NATIONAL REPORT – ICG/PTWS-XXX
Submitted by CANADA

BASIC INFORMATION

1. ICG/PTWS Tsunami National Contact:

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2. Primary Warning Recipient:

(Person, Agency or Organization with primary responsibility receiving and acting upon messages issued by PTWC)

Name: Ministry of Emergency Management and Climate Readiness (EMCR), British Columbia.
Responsible Organization: Ministry of Emergency Management and Climate Readiness.
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3. Tsunami Advisor(s). (Person, Committee or Agency managing Tsunami mitigation)

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Responsible Organization: Ministry of Emergency Management and Climate Readiness
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4. Local Tsunami Procedures. (If a local tsunami exists)

The United States' National Tsunami Warning Centre (NTWC) provides tsunami monitoring, assessment, and alerting for Canada's ocean coasts. Federal, provincial, and municipal organizations, however, are responsible for tsunami emergency management in Canada. The Province of British Columbia maintains tsunami alert procedures for Canada's Pacific Coast in the Tsunami Notification Process Plan (2023 Edition) available on the web: https://www2.gov.bc.ca/gov/content/safety/emergency-management/preparedbc.

The NTWC continuously monitors seismic data provided in near real-time by Natural Resources Canada's (NRCan) Canadian Hazards Information Service (Hazards Service) and other organizations operating seismograph networks.

NRCan streams data from select Canadian National Seismograph Network (CNSN) stations directly to NTWC by radio, satellite, cellular, and landline telecommunications.

If NTWC automated systems and human analysts determine an offshore or near-ocean earthquake is large enough and shallow enough to disturb the ocean floor, NTWC issues Tsunami Warnings, Advisories, or Watches. Tsunami Information Statements are issued for locations where there is an earthquake or tsunami of interest but no threat to coastal residents.

Environment and Climate Change Canada's (ECCC) Pacific Storm Prediction Centre (PSPC) receives, re-formats, and redistributes NTWC tsunami messages to Canadian federal and provincial agencies with tsunami emergency responsibilities. The PSPC delivers the alerts through the ECCC alert dissemination system, such as the weather office website and

WeatherCan app (which also includes other alerts types, for example, rainfall or storm surge). EMCR rebroadcasts NTWC and ECCC messages and issues British Columbia-specific tsunami messages through the Provincial Emergency Notification System.

EMCR is responsible for acting upon the above information in accordance with the British Columbia Tsunami Notification

Process Plan and will be in contact with one of two NRCan Seismologists On Call and the Tsunami Duty Officer of the Canadian Hydrographic Service of the Ministry of Fisheries and Oceans (DFO). EMCR, NRCan, DFO, and ECCC on-call subject matter experts may attend NTWC tsunami threat conferences and provide scientific and technical advice to provinces and territories and to Public Safety Canada (PS) or its Government Operations Centre (GOC). Canadian Coast Guard (CCG) will issue radio navigation warnings to advise vessels at sea.

After the initial tsunami messages, NTWC issues additional messages based on their continued analyses of seismic data and analyses of information from sea-level sensor networks, other tsunami warning centers, coastal observations, and scenario models. The NTWC continuously monitors sea-level data provided in near real-time by Fisheries and Oceans

Canada's (DFO) Canadian Hydrographic Service (CHS) and other water-level network operators. DFO streams sea-level data to NTWC from coastal tide gauges by radio, satellite, cellular, and landline telecommunications.

DART (Deep-ocean Assessment and Reporting of Tsunamis) buoys monitored and installed by NOAA and tide gauges are generally too close to shore to provide early warning to nearby coasts. However, the relative wave amplitude measurements can be used in combination with wave propagation modelling to estimate wave heights at other sites. The West Coast of Canada does not have DART buoy coverage and therefore a subduction earthquake off the coast that generates a tsunami would not be detected by this system by the time the initial waves reach the Canadian Coast.

5. Distant Tsunami Procedures. (When a distant tsunami hazard exists)

Tsunamigenic events from distant source areas are identified by the NTWC and this information (Tsunami Warning, Tsunami Advisory, Tsunami Watch, Information Statement) is transmitted via the NOAA Weather Wire system to Canada.

The Pacific Storm Prediction Centre (PSPC) in Vancouver of Meteorological Service of Canada (MSC), ECCC issues Tsunami Alerts (Warning, Advisory or Watch) which are created directly from these NTWC tsunami alerts or as directed by EMCR. The PSPC delivers the alerts through the ECCC alert dissemination system, such as the weather office website and WeatherCan app (which also includes other alerts types, for example, rainfall or storm surge).

EMCR also disseminates these tsunami alerts and issues British Columbia-specific tsunami alerts through the Provincial Emergency Notification System and coordination procedures are outlined in the British Columbia Tsunami

Notification Process Plan. NRCan and DFO provide observational data and advice to EMCR to support EMCR's decision making.

After the initial tsunami messages, NTWC issues additional messages based on their continued analyses of seismic data and analyses of information from sea-level sensor networks, other tsunami warning centers, coastal observations, and scenario models. The NTWC continuously monitors sea-level data provided in near real-time by Fisheries and Oceans Canada's (DFO) Canadian Hydrographic Service (CHS) and other water-level network operators. DFO streams sea-level data to NTWC from coastal tide gauges by radio, satellite, cellular, and landline telecommunications.

DART (Deep-ocean Assessment and Reporting of Tsunamis) buoys monitored and installed by NOAA and tide gauges are generally too close to shore to provide early warning to nearby coasts. However, the relative wave amplitude measurements can be used in combination with wave propagation modelling to estimate wave heights at other sites. The West Coast of Canada does not have DART buoy coverage and therefore a subduction earthquake off the coast that generates a tsunami would not be detected by this system by the time the initial waves reach the Canadian Coast.

A final tsunami bulletin is issued when it has been determined that the threat has ended. The circumstances may be such that a wave exists but has been observed to be too small to be damaging, or that previous bulletins were based on erroneous information (i.e., no tsunami waves exist.)

6.1. Canada's National Sea Level Network - Permanent Water Level Network (PWLN) and Tsunami Warning System (TWS)

The Department of Fisheries and Oceans (DFO)'s Canadian Hydrographic Service (CHS) collects, generates and disseminates water level and current data (observations, predictions and forecasts). These data are broadly used to support safe and accessible waterways for navigation, particularly for critical areas such as harbours, dredged areas and shipping routes; to support ocean monitoring, prediction and forecasting programs and services; for scientific research; to support international Tsunami and Storm Surge Warning systems operated by Emergency Management Organizations (EMOs) and to support other usages. The delivery of water levels to users remains a very important responsibility for DFO. Information provided to stakeholders must be accurate, comprehensive and delivered in a timely manner.

Water level observations are collected through a national network of 135 water level and current monitoring gauges which includes the Permanent Water Level Network (PWLN) and the Tsunami Warning System (TWS), as well as seasonal and temporary gauges (Figure 1). Data from these gauges are automatically uploaded to the Integrated Water Level System (IWLS) national database and are made available through a range of data services to EMOs, navigational services, the marine industry, the scientific community and the public. The data are also used by the CHS and international hydrographic organizations to maintain and create both Canadian and international navigational products

The management of this data is the joint responsibility of a Tides, Current and Water Level (TCWL) working group

consisting of the regional experts responsible for the program and the Ocean Science Branch (OSB) in Ottawa. OSB's mandate is to manage and archive ocean data collected by DFO, or acquired through national and international programs
conducted in ocean areas adjacent to Canada. In addition, OSB disseminates data, data products, and services to the marine
community in accordance with the policies of the Department, including provision of the official daily means and hourly
heights to Environment and Climate Change Canada (ECCC), U.S. Army Corps of Engineers (USACE) and the International Lake Ontario –St. Lawrence River Board (ILO-SLRB).

In the Pacific Region CHS operates a network of 42 real-time water level and 6 real-time current stations along the British Columbia Coast. Seventeen of these stations serve the Permanent Water Level Network (PWLN) and Tsunami Warning System (TWS).

All stations utilize a combination of Sutron data loggers coupled to multiple types of sensors which include dual encoder/float/dry counterweight systems, radars, bubbler sensors and HADCP's. Sixteen of the stations have dual data loggers for redundancy.

One-second water levels are collected and averaged to provide 1-minute data. At all PWLN and TWS stations data loggers, sensors and ancillary equipment are backed up with dual batteries. The tide gauge clocks are automatically GPS time synced daily and data downloads are quality controlled automatically. All acquired data are further processed (monthly and yearly) to compensate for hardware and site-specific limitations.

Eleven of the Pacific Coast stations also have stations also have GOES satellite transmission to NOAA's Wallups Island download site for access by the National Tsunami Warning Center (Palmer, Alaska). The GOES data, for redundancy purposes, can be downloaded from multiple websites (NOAA, USGS, Sutron) using custom CHS software, enabling access to the data from anywhere there is internet connection. The GOES data are also ingested into the Integrated Water Level System (IWLS) database as a backup to IP or landline interruption.

Ten of the stations - Henslung Cove, Prince Rupert, Winter Harbour, Tofino, Port Alberni, Seal Cove, Port Hardy, Nanaimo, Daajing Giids (Queen Charlotte City) and Patricia Bay, also have barometric pressure sensors providing 1-minute data. Data from these sensors have been valuable in detecting air pressure related 'meteotsunami' events.

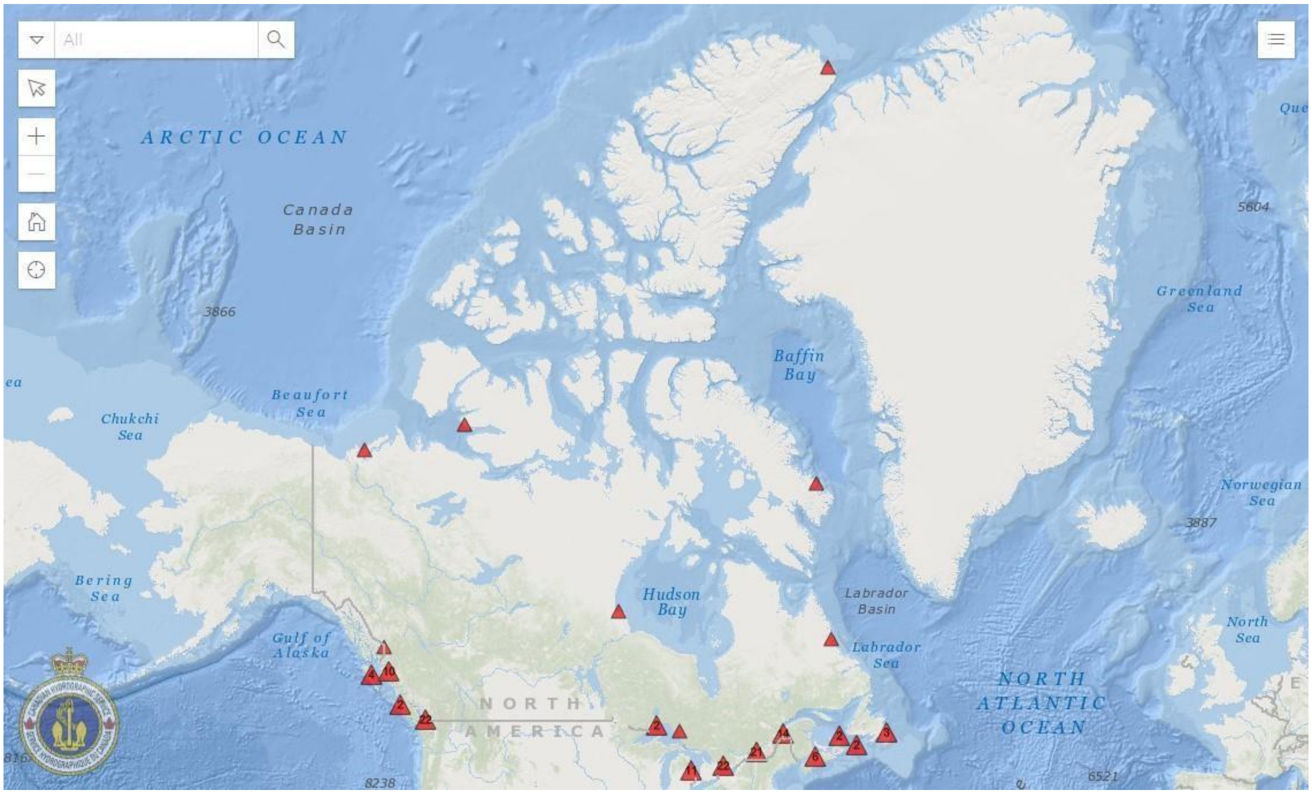

Figure 1. Canada's National Sea Level Network

6.2. Natural Resources Canada - Canadian National Seismograph Network (CNSN)
NRCan's Canadian Hazards Information Service operates the CNSN, a Canada-wide network of over 100 high-gain seismographs and 60 low gain accelerographs (Figure 2). The seismographs provide greater detail of weaker ground motions from lower-magnitude or distant earthquakes. The accelerographs provide greater detail of stronger ground motions from higher-magnitude or nearby earthquakes.

The CNSN streams data in near real-time to parallel and geographically redundant data centres for automated earthquake analyses and rapid notification. Two Seismologists On Call are available 24 hours per day seven days per week to prepare earthquake reports that quickly follow the automated preliminary earthquake notifications. NRCan also streams data from select CNSN stations to NTWC for inclusion in North American tsunami monitoring, assessment, and alerting.

NRCan's Earthquake Early Warning System will be operational in 2024 with hundreds of additional seismic sensors and alerting protocols in British Columbia providing seconds to tens of seconds of early warning of imminent dangerous shaking. NRCan will use the nearly operational system to integrate Global Navigation Satellite System (GNSS) geodetic data with earthquake and tsunami alert.

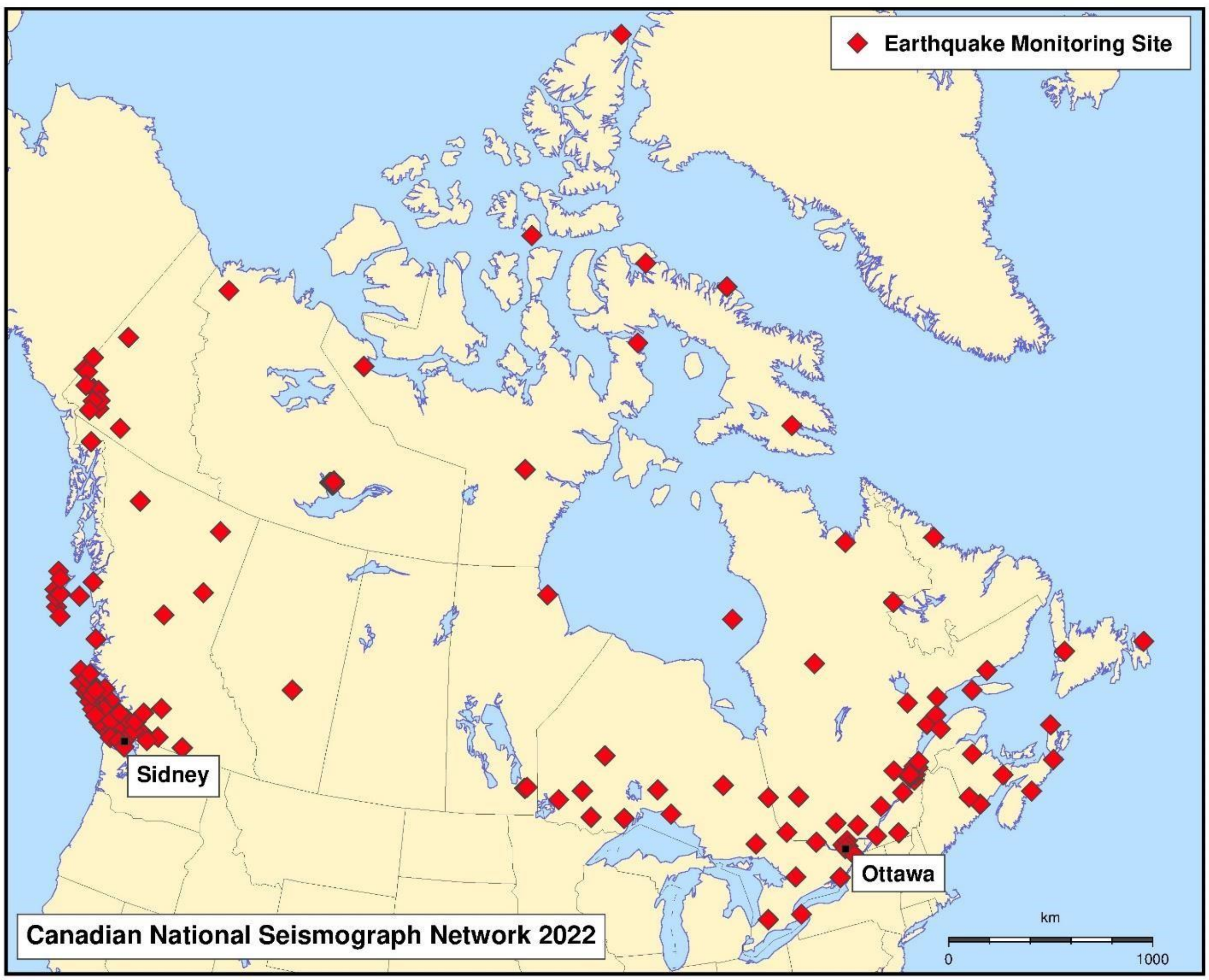

Figure 2. Canadian National Seismograph Network (CNSN)

7. Information on Tsunami occurrences:

There were no noticeable tsunami events in 2019, but there were nine (!) events in 2020-2022 (Table 1, Figure 4), including the volcanic Tonga-Hunga mega tsunami of 15 January 2022. Five more tsunamis were associated with seismic events, two meteotsunamis and an interesting event when tsunami-like waves were resonantly generated by a large moving ship. We consider these events one-by-one.

Table 1. Summary of BC tsunamis of 2020-2022

Year	Mon	Day	Time (UTC) hh:mm:ss	Source Location	Latitude	Longitude	Depth (km)	Mag (M_w)	*I*	H_{max} at BC, (m)	# OBS in BC	C	Val
2020	03	25	02:49:21	Northern Kuril Islands	48.97 N	157.70 E	58	7.5		0.041	5	**T**	4
2020	07	22	06:12:44	Alaska, Shumagin Is.	55.07 N	158.60 W	28	7.8		0.068	4	**T**	4
2020	10	19	21:54:38	Alaska, Shumagin Is.	54.60 N	159.63 W	28	7.6		0.166	16 + 4 offshore	**T**	4
2021	03	04	19:28:31	Kermadec Is.	29.72 S	177.28 W	29	8.1		0.153	11 + 6 offshore	**T**	4
2021	04	30	16;00-17:00	Fraser River, Richmond	-	-	-	-	-	0.35	3	**S**	4
2021	07	29	06:15.49	Alaska Peninsula	55.36 N	157.89 W	35	8.2		0.534	16 + 8 offshore	**T**	4
2022	01	15	04:14:45	Tonga	20.55 S	175.39 W	0	5.8		0.564	32 + 3 offshore	**V**	4
2022	01	21	~07:00	Canada, BC, North Coast	–	–	–	–	–	0.297	16	**M**	4
2022	02	19	~16:00	Canada, BC, Vancouver I.	–	–	–	–	–	0.540	14	**M**	4

Column **"C":** Various types of generated tsunamis: "T" → seismic; "V" → volcanic; ""M" → meteorological; "S" → ship-generated.

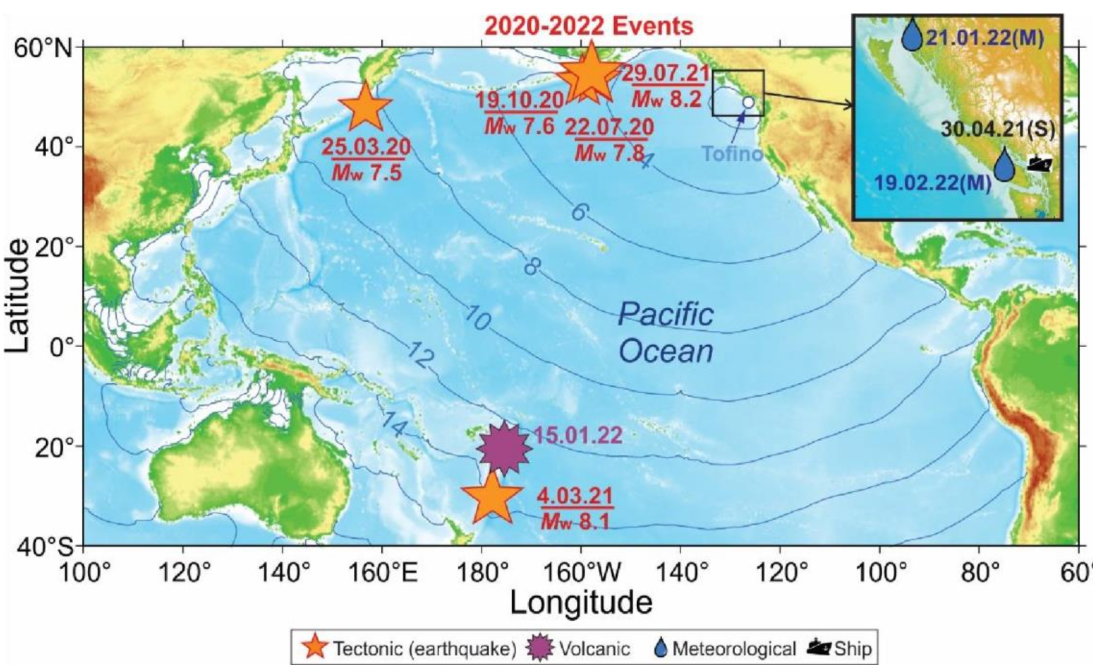

Figure 4. Sources of tsunamis observed on the coast of British Columbia during the 2019-2022 intersessional period.

8. Tsunami measurements

To examine the character of the 2020-2022 tsunami events on the coast of British Columbia we used the Canadian Hydrographic Service (CHS) network of coastal tide gauges and other sources from research network when available. The primary stations used in our analyses are shown in Figure 5; for some events we also used certain additional stations that are described in the subsections related to the respective events.

The preliminary analysis of the records included data verification and correction; then based on tidal harmonic analysis these records were de-tided and the residual time series were additionally high-pass filtered with 3-4-hour Kaiser-Bessel window (depending on the strength of the event).

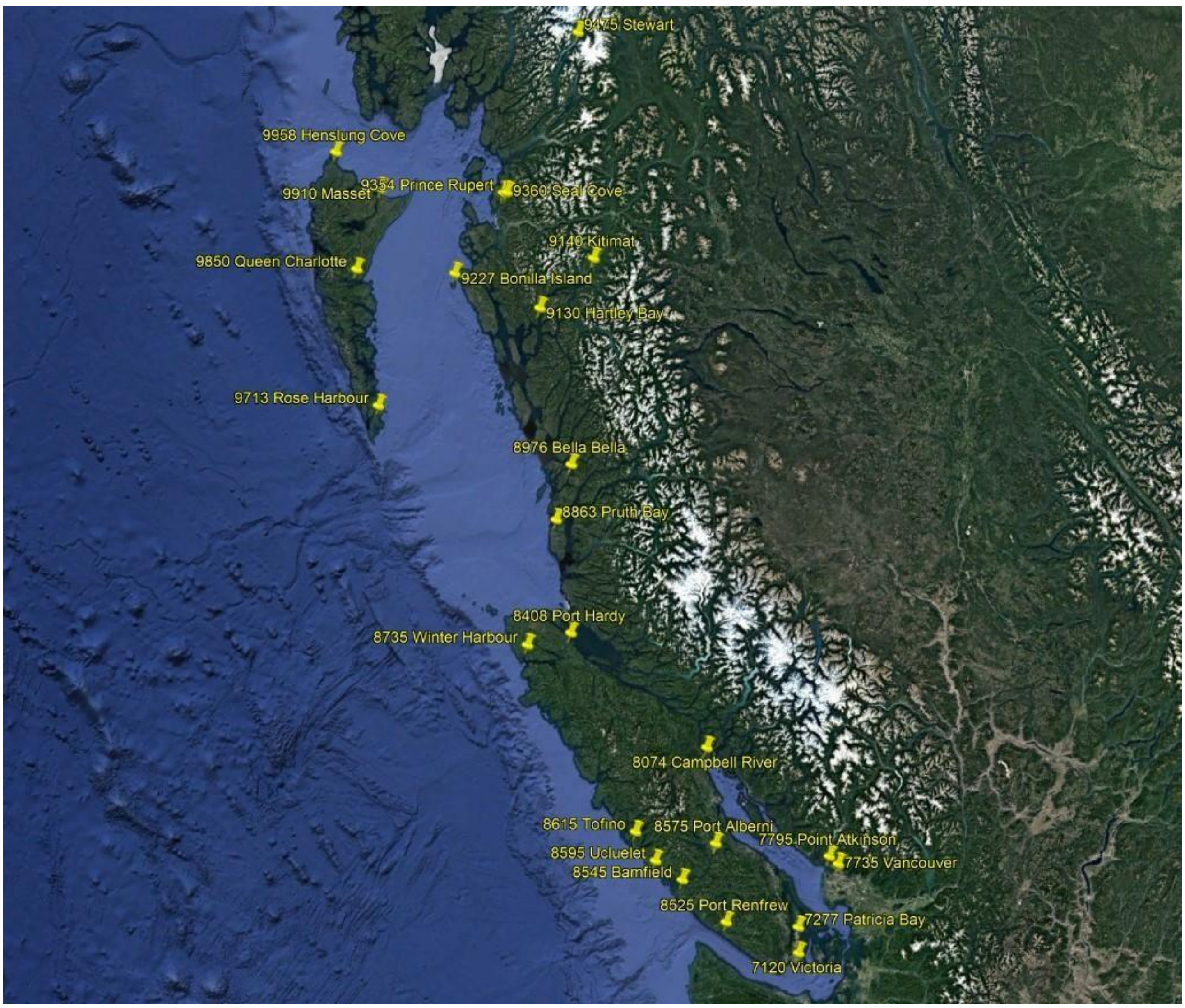

Figure 5. Map of coastal British Columbia showing the location of the Canadian Hydrographic Service Pacific Region coastal tide stations.

8.1. Kuril Islands tsunami of 25 March 2020

The March 2020, Kuril Islands tsunami was generated by a Mw 7.5 earthquake (48.986°N 157.693°E), at 2020-03-25 02:49:21 UTC (according to the USGS). The first and largest peak of the tsunami waveform was detected at DART 21416 located 426 km southeast of the epicenter, approximately 30 minutes after the earthquake with a maximum wave amplitude of just over 3 cm.

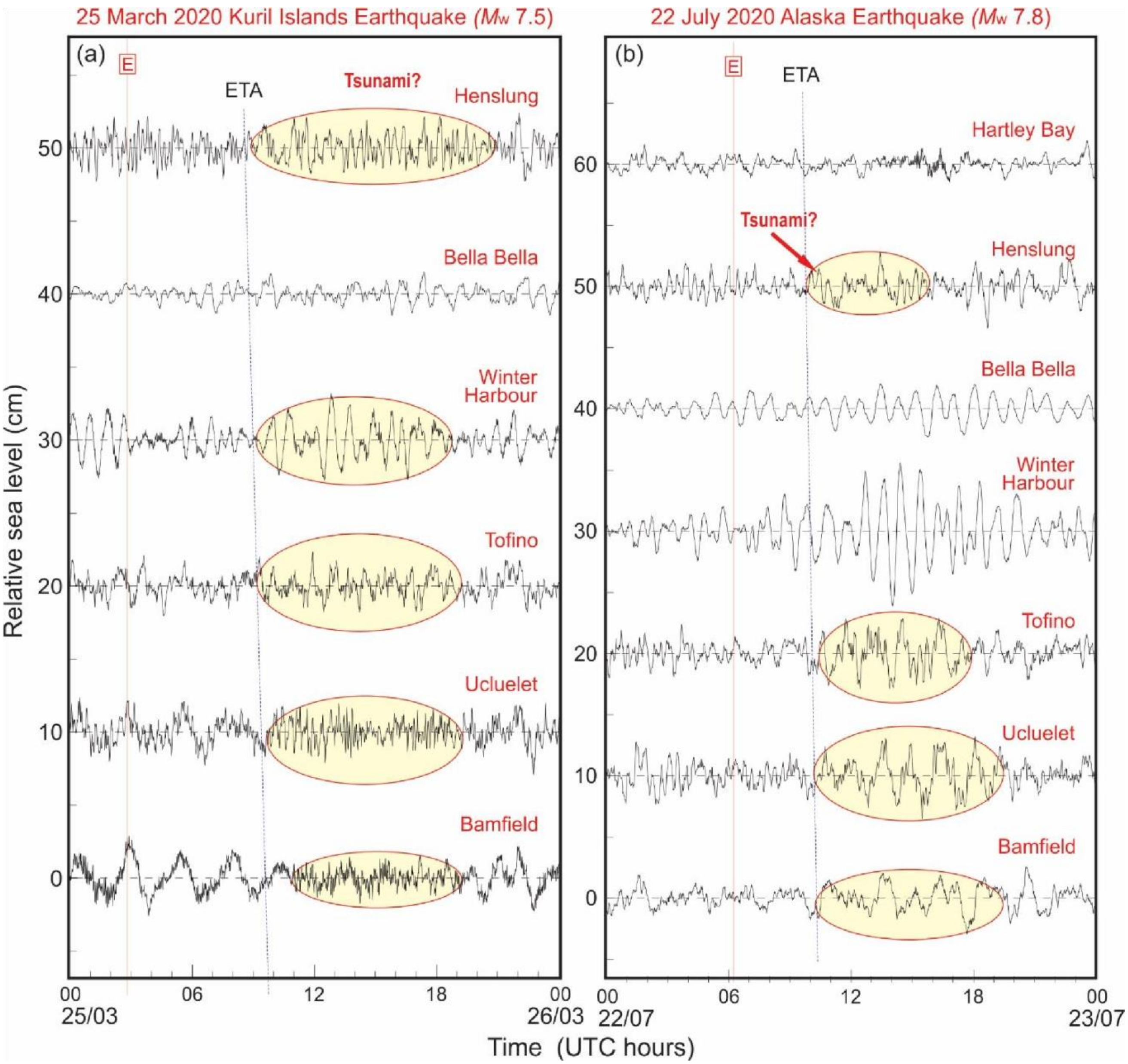

Figure 6. De-tided and high-pass filtered with a 3-hour Kaiser-Bessel (KB) window records at outer coast CHS stations during (a) the Kuril Islands earthquake (M_w = 7.5) of 25 March 2020 and (b) the Alaska earthquake (M_w = 7.8) of 22 July 2020. The solid vertical red lines labelled ‘‘E’’ denote the times of the main shocks of the respective earthquakes, shaded ovals denote identified tsunami waves.

The measured tsunamis on the BC coast were quite weak; nevertheless, we could detect the tsunami signal at six stations (Figure 5a) located at the outer coast. Maximum recorded tsunami amplitudes and trough-to-crest tsunami wave heights are presented in Table 2; the exact station locations are shown in Figure 4. We thoroughly examined the tide gauge record at Bella Bella but could not recognize a tsunami signal at this station.

Table 2. Parameters of the Kuril Islands tsunami of 25 March 2020 (02:49 UTC) and Alaska tsunami 0f 22 July 2020 (02:49 UTC) recorded by CHS tide gauges on the coast of British Columbia

Station	Kuril Islands (M_w 7.5), 25 March 2020		Alaska (M_w 7.8), 22 July 2020	
	Max amplitude (cm)	Max height (cm).	Max amplitude (cm)	Max height (cm).
Hartley Bay	-	-	N/o*	N/o*
Henslung Cove	2.2	3.9	2.8	4.3
Bella Bella	N/o	N/o	N/o	N/o
Winter Harbour	3.2	6.0	N/o	N/o
Tofino	2.3	4.1	2.9	5.8
Ucluelet	2.0	4.1	3.2	6.8
Bamfield	1.4	3.1	2.0	4.9

Comments:

(1) Due to the low signal-to-noise ratios for both events the exact arrival times are undetectable, but in general they are in agreement with the Estimated Time of Arrival (ETA): between 7.0 (Henslung) and 8.5 (Ucluelet) hours for the first event (Figure 3) and 3.5 (Henslung) and 4.5 (Bamfield) hours for the second event.

(2) N/o = Not observed

(3) *No seismic seiches have been observed at Hartley Bay.

8.2. Alaska tsunami of 22 July 2020

The M_w 7.8 earthquake occurred on 22 July 2020 at 06:12:44 UTC, about 60 miles of Perryville on the Alaska Peninsula

(55.068°N 158.554°W). The earthquake generated a relatively small tsunami that arrived approximately 20 minutes later at the closest DART 46403, located approximately 295 km southeast from the epicenter.

A weak tsunami was recorded at four CHS tide gauge stations (Figure 5b, Table 2); no tsunami signal was found at Bella Bella and Winter Harbour. Also, major Alaska earthquakes commonly induce significant seismic seiches at Hartley Bay; however, no seismic seiches were generated this time at that station.

8.3. Alaska tsunami of 19 October 2020

The 19 October 2020, Sand Point, Alaska tsunami was generated by a M_w 7.6 earthquake (54.617°N 159.635°W), at 202010-19 20:54:39 UTC (USGS). The earthquake produced a tsunami that arrived approximately 18 minutes later at the closest DART 46403, located approximately 290 km away from the epicenter. The largest recorded AK coastal tsunami amplitude was ~74 cm at Sand Point; the signal at this station arrived 2 hr 15 min after the earthquake (https://nctr.pmel.noaa.gov/alaska20201019/).

The Alaska (Sand Point) tsunami was clearly recorded at a large number of stations on the coast of British Columbia, including those located deeply in the mainland fjords. Altogether, the tsunami signal was identified at 16 stations (Figure 6). This signal was substantially larger than during two other 2020 tsunamis (Table 2, Figure 5) and this enabled us at almost all stations to estimate main parameters of arriving tsunami waves, including tsunami arrival/travel time, first wave amplitudes and signs, maximum tsunami amplitudes and heights, wave periods (Table 3). The only exception is Bonilla Island located in the northern part of Hecate Strait (see Figure 4): the signal-to-noise (s/n) ratio at this station is too small to evaluate the tsunami parameters.

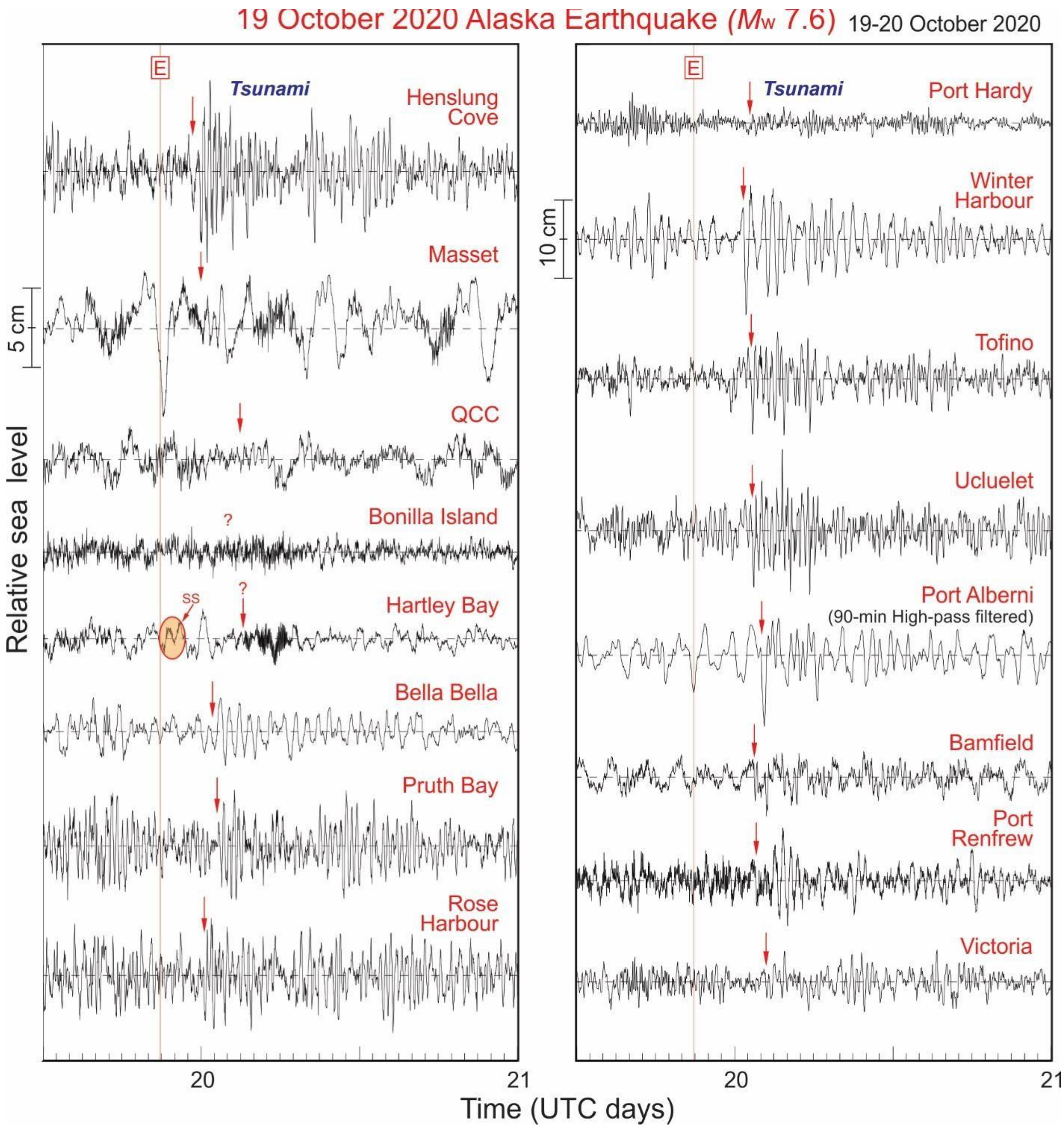

Figure 7. De-tided and high-pass filtered (with a 3-hour KB-window) window records of CHS stations at the BC coast during the Alaska (Sand Point) earthquake (M_w = 7.6) of 19 October 2020. The solid vertical red lines labelled ''E'' denote the times of the main shocks of the respective earthquakes, red arrows indicate the tsunami arrival. Weak seismic seiches ("SS"), denoted by a shaded oval, were generated at Hartley Bay by the earthquake.

Table 3. Parameters of the Alaska tsunami of 19 October 2020 recorded by CHS analogue tide gauges on the coast of British Columbia (Main shock, M_w = 7.6 at 20:55 UTC)

Station	First wave			Max waves			Visible period (min)
	Arrival time (hh:mmUTC)	Travel time	Amplitude (cm) Sign	Max amplitude (cm)	Time (UTC) of max amplitude	Max wave height (cm)	
Henslung Cove	23:13*	2h 18m	-2.5/+1.4	5.8	00:40	11.5	8, 22
Masset	23:52*	2h 57m	-1.4/+1.6	2.3	01:33	5.0	30
QCC	02:57	6h 02m	-0.8/+1.1	1.4	04:58	2.0	7, 12, 27
Bonilla Island	?	?	?	1.2	-	2.1	2, 4, 40
Hartley Bay	03:17?	6h 22m?	-0.3/+0.6?	1.1	06:01	2.2	3.5?
Bella Bella	00:56	4h 01m	-1.2/+2.1	2.1	01:27	4.3	
Pruth Bay	01:14	4h 19m	+1.6/-2.6/+2.8	3.6	02:31	6.9	40-45 21
Rose Harbour	00:10	3h 05m	-2.9/+2.9	3.6	00:45	7.0	25, 90
Port Hardy	01:11	4h 16m	-0.8/+1.1	2.1	03:42	2.7	13
Winter Harbour	00:42	3h 47m	-9.7/+6.9	6.9	01:11	16.6	30, 50
Tofino	01:14	4h 19m	-7.1/+4.3	6.0	03:14	13.3	23, 50
Ucluelet	01:21	4h 26m	-7.3/+4.5	10.4	03:36	15.6	20, 7.5
Port Alberni	01:58	5h 03m	-10.1/+2.5	4.8	03:19	13.6	24, 38
Bamfield	01:27	4h 32m	-3.0/+2.0	3.1	03:35	6.8	22, 17
Port Renfrew	01:34	4h 39m	-3.2/+1.1	6.7	03:39	16.5	30
Victoria	02:19	5h 24m	-2.7/+1.0	3.9	03:46	4.0	23, 50

Comments: *19 October 2020; all other dates are related to 20 October 2020.
The tsunami arrival at Bonilla Island is unclear.

The Alaska tsunami arrived at Henslung Cove (the BC station nearest to the source) 2 hr and 18 after the main shock, while at Victoria it came about 3 hours later (Table 3). The specific feature of this tsunami was the first negative (ebb) wave; the amplitude of this wave at Port Alberni and Winter Harbour was approximately 10 cm. The maximum observed wave height of 15.6-16.6 cm was recorded at Winter Harbour, Ucluelet and Port Renfrew. The wave period is quite different at various stations but at the outer coast of Vancouver Island waves with periods 21-25 min prevailed. Weak seismic seiches were generated by the earthquake at Hartley Bay; they began at this station immediately after the main shock.

8.4. Kermadec tsunami of 4 March 2021

Two earthquakes occurred on 4 March 2021 near the Kermadec Islands, the South Pacific Ocean. The first earthquake with a magnitude M_w 7.4 occurred at 17:41:25 UTC, the second one, M_w 8.1 (the main event), at 19:28:31 UTC. The M_w 8.1 earthquake near the Kermadec Islands resulted from the reverse faulting in the Tonga-Kermadec subduction zone at a depth of ~22 km; this zone extends north-northeast from the North Island of New Zealand for more than 2,500 km, through Tonga to within 100 km of Samoa. The USGS estimated that the rupture zone of this earthquake was 175 km by 75 km in area. The main quake resulted in tsunami warnings being issued around the Pacific Ocean, as far away as Peru, but particularly for the North Island of New Zealand. Actual tsunami heights measured by GeoNet were around 35–40 cm at East Cape (New Zealand) and around 15–20 cm at Great Barrier Island; 64 cm waves were reported at Norfolk Island.

The results of preliminary analysis of observational data throughout the Pacific Ocean and the numerical modelling performed by NOAA/PMEL, Seattle, WA, USA (https://nctr.pmel.noaa.gov/kermadec20210304/) indicate that a weak tsunami propagated across the ocean and reached the west coast of North America, in particular, on the coast of British Columbia. We examined de-tided and high-pass filtered records at eight CHS tide stations of Group 1 located at the outer coast. In all records, except Port Renfrew, the tsunami signal was weak but evident. The Port Renfrew record was very noisy because of strong swell and storm generated IG waves masking the tsunami signal. To suppress these waves in the Port Renfrew record an additional low-pass filter was used with a 6-min KB window. This strongly improved the situation and helped identify the tsunami signal in the corresponding record. Figure 7 shows de-tided and filtered records from all eight stations, the statistical parameters of the recorded tsunami waves are given in Table 4.

This was a minor tsunami; therefore, the observed tsunami waves were only 5-15 cm; however, it is important that these waves could be measured and detected. The actual arrival times were in good agreement with the ETA, which helped identify these waves. Also, the similar wave feature can be seen for the frontal train of waves at various stations (Figure
7). The first tsunami wave reached Henslung Cove at 07:49 UTC on 5 March 2021(12 hours and 20 min after the main (8.1) shock). Approximately 40-50 min later it reached Winter Harbour and Tofino, and then Rose Harbour, Ucluelet, Bamfield and all of the other stations of Group 1 (Table 4). The specific feature of almost all records was a negative (trough) wave that arrived first. The maximum waves of 15.3 and 14.8 cm were recorded at Ucluelet and Tofino, respectively (Table 1). The periods of the observed waves at various stations were significantly different; nevertheless, two periods prevailed: 40 and 20-25 min.

The tsunami records for the four stations of Group 2 (Bonilla Island, Bella Bella, Port Hardy and Port Alberni) were examined in the same way as for Group 1 (Figure 8). The results showed two specific peculiarities related to these records: (1) Significant atmospherically induced seiches (harbour oscillations) at Port Alberni with the fundamental Alberni Inlet period of 100-110 min; after additional 90-min high-pass filtering the tsunami waves became visible. (2) Strong highfrequency oscillations at Bonilla Island on 5 March 2021 in approximately 12 hours earlier than the expected tsunami arrival; it appears that these oscillations were produced by a strong local storm and associated IG-waves.

Tsunami waves were not identified in the Bonilla Island record, but they were detected in the three other records of Group
2 (Figure 8, Table 4). The tsunami waves arrived at Port Hardy at 09:56 UTC on 5 March 2021, 14 hours and 27 min after the main earthquake shock. Ten minutes later they arrived at Port Alberni (10:06 UTC), approximately one hour later than they arrived at Bamfield and Ucluelet. The waves arrived at Bella Bella at 10:10 UTC. Maximum recorded tsunami waves at these three stations were from 5 to 7.5 cm (Table 4).

In addition to coastal tide gauge records of the 2021 Kermadec tsunami, we also examined six bottom pressure records of this event; three of the pressure stations (Endeavour Ridge Main, Endeavour Ridge Mothra and Endeavour Ridge South) created a cluster of the most distant deep stations (2195-2275 m) located within a few kilometers from each other; three other stations, Cascadia Basin NE (2640 m), Clayoquot Slope (1200 m) and Folger Passage (96 m) are located closer to the coast. Figure 9 shows de-tided and high-pass filtered records for the six stations. The records from the five deep stations
(1200 – 2640 m) were alike; the tsunami arrival is evident in all these records, the first (frontal) wave looks the same at all stations. The Folger Passage record was much noisier and the oscillations at this site were much stronger. In general, tsunami waves of a few centimeters were recorded at these six offshore bottom stations (Figure 9); the prevailed periods were 20-25 and 40 min.

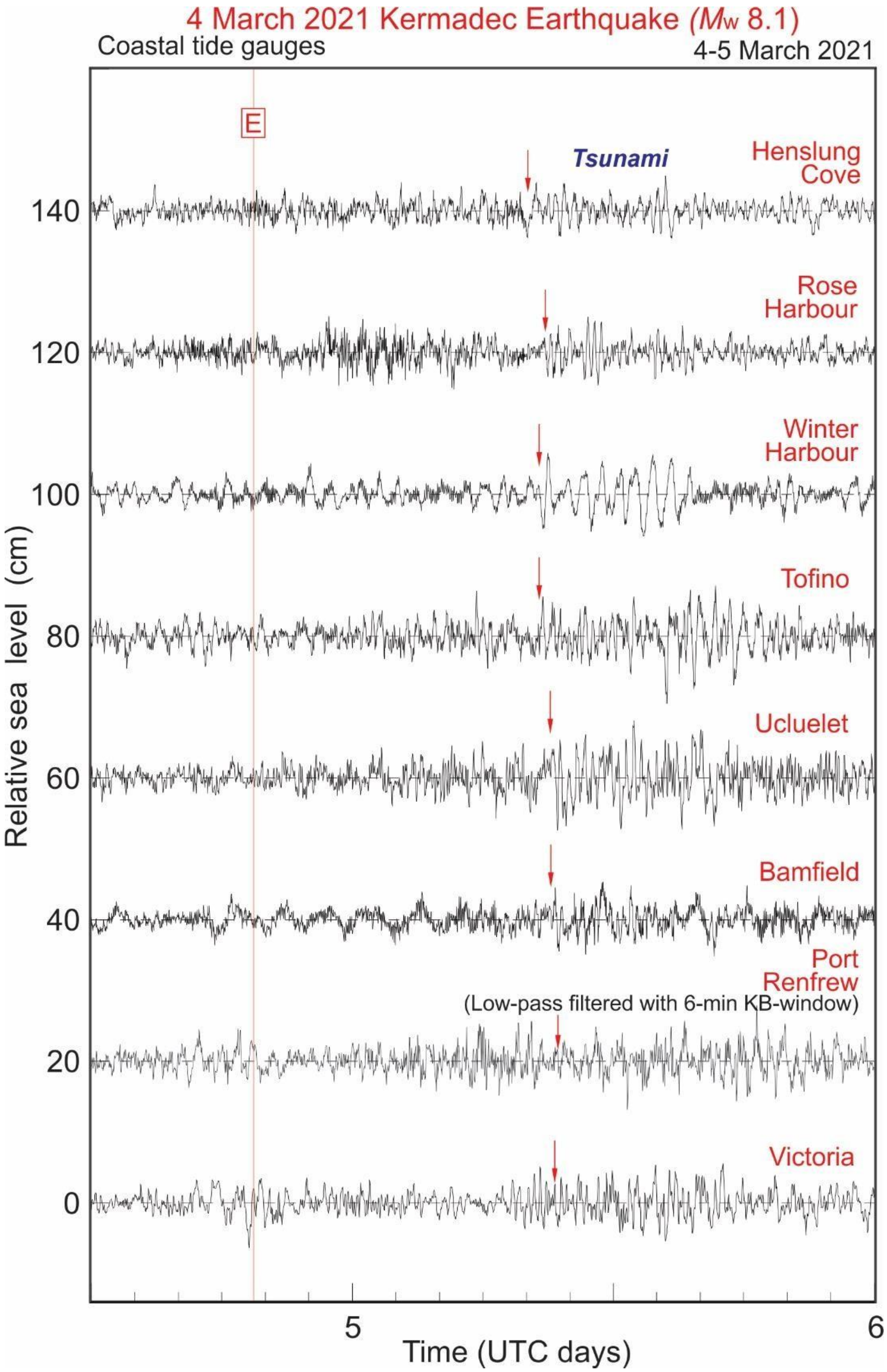

Figure 8. De-tided and high-pass filtered with a 3-hour Kaiser-Bessel (KB) window records at eight stations of Group 1 located on the outer coast of British Columbia for the period of 4-5 March 2021. The record at Port Renfrew was

additionally low-pass filtered with a 6-min KB-window to suppress strong storm wave-induced infragravity (IG) waves.
The solid vertical *red line* labelled ‘‘E’’ denotes the time of the 2021 Kermadec earthquake (main 8.1 shock); the *red arrows* indicate the tsunami arrival.

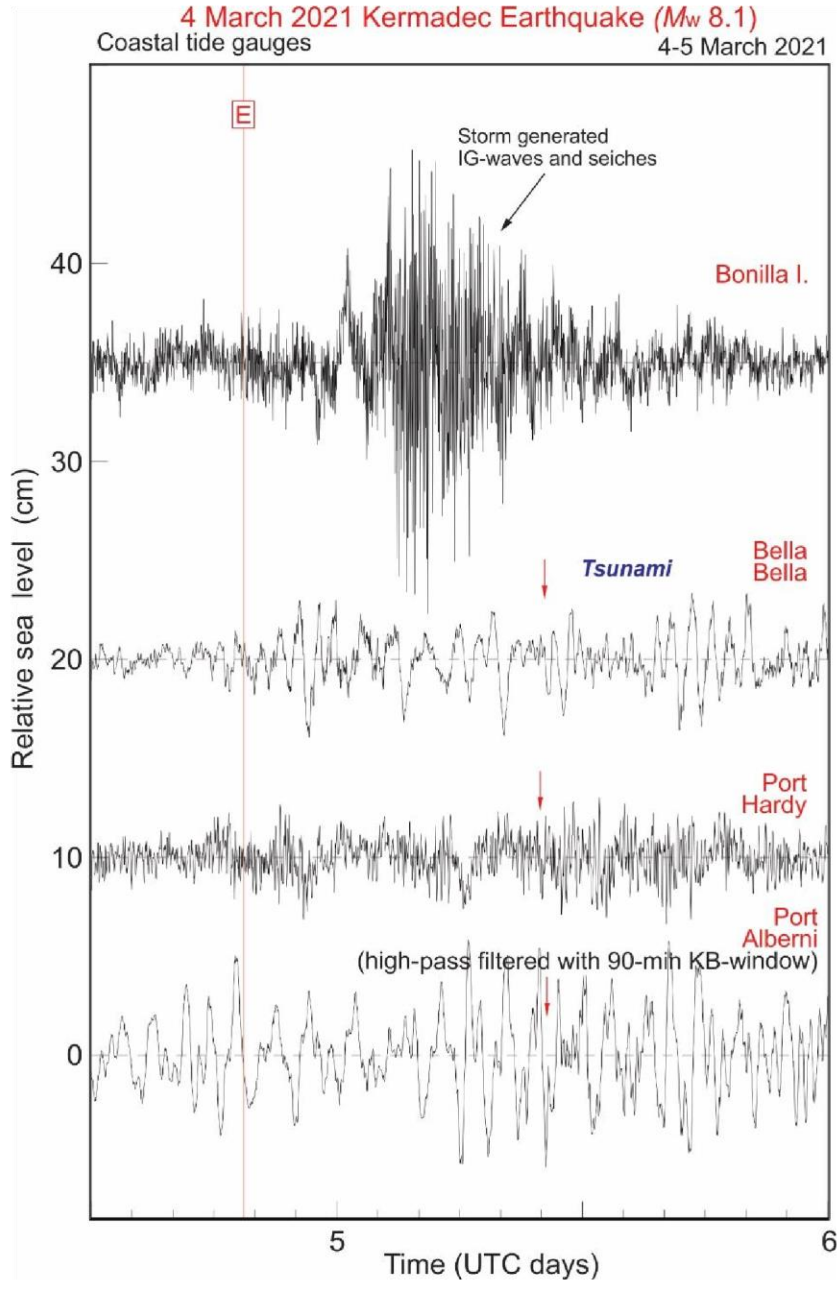

Figure 9. De-tided and high-pass filtered with a 3-hour Kaiser-Bessel (KB) window records at four stations of Group 2 located in a deep fjord (Port Alberni) and on the inner coast of British Columbia for the period of 4-5 March 2021. The record at Port Alberni was additionally low-pass filtered with a 90-min KB-window to suppress significant atmospherically induced seiches with periods >100 min. The solid vertical *red line* labelled ‘‘E’’ denotes the time of the 2021 Kermadec earthquake (main 8.1 shock); the *red arrows* indicate the tsunami arrival. Strong oscillations recorded at Bonilla Island are related not the Kermadec tsunami but to storm-induced IG-waves and local seiches.

Table 4. Parameters of the Kermadec tsunami of 4 March 2021 recorded by tide gauges on the coast of British Columbia (Main shock, M_w = 8.1 at 19:28:31 UTC). All arrival times and times of the maximum waves are related to 5 March 2021.

Station	First wave			Max waves			Visible period (min)
	Arrival time (UTC)	Travel time (hh:mm)	Amplitude (cm) Sign	Max amplitude (cm)	Time (UTC) of max amplitude	Max wave height (cm)	
Henslung Cove	07:49	12:20	-3.8/+4.0	4.9	05:36	8.8	25
Bonilla Island	Not observed		-	-	-	-	-
Rose Harbour	08:53	13:24	-3.4/+2.6	5.0	10:50	9.6	40, 15, 5.5
Bella Bella	10:10	14:41	-1.5/+1.5	2.4	18:23	5.0	45, 10
Port Hardy	09:56	14:27	-2.1/+2.1	3.5	12:50	6.0	12, 6
Winter Harbour	08:36	13:07	-4.9/+5.8	5.8	08:59	11.6	40, 25, 4
Tofino	08:35	13:06	-2.7/+5.5	7.2	16:42	14.8	40, 20, 6
Ucluelet	09:06	13:37	-0.8/+4.1	8.1	12.57	15.3	70, 20, 10
Port Alberni	10:06	14:37	-2.7/+2.5	~3.5	-	~7.5	100, 25
Bamfield	09:08	13:39	-1.4/+4.5	5.3	11:31	10.2	120, 17, 3.5
Port Renfrew	09:27	13:58	-2.6/+3.0	7.9	18:35	13.0	35, 4
Victoria	10:13	14:44	-3.1/+4.2	5.4	13:56	9.9	55, 20, 7.5

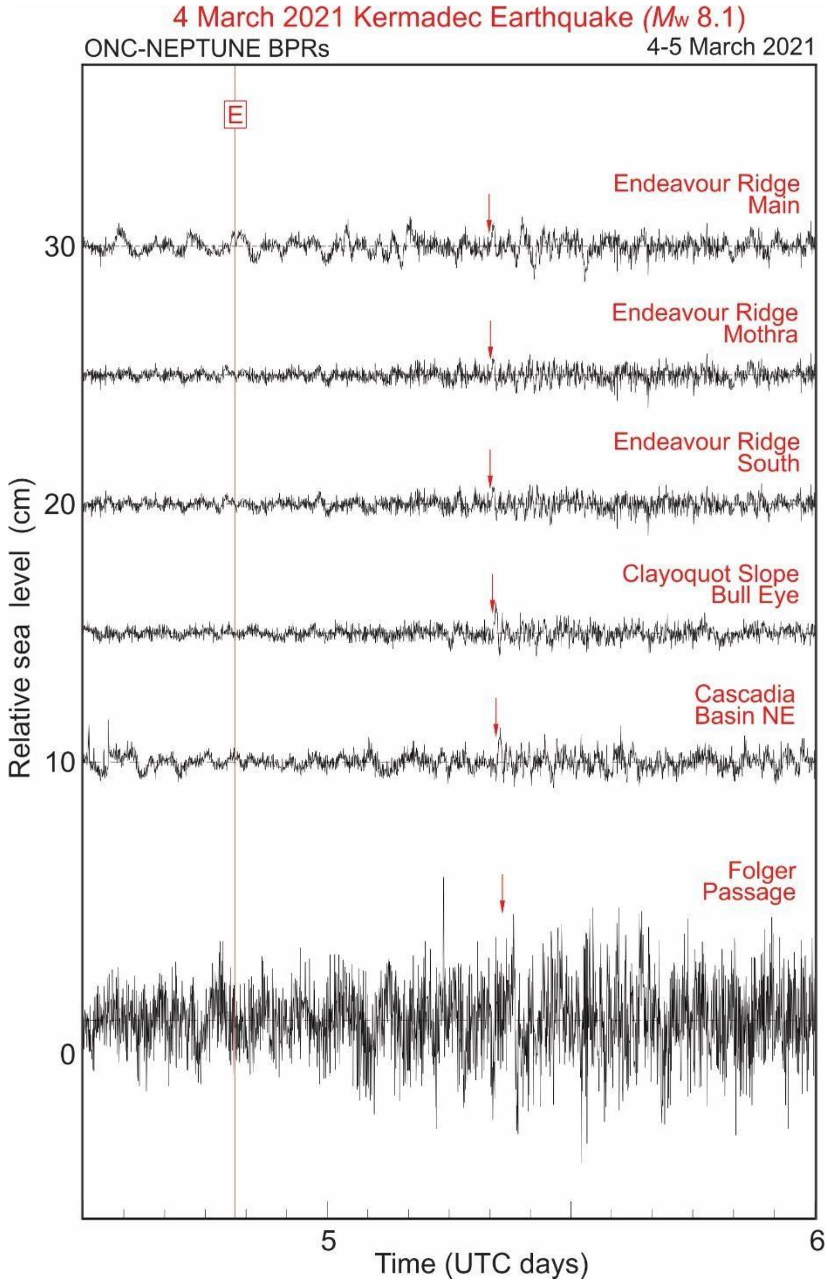

Figure 10. The residual (de-tided) and high-pass filtered with a 3-hour KB window of bottom pressure records offshore of southwestern Vancouver Island for the period of 4-5 March 2021. The solid vertical *red line* labelled ‘‘E’’ denotes the time of the 2021 Kermadec earthquake; the *red arrows* indicate the tsunami arrival.

8.5. Alaska Peninsula tsunami of 29 July 2021

A major megathrust earthquake (M_w 8.2) occurred off the coast of the Alaska Peninsula on 29 July 2021 at 06:16 UTC. This was the largest earthquake in the United States since the 1965 Rat Islands earthquake, and the 7th largest earthquake in U.S. history. Approximately 15 min after the earthquake the tsunami arrived at the closest open-ocean station, DART 46403, located approximately 300 km away from the epicenter. A tsunami height of 21 cm was recorded at Old Harbor

(Kodiak Island) and at a number of other sites along the coast of Alaska and the Aleutian Islands. Tsunami wave amplitudes of ~40 cm were measured at Avila Beach (California) and at several other stations of the U.S. West Coast.

The tsunami signal on the coast of British Columbia was detected at records of 16 CHS coastal tide gauges divided into two groups: North and South. Observed tsunami wave heights at all stations from the North Group were below 10 cm (Figure 10); the maximum trough-to-crest wave heights were recorded at Henslung Cove (9.2 cm), Pruth Bay (9.1 cm) and Masset (8.6 cm) (Table 5). Despite small heights, tsunami waves at all these stations could be measured and detected; the actual arrival times were in good agreement with the ETA. The first tsunami wave reached Henslung Cove at 08:40 UTC on 29 July 2021(2 hours and 24 min after the main earthquake shock). Then, 21 min later it reached Rose Harbour and, 34 min later, Masset (Table 5). The first tsunami arrived at four mainland stations at 10:11 – 10:44 UTC, i.e. roughly 1.5-2 hours after arrival at Henslung and 4-4.5 hours after the main shock. The specific feature of all records was a positive (crest) wave that arrived first. The periods of the observed waves at various stations were significantly different; nevertheless, periods of 40-60 min prevailed.

Despite that the stations of the South Group were mostly located farther from the source than the stations from the North Group, the recorded tsunami waves at these stations were substantially larger. It appears that the northern stations were located in the “shadow” of the main tsunami energy flux, while the southern BC stations were just in the “mainstream” of the main tsunami “tongue”. At five stations from this group, the maximum wave heights were more than 10 cm; the highest waves were recorded at Port Alberni (53.4 cm) and Winter Harbour (21.6 cm) (Figure 11, Table 5). It appears that strong amplification of arriving tsunami waves in Alberni Inlet is due to the closeness of the dominant periods of incoming waves to the fundamental resonant period of this inlet (about 110 min). The first station from the South Group that recorded the incoming tsunami was Winter Harbour: at 09:33 UTC (3 hours and 17 min after the main shock). Then, at 10:12 UTC it arrived at Tofino and at 10:16 UTC (exactly 4 hours after the earthquake) it came to Port Hardy. Specifically, the latter station, from the South Group, recorded the smallest wave height (only 4.9 cm; Table 5). At 10:21-10:26 UTC tsunami waves arrived at Ucluelet, Bamfield and Port Renfrew and then, 35-50 min later they came to Port Alberni and Victoria. At all these stations the first wave was positive and alike.

Two coastal tide gauge stations from the North Group, Masset and Kitimat, recorded seismic seiches that began in a few minutes after the main shock and lasted for 2.5 hours.

In addition to coastal tide gauge records of the 2021 Alaska tsunami, bottom pressure records of this tsunami were also examined. Altogether, there were eight bottom pressure station instruments operating during the event; all these stations clearly recorded the tsunami waves that arrived at the southwestern shelf of Vancouver Island (Figure 12). The main statistical parameters of the recorded waves are presented in Table 6. The background noise level is much lower in openocean than in coastal records and the signal-to-noise (s/n) ratio is much higher. Consequently, the tsunami signal is clearly seen even in the bottom pressure records (Figure 12). The records from the seven deep-water stations (412 – 2690 m) were alike; the tsunami arrival is evident in all these records, the first (frontal) wave looks the same at all stations. The Folger Passage record was much noisier and the oscillations at this site were much stronger. This station is the shallowest (108 m), the closest to the shore and, accordingly, is stronger influenced by coastal topographic effects.

The frontal N-shaped tsunami wave is evident in all these records. The tsunami wave first, at 9:07 UTC, arrived at station Endeavour-Main (2 hours and 51 min after the main shock); then 16 min later at Cascadia Basin, at 9:28 UTC at Clayoquot Slope, 5 min later at Barkley Canyon and finally at 10:12 UTC (3 hours and 56 min after the main shock) at Folger Passage. At Endeavour Bottom Observatory the tsunami signal arrived 1 hour and 5 min earlier than at Tofino and 1 hour 14 min earlier before it arrived at Bamfield (Tables 5 and 6). It is obvious that this station may be effectively used for early tsunami warning of tsunamis incoming from the open ocean. For all deep-water stations the first wave was the highest one; the maximum trough-to-crest wave height at these stations was from 2.7 cm to 3.6 cm, i.e. approximately 5 times smaller than at Tofino and 15 times smaller than at Port Alberni (Tables 5 and 6). The amplification of arriving tsunami waves at the coast in comparison with the open-ocean should be taken into account in the tsunami forecast.

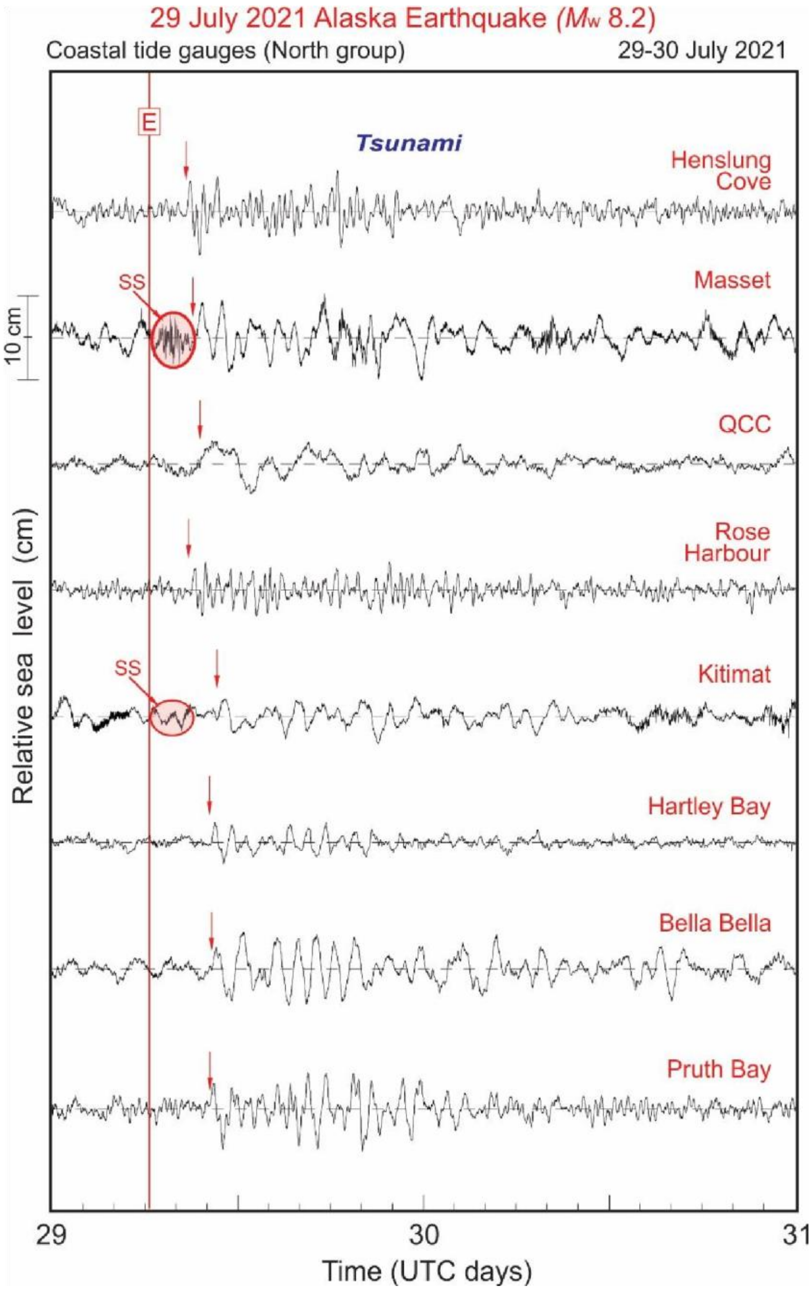

Figure 11. De-tided and high-pass filtered with a 3-hour Kaiser-Bessel (KB) window records at eight stations of the North group of CHS tide gauges located on the Haida Gwaii and mainland coasts of British Columbia for the period of 29-30 July
2021. The solid vertical *red line* labelled ''E'' denotes the time of the 2021 Alaska earthquake; the *red arrows* indicate the tsunami arrival. *Pink ovals* at Masset and Kitimat shows seismic seiches ("SS") recorded at these stations.

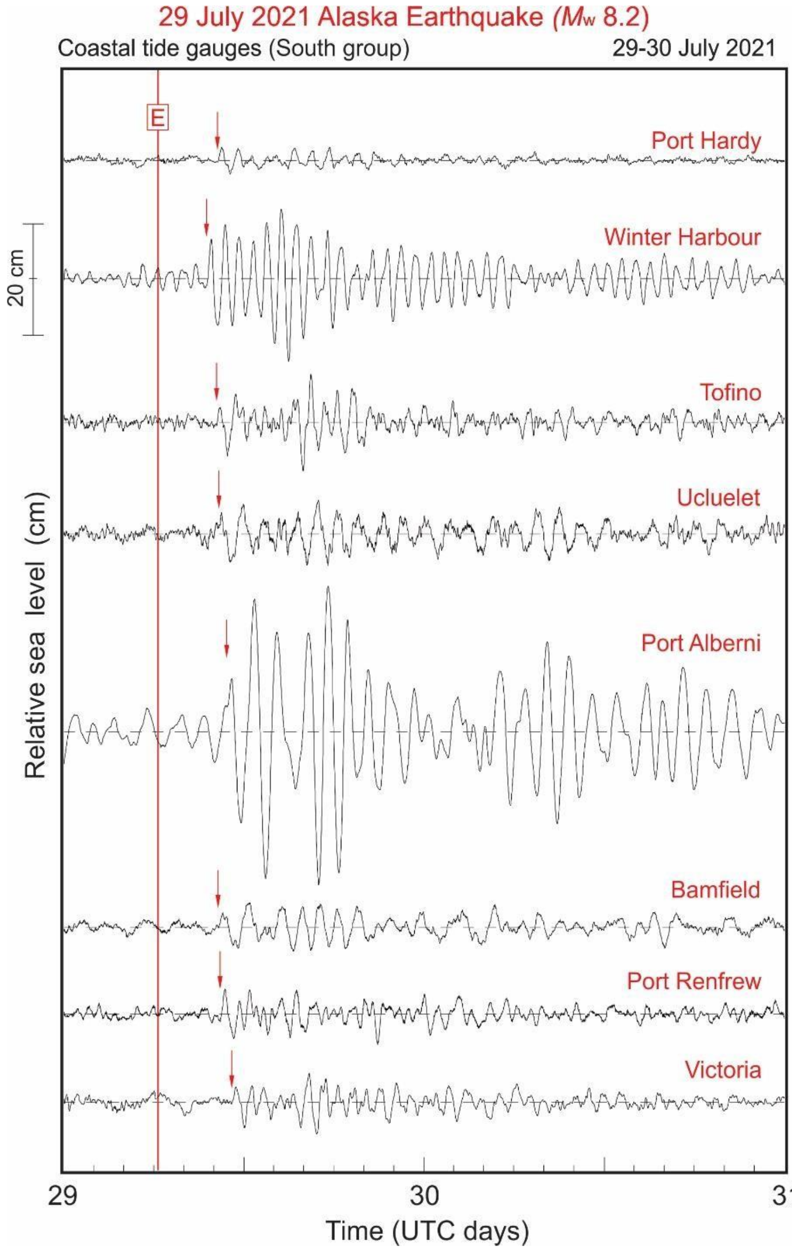

Figure 12. The same as in Figure 4 but for the South group of stations located on the coast of Vancouver Island (in Figure 2 these stations are indicated by *yellow circles*).

Table 5. Parameters of the Alaska tsunami of 29 July 2021 recorded by tide gauges on the coast of British Columbia (Main shock, M_w = 8.2 at 06:16 UTC). All arrival times and times of maximum waves are related to 29 July 2021.

Station	First wave			Max waves			Visible period (min)
	Arrival time (UTC)	Travel time (hh:mm)	Amplitude (cm) Sign	Max amplitude (cm)	Time (UTC) of max amplitude	Max wave height (cm)	
Henslung Cove	08:40	02:24	+4.0	4.9	18:26	9.2	22, 37, 75

Masset	09:14	02:58	+4.2	5.3	17:36	8.6	55, 85
QCC	09:32	03:16	+2.8	2.8	10:19	5.9	65, 120
Rose Harbour	09:01	02:45	+3.1	3.3	09:54	6.4	19, 37
Kitimat	10:44	04:28	+2.3	2.5	23:29	5.2	60, 75
Hartley Bay	10:15	03:59	+2.4	2.4	10:30	4.9	48
Bella Bella	10:21	04:05	+2.6	4.4	12:20	8.2	60, 95
Pruth Bay	10:11	03:55	+3.0	4.2	19:26	9.1	20, 43, 75
Port Hardy	10:16	04:00	+2.6	2.6	10:29	4.9	50
Winter Harbour	09:33	03:17	+7.8	10.0	13:31	21.6	48
Tofino	10:12	03:56	+2.6	8.6	16:27	17.4	50
Ucluelet	10:24	04:08	+3.5	6.1	16:58	11.7	20. 75
Port Alberni	10:55	04:39	+9.5	26.1	17:37	53.4	90
Bamfield	10:21	04:05	+2.6	4.3	12:24	8.1	60, 90, 125
Port Renfrew	10:26	04:10	+5.1	5.1	10:43	8.9	30, 40, 55
Victoria	11:16	05:00	+2.7	5.2	16:20	10.9	20, 55

One of the specific features of five deep-water records (Endeavour-Main, Mothra and West, Cascadia Basin-North and South) are strong high-frequency oscillations caused by the Rayleigh waves (Rw), which are partly measured by open ocean bottom sensors, but not by shallow-water bottom pressure instruments (in particular by three bottom pressure instruments located in depths of 108 – 1285 m) and coastal tide gauges. The Rw oscillations began almost immediately after the main earthquake shock and continued oscillating for more than an hour (Figure 12).

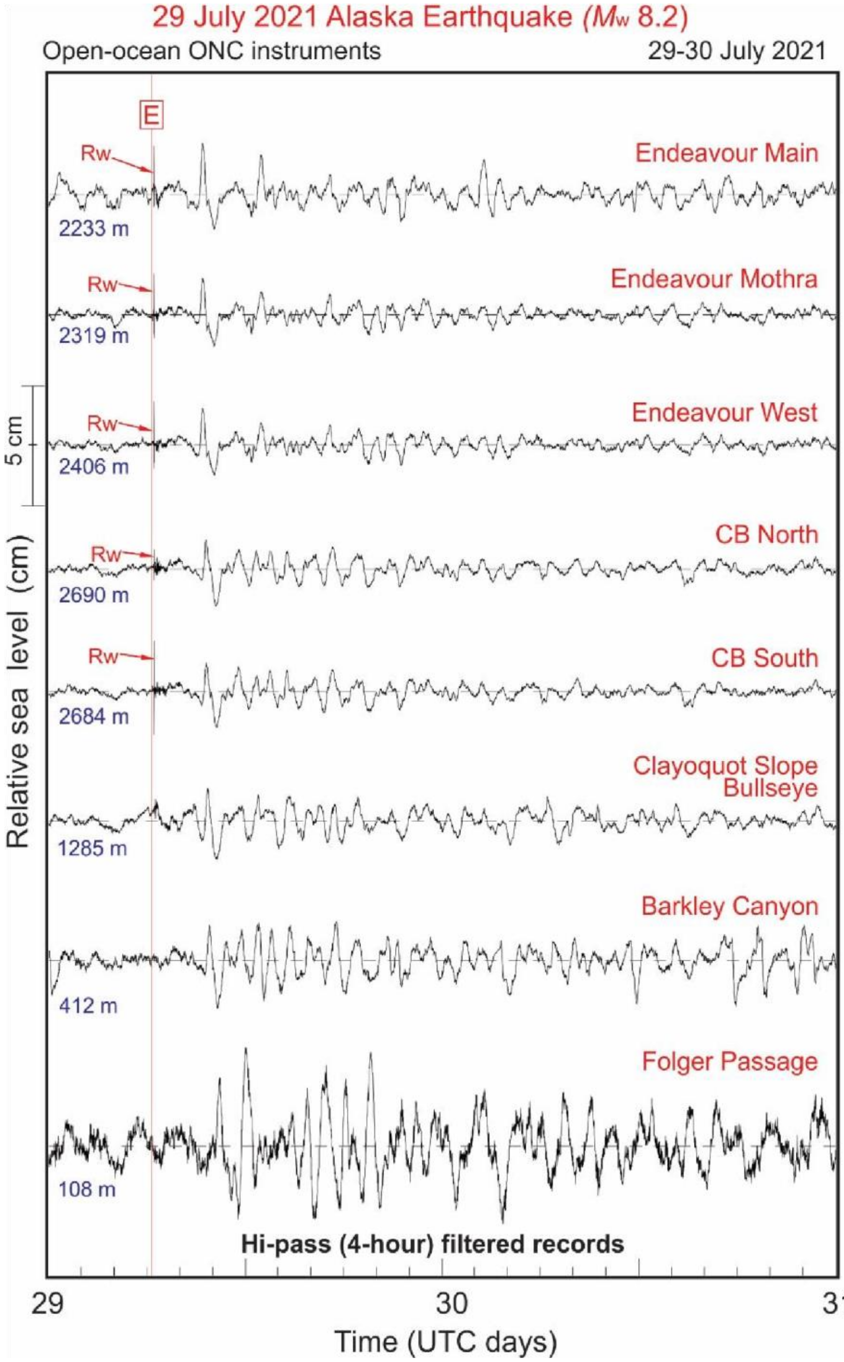

Figure 13. The residual (de-tided) and high-pass filtered with a 4-hour KB window of bottom pressure records offshore of southwestern Vancouver Island for the period of 29-30 July 2021. The solid vertical *red line* labelled "E" denotes the time of the 2021 Alaska earthquake; the *red arrows* labelled Rw indicate the Rayleigh waves. The station locations are shown in Figure 4. Arrival of the 2021 Alaska tsunami is clearly seen at all records.

Table 6. Parameters of the Alaska tsunami of 29 July 2021 recorded at bottom pressure stations on the southwestern shelf of Vancouver Island (Main shock, M_w = 8.2 at 06:16 UTC). All arrival times and times of the maximum waves are related to 29 July 2021.

Station	Depth (m)	First wave			Max waves			Visible period (min)
		Arrival time (UTC)	Travel time (hh:mm)	Amplitude (cm) Sign	Max amplitude (cm)	Time (UTC) of max amplitude	Max wave height (cm)	
Endeavour-Main	2233	09:07	02:51	+2.5	2.5	09:21	3.6	55, 90
Endeavour-Mothra	2319	09:09	02:53	+1.8	1.8	09:23	2.9	55, 90
Endeavour-West	2406	09:09	02:53	+1.8	1.8	09:23	2.8	55, 90
Cascadia Basin-N	2690	09:23	03:07	+1.6	1.6	09:34	2.8	55, 90
Cascadia Basin-S	2684	09:23	03:07	+1.6	1.6	09:35	2.7	55, 90
Clayoquot Slope-BE	1285	09:28	03:12	+2.0	2.0	09:41	3.0	55, 90
Barkley Canyon-Up	412	09:33	03:17	+2.0	2.0	09:47	3.5	55, 90
Folger Passage	108	10:12	03:56	+3.0	4.1	11:59	7.1	50,90,125

8.6. Tonga-Hunga volcanic tsunami of 15 January 2022

A huge Tonga-Hunga submarine volcanic eruption occurred on 15 January 2022 in the vicinity of the Tonga-Kermadec Islands volcanic arc in the southern part of the Tropical Pacific Ocean. The major eruption started at 04:14:45 UTC. The eruption column rose up almost 60 km into the mesosphere and the sound of the eruption was heard in New Zealand, more than 2000 km from the source. The eruption generated prominent tsunami waves that spread throughout the entire Pacific Ocean and even penetrated into the Atlantic Ocean. A defining characteristic of the tsunami was the dual forcing mechanism that sent oceanic waves radiating outward from the source at the longwave speed (Figure A1) and atmospheric pressure Lamb waves radiating around the globe at the speed of sound, i.e. 315-320 m/s (i.e. roughly 1.5 times faster than the longwave phase speed).

Strong tsunami waves with wave heights of more than 2.0-2.5 m were recorded in New Zealand, along the coasts of South and North America, in Japan and even in the Aleutian Islands. The corresponding waves were mostly produced by direct tsunami waves spreading from the source area. However, the eruption-produced strong atmospheric sound waves, which made several circles around the globe, also caused significant tsunami-like waves that impacted the entire World Ocean as far as 18,000 km from the source area. These waves were clearly recorded by numerous tide gauges, including those deployed in the Caribbean, Mediterranean and Black seas, and on the East (Atlantic) Coast of the United States.

The 2022 Tonga tsunami was evidently measured along the entire coast of British Columbia. Altogether we examined 32 tide gauge records and in all of them we could identify the tsunami signal. Moreover, at four stations – Winter Harbour, Port Alberni, Ucluelet and Port Alice – the trough-to-crest tsunami wave height was larger than 50 cm. At Tofino the recorded tsunami wave height was 46.6 cm; during the last 110 years there were only five tsunamis, all of them associated with the strongest earthquakes in the Pacific Ocean (1946 Aleutian, M_w 8.6; 1952 Kamchatka, M_w 9.0; 1960 Chile, M_w 9.5; 1964 Alaska, M_w 9.2; and 2011 Tohoku, M_w 9.1), produced larger tsunami waves. The 2022 Tonga tsunami waves penetrated deeply into sheltered inlets and fjords of the BC coast and were measured at such stations as Port Alice (50.3 cm), Kwokwesta (30.3 cm), both on northwestern Vancouver Island, and Kitimat (7.8 cm) on the mainland coast.

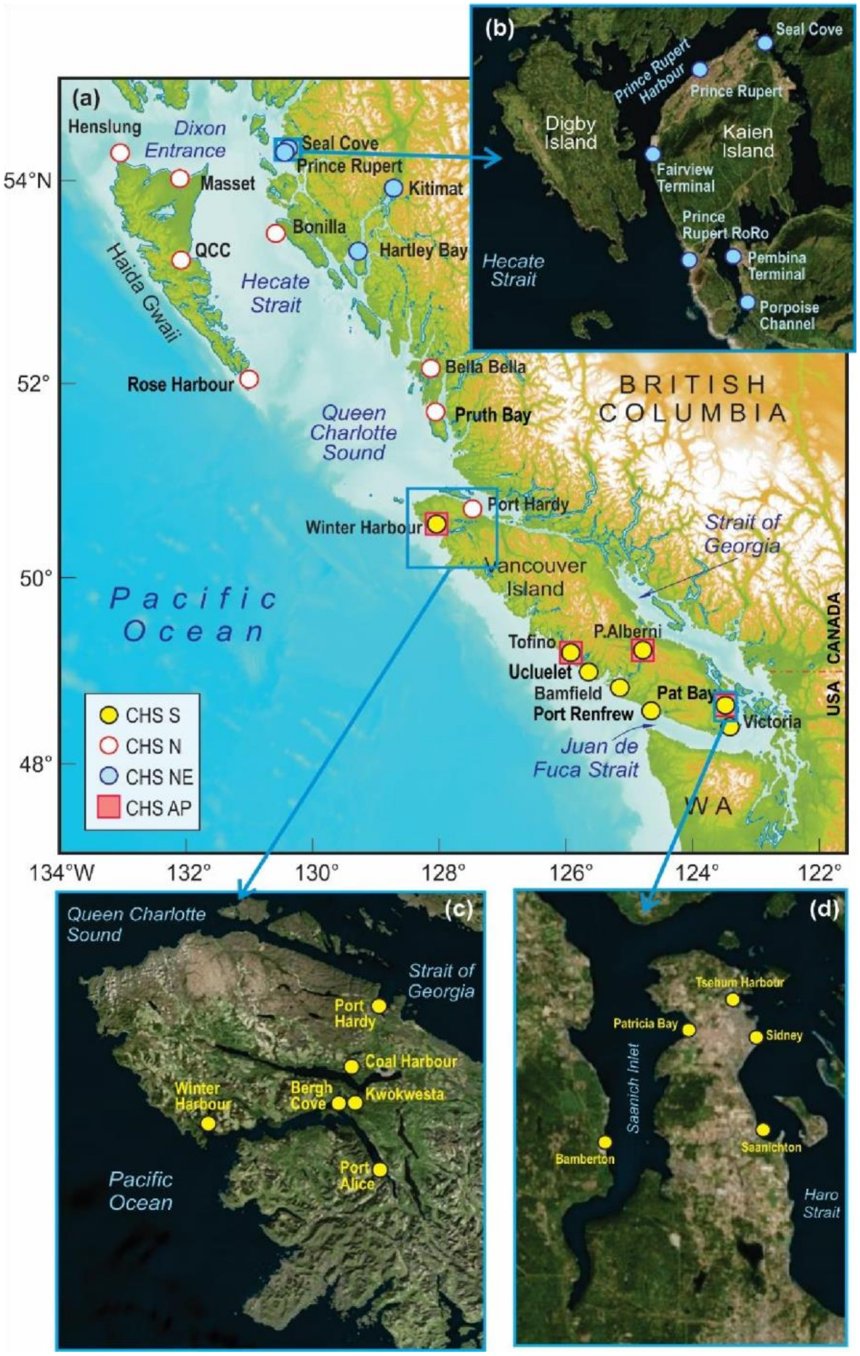

Figure 14. (a) Map of British Columbia with shown locations of the Canadian Hydrographic Service (CHS) coastal tide gauges (TG); all TG are divided into three groups: Northeast (NE), North (N) and South (S). Also are shown four stations on Vancouver Island where atmospheric pressure (AP) was measured. (b) The area of Prince Rupert with shown locations of six stations of the NE (Prince Rupert) group; two more NE stations – Kitimat and Hartley Bay – are displayed in (a). (c) Map showing northwestern Vancouver Island and the Quatsino Sound group of four temporary CHS tide gauges and two permanent tide gauges (Winter Harbour and Port Hardy). (d) Map of the Saanich Peninsula with shown locations of five CHS coastal tide gauges (TG), including a permanent TG at Patricia Bay and four temporary tide gauges.

Incoming tsunami waves produced long-ringing tsunami oscillations at many sites of the BC coast. What is important, significant currents appeared to be associated with the corresponding harbour oscillations. Strong tsunami-induced currents can be the main reason of severe damage of anchored boats and port infrastructure. Intense currents induced by the 2022 Tonga tsunami, in Ucluelet Inlet affected some coastal infrastructure and strongly damaged the water line on the Ucluelet First Nation (UFN) side of the inlet (Figure 14).

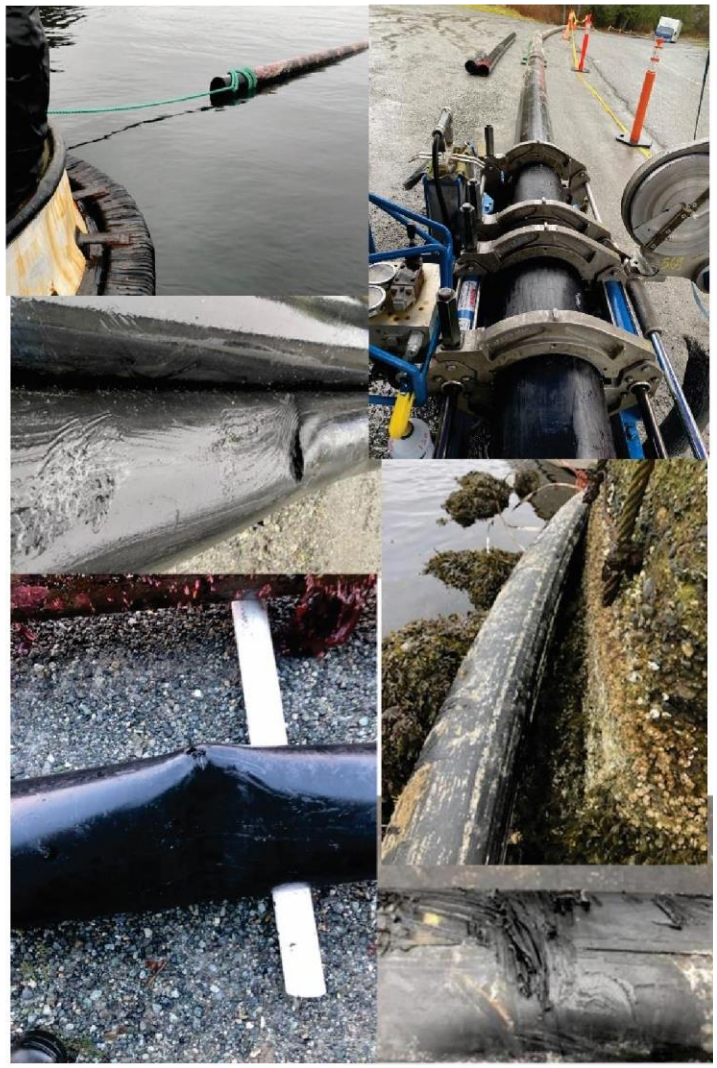

Figure 15. Photos of the damaged water line on the Ucluelet First Nation (UFN) Side of Ucluelet Inlet (Courtesy of *Jen Zimmermann*).

We examined sea level data from 32 tide gauges that recorded sea levels during the Tonga-Hunga event (Figure 13); 19 from them were permanent and 13 temporary. The temporary TG were installed in three regions: (1) Prince Rupert area (Figure 13b); (2) Quatsino Sound region (Figure 13c) and (3) the Saanich Peninsula (Figure 13d). The entire procedure of data analyses was approximately the same as for the 2020-2021 events; some of the records were quite noisy due to storminduced infragravity waves, impeding the tsunami detection. To suppress this HF noise, two of such records, Port Renfrew and Bonilla, were additionally low-pass filtered with 6-min KB-window. Four permanent tide gauges, Patricia Bay, Port Alberni, Tofino and Winter Harbour (all located on Vancouver Island), were also equipped by high-resolution air pressure (AP) sensors. Statistical parameters of all recorded waves are presented in Table 7.

All 32 TG records were separated into five groups:

(1) Southern (S). This group included eight permanent TGs located on Vancouver Island (Figure 15).

(2) Northern (N). This group also included eight permanent TGs, mostly located on and near Haida Gwaii and on the central mainland coast (Figure 16).

(3) Northeastern (NE). This group included three permanent TGs (Prince Rupert, Hartley Bay and Kitimat) and five temporary stations of the Prince Rupert group (Figure 17).

(4) Quatsino Sound. This group included four temporary TGs located in the Winter Harbour/Port Alice region. For comparison, in this group we also included one permanent stations – Winter Harbour – from the “Southern Group”, located in the same region (Figure 18).

(5) Saanich Peninsula. This group included four temporary TGs located on the coasts of the Saanich Peninsula and Saanich Inlet. For comparison, in this group we also included one permanent stations – Patricia Bay – from the “Southern Group”, located in the same region (Figure 19).

Tsunami waves were clearly recorded at stations of the *Southern Group* (Figure 15). At three stations (Winter Harbour, Ucluelet and Port Alberni) the maximum recorded trough-to-crest wave heights were more than 55 cm; at two more stations (Tofino and Bamfield) they were more than 40 cm (Table 7). These are higher than for any other tsunami event on the BC coast, except six major trans-oceanic tsunamis (1946, 1952, 1957, 1960, 1964 and 2011). At all stations of this group, except Winter Harbour, the first wave was negative. Both tsunami waves generated by atmospheric Lamb waves and direct waves arriving from the source were evident in the records. “Direct” waves were higher than “atmospheric” tsunamis.

Tsunami waves recorded at the stations of the *Northern Group* (Figure 16) looked similar to those of the Southern Group but were a little weaker. The highest wave of 44.7 cm (Table 7) was measured at Henslung Cove; at other stations the observed waves were considerably smaller. At some stations of this group (Henslung Cove, Masset and Bonilla) the first wave was negative, at the others positive.

The *Northeastern Group* includes six stations situated in the close area of Prince Rupert and two stations (Hartley Bay and
Kitimat) in Douglas Channel and its continuation, Kitimat Arm (see Figure 13b for the station locations). Tsunami waves at all eight records are evident but relatively weak: from 4.1 cm (Hartley Bay) to 15.4 cm (Seal Cove). The records of the three northernmost stations (Seal Cove, Prince Rupert and Fairview Terminal) are very similar and are formed only by
“direct” tsunami component (no atmospherically generated waves are seen in the corresponding records). At the three other stations in this region, the atmospheric component is evident (Figure 17). All six records are characterized by regular lowfrequency oscillations with dominant periods of 43-85 min. At Hartley Bay and Kitimat, the recorded oscillations are polychromatic and less regular (Figure 17, Table 2).

Tsunami oscillations at stations of the Quatsino Sound Group (Figure 13c) are surprisingly intense (Figure 18), especially at Winter Harbour (56.4 cm) and Port Alice. Tsunami waves arriving from the open Pacific Ocean penetrate deeply inside this sound, attenuating only in the area of Coal Harbour (6.1 cm). Two periods are most typical for the tsunami waves at stations of this group: 30 min and 90 min, however at stations Kwokwesta and Coal Harbour the predominant period of the recorded oscillations is 16 min (Table 2).

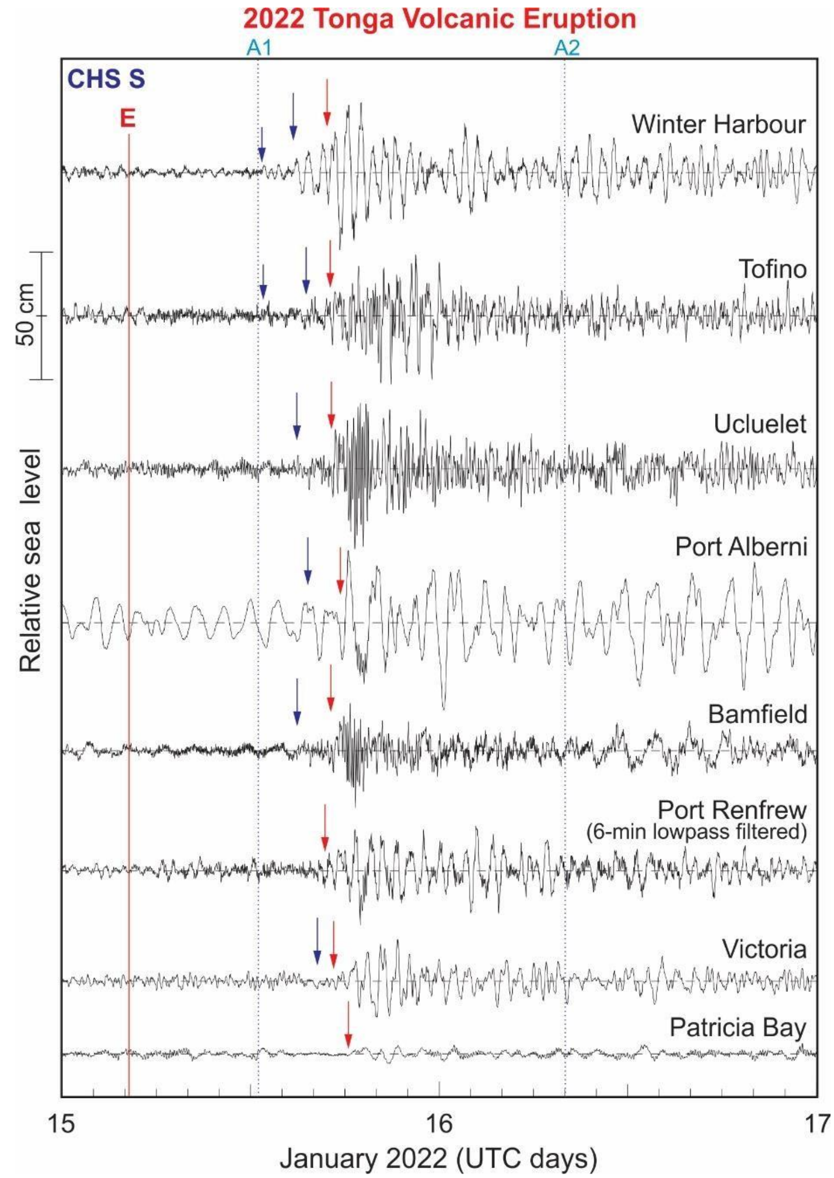

Figure 16. De-tided and high-pass filtered (3-hour Kaiser-Bessel window) records for eight stations of the southern (CHS S) group for a period of two days (15-16 January 2022). The solid vertical red lines labelled “E” indicates the time of the eruption; the dotted blue lines labelled “A1” and “A2” indicate the arrivals of the first and second atmospheric Lamb waves, blue arrows denote the arrival of atmospherically generated tsunami waves (“meteotsunami”), red arrows mark the arrivals od “direct” tsunami waves from the source area.

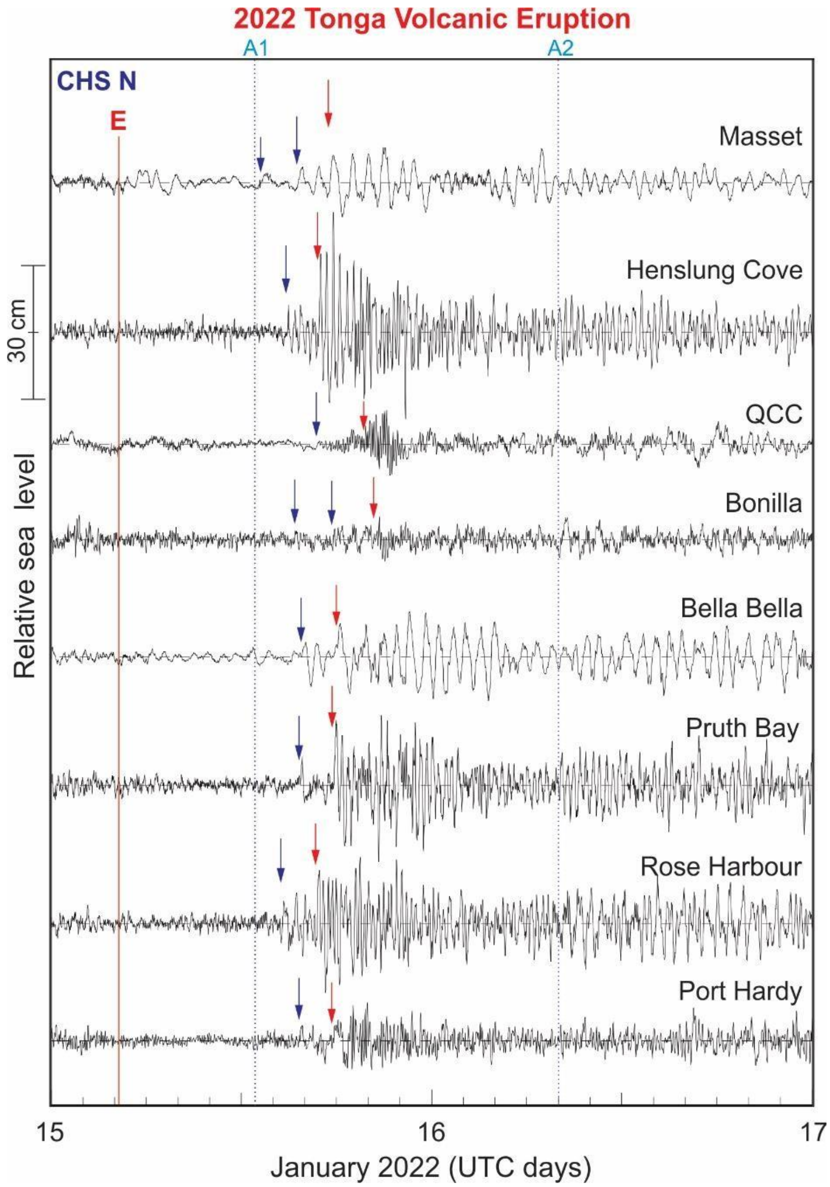

Figure 17. The same as in Figure 16 but for eight stations of the northern (CHS N) group.

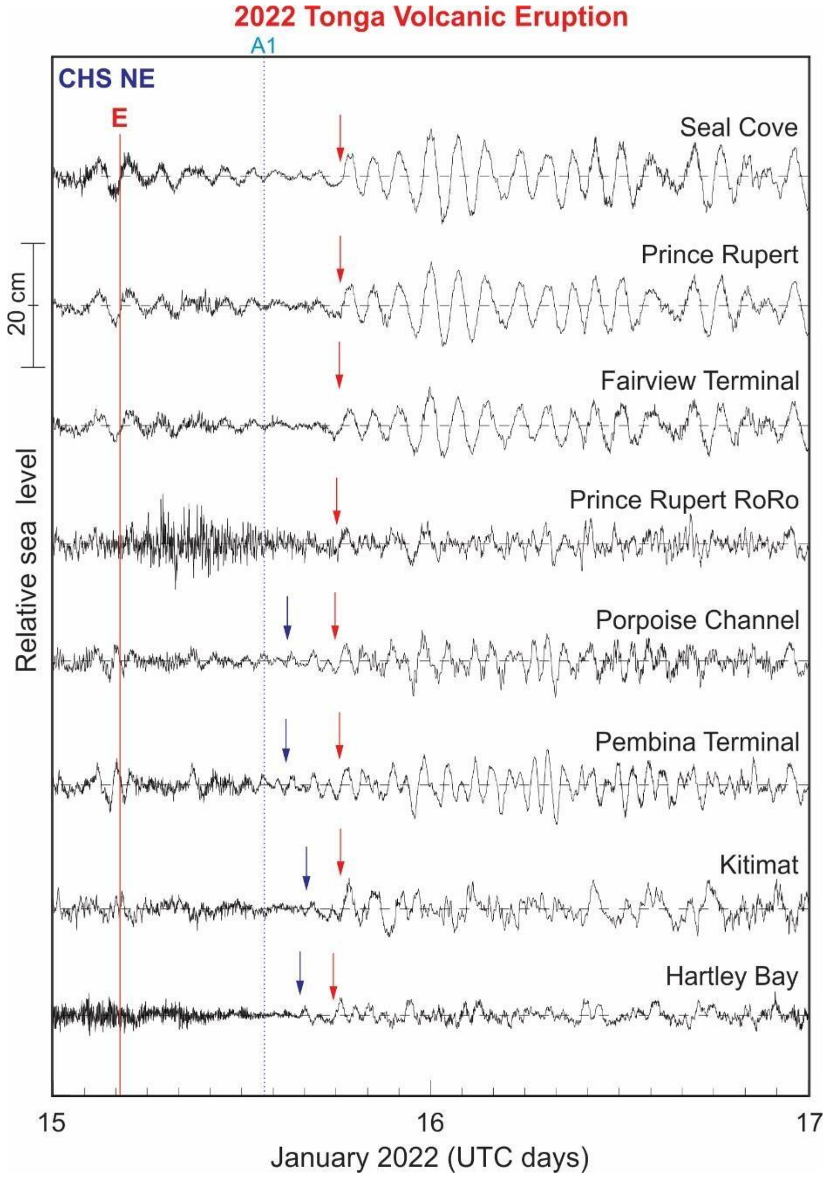

Figure 18. The same as in Figure 16 but for eight stations of the northern (CHS N) Prince Rupert group.

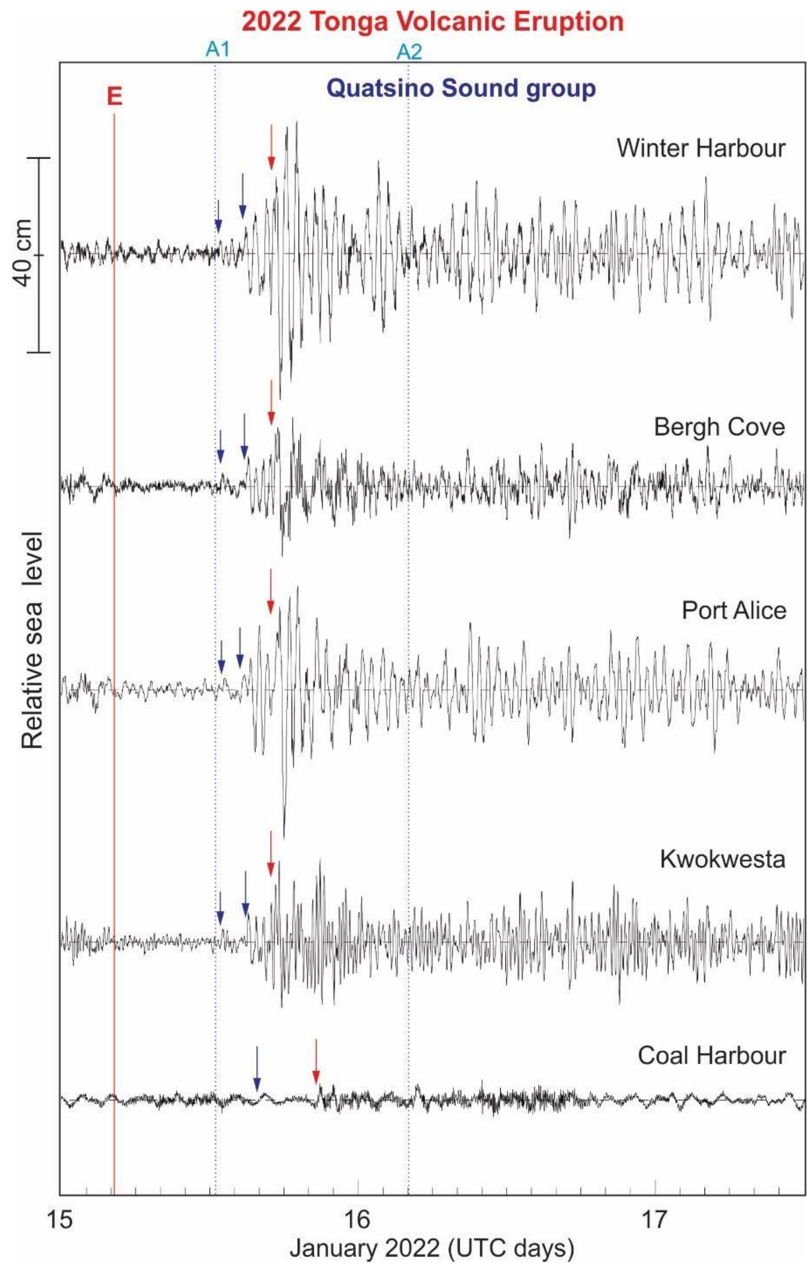

Figure 19. The same as in Figure 16 but for five stations of the Quatsino Sound group.

The fifth, *Saanich Peninsula Group*, are the stations located around the Saanich Peninsula (Figure 13d). The specific properties of the respective records (Figure 19) is that only the "direct" wave arrivals (indicated in Figure 19 by red arrows) is evident. The wave from the Pacific Ocean propagated through Juan de Fuca Strait, came into the southern Strait of Georgia, went through Haro Strait along the eastern coast of the Saanich Peninsula and at 17:44 UTC (i.e. 13 hrs and 29 min after the Tonga-Hunga eruption and 26 min later than at Victoria) the tsunami wave was recorded at Saanichton. Then,

7 min later, it arrived at Sidney and 2 more min later into Tsehum Harbour. It is interesting that because of some topographic amplification, the maximum measured tsunami wave at Tsehum Harbour was even higher than at Saanichton: 22.9 and 20.6 cm, respectively (Table 7). The dominant period at all these three stations was very stable:

50 min. An additional period of the observed oscillations is 30 min at Saanichton and Sidney and of 24 min at Tsehum Harbour. Going around the northern end of the Saanich Peninsula (see Figure 13d), the tsunami wave, strongly attenuating, penetrated into Saanich Inlet and was recorded in Patricia Bay and at Bamberton; the maximum wave heights at these two stations were 7-8 cm. The 8-min period oscillations measured in Patricia Bay are associated with the fundamental period of this bay.

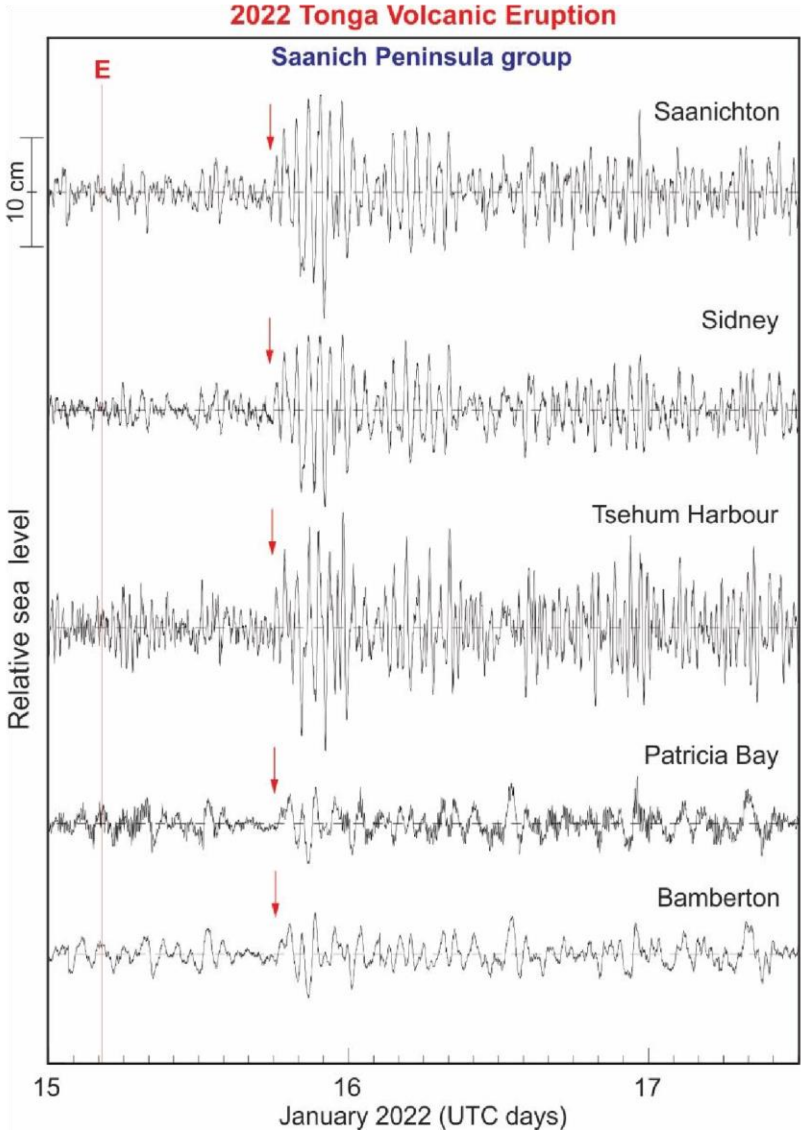

Figure 20. The same as in Figure 16 but for five stations of the Saanich Peninsula group.

Table 7. Parameters of the Tonga tsunami of 15 January 2022 generated by a volcanic eruption at 04:15 UTC. All arrival times and times of the maximum waves (in UTC hours) are related to 15 January 2022.

Station	First wave	Max wave	Visible period (min)

	Arrival time (UTC)	Travel time (hh:mm)	Amplitude (cm) Sign	Max amplitude (cm)	Time (UTC) of max amplitude	Max wave height (cm)	
Bamberton	18:12	13:57	-1.0/+2.8	3.8	21:21	7.8	50
Patricia Bay	18:11	13:56	-0.7/+2.4	3.3	21:22	7.0	50, 8
Tsehum Harbour	17:53	13:38	-3.1/+3.7	10.6	23:34	22.9	50, 24
Sidney	17:51	13:36	-1.3/+2.6	6.9	23:32	15.8	50, 30
Saanichton	17:44	13:29	-2.7/+3.4	9.0	21:46	20.6	50, 30
Victoria	17:18	13:03	-3.5/+3.6	16.3	21:20	29.8	50, 20
Port Renfrew	16:14	11:59	-4.3/+4.0	17.3	02:19*	37.2	45, 28
Bamfield	16:47	12:32	-1.8/+4.1	18.7	18:19	40.8	120, 12, 7
Port Alberni	17:37	13:22	-14.4/+28.4	28.4	18:12	55.0	90, 67, 37
Ucluelet	17:06	12:51	-11.0/+15.4	25.8	18:57	55.3	20, 7
Tofino	17:07	12:52	-11.5/+9.4	23.8	22:30	46.6	40, 18, 8
Winter Harbour	14:44	10:29	+5.5	27.3	19:01	56.4	43
Bergh Cove	14:54	10:39	+6.5	14.5	18:41	28.8	90, 30, 8
Port Alice	15:05	10:50	+7.1	21.5	19:06	50.3	90, 40
Kwokwesta	14:59	10:44	+6.5	17.3	20:54	30.3	90, 30, 16
Coal Harbour	16:44	12:29	+1.0	3.4	17:41	6.1	90, 16, 9
Port Hardy	15:42	11:27	+3.6	8.9	19:56	14.9	48, 8
Pruth Bay	15:43	11:28	+6.6	16.4	20:49	34.5	21, 6
Bella Bella	15:49	11:34	+3.6	10.8	22:36	20.2	46
Rose Harbour	15:22	11:07	+7.2	15.6	19:29	28.9	40, 16
Bonilla	17:36	13:21	-2.6/+2.4	5.2	20:42	10.1	8
QCC	16:42	12:27	+1.8	8.0	21:09	15.3	7
Henslung Cove	14:32	10:17	-3.1/+6.4	28.1	17:47	44.7	22, 11
Masset	15:16	11:01	-2.1/+3.6	8.2	20:56	15.0	50, 30
Seal Cove	18:23	14:08	+4.2	7.6	00:01*	15.4	85
Prince Rupert	18:19	14:04	+4.5	7.0	00:02*	13.6	43, 30, 7
Fairview Terminal	18:19	14:04	+3.5	6.2	23:57	11.5	85
Prince Rupert RoRo	18:16	14:01	+2.8	3.7	23:49	7.3	85, 21
Porpoise Channel	18:12	13:57	+3.7	4.7	23:27	10.2	85

Pembina Terminal	18:16	14:01	+2.9	4.9	23:35	10.5	48, 10
Kitimat	18:25	14:10	+5.0	5.0	18:49	7.8	90, 55, 24, 16
Hartley Bay	17:59	13:44	+2.8	2.8	18:21	4.1	47

* 6 January 2022

Simultaneous records of sea level oscillations and atmospheric waves at the same stations on Vancouver Island are shown in Figure 20. Evident interaction of these waves are seen only at Winter Harbour and, much weaker, at Tofino. It is obvious that the main train of waves observed at all stations is associated with the "direct" tsunami waves that arrived from the source region in the south tropical Pacific Ocean.

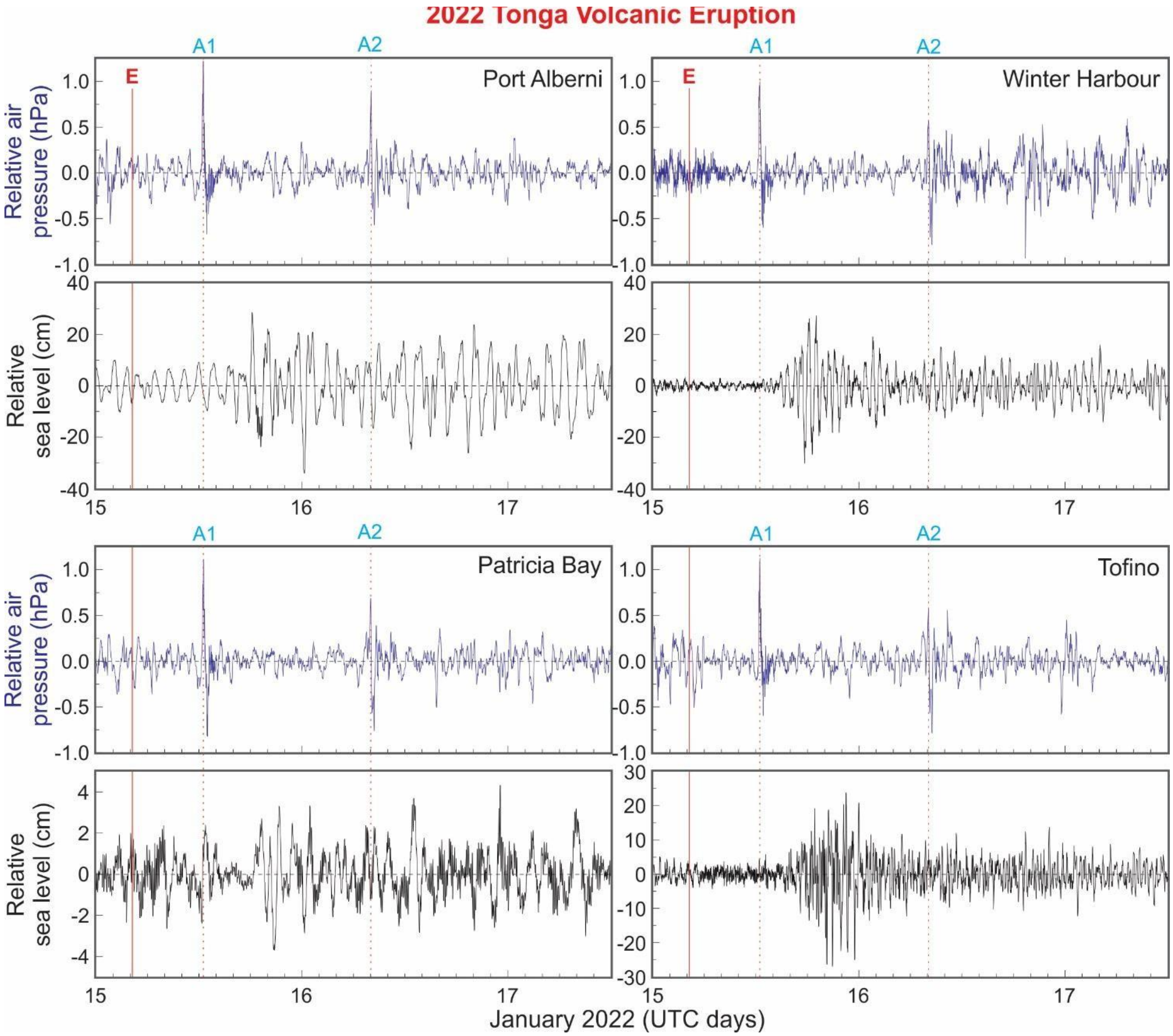

Figure 21. Simultaneous relative atmospheric pressure and sea level records at Port Alberni and Patricia Bay for the period of 2.5 days (from 15 January 00:00 UTC to 17 January 12:00 UTC). The dotted vertical red lines and labels “A1” and “A2” indicate the arrival times of the first two atmospheric pressure waves.

8.7. Meteorological tsunami in the Prince Rupert region on 21 January 2022

An anomalous event occurred on 21 January in the area of Prince Rupert. A train of significant oscillations was recorded at this permanent CHS station. Simultaneous marked oscillations were measures at Henslung Cove and at Bonilla Island (Figure 21). These oscillations took place approximately one day after a strong cyclone passed over the study region that caused a pronounced storm surge at these stations (Figure 21).

The records from two group of stations were examined. The first group includes Prince Rupert and five temporary stations located in the same region (see Figure 13b). This is the same group that six days earlier evidently recorded the TongaHunga tsunami (Figure 17). The records of the events are very clear and similar; the maximum wave heights are from 31 cm (Seal Cove) and 30 cm(Pembina Terminal) to 21 cm (Fairview Port and Prince Rupert RoRo).

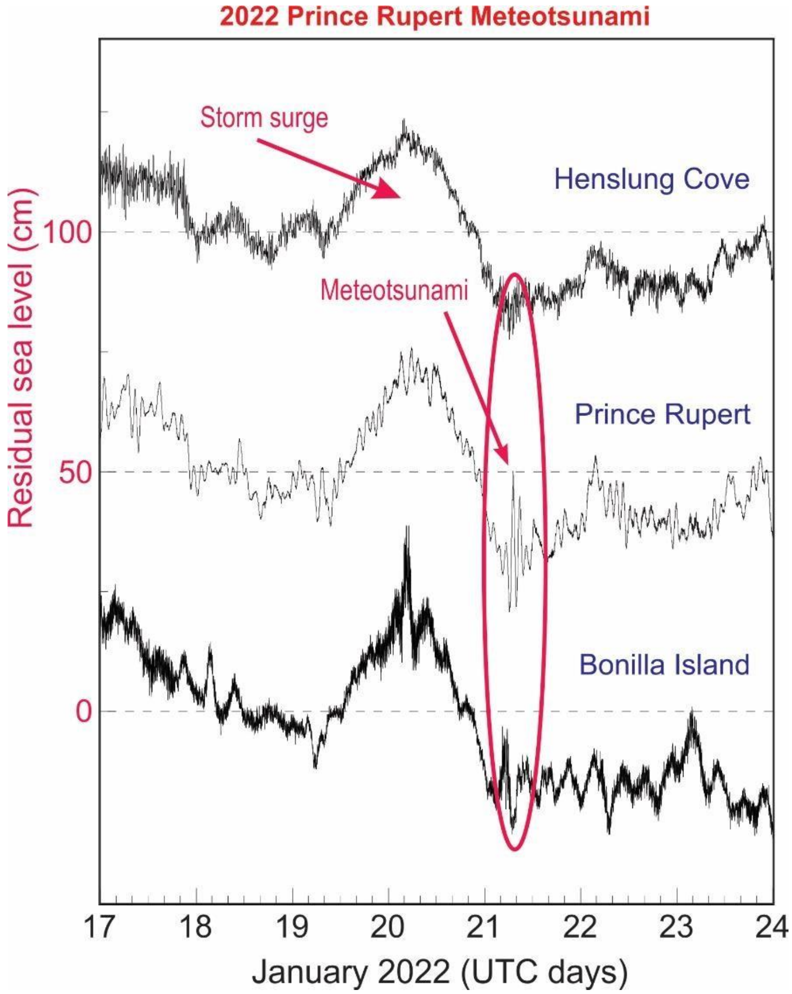

Figure 22. Residual (de-tided) records at three CHS stations in the northern and northeastern parts of British Columbia for the period of 17-24 January 2022. A considerable storm surge occurred on 19-20 January 2022 (indicated). The point of the main interest is a meteotsunami on 21 January 2022. Which had the maximum height at Prince Rupert but is also noticeable at Henslung Cove and Bonilla Island (indicated by the oval). The meteotsunami coincided with low mean sea level, i.e. with high atmospheric pressure (anticyclone): 1029 hPa (sea surface pressure) according to the observations at the Prince Rupert airport.

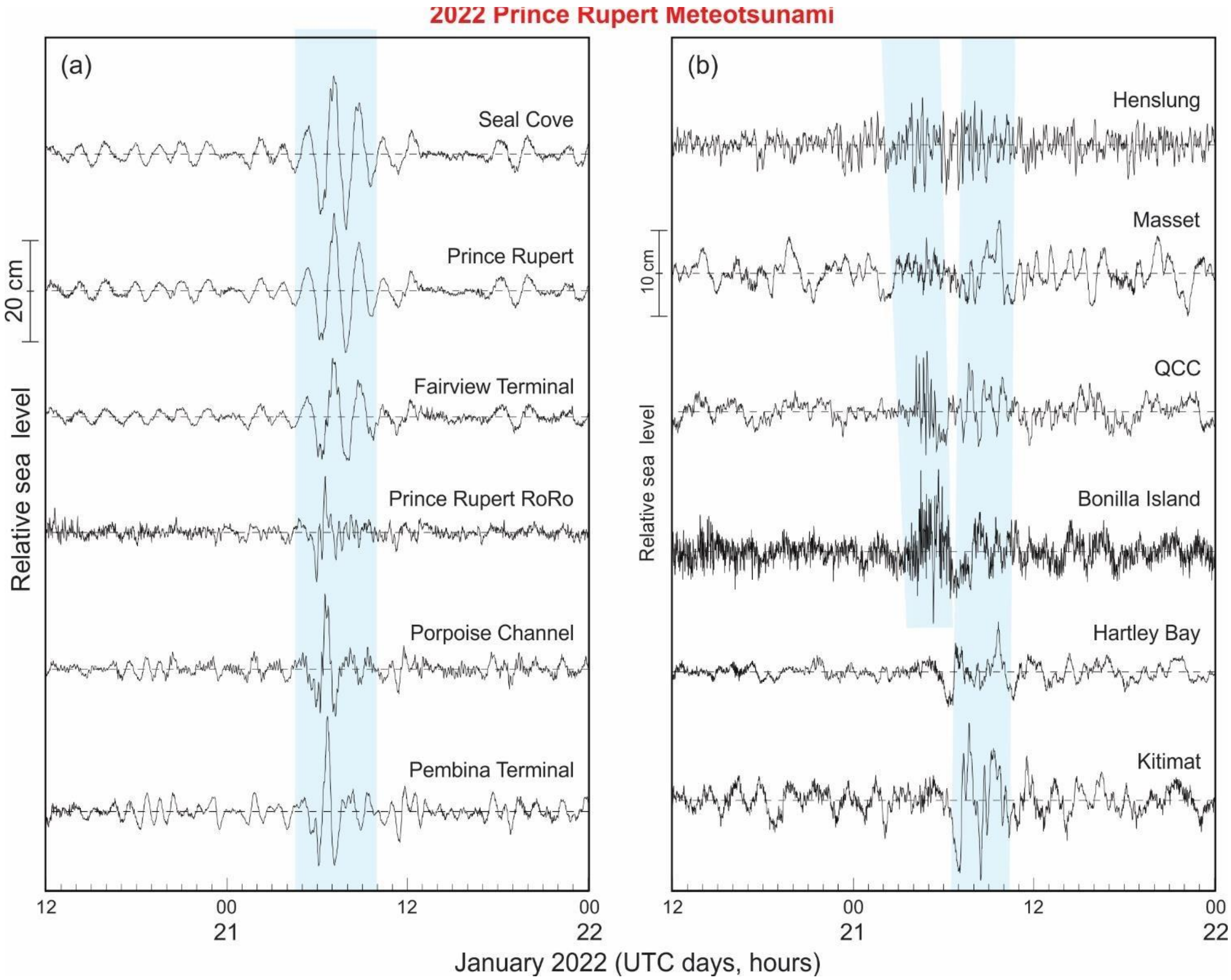

Figure 23. De-tided and high-pass filtered (3-hour Kaiser-Bessel window) records at (a) six CHS tide gauge stations of the Prince Rupert (NE) group (see Figure 13b for the station location) and (b) six stations of the northern group b(Figure 13a) for the period of 12:00 UTC of 20 January 00:00 UTC of 22 January 2022. The light blue band indicates a meteotsunami recorded at all stations. The first light blue band for four upper records in (b) indicates high-frequency oscillations (seiches) probably associated with a passing storm; the second band indicates a weak meteotsunami.

We also found a signature of the same event in records of other CHS stations located in the northern part of British Columbia
(Figure 22b). The most intense oscillations of approximately 18 cm were measured at Kitimat. Unfortunately, there were no high-resolution air pressure measurements at any stations of this region, however, the entire character of the observed oscillations and physical properties of these oscillations indicate that the event of 21 January 2022 was a *meteotsunami.*

Four stations located in the northeastern part of the region (Henslung Cove, Masset, QCC and Bonilla Island)also measured another train of significant oscillations that are probably associated with the storm activity (first blue band in Figure 22b).

8.8. Meteorological tsunami in the Port Alberni region on 19 February 2022

On 19 February 2022 strong sea level oscillations were detected at Port Alberni. To examine the nature of these oscillations we used the data from four microbarographs: Winter Harbour, Tofino, Port Alberni and Patricia Bay (see Figure 23a for the station locations). Analysis of the respective air pressure (AP) data (Figure 23c) revealed that the sea level oscillations were caused by an atmospheric disturbance of ~2 hPa propagating along Vancouver Island from NW to SE (Figure 23a). The estimated speed of this disturbance was 26 m/s (~94 km/h).

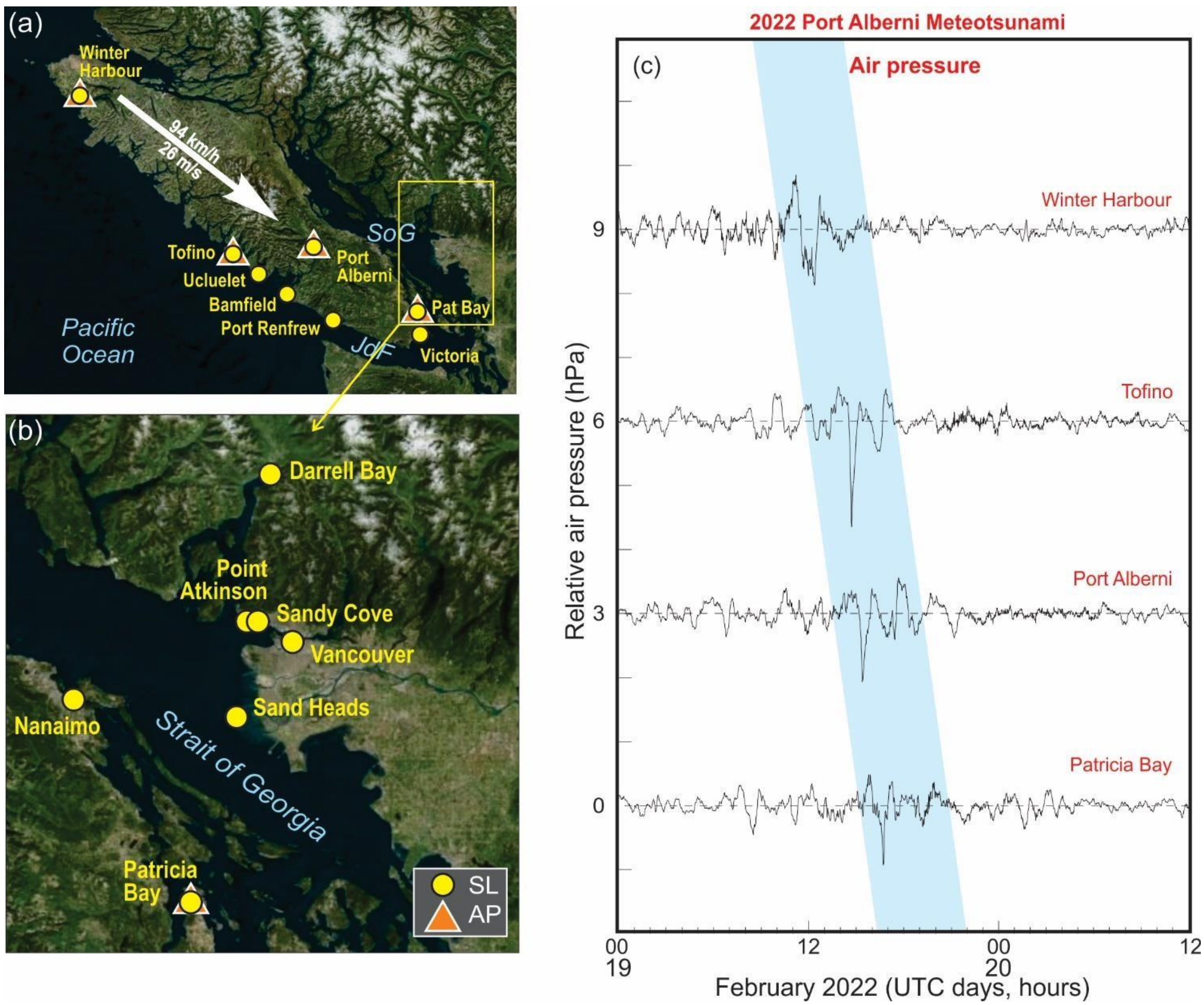

Figure 24. (a) Map of Vancouver Island with shown locations of the Canadian Hydrographic Service (CHS) coastal tide gauges (TG) and air pressure microbarographs (AP). The thick white arrow indicates the propagation direction of the AP disturbance. "SoG" = Strait of Georgia, "JdF" = Juan de Fuca Strait. (b) The same as in (a) but for mainland stations, Nanaimo and Patricia Bay. (c) High-pass filtered (4-hour Kaiser-Bessel window) AP records at four microbarographs: Winter Harbour, Tofino, Port Alberni and Patricia Bay for the period of 19-20 February 2022. The light blue band indicates an atmospheric disturbance propagating over these four stations.

We examined the data from six CHS tide gauge (TG) stations located along the oceanic coast of Vancouver Island plus Victoria (Juan de Fuca Strait) and Patricia Bay (Saanich Inlet) (Figure 23a). In all records, except the northernmost station

Winter Harbour, evident sea level oscillations, corresponding to the propagating AP disturbance, were identified (Figure 24 a). The largest oscillations with the maximum trough-to-crest wave height of 54 cm was found at Port Alberni and of 27 cm at Port Renfrew.

We also examined the records at Nanaimo (Strait of Georgia) and five mainland TG stations located in the area of Vancouver
City (see Figure 23b for station locations). Anomalous sea level oscillations, but weaker than on the oceanic coast of Vancouver Island, were evident in all these records (Figure 24b). The largest wave height of 13 cm was detected at Darrell Bay.

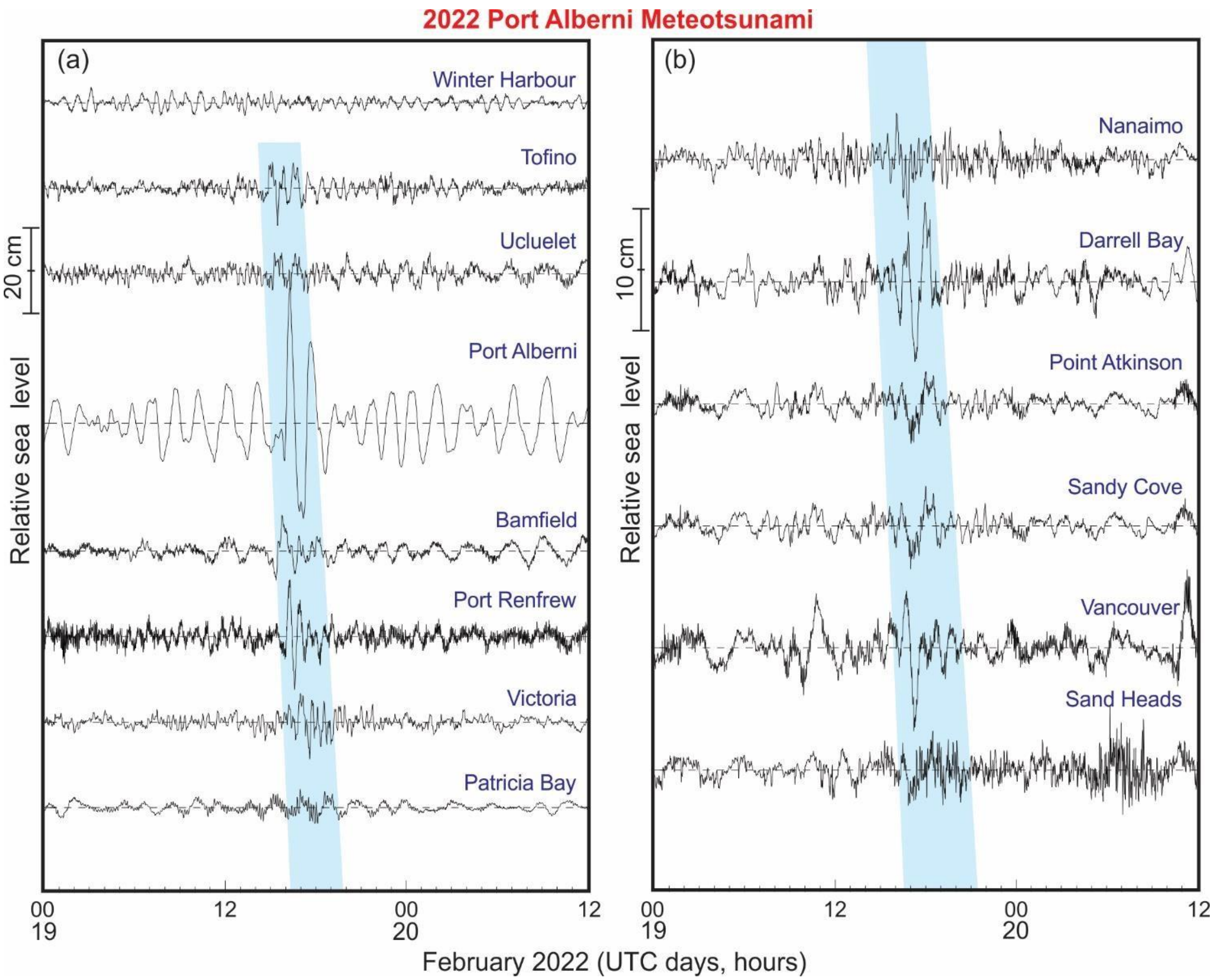

Figure 25. De-tided and high-pass filtered (4-hour Kaiser-Bessel window records for the period of 19-20 February 2022 at (a) eight CHS tide gauge stations located on western and southern coasts of Vancouver Island and (b) Nanaimo and five mainland stations shown in Figure 23b. The light blue band indicates high-frequency oscillations (meteotsunami) associated with a passing atmospheric disturbance

Analyses of all these data enable us to conclude that the observed event was a *meteotsunami* generated by a strong propagating atmospheric disturbance. It is interesting that the strongest sea level oscillations, observed at Port Alberni, were not the direct sea level response to the strongest AP oscillations, which were recorded at Tofino (Figure 23 b). It appears that the corresponding sea level oscillations were formed in Barkley Sound and the entrance of Alberni Inlet and then was strongly amplified in the head of this inlet, i.e. at Port Alberni.

8.9. Ship-generated tsunami-like waves in the Fraser River estuary on 30 April 2021

An extraordinary event occurred on 30 April 2021 in the Richmond's Garry Park in the Fraser River estuary. Priscilla Romero at around 9:30 AM made a video of a passing large ship. Within seconds, a wave came out of nowhere. The water and debris was seen crashing up onto the shore and flowing right across the walking trail (Figure 25). "*I don't know what was happening in that moment but then I was in shock,*" Romero said. The video captured one person falling into the water as the wave surged past them.

In a statement to CTV, the Port of Vancouver said discussions are underway to determine what factors led to the wave, and added they recognize the seriousness of the incident. "*As a port authority, we are responsible for ensuring the safety of the waterways within port jurisdiction, which includes this area of Fraser River,*" the Port said. "*We regularly review and update the safety practices and procedures we have set in place for vessels to follow.*"

Figure 26. The aftermath of the mini-tsunami, with log booms and debris left covering the walking path at Garry Point Park (from Priscilla Romero video)

The examination of the sea level oscillations for the period between 28 April and 2 May 2021 was done for seven CHS tide gauges indicated in Figure 26a. Anomalous sea level oscillations we re found only at three stations located in the western part of the Fraser River estuary (Figure 26b). The main feature of these records (Figure 27) is strong impulse-type shortlife oscillations. At Woodwards Landing and Steveston they were strongly alike and had similar heights of 20-35 cm; at Sand Heads they were significantly weaker but looked similar. The event on 30 April (at about 16:00-17:00 UTC, i.e. 9:0010:00 PDT) was the strongest, but there were several others. To exclude possible atmospheric origin of the observed extreme oscillations, we examined the air pressure (AP) record at Patricia Bay and have not found any anomalous AP disturbances that can be responsible for the Garry Point Park event of 30 April 2021 and for three other events seen in Figure 27. The regular character of their occurrence suggests their artificial (technogenic) nature, with the most probable reason is the cargo ship passing by.

We could not detect the exact periods of these waves because the sampling of sea level records was 1 min and the corresponding Nyquist period, $T_N = 2$ min. Definitely, the real period of these waves, T_e, was <2 min, probably about 3040 s. This means that the actual wave heights were much higher than recorded, probably 2-3 times higher. Such waves certainly could create significant damage in the coastal zone.

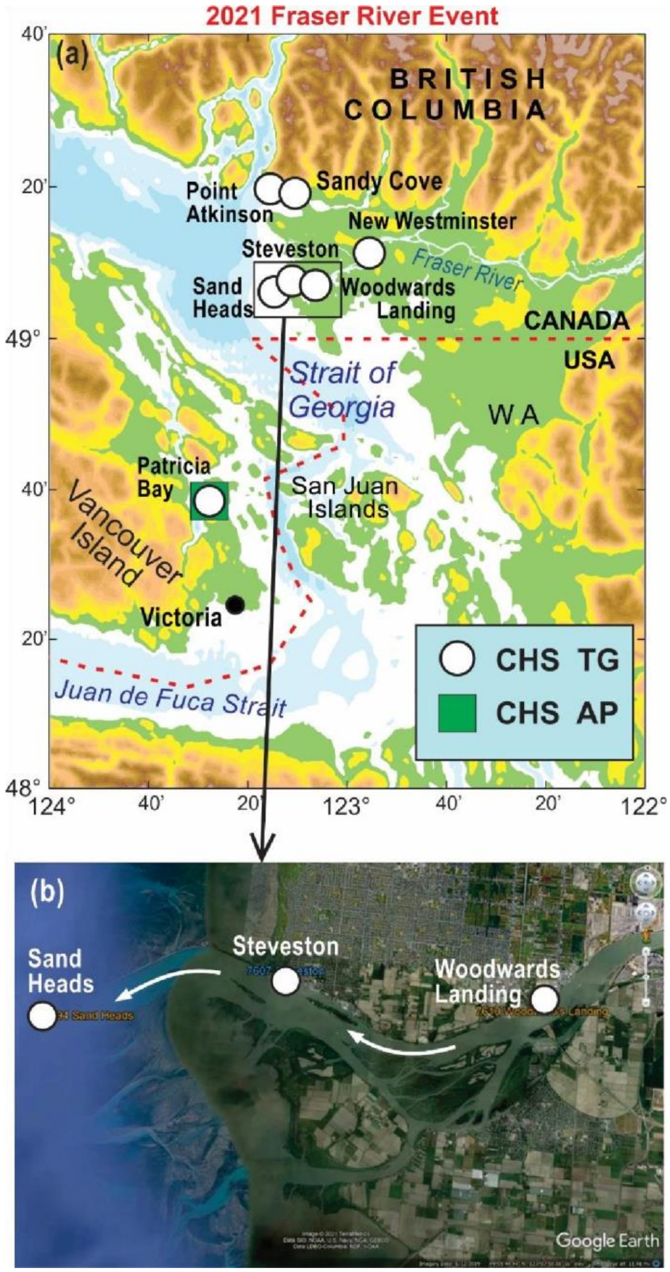

Figure 27. (a) Map of the southern Strait of Georgia with locations of the Canadian Hydrographic Service (CHS) seven coastal tide gauges (TG) and one microbarograph (AP), which were used in the present study. (b) The area of the Fraser River delta with shown locations of three CHS tide gauges that recorded extreme waves on 30 April 2021. White arrows show the tracks of the ships moving from the river estuary to open sea.

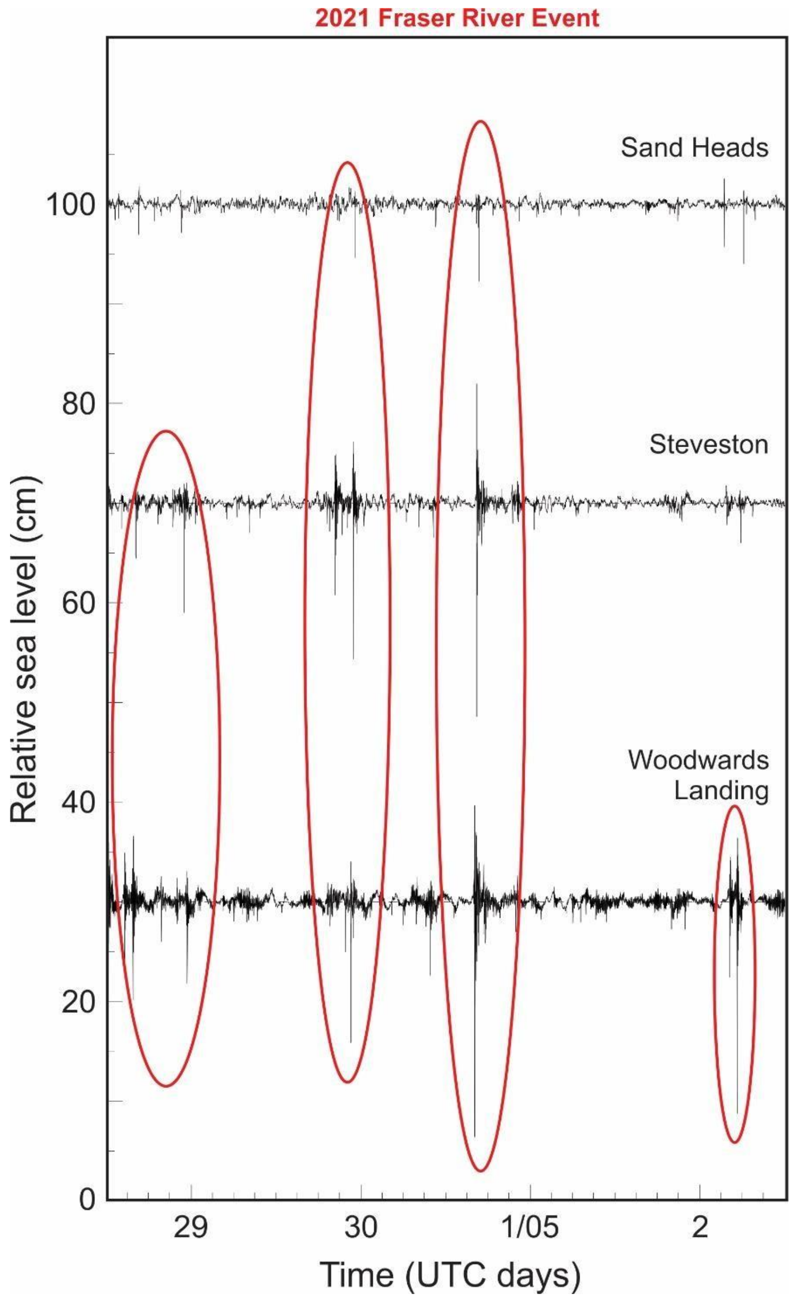

Figure 28. De-tided and high-pass filtered records at three stations located in the western part of the Fraser River estuary for the period of 28 April – 2 May 2021. *Red ovals* denote strong impulse-type oscillations observed at these stations.

Figure 29 shows the enlarged records of this event at the three stations. It is obvious that this was the same event measured at these stations with a little time shift: first at Woodwards Landing, then 18 min later at Steveston, and then at Sand Heads also with a shift of 18 min. The extreme waves lasted for 40-45 min and decayed fast.

All data and information that we could collect evidence that extreme ocean waves impacting the Garry Point Park on 30 April 2021 evidence that they were "ship waves' induced by a huge cargo (container) ship passing by: (1) At the time of the accident Priscilla Romero saw a large vessel loaded with containers passing by. (2) There were no significant atmospheric disturbances at the time of the event that could produce a meteotsunami. (3) Similar, but slightly weaker, long ocean waves are observed regularly at Woodwards Landing and Stevetson; we may assume that they all are "ship waves" and are generated by cargo ships travelling along the Fraser River estuary.

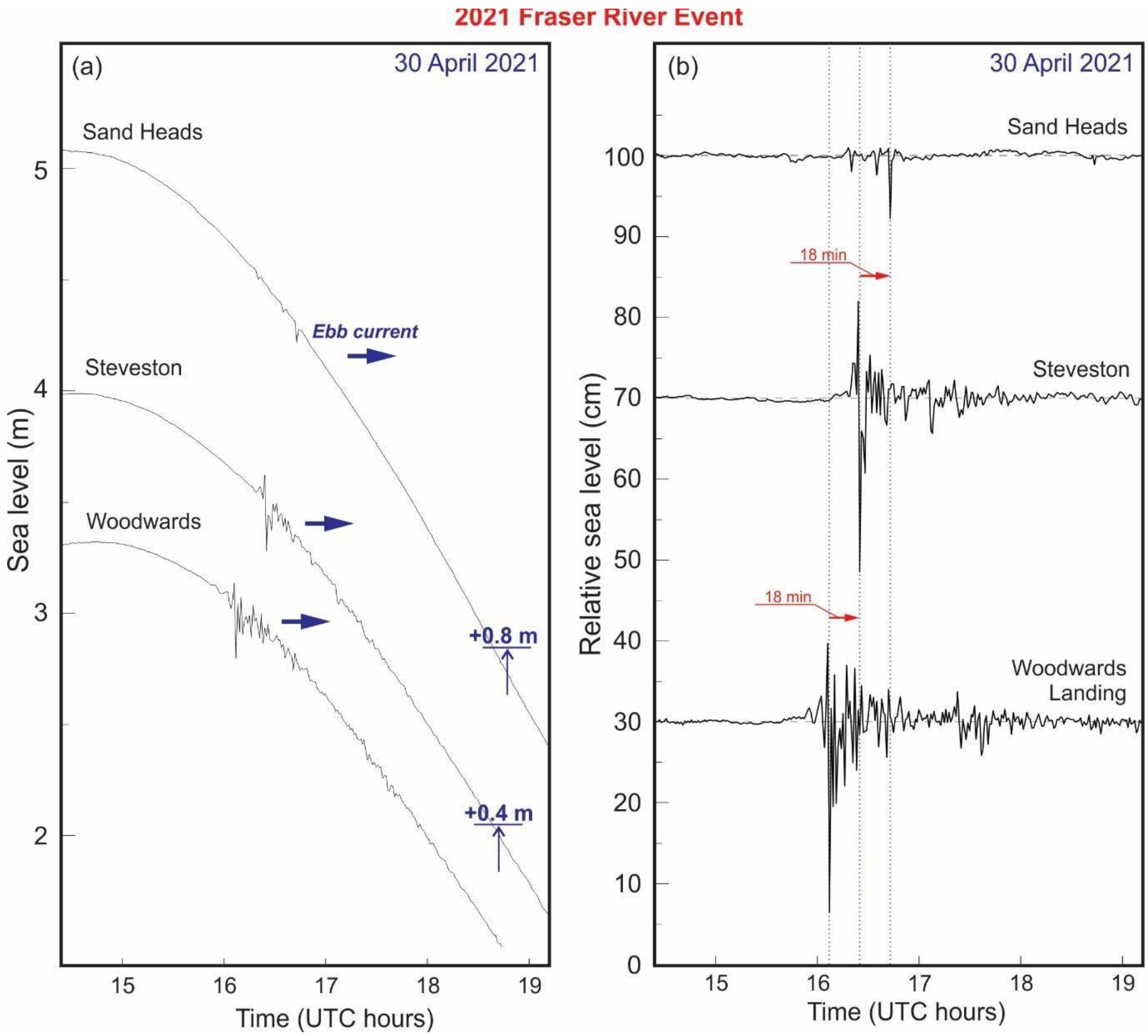

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Figure 29. (a) Original sea level records (with tides) at three CHS tide gauges in the Fraser River estuary during the event of 30 April 2021; for better view, the records are lifted up for 0.4 m relative to each other. Thick blue arrows show the direction of ebb tidal flow during the event. (b) Zoomed (relative to Figure 27) plots of de-tided and high-pass filtered sea oscillations of the event of 30 April 2021 recorded at three stations in the Fraser River estuary; time shifts between the waves recorded at various stations are indicated.

Cargo ships normally come into the Fraser River during flood tidal currents, and they go outside of the Fraser River during ebb tidal currents. Figure 28a shows the original sea level records (with tides) at the three estuary stations; they indicate that the event of 30 April 2021 occurred just during ebb currents. These currents, plus permanent discharge currents of the

Fraser River, added 3-4 knots to the speed of the outgoing ship being in a perfect agreement with the estimated speed of the "wave generator". There were an 18-min time shift between the waves recorded at Woodwards Landing (WL) and Steveston (St) and between Steveston and Sand Heads (SH) (Figure 28b). These time differences are in good agreement with the time required for a ship travelling in the Fraser River estuary to come from the area of WL to St and the into the southern Strait of Georgia to the area of SH.

It appears that the resonance occurred on 30 April 2021 when the speed of the cargo ship (*U*) moving downstream along the Fraser River exactly coincided with mean long wave speed (c $\sqrt{gh}$) in this region, i.e. when the Froude number *Fr* = *U/c* ~ 1.0, and this was the reason of strongly amplified generated ship waves. When the corresponding ship left the estuary and came to the southern Strait of Georgia (to the area of Sand Heads), the depth, *h*, significantly increased and, consequently, increased the long wave speed. Therefore, Fr became much smaller, as well as the generated ship waves; this the reason why recorded wave height were much smaller at Sand Heads than at Steveston or Woodwards Landing (Figure 28b).

9. Tsunami websites

Tsunami related websites are operated by:

1) Ministry of Emergency Management and Climate Readiness, BC (EMCR) – Prepared BC https://www2.gov.bc.ca/gov/content/safety/emergency-management/preparedbc/know-your-hazards/earthquakestsunamis/tsunami#information
2) Canadian Hydrographic Service of Fisheries and Oceans Canada (DFO) https://tides.gc.ca/en
3) Canadian Hazards Information Service of Natural Resources Canada (NRCan) https://earthquakescanada.nrcan.gc.ca/info-gen/tsunami-en.php

10. Summary plans of future tsunami warning and mitigation system improvements

The province of British Columbia has a multi-agency British Columbia Seismic Safety Council which has a Tsunami Subcommittee to focus on tsunami hazard issues. There are regular meetings between federal government departments and EMCR to focus on tsunami notification procedures. The Canadian Hazards Information Service of NRCan's Earthquake Early Warning System (EEW) will be operational in 2024 with hundreds of additional seismographs and alerting protocols providing early warning of imminent dangerous shaking in parts of British Columbia. NRCan will use EEW to integrate Global Navigation Satellite System (GNSS) geodetic data with earthquake and tsunami alerts.

NATIONAL PROGRAMMES AND ACTIVITIES INFORMATION

11. EXECUTIVE SUMMARY

The Ministry of Emergency Management and Climate Readiness (EMCR) is the provincial agency for distributing tsunami warnings to coastal stakeholders and takes the lead in tsunami public education. Environment and Climate Change Canada (ECCC) works on behalf of the EMCR Readiness (EMCR) to issue and carry BC-specific Tsunami alerts on ECCC dissemination networks. EMCR regularly conducts Provincial Emergency Notification System tests with coastal stakeholders.

The Department of Fisheries and Oceans (DFO)'s Canadian Hydrographic Service (CHS) collects, generates and disseminates water level and current data: observations, predictions and forecasts. These data are broadly used to support safe and accessible waterways for navigation, particularly for critical areas such as harbors, dredged areas and shipping routes; to support ocean monitoring, prediction and forecasting programs and services; for scientific research; to support international Tsunami and Storm Surge Warning systems operated by Emergency Management Organizations (EMOs).

NRCan's Canadian Hazards Information Service operates the CNSN, a Canada-wide network of over 100 high-gain seismographs and 60 low gain accelerographs. NRCan streams data from select CNSN stations to NTWC for inclusion in North American tsunami monitoring, assessment, and alerting. NRCan's Earthquake Early Warning System will be operational in 2024 with hundreds of additional seismic sensors and alerting protocols in British Columbia providing seconds to tens of seconds of early warning of imminent dangerous shaking. NRCan will use the nearly operational system to integrate Global Navigation Satellite System (GNSS) geodetic data with earthquake and tsunami alert.

12. NARRATIVE

Province of British Columbia – Ministry of Emergency Management and Climate Readiness (EMCR)
British Columbia has a multi-agency Seismic Safety Council which has a tsunami subcommittee to focus on tsunami hazard issues. Public Safety Canada and the Province of British Columbia, Emergency Management and Climate Readiness (EMCR) have been coordinating regular meetings between federal government departments and EMCR to focus on tsunami notification procedures.

EMCR is responsible for maintaining response plans and public notification during earthquake and tsunami events. s Tsunami warning are issued broadcasted across television, radio and compatible mobile devices through B.C.'s emergency alert system.

These include running Exercise Coastal Response (most recent 2022), a full scale earthquake and tsunami response tabletop exercise that tests and acts upon critical elements of the BC Earthquake Immediate Response Plan. https://www2.gov.bc.ca/gov/search?id=2E4C7D6BCAA4470AAAD2DCADF662E6A0&q=exercise+coastal+response

EMCR also has presentations on earthquakes, tsunamis and emergency preparedness which are made on a regular basis to emergency managers, civic officials and the general public in coastal communities. To strengthen public education, EMCR
has created the Public Emergency preparation and recovery website which contains a suite of preparedness resources which includes tsunami preparedness information. https://www2.gov.bc.ca/gov/content/safety/emergencymanagement/preparedbc

An Earthquake and Tsunami Guide can also be downloaded from the Emergency Management BC website at
https://www2.gov.bc.ca/assets/gov/public-safety-and-emergency-services/emergency-preparedness-responserecovery/embc/preparedbc/preparedbc-guides/earthquake_and_tsunami_guide.pdf

In addition, first implemented by the District of Tofino in April 2016, the High Ground Hike, a community led initiative to engage residents and visitors on the subject of tsunami risks and proper response, are held during Tsunami Preparedness Week (the second full week of April each year). The goal is to raise awareness about B.C.'s tsunami risk and give people along the coast an opportunity to practice reaching a tsunami-safe location. Details of High Ground Hike can be found at https://www2.gov.bc.ca/gov/content/safety/emergency-management/education-programs-toolkits/high-ground-hike

EMCR holds regular tsunami notification tests using the Provincial Emergency Notification System (PENS). The system is capable of disseminating a large number of messages to key stakeholders, First Nations and community emergency personnel in a short period of time. Local emergency officials use this information to activate their community emergency plans and take the necessary life-saving actions to ensure public safety.

Fisheries and Oceans Canada/Canadian Hydrographic Service (DFO/CHS)
The Department of Fisheries and Oceans (DFO)'s Canadian Hydrographic Service (CHS) collects, generates and disseminates water level and current data (observations, predictions and forecasts). These data are broadly used to support
safe and accessible waterways for navigation, particularly for critical areas such as harbors, dredged areas and shipping

routes; to support ocean monitoring, prediction and forecasting programs and services; for scientific research; to support
international Tsunami and Storm Surge Warning systems operated by Emergency Management Organizations(EMOs).

In the Pacific Region CHS operates a network of 42 real-time water level and 6 real-time current stations along the British Columbia Coast (Figure 1). Seventeen of these stations serve the Permanent Water Level Network (PWLN) and Tsunami Warning System (TWS).

Primary data acquisition is achieved using cellular IP modems (with landline, radio, satellite IP and GOES as backup). The
IP data is 'pushed' from the remote station automatically in real-time via the Integrated Water Level System (IWLS). The IWLS is a centralized, national data management system for Canadian coastal water level, current speed and direction time series and metadata.

Data from all CHS water level stations is made available on a number of platforms: standardized Web services (Rest-API) to users both internal and external to DFO; CHS National Water Level Website (https://tides.gc.ca) which provides observations at all real-time, active stations as well as predicted time interval (1 minute for Pacific) times and heights of high and low waters for over seven hundred stations in Canada; Water Level Mobile App: a Progressive Web App which connects to the IWLS through the restful API and provides water level information through any web-service connected device (mobile phones, tablets, laptop, desktop, etc.) and eleven of the stations in the network stations also have GOES satellite transmission to NOAA's Wallups Island download site for access by the National Tsunami Warning Center (NTWC) in Palmer, Alaska.

Natural Resources Canada (NRCan)

NRCan's Canadian Hazards Information Service (CHIS) operates the CNSN, a Canada-wide network of over 100 highgain seismographs and 60 low gain accelerographs. The seismographs provide greater detail of weaker ground motions from lower-magnitude or distant earthquakes. The accelerographs provide greater detail of stronger ground motions from higher-magnitude or nearby earthquakes.

The CNSN streams data in near real-time to parallel and geographically redundant data centres for automated earthquake analyses and rapid notification. Two Seismologists On Call are available 24 hours per day seven days per week to prepare earthquake reports that quickly follow the automated preliminary earthquake notifications. NRCan also streams data from select CNSN stations to NTWC for inclusion in North American tsunami monitoring, assessment, and alerting. The CNSN's high quality digital data are used to conduct research on the properties of earthquakes including seismic hazard assessments and contributions to the earthquake resistance provisions of the National Building Code of Canada.

NRCan's Earthquake Early Warning System will be operational in 2024 with hundreds of additional seismic sensors and alerting protocols in British Columbia providing seconds to tens of seconds of early warning of imminent dangerous shaking. NRCan will use the nearly operational system to integrate Global Navigation Satellite System (GNSS) geodetic data with earthquake and tsunami alert.

The discovery of Episodic Tremor and Slip (ETS) in the Cascadia Subduction zone by NRCan scientists in the Geological Survey of Canada (GSC) and the Canadian Hazards Information Service (CHIS) and subsequent observation and modelling research have led to much improved understanding of the slip behaviour of the megathrust and downward extent and alongstrike segmentation of rupture during subduction earthquakes. Observation and modelling of contemporary crustal deformation and background seismicity have improved the delineation of the locking state of the megathrust and rupture potential.

These NRCan research results help to define the magnitude of future subduction earthquakes, the proximity of shaking to inland population centers – valuable information that has been incorporated into Canada's building code. NRCan sea floor displacement results also provide the key input for tsunami generation estimates. There is also significant advancement in modelling megathrust rupture as tsunami sources which integrates geophysically-constrained fault geometry, paleoseismic studies, the theory of rupture mechanics, and knowledge learned from tsunami-genic earthquakes in other subduction zones. NRCan source models provide the basis for tsunami modelling for the purpose of early warning, design of evacuation strategy, and probabilistic hazard analyses.

The only deaths due to tsunamis in Canada since written records have begun are from tsunamis caused by landslides or landslides triggered by earthquakes. In 1908 a landslide on the Liève River in western Québec produced a wave that inundated the village of Notre-Dame-de-la Salette and killed 27 people. In Newfoundland, a magnitude 7.2 earthquake created an offshore, underwater slump on the Atlantic Ocean's Grand Banks, generating a tsunami of up to 7 m in height, which killed 29 people. The 1946 Vancouver Island M7.2 earthquake caused underwater landslides within the Strait of Georgia, one of which is known to have caused a water wave that reportedly overturned a boat and resulted in one drowning. In Knight Inlet BC, First Nations histories tell of the destruction of a village and over 100 deaths when a rock avalanche descended into the water on the opposite side of the fjord (Bornhold et al., 2010).

Landslide tsunamis occur on a more frequent basis than earthquake generated tsunamis, particular in the steep sided fjords of Canada west coast. The GSC is investigating the magnitude and frequency of these submarine failures around the country (Lintern et al., 2020). Canada has wrapped up a 5-year project aimed to understand the threat of landslide generated tsunami in Douglas Channel BC where there is a recent history of destructive landslide-generated tsunamis (Lintern et al., 2019). The project identified over 200 mass movements throughout the channel system (Stacey et al., 2020). Through collaboration between the GSC, DFO, and the University of Victoria, the work has evolved now in Douglas Channel and elsewhere to modelling of potential failure based on geologies which are indicative of possible failure (eg. Orcas Island USA, Nemati et al, 2023a), and also conducting scientific investigations to determine what technologies can be used to detect and warn of landslide generated tsunamis (Nemati et al, 2023b).

In addition, EMCR, NRCan and DFO all provide tsunami and earthquake information on their web sites. The present DFO modeling studies and tsunami catalogue provide valuable information for public education and mitigation planning. All telephone directories for communities in B.C. coastal areas contain information on earthquake and tsunami response.

Environment and Climate Change Canada (ECCC)

The Meteorological Service of Canada (MSC) of ECCC involves in the Canadian Tsunami Program on both coasts.

On the Pacific Coast of Canada, MSC's Pacific Storm Prediction Centre (PSPC) in Vancouver works on behalf of the British Columbia Ministry of Emergency Management and Climate Readiness (EMCR) who is the Tsunami Warning Focal

Point (TWFP). The PSPC issues Tsunami Alerts (Warning, Advisory or Watch) created directly from the US National Tsunami Warning Centre (NTWC) tsunami alerts or as directed by EMCR. The PSPC delivers the alerts through the ECCC alert dissemination system.

On the Atlantic Coast of Canada, MSC's Atlantic Storm Prediction Centre (ASPC) in Dartmouth, Nova Scotia, serves as the TWFP for the NTWC and for the Canadian Atlantic Tsunami Warning System (CATWS). The ASPC receives the relevant tsunami bulletins from the NTWC, reformats the messages to create Canadian-specific tsunami bulletins, and then transmits the Canadian-specific bulletins to a pre-defined list of stakeholders. These bulletins are also disseminated to the Canadian public through a variety of dissemination systems of ECCC. The purpose of reformatting the NTWC tsunami messages into Canadian-specific products is to simplify and clarify the messages for a Canadian audience by providing provincial Emergency Management Organizations (EMOs) and other Canadian recipients with the specific information they need to make decisions and take actions.

The ASPC serves as the back-up office of the PSPC. Its sister office, Newfoundland and Labrador Weather Office (NLWO) situated in Gander, Newfoundland, is designated as the contingency office for the ASPC.

12.1. Selected tsunami and subduction zone related publications from or about Canada 2019-2023

2019

Itoh, Y., K. Wang, T. Nishimura, and J. He (2019), Compliant volcanic arc and back-arc crust in southern Kurile suggested by interseismic geodetic deformation, *Geophysical Research Letters*, 46, 11790–11798. doi:10.1029/2019GL084656

Luo, H., K. Wang, H. Sone, and J. He (2019), A model of shallow viscoelastic relaxation for seismically induced tension cracks in the Chile-Peru forearc, *Geophysical Research Letters*, 46, 10,773–10,781. doi:10.1029/2019GL084536

Lintern, G., Blais-Stevens, A., Stacey, C., Shaw, J., Bobrowsky, P., Conway, K., et al. (2019). Providing multidisciplinary scientific advice for coastal planning in Kitimat Arm, British Columbia. *Geol. Soc. Lond. Spec. Publ.* 477, 567–581. doi: 10.1144/SP477.40

Rabinovich, A.B., Thomson, R.E., Krassovski, M.V., Stephenson, F.E., and Sinnott, D.C. (2019), Five great tsunamis of the 20th century as recorded on the coast of British Columbia, *Pure and Applied Geophysics*, 176, 2887–2924; doi:
10.1007/s00024-019-02133-3.

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