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

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ABSTRACT

New West Coast/Alaska Tsunami Warning Center (WCATWC) response criteria for earthquakes occurring in the Pacific basin are presented. Initial warning decisions are based on earthquake location, magnitude, depth, and - dependent on magnitude - either distance from source or pre-computed threat estimates generated from tsunami models. The new criteria will help limit the geographical extent of warnings and advisories to threatened regions, and complement the new operational tsunami product suite.

Changes to the previous criteria include: adding hypocentral depth dependence, reducing geographical warning extent for the lower magnitude ranges, setting special criteria for areas not well-connected to the open ocean, basing warning extent on pre-computed threat levels versus tsunami travel time for very large events, including the new advisory product, using the advisory product for far-offshore events in the lower magnitude ranges, and specifying distances from the coast for on-shore events which may be tsunamigenic.

This report sets a baseline for response criteria used by the WCATWC considering its processing and observational data capabilities as well as its organizational requirements. 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 slumps). As further research and development provides better tsunami source definition, observational data streams, and improved analysis tools, the criteria will continue to adjust. Future lines of research and development capable of providing operational tsunami warning centers with better tools are discussed.

1. **INTRODUCTION**

Tsunami warning systems are different from most other natural hazard warning systems in that most systems are able to directly monitor the hazard for which they warn (for example, hurricanes, tornadoes, and solar storms). In order to provide information in a meaningful time frame, tsunami warning centers must issue warnings to the nearest coasts prior to observing the tsunami. Initial warnings are normally based on seismic data which defines the tsunami source as opposed to wave measurements which define the tsunami. However, seismic signal strength is not directly proportional to the tsunami strength. This reality induces warning centers to use conservative warning protocols when basing warnings solely on seismic data.

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 earthquake shaking. At present, seismic data are the best immediate data available to characterize an earthquake's potential to generate a tsunami prior to impact along the nearest coast.

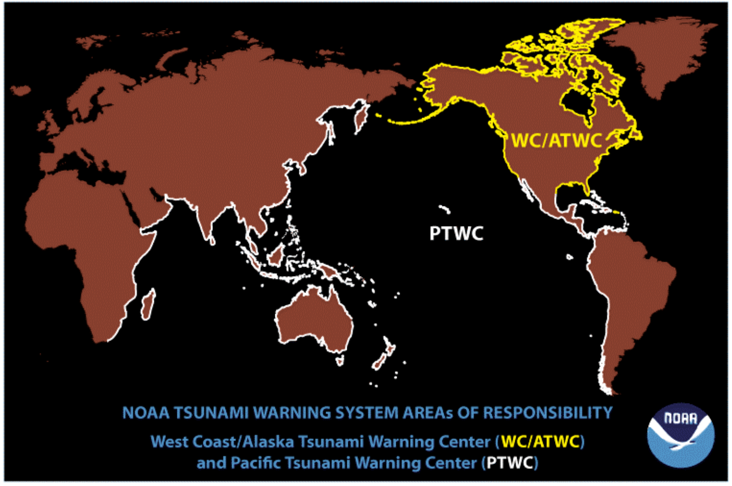


Figure 1. NOAA tsunami warning center area-of-responsibilities.

The purpose of this report is to refine criteria the warning center uses to issue tsunami messages in its Pacific area-of-responsibility (AOR – Figure 1). This AOR consists of the coasts of California, Oregon, Washington, British Columbia, and Alaska. 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.

2. TSUNAMI WARNING CENTER OPERATIONS

Two basic types of data are recorded at tsunami warning centers: seismic and sea level. Data from approximately 300 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, as the wave will not have been measured yet 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. Moment tensor solutions are computed, and - through the USGS CISNDisplay software - ShakeMaps and regional moment tensor solutions are displayed when available.

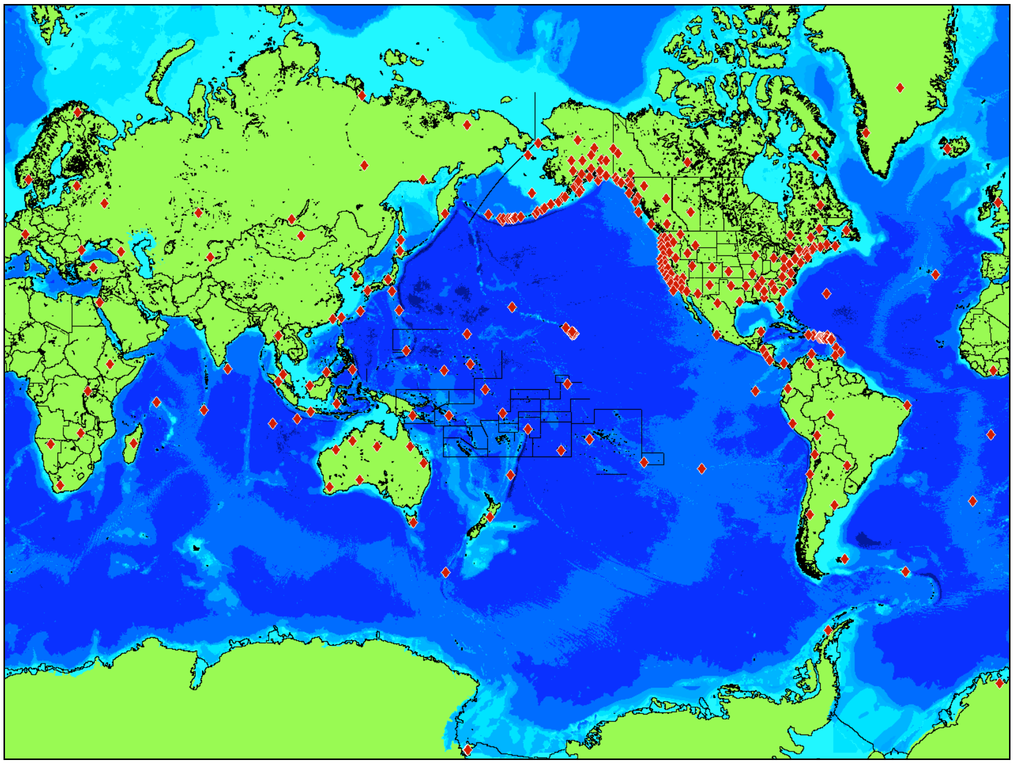


Figure 2. Diamonds represent seismometer locations recorded at the WCATWC.

Concurrent with secondary seismic data analysis, the center monitors sea level data (Figure 3). 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). Since 2005, the amount and quality of both tide gage data and DART data has greatly improved. 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 forecasts for wave heights outside the source zone, or to verify that no wave has occurred and cancel the alert. Within the AOR, upgraded sea level networks have dropped the verification time to 30 minutes in some regions.

The WCATWC's goal is to issue alerts in five minutes or less for events within the AOR (Figure 4). With this short response time, an analyst 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 procedures for all.

For earthquakes magnitude 8 and over, the center's initial magnitude estimate is often low since the earthquake may have not finished rupture by the time the initial processing is completed. Response criteria are set conservatively enough that the initial response will get an alert to those nearest the epicenter even with an under-estimated magnitude for earthquakes of this size.

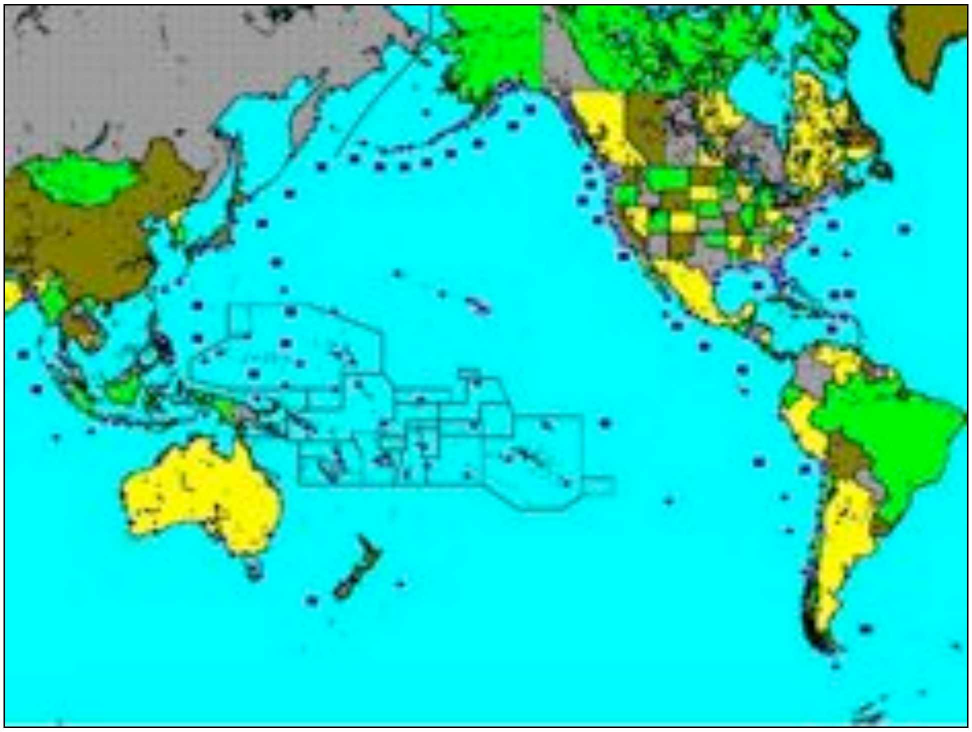


Figure 3. Diamonds represent coastal tide gages and squares represent DARTs recorded at the WCATWC.

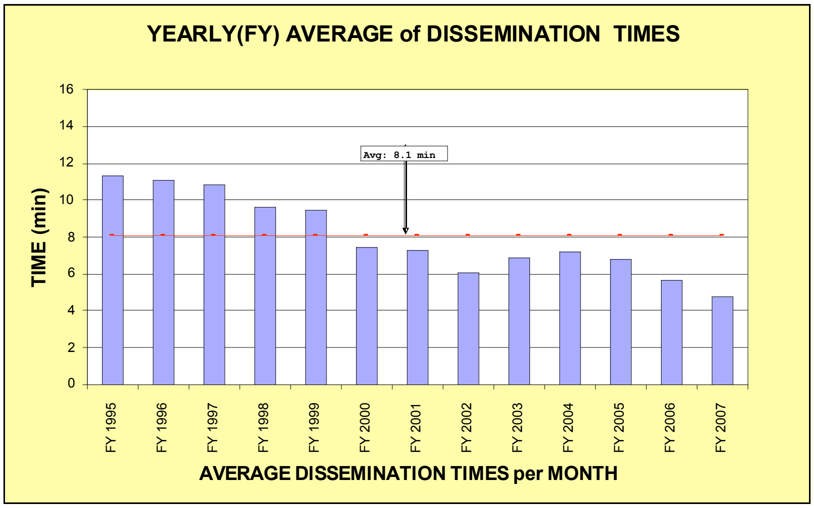


Figure 4. WCATWC response time summary. Response time is defined as the time of bulletin issuance minus the earthquake's origin time. Decrease in response time has been made possible by the use of denser, broadband seismic networks, improved seismic analysis software, and 24x7 staffing of the center.

After an alert is issued, messages are updated every 30 minutes or as necessary. 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 warning center response.

Response time is mainly limited by seismic network density and distribution. For example, a center can respond in five minutes with an accurate location and magnitude if the following network criteria are met (response is defined as the time of bulletin issuance minus the origin time of the earthquake):

- 12 evenly-distributed seismic stations
- Within 900 km of the epicenter (2 minute P-wave travel time)
- 80% station uptime
- Up to 30 seconds data latency (data transmission time)
- Digital, broadband seismic data (necessary to determine moment magnitudes)

If these criteria are met, a typical timeline for warning center response would be:

- 150 seconds to record signal on 9 to 10 stations
- 60 seconds more to record enough P-wave signal for M_{wp} computations
- 30 seconds extra for final analyst review
- 60 seconds to compose and transmit appropriate message

Response timelines can be compressed by increasing seismic network density, reducing data latency, or decreasing process time. However, response time will reach a limit due to source process times for major earthquakes which can exceed 100 seconds and the fixed times of reviewing events and composing bulletins.

3. TSUNAMI WARNING CENTER MESSAGE SUITE

The WCATWC tsunami message suite has recently been revamped. In short, it has progressed from 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 amplitude (dependent on whether the center has obtained sea level data), WCATWC will issue the appropriate product. Warnings and Advisories suggest that action be taken. Watches are issued to provide an early alert for areas that are distant from the wave front, but may have danger. Once the danger level is determined, the watch is upgraded to a warning or advisory, 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.

4 TSUNAMI AMPLITUDE VERSUS IMPACT

One important factor in determining which type of alert to issue is the impact expected from a certain size tsunami. Here, tsunami size is described by amplitude, or the level of the wave above normal sea level. Historic tide gage recordings or measured runup (the highest vertical extent of the wave along the shore) along with corresponding damage provides a relationship between amplitude and impact. Table 1 shows a comparison of recorded tide gage amplitudes or measured runups and corresponding damage along the U.S. west and Alaskan coasts.

Amplitude (m)	Location/Damage	Year
0.35	Shemya, AK; no damage	1996
0.4	Santa Barbara, CA; no damage	2006
0.4	Yakutat, AK; no damage	1987
0.45	Shemya, AK; no damage	2006
0.5	San Francisco, CA; strong current stops ferry	1960

0.5	Port Hueneme, CA; no damage	1957
0.5	Crescent City, CA, no damage	1994
0.5	Crescent City, CA; 1 mooring broke loose	1963
0.5+	San Diego, CA; boat/dock damage	1957
0.51	Adak, AK; no damage	1996
0.55	Port Orford, OR; no damage	2006
0.6	Arena Cove, CA; no damage	2006
0.6	Port San Luis, CA; no damage	2006
0.6	Ketchikan, AK; no damage	1964
0.6	Los Angeles, CA; $200K damage to boats	1964
0.6	Monterrey, CA; 2 almost drowned	1957
0.6	Crescent City, CA, no damage	1968
0.6	San Diego, CA; strong current, boat damage	1964
0.7	Crescent City, CA; no damage	1957
0.7	San Diego, CA; boat/pier damage (20 knot current)	1960
0.8	Unga, AK; dock washed away	1946
0.8	Port Hueneme, CA; railroad tracks flooded	1946
0.8	San Pedro, CA; wharf flooded	1868
0.8	Avila, CA; no damage	1927
0.8	Santa Barbara, CA; no damage	1946
0.8	Santa Barbara, CA; boat damage	1964
0.8+	Los Angeles, CA; $1 million damage, 1 drowning	1960
0.9	Crescent City, CA; $10M damage to docks	2006
0.9	Yakutat, AK; Mooring torn loose	1958
0.9	Adak, AK; no damage	1986
0.9	Shemya, AK; no damage	1969
0.9	Anaheim, CA; boats loose, no damage	1877
0.9	Santa Cruz, CA; boats loose, no damage	1960
0.9	Crescent City, no damage	1946
0.9	Trinidad, CA; cars stuck on beach	1992
1.0	San Pedro, CA; flooding, no damage	1877
1.0	Crescent City, CA; 4 boats sunk	1952
1.0	Cape Pole, AK; log boom broke	1960
1-1.5	San Francisco Bay, CA; $1 million damage	1964
1.1	Attu, AK; no damage	1969
1.2	Seldovia, AK; $500K damage to boats	1964
1.2	Larsen Bay, AK; warehouse flooded	1964
1.2	Annette, AK; no damage	1964
1.2	Seaside, OR; boats swept away	1946
1.4	Avila, CA; no damage	1952
1.4	Noyo River mouth, CA; several near drownings	1946
1.4	Santa Barbara, CA; much damage	1960
1.4	Ilwaco, WA; streets flooded	1964
1.4	Gearhart, OR; houses flooded	1964
1.5	Charleston, OR; no damage	1946
1.5	Taholah, WA; boats swept away	1946
1.5	Santa Cruz, CA; 1 dead, many rescued	1946
1.5	Santa Cruz, CA; minor damage	1896
1.5	Seaside, OR; boat/pier damage	1960
1.5	Stinson Beach, CA; no damage	1960
1.5	King Cove, AK; cannery damage	1946

1.6	Attu, AK; minor damage	1965
1.7	Crescent City, CA; boats sunk, pier damage, 3 injured	1960
1.8	Surf, CA; railroad station inundated	1927
1.9	Humboldt Bay, CA; some damage, flooding	1964
1.9	Adak, AK; bridge, structure destroyed	1957
2.0	Noyo Harbor, CA; boat/dock damage	1960
2.0	Noyo Harbor, CA; 10 boats sunk	1964
2.0	Copalis, WA; some injuries, much damage	1964
2.2	Half Moon Bay, CA; 3 near drownings, flooding, boat damage	1960
2.3	Umnak I. , AK; moorings destroyed	1957
2.3	Montague I. , AK; minor damage	1960
2.5	Pacific Beach, CA; injuries, damage	1964
2.6	Half Moon Bay, CA; homes flooded	1946
2.6	Drake’s Bay, CA; boat capsized	1946
3.0	Santa Monica, CA; boat/pier damage	1930
3.0	Redondo Beach, CA; 1 dead, many rescued	1930
3.0	Seaside, OR; 1 dead, structural damage	1964
3.0	Cape St. Elias, AK; 1 drowned	1964
3.0+	Florence, OR; much damage	1964
3.0+	Klamath River, CA; 1 dead, some damage	1964
3.4	Gaviota, CA; ships run aground	1812
3.4	Moclips, WA; houses damaged	1964
3.5	DePoe Bay, OR; 4 deaths, some damage	1964
3.7	Yakataga, AK; no damage reported	1964
4.5	Wreck Creek, WA; minor damage	1964
4.8	Crescent City, CA; 10 dead, $15 million damage	1964

Table 1. Examples of tsunami amplitude or measured runup and resulting damage (Lander *et al.*, 1993; Lander, 1996, NGDC, 2007). Amplitudes are taken from original tide gage records where possible. There are many other recordings below 0.5m within the AOR. None of these had any associated damage.

Table 1 indicates that tsunami damage due to strong currents can occur at amplitudes as low as 0.5m. More severe damage and inundation tends to occur in the 1.5-2.0m amplitude range. Whitmore (2003) showed that tsunami amplitude forecast accuracy for events up to 1.5m amplitude is approximately 50%. This general accuracy level was also observed during the November 15, 2006 Kuril Islands tsunami for forecasts along the U.S. coast. Based on this level of accuracy, the observed amplitude/impact relationship, and the tsunami product definitions, advisories will normally be issued when forecasts are in the range 0.3m to 1.0 m and warnings when the forecast is above 1.0m.

5. WARNING CRITERIA

Tsunami response criteria can be based on historic event data. Since significant tsunamis are uncommon events, the amount of data on which to base analysis is small. Figure 5 displays tsunamis which have been recorded along the WCATWC Pacific AOR. One way to expand the data set is to use historic data from other areas in addition to the region of interest. NOAA’s National Geophysical Data Center (NGDC) compiles a historic tsunami database which can be used for this purpose (NGDC 2007). Tsunami amplitudes in the database have been compared to sea level records when available and updated as necessary.

Modeling hypothetical events can also help define procedures. For example, Knight (2006) showed by modeling potential events in the Atlantic Basin, Caribbean Sea, and Gulf of Mexico that events in the Atlantic will not pose a threat to the Gulf of Mexico and vice-versa. This type of study is particularly helpful in areas with little historic tsunami information.

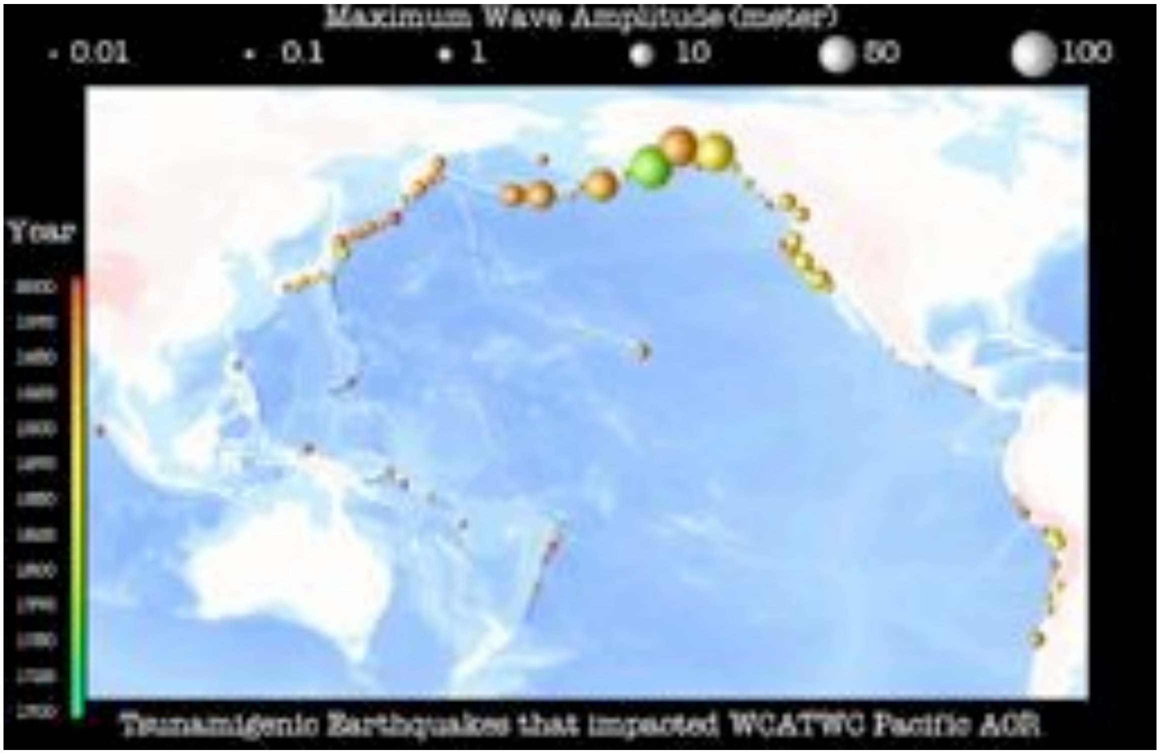


Figure 5. Events which have produced tsunamis recorded in the WCATWC Pacific AOR (NGDC, 2007). Spheres are located at the event's source location with a size related to the maximum recorded amplitude or runup within the AOR. The sphere color relates to the event's year of occurrence.

There are some pitfalls in using modeling to base criteria for local events. Most sub-sea earthquakes less than or near magnitude 7.5 do not trigger significant tsunamis. However, occasionally a major tsunami will be triggered by an earthquake in this range (e.g., 1998 Papua New Guinea, 1994 Java, and 2006 Java, etc). 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).

Regardless of the reason for these larger than expected waves, criteria for local events can not be set only by forward modeling from earthquake sources. Criteria must be set conservatively enough so that the odds of a dangerous local event not falling within the warning category are very low.

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, or slip. These other parameters are not known to the center analysts within the time frame necessary to issue the first message. There is little time for analysis during that first message output, so criteria must be kept as simple as reasonably possible.

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 can influence how large an area can be affected by a wave if one is generated.

The influence of earthquake source parameters on tsunami generation is examined using the NGDC tsunami database. Table 2 compares hypocentral depth versus tsunami generation. Large, deep earthquakes are unusual in the AOR, so there is not much historical data for the AOR only. Table 2 includes all tsunamis throughout the entire planet since 1900 with amplitude 0.5m or over, and shows the percentage of occurrence at different hypocentral depth ranges.

Hypocentral Depth (km)	Number Tsunamis (entire database since 1900)	% of total tsunamis	Total # of earthquakes since 1900; M >= 7
< 50	343	90%	1300
50-100	35	9%	140
> 100	2	<1%	70

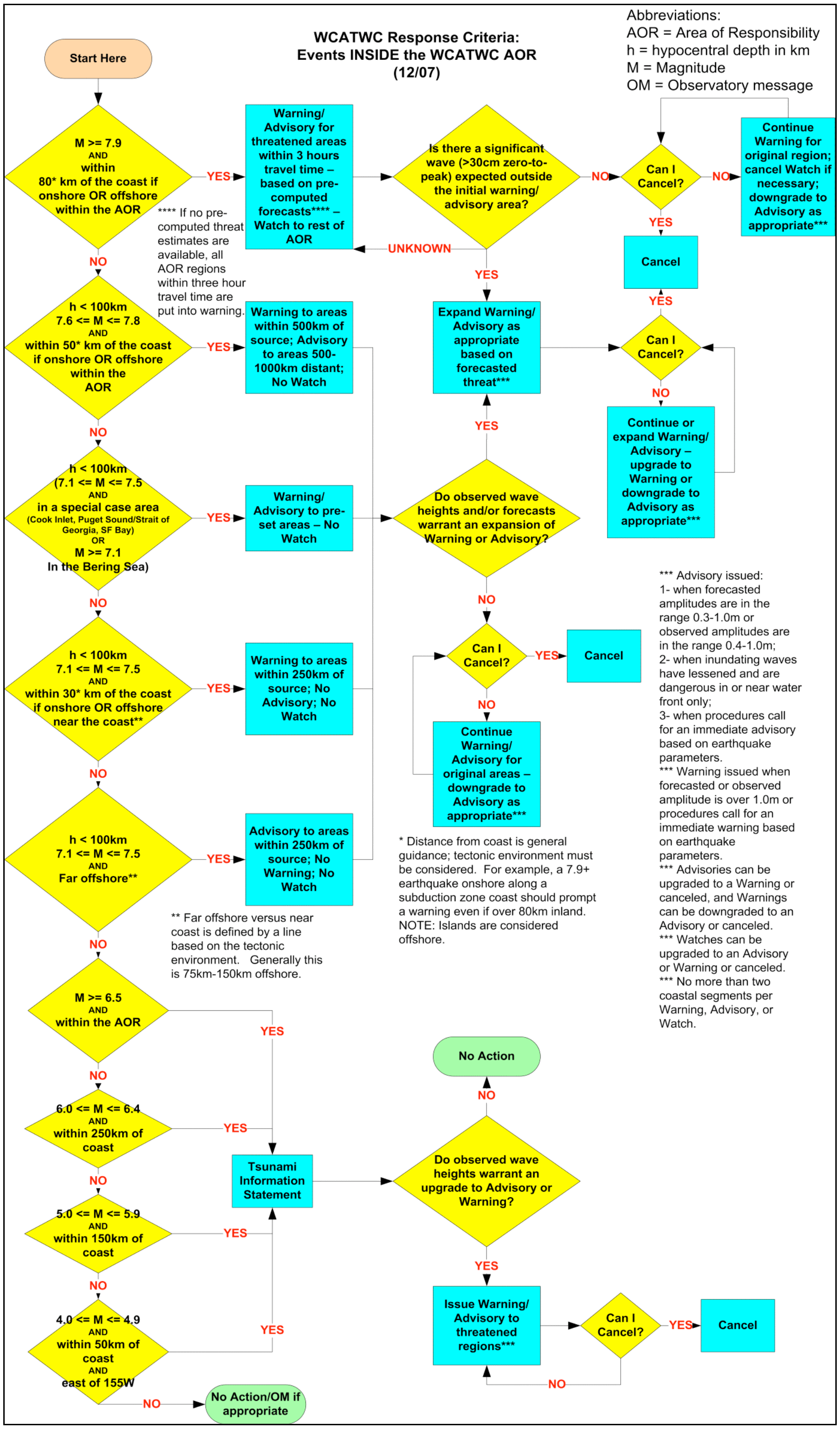
Table 2. Tsunami generation versus depth. Tsunamis included are all high-validity events worldwide since 1900 with amplitude greater than 0.5m. The last column shows the estimated total number of events over magnitude 7 for each depth range in this time period based on an extrapolation of the USGS Preliminary Determination of Epicenters catalog (2007).

Table 2 shows that the likelihood of tsunami generation by earthquakes greater than 100km depth is very low. However, earthquakes in the range 50km to 100km produce a sizeable portion of significant tsunamis. Results from this table support the international tsunami standard of not issuing tsunami warnings for earthquakes over 100km in depth except in cases where the size, depth, and location of the quake indicate possible rupture to shallow depths.

Table 3 compares earthquake magnitude with tsunami generation. Magnitudes are grouped by existing WCATWC criteria levels which match international standards.

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 >= 0.5m amp.	Maximum amplitude (m)	Maximum "reach" – max. epicentral distance with recorded amp. >= 0.5m (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 3. Tsunami generation versus magnitude within the WCATWC AOR. 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.



Abbreviations:
AOR = Area of Responsibility
h = hypocentral depth in km
M = Magnitude
OM = Observatory message

**** If no pre-computed threat estimates are available, all AOR regions within three hour travel time are put into warning.

** Far offshore versus near coast is defined by a line based on the tectonic environment. Generally this is 75km-150km offshore.

* Distance from coast is general guidance; tectonic environment must be considered. For example, a 7.9+ earthquake onshore along a subduction zone coast should prompt a warning even if over 80km inland. NOTE: Islands are considered offshore.

*** Advisory issued:
1- when forecasted amplitudes are in the range 0.3-1.0m or observed amplitudes are in the range 0.4-1.0m;
2- when inundating waves have lessened and are dangerous in or near water front only;
3- when procedures call for an immediate advisory based on earthquake parameters.

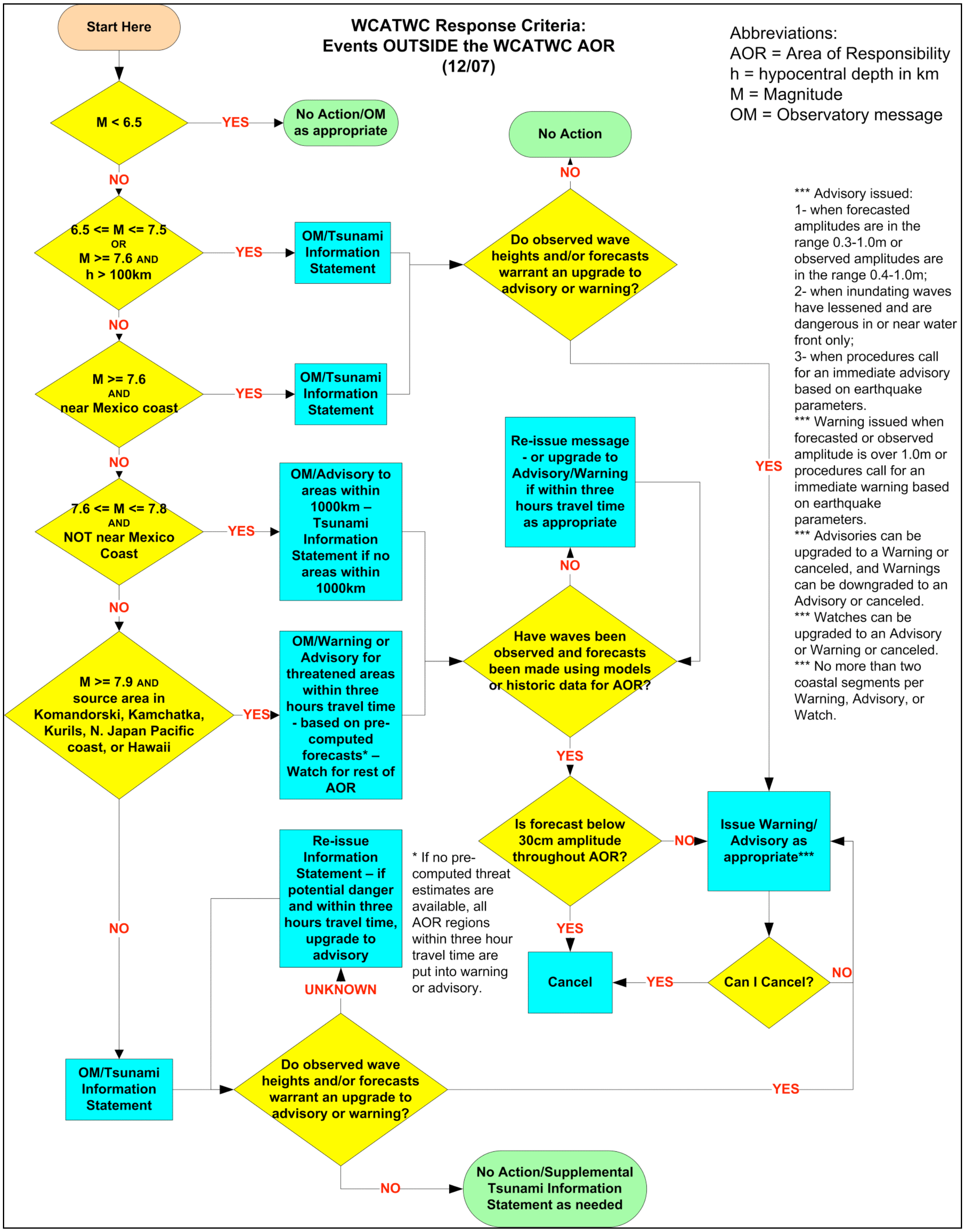
*** Warning issued when forecasted or observed amplitude is over 1.0m or procedures call for an immediate warning based on earthquake parameters.

*** Advisories can be upgraded to a Warning or canceled, and Warnings can be downgraded to an Advisory or canceled.

*** Watches can be upgraded to an Advisory or Warning or canceled.

*** No more than two coastal segments per Warning, Advisory, or Watch.

Figure 6. Warning criteria for events inside the WCATWC AOR.



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*** Advisory issued:
1- when forecasted amplitudes are in the range 0.3-1.0m or observed amplitudes are in the range 0.4-1.0m;
2- when inundating waves have lessened and are dangerous in or near water front only;
3- when procedures call for an immediate advisory based on earthquake parameters.
*** Warning issued when forecasted or observed amplitude is over 1.0m or procedures call for an immediate warning based on earthquake parameters.
*** Advisories can be upgraded to a Warning or canceled, and Warnings can be downgraded to an Advisory or canceled.
*** Watches can be upgraded to an Advisory or Warning or canceled.
*** No more than two coastal segments per Warning, Advisory, or Watch.

* If no pre-computed threat estimates are available, all AOR regions within three hour travel time are put into warning or advisory.

Figure 7. Warning criteria for events outside the WCATWC AOR.

Data in Table 3 show the general trend that the higher the earthquake magnitude, the more likely a tsunami will be generated. Also, the higher the magnitude, the further away from the epicenter the wave may be dangerous. Data on this table support keeping warning zones small for events magnitude 7.5 and below, and increasing the geographic extent with magnitude. WCATWC response criteria corresponding to the magnitude ranges given in Table 3 are shown in the flow charts in Figures 6 and 7.

Earthquake fault mechanism also influences tsunami generation. Intuitively, it might seem that events with horizontal fault motion should not produce tsunamis as little sea floor is vertically moved. However, Knight (2006) 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 4 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 1m amplitude. Of those 41 events, 5 (12%) were triggered by strike slip earthquakes (with slip vectors within 20 degrees of horizontal).

Event Date	Region	Magnitude	Maximum amplitude (m)	"Reach" – max. epicentral distance with recorded amp. >= 0.5m (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

Table 4. Strike slip earthquakes which produced significant tsunamis in the period from 1977 to 2004 (Knight, 2006).

Table 4 shows that strike slip events can cause tsunamis, though, all of these earthquakes were located near the coast. In each case, the event was located within 25km of the coastline the tsunami impacted.

Based on the information given in Tables 3 and 4 and the high likelihood of strike slip events occurring far offshore the Pacific Northwest coastline, events in the magnitude range 7.1-7.5 and located far offshore will trigger the issuance of an advisory for nearby coasts. Those located near shore will trigger the issuance of a warning. The definition of zones which trigger warning versus advisory in the 7.1 to 7.5 magnitude range is defined by an examination of the tectonic environment, and is normally based on distance ocean-ward from the trench. Figure 8 shows the warning/advisory boundary for the Cascadia subduction zone region.

An interesting strike slip event not shown on Table 4 which occurred in the WCATWC AOR is the 1987, M=7.8, Gulf of Alaska event. This event triggered an observable wave in Yakutat, Alaska of 0.4m amplitude. The event occurred well onto the oceanic plate, far from any inclined features or slopes expected to slide, but still produced a near-dangerous-amplitude wave. Based on the procedures listed in Figure 6, a warning would be issued for this event to areas within 500km and an advisory to areas from 500km to 1000km distant. Appendix A shows the distribution of warning/watch/advisory areas for this event and other historic events using both the criteria listed in this report and criteria used at the time of the event.

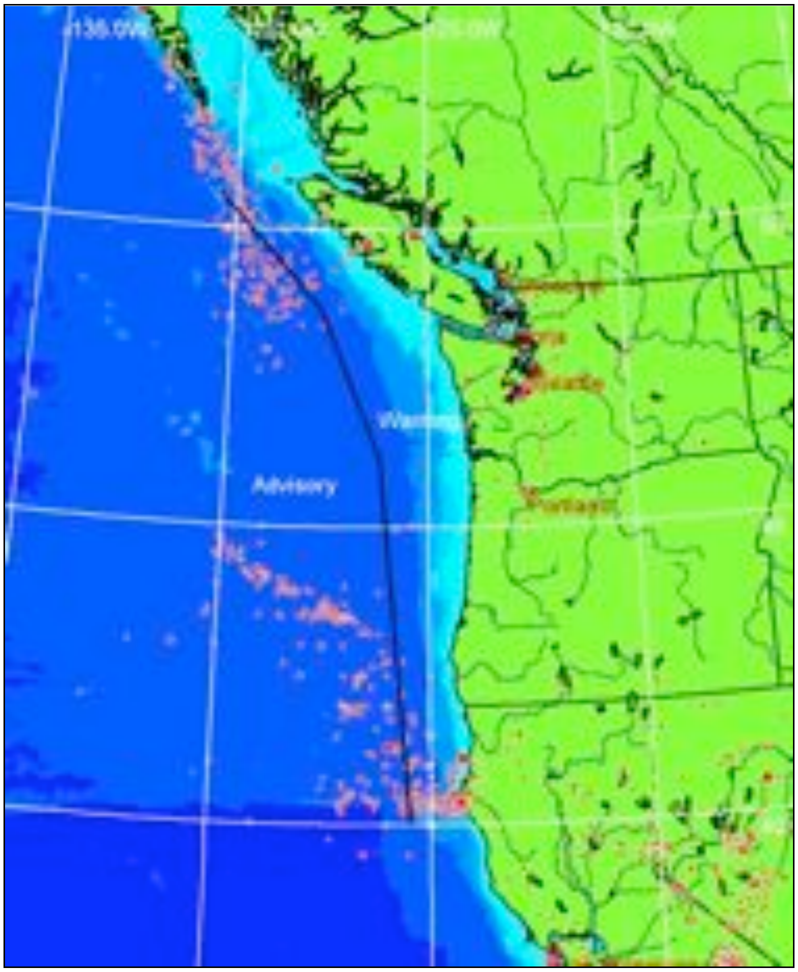

Figure 8. Line dividing offshore magnitude 7.1 to 7.5 earthquakes (which trigger advisories) from near shore earthquakes (which generate warnings) in the Cascadia subduction zone region. Historic earthquakes are shown with red dots.

Criteria relating to epicentral distance from the coast for on-shore events are also provided in Figure 6. The distances vary with magnitude and are relevant for epicenters located on the North American mainland. Epicenters located on islands such as Kodiak and Vancouver are treated as offshore events.

There are a few examples of on-shore events which have produced tsunamis. The two main reasons that an on-shore event can trigger a tsunami are: 1) the fault rupture extends under the ocean (e.g., 1964 Alaska quake and 1906 San Francisco quake), and 2) strong shaking induces a sub-aerial or sub-marine landslide (e.g., 1989 Loma Prieta).

Table 5 summarizes on-shore events in the AOR which have triggered tsunamis. Since 1900, 37 known tsunamis have been generated in the AOR. Seven of these were generated by events with an epicenter on land.

Table 5. Onshore events in the WCATWC AOR which have triggered a tsunami (NGDC, 2007).

Event Date	Region	Magnitude	Maximum amplitude (m)	Epicentral distance from coast (km)	Cause
6/23/1946	Vancouver I.	7.3	3 (?)	10	Landslide
4/13/1949	Washington	7.0	2.2	2	Landslide
7/10/1958	Alaska	8.2	525	1	Landslide
3/28/1964	Alaska	9.2	67	2	Extended fault rupture and landslides
2/28/1979	Alaska	7.4	0.1	65	Ice fall (?)
10/18/1989	California	6.9	1	3	Landslide
4/25/1992	California	7.2	0.9	4	Extended fault rupture

The events in Table 5 indicate that sources have to be near the coast to trigger a tsunami. The 1964 event is a little misleading, though. It was located within 2km of the ocean, but next to a fjord which extended well into the mainland. The fault rupture (and tsunami source zone) extended several hundred kilometers seaward from the epicenter.

The distance an earthquake ruptures is roughly related to its magnitude. Several studies have developed rupture length versus magnitude relationships. All these relationships are best fits to the observed data and do not provide an accurate estimate for all events. Papazachos, et al. (2004) separated the relationship into strike slip, continental dip slip, and subduction dip slip categories. Table 6 summarizes expected fault length for these categories. These values could be used as guidelines as they would limit how far an event could be from the coast and still directly disturb the sea floor (if the hypocenter is located near one end of a rupture zone).

Table 6. Expected rupture length for various size earthquakes and tectonic settings (Papazachos et al., 2004).

Magnitude	Fault Type	Expected Rupture Length (km)
7.0	Strike Slip	67
7.0	Continental Dip Slip	44
7.0	Subduction Zone Dip Slip	46
7.5	Strike Slip	133
7.5	Continental Dip Slip	78
7.5	Subduction Zone Dip Slip	86
7.8	Strike Slip	200
7.8	Continental Dip Slip	110
7.8	Subduction Zone Dip Slip	126
8.0	Strike Slip	263
8.0	Continental Dip Slip	138
8.0	Subduction Zone Dip Slip	162

Tables 5 and 6 provide much different sets of guidelines for onshore earthquake criteria. Using the fault lengths in Table 6 as a guide would lead to over-warning based on the history shown in Table 5. Another factor which could help a TWC analyst in certain cases is the ShakeMaps produced by the Advanced National Seismic System (ANSS). For many areas of the United States, ShakeMaps are quickly distributed by the ANSS and available at the WCATWC shortly after initial bulletin issuance. Further work is necessary to integrate ShakeMaps fully into tsunami warning center operations.

Onshore distance guidelines are set conservatively based on the history in Table 5. Following initial message issuance, the analyst would attempt to verify that fault rupture has not extended to sea by using the ShakeMap, fault mechanism, and/or nearby sea level data (upgrading the message if necessary). As specified in the Figure 6 flowchart, one exception to the distance rule is major (magnitude 7.9+) onshore earthquakes in a subduction zone. These will prompt a warning even if the hypocenter is greater than the set distance from the coast.

Based on the discussion above and information in Tables 2 through 6, warning criteria for events inside and outside the WCATWC AOR are given in a flowchart form in Figures 6 and 7. These criteria have several differences from the previous criteria used at the center:

- Hypocentral depth is included,
- Geographical warning extent is generally reduced,
- Special procedures are set for regions not well-connected to the open ocean,
- For events magnitude 7.9+, warning/advisory areas are based on threat level from pre-computed models instead of tsunami travel times,
- The new advisory product is included in the criteria,
- Advisories are issued for far-offshore events in the lower magnitude ranges, and
- For onshore events, distance from the coast is specified.

Operationally, basing the warning extent on modeled threat level versus tsunami travel times for events magnitude 7.9 and greater is a significant change. Recent improvements in modeling and sea level data acquisition make this change possible. The new DART array provides data to the TWC which allows the center to forecast impact for distant events well before wave impact along the AOR coast. The new criteria take advantage of this array by only issuing immediate warnings/advisories to areas that could be affected within three hours of the event. Within this three-hour region, only areas that pre-computed tsunami models indicate will be threatened are put into a warning or advisory. If no threat analysis is available for a source, warnings/advisories will be issued to all AOR coasts within three hours travel time until recorded sea level data allows cancellation or restriction of the warning/advisory.

Threatened areas are defined by using tsunami models (Titov and Gonzalez 1997, Whitmore and Sokolowski 1996). Models are computed for different magnitude events at subduction zones around the Pacific basin which could threaten the AOR. Based on the amplitudes computed, the region of the AOR threatened in each model is defined. During an event, the most appropriate model is selected and its threatened area is compared with travel times to determine the region placed in a warning or advisory.

For example, during the November 15, 2006 Kuril Islands event, warnings were issued for regions of the Aleutian Islands within three hours of the wave front until a forecast could be made (based on procedures of the time). Areas east to Sand Point, AK were eventually included in warnings. Pre-computed, unscaled models forecasted minor waves (0.12m and less) east of Adak in Alaska, and moderate waves (0.2m to 0.4m) from Adak west to Attu. Under the new procedures, the region from Adak to Attu would have been issued an immediate advisory which would not have expanded to the east unless observed wave heights indicated otherwise (Figure A4). The region from Adak to Attu was the only region in Alaska that models forecasted an advisory level impact (0.3m to 1.0m). Warnings and advisories for areas along the west coast would be based on a forecast calibrated with observed sea level heights.

Warning, watch, and advisory areas are delineated by known break points. These break points are listed below.

Attu, AK
Adak, AK
Nikolski, AK
Dutch Harbor, AK
Sand Point, AK
Kodiak, AK
Seward, AK
Cordova, AK
Yakutat, AK
Sitka, AK
Langara Island, BC
Northern Tip Vancouver Island, BC
Washington-BC Border
Clatsop Spit, OR
Cascade Head, OR
Cape Blanco, OR
Oregon-California Border
Cape Mendocino, CA
Point Reyes, CA
Point Sur, CA
Point Conception, CA
California-Mexico Border

The flow chart in Figure 6 lists four areas which have special procedures (Bering Sea, Cook Inlet, Puget Sound/Strait of Georgia, and San Francisco Bay). Figure 9 depicts the Puget Sound special procedure area. Tsunamis generated in these areas are expected to be confined to the source region only. Warning zones are pre-determined for events that occur within the specified region and magnitude range. These zones are based on a study of potential sources and wave propagation for each region. For example, a magnitude 7.1 or greater earthquake located east of Russia in the Bering Sea would prompt a warning for the Pribilof Islands, and the Aleutian Islands from False Pass to Attu. Another example is the Puget Sound special procedural region for earthquakes in the magnitude range 7.1 to 7.5 (Figure 9). Earthquakes within this magnitude range and region would prompt a warning for the Puget Sound and Strait of Juan de Fuca and not the outer coast.

Figure 9. Puget Sound special procedure region.

The seismic-based criteria given on the left sides of Figures 6 and 7 are for initial message issuance. Supplemental messages can be further guided by fault mechanism analysis, ANSS ShakeMaps, and slow earthquake discrimination by energy versus moment comparisons if sea level data and associated forecasts are not available.

6. FUTURE WORK

Warning criteria refinement is an ongoing process. Continued collaboration between warning centers, research agencies, and emergency management through channels such as the U.S. National Tsunami Hazard Mitigation Program (Bernard 2005) are necessary to keep criteria up-to-date with the latest knowledge and emergency management response capabilities. New observational data sets, processing techniques, and basic hazard research must be incorporated into the criteria as they become available. Some ideas to address are:

- Utilize USGS ShakeMap and mechanism products and slope stability analysis to determine areas at highest risk of landslide tsunami generation,
- Improve near source tsunami observations and corresponding forecast models,
- Incorporate real time GPS/accelerometer data streams to improve finite fault parameter determinations, and
- Investigate seismic techniques which help discriminate earthquakes likely to generate a tsunami from those that are not.

7. ACKNOWLEDGEMENTS

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APPENDIX A

Four examples are provided below which show the initial warning/ watch/ advisory status for historic events. Both the status using criteria in use at the time of the event and the criteria given in this report are shown.

Example 1:
1987 M=7.8 Gulf of Alaska

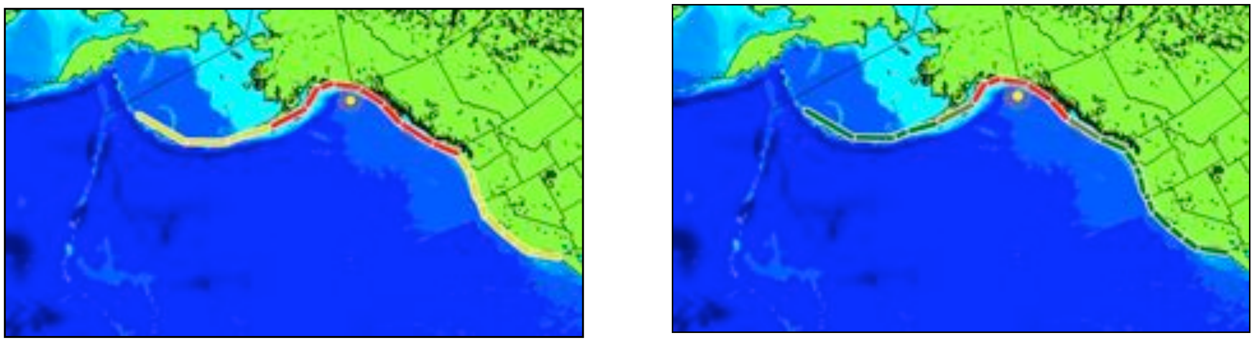

Figure A1: Initial Warning/Watch/Advisory extent for the 1987 Gulf of Alaska event. The left side shows the actual extent of the initial alert and the right shows the extent under the criteria listed in this report. Warning areas in red; advisory in grey, watch in yellow; information only in green.

Example 2:
1997 M=7.8 Kamchatka

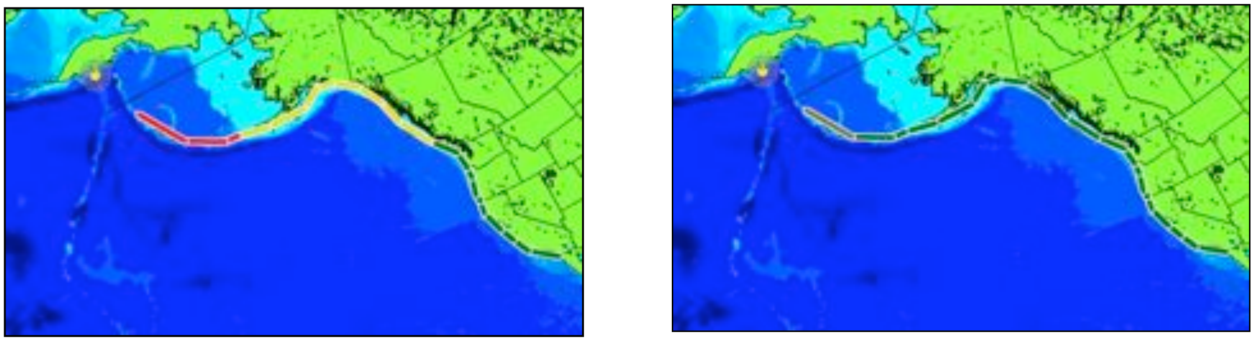

Figure A2: Initial Warning/Watch/Advisory extent for the 1997 Kamchatka event. The left side shows the actual extent of the initial alert and the right shows the extent under the criteria listed in this report. Warning areas in red; advisory in grey, watch in yellow; information only in green.

Example 3:

2005 M=7.2 Gorda Plate

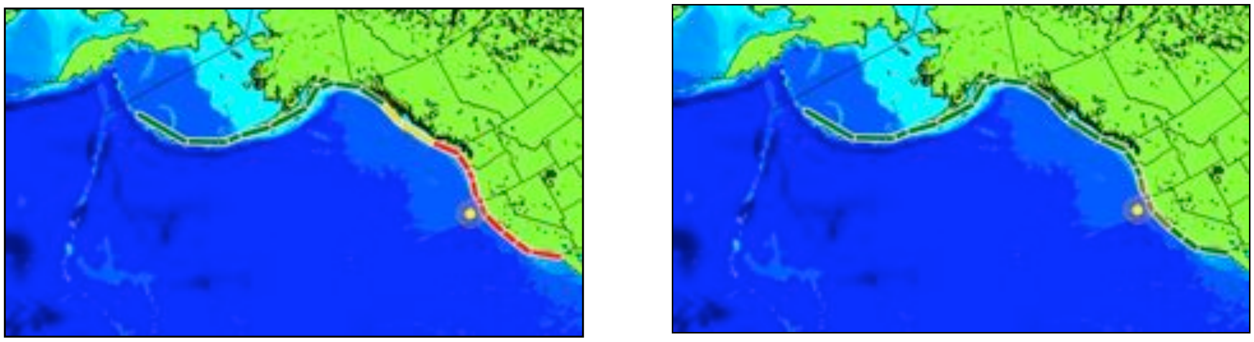

Figure A3: Initial Warning/Watch/Advisory extent for the 2005 Gorda plate event. The left side shows the actual extent of the initial alert and the right shows the extent under the criteria listed in this report. Warning areas in red; advisory in grey, watch in yellow; information only in green.

Example 4:

2006 M=8.3 Kuril Islands

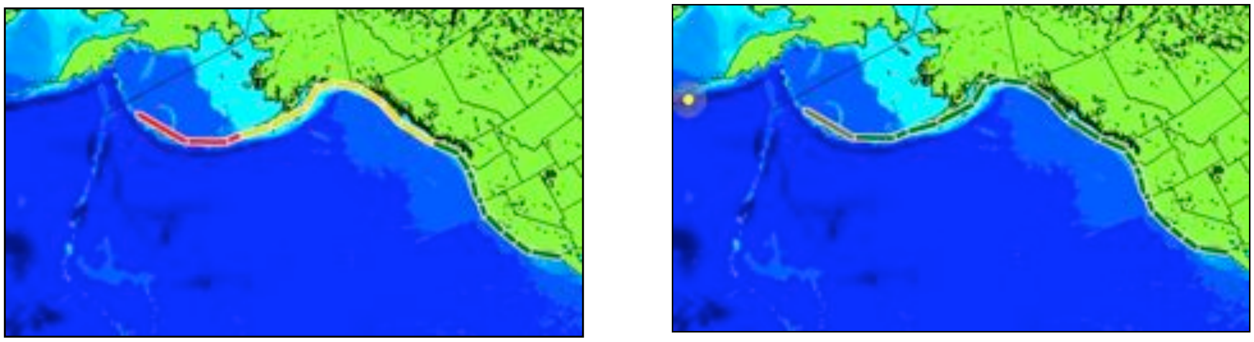

Figure A4: Initial Warning/Watch/Advisory extent for the 2006 Kuril Islands event. The left side shows the actual extent of the initial alert and the right shows the extent under the criteria listed in this report. Warning areas in red; advisory in grey, watch in yellow; information only in green.