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Tsunamis on the Pacific Coast of Canada Recorded in 1994–2007

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Abstract—In the last 15 years there have been 16 tsunami events recorded at tide stations on the Pacific Coast of Canada. Eleven of these events were from distant sources covering almost all regions of the Pacific, as well as the December 26, 2004 Sumatra tsunami in the Indian Ocean. Three tsunamis were generated by local or regional earthquakes and two were meteorological tsunamis. The earliest four events, which occurred in the period 1994–1996, were recorded on analogue recorders; these tsunami records were recently re-examined, digitized and thoroughly analysed. The other 12 tsunami events were recorded using digital high-quality instruments, with 1-min sampling interval, installed on the coast of British Columbia (B.C.) in 1998. All 16 tsunami events were recorded at Tofino on the outer B.C. coast, and some of the tsunamis were recorded at eight or more stations. The tide station at Tofino has been in operation for 100 years and these recent observations add to the dataset of tsunami events compiled previously by S.O. Wigen (1983) for the period 1906–1980. For each of the tsunami records statistical analysis was carried out to determine essential tsunami characteristics for all events (arrival times, maximum amplitudes, frequencies and wave-train structure). The analysis of the records indicated that significant background noise at Langara, a key northern B.C. Tsunami Warning station located near the northern end of the Queen Charlotte Islands, creates serious problems in detecting tsunami waves. That station has now been moved to a new location with better tsunami response. The number of tsunami events observed in the past 15 years also justified re-establishing a tide gauge at Port Alberni, where large tsunami wave amplitudes were measured in March 1964. The two meteorological events are the first ever recorded on the B.C. coast. Also, there have been landslide generated tsunami events which, although not recorded on any coastal tide gauges, demonstrate, along with the recent investigation of a historical catastrophic event, the significant risk that landslide generated tsunami pose to coastal and inland regions of B.C.

Key words: Tsunami records, British Columbia, tide gauge, meteorological tsunami, landslide generated tsunami, tsunami catalogue.

1. Introduction

The Pacific Coast of Canada, in the province of British Columbia (B.C.) extends from approximately 48°N to 55°N, a distance of about 775 kilometres. However, this coast is a complex network of inlets, straits, passes, sounds, and narrows, which has a coastline length, including islands, of approximately 27,300 kilometres (Thomson, 1981).

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Significant parts of this coastline are susceptible to the effects of tsunamis generated within the Pacific basin (RAPATZ and MURTY, 1987; MURTY, 1992; CLAGUE *et al.*, 2003). Geological and geophysical evidence gathered along the western coastline of Vancouver Island, as well as on the Washington and Oregon coasts, show that major Cascadia earthquakes accompanied by destructive tsunamis have an average recurrence interval of about 500 years (CLAGUE and BOBROWSKY, 1999; CLAGUE *et al.*, 2003). Trans-Pacific tsunamis caused by major earthquakes elsewhere in the Pacific "Rim of Fire" can also significantly affect the B.C. coast (MURTY, 1992; CLAGUE, 2001). The March 1964 Alaska earthquake with magnitude $M_w = 9.2$ produced a catastrophic tsunami which swept southward from the source area in Prince William Sound along the B.C. coast causing about $10 million in damage (WIGEN and WHITE, 1964; CLAGUE, 2001; CLAGUE *et al.*, 2003). According to RAPATZ and MURTY (1987) and HEBENSTREIT and MURTY (1989) for the coast of British Columbia there is also a high potential risk of destructive tsunamis caused by local major earthquakes. The coasts and underwater slopes of B.C. contain significant amounts of unstable material, so submarine and subaerial landslides, slumps and rock falls and associated tsunamis are often the secondary effects of earthquakes (EVANS, 2001; RABINOVICH *et al.*, 2003).

Until the mid-1980s all tide gauges on the B.C. coast were analogue. Records of reasonably high quality were collected (WIGEN, 1983), but with the exception of a very rudimentary automated warning system at Tofino and Langara, sea-level records were not available for real-time analysis in response to potential tsunami events. Basic information could be obtained from gauge attendants by radio or telephone, but the record could only be analysed and digitised days or weeks after the event. The accuracy of these instruments was a few centimetres and WIGEN (1983) was able to identify some tsunami as small as 6 cm. Given that the typical range of tide at these stations is about 5 metres it was impossible to identify any events with tsunami wave heights smaller than that. In the 1980s the Canadian Hydrographic Service (CHS) began to operate both digital and analogue gauges at key stations on the B.C. coast. This provided access to the data in real-time by either telephone modem or Meteor Burst communication. For the most part though, on-site data storage and throughput considerations limited the data sampling interval to 15 minutes.

The destructive tsunamis of the last decade (e.g., Shikotan tsunami of October 4, 1994) initiated a major upgrade of the existing Tsunami Warning and Permanent Water Level Network (PWLN) stations on the B.C. coast (see Fig. 1). The new digital instruments were designed to continuously measure sea-level variations with considerably higher precision than earlier analogue gauges, and to store corresponding sea-level samples every minute; a significant improvement from the previous digital instruments. During the period 1999–2001 near-continuous series of high-quality 1-minute sea-level data were collected at all stations and two weak tsunamis (the trans-Pacific Peru tsunami of June 23, 2001 and the local Queen Charlotte tsunami of October 12, 2001) were recorded (RABINOVICH and STEPHENSON, 2004). These two observed tsunami events, and the high quality of the data from the new instruments, initiated a review of tide gauge records for the period 1981–1998. The review identified four events in the 1990s in

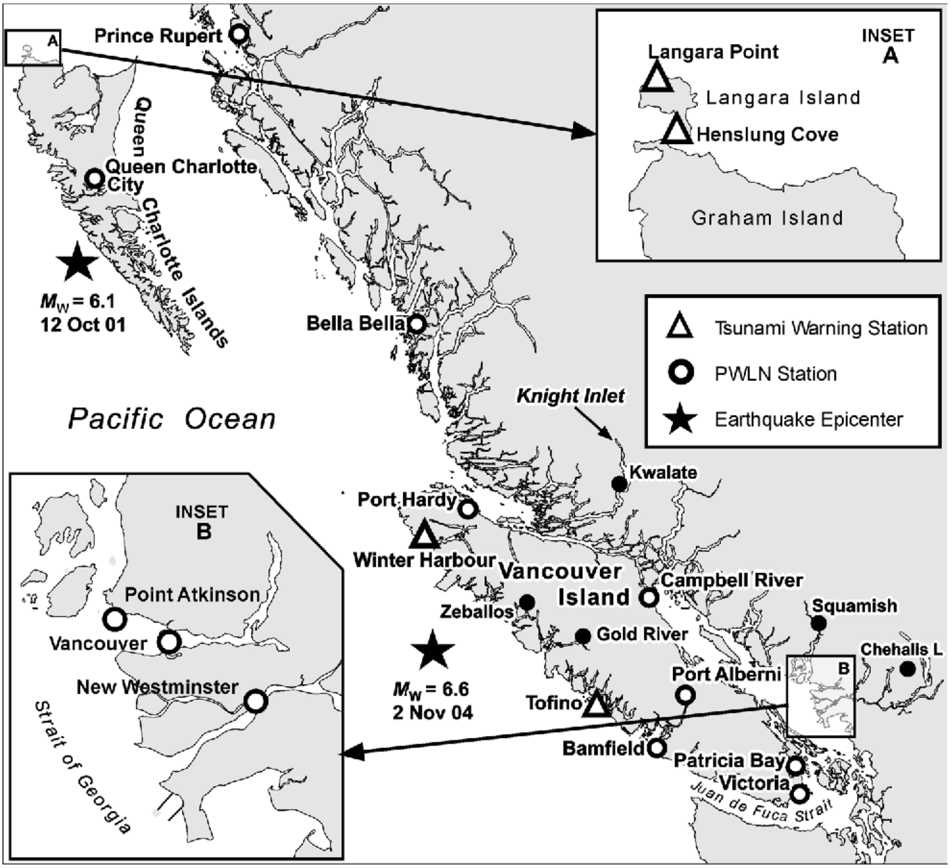

Figure 1
A map showing the location of Permanent Water Level Network (PWLN) and Tsunami Warning stations on the coast of British Columbia. Also shown are epicenters of the earthquakes of October 12, 2001 and November 2, 2004 (stars) and locations of some geographical sites mentioned in the text (solid circles).

addition to two events previously described by González *et al.* (1991) and González and Kulikov (1993). As had been indicated by González *et al.* (1991) the Alaska earthquake events of November 30, 1987 and March 6, 1988 produced tsunami "observed in Alaska, B.C. and the Hawaiian Islands." These weak tsunami events were observed at Langara Island near the northern coast of the Queen Charlotte Islands (Fig.1) and had heights of 14 cm and 11 cm, respectively. A review of analogue records from four stations on the west coast of Vancouver Island (Tofino, Gold River, Zebellos and Winter Harbour) failed to identify a tsunami at any of these locations for either of the Alaska events. The tsunami wave recorded at Langara Island either did not reach the southern B.C. coast, or it was too small to be detected on any of these analogue records.

Of the sixteen tsunami events observed since 1994, eleven were far-field events from various areas of the Pacific, three were local (B.C. coast) or regional (less than 3 hrs

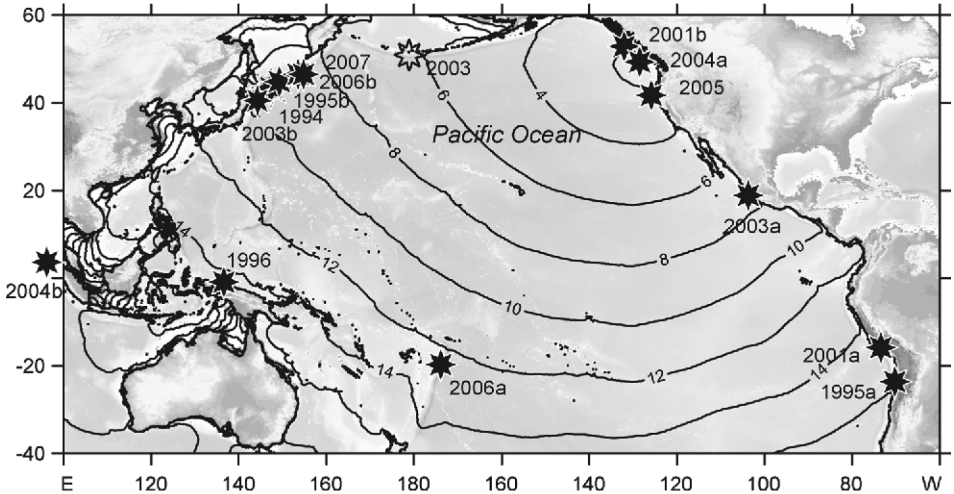

Figure 2
A map showing earthquake epicenters that have produced tsunami observed on the B.C. coast (1994–2007). Also shown is the epicenter of the 2003 Rat Islands earthquake (clear star), which did not produce tsunami waves measurable on the coast of B.C. Solid thin lines are 2-hourly inverse isochrones of the tsunami travel time from any point in the Pacific Ocean to Tofino.

tsunami travel time from the source region) events, and two were meteorological tsunamis (Fig. 2). All of these sixteen tsunami events were recorded at Tofino on the outer B.C. coast and some of the tsunamis were recorded at eight or more stations. The tide station at Tofino has been in operation for 100 years and these recent observations add to the dataset of tsunami events compiled previously by S.O. WIGEN (1983) for the period 1906–1980. WIGEN detected 43 tsunami events for this 75-year period. All these events were far-field, with no local or regional events, and no meteorological tsunamis identified.

The fact that the 16 tsunami events observed since 1994 were all recorded at Tofino demonstrates that Wigen's selection of this station for his study was an excellent choice. In addition, Tofino was the location of the maximum observed wave height for 5 of the 15 events. Tofino as a Tsunami Warning station plays a key role for the B.C. coast. Our experience indicates that if a tsunami signal has been detected in the Tofino record, it could be also detected in some other records; however, if there is no tsunami signal in Tofino, there is very little chance that such signal will be found at other sites. We might say that Tofino is an "alarm bell" that always rings in the case of a tsunami. Some of the other "bells" (other stations) sometimes ring louder, but they do not ring as reliably.

This paper will first look at the seismically generated events, and these will be organized in four groups: (1) Far-field events for the period 1994–1998 (analogue instruments), (2) far-field events for the period 1999–2007, (3) local and regional events, and (4) a major event where no tsunami was detected. Two meteorological tsunami events will then be described, followed by a discussion of two recent landslide tsunami events. The paper will conclude with a discussion of the knowledge gained from these events and how this knowledge is being applied to enhance Canadian tsunami warning and mitigation capabilities.

2. *Seismically Generated Tsunamis*

2.1. 1994–1998

As mentioned previously, the analogue records from stations on the coast of Vancouver Island were checked for evidence of tsunami events during the period 1981–1998. Altogether we checked about 20 major events (trans-Pacific tsunamis or strong local tsunamis), with particular attention to events observed on the nearby coast of Alaska and on the West Coast of the U.S.A. (cf., LANDER, 1996, 2003). We were able to identify a definite tsunami signal for four events. Table 1 lists these four far-field tsunami events that occurred during the period 1994–1996; the locations of the epicentres of the corresponding earthquakes are shown in Figure 2. The October 4, 1994 Kuril Islands tsunami was well known, as it resulted in a Tsunami Warning being issued for the west coast of North America (see RABINOVICH *et al.*, 2006b for discussion of this warning). The other three events had not been identified previously in B.C. records.

1994 Shikotan tsunami. The Shikotan (Kuril Islands) earthquake on October 4, 1994 had a magnitude of $M_w = 8.3$. On Shikotan Island, one of the South Kuril Islands closest to

Table 1

Summary of the 16 recorded tsunami events that occurred between 1994 and 2007. The locations of earthquake epicenters for events 2001b and 2004a are shown in figure 1; all others are shown in Figure 2

Year, Event*	Date	Earthquake parameters				Obs.	Station, Max. height (cm)
		Location	Lat.	Long.	M_w		
1994	04 Oct	Kuril Is., Russia	43.8 N	147.3 E	8.3	5	Port Alberni (26.2)
1995a	30 Jul	Antofagasta, Chile	23.3 S	70.3 W	8.0	6	Port Alberni (24.9)
1995b	03 Dec	Kuril Is., Russia	44.7 N	149.3 E	7.9	5	Port Alberni (37.5)
1996	17 Feb	Irian Jaya, Indonesia	0.9 S	137.0 E	8.2	6	Port Alberni (36.7)
2001a	23 Jun	Peru	16.3 S	73.6 W	8.4	8	Tofino (15.1)
2001b	12 Oct	Queen Charlottes, Canada	52.6 N	132.2 W	6.1	4	Winter Harbour (22.7)
2003a	22 Jan	Colima, Mexico	18.8 N	104.1 W	7.5	3	Tofino (10.5)
2003b	25 Sep	SE Hokkaido I., Japan	41.8 N	143.9 E	8.3	5	Winter Harbour (10.0)
2004a	02 Nov	Vancouver I., Canada	49.0 N	129.2 W	6.6	2	Tofino (10.8)
2004b	26 Dec	Sumatra, Indonesia	3.3 N	96.0 W	9.3	6	Winter Harbour (21.0)
2005a	15 Jun	N. California, USA	41.3 N	126.0 W	7.2	2	Tofino (4.3)
2005b	09 Dec	Vancouver I., Canada	Meteotsunami			11	Tofino (15.5)
2006a	03 May	Tonga Islands	20.2 S	174.1 W	7.9	6	Winter Harbour (10.8)
2006b	15 Nov	Kuril Is., Russia	46.6 N	153.3 W	8.3	10	Langara (38.5)
2007a	13 Jan	Kuril Is., Russia	46.2 N	154.5 W	8.1	8	Langara (17.1)
2007b	13 Jul	Vancouver I., Canada	Meteotsunami			3	Victoria (10.2)

the epicentre, ground-shaking was extremely intense, and maximum runup of 10 m was observed (YEH *et al.*, 1995). A runup of approximately 1.8 m was reported soon after the earthquake at Nemuro (Japan) and a Pacific-wide Tsunami Warning was issued. At that time, only the Tsunami Warning stations at Winter Harbour and Bamfield were equipped with digital instruments and these were the only records utilized. These digital records indicated maximum wave heights of 19.8 cm at Winter Harbour and 9.3 cm at Bamfield. The recent review of the analogue records revealed that the wave was also recorded at Tofino, Port Alberni and Victoria, and that a maximum wave height of 26.2 cm was measured at Port Alberni. The digitized tsunami records (with predicted tides removed and high-pass filtered with a 3-hour Kaiser-Bessel window) for these three stations, and for the stations at Winter Harbour and Bamfield, are shown in Figure 3. The first-wave reached the B.C. coast 8 h 25 m after the earthquake and there was good agreement between the expected and observed wave arrival times at all five stations. At each of the stations the first-wave arrival was positive (a crest) and the maximum wave arrived four or more hours after the first wave.

1995 Chile (Antofagasta) tsunami. On July 30, 1995 an earthquake near Antofagasta in Northern Chile ($M_w = 8.0$) generated a tsunami which was recorded at six tide gauges on the B.C. coast—the same five stations as the previous event in October 1994, as well as

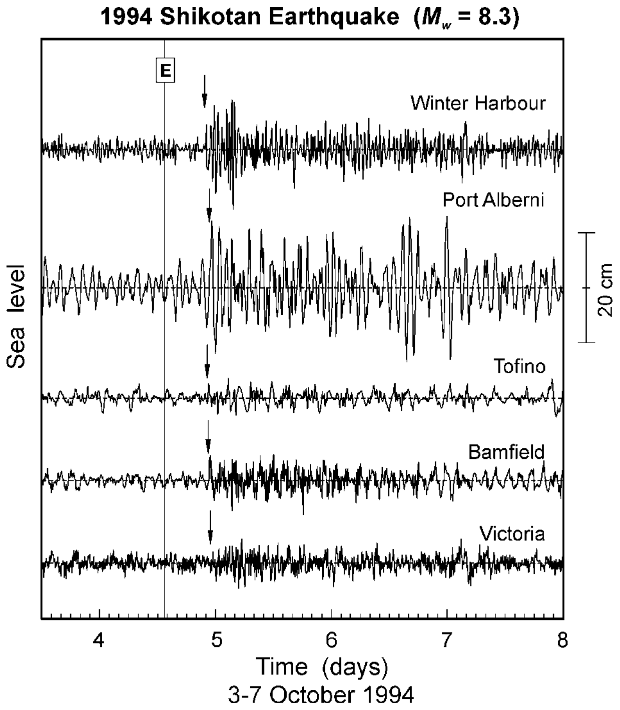

Figure 3
Tsunami records of the Shikotan tsunami of October 4, 1994. Solid vertical line labeled "E" denotes the time of the main earthquake shock; arrows indicate the first tsunami arrival.

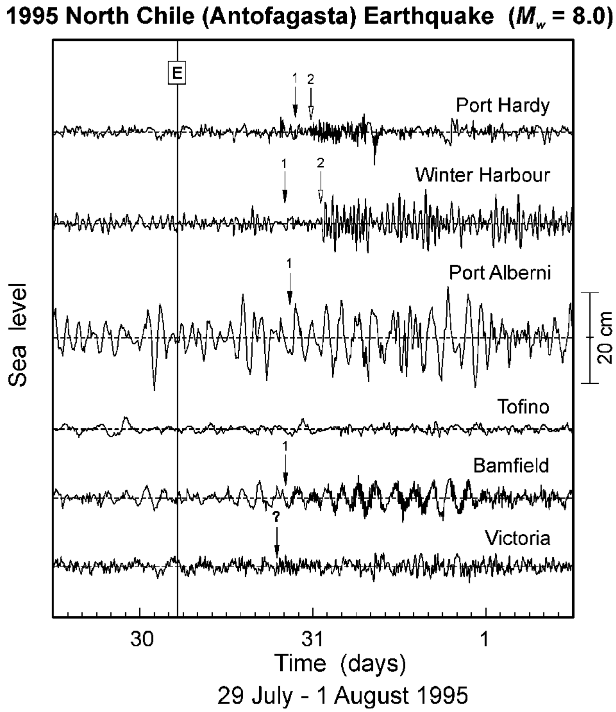

Figure 4
As for Figure 3 but for the Antofagasta tsunami of July 30, 1995. Arrows and numbers indicate arrivals of the first and second tsunami wave train. Solid vertical line labelled ''E'' denotes the time of the main earthquake shock.

Port Hardy. A maximum wave height of 24.9 cm was observed at Port Alberni. The digitized high-pass filtered tsunami records for these six stations are shown in Figure 4. At Winter Harbour the arrival of the first train of waves is not clear, but the arrival of the second train is evident approximately 4 hours later. At Bamfield the record clearly shows both a low-frequency modulating oscillation and high-frequency waves. The high frequency waves, with a period of about 12 minutes, are a common characteristic of tsunami at Bamfield. The tsunami was observed at Port Hardy, Tofino and Victoria, but at each of these stations the tsunami was small and in some instances irregular.

1995 Kuril Islands (Iturup) tsunami. On December 3, 1995 an $M_w = 7.9$ earthquake occurred near Iturup Island (the southern Kuril Islands). A tsunami was observed at the same five stations as the October 1994 Kuril Islands event, and once again the largest wave height (37.5 cm) was at Port Alberni. The digitized tsunami records for Port Alberni, Winter Harbour, Bamfield, Tofino and Victoria are shown in Figure 5. At Bamfield, the first train of high-frequency (12 min) relatively small waves is followed approximately 4.5 h later by a second train of more energetic waves with a period of about 80 min. The arrival of this second train of waves corresponds well with the maximum wave heights at Port Alberni.

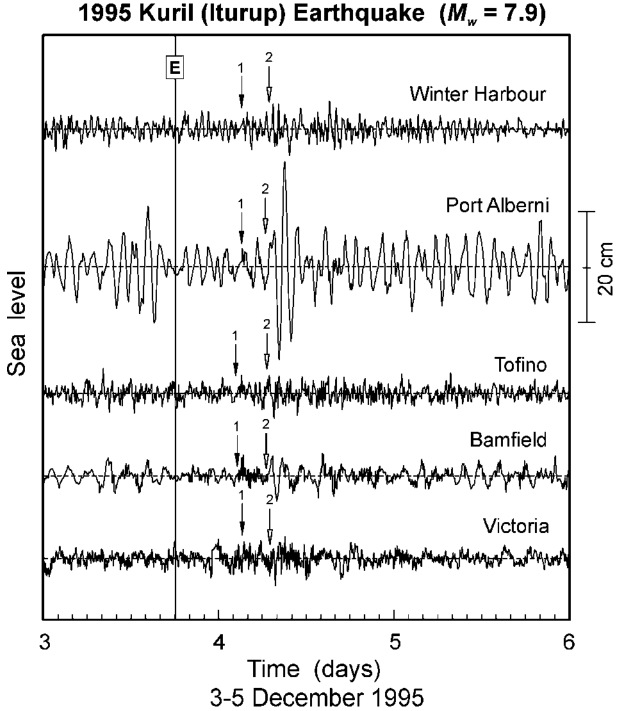

Figure 5
As for Figure 4 but for the Kuril Islands (Iturup) tsunami of December 3, 1995.

1996 Irian Jaya tsunami. The last of the four events identified from the review of the analogue records was the $M_w = 8.2$ earthquake which occurred near Irian Jaya (Indonesia) on February 17, 1996. This tsunami was observed at the same six stations as the July 1995 Chile event. The digitized records for this tsunami are shown in Figure 6. It is noteworthy that tsunami generated near Indonesia rarely reach the coast of B.C.. WIGEN (1983) was able to identify only three tsunami events originating from this region of the Pacific, and in each of these cases the maximum wave height observed at Tofino was less than 10 cm (actually, two of these events are dubious). For the 1996 event the maximum wave height observed at Tofino was only about 5 cm,[1] but larger waves were observed at the other five stations and at each of these stations the first wave arrival was positive (a crest). Once again the maximum wave height (36.7 cm) was recorded at Port Alberni.

These four tsunami events were all far-field events and were from three distinct regions of the Pacific—Russia, Chile and Indonesia. All four of these events were recorded at the same five stations—Victoria, Bamfield, Tofino, Port Alberni and Winter Harbour. The

[1] This estimate for Tofino is unreliable: The main tide gauge was not working during the event, for this reason we used the record from a reserve digital tide gauge with 5-min sampling but with unknown response characteristic.

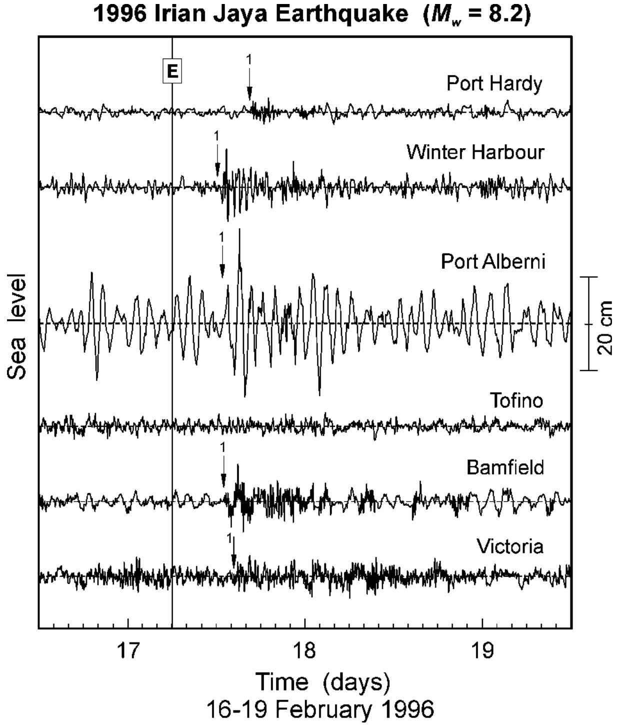

Figure 6
As for Figure 3 but for the Indonesia (Irian Jaya) tsunami of February 17, 1996.

Indonesia and Chile events were also weakly observed at the sixth station—Port Hardy. For each of these events the maximum wave heights were recorded at Port Alberni and at Winter Harbour. Surprisingly, the signals at Tofino were quite modest in each instance. The maximum wave height at Tofino was smaller than at Bamfield for three of the four events and comparable to Bamfield for the fourth event. In contrast, the maximum wave height at Tofino was greater than at Bamfield for every one of the 12 events since 2001.

Tofino is a unique station in that it is one of only two B.C. stations designed expressly for Tsunami Warning. Each of the three stilling wells has a horizontal intake pipe connecting it to the sea. While this provides a linear response to the incoming signal, it requires the horizontal intake to be well maintained. This has been the case in recent years and these horizontal intake pipes are now checked and cleaned annually. WIGEN (1983) noted that, as a result of sediment build-up in the intake pipes at Tofino, “from 1975 to 1978 response may have been diminished” and “from 1979 through 1980 the gauge may at times have been unable to respond to a smaller tsunami, or register accurately a larger one.” It now seems that this problem continued for a much longer period of time. A more detailed review of the residuals (observed heights minus predicted heights) may identify additional periods when the station’s response was reduced. It seems very likely that 1994–1996 will be one of those periods.

2.2. 1999–2007: Distant Events

Seven tsunami events with distant or far-field sources have been observed on the B.C. coast since the upgraded digital instruments were installed in 1998. Two of these events, Peru (2001) and Sumatra (2004) have been partly discussed in previous papers (Rabinovich and Stephenson, 2004; Rabinovich *et al.*, 2006a); the other five far-field events have not been described previously. These are the Colima, Mexico tsunami (2003), the Hokkaido (Tokachi-oki) tsunami (2003), the Tonga tsunami (2006), and two recent tsunami events with source regions in the Central Kuril Islands (2006 and 2007).

2001 Peru tsunami. The Peru earthquake ($M_w = 8.4$) on June 23, 2001 generated a widespread tsunami, which was observed at distant locations around the Pacific, including Australia and Japan (cf., Okal *et al.*, 2002). Most of the energy went southwestward, i.e., in the direction of New Zealand and Australia. However, a certain portion of the energy also went poleward (to the north and south) along the coasts of the Americas. The tsunami event was clearly evident at three stations on the west coast of Vancouver Island (Tofino, Winter Harbour and Bamfield) as well as at five other locations on the B.C. coast or in adjoining waterways (Rabinovich and Stephenson, 2004).

To better display the data a high-passed Kaiser-Bessel filter with a 3-hour window was used (cf., Emery and Thomson, 2003). Several well-defined packets of long waves were apparent in each of these records, and the maximum tsunami wave heights were mainly associated with the second or third packet at a time 1.5–2.0 days after the earthquake event (Fig. 7), i.e., 1.0–1.5 days after the expected tsunami arrival times. Also, a significant increase of wave energy (compared with normal background noise) during the tsunami event was observed to persist for more than four days. Such a prolonged “ringing” could only be explained by persistent incoming wave energy. These features suggest that the tsunami waves measured on the coast of B.C. were mainly edge waves, which propagated along the continental coast from the source region to the observational sites.

The 2001 Peru tsunami waves detected on the B.C. coast demonstrated clearly that the data quality from the upgraded PWLN instruments had improved considerably and become appropriate to detect even weak tsunami events. Though the 2001 wave heights were relatively small (from 3.7 cm in Queen Charlotte City to 15.1 cm in Tofino) the tsunami signal was quite clear and easily distinguishable from the background noise.

2003 Colima tsunami. The Colima earthquake ($M_w = 7.5$) on January 22, 2003 created strong damage in Colima State (Mexico), killed 18 people and produced a small tsunami that was recorded by several tide gauges on the Pacific coast of Mexico with a maximum trough-to-crest height of 122 cm at Manzanillo (Ortiz *et al.*, 2003). The tsunami was observed at three stations on the outer B.C. coast (Fig. 8). The largest observed wave height was 10.5 cm at Tofino. The initial waves reached the B.C. stations about 7 hours after the earthquake event. Approximately 14 hours later a second train of waves arrived

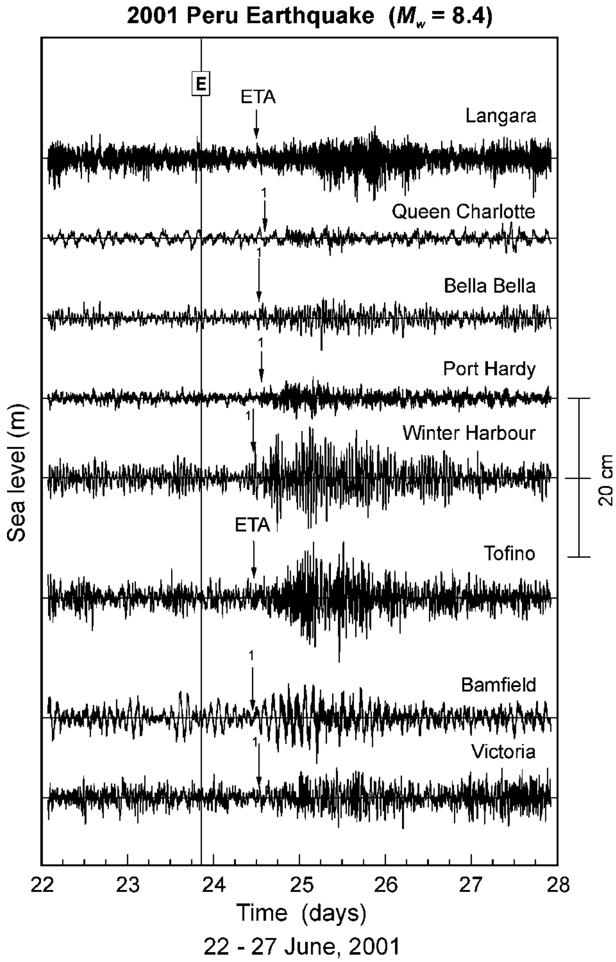

Figure 7
As for Figure 3 but for the Peru tsunami of June 23, 2001.

and this was followed by a third wave train another 8 hours later. This mirrors the sequence of events following the Peru tsunami in 2001 and suggests that once again the tsunami waves measured on the coast of B.C. were mainly edge waves, which propagated along the continental coast from the source region.

2003 Hokkaido (Tokachi-oki) earthquake. A great earthquake on September 25, 2003 ($M_w = 8.3$) injured more than 700 people and produced severe damage in southeastern Hokkaido. The associated tsunami was observed along the entire Pacific coast of Japan. The maximum wave height (254 cm) was recorded at Tokachiko (southeastern coast of Hokkaido Island), maximum runups on this coast were more than 4 m (TANIOKA *et al.*, 2004). Tsunami waves were also observed on the coast of Alaska, at many sites in the Hawaiian Islands and at eight stations on the coasts of Oregon and California with a

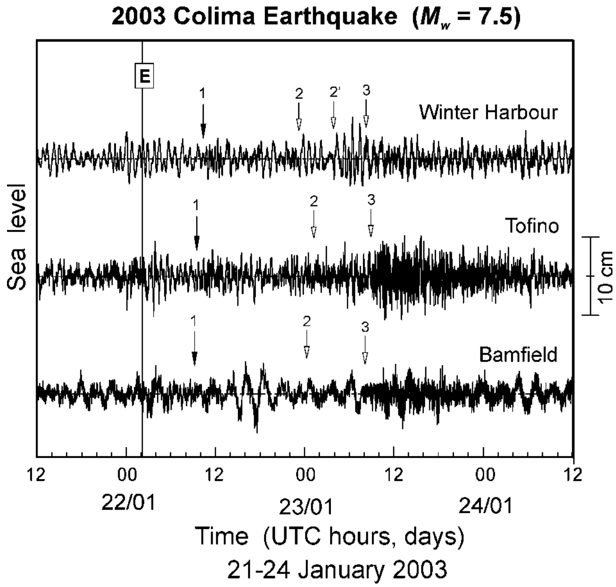

Figure 8
As for Figure 4 but for the Mexico (Colima) tsunami of January 22, 2003.

maximum wave height (trough-to-peak) of 35 cm at Crescent City, CA and 4–9 cm at the other seven sites. These West Coast gauges had a 6-minute sample interval, and would therefore slightly underestimate the actual maximum height. Tsunami waves were expected to be recorded at some stations on the coast of B.C. However, the immediate post-event examination of tide gauge data did not reveal evident tsunami signals. Working on the present paper, we re-examined the data and came to the conclusion that the 2003 Hokkaido tsunami waves had, in fact, been detected on this coast.

Figure 9 shows the records of six stations on or near the outer (Pacific) coast of B.C. (Fig. 1); time of the main shock and estimated arrival time (ETA) for Tofino are indicated (ETA for Langara is approximately 1.5 h earlier, for Victoria 1 h later, while for the other three stations it is approximately the same as for Tofino). The same disturbance ($\sim$1.5 wavelengths beginning from a crest), arriving at the time of ETA is clearly seen at Tofino, Bamfield, Port Hardy and Victoria (indicated by arrows in Fig. 9). The height of this initial disturbance ranges from 3.5 cm to $\sim$7 cm. The same disturbance is apparently seen at Winter Harbour (indicated by an arrow with a question mark) but it is masked by earlier induced seiches. In general, the post-ETA oscillations observed at two neighbouring stations, Tofino and Winter Harbour, in particular the timing of the largest waves, are highly correlated, supporting the assumption of their mutual tsunami origin. The largest observed wave heights are 8 cm at Tofino, 10 cm at Winter Harbour, and $\sim$5.5 cm at Bamfield and Victoria. The Langara record (top record in Fig. 9) is very noisy, preventing identification of tsunami waves at this site.

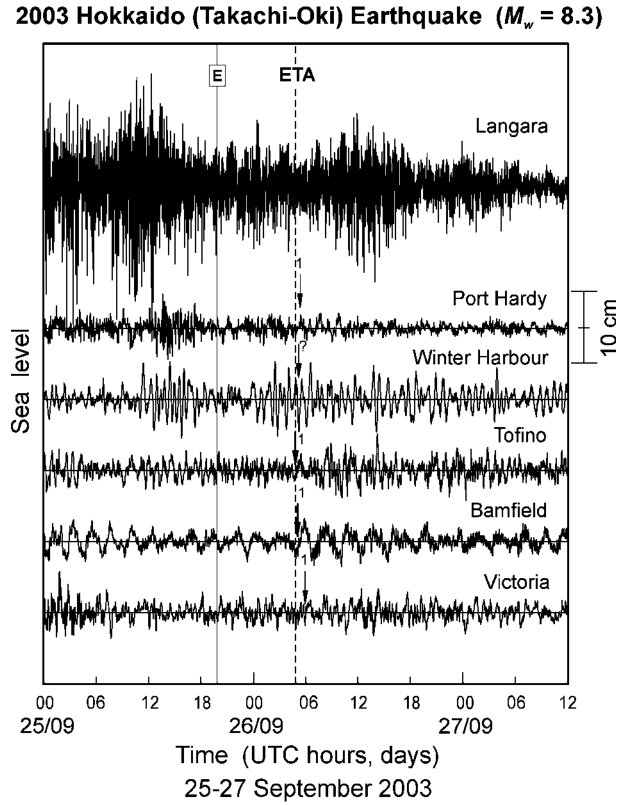

Figure 9

As for Figure 3 but for the Hokkaido (Tokachi-oki) earthquake of September 25, 2003. Dashed vertical line labeled "ETA" denotes the expected tsunami arrival time for the Tofino Warning Station. Tsunami waves have not been identified in the record of Langara, which was too noisy.

2004 Great Sumatra tsunami. The Sumatra megathrust earthquake on December 26, 2004 ($M_w = 9.3$) generated a catastrophic tsunami that caused widespread damage in coastal areas throughout the Indian Ocean. It was soon apparent that this tsunami had the potential to be a global-scale tsunami. We expected the Sumatra tsunami would propagate into the North Pacific and given the excellent tsunami observations collected on the B.C. coast in 2001–2004, supposed that it would be recorded by many PWLN stations.

Several criteria were used to identify the 2004 Sumatra tsunami waves in the B.C. records. The most important criteria were: (1) Close agreement between the expected tsunami arrival times and the observed times of arriving tsunami waves; (2) agreement between nearby stations (it is much easier to detect tsunami wave arrival for a group of stations than for a single tide gauge); (3) the presence of dominant periods in the arriving waves; and (4) relatively sharp amplification and abrupt temporal structure change in the observed longwave observations. The high quality of the instruments, the 1-minute sampling interval, as well as the cumulative effects of the detection criteria enabled us to

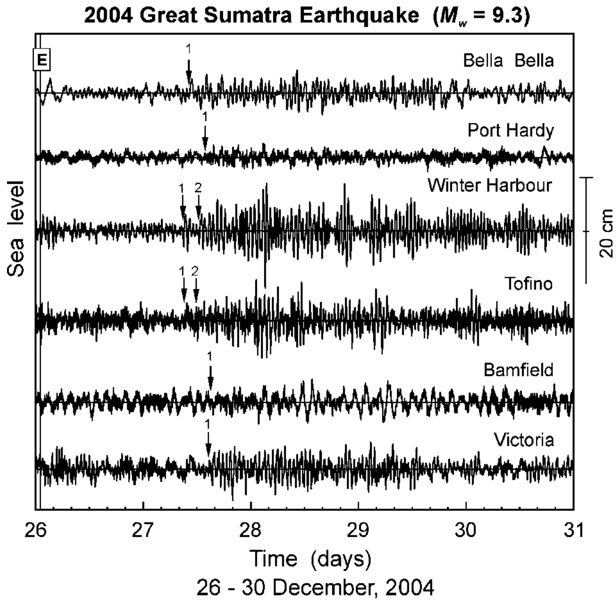

Figure 10
As for Figure 4 but for the Great Sumatra tsunami in the Indian Ocean of December 26, 2004.

recognize a tsunami signal at six of the stations on the B.C. coast (Rabinovich *et al.*, 2006a). The maximum wave heights ranged from 21.0 cm at Winter Harbour to 4.5 cm at Port Hardy (Fig. 10). Tsunami energy for these stations was principally in the 45–60 minute range. In addition, the observed wave heights, tsunami arrival times, and the general character of the wave trains for stations in the North Pacific were all found to be in good agreement with the results of numerical computations (Titov *et al.*, 2005b).

Further analysis demonstrated that the 2004 Sumatra tsunami waves were actually recorded along the entire Pacific Coast of North America, from Mexico to the Aleutian Islands, with maximum measured wave heights at Manzanillo (Mexico)—89.3 cm, Crescent City (CA)—60.5 cm, and Port San Luis (CA)—53.0 (Rabinovich *et al.*, 2006a). The main properties of the waves observed on the coasts of Alaska, Oregon, California (CA) and B.C. were approximately the same, despite significant differences in wave heights and oscillation frequencies associated with the resonant features of the station sites.

All B.C. records had a wave-train structure with maximum recorded waves mainly in the second or third trains (i.e., 18–24 hours after the first wave arrival). Wave trains at neighbouring stations (e.g., Tofino and Winter Harbour) are highly correlated, indicating that they are related through properties inherent to the open-ocean tsunami wavefield. A pronounced feature of the tsunami records for the B.C. and West Coast U.S. sites is the very long (> 3.5 days) ringing (Fig. 10). Similar long-period ringing of tsunami waves for the entire coast of North America was observed by Miller *et al.* (1962) following the

1960 Chile earthquake. Such long-duration ringing is only possible if persistent external energy "pumping" is provided through continued arrival of the open-ocean tsunami energy. This additional energy may be associated with waves reflected from the continental margins or other large-scale topographic features, which may, in turn, account for the wave-train structure of the tsunami waves.

2006 Tonga tsunami. The Tonga Islands earthquake on May 3, 2006 ($M_w = 7.9$) was felt throughout the surrounding islands. It produced a widespread Pacific tsunami with substantial wave heights in the near field, although no damage or fatalities were reported. Measured heights (peak-to-trough) of approximately 0.5 m were recorded at a number of islands in the SW Pacific and at Kalului, Hawaii. The wave was also observed in Japan and New Zealand, where the maximum wave heights were 0.15 m. On the West Coast of North America the wave was observed at a number of locations from Santa Barbara, CA to King Cove, AL. The maximum observed wave height on the coast of North America was 0.54 m at Crescent City. On the B.C. coast the tsunami was observed at six locations. The maximum recorded wave height was 10.8 cm at Winter Harbour on the west coast of Vancouver Island. The travel time to the B.C. coast was 12–14 hours and the arrival of the tsunami is clearly shown in de-tided plots with a high-passed Kaiser-Bessel filter with 3-hour window used (Fig. 11).

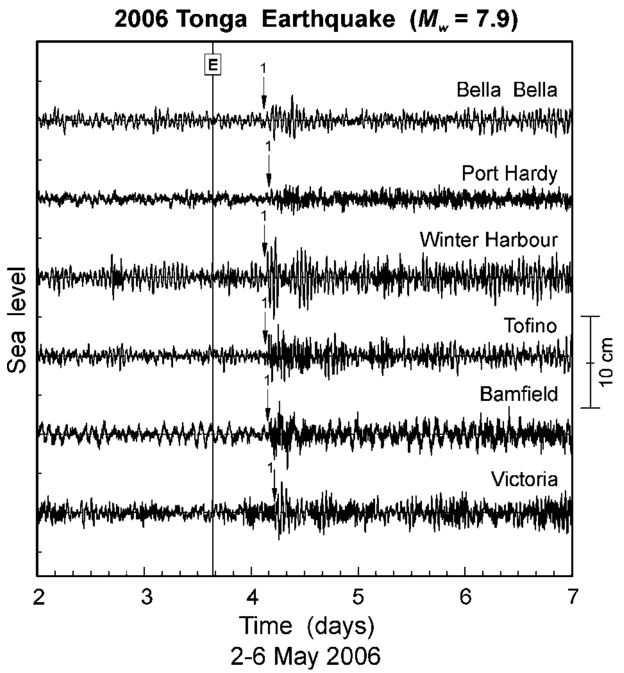

Figure 11
As for Figure 3 but for the Tonga tsunami of May 3, 2006.

2006 and 2007 Kuril Islands tsunamis. Two of the most recent events, the central Kuril Islands earthquakes on November 15, 2006 and January 13, 2007, produced tsunamis clearly observed at stations on the B.C. coast. The maximum wave height in each instance was recorded at Langara Island −38.5 cm and 17.1 cm, respectively. The November 15, 2006 event ($M_w = 8.3$) generated a trans-oceanic tsunami, the strongest tele-tsunami in the Pacific since the 1964 Alaska tsunami (Rabinovich *et al.*, 2008a). Tsunami wave heights were recorded at more than 100 tide gauge stations throughout the Pacific, including ten stations on the B.C. coast (Fig. 12). Two of these ten stations were the recently installed Tsunami Warning station at Henslung Cove, where the maximum wave height was 28.2 cm, and the recently reactivated station at Port Alberni, where the

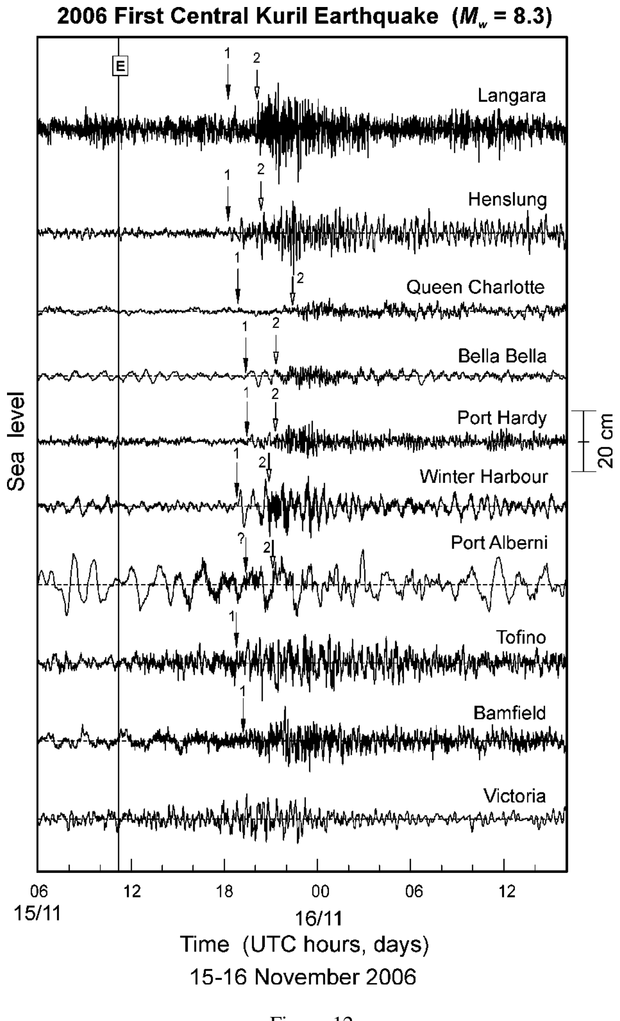

Figure 12
As for Figure 4 but for the Central Kuril Islands tsunami of November 15, 2006.

maximum wave height was 24.5 cm. At eight stations where the first wave arrival was clearly determined, it was positive (a crest). At many of the stations the first train of waves was followed by a second train of high frequency waves approximately two hours later.

The second central Kuril Islands earthquake ($M_w = 8.1$) occurred on January 13, 2007. It produced a tsunami that was observed at 8 locations on the B.C. coast (Fig. 13). The maximum observed wave height was 17.1 cm at Langara Island. At each of the seven stations shown in Fig. 13 plus Langara the first wave arrival was positive (a crest) and at all stations except Victoria the first train of waves was followed by a second train of high frequency waves approximately two hours later. The tsunami was not observed at Port

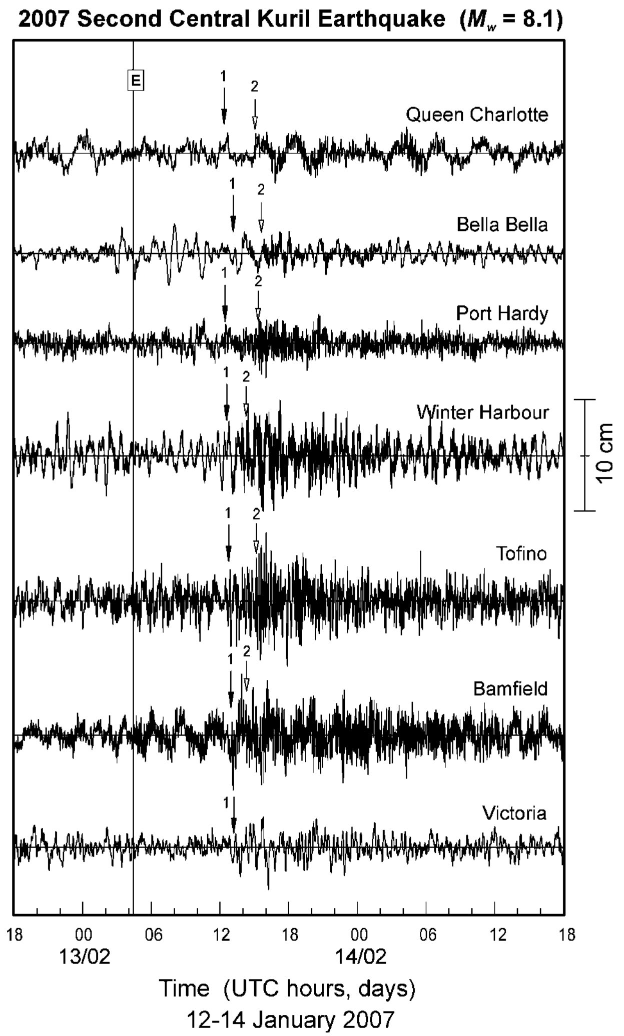

Figure 13
As for Figure 4 but for the Central Kuril Islands tsunami of January 13, 2007.

Alberni, probably because of a strong mismatch between the typical periods of this tsunami in the open ocean (from a few minutes to approximately 20 min, cf. RABINOVICH *et al.*, 2008a) and the eigen periods of Alberni Inlet (about 112 min, cf. FINE *et al.*, 2008).

2.3. 1997–2007: Local and Regional Events

WIGEN (1983) studied tsunamis recorded at Tofino during the period 1906–1980 and identified 43 events. These were all far-field tsunamis, with no local or regional events. Our examination of analogue records for the period 1981–1998 also had not revealed any local tsunami events. However, during the last 10 years, i.e., since the installation of high-quality digital instruments, there have been two local events and one regional event identified in the records.

2001 Queen Charlotte Islands tsunami. An earthquake of magnitude $M_w = 6.1$ occurred on October 12, 2001 on the continental slope of the Queen Charlotte Islands at 52.63° N, 132.20° W (Fig. 1). Shaking was felt all over the Queen Charlotte Islands and on the adjacent mainland. The earthquake epicentre was located just to the east of the major strike-slip Pacific-North American plate boundary known as the Queen Charlotte Transform Fault. A well constrained moment tensor solution based on regional broad-band data from B.C. and Alaska shows that the earthquake had almost pure thrust faulting. Rupture initiated at a depth of about 22 km, typical for many earthquakes in this region, and the center of energy release as determined by the regional moment tensor solution was at a depth of 14 km.

Despite its relatively low magnitude, this underwater earthquake generated a tsunami which was clearly recorded by four tide gauges on the coast of Vancouver Island—Bamfield, Tofino, Winter Harbour, and Port Hardy (RABINOVICH and STEPHENSON, 2004; RABINOVICH *et al.*, 2008b). Maximum wave heights for the four gauge sites were quite consistent, ranging from a minimum of 11.3 cm at Bamfield to a maximum of 22.7 cm at Winter Harbour (Fig. 14). Unfortunately, the Langara tsunami station was not in operation during this event, while at other PWLN stations, including nearby stations Queen Charlotte, Bella Bella, and Prince Rupert (Fig. 1) the tsunami was not detected, apparently because of coastal sheltering and spatial energy decay. The duration of "ringing" at Bamfield, Tofino, Winter Harbour and Port Hardy was relatively short, lasting for only 6–8 hours.

Despite an obvious increase of long-wave energy during the event (Fig. 14), the exact arrival time (and the respective travel time) of the first wave were not clearly delineated in the records. In this case, the tsunami-driven seiches simply augmented the atmospherically generated seiches (eigen oscillations) that were occurring in the corresponding bays, inlets or harbours at the time. This earthquake has some of the characteristics typical of a "tsunami earthquake" (cf., KANAMORI, 1972; ABE, 1979) because the effective source is larger than would be expected from the magnitude of the generating earthquake. It is likely that the rupture extended into the soft sediments of

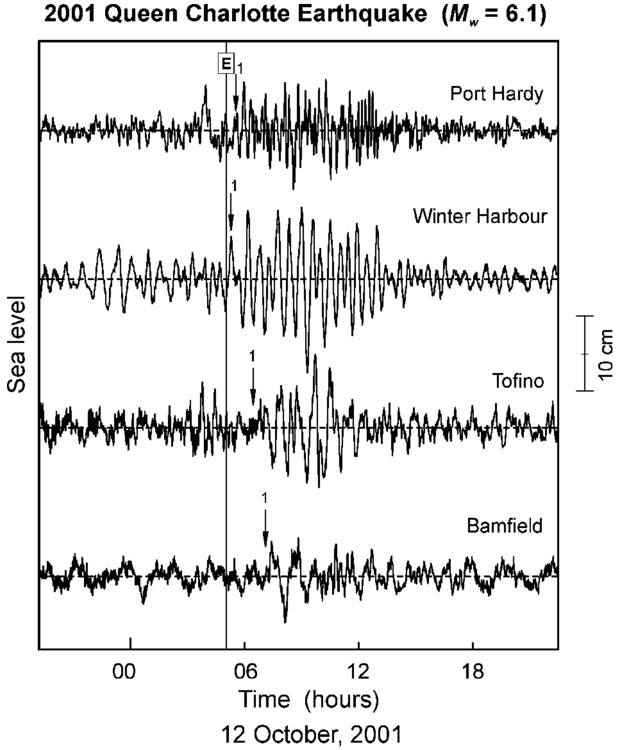

Figure 14
As for Figure 4 but for the Queen Charlotte tsunami of October 12, 2001.

the Queen Charlotte terrace, thus exceeding the effective displacement for a typical earthquake of this size.

2004 Vancouver Island tsunami. An intense swarm of earthquakes occurred about 200 km west of Vancouver Island during the first week of November 2004. Over 700 earthquakes were detected. While swarm activity is not uncommon in the tectonically active, thin oceanic lithosphere west of Vancouver Island, this swarm was unusual because it did not occur along any of the previously recognized offshore fault zones (Rabinovich *et al.*, 2008b). The largest event ($M_w = 6.6$) was on November 2 at 10:02 UTC at an effective depth of 9 km. The earthquake epicentre (49.01°N, 129.18°W) was located within the region of the Explorer Plate about 190 km from Port Hardy and 230 km from Tofino. The earthquake was felt at Alert Bay, Bamfield and Port Alice on Vancouver Island, but there were no reports of damage. Locations and focal mechanisms from regional moment tensor solutions of the larger earthquakes reveal a previously unknown left-lateral strike-slip fault about 80-km long within the Explorer Plate. It trends about 15 degrees counter-clockwise to the very active Nootka Fault Zone. Rupture length of the largest earthquake ($M_w = 6.6$) in the sequence swarm was about 40 km, estimated

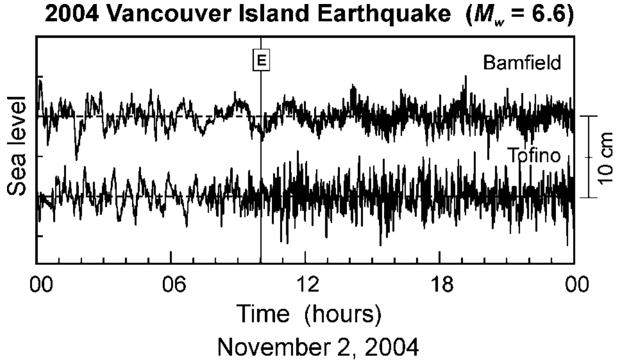

Figure 15
As for Figure 4 but for the Vancouver Island tsunami of November 2, 2004.

from the empirical Green's Function technique using surface waves. While most of the motion was strike-slip, there was a small thrust component with the east side down.

Examination of the digital records for nearby tide gauge stations—Winter Harbour, Port Hardy, Tofino, Bamfield, and Victoria (Fig. 1) reveals that the November 2004 earthquake generated a weak tsunami, which was only measurable at Tofino and Bamfield on the outer southwest coast of Vancouver Island (Fig. 15). The maximum recorded trough-to-crest wave heights of 10.8 cm at Tofino and 7.5 cm at Bamfield, are approximately 35% smaller than for the October 2001 Queen Charlotte Islands tsunami. This suggests that the November 2004 earthquake was a markedly less efficient source mechanism.

The observed tsunami travel times of 52 min and 75 min for Tofino and Bamfield respectively, were in reasonable agreement with the expected tsunami travel times of 58 min and 70 min. The first tsunami semiwave recorded on the coast was negative (wave trough) agreeing with the east side down motion of the fault. This caused a negative wave to travel outward to the southeast and a positive wave to move outward to the northwest.

2005 California tsunami. An $M_w = 7.2$ earthquake occurred on June 15, 2005 seaward of northern California off the west coast of North America. Based on the earthquake location and source parameters the possibility existed for a locally destructive tsunami and a Regional Tsunami Warning was issued. Tsunami waves were recorded at four stations in California and Oregon with the maximum trough-to-crest wave height of 27.7 cm observed at Crescent City, CA. Tsunami waves of 0.5 and 1.5 cm were also recorded by open-ocean DART buoys 46404 and 46405, respectively, closely matching wave heights derived from numerical models (RABINOVICH *et al.*, 2006b). The tsunami signal was clearly detected at Tofino and Bamfield on the coast of Vancouver Island (B.C.) with arrival times in good agreement with estimated arrival times (Fig. 16).

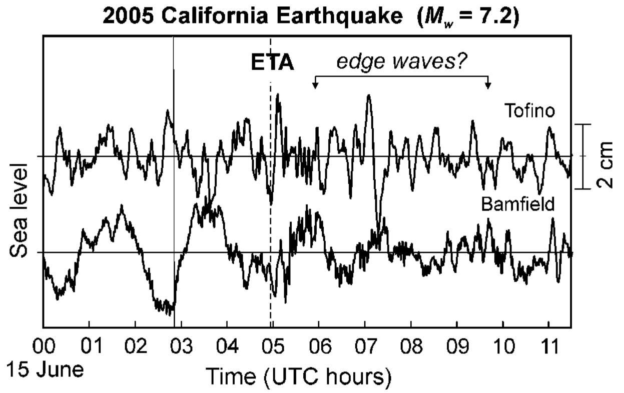

Figure 16
As for Figure 4 but for the California tsunami of June 15, 2005.

At both Tofino and Bamfeld the first observed wave was negative and had respective trough-to-crest heights of 3.3 cm and 1.8 cm.

The first tsunami waves to arrive at Tofino were irregular, but were followed an hour later by a train of regular waves with typical periods of about 22 min. The regular waves persisted for about four hours and had maximum trough-to-crest wave heights of 4.3 cm. It has been speculated (Rabinovich *et al.*, 2006b) that the more regular train of waves was associated with edge waves. Tsunami signals were also identified at Winter Harbour and Port Hardy, but they were less than 1 cm.

2.4. *Events where no Tsunami was Identified*

Table 1 lists 16 tsunami events observed during the study period. There was, however, one significant event that has not been identified in the tide gauge records on the coast of B.C. This was the tsunami associated with the November 17, 2003 ($M_w = 7.8$) Rat Islands earthquake (Aleutian Islands). The earthquake produced a tsunami which was observed at a number of locations along the west coast of North America.

2003 Rat Islands earthquake. The earthquake occurred near Amchitka Island in the Rat Islands (Aleutian Islands, Alaska). The earthquake was the largest to occur in North America since the Denali earthquake ($M_w = 7.9$) of November 3, 2002, and the largest in the region of the Aleutian Islands since the $M_w = 7.9$ earthquake in June 1996. A small tsunami was recorded locally (52 cm at Shemya, 20 cm at Adak) and across the Pacific in Hawaii (65 cm at Kahului and 44 cm at Hilo) and Chile (30 cm at Caldera and 8–10 cm at several other stations). The November 17, 2003 tsunami was observed at several stations in Oregon and California, with maximum wave heights varying between 10 cm and 22 cm. The tsunami was also recorded by deep-ocean DART station D171 ($\sim$7 cm) and this record was successfully used to numerically simulate and predict tsunami waves

Table 2

Maximum wave height (cm) observed at stations on the coast of British Columbia

Year, Event*	Stations							
	Victoria	Bamfield	Tofino	Port Alberni	Winter Harbour	Port Hardy	Bella Bella	Langara/ Henslung
1994	8.7	9.3	6.1	26.2	19.8	x	x	x
1995a	8.2	12.2	3.0	24.9	13.2	7.2	x	x
1995b	6.4	9.7	10.0	37.5	11.1	–	x	x
1996	9.1	13.9	5.0	36.7	15.1	5.2	x	x
2001a	7.4	9.7	15.1	x	12.9	5.4	6.7	9.5
2001b	–	11.3	18.2	x	22.7	14.5	–	x
2003a	–	8.0	10.5	x	8.5	–	–	x
2003b	5.5	5.5	8.0	x	10.0	4.5	–	x
2004a	–	7.5	10.8	x	–	–	–	x
2004b	11.7	4.5	15.4	x	21.0	4.5	9.0	x
2005a	0	2.6	4.3	x	< 1	< 1	–	x
2005b	13.9	14.5	15.5	x	10.7	8.0	7.5	x
2006a	9.0	5.6	6.9	x	10.8	3.7	5.7	x
2006b	17.5	21.4	25.4	24.5	23.9	13.5	8.6	38.5 / 28.2
2007a	7.4	7.3	10.3	x	9.0	5.3	4.5	17.1 / x
2007b	10.2		3.4					

as shown in Table 1 and Fig. 2
"x" indicates the station was not operational, or the record was not checked
"–" indicates the record showed no evidence of a tsunami

on the coasts of the Hawaiian Islands (Titov *et al.*, 2005a). The records from six B.C. stations were analysed, but no signal was identified in any of them (Fig. 17).

In general, our ability to detect tsunami waves in a tide gauge record depends strongly on the signal-to-noise ratio (the ratio between tsunami and background oscillations). Infragravity waves generated by nonlinear interaction of wind waves and tsunami-like, atmospherically-induced seiches create serious problems in identifying weak tsunamis (Rabinovich and Stephenson, 2004; see also Rabinovich *et al.*, 2006a). In fact, one of the main purposes of any preliminary analysis of tide gauge data is to reduce the background noise level and thereby improve the tsunami-to-noise ratio. Once a tide gauge record has been de-tided several criteria are used to identify tsunami waves (see discussion on the 2004 Sumatra tsunami in Section 2.2). However, based on these criteria for the November 17, 2003 event (Fig. 17) we cannot unambiguously detect tsunami waves, either because these waves are too weak or because background oscillations are too strong.

Note that the Rat Islands tsunami should have been recorded at least at Langara, the station located relatively close to the source area. However, the signal at Langara is very noisy and was of no use for this particular event, or for the 2003 Hokkaido tsunami. The observational problems at Langara are discussed in more detail in the next section.

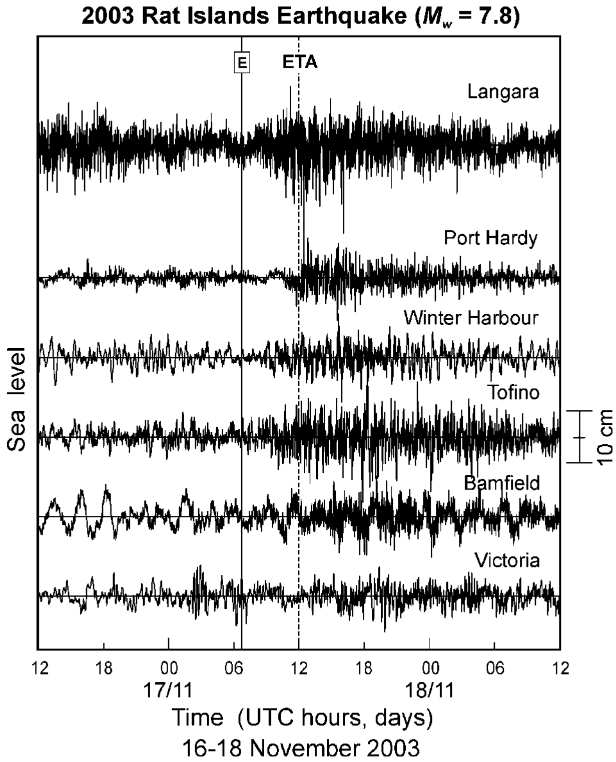

Figure 17
As for Figure 3 but for the Rat Islands earthquake of November 17, 2003.

In addition to this event, there were ten other events where the tidal records were checked for evidence of a tsunami and where no tsunami could be identified in the records. These earthquake events are listed in Table 3.

Table 3

Earthquake events (1994–2007) where no tsunami could be identified in the records of B.C. tide stations

Year	Date	Time (UTC)	M_w	Source area	Where recorded	Type of recording
1996	February 21	12:51	7.5	Northern Peru	Peru, Chile, Mexico, Hawaii	Analogue
1996	June 10	04:04	7.9	Adak, Aleutian Is.	Alaska, Hawaii, US west coast	Analogue
1997	April 21	12:02	7.7	Santa Cruz Is. (Solomon Is.)	Pacific Is., Japan	Analogue
1997	December 5	11:27	7.8	Kamchatka	Russia, Aleutian Is., Hawaii	Analogue
1998	July 17	08:49	7.0	Papua New Guinea	PNG, Japan	Digital
2000	November 16	04:54	8.0	New Ireland, PNG	Solomon Is.	Digital
2001	January 10	16:03	7.1	Kodiak I., Alaska		Digital
2001	February 17	05:02	6.3	Queen Charlotte Is., BC		Digital
2002	March 5	21:16	7.5	Mindanao, Philippines	Philippines	Digital
2002	September 8	18:44	7.6	Papua New Guinea	PNG, Japan	Digital
2003	November 17	06:43	7.8	Rat Islands., Alaska	Chile, Hawaii, US west coast	Digital

2.5. Observational Problems

Previous studies have confirmed that the Langara Point station has a very noisy signal, making detection of small tsunami events very difficult. To improve our tsunami detection capability at that important site (located close to Alaska and the Aleutian Islands, the regions with the highest seismic risk) and to estimate the influence of local topographic factors, a second gauge was installed at Henslung Cove on the south side of Langara Island.

We believe that this intensive high-frequency background noise at Langara (Figs. 9 and 17) is due to the particular location of the respective station on the outer (oceanic) coast of Langara Island where it is exposed to storm waves and swell. The nonlinear interaction of wind waves or swell generates a specific type of long waves known as *infragravity (IG) waves* (cf., BATTJES, 1988). These waves have typical periods of 30 s to 300–600 s and length scales from 100 m to 10 km. The occurrence of relatively high-frequency long waves is highly correlated with the modulation of groups of storm or swell waves. In general, the significant high-frequency background noise is likely related to the IG-waves (a common feature of several US tide gauges, in particular, Shemya (Aleutian Islands), Charleston (Oregon), Arena Cove, Point Reyes, Port San Luis, and Santa Monica (California) (RABINOVICH *et al.*, 2006a)). The tsunami signal at these stations is often buried in high levels of noise associated with IG-waves, creating major difficulties in identifying weak tsunami waves and detecting their exact arrival time at some stations.

In contrast to the Langara Point tide gauge, an instrument installed in Henslung Cove, on the south side of Langara Island (8 km from the old location, see the inset in Fig. 1), was sheltered from storm waves and swell and associated IG-waves. In addition, although both stations use pneumatic bubbler tide gauges equipped with differential pressure transducers, the gauge at Henslung Cove has a gas buffer volume which improves measurement accuracy. Figure 18a shows the de-tided signals from both of these stations for a two-month period in 2004. Three segments of those residual (longwave) plots are shown in greater detail in Figure 18b. These records clearly show that low-frequency oscillations at the two stations almost coincide, but the Langara signal is much noisier due to high-frequency oscillations and suffers from periodic “spikes.”

The Langara Point gauge has no gas buffer volume (reservoir bell). A comparison of the records late on Julian Day 110 shows quite clearly that the Langara Point record most closely matches the Henslung Cove record at the times of the spikes. This is when the orifice point is the actual point of the measurement. Between the spikes wave action is causing gas to escape from the bubbler line faster than it can be replenished and the reference point has moved some distance up the bubbler line.

The Tsunami Warning station for the northern B.C. coast has been moved from Langara Point to a new location at Henslung Cove and in this new location appears to respond well to tsunami events. More time is required to fully assess the response of this station to a number of tsunami scenarios.

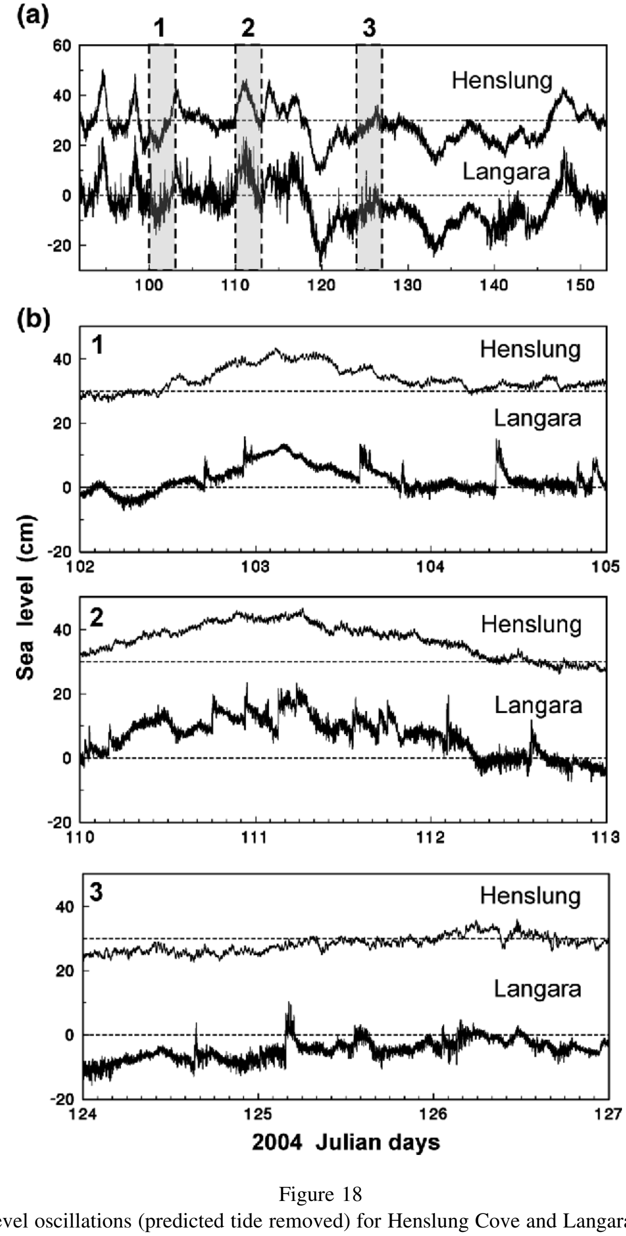

Figure 18
(a) Residual sea-level oscillations (predicted tide removed) for Henslung Cove and Langara Point records for a two month period in 2004 (top panel) and (b) three-zoomed segments (panels 2–4). Each of the high resolution plots covers a period of 3 days.

In section 2.1 it was noted that the maximum wave heights observed at Tofino (1994–1996) were unusually small with irregular oscillations and no clearly defined arrival times. This was almost certainly due to siltation in the horizontal intake pipes. In order for the wells to respond correctly to the incoming signal the horizontal intakes need to be well maintained. This has been the case since new digital instruments were installed in 1998, and these horizontal intake pipes are now checked and cleaned annually. A more detailed review of the residuals (observed heights minus predicted heights) may identify additional periods when the station's response was reduced. It seems very likely that 1994–1996 will be one of those periods and there may be other periods after 1981 when siltation was a problem; e.g., the two Alaska tsunami events studied by GONZÁLEZ *et al.* (1991) may not have been observed at Tofino for this reason.

The largest tsunami ever recorded on the B.C. coast was at Port Alberni on March 28, 1964 (WIGEN and WHITE, 1964; FINE *et al.*, 2008) and that station was in continuous operation from 1970 to 1997, however, lulled by a long period of little tsunami activity and faced with budget restrictions the station was then shut down. It was only as a result of the review of analogue records (1981–1997) that the importance of Port Alberni for tsunami research was again appreciated. The station was reactivated in 2006 and, along with the station at Bamfield, provides important observations for ongoing study and tsunami modelling of Barkley Sound and Alberni Inlet.

The twelve tsunami events recorded on the B.C. coast since 1998, and the analysis of the data collected has clearly shown that a sampling interval of 1 min is appropriate for this region. Changing the data recording to 6-min sample intervals would reduce the data storage and data transmission costs, however, the Nyquist period in that case would become 12 min. The major topographic admittance peaks at most of the stations were determined to be located at periods less than 12 min (cf., RABINOVICH and STEPHENSON, 2004; FINE *et al.*, 2008). Also some of the recent tsunami events (2001 Queen Charlotte; 2004 Vancouver Island; 2005 California; 2006 and 2007 Kuril Islands) had major source energy at relatively high frequencies (cf., RABINOVICH and STEPHENSON, 2004; RABINOVICH *et al.*, 2006b, 2008b). Thus, reducing the sample interval to 6 minutes would deprive us of some important information about long waves in the tsunami frequency band and may create serious aliasing problems (cf., EMERY and THOMSON, 2003). At the same time, there is no apparent reason to reduce the sample interval to 30 or 15 sec; this can be important for investigation of IG-waves, but is not crucial for tsunami waves.

3. Landslide-Generated Tsunami

As mentioned earlier, the coasts and underwater slopes of B.C. contain significant amounts of unstable material, so submarine and subaerial landslides, slumps and rock falls, and associated tsunamis are often the results of earthquakes. Extended periods of heavy rain can also produce conditions that trigger landslides, particularly in coastal areas with very steep slopes. Some landslide generated tsunami events on the B.C. coast have been documented in the scientific literature, e.g., Kitimat (MURTY, 1979) and Knight Inlet (BORNHOLD *et al.*, 2007). These conditions are not limited to tidal waters, as many lakes and rivers in B.C. have similar conditions (steep slopes, unstable material, periods of heavy rain) (cf., EVANS, 2001).

Historical Kwalate landslide-generated tsunami. The Kwalate landside-generated tsunami event is historical and occurred in Knight Inlet roughly 400 years ago. An 840-m high rock avalanche descended into the water of Knight Inlet and produced a tsunami which destroyed the aboriginal community of Kwalate on the opposite side of the inlet (BORNHOLD *et al.*, 2007). This tsunami is thought to have killed 100 or more inhabitants. The initial interest and "awareness" of this tsunami was due to a traditional First Nations oral narrative of the event, and scientific investigation of the village site and the slide site began in 2005. Tsunami height estimates for possible scenarios were subsequently determined and range from 1 m to 6 m. Many parts of the B.C. coast are remote and sparsely populated (e.g., Knight Inlet). These coastal areas are generally susceptible to tsunamis generated by landslides and rock avalanches. As the pace of development increases in these coastal areas the potential for rare but possibly devastating tsunami events need to be considered as part of the planning and development process.

2006 Squamish submarine landslide. Two additional tsunami events have been identified and investigated in the past five years. The first event occurred in 2006 at Squamish, about 40 km north of Point Atkinson (see Fig. 1). Squamish is located at the head of Howe Sound on a low-lying area adjacent to the Squamish River. The site is typical of many inlets on the B.C. coast – a deep water fiord-like inlet with a river at its head where silt carried by the river forms a small shallow delta. At Squamish this shallow delta area is adjacent to a "deep water, break-bulk" terminal and dredging is required to maintain sufficient water depth on the approaches to the terminal berths. Hydrographic surveys are carried out, as required, to monitor changes to the delta. The seaward edge of this growing delta is steep and unstable and therefore susceptible to submarine landslides.

In October 2006 it was noted that one of the navigation buoys marking the approach to the terminal had moved a considerable distance seaward. The buoy was recovered and repositioned. Two multibeam surveys of this area, the first in March 2006 and the second in November 2006, provided a detailed map of the underwater landslide event. The slump occurred on the steep slope of the delta front, an area with initial water depths of 0–50 m. After the landslide, the water depths in this area increased by 10–20 m. The debris field is clearly visible, flowing downslope from the slide site in a southwest direction for a distance of about 1 km and ending at the bottom of the inlet in a water depth of approximately 120 m. This debris field has a height of 5–10 m along its length.

The record of the tide station at Point Atkinson was studied for any evidence of a tsunami, but no definitive tsunami event was identified there or observed at Squamish. The height of the possible tsunami in the area of the slide is unknown, but given that the wharf deck and assembly area of the bulk terminal are less that 2 m above the highest normal tide, and only 1 m above the historical extreme high water as measured at Point Atkinson, a moderate tsunami event, if it occurred during a time of high water, could cause considerable damage. The areas adjacent to the Squamish River and the bulk terminal were surveyed twice more in 2007 to monitor the movement and growth of this area. These surveys indicate that the delta front immediately in front of the river mouth is slowly growing and will at a future date again become unstable.

2007 Chehalis Lake landslide-generated tsunami. Chehalis Lake is a small lake approximately 8-km long and 1-km wide located in the coastal mountains about 80-km east of Vancouver (see Fig. 1). On or about December 4, 2007 a landslide into Chehalis Lake, during a period of heavy rain, produced a tsunami with a maximum wave height in excess of 10 m in the vicinity of the landslide area and of 4–10 m throughout the lake. The volume of the slide has been estimated to be 2 million m^3.

One campground opposite the slide site was completely destroyed and two other campgrounds on the lake were severely damaged by the tsunami. Fortunately, there was no one using any of the campgrounds at the time. Had this landslide been triggered by an earthquake, during the summer months when the campgrounds were full, there could have been considerable loss of life. In addition, the shore of the lake was scoured of all vegetation and a large pile of floating log debris, covering approximately 13 hectares, was deposited at the outlet to the lake about 7 km from the site of the landslide. This large pile of debris poses a risk to the environment of the river (fish habitat) and to the properties and infrastructure located downstream.

4. *Meteorological Tsunami Events*

The earlier study of tsunamis at Tofino (WIGEN, 1983) identified no meteorological tsunami events, and no such events had been identified in B.C. prior to December 2005. The trigger for the 2005 meteorological tsunami event was alarm software incorporated into each of the three B.C. Tsunami Warning stations (Tofino, Winter Harbour and Langara, see Fig. 1). On this occasion it was the Tsunami Warning station at Tofino that detected an abnormal variation in sea level and issued an alarm message. Without this feature this event would likely have been overlooked, as stations on the B.C. coast routinely have seiches superimposed on the tidal signal. This feature did not exist for the many years when water levels were recorded using analogue recorders. It could be that meteorological tsunamis are a fairly common event on the B.C. coast.

Meteorological tsunami of December 9, 2005. Unusual sea-level measurements took place on December 9, 2005 along the entire coast of B.C. from Prince Rupert to Victoria, a distance of approximately 1000 km. These unusual sea-level variations were also observed at eight stations in Washington State. No seismic events had occurred that could generate a noticeable tsunami, and therefore the waves are ascribed to be of meteorological or atmospheric origin, and most probably a manifestation of high-frequency irregularities in atmospheric pressure as the weather was calm that day.

Examination of the sea-level records showed that stations on both the open ocean and in the sheltered straits recorded noticeable tsunami-like oscillations. Tofino, Bamfield, and Winter Harbour in B.C., and Neah Bay and Toke Point in Washington are all located along the ocean coast and are relatively open to waves arriving from the open ocean. On the other hand, Patricia Bay, Vancouver and Point Atkinson in B.C., and Port Angeles, Port Townsend, Friday Harbor, Cherry Point, Seattle and Tacoma in Washington are located in areas more protected from tsunami coming from the open ocean. The wave oscillations continued for approximately 9–12 hours and had mainly irregular (polychromatic) characteristics with dominant periods of 10 to 60 min. A very clear time shift between oscillations observed at various sites suggests that the disturbance propagated from north to south (Fig. 19).

The generation mechanism of such waves is thought to be related to Proudman resonance resulting from a rapidly propagating low-pressure system (RABINOVICH, 2008). MONSERRAT *et al.* (2006) proposed that the international community considers adopting a general term independent of geographic location to describe such oscillations. The term “meteorological tsunami” seems to be the best. It is important to distinguish very clearly the difference between “meteorological tsunamis” and storm surges, since the latter have periods from several hours to several days, while the former have the same periods as ordinary tsunami waves (from a few minutes to a few hours). Tsunami catalogues often contain a number of events described as “probably of meteorological origin.”

Meteorological tsunami of July 13, 2007. A second meteorological tsunami event occurred on the morning of July 13, 2007. It was first noticed in the record of the Patricia Bay station during the daily quality control check of that station’s data. Later in the day a call was received from a resident of Thetis Island, located about 37 kilometres north of Patricia Bay, asking if a tsunami had occurred that morning at about 5:15 PDT (12:15 UTC). Anomalous oscillations are clearly seen in the observed water level records for Patricia Bay and Victoria, and are also identifiable in the record for Tofino (Fig. 20). There was no earthquake at that time that could have directly or indirectly produced a tsunami.

During the final preparation of this paper another meteorological tsunami occurred in the region on February 25, 2008. This event is similar to the event of December 9, 2005; significant tsunami-like oscillations of non-seismic nature were observed at several stations of British Columbia and Washington. Atmospheric pressure records found for the period of this event indicate that these oscillations were induced by a sharp pressure jump of $\sim$1 hPa.

In general, it appears that meteorological tsunamis are quite common in this region. Their examination is crucial because of two important reasons: (1) The necessity to distinguish meteorological tsunamis from ordinary tsunamis, to reduce the number of false alarms and to improve the Tsunami Warning System; (2) to avoid possible risk associated directly with meteorological tsunamis: for example a recent destructive meteorological tsunami on June 25, 2006 produced 30 million euros of damage on Menorca Island, Western Mediterranean (MONSERRAT *et al.*, 2006; RABINOVICH, 2008).

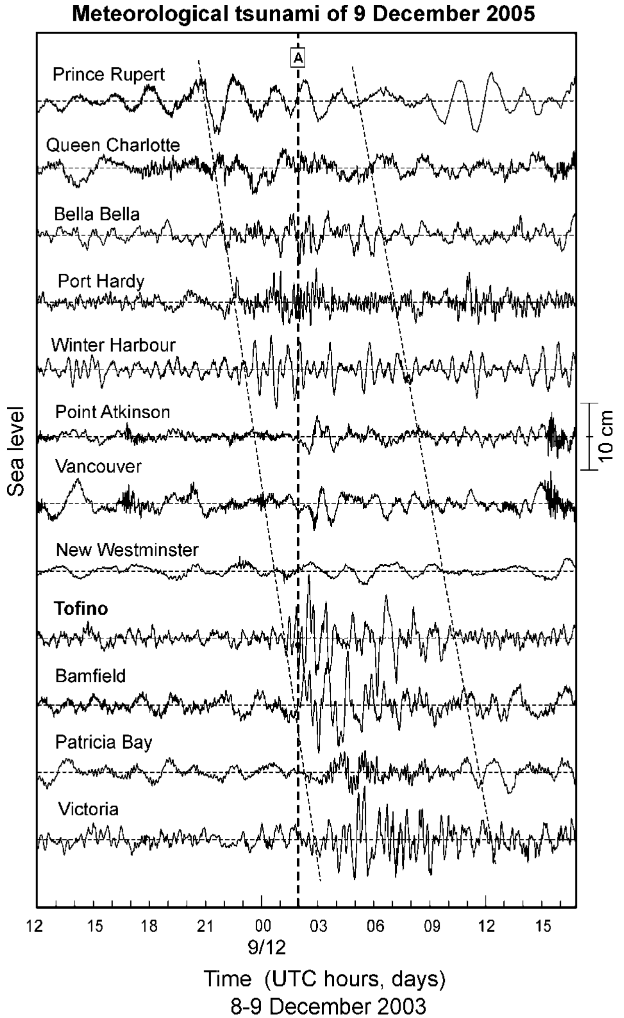

Figure 19
The meteorological tsunami of December 9, 2005 recorded at the B.C. PWLN and Tsunami Warning stations. The non-tidal signal triggered the automatic tsunami alarm of the Tofino tide gauge. The dashed line with the label "A" marks the time of that automatic alarm. The station plots are ordered by latitude (from north to south.).

5. Discussions and Conclusions

Sixteen tsunamis have been measured at locations on the British Columbia coast over the past 15 years. None of these tsunamis were destructive or placed coastal communities at risk, however, these events have provided valuable information on the character of tsunamis at a number of coastal locations and also the performance of our instrumentation

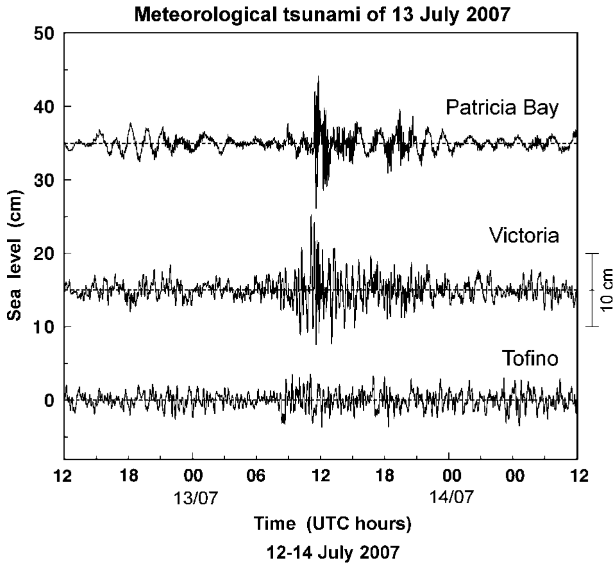

Figure 20
The meteorological tsunami of July 13, 2007 observed at 3 tide gauges on the B.C. coast.

at some of the stations. This information has resulted in modifications to our coastal network and to the measuring systems at some of those locations.

These data have verified that the Tsunami Warning stations at Tofino and Winter Harbour on the west coast of Vancouver Island and the PWLN station at Bamfield are reliable indicators of tsunamis from both regional and far-field events. Most tsunami events are also recorded at Victoria and Port Hardy, however, at each of these stations the signal is smaller and/or not as timely due to the location of the station. The station at Port Alberni, which had been shut down for almost 10 years, has now been reactivated and will be an excellent station for detecting and measuring future tsunamis.

The Tsunami Warning station at Langara Point has been moved to a new location at Henslung Cove and in this new location appears to respond well to tsunami events. More time is required to fully assess the response of this station to a number of tsunami scenarios.

The Tofino station operates well if properly maintained. Insufficient maintenance has affected the quality of the station record in the past and this may be the case during the period 1994–1996 when four tsunami events were recorded. More investigation will be required to determine if this is in fact the case and to determine if any other tsunami events are likely to have been under measured.

The detection and measurement of tsunamis on the B.C. coast is challenging because the range of tide is large and at many locations in harbours or inlets seiching is a common phenomenon. The modern instrumentation, with higher sample rates and better resolution, and the data analysis tools have significantly improved our ability to detect and analyse tsunami events. The automated detection algorithm on the Tsunami Warning station gauge at Tofino alerted us to the meteorological tsunami event on December 9, 2005 and should be effective for other meteorological or landslide-generated tsunami. Consideration should be given to incorporating this algorithm into the software of all stations in the B.C. network. Incorporating microbarometers into some of the Tsunami Warning and PWLN stations would also increase our ability to detect and analyse meteorological tsunami events.

The NEPTUNE cable-linked seafloor observatory is presently being installed off the B.C. coast. While not specifically designed as a tsunami warning system, the NEPTUNE tsunami array will contribute substantially to our understanding of tsunamis and their propagation off western North America.

In addition to the residual plots (tidal signal removed) included in this paper, frequency-time plots and plots showing the spectra of background and tsunami oscillations at the tide gauge locations have also been extremely valuable tools for understanding these tsunami events. Space precludes including some of this material in the paper, however, examples are available in other publications (e.g., Rabinovich *et al.*, 2006a, 2006b, 2008b).

The new tide gauge hardware has been in operation since early 1999. During this period the data return has been in excess of 99.6% from the network. The present network is reliable, and the data it provides are accurate and timely. It is important to note that most of the tsunamis recorded on the B.C. coast have trough-to-crest heights less than 20 cm, and over the last 37 years none have had heights greater than 40 cm. When a potentially tsunamigenic earthquake occurs, the West Coast and Alaska Tsunami Warning Center (WC/ATWC) provides information on the location and magnitude of the event, as well as expected tsunami arrival times at various locations around the Pacific Coast. Soon after the predicted tsunami arrival time at a coastal location emergency response personnel expect to begin receiving information on the observed tsunami. Response staff must be able to quickly and accurately estimate the wave heights of arriving waves, determine if the measured signals are tsunami or merely atmospherically generated seiches, and assess the danger of the arriving waves for the coastal communities. That information must then be passed to the WC/ATWC and to local emergency response personnel.

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