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PROBABILISTIC TSUNAMI HAZARD OF CANADA: A PRELIMINARY ASSESSMENT, ITS LIMITATIONS, AND FUTURE NEEDS

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ABSTRACT: A preliminary probabilistic tsunami hazard assessment of the Pacific, Atlantic and Arctic coastlines of Canada has been completed considering local and far-field earthquakes, and large submarine landslide sources. The analysis used published historical, paleotsunami and paleoseismic data, modelling, and empirical relations between fault area, earthquake magnitude, and tsunami run-up. Results are presented as national maps showing the probability of a potentially damaging tsunami (exceeding 1.5 m run-up) and a tsunami having significant damage potential (≥ 3 m run-up) within a 50-year time period at Canadian coastlines. Maps showing the estimated run-up with return periods of 100, 500, 1000 and 2500 years are also provided. The cumulative estimated tsunami hazard for potentially damaging run-up on the outer Pacific coastline is one order of magnitude greater than the outer Atlantic and two orders greater than the Arctic. For tsunamis with significant damage potential (≥ 3 m), Pacific hazard is again much larger than both the Atlantic and Arctic. For next generation maps with more site-specific information for use in tsunami hazard mitigation, the empirical relationships used for these maps need to be replaced by detailed tsunami source, propagation and inundation modelling taking into account a wider variety of source scenarios and local bathymetry and topography.

1. Introduction

The Canadian coastline is at risk from tsunamis generated in three oceans. The preliminary assessment presented here represents the first attempt to quantify the hazard from the various local and far-field, earthquake and large landslide tsunami sources that threaten the Pacific, Atlantic and Arctic coasts of Canada. More details are provided by Leonard et al. (2012; 2014). This paper provides a short description of the methods used to estimate tsunami hazard from these diverse sources, for which the nature of available data varies widely. Preliminary tsunami hazard maps are provided, showing the probability of tsunami run-up exceeding two levels within a 50-year time period, as well as run-up with return periods of 100, 500, 1000, and 2500 years. Finally, the limitations of this preliminary assessment are discussed, along with the steps and data needed to progress to a full probabilistic assessment of use to local authorities for planning and to engineers for tsunami damage mitigation.

2. Tsunami Hazard Assessment: Methods

2.1. Probabilistic Tsunami Hazard Assessment

Probabilistic tsunami hazard analysis (e.g., Geist and Parsons, 2006) involves the estimation of the probability of exceeding specific tsunami wave heights (or run-up height above the state of tide) at given locations, from any source. This requires estimates of tsunami run-up at each coastal location from all possible sources as well as the recurrence interval of each run-up level; these estimates are ideally attained from a combination of empirical tsunami data (tide gauge and paleoseismic/paleotsunami data) and high-resolution modelling of a wide range of source scenarios from tsunamigenesis to inundation.

A full probabilistic analysis was not feasible at this preliminary stage. Instead, we use a variety of methods, described below, to estimate tsunami run-up and recurrence based on available data and the limited published modelling results. Table 1 shows the data type used for each source considered (Leonard et al., 2012, and references therein). We divide the Canadian coastline into 19 hazard zones (12 Pacific; 6 Atlantic; 1 Arctic), based on the simplifying expectation that the majority of each zone will experience similar run-up heights during the same tsunami, for all applicable sources. Within each zone, tsunami hazard is generally estimated at two levels: run-up exceeding 1.5 m and 3 m. In this paper, we also assess the hazard of tsunami run-up exceeding 5 m. The lower threshold corresponds to a tsunami with the potential to cause coastal damage. Based on historical Pacific tsunamis, damage to boats, docks, and swimmers may occur due to strong currents during tsunamis with amplitude/run-up as small as 0.5 m; more severe damage and inundation is likely at a 1.5–2-m minimum (Whitmore et al., 2008). We define tsunamis with run-up exceeding 3 m as having significant damage potential, i.e., major damage expected that may be geographically extensive.

Table 1 – Summary of data available for potential tsunami sources.

Tsunami Source	Tsunami run-up data	Tsunami frequency data
Pacific far-field subduction zones	Tide gauge data from Tofino, BC; scaled for other BC locations	Tide gauge data from Tofino, BC; scaled for other BC locations
Atlantic far-field subduction zones	Tsunami modelling; assumptions made outside modelled areas	Paleotsunami data (Gibraltar-Cadiz); earthquake magnitude-frequency data (Antilles)
Cascadia subduction zone	Tsunami modelling for southern BC; empirical relations elsewhere	Paleoseismic data
Explorer and Haida Gwaii thrusts	Geophysical data for rupture area; empirical relations for earthquake magnitude and tsunami run-up	Geodetic data for convergence rate
Crustal faults	Geophysical data for rupture area; empirical relations for earthquake magnitude and tsunami run-up	Earthquake magnitude-frequency data
Atlantic and Arctic continental slope landslides	Historical data and tsunami modelling	Landslide size-frequency data
Far-field large landslides	Tsunami modelling	Landslide size-frequency data

Given an annual rate, λ, of tsunami run-up height Hr_0, the probability of exceeding that run-up at least once in the time period T is given by:

$$P(Hr > Hr_0, T) = 1 - e^{-\lambda T} \quad (1)$$

assuming a Poisson process (Geist and Parsons, 2006). For multiple sources with independent annual rates (λ_1, λ_2, λ_3,…) of Hr_0, the combined probability of exceedance in time T is:

$$P(Hr > Hr_0, T) = 1 - e^{-\lambda_c T} \quad (2)$$

where λ_c is the cumulative annual rate. For each tsunami source, we estimate annual rates of run-up of 1.5, 3, and 5 m in each hazard zone and probabilities of exceeding those values in a 50-year period (Eq. 1). Minimum and maximum values represent the combined effect of uncertainties on the source parameterisation (e.g. tsunami propagation, earthquake magnitude); more details are provided in Leonard et al. (2012; 2014).

2.2. Thrust earthquake sources

2.2.1 Subduction zones

Modelling of the many tsunami sources with the potential to impact Canadian coasts is beyond the scope of this preliminary assessment. Various scenario fault sources have previously been modelled to assess their tsunami impact, often with historical constraints; we use the results, along with paleoseismic or geodetic recurrence intervals, for preliminary probabilistic analysis. These sources include the Pacific near-field Cascadia subduction zone and the Atlantic far-field Gibraltar-Cadiz thrust source (Table 1). For Pacific far-field sources, we use a century-long tide gauge dataset from Tofino, BC, for an empirical analysis that is scaled to other locations on the Pacific coast (for details, see Leonard et al., 2012; 2014).

For unconstrained potentially tsunamigenic faults, we use a series of empirical relations to: (1) derive an estimate of earthquake magnitude and probability based on fault rupture area and convergence rate, (2) derive the corresponding tsunami run-up in each zone, and (3) integrate the source event probability with the estimated run-up to provide probabilities of potentially damaging (≥ 1.5 m) and significant (≥ 3 m) tsunami run-up in each zone. Steps (1) and (2) are shown schematically in Figure 1 (see Leonard et al., 2012 for a complete description).

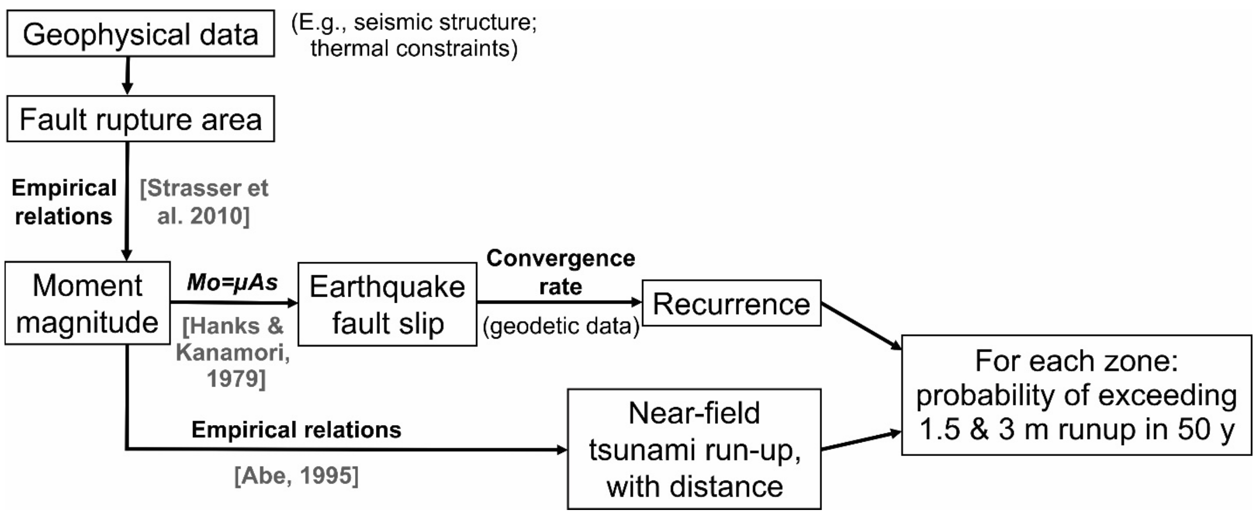


Figure 1 – Schematic diagram showing an empirical relation-based method of tsunami hazard assessment for tsunamigenic thrust fault sources with unknown history.

2.2.2 Crustal faults

We also assess the hazard from tsunamis generated by submarine crustal earthquakes on the Pacific margin; several tsunamigenic paleo-earthquakes have been recognised in Juan de Fuca Strait and Puget Sound, dating from the past few thousand years (e.g., Seattle fault earthquake ~1100 years ago; Atwater and Moore, 1992). With a number of mapped faults and the possibility of unrecognized faults, we do not treat each fault source separately but estimate potential runup using the empirical relations of Abe (1995) and the rate of damaging tsunamigenic earthquakes based on the seismicity statistics of the submarine area (full details are provided in Leonard et al., 2012).

2.3. Landslide sources

2.3.1. Far-field landslides

In contrast to large earthquake tsunamis, significant far-field attenuation occurs during propagation of landslide tsunamis. However, modelling suggests that very large failures (e.g. volcanic flank collapses) may result in damaging run-up at transoceanic distances. With sufficient identification and dating of past slides, the frequency of large events may be estimated and can be used, along with tsunami modelling, to approximate the probability of potentially damaging run-up. This approach is applied to Pacific far-field landslide sources at the Hawaiian and Aleutian Islands and Atlantic sources at the Canary Islands.

2.3.2. Near-field landslides

The 1929 Grand Banks tsunami caused 28 deaths and significant damage in Newfoundland (e.g., Fine et al., 2005), demonstrating the danger of tsunamigenic continental slope landslides. We use a landslide size-frequency relation from a well-studied part of the Atlantic continental margin, along with published tsunami modelling for the Grand Banks and other Atlantic continental slope failures, to estimate the frequency of run-up exceeding 1.5 and 3 m (Leonard et al., 2012). Without other constraints we assume a similar hazard along the outer Atlantic and Arctic coastlines. On the Pacific margin, continental slope landslides contribute a far smaller percentage of the cumulative tsunami hazard and their occurrence is expected to be triggered by major plate boundary earthquakes. Thus, we do not estimate their hazard independently.

Coastal landslide tsunamis are typically triggered by failure of steep subaerial slopes or submarine delta fronts, resulting from phenomena such as ground shaking, rainfall, and local construction. Several cases are noted in Canada (e.g., Leonard et al., 2012), but empirical data for long-term landslide histories are not widely available; without these the probability of landslide-generated waves cannot be estimated. An alternative approach (e.g., ten Brink et al., 2009) assumes earthquake shaking is the dominant trigger, and involves slope stability and earthquake statistical analyses that are beyond the scope of this study. Instead, we identify coastlines that may be at risk, based on the landslide susceptibility map of Bobrowsky and Dominguez (2012), who assessed various factors including topography, geology, vegetation, and precipitation to divide the Canadian landscape into susceptibility classes ranging from 1 (lowest) to 6 (highest). We consider coastal areas in classes 5 and 6 (and neighbouring areas) to be at risk from damaging landslide-generated waves. We also highlight Arctic coastlines that may be susceptible to local waves from iceberg calving or jökulhlaup events (catastrophic releases of water from a glacier).

3. National Tsunami Hazard Maps

The national tsunami hazard maps are shown in Figures 2-4 (specific values are provided by Leonard et al., 2012; 2014). Estimated cumulative tsunami hazard is given for each zone in Figure 2 in terms of probability of exceedance of 1.5 and 3 m run-up in a 50-year period. Figure 3 shows the maximum run-up expected within 100 to 2500-year time periods, based on the estimated probabilities of tsunami run-up exceeding 1.5, 3, and 5 m. Regions with apparent negligible hazard may still be vulnerable to local landslide-generated waves (Fig. 4).

For a potentially damaging tsunami (run-up exceeding 1.5 m), hazard in outer Pacific coastal zones (40-80% probability of exceedance; 30-100 y equivalent mean recurrence) is, respectively, one and two orders of magnitude greater than the outer Atlantic (1-15%; 300-1,700 y) and Arctic (< 1 %; 6,500-17,000 y). For run-up exceeding 3 m, the Pacific hazard (10-30 %; 150-560 y) is significantly higher than both the Atlantic (1-5 %; 650-4,000 y) and Arctic (< 1 %; 7,000-20,000 y). On the outer Pacific coast, the hazard of a potentially damaging tsunami is dominated by far-field subduction zones; the hazard of a significant tsunami (run-up exceeding 3 m) is almost entirely contributed by local megathrust faults (for details, see Leonard et al., 2012; 2014). For inner Pacific coasts (Juan de Fuca and Georgia Straits), the Cascadia subduction zone contributes most hazard at both levels. Tsunami hazard on the Atlantic coast is dominated by poorly constrained far-field subduction zone sources at both run-up levels. Tsunami hazard on the Arctic coastline remains uncertain, but this region is assumed to be sheltered from far-field tsunamis; the hazard is provided by local landslide sources.

4. Future Directions for Tsunami Hazard Assessment in Canada

4.1. Requirements for tsunami mitigation

Standards for tsunami design provisions are yet to be defined for Canadian construction codes. New standards recently developed by the American Society of Civil Engineers/Structural Engineering Institute (ASEC/SEI) will apply to the U.S. west coast states, Alaska and Hawaii (Chock, 2014; Chock and Wilson, 2014). Key components include the following: probabilistic tsunami hazard assessment will incorporate modelling of multiple source scenarios in a logic tree structure, and will be used to determine a Maximum Considered Tsunami, defined as the inundation with a 2% probability of being exceeded in a 50-year period, i.e., a 2475-year average recurrence. Probabilistic maps for each state will include offshore tsunami amplitude (at 100 m depth), as well as onshore tsunami run-up and inundation limit. The

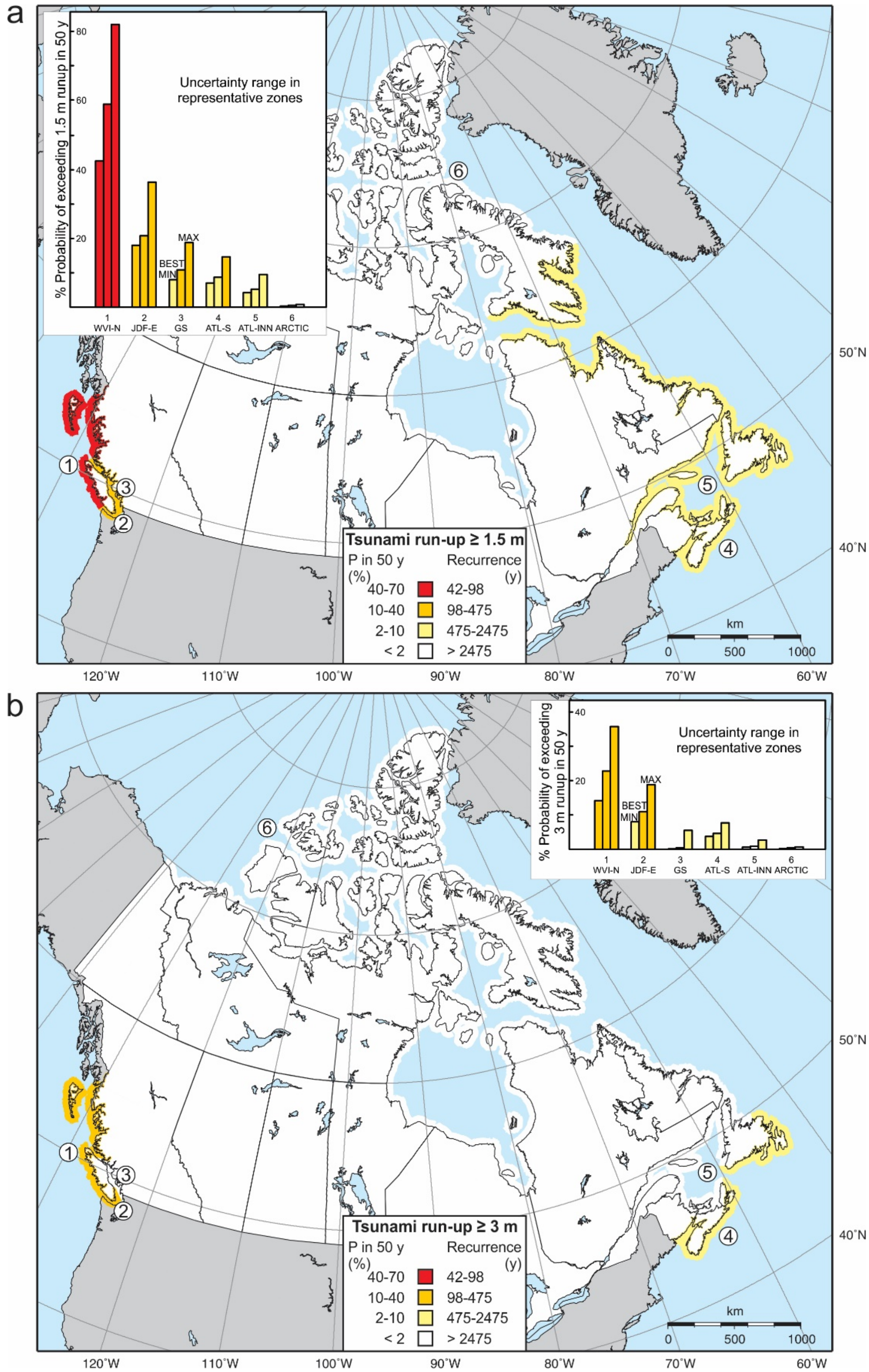


Figure 2 – Probabilistic tsunami hazard maps for the Canadian coast. (a) Probability (P) of tsunami run-up exceeding 1.5 m. (b) Probability (P) of tsunami run-up exceeding 3 m. Colours on maps correspond to best estimate cumulative values; inset graphs show uncertainty ranges for representative zones (WVI: W. Vancouver Is.; JDF: Juan de Fuca Strait; GS: Georgia Strait; ATL-S: S. Atlantic coast; ATL-INN: Inner Atlantic coast).

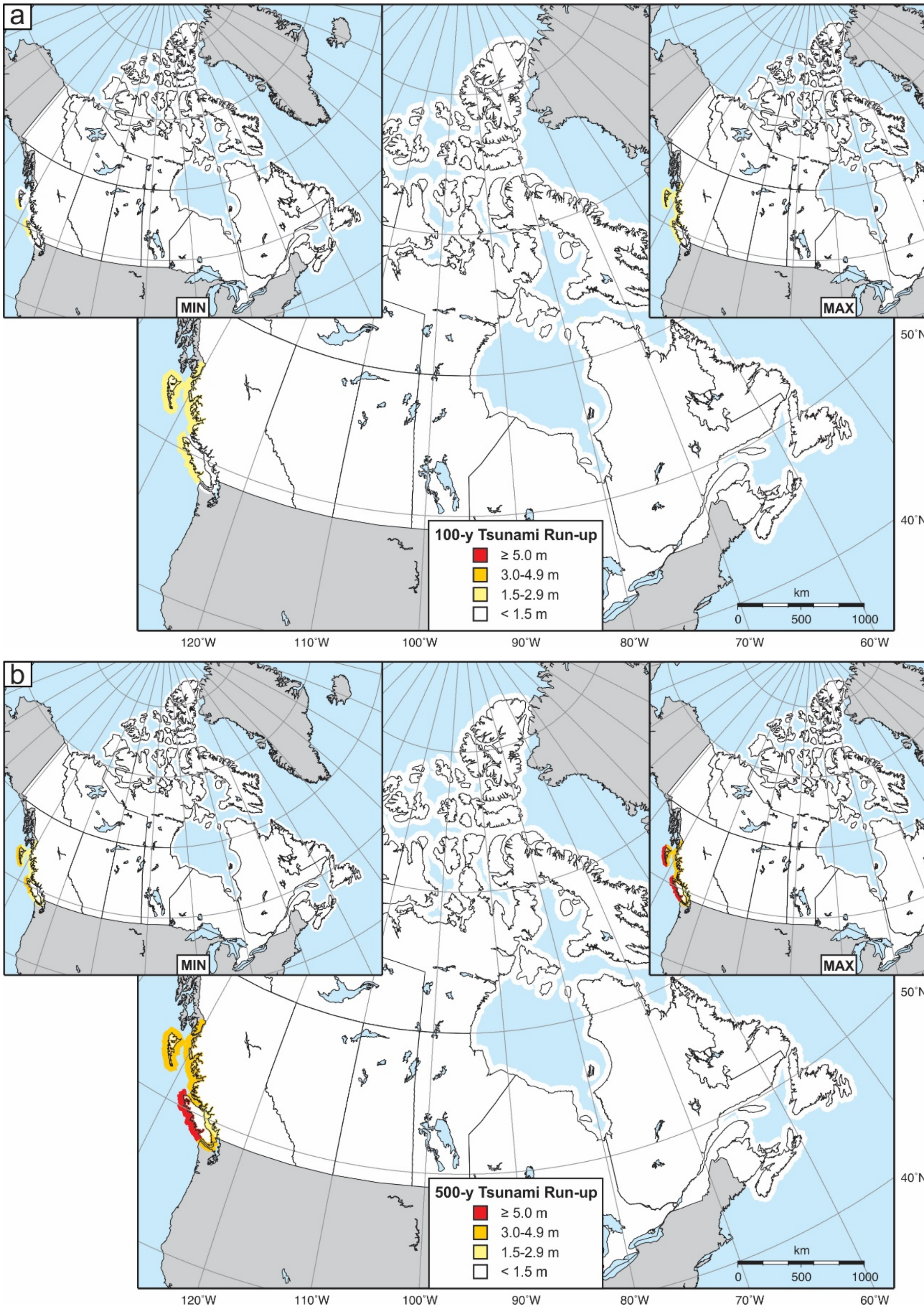
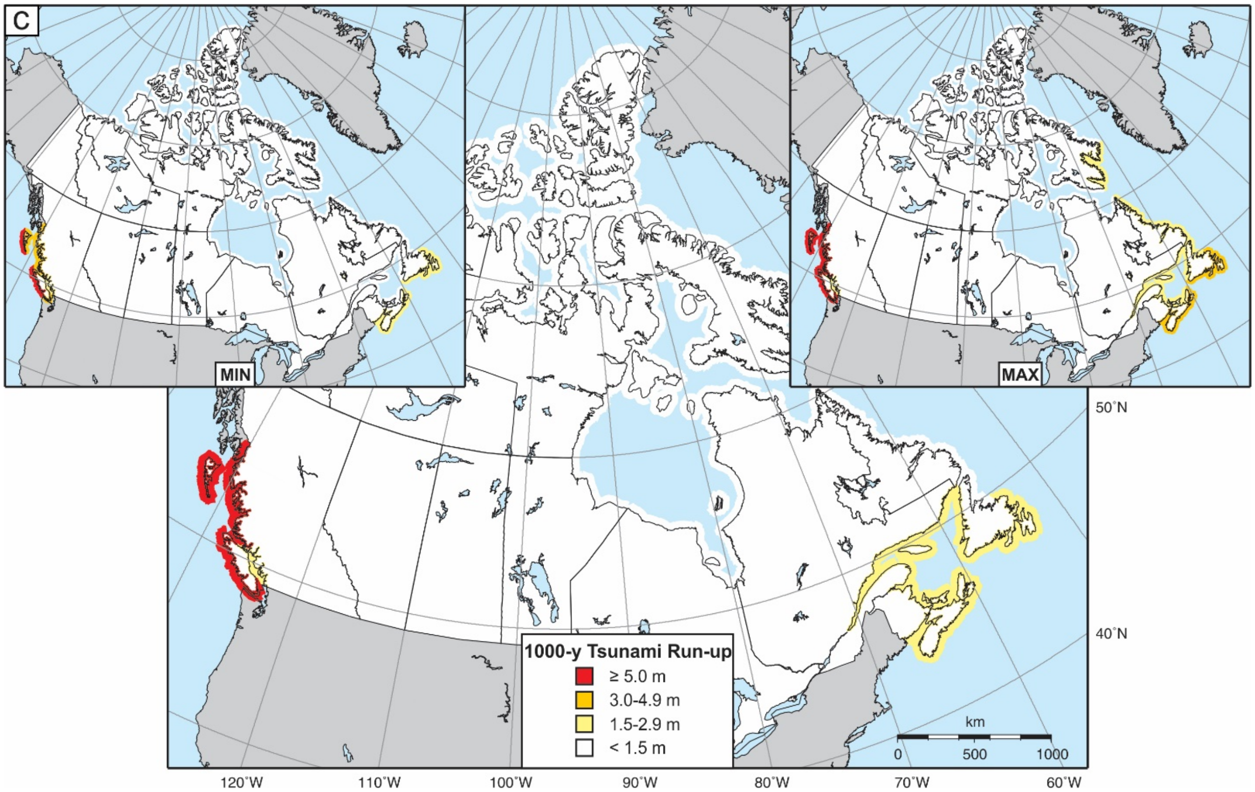


Figure 3 – Probabilistic tsunami hazard maps. Run-up levels for the (a) 100-y tsunami (probability ≥ 39.35% in 50 y), (b) 500-y tsunami (P ≥ 9.52% in 50 y), (c) 1000-y tsunami (P ≥ 4.88% in 50 y), (d) 2500-y tsunami (≥ 1.98% in 50 y). Best estimate values are shown on main maps, with minimum and maximum values on inset maps.



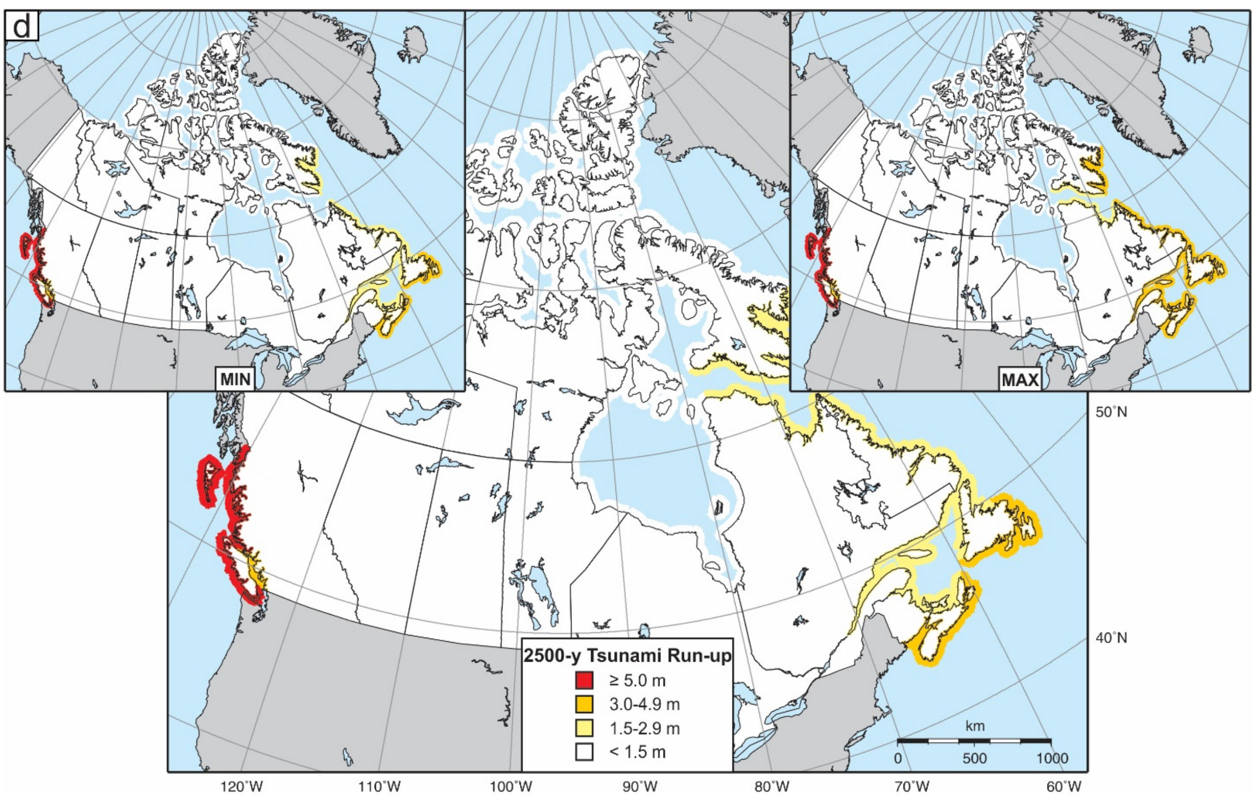


Figure 3 (cont'd)

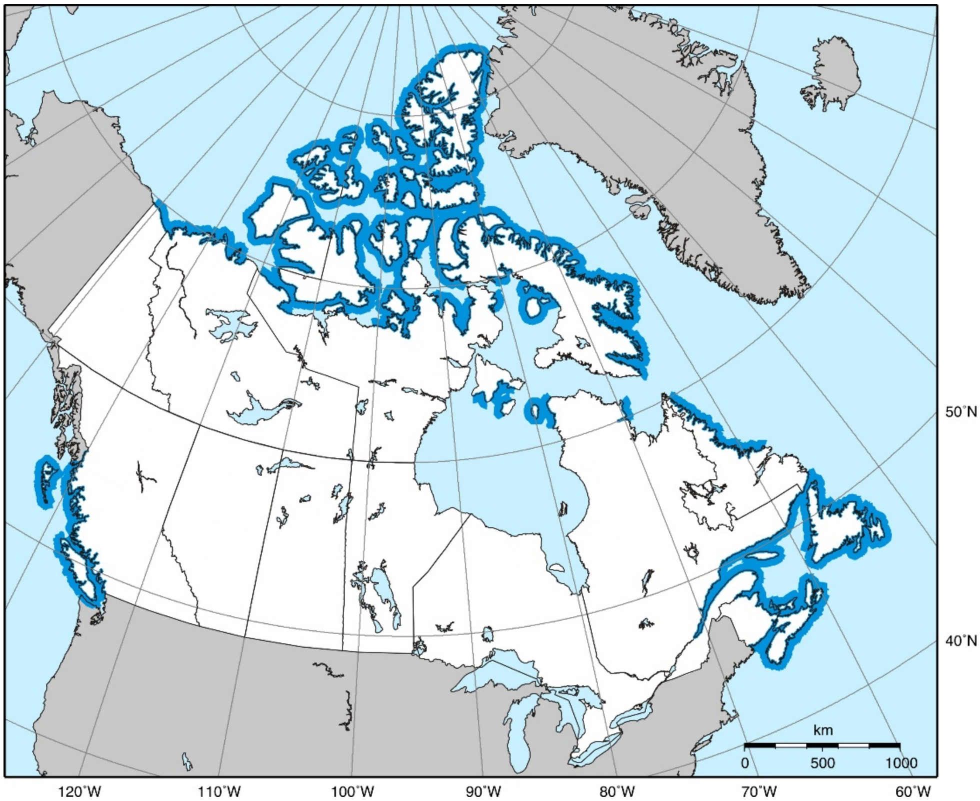


Figure 4 – Coastlines identified as susceptible to damaging local waves triggered by subaerial or submarine landslides or glacial calving. Hazard is based on the landslide susceptibility map of Bobrowsky and Dominguez (2012) and on the presence of glacial fjords.

Tsunami Design Zone is defined as the region vulnerable to inundation by the Maximum Considered Tsunami. Design requirements within the Tsunami Design Zone vary by risk category; highest standards apply to critical infrastructure and essential buildings that would not be evacuated during a tsunami (this category includes buildings designated to act as vertical evacuation structures). Here, site-specific simulations using high-resolution nearshore bathymetry and onshore topography will provide estimates of flow depths, velocities, and directional effects over a minimum of two cycles of in-flow and out-flow. Standards for structural design are informed by case-study analyses of the 2011 Tohoku tsunami and consider hydrostatic, buoyant, hydrodynamic, and debris impact forces as well as foundation and substrate damage.

4.2. Limitations of preliminary assessment

The national assessment presented here provides first-order probabilistic estimates of tsunami hazard for the Canadian coastline, considering tsunami sources that include local and far-field earthquakes as well as large submarine landslides. The resultant maps highlight the coastal zones with relatively high and low tsunami hazard from various sources, and the analysis determines which sources represent the highest hazard for each coastal zone. However, improvements on this assessment are required in order to facilitate adequate mitigation of tsunami hazard in specific coastal locations.

The occurrence of a tsunami following a magnitude 7.8 thrust earthquake offshore western Haida Gwaii in October 2012 provided a timely test of our empirical relation-based methods of tsunami hazard assessment. The earthquake magnitude and mean tsunami run-up surveyed on the west coast of Haida Gwaii (Leonard and Bednarski, 2014) are both in close agreement with our assessment of the hazard from this submarine thrust fault source that had no known history of tsunamigenic earthquakes. However, at a few sites, surveyed tsunami run-up was significantly higher than expected (maximum 13 m at the head of one inlet compared to the maximum 8 m derived from the empirical relations of Abe, 1995), highlighting the need for a comprehensive probabilistic approach that considers a range of source scenarios and tsunami modelling using high-resolution bathymetry and topography data and allowing for resonance in inlets.

Our probabilistic approach to quantifying the tsunami hazard from Pacific far-field subduction zones is based on empirical data and is useful on a regional scale. However, site-specific conditions are not included, as illustrated by the high run-up (> 6 m) recorded at Port Alberni, BC, during the 1964 Alaska tsunami due to resonance amplification in the Alberni Inlet (e.g., Henry and Murty, 1995). Such run-up maxima are outside the range of far-field subduction zone tsunami run-up estimated from analysis of the Tofino, BC, tide gauge data.

A major limitation of this preliminary assessment is that maximum run-up values are not provided for each hazard zone. For example, the tsunami run-up for western Vancouver Island at mean recurrence intervals of 500, 1000, and 2500 years is estimated to exceed 5 m (Fig. 3), but modelling is required to determine the maximum run-up at each hazard level, and at specific locations within each zone. Flow velocities and time series of flow parameters are also not provided and are not generally available.

4.3. Needs for improved Canadian tsunami hazard assessment

Several steps, outlined below, are required to improve Canadian tsunami hazard assessment for use in construction codes and other forms of tsunami mitigation, following the example of the newly-defined U.S. standards summarized in section 4.1 and described in detail by Chock (2014) and Chock and Wilson (2014).

(1) Definition of the maximum considered tsunami to be used in determining potential tsunami inundation zones. This could be a 2% probability of exceedance in a 50-year period or other defined maximum depending on the information available. Critical facilities such as nuclear power plants may be required to consider a larger maximum considered tsunami, i.e., a lower-probability, higher-consequence event.

(2) Estimation of run-up height and inundation limit of the maximum considered tsunami for all coastlines including inlets. At a regional level, this requires modelling of all potential sources that may contribute the maximum considered tsunami. Some sources also require further investigation of event magnitude and frequency through paleoseismology, geodesy and other geophysical studies. The source of the maximum considered tsunami will vary between coastal zones and may differ between hazard levels. For example, on the Atlantic coast, far-field subduction zones are estimated to provide the maximum run-up at a 2% probability in 50 years (equivalent to a 2475-year mean recurrence), whereas continental slope landslides could produce larger run-up at longer recurrence intervals. For Pacific coastal zones, near-field subduction zones provide the maximum run-up at most hazard levels, but in eastern Juan de Fuca and Georgia Straits there is the potential for higher run-up from crustal fault sources at longer recurrence times. For each source, multiple scenarios and their relative probabilities should be considered. For example, modelling of the Cascadia megathrust should include various rupture scenarios and landslide contributions, most of which were explored by Priest et al. (2009) for a site-specific analysis in Oregon. Efforts are underway to model multiple rupture scenarios of the northern Cascadia megathrust (Insua et al., 2015).

(3) Estimation of time series of flow depths, velocities and directions during the maximum considered tsunami in site-specific simulations for mitigation of critical structures designed to withstand inundation. Tsunami design should also factor in the likely effects of debris impacts and post-earthquake shaking conditions, where applicable (Chock, 2014). High-resolution nearshore bathymetry and onshore topography data are particularly important for site-specific simulations. A recent study by AECOM (2013) builds on the Cascadia megathrust rupture scenario modelling of Cherniawsky et al. (2007) by incorporating available topography data to model inundation in the Victoria Capital Regional District. Insua et al. (2015) highlight ongoing efforts by Ocean Networks Canada to gather and merge bathymetry and topography data in coastal British Columbia for use in tsunami modelling and other studies.

(4) Assessment of local-scale subaerial and subaqueous landslide sources of locally-hazardous waves. These sources may contribute the maximum considered tsunami for many sites such as coastal fjords. Additionally, there have been a number of locally-damaging and even fatal historical examples of landslide-generated waves in inland areas of Canada, on the shores of lakes and rivers (e.g., as listed in Leonard et al., 2012). Such an assessment would require magnitude-frequency data of past landslide deposits, slope stability analyses, and site-specific modelling of a range of potential failures.

5. References

ABE, K. “Estimate of tsunami run-up heights from earthquake magnitudes”, In: TSUCHIYA, Y., and SHUTO, N. (eds.) “Tsunami: progress in prediction, disaster prevention and warning”. *Advances in technological hazards research*, Vol 4. Kluwer, Netherlands, 1995, pp 21–35.

AECOM. “Capital Regional District modelling of potential tsunami inundation limits and run-up”, *Report contracted by Capital Regional District, Victoria, BC*, Project No. 60242933, 2013, 36 p.

ATWATER, B.F., and MOORE, A.L. “A tsunami about 1000 years ago in Puget Sound, Washington”, *Science*, Vol. 258, No. 5088, 1992, pp. 1614-1617.

BOBROWSKY, P.T., and DOMINGUEZ, M.J. “Landslide susceptibility map of Canada”, *Geological Survey of Canada, Open File 7228*, scale 1:6 million, 2012.

CHERNIAWSKY, J.Y., TITOV, V.V., WANG, K., and LI, J.-Y. “Numerical simulations of tsunami waves and currents for southern Vancouver Island from a Cascadia megathrust earthquake”, *Pure and Applied Geophysics*, Vol. 164, No. 2-3, 2007, pp. 465-492.

CHOCK, Gary. “The ASCE 7 tsunami loads and effects design standard for the U.S.”, *Coastal Disasters – Lessons learnt for engineers*, July 2014, 24 p.

CHOCK, Gary, and WILSON, Rick. “The development of a tsunami design chapter for the ASEC 7-2016 Standard”, *Structural Engineers Association of California 83rd Annual Convention Proceedings*, Sept 2014, 13 p.

FINE, I.V., RABINOVICH, A.B., BORNHOLD, B.D., THOMSON, R.E., and KULIKOV, E.A. “The Grand Banks landslide-generated tsunami of November 18, 1929: preliminary analysis and numerical modeling”, *Marine Geology*, Vol. 215, No. 1-2, 2005, pp. 2019-2044.

GEIST, E.L., and PARSONS, T. “Probabilistic analysis of tsunami hazards”, *Natural Hazards,* Vol. 37, 2006, pp. 277–314.

HANKS, T.C., and KANAMORI, H. “A moment magnitude scale”, *Journal of Geophysical Research*, Vol. 84, No. B5, 1979, pp. 2348-2350.

HENRY, R.F., and MURTY, T.S. “Tsunami amplification due to resonance in Alberni Inlet: normal modes”, In: TSUCHIYA, Y., and SHUTO, N. (eds.) “Tsunami: progress in prediction, disaster prevention and warning”. *Advances in technological hazards research*, Vol 4. Kluwer, Netherlands, 1995, pp 117-128.

INSUA, Tania L., MORAN, Kate, MCLEAN, Scott, MOORE, Teron, HEESEMANN, Martin, SCHERWATH, Martin, PIRENNE, Benoit, GAO, Dawei, HOEBERECHTS, Jay, SALOMONSSON, Peter, COADY, Yvonne, LEONARD, Lucinda, and WANG, Kelin. “Advancing tsunami detection: the Ocean Networks Canada Tsunami project”, *Proceedings of the 11th Canadian Conference on Earthquake Engineering*, Victoria, July, Paper 98197, 10 p.

LEONARD, Lucinda J., and BEDNARSKI, Jan M. “Field survey following the 28 October 2012 Haida Gwaii tsunami”, *Pure and Applied Geophysics*, Vol. 171, 2014, pp. 3467–3482.

LEONARD, Lucinda J., ROGERS, Garry C., and MAZZOTTI, Stephane. “A preliminary tsunami hazard assessment of the Canadian coastline”, *Geological Survey of Canada Open File 7201,* 2012, 126 p.

LEONARD, Lucinda J., ROGERS, Garry C., and MAZZOTTI, Stephane. “Tsunami hazard assessment of Canada”, *Natural Hazards,* Vol. 70, 2014, pp. 237-274.

PRIEST, G.R., GOLDFINGER, C., WANG, K., WITTER, R.C., ZHANG, Y., and BAPTISTA, A.M. “Confidence limits for tsunami inundation limits in northern Oregon inferred from a 10,000-year history of great earthquakes at the Cascadia subduction zone”, *Natural Hazards*, Vol. 54, No. 1, 2009, pp. 27-73.

STRASSER, F.O., ARANGO, M.C., and BOMMER, J.J. “Scaling of the source dimension of interface and intraslab subduction-zone earthquakes with moment magnitude”, *Seismological Research Letters*, Vol. 81, No. 6, 2010, pp. 941-950.

TEN BRINK, U.S., LEE, H.J., GEIST, E.L., and TWICHELL, D. “Assessment of tsunami hazard to the US east coast using relationships between submarine landslides and earthquakes”, *Marine Geology*, Vol. 264, No. 1–2, 2009, pp. 65–73.

WHITMORE, P., BENZ, H., BOLTON, M., et al. “NOAA/West Coast and Alaska tsunami warning center Pacific Ocean response criteria”, *Science of Tsunami Hazards*, Vol. 27, No. 1, 2008, pp. 1–21.