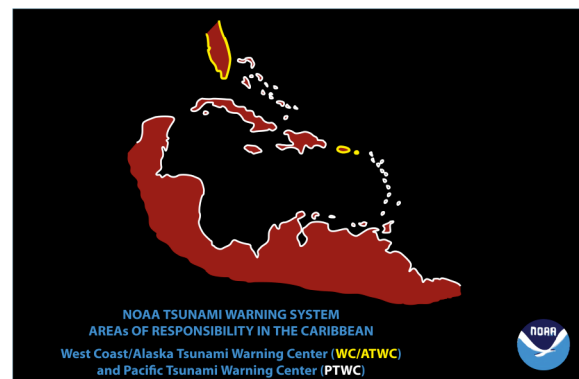
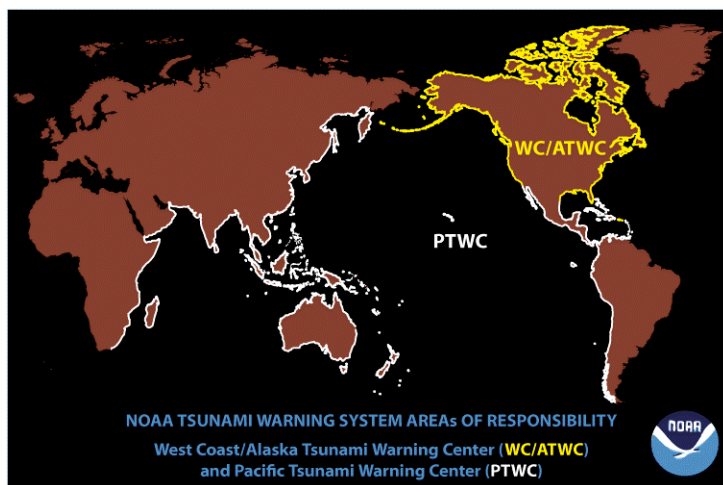


Figure 1. NOAA tsunami warning center area-of-responsibilities with Caribbean region expanded on the right.

The NOAA/National Geophysical Data Center’s Tsunami Database (2007) shows that approximately 85% of tsunamis are generated by earthquake disturbance of the sea floor. Many of the other tsunamis are generated by landslides that are often triggered by strong earthquake shaking. Due

to this relationship between earthquake activity and tsunami generation, seismic data (provided by the United States Geological Survey (USGS), the Global Seismic Network, Earthquakes Canada, Puerto Rico Seismic Network, regional seismic networks, and others) are used by tsunami warning centers (TWCs) to characterize an earthquake's potential to generate a tsunami. Unfortunately, seismic signal strength is not directly proportional to the tsunami strength. Tsunami generation mechanisms can vary greatly for two equally-sized earthquakes. This reality forces warning centers to use conservative warning protocols when basing warnings solely on seismic data; particularly for those nearest the source as the wave will not be recorded prior to impact. A tsunami warning system's inability to see the phenomena for which it warns distinguishes it from hazard warning systems for hurricanes, volcanic ash emissions, and solar storms.

TSUNAMI WARNING CENTER OPERATIONS

Two basic types of data are recorded at tsunami warning centers: seismic and sea level. Data from approximately 350 seismometers are recorded at the WCATWC (Figure 2). The center's seismic data processing system is optimized to characterize large earthquakes as quickly as possible. Normally, the first message concerning an event is based strictly on seismic data, because at that point the tsunami will not have been measured on a sea level gage.

After the initial bulletin is issued, seismic data are further analyzed to verify the magnitude, location, and depth, and to better characterize the event. Fault plane solutions, moment tensors, aftershock locations, and other fault parameters are determined at this point. Through the California Integrated Seismic Network's CISEN Display software, earthquake characteristics computed at other seismic laboratories are shared with the WCATWC.

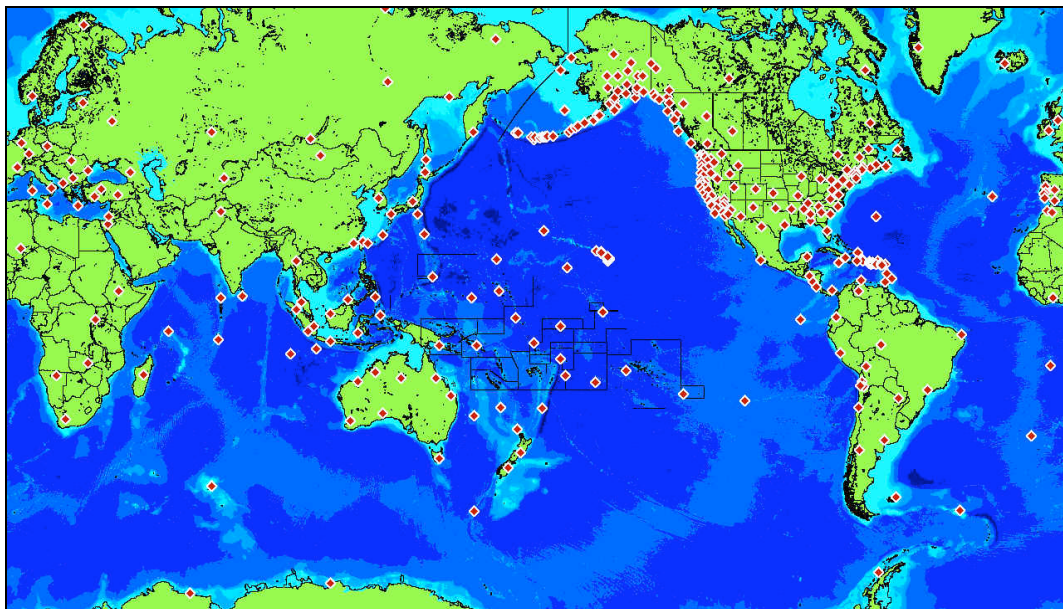


Figure 2. Diamonds represent seismometer locations recorded at the WCATWC from sources such as the USGS, NOAA, Global Seismic Network, Puerto Rico Seismic Network, regional seismic networks, Earthquakes Canada, and others.

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Concurrent with secondary seismic data analysis, the center monitors data from over 400 sea level stations worldwide in near real-time (Figure 3). The center also has access to sea level information from eastern Canada over the internet. Two types of sea level data are available: coastal tide gage data and deep-ocean pressure sensor data (Deep-ocean Assessment and Reporting of Tsunamis (DART) Gonzalez, *et al.*, 2005). Since 2005, the amount and quality of both tide gage data and DART data has greatly improved. Seven DARTs are operated by NOAA in the Atlantic, Caribbean, and Gulf of Mexico basins. NOAA's National Ocean Service also operates an extensive tide gage network along the U.S. coast and the PRSN operates seven tide gauges in Puerto Rico and the Dominican Republic. Internationally, the sea level data are sparse, but improving in quantity. These data are critical to verify the existence of tsunamis and to calibrate models used to forecast amplitudes throughout the basin. Depending on the source location, it can take anywhere from 30 minutes to 3 hours to obtain sufficient sea level data to provide estimates of wave heights outside the source zone, or to verify that no wave has occurred and cancel the alert. Coastal sea level data coverage within the AOR is relatively dense. Even with dense network coverage, tsunami verification can take over an hour for Atlantic AOR earthquakes due to the large width of relatively shallow continental shelf and corresponding low tsunami velocities along the eastern coast of North America.

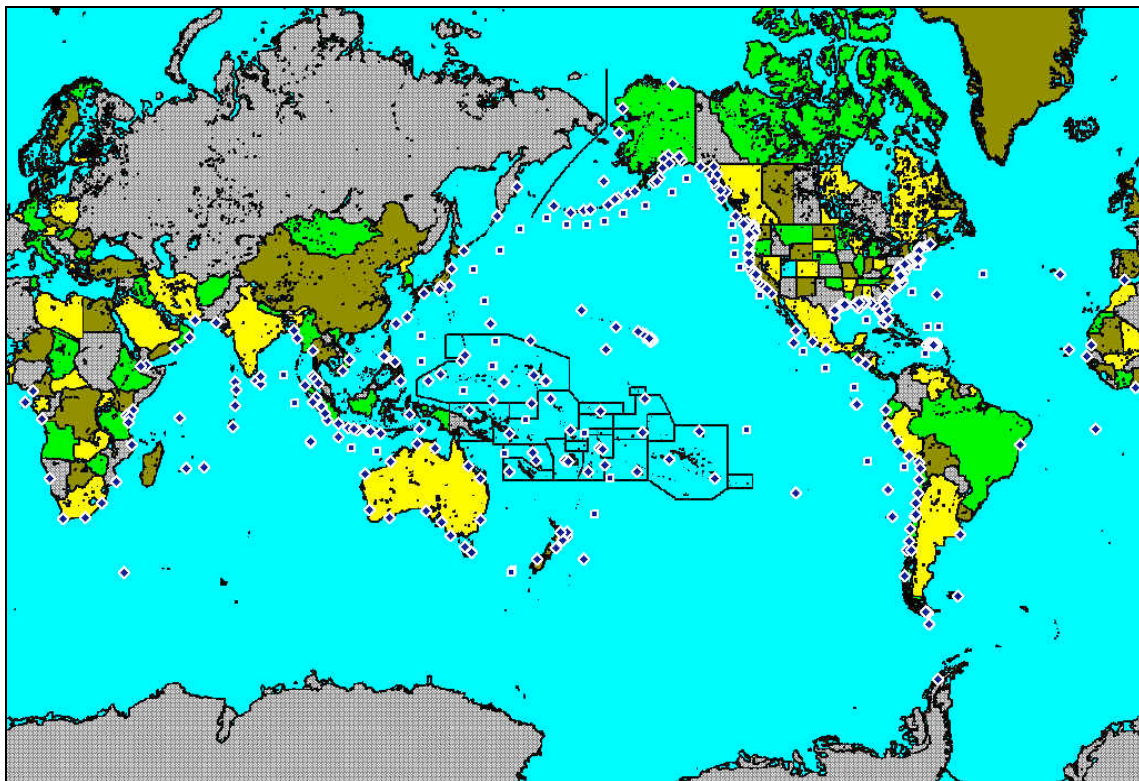


Figure 3. Diamonds represent coastal tide gages and squares represent DARTs recorded at the WCATWC. Gages are operated by NOAA, the Canadian Hydrographic Service, Puerto Rico Seismic Network, the University of Hawaii Sea Level Center, and many other national networks.

To issue alerts within the WCATWC's goal of five minutes or less for events within the AOR (Figure 4), analysts must quickly review events. Procedures for the initial message must be well planned in advance and set for all potential earthquakes. Following the initial response, analyst judgment of the situation becomes a greater part of the procedures. There are literally an infinite number of different scenarios which can play out during an event, and it is impossible to set criteria for each situation.

One of the biggest challenges to TWCs considering the rapid response requirement is computing accurate earthquake magnitudes. Figure 5 shows that WCATWC magnitude accuracy is generally within ± 0.2 units when compared to final USGS results. For earthquakes with magnitude 8 and above, the center's initial magnitude estimate is often low because the earthquake rupture may have not finished rupture by the time the initial processing is completed. Response criteria are set conservatively enough that the initial response will provide the proper alert to those nearest the epicenter even with an under-estimated magnitude for earthquakes of this size.

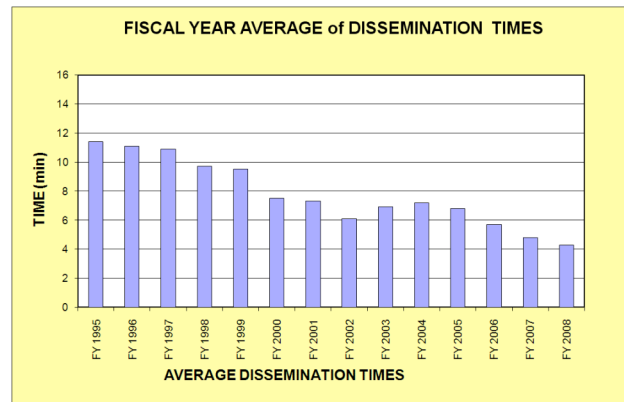


Figure 4. WCATWC response time summary. Response time is defined as the time of bulletin issuance minus the earthquake's origin time. Decrease in response time has been made possible by the use of denser broadband seismic networks, improved seismic analysis software, and 24x7 staffing of the center.

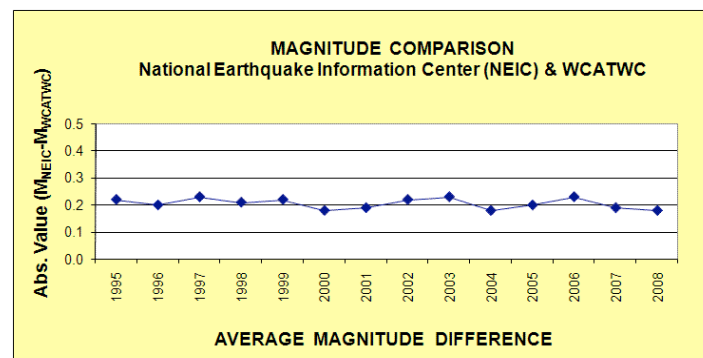


Figure 5. WCATWC magnitude accuracy summary. The values shown by diamonds are the yearly averages of the absolute value of the difference between the initial WCATWC magnitude and the final USGS magnitude for earthquakes located in the WCATWC AOR.

After an alert is issued, messages are updated every 30 minutes during the early parts of an event with the frequency decreasing in the latter times of the event. In the early stages of an event, there may be no sea level data to support analysis in these supplemental messages (often the case when the event is outside the AOR). In these cases, secondary seismic analysis to better characterize the source can help guide the response of the warning center.

TSUNAMI WARNING CENTER MESSAGE SUITE

The WCATWC tsunami message suite was revamped in February 2008. The suite has progressed from effectively a three-level suite to a four-level suite. The products issued by the center are warning, watch, advisory, and information statement. Each has a distinct meaning relating to local emergency response. In summary:

Warning	->	Inundating wave possible	->	Full evacuation suggested
Watch	->	Danger level not yet known	->	Stay alert for more info
Advisory	->	Strong currents likely	->	Stay away from the shore
Information	->	Minor waves at most	->	No action suggested

Based on seismic data analysis or forecasted tsunami amplitude (dependent on whether the center has obtained sea level data), WCATWC will issue the appropriate alert. Warnings and Advisories suggest that action should be taken. Watches are issued to provide an early alert for areas that are distant from the wave front, but may be in danger. Once the danger level is determined, the watch is converted to a warning or advisory based on expected impact, or canceled. The full definition of each message is given below:

Tsunami Warning - a tsunami warning is issued when a potential tsunami with significant widespread inundation is imminent or expected. Warnings alert the public that widespread, dangerous coastal flooding accompanied by powerful currents is possible and may continue for several hours after arrival of the initial wave. Warnings also alert emergency management officials to take action for the entire tsunami hazard zone. Appropriate actions to be taken by local officials may include the evacuation of low-lying coastal areas, and the repositioning of ships to deep waters when there is time to safely do so. Warnings may be updated, adjusted geographically, downgraded, or canceled. To provide the earliest possible alert, initial warnings are normally based only on seismic information.

Tsunami Watch - a tsunami watch is issued to alert emergency management officials and the public of an event which may later impact the watch area. The watch area may be upgraded to a warning or advisory - or canceled - based on updated information and analysis. Therefore, emergency management officials and the public should prepare to take action. Watches are normally issued based on seismic information without confirmation that a destructive tsunami is underway.

Tsunami Advisory - a tsunami advisory is issued due to the threat of a potential tsunami which may produce strong currents or waves dangerous to those in or near the water. Coastal regions historically prone to damage

due to strong currents induced by tsunamis are at the greatest risk. The threat may continue for several hours after the arrival of the initial wave, but significant widespread inundation is not expected for areas under an advisory. Appropriate actions to be taken by local officials may include closing beaches, evacuating harbors and marinas, and the repositioning of ships to deep waters when there is time to safely do so. Advisories are normally updated to continue the advisory, expand/contract affected areas, upgrade to a warning, or cancel the advisory.

Tsunami Information Statement - a tsunami information statement is issued to inform emergency management officials and the public that an earthquake has occurred, or that a tsunami warning, watch or advisory has been issued for another section of the ocean. In most cases, information statements are issued to indicate there is no threat of a destructive tsunami and to prevent unnecessary evacuations as the earthquake may have been felt in coastal areas. An information statement may, in appropriate situations, caution about the possibility of destructive local tsunamis. Information statements may be re-issued with additional information, though normally these messages are not updated. However, a watch, advisory or warning may be issued for the area, if necessary, after analysis and/or updated information becomes available.

Whitmore, et al. (2008) provided data from historic tsunami events which showed that coastal damage due to strong tsunami currents can occur with tsunami amplitudes measured at the shoreline as small as 0.5 m (amplitude is the level of the wave above normal sea level). Severe damage and inundation generally doesn't occur until amplitudes or vertical runups along the coast reach the 1.5-2.0 m range. These observations, combined with tsunami forecast accuracy which is expected to be in the range of 50% (Whitmore, 2003), prompt the WCATWC to issue advisories when the forecast is from 0.3 m to 1.0 m and warnings when the forecast is above 1.0 m.

WARNING CRITERIA

Tsunami response criteria can be based on historic event data when sufficient data exist for a region. The WCATWC Atlantic AOR has few historic tsunami events as shown in the National Geophysical Data Center (NGDC, 2007) historic tsunami data base and summarized here. The most active section of the AOR is the Puerto Rico/Virgin Islands region. The U.S. Virgin Islands and other nearby islands were struck by an earthquake-generated tsunami up to 10 m high in 1867 which killed 30 people. Over 140 people were killed in western Puerto Rico by a tsunami with an amplitude up to 6 m in 1918. Just to the west of Puerto Rico a magnitude 8.0 earthquake in 1946 triggered a tsunami which resulted in approximately 1800 deaths in the Dominican Republic. Another area in the Atlantic Ocean capable of producing large earthquakes and tsunamis is the region between Portugal and the Azores Islands. In 1755 an earthquake located in this region estimated at over magnitude 8.0, generated a tsunami up to 30 m in Portugal. The tsunami was recorded widely around the Atlantic, producing damage at several locations including Canada and the Caribbean. The largest historic tsunami along the U.S. and Canadian east coast was produced by a magnitude 7.2 earthquake in 1929 which triggered a large sub-sea landslide. This tsunami had maximum amplitude of 7 m along the Newfoundland coast and resulted in 22 deaths. Two other reports of smaller tsunamis along the U.S. Atlantic coast are provided by the NGDC (2007). First, a tsunami was reported in northern Florida after the 1886 Charleston, South Carolina earthquake (estimated magnitude 7.7), and a second minor

tsunami was observed in the New York region in 1964. This tsunami produced no damage and its cause is poorly understood.

In the absence of historic data for a specific region, historic data from other regions can be extrapolated. The National Geophysical Data Center (NGDC, 2007) database can be used for this purpose. Tsunami amplitudes in the database have been compared to sea level records when available and updated as necessary. Figure 6 displays tsunamis which have been recorded along the WCATWC Atlantic AOR.

The Atlantic and Gulf of Mexico Tsunami Hazard Assessment Study Group (AMTHAG, 2008) summarized the current state of knowledge of potential tsunami sources which could impact the U.S. Atlantic and Gulf of Mexico coasts. While there still remains a significant amount of research to be performed, the information contained in the report provides a basis for criteria proposed in this study. The report addressed many potential sources: events distant to the AOR in offshore Portugal and elsewhere in the eastern and mid-Atlantic, continental slope failures along the U.S. Atlantic and Gulf of Mexico coasts, landslide sources in the Puerto Rico region, and earthquake sources in the Puerto Rico region, the wider Caribbean basin, and along the U.S. and Canadian coast. Modeling performed in conjunction with some of the studied sources provides impact estimates. An earlier study by Knight (2006a) also provided important information on level of tsunami threat between basins. Knight (2006a) finds that tsunamis generated in the Atlantic/Caribbean are not expected to affect the Gulf of Mexico and vice-versa.

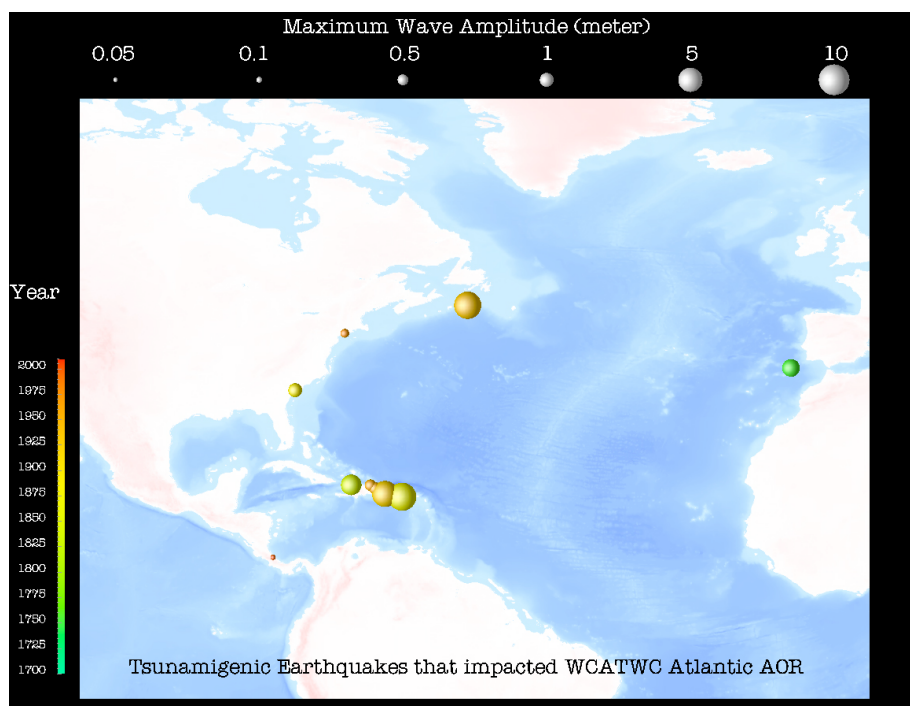


Figure 6. Events which have produced tsunamis recorded in the WCATWC Atlantic AOR (NGDC, 2007). Spheres are located at the event's source location with a size related to the maximum recorded amplitude or runup within the AOR. The sphere color relates to the event's year of occurrence.

There are some pitfalls in using forward tsunami modeling based on earthquake sources alone to set criteria for local events. Most sub-sea earthquakes less than or near magnitude 7.5 do not trigger significant tsunamis as shown later in this report. However, occasionally a major tsunami will be triggered by an earthquake of this magnitude range (e.g., 1998 Papua New Guinea, 1994 Java, and 2006 Java (NGDC, 2007)). For these events, models computed using the expected sea floor displacement will normally show a non-dangerous wave about an order of magnitude less in size than the actual wave produced. The larger waves have been attributed to many phenomena, such as associated landslides, slow slip, and slip on splay faults through the accretionary wedge (e.g., associated landslides – Tappin, *et al.* 2001; slow slip – Kanamori and Kikuchi, 1993; slip through accretionary wedge – Fukao, 1977).

Due to the lack of historical data in the Atlantic AOR, tsunami source and modeling studies refined with observations and statistics obtained from the NGDC worldwide historical tsunami data base are used to set criteria. Basic statistics relating earthquake parameters to tsunami generation observed in the NGDC database and discussed in Whitmore, *et al.* 2008 are also examined.

Several earthquake source characteristics influence whether a tsunami is generated by an earthquake and how large an area it may affect. The most obvious is earthquake size, or magnitude. Earthquake size can also be estimated by other features such as fault length, width, and slip. These other parameters are not known to the center analysts within the time frame necessary to issue the first message.

Other earthquake source factors which can influence the likelihood of tsunami generation are earthquake location (onshore distance, relationship to tectonic features, and depth of water at epicenter), hypocentral depth, and the earthquake fault mechanism. All of these characteristics influence how large an area can be affected by a tsunami if one is generated.

The influence of earthquake source parameters on tsunami generation is examined using the NGDC tsunami database. Table 1 compares hypocentral depth versus tsunami generation for all tsunamis worldwide since 1900 with amplitude 0.5 m or greater, and gives the percentage of occurrence at different hypocentral depth ranges.

Table 1. Tsunami generation versus depth (Whitmore, *et al.*, 2008). Tsunamis included are all high-validity events worldwide since 1900 with amplitude greater than 0.5 m. The last column shows the estimated total number of events over magnitude 7 for each depth range in this time period based on an extrapolation of the USGS Preliminary Determination of Epicenters catalog (2007).

Hypocentral Depth (km)	Number Tsunamis (entire database since 1900)	% of total tsunamis	% earthquakes in this depth range which produced a tsunami	Total # of earthquakes since 1900; M $\geq$ 7
< 50	343	90%	26%	1300
50-100	35	9%	25%	140
> 100	2	<1%	3%	70

Table 1 shows that the likelihood of tsunami generation by earthquakes greater than 100 km depth is very low. However, earthquakes in the range 50 km to 100 km produce a sizeable portion of significant tsunamis. Results from this table support the international tsunami standard of not issuing

tsunami warnings for earthquakes over 100 km in depth except in cases where the size, depth, and location of the earthquake indicate possible rupture to shallow depths; such as a magnitude 9 earthquake located near a subduction zone.

In the WCATWC Atlantic AOR there are not enough events to form a meaningful relationship between earthquake magnitude and tsunami generation. Table 2 compares earthquake magnitude with tsunami generation for earthquakes along the U.S. west, Alaska and British Columbia coasts.

Magnitude	Total number of earthquakes (U.S. west coast, BC, and Alaska) in potential tsunami generation areas (1900-2004)	Number of events which produced a tsunami $\geq$ 0.5m amp.	Maximum amplitude (m)	Maximum "reach" – max. epicentral distance with recorded amp. $\geq$ 0.5 m (km)	Percentage of occurrence
5.0-5.9	3549	1	3	16	0.028%
6.0-6.4	422	0			0%
6.5-7.0	266	2	2.2	28	0.75%
7.1-7.5	55	3	3	146	5.5%
7.6-7.8	10	2	1+	870	20%
7.9+	13	7	525	Tele-tsunamis	59%

Table 2. Tsunami generation versus magnitude within the WCATWC Pacific AOR (Whitmore, *et al.*, 2008). Earthquakes of all depths are included in this table. Note: Three earthquakes $M > 8.5$ have occurred in the region since 1900 and all three triggered basin-wide tsunamis.

Data in Table 2 show a general trend where the higher the earthquake magnitude, the more likely a tsunami will be generated. Furthermore, the higher the magnitude, the larger the area over which the wave may be dangerous. Historic data in this table support keeping warning zones small for earthquakes magnitude 7.5 and below, and increasing the geographic extent with increasing magnitude.

Tsunami generation is also influenced by an earthquake's source mechanism. That is, the more the sea floor moves vertically, the more likely it is to trigger a tsunami. Intuitively, it might seem that events with horizontal fault motion should not produce tsunamis as little sea floor is vertically moved. However, Knight (2006b) and Geist and Parsons (2005) showed that earthquakes with horizontal fault motion can produce significant tsunamis. Potential generation mechanisms include triggering of sub-aerial or sub-marine landslides, horizontal motion of an inclined sea floor, and slip vector obliqueness. Table 3 summarizes strike-slip events which produced large tsunamis from 1977 to 2004. Fault parameters are taken from the Global Centroid Moment Tensor Project Database (2007). Of the nearly 4000 earthquakes listed in the database, 109 produced a tsunami and 41 of those produced tsunamis greater than 1 m amplitude. Of those 41 events, 5 (12%) were triggered by strike slip earthquakes (with slip vectors within 20 degrees of horizontal). Each of these events only produced a tsunami dangerous near the source, and in each case the source was within 25 km of the impacted coast.

Table 3. Strike slip earthquakes which produced significant tsunamis in the period from 1977 to 2004 (Knight, 2006b; Whitmore *et al.*, 2008).

Event Date	Region	Magnitude	Maximum amplitude (m)	“Reach” – max. epicentral distance with recorded amp. ≥ 0.5 m (km)	Notes
9/12/1979	Irian Jaya	7.5	2.0	75	
1/21/1994	Indonesia	6.9	2.0	30	
10/8/1994	Indonesia	6.8	3.0	10	1 death
11/14/1994	Philippines	7.1	7.2	35	24 deaths
10/10/2002	Irian Jaya	7.5	4.0	75	Flooding

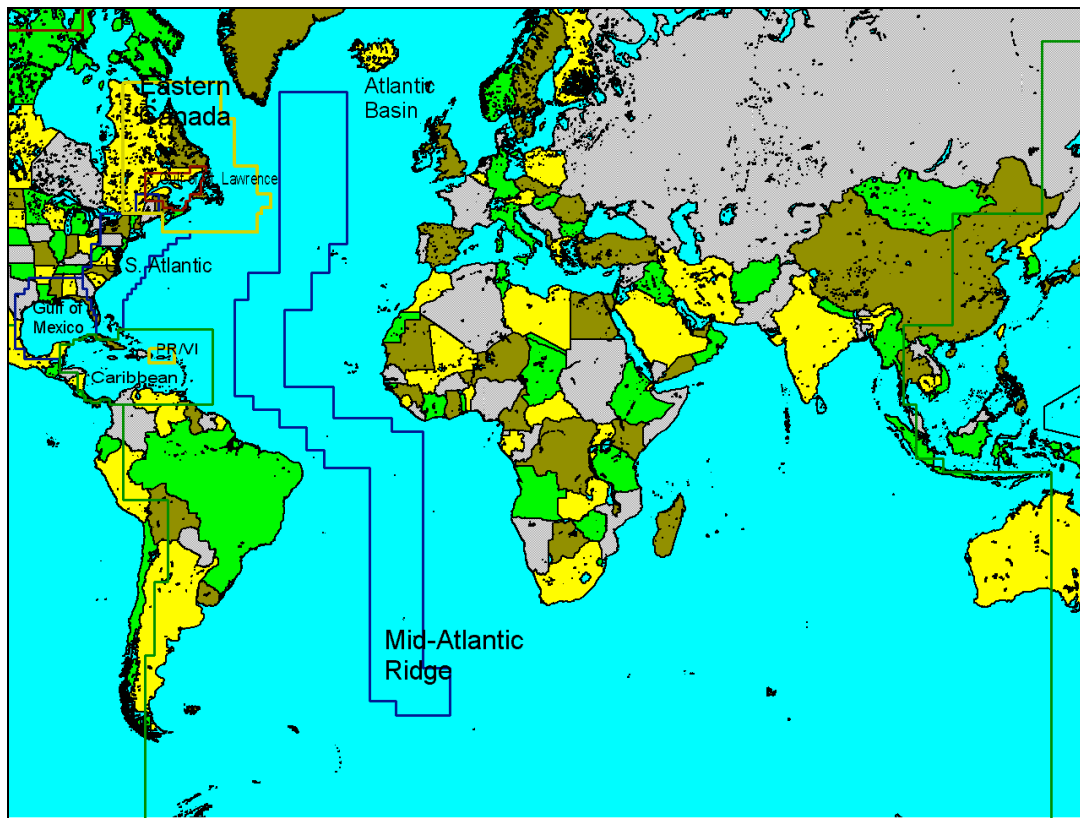


Figure 7. WCATWC Atlantic AOR geographic regions.

Earthquake/tsunami relationships based on historical data summarized above are combined with potential tsunami source information summarized in AMTHAG (2008) to set response criteria in the Atlantic by region. WCATWC Atlantic AOR regionalization is shown in Figure 7. Four criteria flowcharts are shown in Figures 8 through 11.

- Figure 8 displays criteria for earthquakes which occur in the WCATWC eastern Canada, U.S. Atlantic coast, and Gulf of Mexico AORs.
 - One potential source of a significant, widespread tsunami in this region is due to a continental slope landslide as occurred along the Grand Banks in 1929. This landslide was triggered by the largest earthquake along the U.S./Canadian Atlantic in at least the last 100 years. Historic data and tectonics suggest that large tsunami-generating earthquakes are uncommon in this region, though criteria must be set for them anyway.
 - Studies by Lee (2008) show that large continental slope failures occur periodically along the U.S. Atlantic continental slope. ten Brink, *et al.* (2008) show that these failures can trigger significant tsunamis and have attempted to relate the likelihood of a large slope failure to earthquake magnitude, distance from the slope, and slope steepness. Through tsunami modeling, Geist, *et al.* (2008) and Hornbach, *et al.* (2007) show that large continental slope failures are expected to trigger tsunamis of several meters amplitude along the U.S. Atlantic coast. The 1929 Grand Banks landslide-generated tsunami provides confirmation of this potential (Fine, *et al.*, 2004).
 - ten Brink, *et al.* (2008) show that quakes as small as 5.5 and located very near the continental slope could trigger slope failures large enough to generate tsunamis damaging to development along the Atlantic coast. There is little historical earthquake data along the Atlantic coast to verify this, though data from other regions (e.g., Table 2) show that offshore earthquakes less than magnitude 6.5 have a very small probability of generating a tsunami either directly through sea-floor uplift or indirectly through an associated sub-sea landslide. Based on the historic data and the relations shown in ten Brink, *et al.* (2008), the magnitude threshold for calling warnings along the east coast is set at 6.5. Smaller events near the slope will prompt warning center analysts to trigger DARTs near the slope and monitor coastal tide gages to verify tsunami generation prior to issuing an alert.
 - The Gulf of Mexico and Gulf of St. Lawrence have specialized procedures. Tsunamis generated within those basins are not expected to be dangerous outside the basins. Earthquakes greater than or equal to magnitude 6.5 will trigger a warning for coastal areas within the Gulf. No warning, watch, or advisory will be called for areas outside the Gulf, unless observations indicate otherwise. No warning, watch, or advisory will be called for either the Gulf of Mexico or the Gulf of St. Lawrence coast when a warning, watch, or advisory has been issued for the wider Atlantic or Caribbean basins unless observations indicate otherwise.
 - The Gulf of Mexico warning threshold is set at magnitude 6.5. The threat database will specify that earthquakes located in the deep-water Gulf and farther than 75 km from the continental slope will not trigger warnings unless their magnitude is over 7.0.

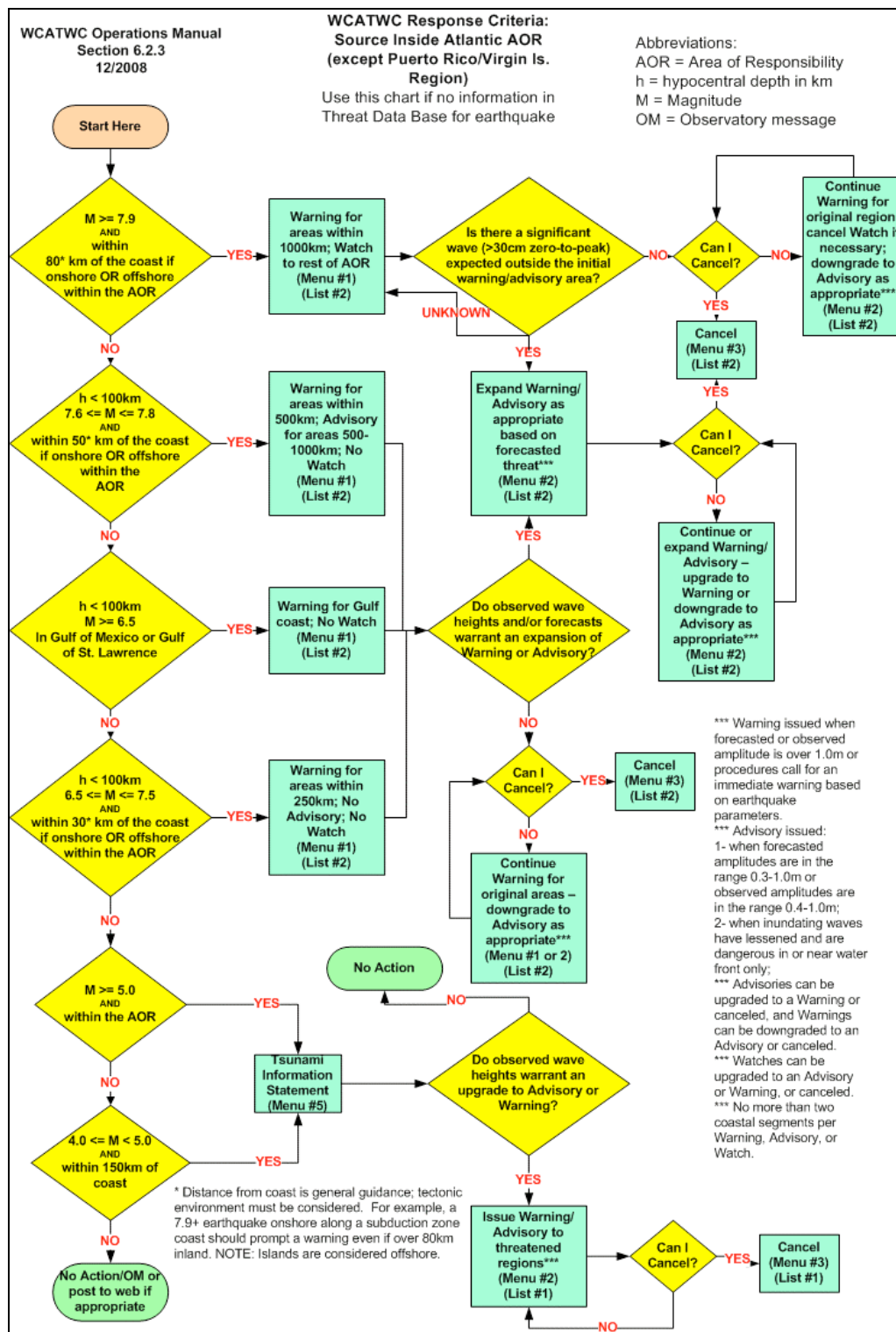


Figure 8. Criteria used for earthquakes located within the Gulf of Mexico, eastern U.S., and eastern Canada AOR.

- Figure 9 displays criteria for earthquakes which occur in the Atlantic outside WCATWC AOR regions and outside the Caribbean region.
 - The only historic basin-wide Atlantic tsunami that has occurred is the 1755 Lisbon tsunami (Barkan, *et al.*, 2008). No impact was noted on the U.S. Atlantic or Gulf coasts, however the tsunami was observed in the Caribbean and in eastern Canada (Lockridge, *et al.*, 2002).
 - Tsunamis generated in the Puerto Rico trench have the potential to impact U.S. and Canadian east coasts with tsunami amplitudes estimated from 1 m (Knight, 2006a) 4 m (AMTHAG, 2008) dependent on earthquake source parameters. Historic tsunamis generated near this trench have been too small to significantly impact the U.S./Canadian coast.
 - Ward and Day (2001) report that a catastrophic flank collapse on the Cumbre Viejo volcano on the island of La Palma located off the northwest Africa coast could trigger a tsunami 10-25 m high along the North American coast. More recent modeling by Gisler, *et al.* (2006) suggests much smaller amplitudes on the order of less than one meter.
 - The mid-Atlantic Ridge is the site of many large earthquakes (Global Centroid Moment Tensor Project Database, 2007). , though none of these are known to have triggered a tsunami observed in the WCATWC AOR.
 - Given the lack of widespread, significant potential tsunami sources throughout the area outside the WCATWC AOR/Caribbean and the ability to observe a tsunami on sea level gages well before impact along AOR coasts from distant sources, criteria in Figure 9 require observation of a significant wave prior to issuance of an alert for the WCATWC AOR. Alerts are not issued based on earthquake parameters alone as they are within the AOR when travel times are short.
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- Figure 10 displays criteria for earthquakes which occur in the Puerto Rico/Virgin Islands (17°N to 20°N and 63.5°W to 69°W) region.
 - Two significant tsunamis have been generated in the PR/VI region in the last 150 years: the 1867 Virgin Islands tsunami (Zahibo, *et al.*, 2003) and the 1918 Puerto Rico tsunami (e.g., Mercado and McCann, 1998).
 - Zahibo, *et al.* (2003) show that the 1867 tsunami can be described by co-seismic sea floor displacement from an earthquake source north of St. Croix Island based on a magnitude 7.5 earthquake. Observed tsunami runups ranged from 1 to 10 m. Models given in Zahibo, *et al.* (2003) simulated the observations well except for those reported from the island of Guadeloupe.
 - The 1918 Puerto Rico tsunami has been proposed to be both landslide generated (Hornbach, *et al.*, 2007; Lopez-Venegas, *et al.*, 2008), and generated by co-seismic sea floor uplift due to the magnitude 7.5 earthquake (Mercado and McCann, 1998). Landslide generation was confirmed by broken oceanic communication cables.

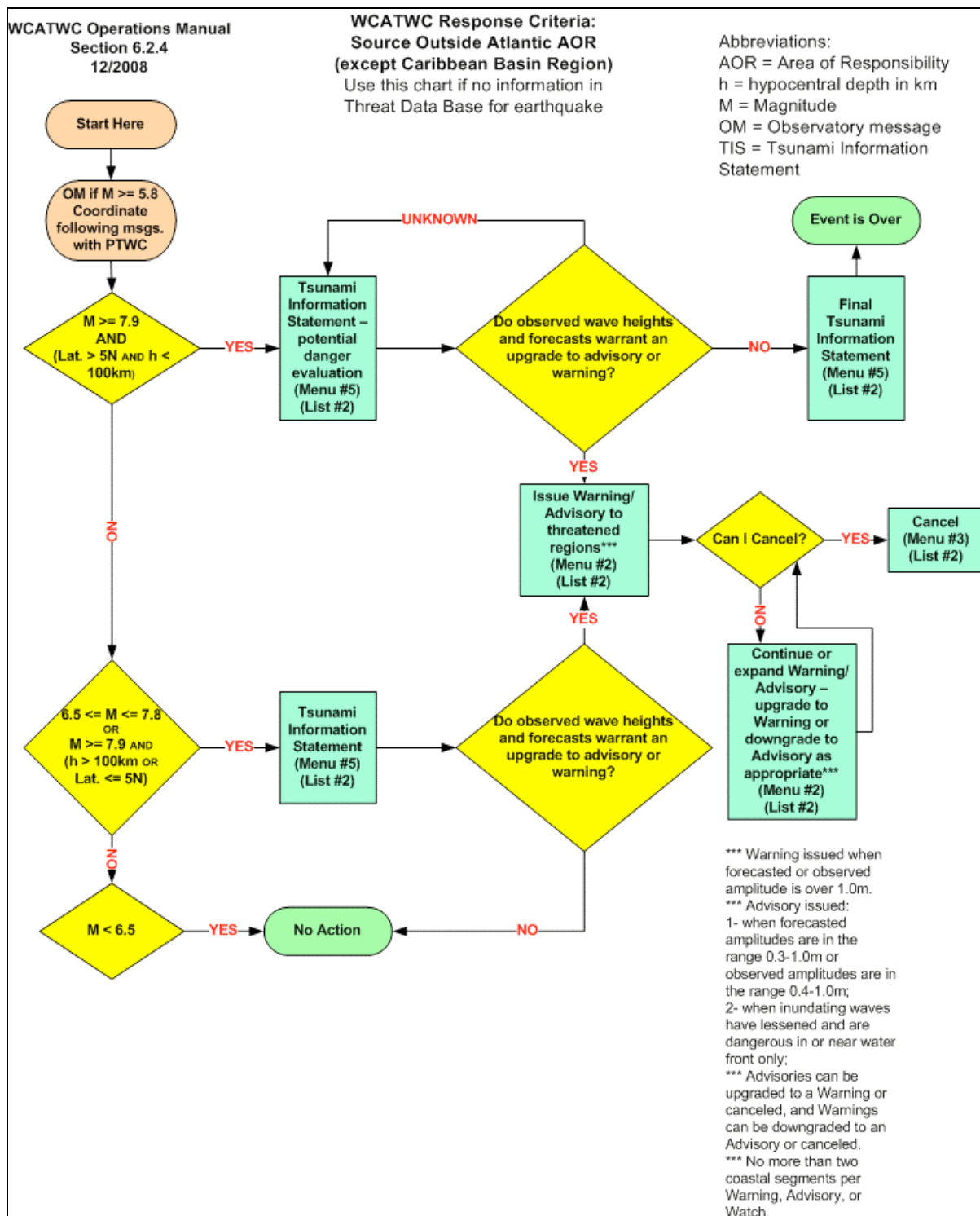


Figure 9. Criteria for Atlantic earthquakes located outside the Caribbean and WCATWC AOR.

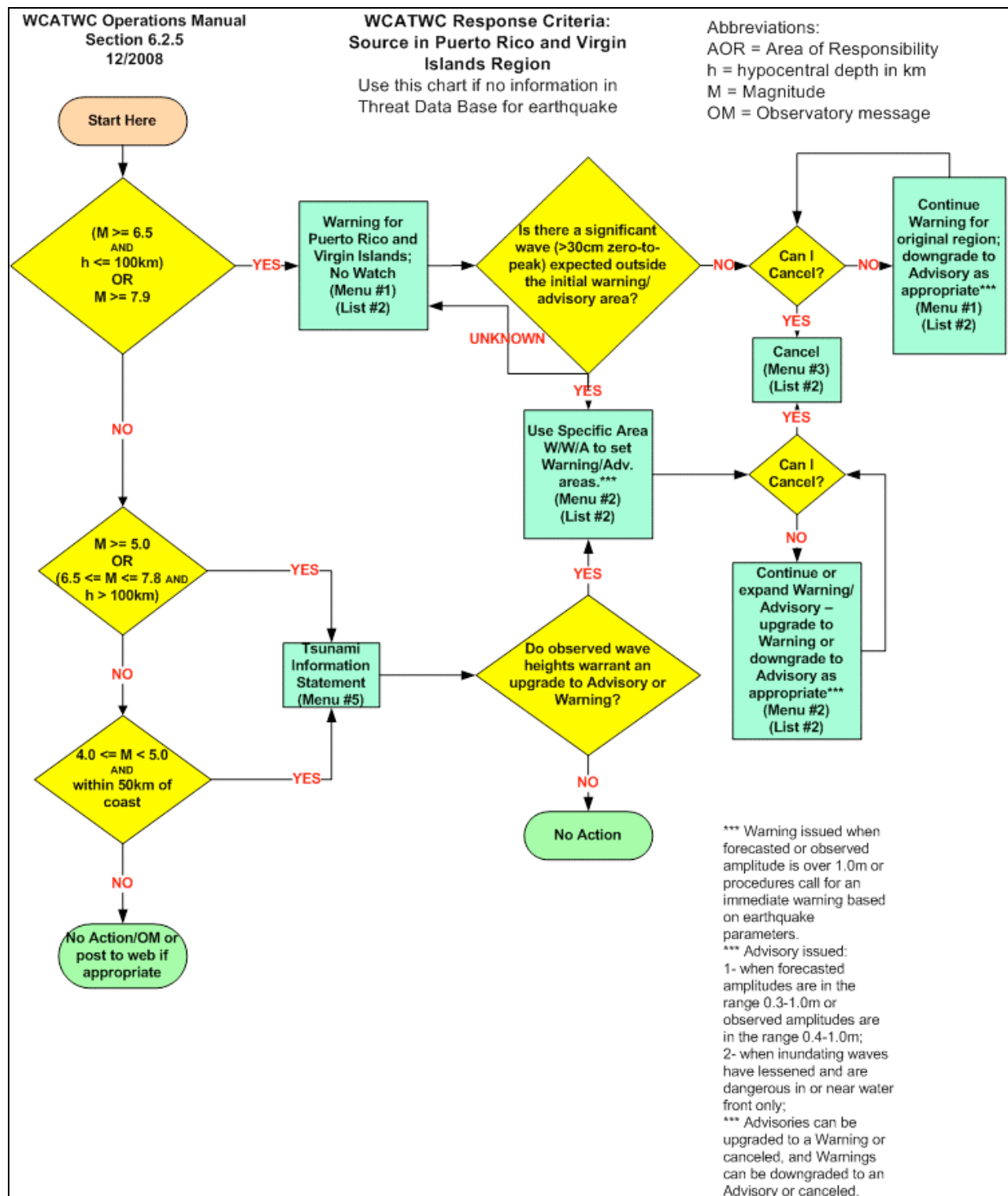


Figure 10. Criteria for earthquakes located near Puerto Rico and the Virgin Islands.

- The PR/VI region contains several potential tsunami sources. These include sources west and east of Puerto Rico as occurred in 1918 and 1867, subduction zone events to the north, and Muertos Trough events to the south (Carbo, *et al.*, 2005; ten Brink, *et al.*, 2004 for more details on PR/VI region tectonics).
- Based on the potential for landslide generation and the history of events within the PR/VI AOR, earthquakes magnitude 6.5 and greater will trigger the issuance of a tsunami warning for Puerto Rico and the Virgin Islands.
- Development of the threat data base and use of finer break points will allow better constraints on PR/VI warning extent. For example, magnitude 7.0 earthquakes on the western coast of Puerto Rico are not expected to significantly impact eastern Puerto Rico and the Virgin Islands. For cases like this, the threat database used in conjunction with finer-grained warning zones will allow limiting the warning to threatened regions.
- Figure 11 displays criteria for earthquakes which occur in the Caribbean region outside PR/VI.
 - The only historic tsunami observations over 0.5 m amplitude in PR/VI from tsunamis generated outside the PR/VI region were due to earthquakes in 1842 (magnitude 7.7) and 1946 (magnitude 8.1) north of the island of Hispanola (NGDC, 2007).
 - Potential Caribbean tsunami sources that may have a significant impact in PR/VI include the tectonically active areas of the Lesser Antilles, northern Venezuela, north of Hispanola, and the region north of Costa Rica and Panama.
 - Volcanic tsunami sources in the Lesser Antilles described by Pararas-Carayannis (2004) have historically only been dangerous locally.
 - Due to the proximity to PR/VI, Caribbean earthquakes (located outside the PR/VI AOR) east of 75°W and magnitude 7.9 or greater will trigger the issuance of a tsunami warning for PR/VI. An advisory will be issued to PR/VI for earthquakes in this region from magnitude 7.6 to 7.8.
 - Earthquakes located west of 75°W and with magnitude 7.9 or greater will trigger the issuance of an advisory for PR/VI. Earthquakes less than magnitude 7.9 in this region will not trigger an alert for PR/VI unless observations indicate otherwise. The longitude 75°W is chosen because it is the general longitude west of which tsunami directivity due to source orientation is such that a major tsunami impact is not expected along the PR/VI coasts.

The flowcharts refer to a threat database. This database will contain warning/watch/advisory zones for events categorized by location and magnitude. The zones will be determined from tsunami models based on likely source parameters for maximum expected events within that location and magnitude range. The database will provide a mechanism for finer zonation of threatened regions than is possible by only using distance from the source as criteria. For example, tsunamis generated by U.S. Atlantic margin continental slope failures based on characteristics given in ten Brink, *et al.* (2008) can be modeled and the threatened AOR coastal regions saved in the database along with the expected impact. When an earthquake occurs which could trigger a continental slope failure, the database is first checked for information. If no information has been computed for that region or magnitude range, the

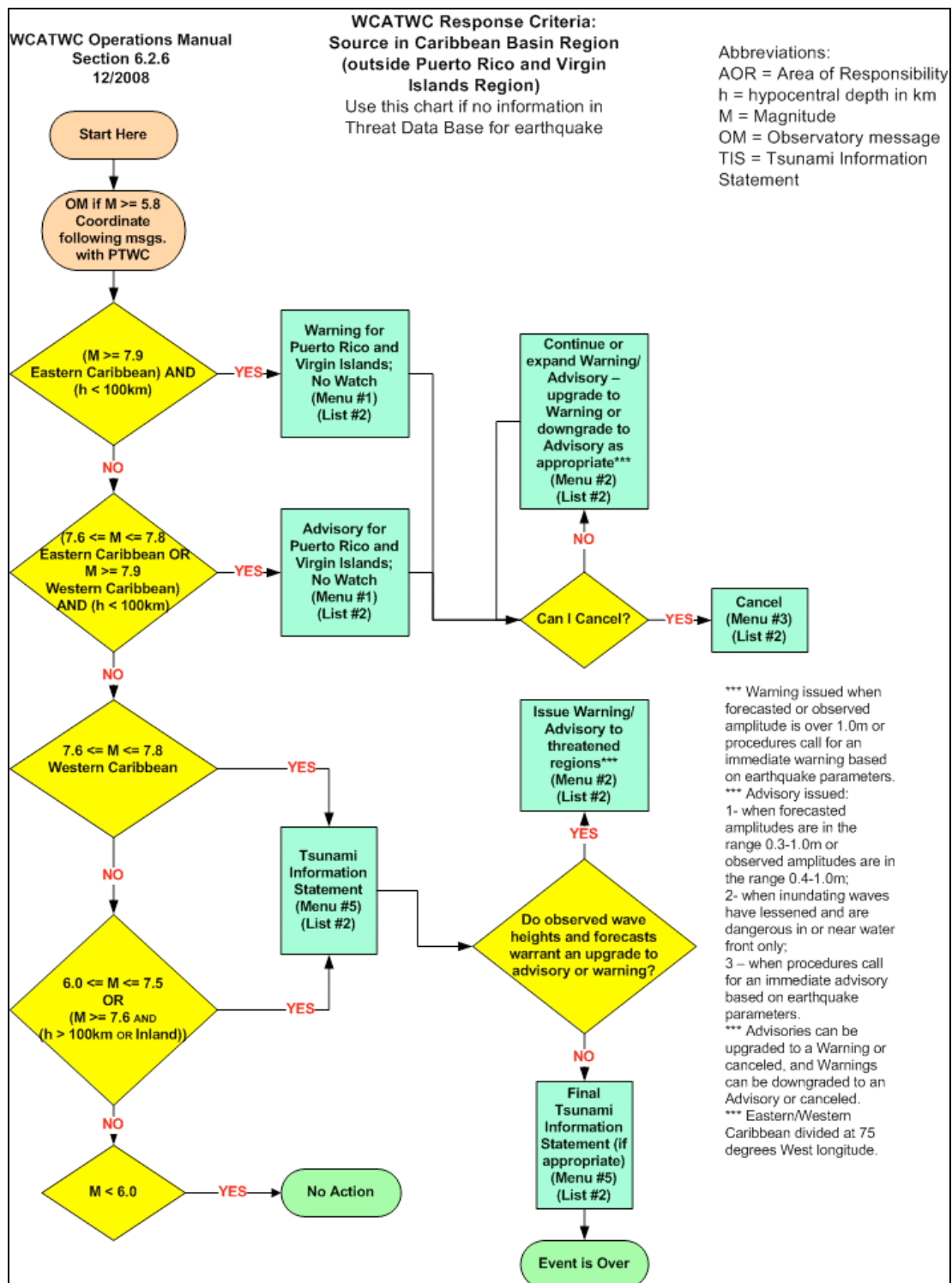


Figure 11. Criteria for Caribbean earthquakes located outside the Puerto Rico/Virgin Islands AOR.

standard response criteria will be used as given in the flow chart. If threatened zones have been pre-computed for this event, those regions will be immediately put in the appropriate alert level. The alert zones will not be adjusted until sea level data are observed on gages. Zones will then be further refined based on this information and any other forecast model or historical information available.

The seismic-based criteria given on the left sides of Figures 8 through 11 are for initial message issuance. Supplemental messages are mainly based on sea level observations and corresponding forecast models, but can be further guided by fault mechanism analysis, USGS Shake Maps, and slow earthquake discrimination by energy versus moment comparisons if sea level data and/or forecast models are not available.

FUTURE WORK

Warning criteria refinement is an ongoing process. Development of a threat database will continue as potential sources are better defined and models are computed based on those sources. Presently, these pre-computed sources are limited to tsunami generated by co-seismic, static sea floor motion, but could be expanded to include landslide sources. Continued collaboration between warning centers, tsunami research labs, and emergency management is necessary to keep criteria up-to-date with the latest research and emergency management response capabilities. New observational data sets such as better remote sensing of tsunamis, processing techniques, and basic hazard research must be incorporated into the criteria as they become available.

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