TSUNAMI AMPLITUDE PREDICTION DURING EVENTS: A TEST BASED ON PREVIOUS TSUNAMIS

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ABSTRACT

The U.S. West Coast/Alaska Tsunami Warning Center's (WC/ATWC) far-field tsunami amplitude prediction method is tested by applying the technique to nine previous, well-recorded tsunamigenic events. Predicted tsunami amplitudes outside the source area are shown to be sufficiently accurate to guide warning cancellation/restriction/expansion decisions. Average error per event ranged from 0.04m to 0.29m with error defined as the absolute value of the difference between the recorded amplitude and the predicted amplitude. Had this technique been available during the 1986 Aleutian Is. and the 1994 Kuril Is. tsunami warnings, the warned areas likely would not have been expanded to include the U.S. West Coast, Canada, and Alaska east of Kodiak Island.

PREDICTION METHOD SUMMARY

The basic tsunami modeling technique used in the WC/ATWC far-field prediction method is described by Kowalik and Whitmore (1991). Initial tsunami profile is computed from fault dislocation formulae of Okada (1985). Waves are propagated using the shallow-water wave equations with non-linear terms and friction included in areas of fine grid resolution. An explicit-in-time finite difference scheme is used with grid increments of 5’ over the deep ocean, 1’ over the shelf and 12” where necessary to describe near-shore coastline configuration. All grids interact dynamically throughout the computations. The ocean/land boundary is fixed. That is, inundation is not taken into account.

The methodology which utilizes models computed as described above to predict far-field tsunami amplitudes is described by Whitmore and Sokolowski (1996). To summarize, tsunami models are computed for 204 hypothetical earthquakes along the coasts of northern Honshu, Kuril Is., Kamchatka, Aleutian Is., Alaska, British Columbia, Cascadia, and Chile. The hypothetical earthquake source parameters are determined by regional tectonic setting and past earthquakes. Moment magnitudes range from 7.5 to 9.5. Figure 1 shows modeled fault locations.

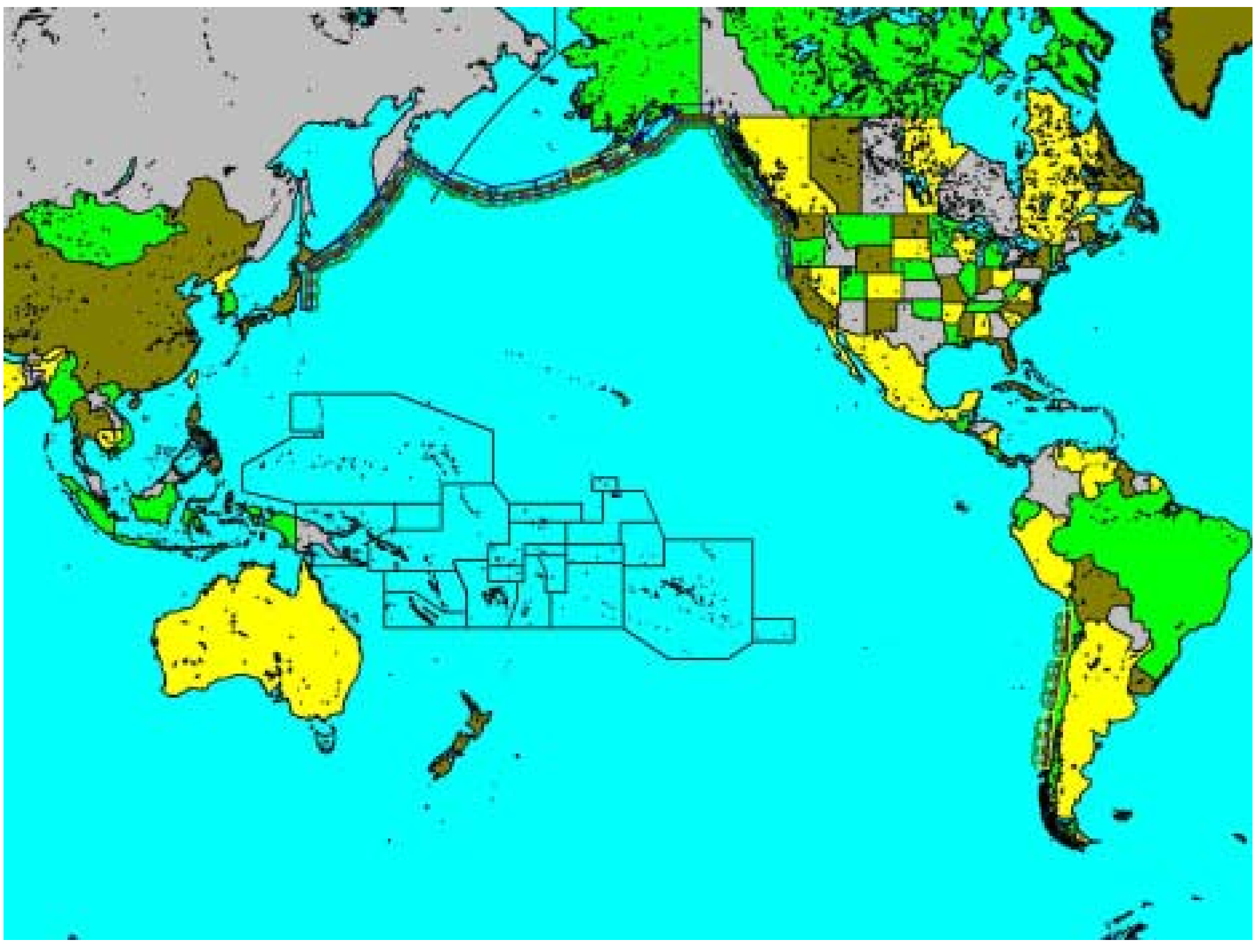


Figure 1. Model fault zones: yellow boxes represent Mw=9.5 models, blue boxes represent Mw=9.0 models, red boxes represent Mw=8.2 models, and green circles represent Mw=7.5 models.

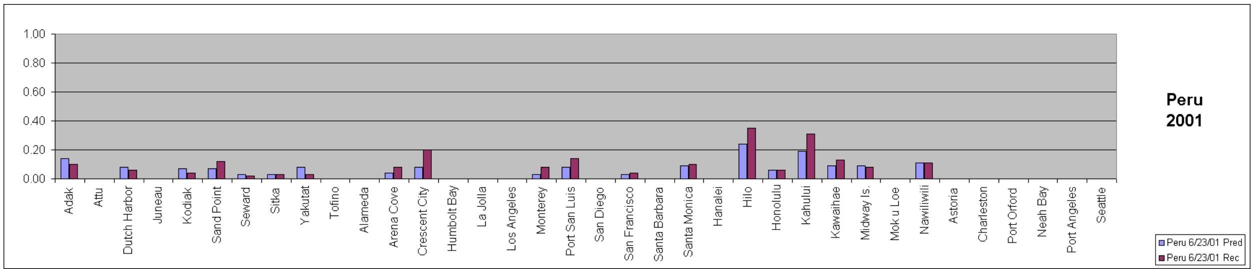
Maximum modeled amplitudes (amplitude defined as zero-to-peak distance in meters) are saved at 99 locations along the Pacific coasts of Alaska, British Columbia, Washington, Oregon, California, Hawaii, and at the DART buoys (Bernard, *et al.*, 2001) for each of the 204 models. During a tsunami warning, the model closest to the epicenter with the nearest moment magnitude is chosen. The previously computed amplitudes at all modeled sites are scaled as the tsunami is recorded on tide gages or DART recorders by simple proportions. Scaling can only be performed with data from gages which were included in the models. As the tsunami progresses, scaling factors are averaged. The predicted tsunami amplitudes are the scaled modeled results. Model results are not trusted until scaled with an observed tsunami.

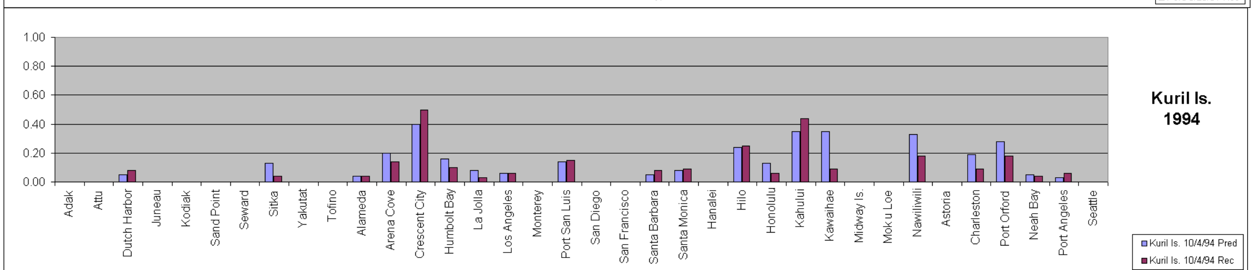
TEST RESULTS

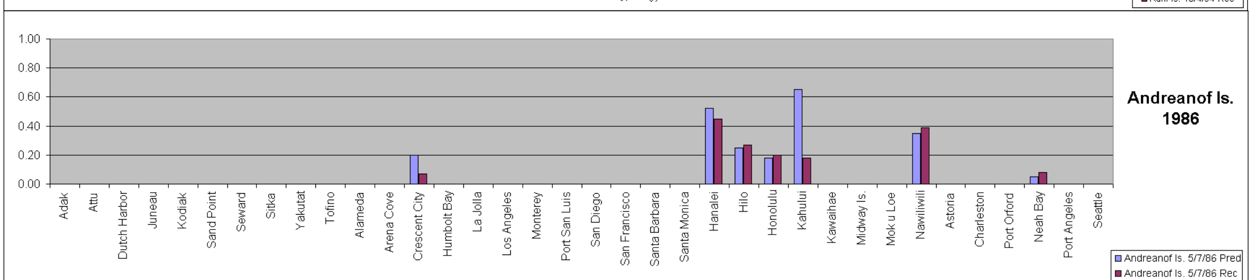
The predictive methodology is tested on nine historic tsunamis. Events tested are those that had moderate-sized or greater tsunamis in the WC/ATWC area-of-responsibility (AOR – Alaska, British Columbia, Washington, Oregon, and California), and were well-recorded on tide gages. Only tsunami amplitudes from tide gages are used for comparison and scaling as the modeling technique does not account for inundation (i.e., runup heights are not used for comparison). A wide variety of tsunami events are tested. Moderate size tsunamis, large tsunamis, and a tsunami produced by a "tsunami" earthquake are tested. In each case the model closest to the epicenter in distance and closest to the earthquake in moment magnitude is chosen. Amplitude data from the nearest 2 to 4 tide gages are used to scale the chosen model. The number of scaling stations depends on tide gage availability around the source. Table 1 is a summary of the average error, maximum error, number of scaling sites, and the scaling factor for each tested event. Error is defined as the absolute value of the difference between the recorded and modeled amplitudes. Figure 2 shows a summary of individual tide gage/model comparisons along with scaling sites for each event.

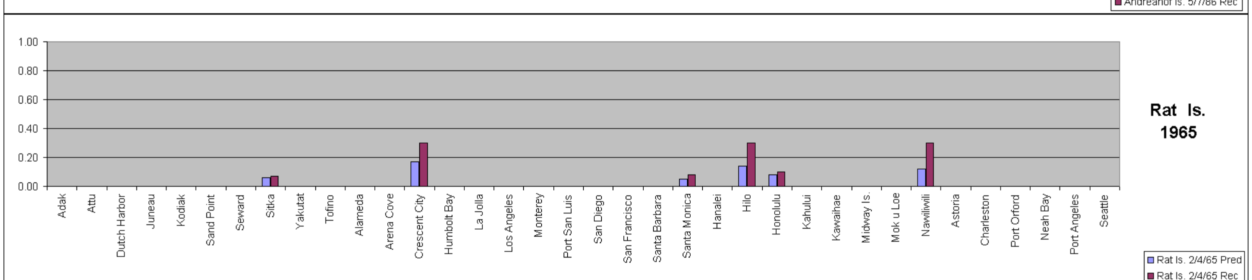
Source Region	Date	# Scaling Sites	Scale Factor	# Observations	Maximum Error (m)	Average Error (m)
Peru	2001/6/23	2	0.86	19	0.12	0.04
Kuril Is.	1994/10/4	3	0.94	20	0.26	0.06
Aleutian Is.	1986/5/7	4	0.59	7	0.47	0.11
Rat Is.	1965/2/4	4	0.25	6	0.18	0.09
Gulf of Alaska	1964/3/28	3	1.69	21	0.76	0.28
Southern Chile	1960/5/22	4	1.07	17	1.52	0.29
Aleutian Is.	1957/3/9	3	1.84	16	0.40	0.13
Kamchatka	1952/11/4	3	1.14	17	1.20	0.25
Alaska Peninsula	1946/4/1	3	3.42	10	0.72	0.26

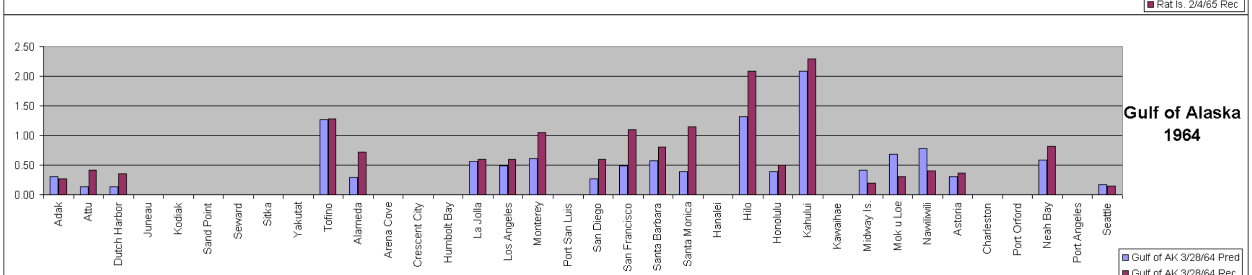
Table 1. Predicted amplitude error summary for each of the nine tested tsunamigenic events. Comparisons for individual observations are shown in Figure 2.

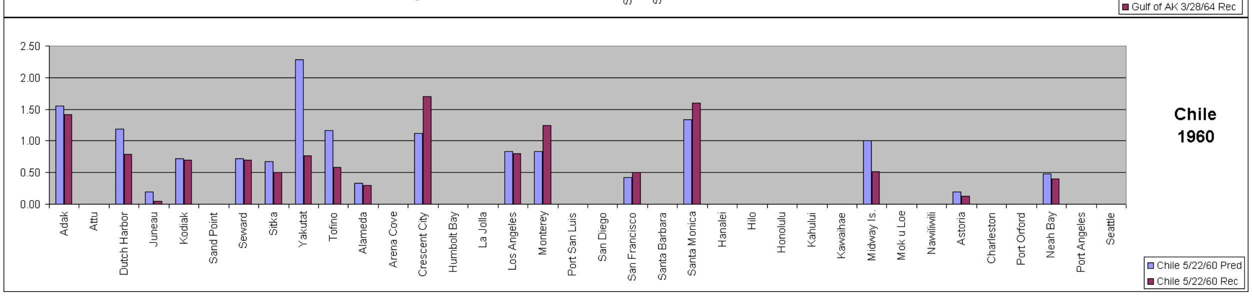

Peru
2001
Peru 6/23/01 Pred
Peru 6/23/01 Rec


Kuril Is.
1994
Kuril Is. 10/4/94 Pred
Kuril Is. 10/4/94 Rec


Andreanof Is.
1986
Andreanof Is. 5/7/86 Pred
Andreanof Is. 5/7/86 Rec


Rat Is.
1965
Rat Is. 2/4/65 Pred
Rat Is. 2/4/65 Rec


Gulf of Alaska
1964
Gulf of AK 3/28/64 Pred
Gulf of AK 3/28/64 Rec


Chile
1960
Chile 5/22/60 Pred
Chile 5/22/60 Rec

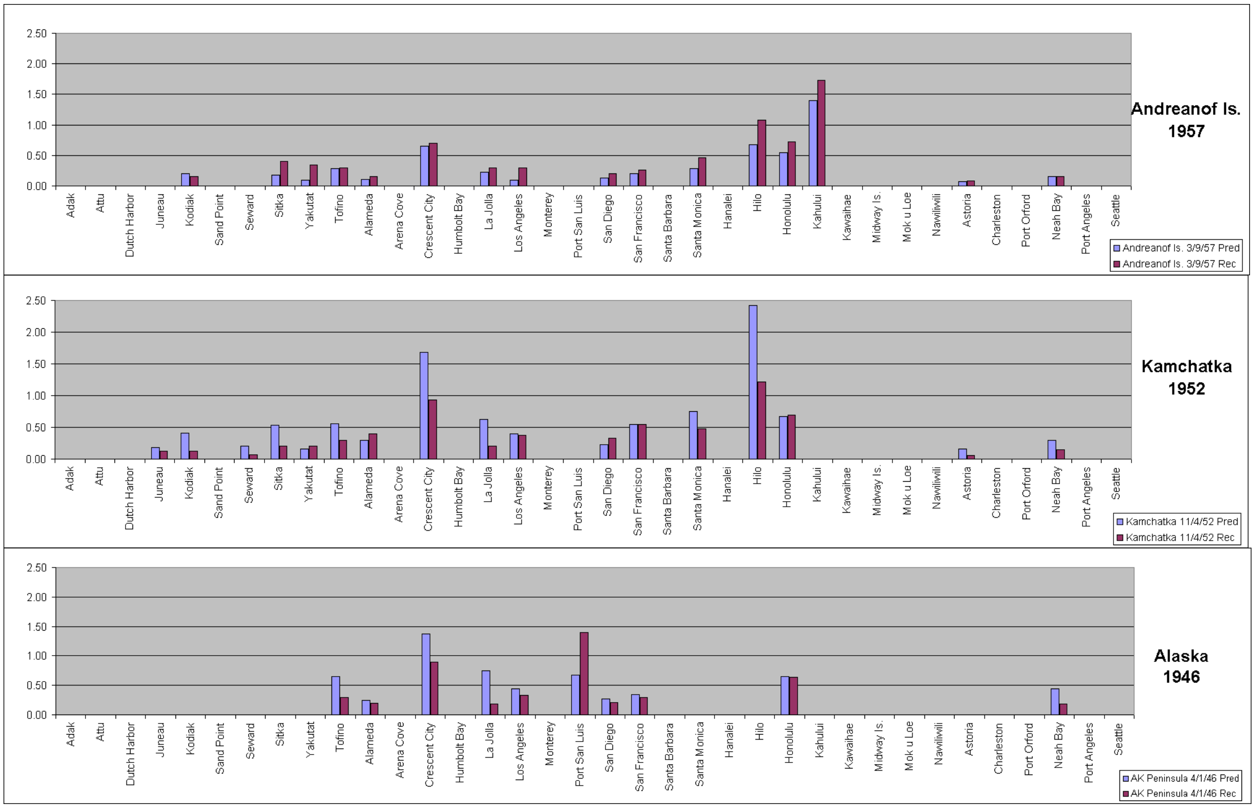


Figure 2. Predicted and recorded tsunami amplitudes (in meters) for the nine events. Notes on each model:

2001 Comparison model is Mw=8.2 located off the northern Chile coast. DART buoy 125 had not been installed at the time of this tsunami so is not available for scaling. The nearest modeled sites were used instead: San Diego – 0.05m, Los Angeles – 0.05m, La Jolla – 0.05m.

1994 Comparison model is Mw=8.2 located off the east coast of Hokkaido, Japan. Scaling sites are: Shemya – 0.15m, Adak – 0.15m, Midway Is. – 0.27m.

1986 Comparison model is Mw=8.2 located south of the Andreanof Is, Alaska. Scaling sites are: Adak – 0.90m, Midway Is. – 0.32m, Dutch Harbor – 0.15m, Sand Point – 0.10m.

1965 Comparison model is Mw=9.0 located south of the Rat Is., Alaska. Scaling sites are: Attu – 1.37m, Midway Is. – 0.20m, Dutch Harbor – 0.20m.

1964 Comparison model is Mw=9.0 located in the eastern Gulf of Alaska. The chosen model was not the most representative of the actual fault break. The model was chosen as it was the closest to the epicenter (which was located at the eastern edge of the fault zone). Scaling sites are: Sitka – 2.1m, Yakutat – 1.5m, Juneau – 1.0m.

1960 Comparison model is Mw=9.5 located off the southern Chile coast. No Hawaiian sites are predicted here as the tide gage observations could not be compared. Predicted heights for some Hawaiian sites are Hilo – 5.58m, Kahului – 4.33m, and Nawiliwili – 1.54m. Scaling sites are: La Jolla – 0.5m, San Diego – 0.7m, Honolulu – 1.07m, Mok u Loe – 0.22m.

1957 Comparison model is Mw=8.2 located south of the Andreanof Is., Alaska. Scaling sites are: Dutch Harbor – 0.70m, Midway Is. – 0.53m, Attu – 0.60m.

1952 Comparison model is Mw=9.0 located off the east coast of Kamchatka. The chosen model was not the most representative of the actual fault break. This model was chosen as it was the closest to the epicenter (which was located at the northern edge of the fault zone). This model is north of the fault rupture. Scaling sites are: Adak – 1.1m, Dutch Harbor – 0.6m, Midway Is. – 1.3m.

1946 Comparison model is Mw=8.2 located near the Shumagin Is., Alaska. Only one Hawaiian site is compared as other tide gage observations could not be obtained. Predicted heights for other Hawaiian sites are Hilo – 1.54m, Kahului – 3.35m, Nawiliwili – 1.30m. Scaling sites: Adak – 0.2m, Yakutat – 0.33m, Sitka – 0.48m.

Site	Amp. (m)	Damage	Year
Los Angeles, CA	0.33	None	1946
Yakutat, AK	0.33	None	1946
Attu, AK	0.3	None	1944
Shemya, AK	0.35	None	1996
Los Angeles, CA	0.38	None	1952
Yakutat, AK	0.4	None	1987
Sitka, AK	0.4	None	1957
Alameda, CA	0.4	None	1952
Santa Monica, CA	0.48	None	1952
Sitka, AK	0.48	None	1946
Sitka, AK	0.5	None	1960
La Jolla, CA	0.5	None	1960
San Francisco, CA	0.5	Strong currents stops ferry	1960
Port Hueneme, CA	0.5	None	1957
Crescent City, CA	0.5	Mooring broke loose	1963
Shelter I., CA	0.5	Boat/dock damage	1957
Adak, AK	0.51	None	1996
San Francisco, CA	0.54	None	1952
Los Angeles, CA	0.6	$200K damage to boats	1964
Monterey, CA	0.6	2 almost drown	1957
San Diego, CA	0.6	Strong current, boat damage	1964
Newport, OR	0.6	None	1960
Tokeland, WA	0.6	None	1960
Brandon, OR	0.6	None	1946
Kodiak, AK	0.6	None	1946
Attu, AK	0.6	None	1957
Ketchikan, AK	0.6	None	1964
Dutch Harbor, AK	0.6	None	1952
Crescent City, CA	0.7	None	1957
San Diego, CA	0.7	Boat/pier damage (20 Knot current)	1960
Port Hueneme, CA	0.7	None	1952
Dutch Harbor, AK	0.7	None	1957
Yakutat, AK	0.76	None	1960
Dutch Harbor, AK	0.79	None	1960
Unga, AK	0.8	Dock swept away	1946
Port Hueneme, CA	0.8	RR tracks flooded	1946
San Pedro, CA	0.8	Wharf flooded	1868
Avila, CA	0.8	None	1927
Santa Barbara, CA	0.8	Boat damage	1964
Los Angeles, CA	0.8	$1M damage, 1 drowning	1960
Adak, AK	0.9	None	1986
Shemya, AK	0.9	None	1969
DePoe Bay, OR	0.9	None	1946
Crescent City, CA	0.9	None	1946
Santa Barbara, CA	0.9	None	1946
Yakutat, AK	0.9	Mooring broke	1958
Santa Cruz, CA	0.9	Boats loose, swift currents	1960
Trinidad, CA	0.9	Cars stuck on beach	1992
Pacific Grove, CA	0.9	None	1960
Avila, CA	0.9	None	1960

Table 2. Tsunami damage listed with tsunami amplitude. Impact information from Lander, *et al*. (1993) and Lander (1996).

TSUNAMI DAMAGE VERSUS AMPLITUDE

When regional tsunami warnings are initially issued, the expected tsunami amplitude is unknown. Using the technique described in this report, tsunami amplitudes can be predicted outside the source zone. For tsunami warning purposes, an amplitude threshold must be chosen such that if predicted amplitudes are above this threshold outside the source zone, the warning will be expanded. Conversely, if predicted amplitudes outside the source zone are lower than the threshold, the warning will be cancelled or restricted to the source area.

To determine the proper amplitude threshold, historic tsunamis in the WC/ATWC AOR are examined. Table 2, based on the works of Lander, *et al.*, (1993) and Lander (1996), lists damage along with corresponding tsunami amplitude. Several other recorded tsunamis greater than 1m amplitude have occurred in the WC/ATWC AOR and are clearly dangerous. These are not listed in the table. Based on the damage/amplitude comparison shown in Table 2, tsunamis above 50cm must be considered potentially dangerous. If tsunami amplitudes are expected to be above 50cm outside the source zone, the warning should be expanded.

DISCUSSION

Based on a 50cm amplitude warning threshold level, Table 3 lists warning expansion decisions for the nine tested events. The maximum predicted amplitude outside the source region within the AOR and its location are also given. All damaging tsunamis tested would have prompted an expanded warning (1946, 1952, 1957, 1960, and 1964). All non-damaging tsunamis outside the source zone would not have prompted an expanded warning (1965, 1986, 1994, and 2001). During the actual events, both the 1986 and 1994 events triggered warnings which covered the entire WC/ATWC AOR. These warnings were considered “false” by most emergency managers. If the numerical backing provided by this predictive amplitude technique had existed at the time of those two warnings, it is likely that warnings would have been restricted to AOR regions nearest the epicenters.

Source Region	Date	Maximum predicted amp. outside source zone within AOR (m)	Warning expansion decision
Peru	2001/6/23	0.14 – Adak, AK	No
Kuril Is.	1994/10/4	0.40 – Crescent City, CA	No
Aleutian Is.	1986/5/7	0.21 – Rio Del Mar, CA	No
Rat Is.	1965/2/4	0.18 – Port Orford, OR	No
Gulf of Alaska	1964/3/28	1.93 – Arena Cove, CA	Yes
Southern Chile	1960/5/22	2.49 – Attu, AK	Yes
Aleutian Is.	1957/3/9	0.65 – Crescent City, CA	Yes
Kamchatka	1952/11/4	1.68 – Crescent City, CA	Yes
Alaska Peninsula	1946/4/1	1.44 – Half Moon Bay, CA	Yes

Table 3. Warning expansion decision summary for the nine tested events. “Outside the source zone” indicates areas not included in the initial warning region.

A few potential problems with the method should be noted. Tide gages in the immediate vicinity of the source may record localized effects, such as waves generated by sub-sea landslides. The models are based strictly on earthquake-related sea floor displacement. Scaling the model with tide gage data which includes a secondary component will lead to over-estimating the amplitude outside the source zone. To help prevent this effect, where feasible only tide gage or DART data from outside the immediate source zone should be used.

Another potential problem occurs for great earthquakes with large fault length and a unidirectional rupture. In this case the wrong model may be chosen based on the epicenter location. For example, the 1952 and 1964 earthquakes had rupture lengths over 500km and were mainly unidirectional rupture (Kanamori, 1976; Kanamori, 1970). For both cases, a different magnitude 9.0 model was chosen in this test than would have been selected had the areal extent of the fault zone been known. Predicted amplitudes for both events were still adequate for warning purposes, though, due to the scaling process.

Amplitude prediction using this technique could lead to a two level tsunami warning scheme. Historic tsunami impacts have shown that amplitudes between 0.5 and 1.0m have not induced major inundation damage (Table 2). Tsunami damage in this range is limited to boat and dock damage along with danger to swimmers. When a tsunami in this range is expected, a Level 1 or "clear-the-beach" warning would be more appropriate than a complete evacuation to some pre-determined maximum inundation line. If amplitude predictions were greater than 1m, or no prediction could be made, a Level 2 or full warning would be issued. Due to assumptions made in the tsunami models, predicted amplitudes greater than 1m may indicate a much greater inundation level. Splitting warnings into 2 levels would reduce unnecessary evacuations and yet still provide needed protection to those near the waterfront.

The predictive technique tested in this report can be improved with the addition of near real-time fault dimension determinations, real-time tsunami propagation models, improved scaling procedures, and inclusion of inundation. With the present limitations, though, it is shown here to be sufficiently accurate to use as a tool to aide in tsunami warning expansion, cancellation, and restriction decisions.

DISCLAIMER

The views expressed are those of the author and do not necessarily represent those of the National Weather Service.

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