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Estimation of Shaking Intensity in a Few Seconds: An Earthquake Early Warning System for Southwestern British Columbia, Canada

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ABSTRACT

Ocean Networks Canada (ONC) has developed an Earthquake Early Warning (EEW) system for southwestern British Columbia. A key objective of this system is the estimation of shaking intensity in the seconds following an earthquake. Here, we assessed the validity of our intensity estimations by comparing them to felt intensities. Community Decimal Intensity (CDI) was obtained from USGS's "*Did You Feel It?*" program for earthquakes of magnitudes > 4, with at least 50 felt reports, that occurred within the ONC's EEW coverage area between 2000 and 2023. We estimated modified Mercalli intensity for each earthquake on a 0.1 x 0.1-degree grid based on Intensity Prediction Equation (IPE) of Allen et al. (2012; AWW12) and compared them with the CDI average values within the same grid cells, where available.

Differences between the estimated and observed intensities show three distinct behaviors. For events that occurred offshore within the Explorer Plate, AWW12 IPE overestimates intensities over the entire distance range by as much as 4 intensity units. On the other hand, for events that occurred onshore, within the Puget Sound and southeastern Vancouver Island, the estimated intensities match the observed values at distances below 200 km. At larger distances, however, the observed values are underestimated by as much as 3 intensity units. The behavior of residuals for events that occurred on the west coast of Vancouver Island, between the offshore and onshore events, is more complex; those that occurred to the west, near the intersection of the Explorer and Juan de Fuca plates, show trends that are similar to the offshore residuals, whereas events that occurred to the east, near Vancouver Island, show trends that are similar to the onshore residuals. The observed trends in the residuals do not appear to be systematically dependent on earthquake depth or site condition.

Keywords: Ocean Networks Canada, Earthquake Early Warning, Modified Mercalli Intensity, Community Decimal Intensity, British Columbia

INTRODUCTION

Southwestern British Columbia is exposed to a high level of seismic hazard from both onshore and offshore earthquakes that threatens a population of ~4 million. Historical and paleoseismological records show evidence for large megathrust earthquakes (e.g., M9 January 26, 1700) across the Cascadia subduction zone that potentially endanger the communities from northern California to Vancouver Island ([1]). Onshore earthquakes on Vancouver Island have also caused damages to structures and loss of life (e.g., M6.9 December 6, 1918, and M7.3 June 23, 1946; [2]). Growing cities and population have brought special attention to quantification of earthquake hazard and mitigation strategies. Since 1953, Natural Resources Canada have been publishing seismic hazard maps for the entire country ([3]). These maps provide hazard values for different probabilities, ground motion parameters, and site conditions, and are the basis for seismic code provisions in the National Building Code of Canada. Although reliable prediction of earthquakes is not feasible at present, mitigation strategies can be put in place if the arrival of damaging ground shaking can be known in advance. Earthquake Early Warning (EEW) systems can provide such information and are vital technologies for emergency preparedness and reducing the effects of secondary hazards following earthquakes (e.g., risk of fire). Several countries have successfully implemented such systems at different rollout phases (e.g., Mexico, Japan, Taiwan, and USA; [4],[5]).

In Canada, Ocean Networks Canada (ONC) began developing an EEW system for southwestern British Columbia in 2015 ([6],[7]). The system previously passed the initial development stage (2015-2019) and the systems commissioning period

(2020-2023) and has been in operation since April 2023. Since 2018, the system has detected over 100 earthquakes, with magnitudes as small as 1.8, within a coverage area of -131.75° to -123° W and 46° to 52.2° N. An essential component of this system is the estimation of shaking intensity following an earthquake occurrence when its location and magnitude are determined. The aim of this study is to analyze estimated intensities by ONC's EEW system and compare them with observed values from felt reports. Validating the underlying algorithms to estimate shaking intensities is an important step toward establishing a comprehensive warning system.

DATA AND METHODOLOGY

ONC's EEW system estimates Modified Mercalli Intensity using the Intensity Prediction Equation (IPE) of Allen et al. (2012; AWW12; [8]). This IPE was developed based on global data from shallow crustal earthquakes in active tectonic regions (hypocentral depth of < than 20 km), with moment magnitudes (M_w) between 5.0 and 7.9, intensity values between 2 and 10, and for a maximum hypocentral distance of 300 km. AWW12 also included a site factor in their intensity model. ONC, however, uses the base model of AWW12 IPE without the site factor. The base model is applicable for sites with site condition about the NEHRP (National Earthquake Hazard Reduction Program) CD boundary or Vs30 (time-averaged shear-wave velocity to 30 meters depth) of ~400 m/sec.

We utilized intensity data (Community Decimal Intensity, CDI [9], in 1km geocoded resolution) from the USGS "*Did You Feel It?*" database (also known as community internet intensity map, [10]) for earthquakes with magnitudes > 4, with at least 50 felt reports, that occurred within ONC's EEW system coverage area between 2000 and 2023. Although our system detects smaller earthquakes, we only focus on events with magnitudes > 4 as this is the threshold for which ONC aims to reliably provide alert notifications ([6]). Additionally, Vs30 data from USGS Vs30 dataset ([11]) was obtained. Table 1 shows the parameters of earthquakes considered in this study. Different magnitude types are shown in Table 1. The priority of magnitude assignment is always M_w but for events when this value was not available, local (M_L), and duration (M_D) magnitudes were used. For each earthquake in Table 1, we estimated intensities on a 0.1 × 0.1-degree grid using the AWW12 IPE for an area that covers the majority of the felt reports; entries with distances > 1000 km were not considered. A hypocentral depth of 25 km ([6]) was used in the estimation of intensities. At each grid cell, we also took the average of Vs30 and all available CDI values. We then calculated the difference between the estimated and observed intensities (observed minus estimated).

Table 1. Parameters of the earthquakes considered in this study. M_w, M_L, and M_D are moment, local, and duration magnitudes.

EQ ID	Year	Month	Day	Hour	Minute	Second	Lat.	Long.	Depth (km)	Mag.	Mag. Scale
1	2022	11	26	3	50	18	49.271	-126.092	33	4.9	M_w
2	2020	1	24	21	35	29	48.549	-125.185	10	4.5	M_w
3	2019	7	4	4	30	44	51.237	-130.501	10	6.2	M_w
4	2018	11	19	11	9	13	47.698	-123.552	39	4.1	M_L
5	2018	10	22	6	16	26	49.335	-129.289	10	6.8	M_w
6	2018	10	22	5	39	40	49.259	-129.412	10	6.5	M_w
7	2017	2	23	4	59	4	47.480	-123.035	15	4.1	M_L
8	2015	12	30	7	39	29	48.587	-123.300	52	4.8	M_L
9	2015	1	8	2	2	54	49.171	-125.647	25	4.8	M_w

10	2014	4	24	3	10	10	49.639	-127.732	10	6.5	M_w
11	2011	9	9	19	41	34	49.535	-126.893	22	6.4	M_w
12	2003	4	25	10	2	13	47.671	-123.250	51	4.8	M_D
13	2002	9	21	0	55	21	48.485	-123.127	23	4.1	M_D
14	2001	6	10	13	19	11	47.168	-123.503	40	5.0	M_D

Figure 1 shows the map of southwestern British Columbia and northwestern Washington State with the earthquake distribution described in Table 1 (stars). Also shown in Figure 1 is the seismicity between 1900 and 2023 for events with magnitudes > 2.5 (small circles).

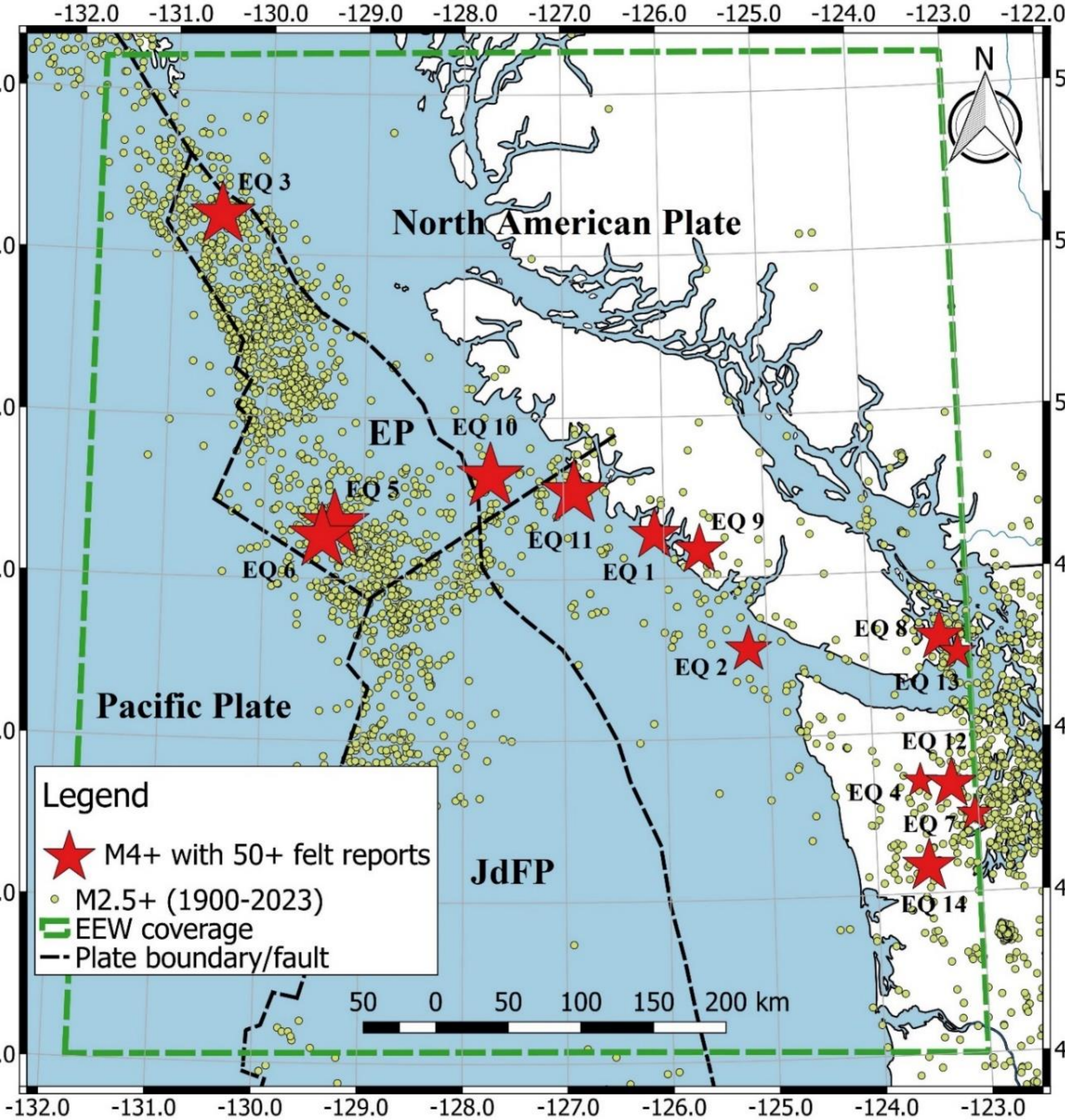

Figure 1. Distribution of earthquakes in southwestern British Columbia and northwestern Washington State. EP: Explorer Plate, JdFP: Juan de Fuca Plate. Parameters of each earthquake (EQ) are presented in Table 1.

The seismicity distribution in Figure 1 shows that earthquakes are concentrated in several different regions. The complex seismotectonic setting of the studied area includes five types of earthquakes that can occur at the southwest coast of British Columbia and in northwestern Washington State, complicating ground motion propagation in the region. These earthquake types include, 1) offshore earthquakes within the shallow oceanic crust, 2) transitional events that occur within the subducting Juan de Fuca slab at the continental margin along the west coast of Vancouver Island with depths mostly between 25 and 40 km, 3) events that occur within the Juan de Fuca subducting slab beneath the continent (e.g. those in the Puget Sound region with depths of mostly between 40 and 60 km), 4) earthquakes that occur within the continental crust, and 5) megathrust earthquakes that occur at the interface between the subducting Juan de Fuca Plate and the overriding North American Plate ([12], [13]). Except for earthquake type 5, we have the first 4 types of events in Table 1. Earthquakes 3, 5, and 6 (M_w above 6 and with fixed depth of 10 km) are offshore earthquakes (type 1) that occurred within the shallow oceanic crust (Explorer Plate). Events 1, 2, 9, 10, and 11 appear to have occurred in the transitional setting (type 2). These earthquakes have diverse magnitudes between M_w 4.5 and 6.5 and depths of 10 to 33 km. The rest of the events to the east occurred onshore and are combinations of in-slab (type 3) and crustal (type 4) earthquakes with magnitudes (M_L and M_D) between 4.1 and 5.0 and depths of 15 to 52 km. Events 4, 8, 12, and 14 appear to be in-slab earthquakes (depths 39, 52, 51, and 40 km, respectively), whereas events 7 and 13 are crustal earthquakes (depths 15 and 23 km, respectively).

RESULTS

To assess the validity of our intensity estimations, residuals (observed minus estimated intensity) are studied with respect to hypocentral distance, earthquake location, earthquake depth, and Vs30. Figure 2 shows the intensity difference versus hypocentral distance for each earthquake. Residuals are shown in three categories of offshore, transition, and onshore, based on the behavior of residuals and earthquake location. The onshore category includes both the in-slab and crustal earthquake types described above (types 3 and 4, respectively). The gray vertical dashed line is the maximum applicable distance of 300 km as indicated by AWW12 IPE. Solid gray circles are the average differences in each distance bin (20 km increments linearly). Error bars show one standard deviation.

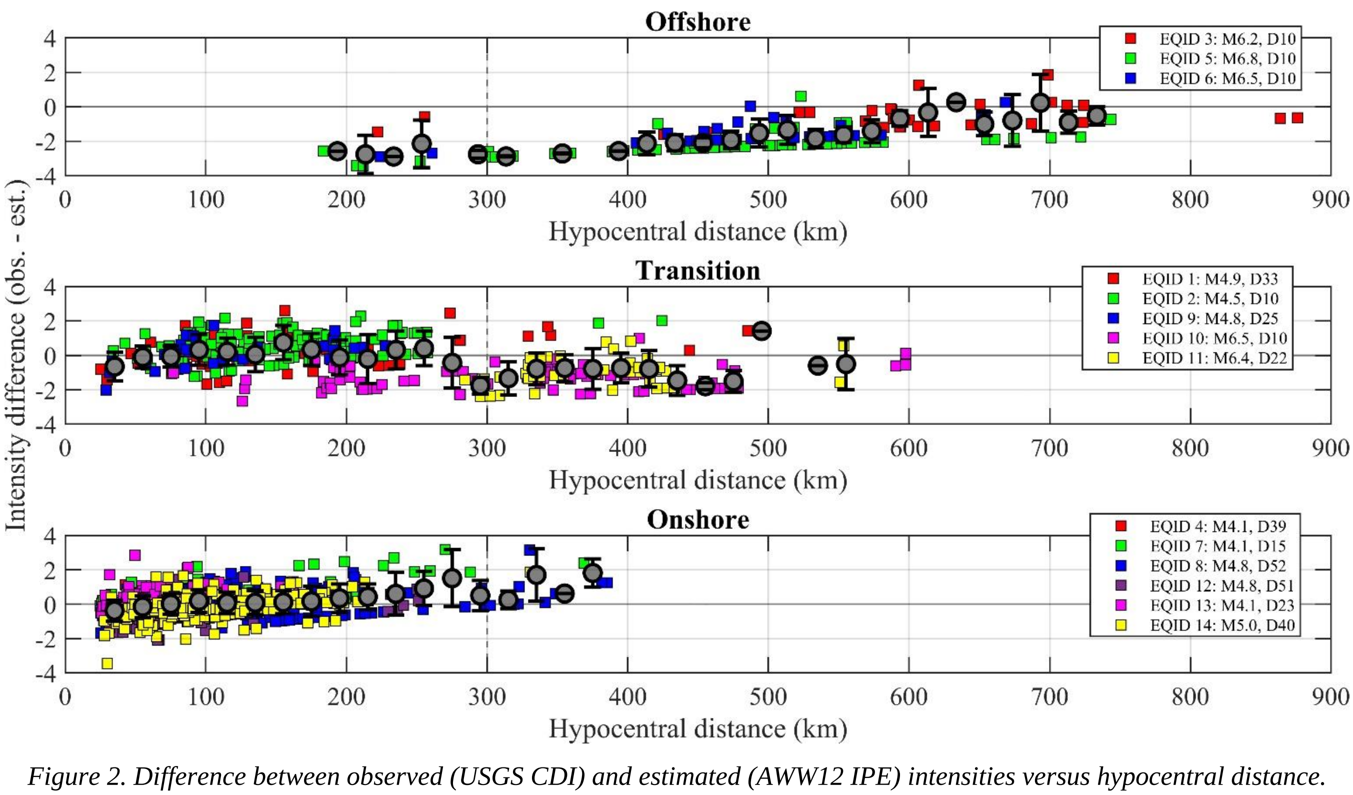

Figure 2. Difference between observed (USGS CDI) and estimated (AWW12 IPE) intensities versus hypocentral distance. Vertical dashed line is the 300 km applicable distance threshold for AWW12 IPE. Solid gray circles are average differences in distance bins with error bars showing one standard deviation.

As can be seen in Figure 2, AWW12 IPE overestimates intensities at all distances for events in the offshore category. On the other hand, intensities for events in the onshore category are well aligned with the estimated values by AWW12 IPE for distances up to 200 km. For both categories (offshore and onshore), the intensity differences show an increasing trend over larger distances, resulting in an underestimation of intensities at larger distances. This is especially profound for the onshore category (in-slab and crustal earthquakes) where intensities are underestimated by AWW12 IPE at distances above 200 km. This has significant implications for earthquake risk assessments for perils that can cause damage at large distances within the

Puget Sound and southeastern Vancouver Island. Overestimation of intensities for offshore events can also present significant economic implications since infrastructure stakeholders can potentially impose mitigation strategies for false alarms. The middle panel in Figure 2 shows intensity differences for events that occurred within the transitional setting (earthquake type 2 as described above). Of the five earthquakes within this category (events 1, 2, 9, 10, and 11), similar trends are observed for events 1, 2, and 9 as in the onshore category, whereas events 10 and 11 show results that are similar to those observed in the offshore category. As can be seen from Figure 1, events 10 and 11 are in the western part of the transitional setting close to the boundary between the Explorer and Juan de Fuca plates, which is known as the Nootka Fault Zone ([14]).

Figure 3 summarizes the behavior of intensity residuals by showing average of intensity differences over all observations for each event. Intensities are overestimated by AWW12 IPE for earthquakes 3, 5, 6, 10, and 11, which are the offshore events (within the Explorer Plate) and those occurred within the Nootka Fault Zone. The observed and estimated values match, with some underestimation by AWW12 IPE (see above discussion), for events in the eastern part of transitional setting, near Vancouver Island (events 1, 2, and 9), and those occurred onshore within the subducting Juan de Fuca Plate (4, 8, 12, and 14) and within the North American crust (events 7 and 13).

The observed behavior of residuals shown in Figures 2 and 3 can be explained by attenuation characteristics between different event types. As observed by other works (e.g., [12]), ground motions from offshore events do not propagate efficiently into the continental crust and thus have reduced amplitudes compared to onshore events with the same magnitude. A 0.5 magnitude unit adjustment has been suggested between the offshore and shallow crustal Californian earthquakes ([12],[13]). This means that ground motions from a magnitude 5 earthquake in California correspond to ground motions from a magnitude 5.5 offshore event.

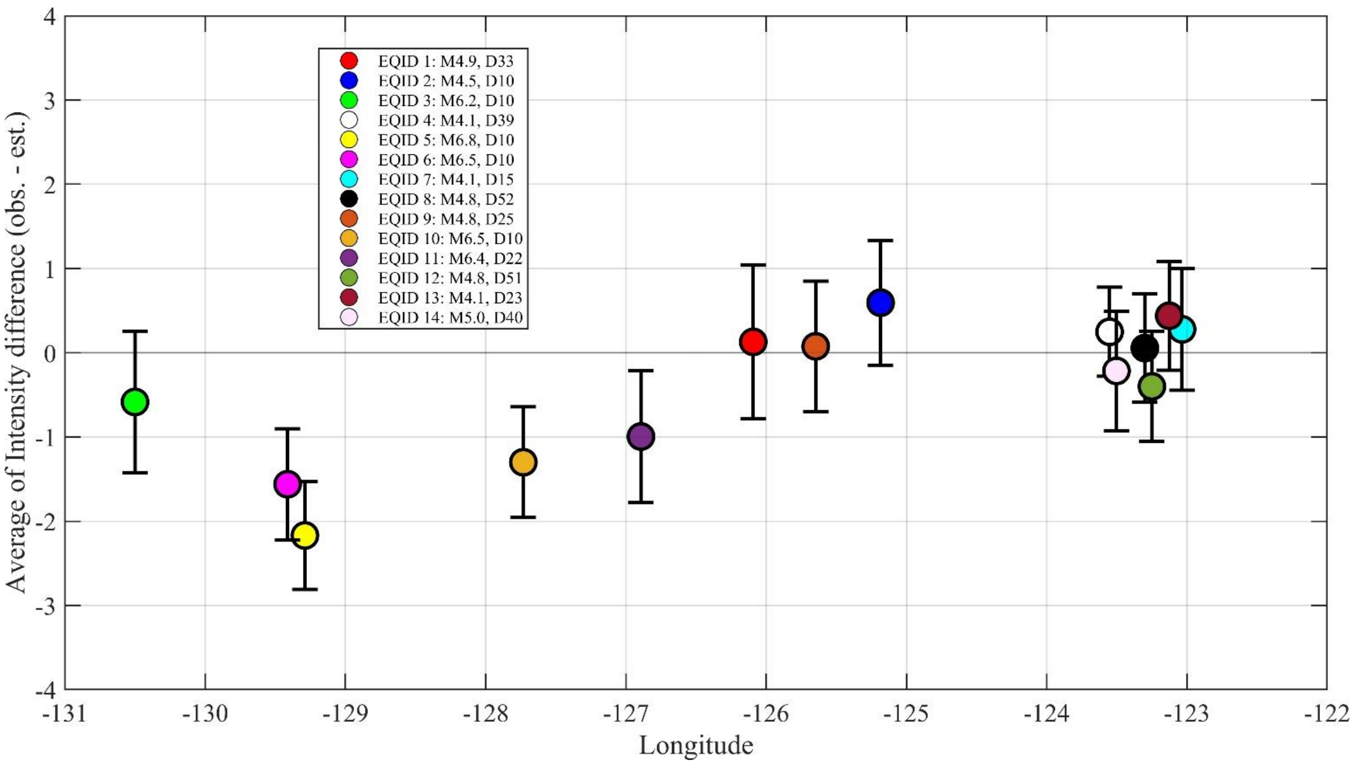

Figure 3. Average difference between the observed (USGS CDI) and estimated (AWW12 IPE) intensities, over all observations for each event, versus earthquake location. Error bars show one standard deviation.

Figure 4 shows intensity residuals versus earthquake depth. The solid gray circles are the average residuals with error bars representing one standard deviation. There are no observed systematic trends of residuals depending on depth. Note that for regional networks, earthquake depth is the most difficult parameter to be determined. Among the 14 earthquakes considered in this study, 5 events have a fixed depth of 10 km.

Figure 5 shows the histogram of Vs30 values. As explained earlier, the AWW12 IPE base model corresponds to a site condition of the CD boundary or a Vs30 value of ~400 m/sec. Most Vs30 values are within the NEHRP site class C, with an average Vs30 of ~500 m/sec, with a few observations located at grid cells with Vs30s belonging to the B and D site classes. Figure 6 shows the intensity residuals versus Vs30 to assess the dependence of the results on site conditions that are different from the CD boundary (dashed line in Figure 5). In Figure 6, solid gray circles are the average residuals in Vs30 bins with 50 m/sec increments. Error bars represent one standard deviation. There are no trends in the residuals regarding Vs30 values. Similar to

Figure 2, AWW12 IPE overestimates intensities at all distances for events that occurred offshore, within the Explorer Plate, and those in the western part of the transitional setting, within the Nootka Fault Zone. However, the AWW12 IPE matches the observed values for events within the eastern section of the transitional setting, near Vancouver Island, and those onshore events within the Puget Sound and southeastern Vancouver Island areas (in-slab and crustal).

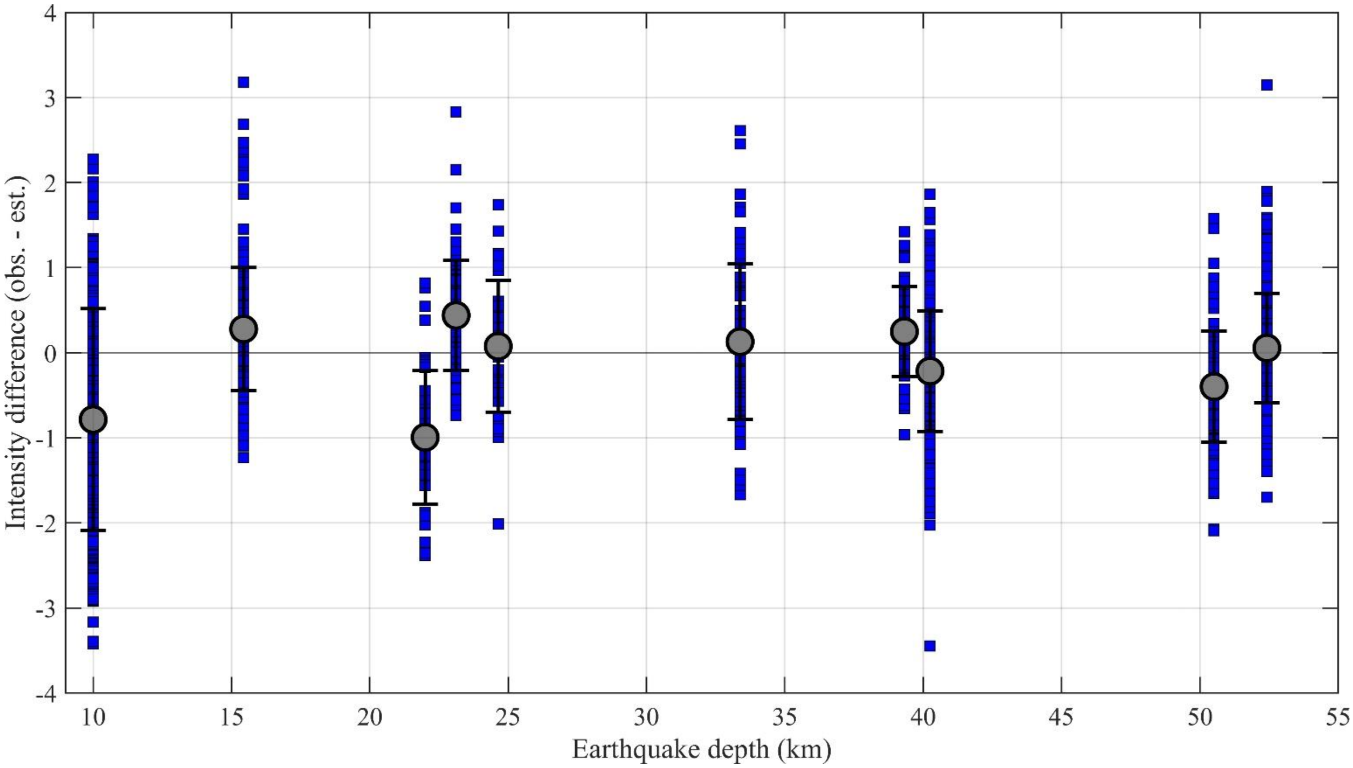

Figure 4. Difference between the observed (USGS CDI) and estimated (AWW12 IPE) intensities versus earthquake depth. Solid gray circles are average values, over all observations from events with the same depth, with error bars showing one standard deviation.

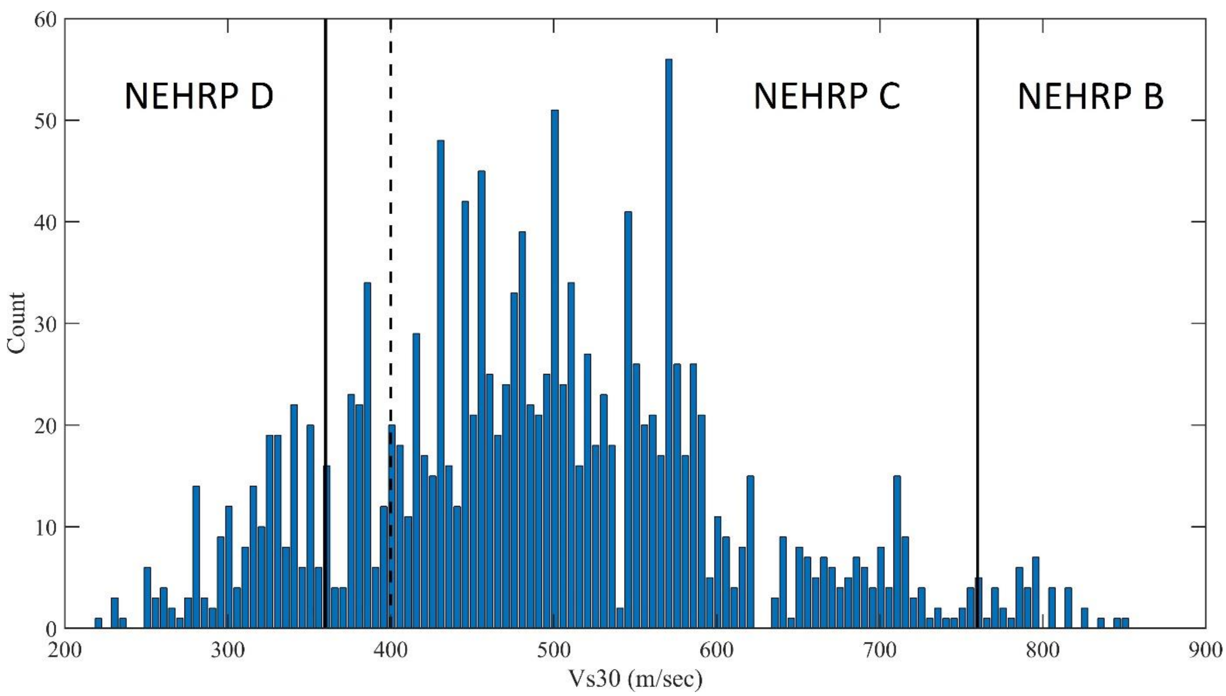

Figure 5. Histogram of Vs30 values. Dashed line marks the corresponding Vs30 for the base model of AWW12 IPE.

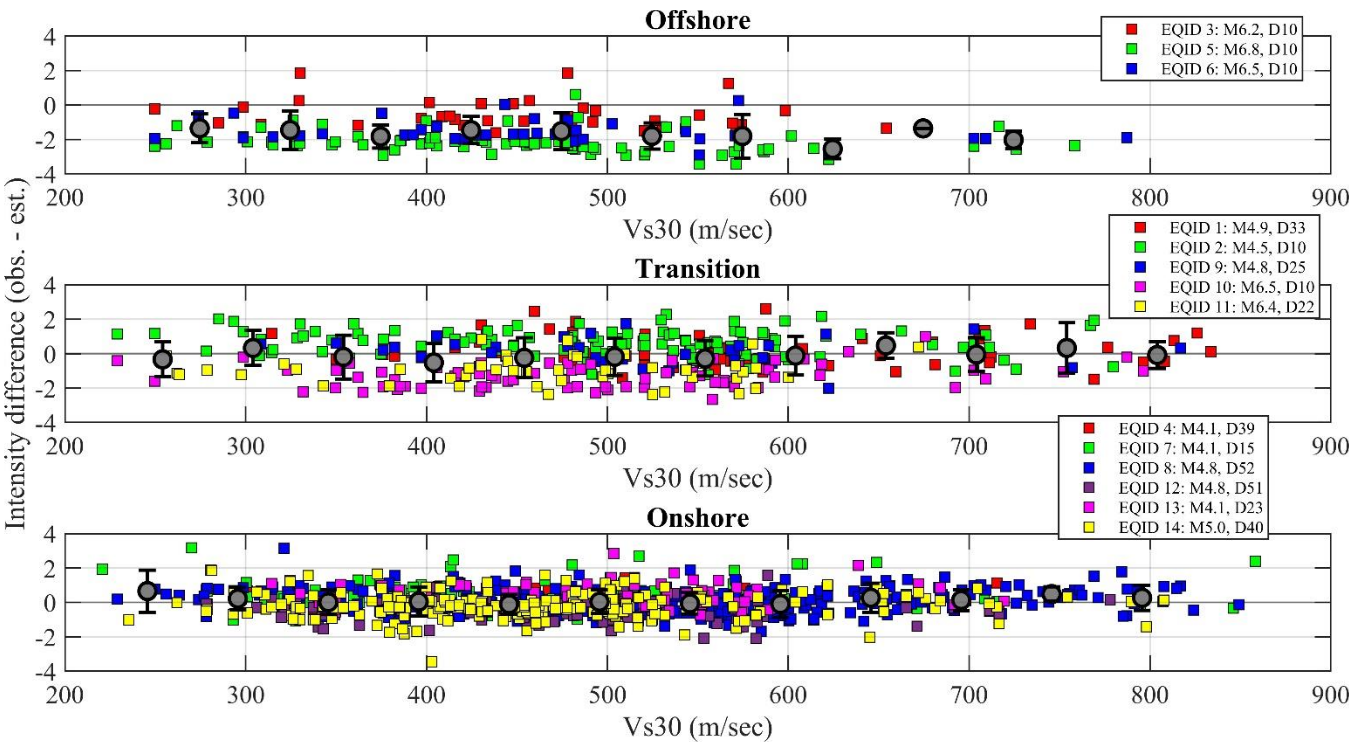

Figure 6. Difference between the observed (USGS CDI) and estimated (AWW12 IPE) intensities versus Vs30. Solid gray circles are average differences in Vs30 bins with error bars showing one standard deviation.

CONCLUSIONS

In this study, we assessed the validity of intensity estimations by Ocean Networks Canada (ONC) Earthquake Early Warning (EEW) system. We used the Intensity Prediction Equation (IPE) of Allen et al. (2012; AWW12) and obtained Community Decimal Intensity (CDI) and Vs30 data from USGS's database. The CDI and Vs30 values were averaged on a 0.1 × 0.1 grid cell with intensity estimations on the same grid. CDI data were obtained for earthquakes with magnitudes > 4, with at least 50 felt reports, that occurred within the ONC EEW coverage area (-131.75° to -123° W and 46° to 52.2° N) between 2000 and 2023. Analysis of intensity residuals (observed minus estimated) show three distinct categories. For events that occurred offshore within the Explorer Plate, AWW12 IPE overestimates intensities over the entire distance range by as much as 4 intensity units. On the other hand, for events that occurred onshore the Puget Sound area and southeastern Vancouver Island, within the North American curst and the subducting Juan de Fuca Plate, estimated intensities match observed values at distances below 200 km. However, intensities are underestimated at larger distances by as much as 3 intensity units. The behavior of residuals for events that occurred on the west coast of Vancouver Island, between the offshore and onshore events, is more complex; those western events that occurred closer to the intersection of the Explorer and Juan de Fuca plates show trends that are similar to the offshore residuals, whereas events that occurred to the east, near Vancouver Island, show trends that are similar to the onshore residuals. These observations do not appear to be systematically dependent on earthquake depth or site condition.

Both underestimation and overestimation of intensities have significant implications regarding mitigation strategies. Underestimation of intensities can potentially lead to emergency responses being insufficient or unprepared, whereas overestimation of intensities can lead to generation of false alarms for infrastructure stakeholders. While the accuracy of AWW12 IPE can be regarded as sufficient for intensity estimation for onshore regions, the complexity of seismotectonic setting for offshore earthquakes requires models that account for the difference in the characteristics of ground motion attenuation between onshore and offshore propagation paths.

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