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Meteorological tsunamis on the coasts of British Columbia and Washington

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ABSTRACT

Tsunami-like sea level oscillations recently recorded by tide gauges located at offshore, as well as sheltered, sites along the coasts of British Columbia (Canada) and Washington State (USA) are identified as meteorological tsunamis. The events resemble seismically generated tsunamis but have an atmospheric, rather than seismic, origin. The event of 9 December 2005 was sufficiently strong to trigger an automatic tsunami alarm, while other events generated oscillations in several ports that were potentially strong enough to cause damage to marine craft. Analysis of coincident 1-min sea level data and high-frequency atmospheric pressure data confirms that the events originated with atmospheric pressure jumps and trains of atmospheric gravity waves with amplitudes of 1.5–3 hPa. The pronounced events of 13 July 2007 and 26 February 2008 are examined in detail. Findings reveal that the first atmospheric pressure event had a propagation speed of 24.7 m/s and an azimuth of 352°; the second event had a speed of 30.6 m/s and an azimuth of 60°. These speeds and directions are in close agreement with high-altitude geostrophic winds (the jet stream) indicating that the atmospheric disturbances generating the tsunami-like sea level oscillations are likely wind-transported perturbations rather than freely propagating atmospheric gravity waves.

1. Introduction

The coasts of British Columbia and Washington form a complex network of straits, channels, sounds, narrows, inlets and bays (Fig. 1). Much of this coastline is susceptible to tsunamis generated within the Pacific Ocean (cf. Lander et al., 1993; Clague et al., 2003). Because of its complicated geometry and numerous partially isolated basins, the coastal region is also susceptible to the generation of atmospherically induced seiches. Such motions are commonly observed in Whaler Bay, Campbell River, Pedder Bay, Port San Juan, Ucluelet Inlet, and Esquimalt Harbour in British Columbia (Lemon, 1975; Thomson, 1981). Because the heights of these oscillations are normally small compared with the tides (which typically range from 3 to 8 m in this region), and because local tide gauges were not originally designed to measure seiches or other high-frequency sea level oscillations, occurrences of meteotsunamis have been poorly documented. Nevertheless, "tsunami-like waves of unknown origin" (which were likely strong atmospherically generated seiches) have been reported for the Pacific coast (cf. Lander et al., 1993; Stephenson et al., 2007).

The destructive Pacific tsunamis of the 1990s initiated a major upgrade of the existing Tsunami Warning Stations (TWS) and Permanent Water Level Network (PWLN) stations on the British Columbia (BC) coast. The new digital instruments, deployed by the Canadian Hydrographic Service (CHS), were designed to continuously measure sea level variations with high precision and to store the resulting sea level records once every minute. By 1999, 13 tide gauge stations were upgraded and operational; three of these stations, located along the outer coast at Tofino, Winter Harbour, and Langara (Fig. 1), were selected for use in tsunami warning (Rabinovich and Stephenson, 2004). During the period 1999–2008, long time series of high quality 1-min sea level data were collected and several weak tsunamis were recorded and identified (Stephenson and Rabinovich, 2009). The National Oceanic and Atmospheric Administration (NOAA) conducted similar coastal tide gauge upgrades for the US West Coast in order to provide digital recordings of sea level with 1-min sampling (cf. Allen et al., 2008). The newly upgraded Canadian and US instruments are accurate enough to measure local seiches.

The Tsunami Warning gauges located on the BC coast compute the mean per-minute change in sea level based on the last 3 min of observation and compare this value with a threshold value (e.g., 16 mm/min at Tofino). If the threshold value is exceeded for three

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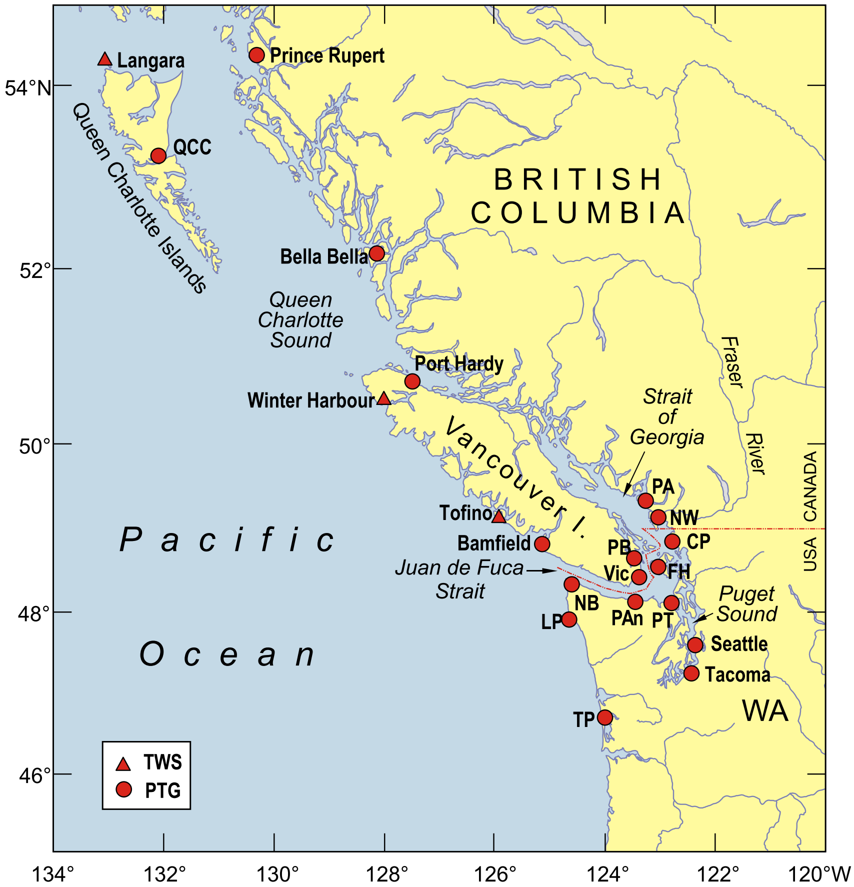

Fig. 1. Location of selected tide gauge stations on the coasts of British Columbia (Canada) and Washington State (USA). Solid triangles denote the Tsunami Warning Stations (TWS) operated by the Canadian Hydrographic Service (CHS); solid circles denote the CHS Permanent Water Level Network (PWLN) and NOAA permanent tide gauges (PTG). "QCC", Queen Charlotte City; "PB", Patricia Bay; "Vic", Victoria; "PA", Point Atkinson; "NW", New Westminster; "CP", Cherry Point; "FH", Friday Harbor; "PT", Port Townsend; "PAn", Port Angeles; "NB", Neah Bay; "LP", La Push; "TP", Toke Point.

consecutive 1-min estimates, a tsunami alarm is generated. The algorithm has been designed to provide the lowest possible detection threshold without triggering false alarms due to ordinary background oscillations. A host computer at the Institute of Ocean Sciences (IOS) receives the alarm message and automatically issues a pager call to alert response personnel to investigate the tsunami event (Rabinovich and Stephenson, 2004). On 9 December 2005 at 01:57 UTC (17:57 PST, 8 December 2005) an automatic tsunami alarm was generated by the Tofino TWS. The tide gauge recorded an exceptional change in sea level that exceeded the specified threshold value. There were no distant or local seismic events at the time that could have generated the sea level oscillations and a visual inspection of the corresponding records from TWSs at Winter Harbour and Langara revealed no potentially threatening surface waves. As a result, no tsunami warning was issued for the BC coast. However, a post-event examination of the sea level records revealed that pronounced sea level oscillations (Fig. 2a) had occurred at outer coastal stations (Tofino, 15.5 cm; Bamfield, 14.5 cm; and Winter Harbour, 10.7 cm) as well as in the sheltered bays, inlets and channels of the Strait of Georgia (e.g., Patricia Bay, 5.3 cm; Vancouver, 6.4 cm; and Point Atkinson, 5.4 cm), sites that are well protected from tsunami waves arriving from the open Pacific. Further analysis indicated that unusual short-period sea level oscillations took place along the entire BC coast, from Prince Rupert to Victoria, a distance of approximately 1000 km (Rabinovich, 2005). A preliminary examination of the records showed that these oscillations continued for approximately 9–12 h and had a polychromatic frequency distribution with dominant periods in the range of 10–60 min. Noticeable tsunami-like oscillations occurred almost simultaneously on the opposite (oceanic and mainland) coasts of Vancouver Island, excluding the possibility that the December 2005 oscillations were generated by a local submarine landslide or distant tsunami. A clear time shift between oscillations observed at the northern and southern sites suggests that they were induced by a disturbance propagating from the northwest to the southeast at a speed of about 30–35 m/s. Anomalous sea level oscillations were also observed at several stations in Washington State (Fig. 2b) including sheltered sites in the Strait of Georgia, Puget Sound, and Juan de Fuca Strait, as well as at stations on the oceanic coast. Records indicate that the disturbance continued to move southeastward at a speed of about 25 m/s. The duration and properties of the observed seiches were very similar to those observed at the BC stations (Fig. 2a and b).

The weather during the December 2005 event was calm. A high-pressure system was situated over the West Coast at this time and there were no storms, fronts or squalls in the region. Thus, the December event was not related to storm activity. On the other hand, the properties of the anomalous sea level oscillations observed along the coasts of British Columbia and Washington (WA), combined with the broad (~1200 km) extent of the region affected, the occurrence of oscillations on both the open coast and in sheltered areas, and the duration and frequency content of the recorded waves, are typical of meteorological tsunamis; i.e., tsunami-like waves produced by atmospheric activity (Defant, 1961; Rabinovich and Monserrat, 1996, 1998). Such events are common in Nagasaki Bay, Japan (locally known as '*abiki*' waves)

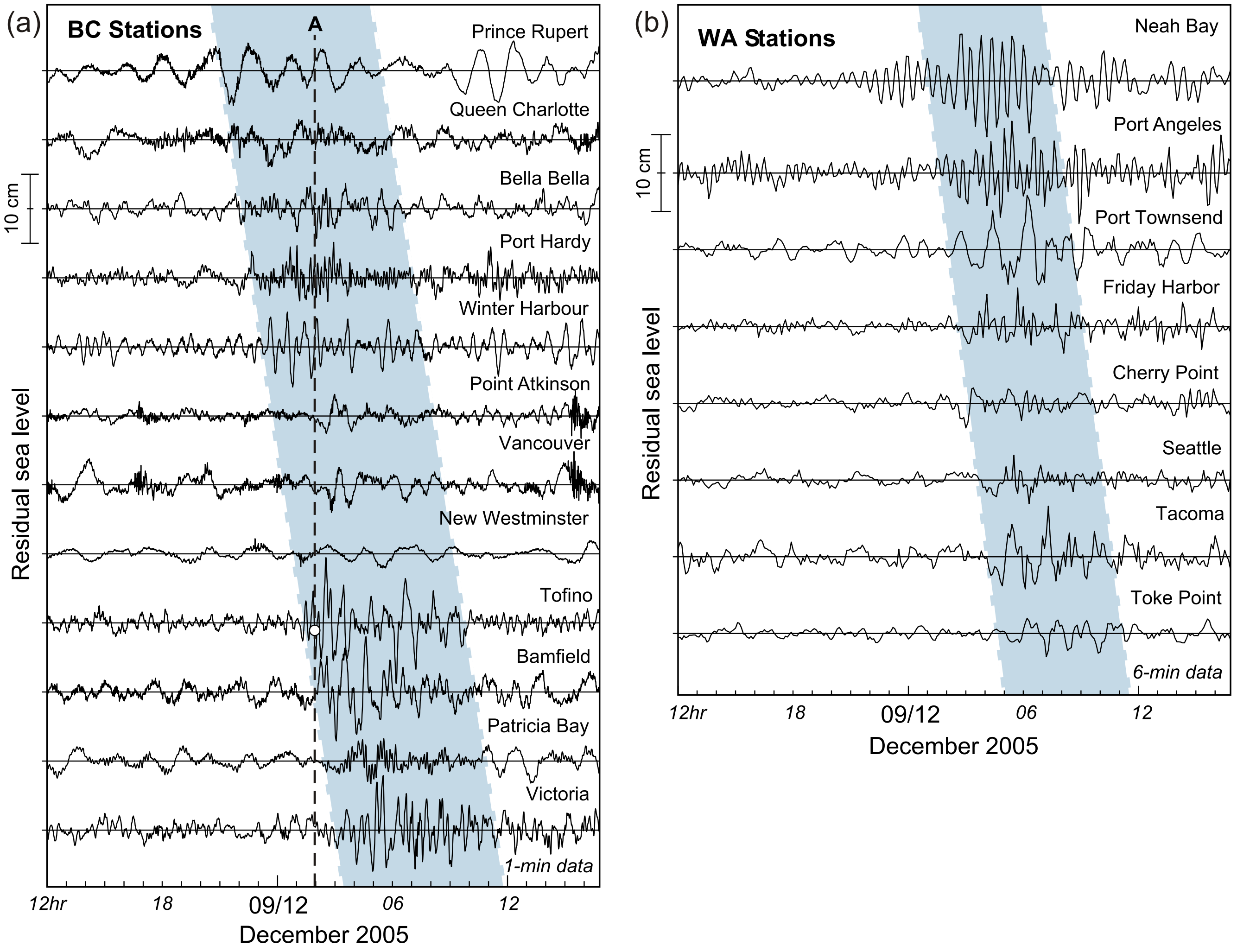

Fig. 2. The meteorological tsunami of 9 December 2005 at: (a) British Columbia CHS and (b) Washington NOAA stations. Predicted tides were removed from the records which were then high-pass filtered with a 3-h Kaiser–Bessel (KB) window (cf. Emery and Thomson, 2003). The dashed line in: (a) with the label "A" marks the time of the automatic alarm at Tofino. The station plots are ordered by latitude (from north to south). The shaded regions approximate the times of high sea level variability at the different locations and are not meant for quantitative analyses.

(Hibiya and Kajiura, 1982), in the Balearic Islands, Western Mediterranean ('*rissaga*' waves) (Tintoré et al., 1988; Gomis et al., 1993; Rabinovich and Monserrat, 1996, 1998; Vilibić et al., 2008), on the Croatian coast of the Adriatic Sea ("*šćiga*") (Vilibić et al., 2004; Vilibić and Šepić, 2009; Šepić et al., 2009) and in several other regions of the World Ocean (cf. Rabinovich and Monserrat, 1996; Monserrat et al., 2006; Rabinovich, 2009). These waves are most commonly generated by atmospheric pressure disturbances, especially "jumps" in atmospheric pressure, and by trains of internal waves. Both types of disturbances are commonly associated with high-pressure systems and calm weather (cf. Gossard and Hooke, 1975; Monserrat et al., 1991).

Due to a lack of precise high-frequency atmospheric pressure fluctuation data, the exact source of the observed sea level oscillations was not identified immediately after the 2005 event. Nevertheless, for the reasons given above, the event of 9 December 2005 was recognized as a meteorological tsunami and listed as such in the Catalogue of Tsunamis for the coast of British Columbia (Stephenson et al., 2007; see also Stephenson and Rabinovich, 2009). Subsequently, we were able to locate simultaneous 6-min sea level and atmospheric pressure records for La Push (WA) that indicated that these oscillations had been generated by passage of an abrupt air pressure jump of 2.5 hPa (Fig. 3). This was probably the first

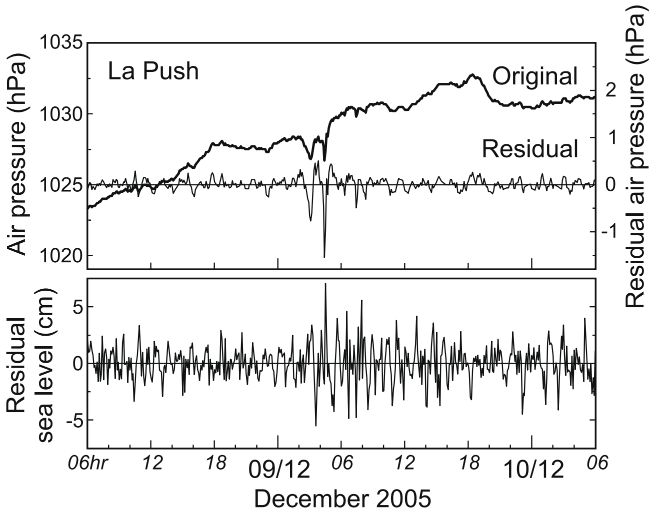

Fig. 3. La Push (WA) records of original air pressure (6-min data), residual air pressure (after high-pass filtering with a 3-h KB-window) and residual high-pass filtered sea level (1-min data) for the event of 9 December 2005.

meteorological tsunami reported for the coast of British Columbia. Earlier tsunami studies for this region (cf. Wigen, 1983) did not recognize meteorological tsunamis and none were described for the BC coast prior to December 2005. However, Lander et al. (1993), listed 23 tsunamis of meteorological origin and 6 tsunamis of "unknown origin" (which were also likely atmospherically induced) for the West Coast of the United States for the period 1806–1992. The trigger for recognition of the 2005 meteorological tsunami event was the alarm software incorporated into the TWS 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 because stations on the BC coast routinely have pronounced seiches superimposed on the tidal signal. This alarm feature did not exist when water levels were recorded using only analogue recorders.

It is safe to assume that tsunami-like events of meteorological origin are fairly common on the BC-Washington coast. This is supported by the measurement and analysis of long waves observed from 2006 to 2008 in tide gauge records for the coast of British Columbia which reveal several events with marked tsunami-like oscillations of non-seismic origin. Two impressive events occurred on 13 July 2007 and 26 February 2008. In contrast to the 2005 event, we were able to locate high-frequency atmospheric pressure data for these two events for analysis and comparison with coincident sea level oscillations. This study presents results for the 2007 and 2008 events for which we were able to locate simultaneous sea level and atmospheric pressure data.

2. Meteotsunami of 13 July 2007

An unusual tsunami-like event occurred on the morning of July 13, 2007. It was first noticed in the tide gauge record for Patricia Bay during the daily data quality control check by the Canadian Hydrographic Service. Patricia Bay is located in Saanich Inlet on the inner (southeastern) corner of Vancouver Island, and is well protected by numerous islands from waves arriving from the Strait of Georgia or from the Pacific Ocean (Fig. 4). Later that day, a phone call was received from a resident of Thetis Island (37 km north of Patricia Bay, Fig. 4a), asking if a tsunami had occurred that morning at about 5:00 PDT (12:00 UTC). Residents Ken Youds and Jan Therrien of Thetis Island sent the following eye-witness report:

> *"Our home is on a large rural property bounded on the east by a shallow, 1.5 km long, inlet/lagoon. . .On rising at about 5 a.m. on the date in question, I <Ken> heard the sound of a northwest wind building (one can hear it high in the trees on the far side of the inlet). . . As I walked down the path from the house toward the dock, I could see the inlet water flowing in (as if it was an incoming tide) at an unusually fast rate. I didn't pay too much attention until I got to the dock. On the dock I started picking up various abandoned items and then noticed that the dock was being forcibly shifted southward by the unusually strong inflowing tide – as though it was a 2–3 knot current. I have done a lot of kayaking along the BC coast, including through tidal currents, so am familiar with gauging current speed. Anyway, just as I was staring at the fast moving water, I noticed it start to swirl. Kelp, buoys, lines of the dock all started to twist about, and then the water began to move rapidly (2–3 knots) outwards (toward the north, where in inlet entrance is). I watched for about a minute, and then the tidal surge reversed again, running inward. After another minute or so, it reversed again. I kept watching and wishing I could share this event with someone, but alas everyone was sound asleep. I knew that I was watching the inlet (which is 100 meters across) behave as if it was a surge channel, and therefore I concluded that some kind of physical event had happened somewhere to cause this.*
>
> *As our property (and dock) are along the north–south shore of the inlet, there was no significant change in water depth. I would expect that there was a depth change at the south end each time the surge crested – like the far end of large bathtub when movement occurs. No one lives down there full time, and no one would have at the water's edge at that time of day anyway. . .I figure that the shallow, long, narrow nature of the inlet gives it the ability to act as a sensitive "fingertip" on pressure waves, etc."*

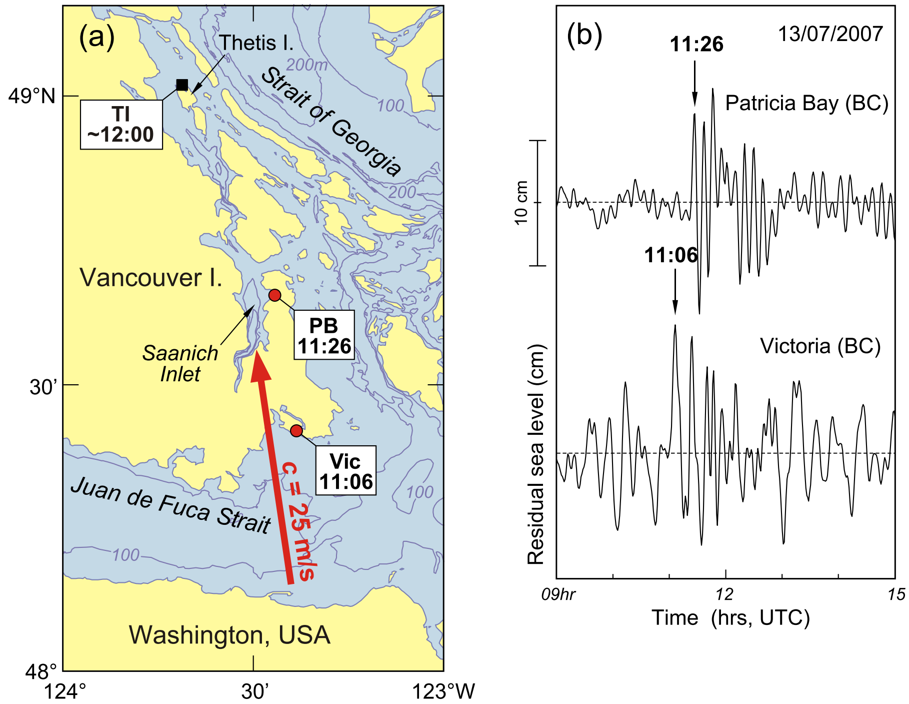

Fig. 4. The 13 July 2007 meteotsunami event: (a) locations of the Victoria (Vic) and Patricia Bay (PB) tide gauges and Thetis Island where the event was observed. Also shown are the arrival times of the first crest wave and the velocity vector for the atmospheric disturbance and (b) residual tide gauge records of the event at Patricia Bay and Victoria.

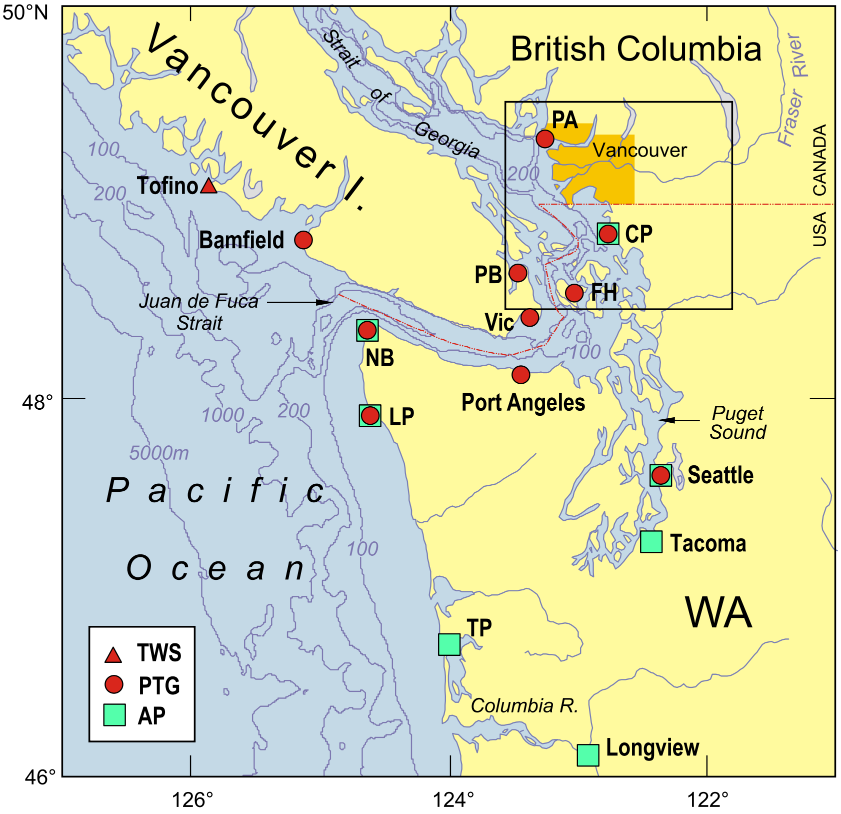

Fig. 5. Locations of British Columbia and Washington State tide gauges (solid circles), Tofino Tsunami Warning Station (solid triangle) and Washington atmospheric pressure stations (solid squares). The box encompasses the BC atmospheric pressure recording sites near Vancouver (see Fig. 7). "TWS", Tsunami Warning Station; "PTG", permanent tide gauge; "AP", air pressure station. The box encloses the Vancouver Metro air pressure stations shown in Fig. 7. "PB", Patricia Bay; "Vic", Victoria; "PA", Point Atkinson; "CP", Cherry Point; "FH", Friday Harbor; "NB", Neah Bay; "LP", La Push; "TP", Toke Point.

Inspection of the Victoria tide gauge (located in Juan de Fuca Strait; Fig. 4a) indicated anomalous seiche oscillations at the time of the Thetis Island event which were similar to those observed in Patricia Bay (Fig. 4b). High-frequency sea level activity was also observed in the Tofino tide gauge record on the west coast of Vancouver Island (Fig. 1). Because there was no earthquake at the time, the event was categorized as a meteorological tsunami (Stephenson and Rabinovich, 2009). To determine the forcing mechanism for the July 2007 meteotsunami, we collected sea level and atmospheric pressure data from British Columbia and Washington State stations for the time of the event. As indicated by Fig. 5, most stations in the Juan de Fuca Strait – Puget Sound – Southern Strait of Georgia region recorded the event.

2.1. Tide gauge records

Sea level oscillations were examined using the 1-min digital data from CHS tide gauges located in the southern part of British Columbia and from NOAA NOS/CO-OPS[1] tide gauges in northern Washington State (Fig. 5). Unfortunately, the CO-OPS data were gappy. Gaps were typically of 6-min duration and appear to have been related to data transmission and storage problems (the data are transmitted in 6-min blocks). These gaps were linearly interpolated, causing some extreme values associated with meteorological tsunamis to be lost. Fig. 6 shows records of the 13 July 2007 event at seven sites: two in BC (Victoria and Patricia Bay) and five in WA (Seattle, Neah Bay, Port Angeles, Friday Harbor and Cherry Point). The event was also identified in other records (e.g., Point Atkinson, Vancouver, Tofino, La Push and Tacoma) but the oscillations at these sites were weak (<4 cm) and the signal/noise ratios low. Conversely, the seven records in Fig. 6 had relatively high signal/noise ratios and were therefore subject to further analyses. As shown in Table 1, the maximum trough-to-crest wave heights for the seven sites ranged from 5 to 6 cm (Cherry Point, Friday Harbor and Neah Bay) to 16–17 cm (Victoria and Patricia Bay); the observed periods were from 6 to 22 min (i.e., similar to typical periods of tsunami waves observed in this region, cf. Rabinovich and Stephenson, 2004; Rabinovich et al., 2006); and the duration of the events was a few hours.

The arrival times of the main train of sea level oscillations indicate a general northward propagation with estimated arrival times of 10:24 UTC at Port Angeles, 10:59 at Victoria, 11:23 at Patricia Bay, 11:27 at Friday Harbor, and 11:32 at Cherry Point. According to the eyewitness account quoted above, the anomalous oscillations at Thetis Island began around 12:00 UTC, consistent with the propagation speed based on arrival times for other sites (Fig. 4a). At some sites (e.g., Patricia Bay), the first arrival was clear and abrupt, while at other sites it was obscured by preceding oscillations (Figs. 4b and 6). At certain sites (e.g., Victoria, Port Angeles and Seattle), these pre-event oscillations formed a well-defined "first wave train" that foretold the arrival of the "main wave train" (at Neah Bay, the first wave train, but not the main wave train, was observed). The arrival times of the first wave train in Table 1 are shown in brackets. We assume that spatial transformation and distortion of the propagating atmospheric disturbances strongly affect sea levels at local sites, leading to differences in the sea level oscillations at the different sites.

2.2. Atmospheric pressure records

Access to simultaneous, high quality, high-frequency sea level and atmospheric pressure measurements are the key to establishing

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[1] National Oceanic and Atmospheric Administration, National Ocean Service, Center for Operational Oceanographic Products and Services.

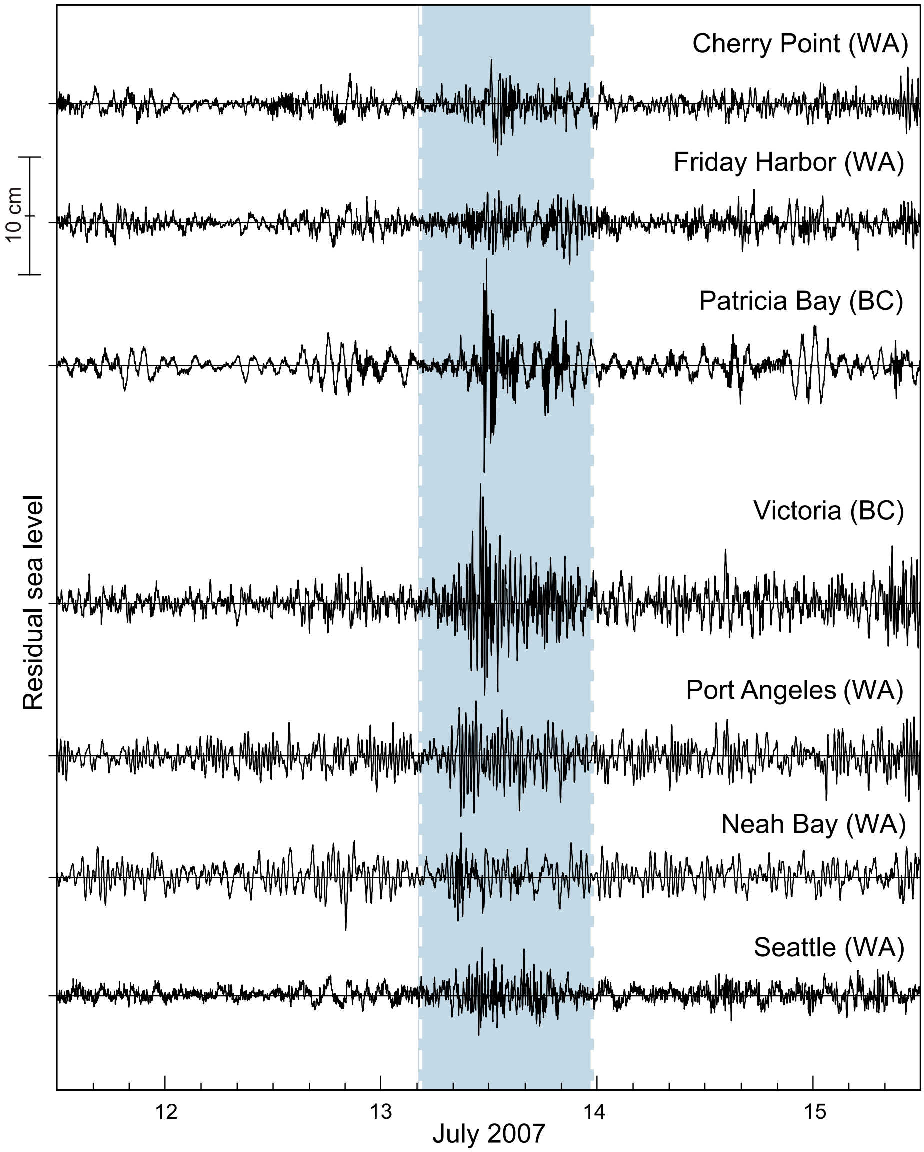

Fig. 6. Records of the meteorological tsunami of 13 July 2007 from British Columbia and Washington State tide gauges. Predicted tides were removed from the records and the records then high-pass filtered with a 3-h KB-window. The shaded regions approximate the times of high sea level variability at the different locations and are not meant for quantitative analyses.

Table 1
Estimated parameters for the meteotsunami waves of 13 July 2007 recorded by tide gauges located on the coasts of British Columbia (BC) and Washington (WA). Values in brackets denote the arrival times of the first wave train.

No.	Station	Country, state or province	Coordinates	Event start time (UTC) hh:mm	First crest arrival (UTC) hh:mm	Max wave height (cm)	Observed period (min)
1	Cherry Point	USA, WA	48.86°N; 122.76°W	11:32	11:38	6	7; 12
2	Friday Harbor	USA, WA	48.55°N; 123.01°W	11:27	11:31	5	10; 19
3	Patricia Bay	Canada, BC	48.65°N; 123.45°W	11:23	11:26	16	9
4	Victoria	Canada, BC	48.42°N; 123.37°W	10:59 (09:24)	11:06 (09:35)	17 (12)	8; 17 (17)
5	Port Angeles	USA, WA	48.37°N; 124.62°W	10:24 (08:33)	10:37 (08:45)	11 (9)	22 (22)
6	Neah Bay	USA, WA	48.12°N; 123.44°W	(08:18)	(08:21)	6	6
7	Seattle	USA, WA	47.60°N; 122.33°W	10:41 (09:07)	10:45 (09:12)	8 (4)	20 (18)

the atmospheric origin of anomalous tsunami-like sea level oscillations. Such measurements on, and in the vicinity of Menorca Island (Balearic Islands, Spain), indicate that the catastrophic rissaga waves that regularly occur in this region are induced by atmospheric gravity waves and pressure jumps propagating in the northeast direction over the Western Mediterranean (Monserrat et al., 1991, 1998; Rabinovich and Monserrat, 1996, 1998). Digital 1-min records of atmospheric pressure fluctuations for this region were obtained by precise microbarographs installed during hydrophysical experiments targeted specifically to examine the rissaga phenomenon. However, routine atmospheric pressure observations from meteorological network stations normally cannot be used for this purpose because of long sampling intervals (typically 1 h) and a lack of precision. To overcome this problem, the investigators working on

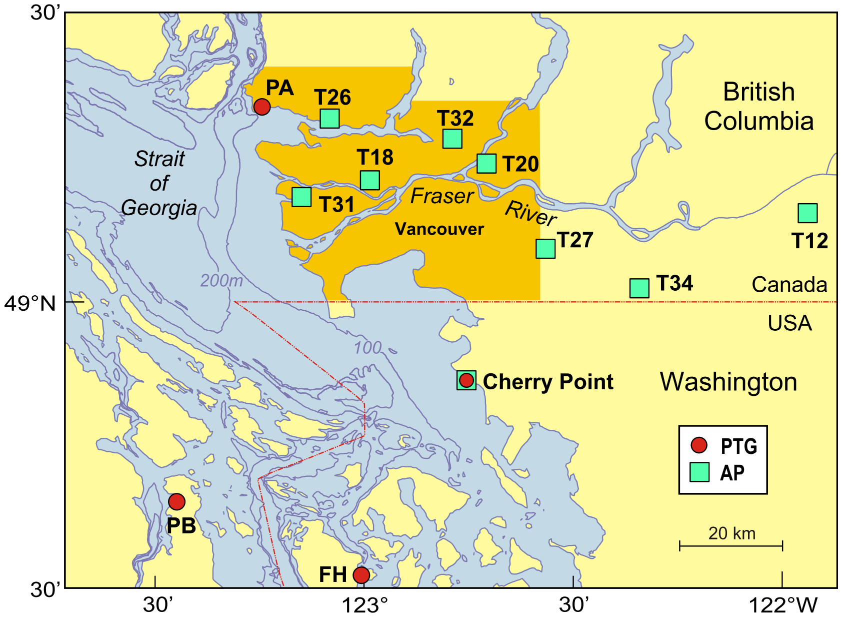

Fig. 7. Locations (solid squares) of the eight lower fraser valley (LFV) air quality monitoring network stations in Metro Vancouver and the Cherry Point station in northern Washington where atmospheric pressure is recorded. Also shown are the Patricia Bay (PB), Point Atkinson (PA), Friday Harbor (FH), and Cherry Point tide gauges (solid circles).

meteorological tsunamis had to digitize analogue paper records to uncover and then isolate potential atmospheric disturbances and to examine their relationship to extreme sea level oscillations (cf. Vilibić et al., 2004; Šepić et al., 2009).

For the present study, an extensive search for rapidly sampled atmospheric pressure time series for the time of the 13 July 2007 event revealed two types of appropriate digital data:

(1) For the British Columbia coast, data from the Lower Fraser Valley (LFV) Air Quality Monitoring Network;
(2) For the Washington coast, data from NOAA CO-OPS pressure observations.

The LFV Air Quality Monitoring Network comprises 27 air quality stations located from Horseshoe Bay in West Vancouver to Hope in the Fraser River Valley. A total of 23 stations are located in the Greater Vancouver Regional District (GVRD) and 4 in the Fraser Valley Regional District (FVRD). The main purpose of these automatic stations is to measure pollutants and weather factors influencing pollutants. Eight of the 27 stations indicated in Fig. 7 (T12, T18, T20, T26, T27, T31, T32 and T34) measure atmospheric pressure with a 1-min sampling interval and store the data with a resolution of 0.1 or 0.3 hPa (more precisely, with 0.01 in. of mercury ≈0.34 hPa). The actual resolution of the instruments appears to be higher than this nominal resolution, although the latter is considered sufficient for the applied purposes of the system operators.

Some station records had gaps during the events. Therefore, for the event of 13 July 2007 we selected four records: T18 (Burnaby South), T20 (Pitt Meadows), T31 (Vancouver Airport) and T34 (Abbotsford Airport) which had highest quality and fewest gaps. Positions of these stations are shown in Fig. 7, while the records themselves are plotted in Fig. 8a. The records look step-like because of inadequate pressure resolution. Despite these shortcomings, the main features of the atmospheric pressure signal remain evident, including marked high-frequency oscillations at the sites between ~03:00 and 23:00 (UTC) on 13 July 2007. There was also an abrupt jump in atmospheric pressure of ~2.6 hPa at Station T34 at about noon on July 13. A weaker atmospheric disturbance was also observed at stations T18, T20 and T31. The time of this disturbance matches the time of the anomalous sea level event recorded at the Victoria and Patricia Bay tide gauges and reported by the resident of Thetis Island (Fig. 4). Other noticeable high-frequency atmospheric fluctuations observed at stations T18, T20, T31 and T34 correlate well with intensification of the sea level oscillations (Figs. 6 and 8a). We remark that all events occurred during a time of calm weather and high atmospheric pressure (>1020 hPa), rather than during a storm or intense low pressure.

The NOAA CO-OPS air pressure stations were generally located at the same locations as the tide gauges. Prior to 2004, the air pressure stations recorded atmospheric pressure with a 1-h sampling but then began gradually switching over to 6-min sampling. To examine the event of 13 July 2007, we were able to use five stations: Longview, Tacoma, Seattle, La Push and Neah Bay (the locations are shown in Fig. 5). Unfortunately, Cherry Point, the station nearest to the Metro Vancouver pressure stations, had 1-h sampling and therefore could not be used to examine the 2007 event.

The CO-OPS stations recorded high-frequency atmospheric pressure fluctuations in Washington that were similar to those recorded by Vancouver Metro stations in southern British Columbia. Pronounced atmospheric disturbances were observed at Longview, Tacoma, and Seattle, while at two other stations (La Push and Neah Bay) they were much weaker (Fig. 8b). The first three stations are located in the inland Georgia Depression (Thomson, 1981), while the last two are on the Pacific coast. This suggests that the disturbances were horizontally variable and propagating along-valley.

Our examination of the pressure records shows the complicated spatial structure of the atmospheric disturbances and indicates that they undergo rapid modification and transformation during propagation. Residual (high-pass filtered) air pressure records reveal additional spatial and temporal changes in the disturbances (Fig. 9). For example, the train of significant atmospheric waves that propagated along the Georgia Depression between 5:00 and 11:00 UTC on 13 July 2007 were apparently responsible for the sea level oscillations (“first train”) observed at Seattle, Port Angeles, and Victoria (Table 1, Figs. 4a and 6). The strongest waves (>2 hPa) in this train were recorded at Tacoma. The waves were weaker at Seattle (Fig. 9b) and not observed at the Canadian stations (T18, T20, T31 and T34). Several other disturbances were

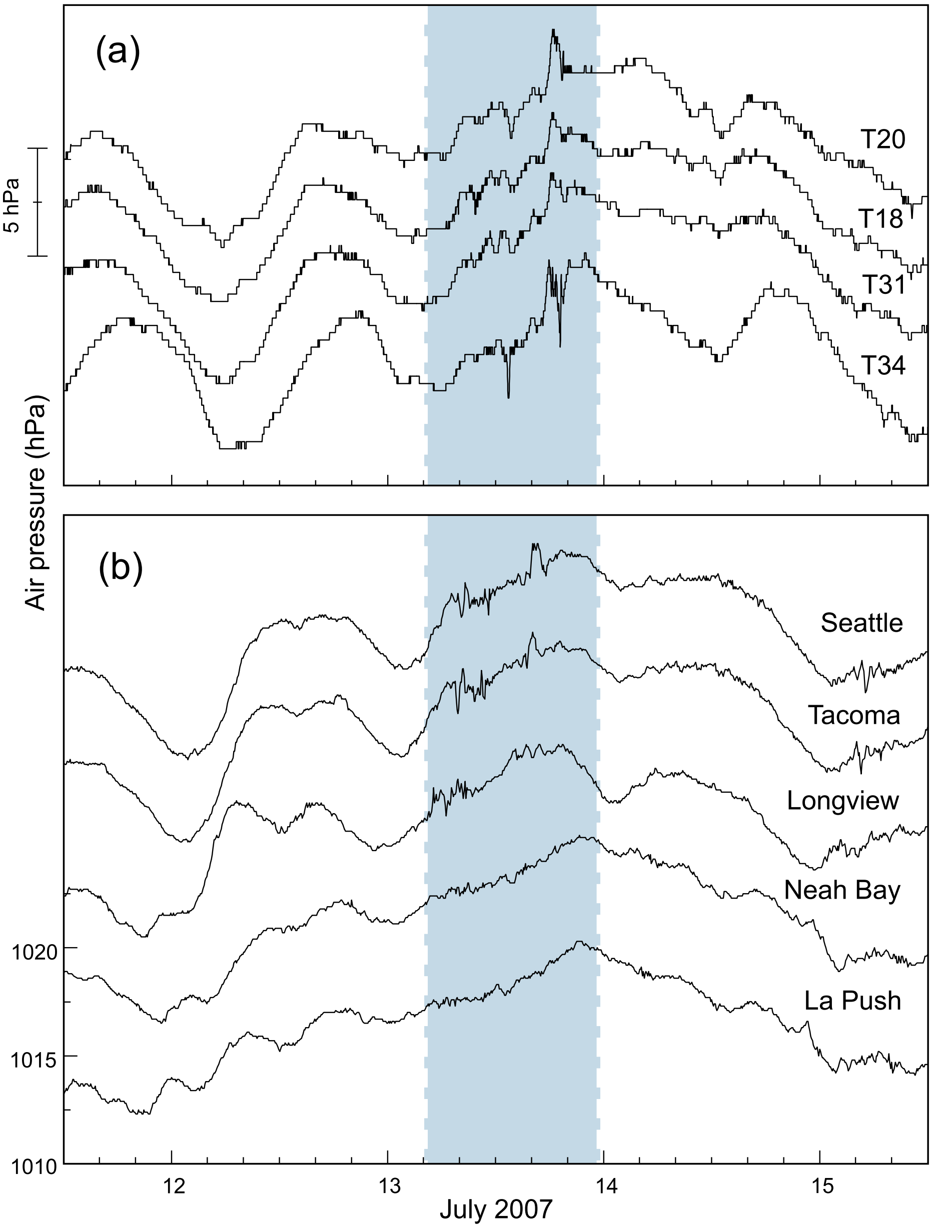

Fig. 8. Air pressure records for: (a) four BC stations (see Fig. 7 for locations) and (b) five WA stations (see Fig. 5 for locations) for the July 2007 event. The shaded region approximates the period of intense high-frequency air pressure fluctuations. The step-like character of the BC records is due to the low air pressure resolution (~0.3 hPA). The sampling intervals for the BC and WA records were 1 min and 6 min, respectively.

recorded at selected pressure stations but absent at others. So, either these oscillations were short-lived or they had short spatial scales across the direction of propagation. The disturbance that was recorded at almost all BC and WA stations (except oceanside stations La Push and Neah Bay) occurred between 15:00 and 20:00 UTC on 13 July. This disturbance reached a maximum height of about 4 hPa at the easternmost Station T34 (Abbotsford Airport). The fact that the specific atmospheric disturbance at T34 did not generate detectable sea level oscillations in the study region supports our conclusion that the generation process is far from trivial.

2.3. Estimation of wave velocities

To estimate the atmospheric wave velocities, we used an isochronal analysis method, similar to that used by Orlić (1984) and Šepić et al. (2009). The method is based on the assumption that the air pressure disturbances propagate as plain waves with uniform speed and direction. In this case, the theoretical arrival time is a linear function of position. We applied a linear regression model to estimate regression coefficients which are components of the “inverted velocity vector” (c^{-1}); this vector, which represent an “effective” wavenumber vector integrated over the wave frequency band, was then used to estimate wave speed and direction (azimuth). The calculations were made with two sets of data: (1) four BC stations (T18, T20, T31, and T34); (2) the same four BC stations plus three WA stations (Longview, Tacoma, and Seattle). We used features in the air pressure signal which could be distinguished in all coincident records. As part of a sensitivity analysis, we conducted independent calculations for several distinct features during the active atmospheric period of 13 July 2007 and obtained almost identical results. These results indicate that the velocity vectors of the atmospheric disturbances during the “active” period remained nearly constant over time.

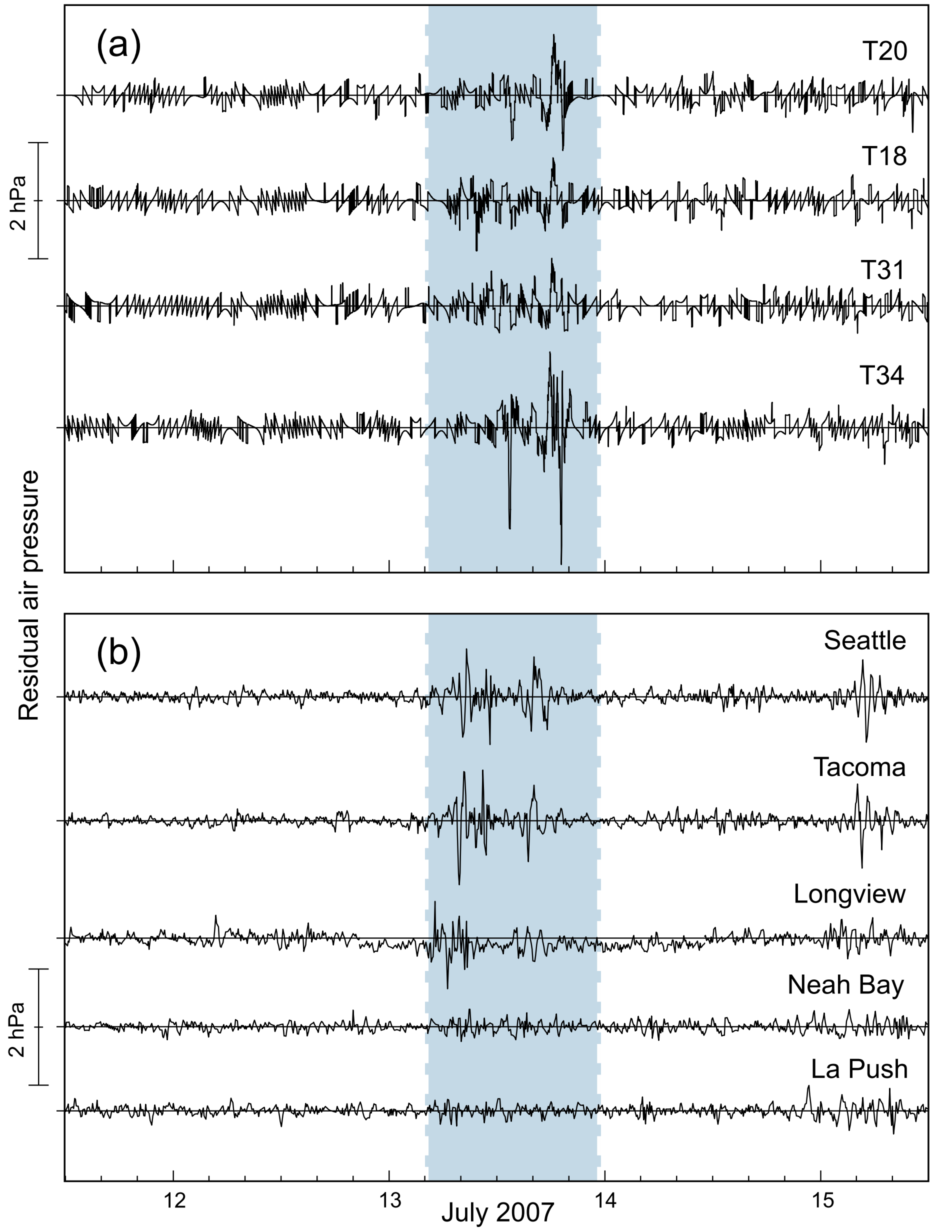

Fig. 9. As in Fig. 8 but after high-pass filtering with 3-h Kaiser–Bessel window.

The results of our computations are presented in Table 2 and Fig. 10. To estimate the 95% confidence regions of the inverted velocity vectors, we constructed *error ellipses*[2]. The orientation and ratio of minor to major ellipse axes are primary determined by the relative distribution and orientation of the stations ("station antenna orientation"). In particular, for the first set of stations (4 BC stations), the spatial resolution in the meridional direction was quite poor; consequently, the accuracy of the vector computations in this direction was low (Fig. 10a). The addition of three stations to the south of the BC stations significantly improved the resolution, thereby enhancing the accuracy of the inverted velocity estimates (Fig. 10b). According to these estimates (for the second set of stations), the atmospheric disturbance propagated almost northward (azimuth of 352°) with a speed of about 25 m/s. These estimates are in close agreement with the anomalous sea level oscillations reported for Victoria, Patricia Bay, and Thetis Island (Fig. 4). Comparison of the observed sea level records at these sites with the derived air pressure propagation velocity (and projected spatial position) shows that the timing of the sea level events at each site is highly correlated with the predicted arrival times for the pressure signal.

2.4. Time–frequency analysis

We examined temporal variations in the dominant frequency bands in the observed sea level and air pressure oscillations using a multiple-filter method (Dziewonski et al., 1969). The method, which is similar to wavelet analysis (Emery and Thomson, 2003),

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[2] Ellipses of this type are the common way to illustrate the accuracy of vector processes; the 95% confidence ellipse is related to 2.45σ (compared with 2σ for 1-D processes). This means that with 95% probability the head of the vector is located inside this ellipse. Had we used phase velocity vectors instead of inverted velocity (effective wavenumber), the graphical interpretation of the results and construction of the confidence regions would have been much more complicated.

Table 2
Estimated parameters for the propagating atmospheric pressure disturbance of 13 July 2007 based on British Columbia (BC) and Washington State (WA) air pressure stations.

Set of stations	c^{-1} (s/m)	Error ellipse (s/m)		Speed (m/s)	Azimuth (°)
		Major axis	Minor axis		
4 BC stations	0.0787	0.19	5.4×10^{-2}	12.7	7.9
4 BC and 3 WA stations	0.0405	1.45×10^{-2}	2.6×10^{-3}	24.7	352.2

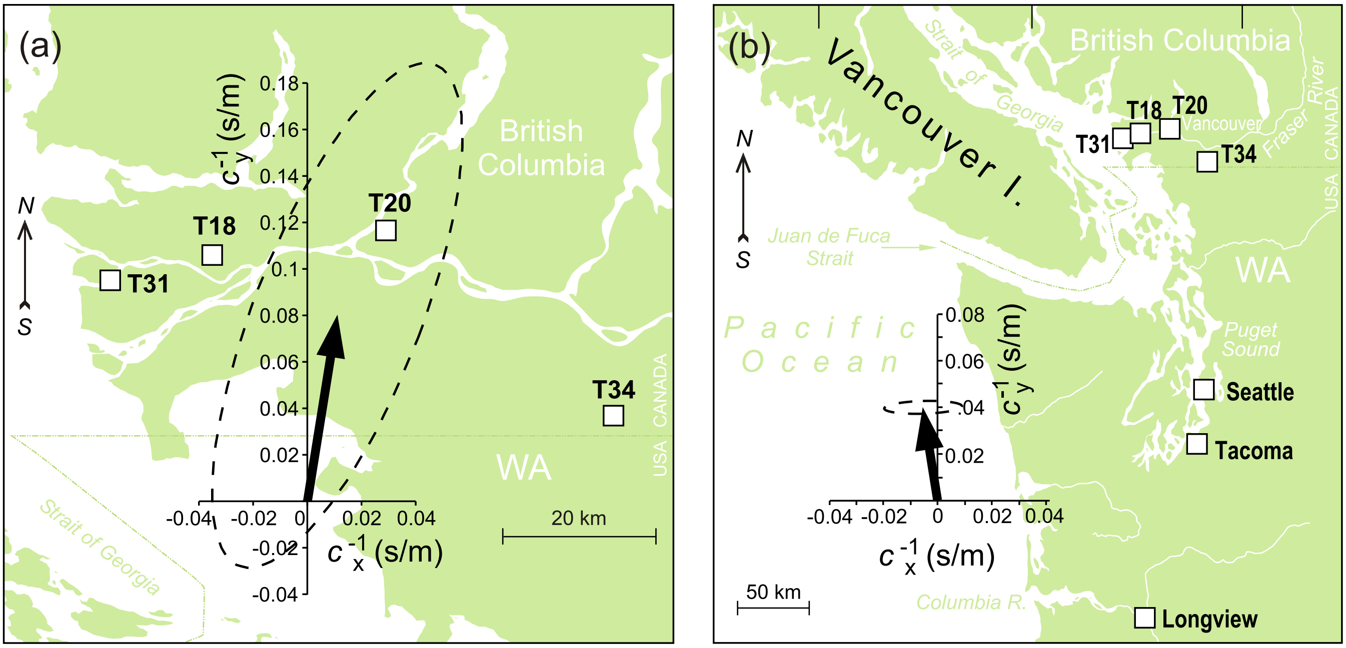

Fig. 10. Inverted phase velocity (thick black arrows) for propagation of the atmospheric disturbance of July 2007 computed from air pressure records from: (a) four BC stations and (b) four BC and three WA stations. Inverted velocity components are in seconds per meter. Station locations are shown on the background maps. The dashed lines denote 95% confidence error ellipses for the computed vectors. c_x^{-1} and c_y^{-1} indicate the *x*- and *y*-components of the inverted phase velocity (in seconds per meter).

is based on narrow-band filters, $H(\omega)$, with a Gaussian window that isolates a specific center frequency, $\omega_n = 2\pi f_n$:

$$H_n(\omega) = e^{-\alpha\left(\frac{\omega-\omega_n}{\omega_n}\right)^2}.$$

The frequency resolution is controlled by the parameter α. The higher the value of α, the better the resolution in the frequency domain but the poorer the resolution in the time domain (and vice versa). A system of Gaussian filters leads to a constant resolution on a log (ω) scale. Demodulation of the sea level and air pressure time series yields a matrix of amplitudes (phases) of wave motions (f–t diagrams) with columns representing time and rows representing frequency. This method can be effectively used to identify tsunami waves and to examine how the tsunami wave energy $E(f, t)$ changes as a function of frequency and time (cf. Rabinovich et al., 2006; Thomson et al., 2007).

Fig. 11 presents f–t diagrams for two tide gauges (Patricia Bay and Victoria) and two Metro Vancouver atmospheric pressure stations (T20 and T34). The diagrams were constructed for the frequency range 1–20 cph (periods 60–3 min); parameter α was chosen to be 80. The 13 July 2007 event is well-defined and mutually consistent among all four plots. The plots reveal a strong coincidence of the sea level and air pressure oscillations. Two burst-like increases in wave energy were observed in both sea level and air pressure at ~10:00–13.00 and ~18:00–20.00 UTC. For sea level, the earlier event was significantly stronger than the later event, while for air pressure the reverse was true. The reasons of these differences are unclear but are probably related to the cross-track structure of the air pressure disturbances and the fact that the observed intensity at stations T20 and T34 was not representative of the pressure events at the tide gauges (the distance between the sea level gauges and the air pressure recorders is more than 110 km).

The sea level energy during the principal event was broadband (5–60 min) with peak periods of approximately 35, 23, 18 and 9 min. A remarkable feature of the December 2005 and July 2007 events is the fast energy decay following each event. More specifically, "ringing" of the sea level oscillations for the meteotsunami events lasted for only a few hours, whereas "ringing" in Victoria Harbor following the arrival of the 2004 Sumatra tsunami lasted for more than three days (Rabinovich et al., 2006).

3. Meteotsunami of 26 February 2008

Anomalous seiches were reported in Victoria Harbour on 26 February 2008. Although not very pronounced (~15 cm), the events were readily distinguishable and had an abrupt beginning. Similar sea level oscillations were observed at other BC stations located on the oceanic coast and in the Strait of Georgia. Because there was no seismic activity at that time, we have assumed that these oscillations were associated with atmospheric processes and identified this event as a meteorological tsunami. The structure and generation mechanism for this event have been examined using tide gauge and air pressure data available for BC and Washington stations.

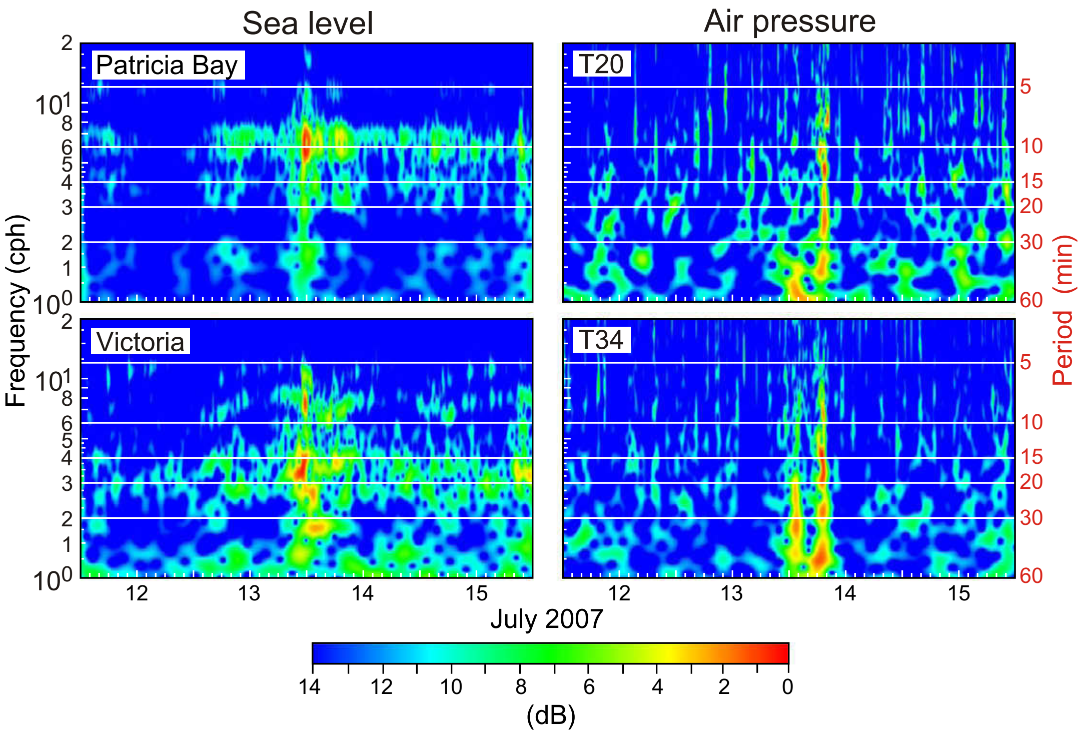

Fig. 11. Frequency–time (f–t) diagrams for the 13 July 2007 event for sea level (left column) and air pressure (right column).

3.1. Tide gauge records

As with the July 2007 event, the February 2008 event was examined using 1-min digital records from the CHS tide gauges in the southern part of British Columbia and NOAA NOS/CO-OPS tide gauges in northern Washington State (Fig. 5). Once again, some of the gauges had instrumental or transmission problems so we have confined our attention to eight stations (four in BC and four in WA) that had records of sufficiently high quality. These eight records for the period 24–29 February 2008 are shown in Fig. 12a. Predicted tides were subtracted from the records and the records then high-pass filtered with a 3-h KB-window.

The event of 26 February 2008 is clearly identified in all records. In contrast to the event of 13 July 2007, when intense oscillations were observed for only a few hours, there were persistent sea level oscillations beginning on 26 February 2008 that lasted for several days (26–29 February) (Fig. 12a). The strongest event occurred on 26 February at Victoria, on 27 February at Tofino and Neah Bay, and on 28 February at Port Angeles. In general, the sea level oscillations measured at the latter four stations were significantly stronger than at the other four stations (Point Atkinson and Patricia Bay, BC; Cherry Point and Friday Harbor, WA), with heights ranging from roughly 10 to 15 cm and 3 to 8 cm, respectively. An expanded time scale plot for the first group (25–27 February) is presented in Fig. 12b. Several trains of waves with typical durations of 6–8 h are evident in the records. Our main focus is on the first train of waves on February 26 which began in Victoria at ~03:30 UTC and attained maximum heights of 15 cm on ~04:15 UTC. The same train of waves, but with slightly smaller heights, is clearly apparent in the records for Port Angeles, Neah Bay, and Tofino. The oscillations had periods of about 8 min (Victoria), 11 min (Port Angeles), 17 min (Neah Bay), and 15 min (Tofino). At most of the stations, the exact beginning of the tsunami-like sea level oscillations was ill-defined because of background seiche "noise". For this reason, we could not use sea level data to estimate the propagation direction of the atmospheric forcing disturbance.

3.2. Atmospheric pressure records

The air pressure event responsible for the anomalous sea level oscillations in February 2008 was examined using Washington NOAA stations at Cherry Point, Seattle, Tacoma, Neah Bay, La Push, and Toke Point (Fig. 5). We also used British Columbia AQMT stations T18, T20, T31, and T34 (the same sites applied to the July 2007 event) plus stations T12 (Chillwack, Fraser Valley), T26 (North Vancouver), and T32 (Coquitlam) (Fig. 7). As illustrated by Fig. 13a, the air pressure records for the six WA stations are mutually consistent. All records show high pressure of more than 1030 hPa on 26 February 2008 and each record contains several high-frequency bursts of intense oscillation, with especially strong oscillations on February 27 and 29. As indicated by the dashed line in Fig. 13b, the disturbance of 26 February propagated roughly towards the northeast, along the direction from Toke Point to Cherry Point. The high-pass filtered air pressure records of this event (shaded area, Fig. 13c) show that the disturbance retained its sinuous, roughly 1.5 hPa-amplitude shape as it propagated between stations. Although the resolution of the AQMT air pressure resolution data was not sufficient for examining this disturbance in greater detail, the event is clearly evident at all seven stations (Fig. 14, dashed line).

3.3. Estimation of wave velocities

The propagation velocities of the 26 February 2008 atmospheric event were examined in the same way as the 13 July 2007 event. Three sets of data were used in the calculations: (1) six Metro Vancouver stations (T18, T20, T26, T31, T32, and T34) plus Cherry Point; (2) five Washington stations (La Push, Neah Bay, Tacoma, Seattle, and Cherry Point); and (3) six BC and five WA stations

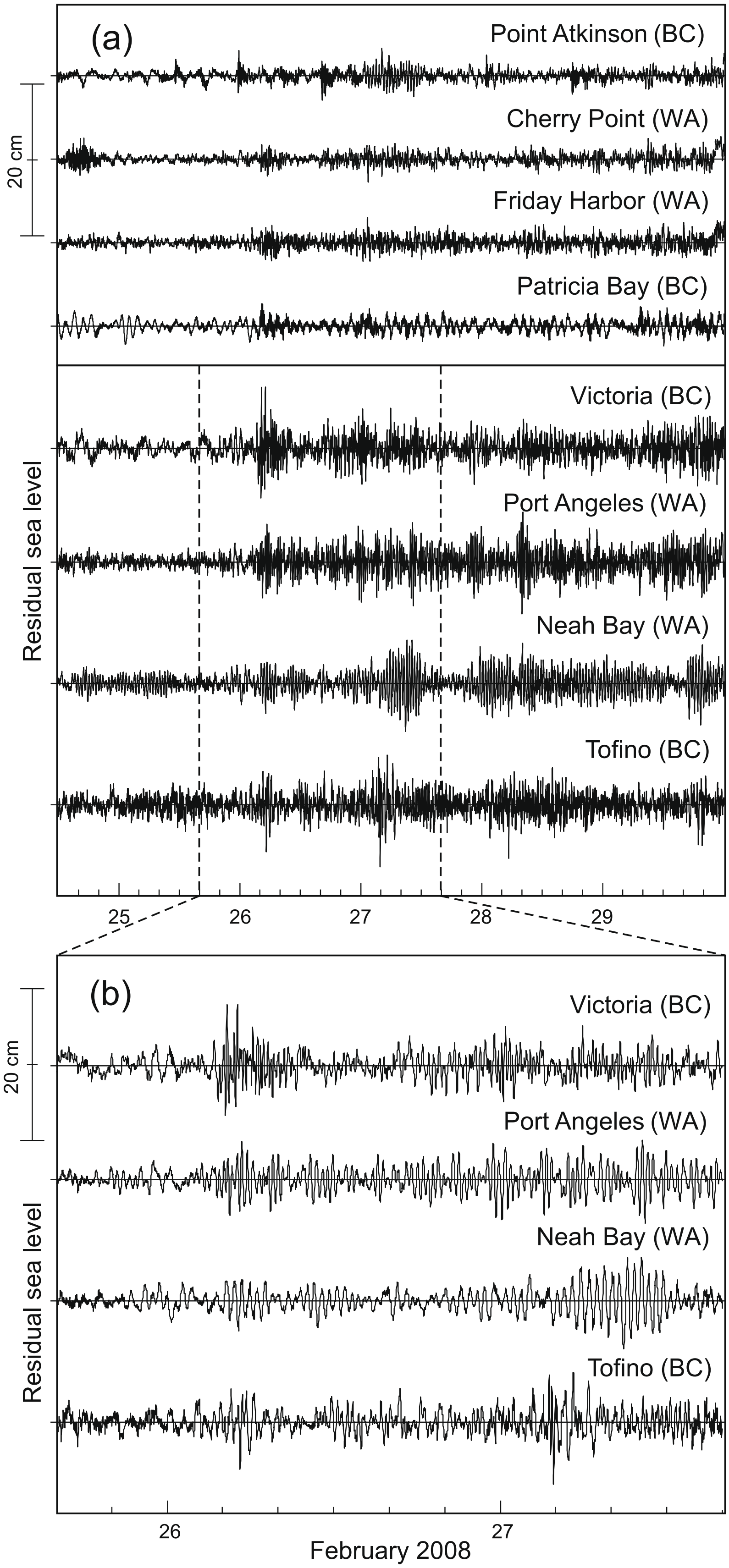

Fig. 12. Sea level records for the 26 February 2008 meteotsunami event: (a) BC and WA tide gauge records for the period 24–29 February 2008 and (b) expanded sea level records for Victoria, Port Angeles, Neah Bay and Tofino focusing on 26 February.

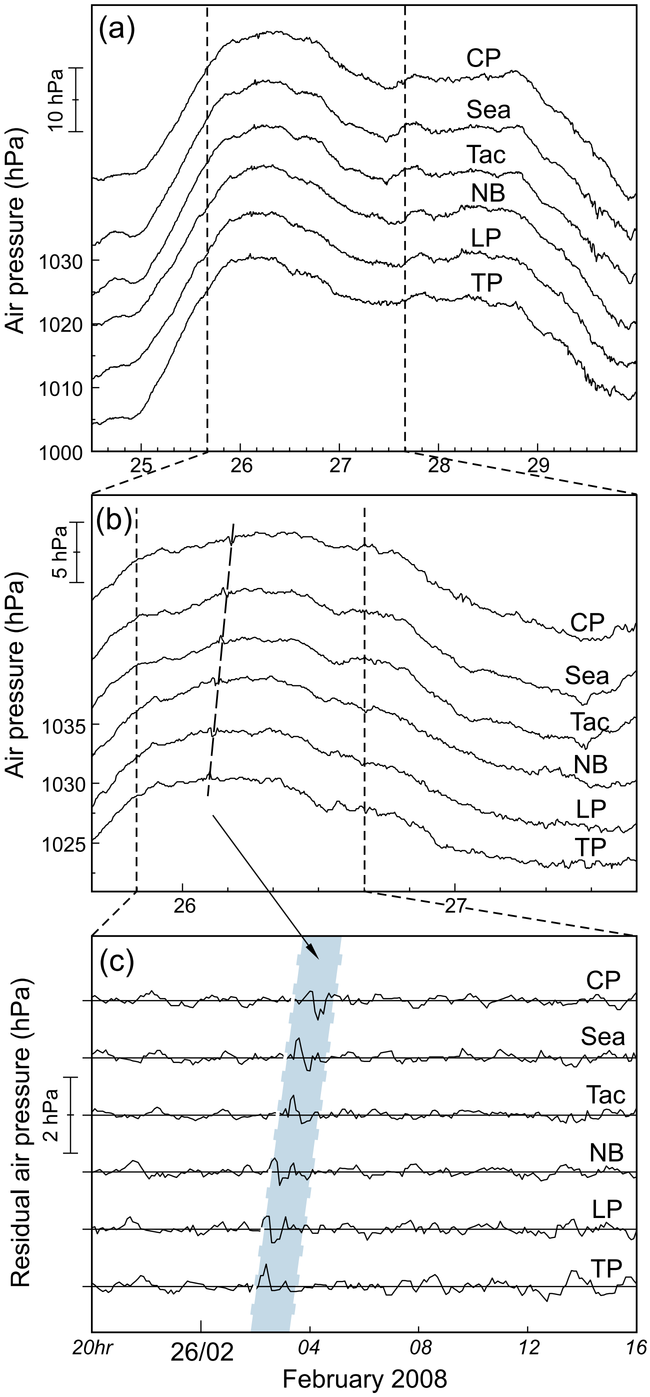

Fig. 13. Air pressure records for the February 2008 meteotsunami event: (a) Records for six WA stations (see Fig. 5 for locations) for the period 24–29 February 2008, (b) expanded records for the same stations for the narrower period 25–27 February 2008. The long-dashed line indicates the atmospheric disturbance likely responsible for the pronounced sea level oscillations shown in Fig. 12b, and (c) residual records (after high-pass filtering with a 3-h KB-window) at the same stations for 26 February 2008; the shaded area shows the enhanced pressure records for the atmospheric disturbance highlighted in (b). “CP”, Cherry Point; “Sea”, Seattle; “Tac”, Tacoma; “NB”, Neah Bay; “LP”, La Push; and “TP”, Toke Point.

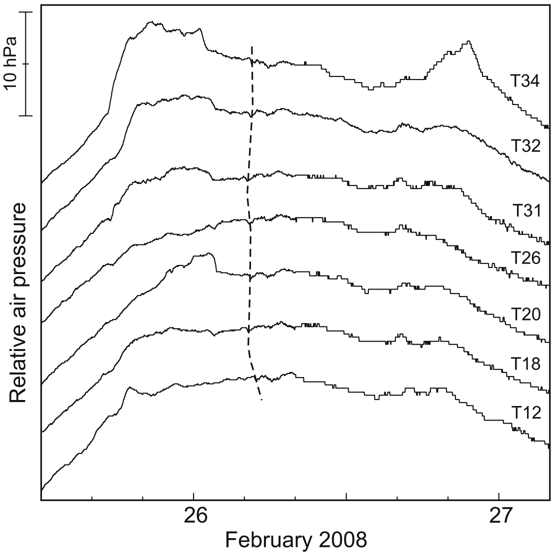

Fig. 14. Air pressure records for 7 stations in the Metro Vancouver area for 25–26 February 2008. The dashed line indicates the atmospheric disturbance considered responsible for the meteotsunami event.

combined. Stations T12 and Toke Point were not used because they were located too far from the other stations. Once again, we selected features in the air pressure signal which were distinguishable in all coincident records. The remarkable aspect of the resulting computations presented in Table 3 and Fig. 15 is the striking consistency of the estimated vector parameters for the two independent sets of data: the difference in computed speeds was only 0.2 m/s (less than 0.7%), while the difference in directions was 0.9°. Based on the set of six BC and five WA stations, the atmospheric disturbance propagated with an azimuth of 60°; i.e., toward the land from the ocean, roughly normal to the mainland coast.

3.4. Time–frequency analysis

We examined the observed sea level and air pressure oscillations for the February 2008 event as a function of frequency and time in the same manner as for the July 2007 event. Fig. 16 presents *f–t* diagrams for four tide gauges (Victoria, Tofino, Port Angeles, and Neah Bay) and four WA air pressure stations (Neah Bay, Cherry Point, Toke Point, and Tacoma). The diagrams were constructed for the frequency ranges 0.5–10 cph (periods 120–6 min) for sea level and 0.5–5 cph (120–12 min) for air pressure. Slightly different ranges were required because of the different sampling intervals: 1 min for tide gauges and 6 min for WA air pressure stations. In all eight panels, the main event of 26 February 2008 is well-defined and has a similar structure. There is a marked correlation between the atmospheric pressure and sea levels oscillations: bursts of energy in air pressure immediately induce energetic responses in sea level. Despite the coincidence in the pressure and sea level events, the periods with the most energetic oscillations are different, ranging from 40–50 min for air pressure and 12–35 min for sea level. It appears that the periods of the sea level oscillations (local seiches) are more determined by the resonant properties of the specific site than by the forcing periods of the air pressure disturbances. This also follows from the fact that the periods of all analyzed air pressure records are similar (Fig. 16b) while those for sea levels differ between stations: 15–20 min for Victoria; 12–15, 20–22, and 35 min for Tofino; 22–27 min for Port Angeles; and 32 min for Neah Bay. The remarkably persistent “ringing” in the Port Angeles sea level record is likely attributable to the location of this site inside a harbour formed by a long sand spit on the southern shore of Juan de Fuca Strait (Fig. 5).

Table 3
Estimated parameters for propagating atmospheric pressure disturbances on 26 February 2008 over British Columbia (BC) and Washington State (WA). "CP" is the Cherry Point station (WA).

Set of stations	c^{-1} (s/m)	Error ellipse (s/m)		Speed (m/s)	Azimuth (°)
		Major axis	Minor axis		
6 BC stations + CP	0.0325	5.4×10^{-3}	3.1×10^{-3}	30.8	60.3
5 WA stations	0.0327	3.5×10^{-3}	2.3×10^{-3}	30.6	59.4
6 BC and 5 WA stations	0.0327	8.6×10^{-4}	6.1×10^{-4}	30.6	60.0

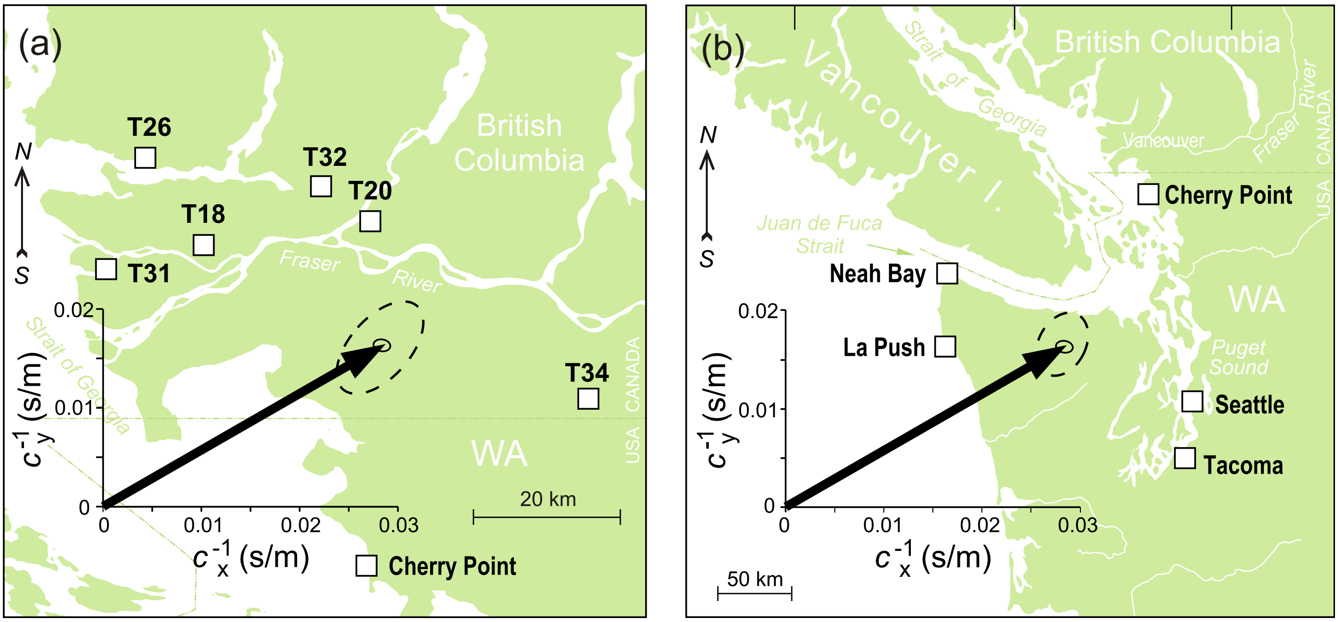

Fig. 15. Inverted phase velocity (thick black arrows) for propagation of the atmospheric disturbance of February 2008 computed from air pressure records from: (a) six BC stations and Cherry Point (WA) and (b) five WA stations. Station locations are shown in the background maps. Inverted velocity components are in seconds per meter. The dashed lines denote 95% confidence error ellipses for the computed vectors. The small ellipse bordered by a solid line indicate the error ellipse when the entire set of records (11 stations) is used for the computations. c_x^{-1} and c_y^{-1} indicate the *x*- and *y*-components of the inverted phase velocity (in seconds per meter).

4. Discussion and conclusions

Despite their similarity to seismically-generated waves, the tsunami-like sea level events recorded on the coasts of British Columbia and Washington State on 9 December 2005, 13 July 2007, and 26 February 2008 were most likely forced by high-frequency air pressure disturbances propagating over the region and can therefore be categorized as meteorological tsunamis. This is the first time that such features have been clearly identified for the study region and suggests that they are not infrequent occurrences. Although not catastrophic in the same sense as major seismically induced events, even moderate meteotsunamis can have damaging impacts on boats and ships in harbours and small embayments. Stronger events than we have examined may occur in this region in the future and lead to severe damage to vessels and port facilities. Thus, in general, it is important to understand: (1) How intense can tsunamigenic atmospheric disturbances be and how often do these disturbances occur?; (2) how strongly does the ocean's response depend on the characteristics of the atmospheric disturbance, such as its phase speed and propagation direction?; (3) what is the role of local topographic resonance on the forced waves?; and (4) what locations along the coasts of British Columbia and Washington are most susceptible to destructive meteotsunamis?

Answers to the above questions are not trivial and call for further study. Until now, little attention has been paid to high-frequency pressure-induced wave phenomena in coastal British Columbia and Washington State, in part because of their low population densities. This is certainly true when compared to the Mediterranean where meteorological tsunamis are most common and invariably destructive (cf. Rabinovich, 2009; Šepić et al., 2009). In addition, it has only been very recently that precise digital tide gauges with short sampling intervals (capable of recording high-frequency longwave oscillations) have been installed in British Columbia and Washington State waters. Lastly, meteotsunamis typically have small amplitudes relative to the tides (which range from 3 to 8 m on the BC-Washington coast) and therefore have gone unnoticed and/or were poorly documented in the past.

We note that much of the damage from meteotsunamis arises from the strong currents they induce rather than from the anomalous water heights (Vilibić et al., 2004, 2008; Monserrat et al., 2006). The periods of astronomical tidal motions are approximately 50 times longer than the typical periods of meteorological tsunamis (extreme seiches), so a meteotsunami of comparable height to the tide will produce a current that is 50 times stronger. This means that a 50-cm meteorological tsunami (a realistic height for extreme events along the BC-Washington coast) will generate a current that is five times stronger than that generated by a 5-m tide. In narrow straits and fjords, as well as in harbour entrances, such currents can have serious destructive effects. Meteotsunamis in certain bays and harbours in the Global Ocean can reach 5–6 m, with accompanying currents that exceed 20–25 knots (10–12 m/s). Such catastrophic events regularly occur in Ciutadella Harbour, Menorca Island, Spain (Monserrat et al., 1991, 1998, 2006;

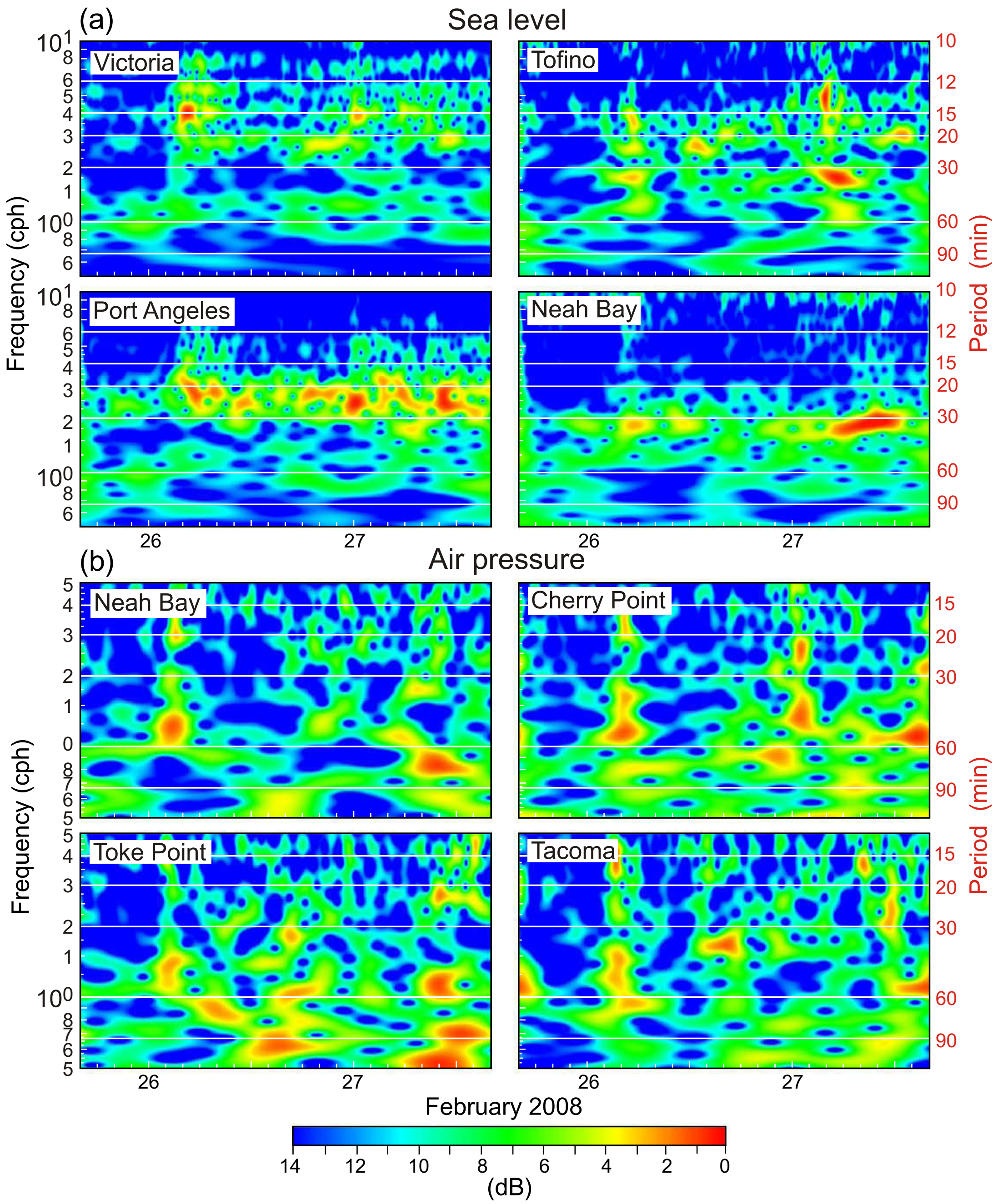

Fig. 16. Frequency–time (*f*–*t*) diagrams for the 26 February 2008 event for: (a) sea level and (b) air pressure records.

Rabinovich and Monserrat, 1996, 1998; Vilibić et al., 2008) and in Nagasaki Bay, Japan (Hibiya and Kajiura, 1982). Similar intermittent events also occur along the Croatian coast in the Adriatic; meteotsunamis in Vela Luka, Stari Grad, Mali Ston, and Široka bays occasionally produce particularly catastrophic effects (Vilibić et al., 2004; Šepić et al., 2009).

It is of interest to compare meteorological tsunamis described in the present study with those recorded in Ciutadella Harbour (Menorca, Balearic Islands, Western Mediterranean), the harbour where this "rissaga" phenomenon has been investigated more thoroughly than at any other oceanic site. In both regions, meteotsunamis are not normally associated with extreme weather (such as deep cyclones, severe storms, waterspouts, or local thunderstorms) but with high-pressure systems and relatively calm weather. Although extreme weather can be efficient meteotsunami generators in some regions of the world[3], none of three events we examined for the BC-Washington coast or most of the known destructive events for Ciutadella (cf. Tintoré et al., 1988; Monserrat et al., 1991, 2006; Gomis et al., 1993; Rabinovich and Monserrat, 1996, 1998) have been related to extreme weather conditions (except for squall lines which are associated with abrupt jumps in atmospheric pressure). The same is true for the Adriatic coast of

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[3] In particular, Thomson et al. (2007) describe significant seiches generated by a strong storm travelling up the Atlantic coast of the USA and Canada on 25–28 December 2004, which coincided with the arrival of waves from the 26 December 2004 tsunami in the Indian Ocean. Similarly, Mercer et al. (2002) examined major tsunami-like events on the southeast coast of Newfoundland (Canada) generated by tropical storms which moved rapidly (30 m/s) across the Grand Banks of Newfoundland.

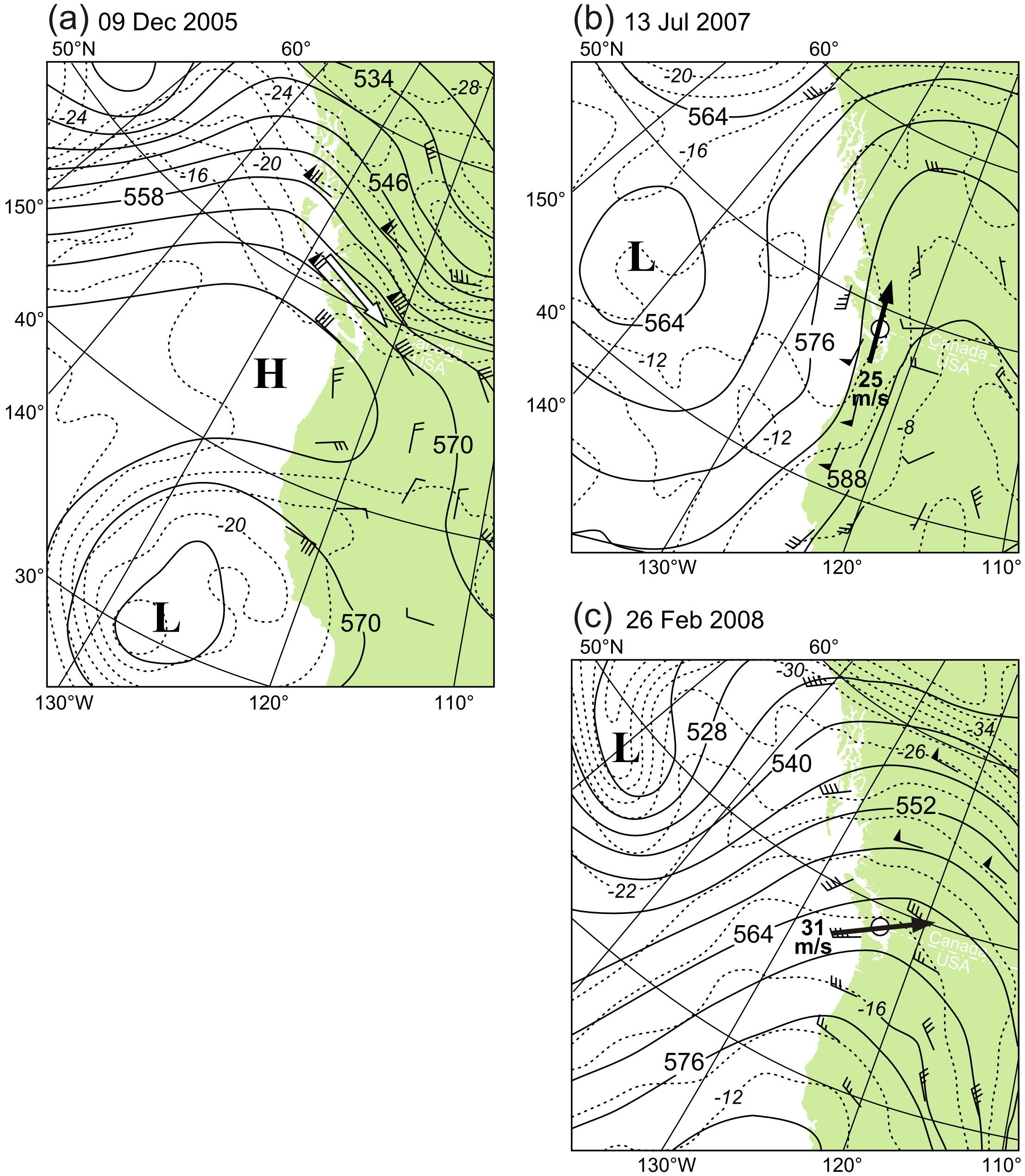

Fig. 17. 500-hPa height contours (AT-500 maps) at 12:00 (UTC) for: (a) the 9 December 2005 event, (b) the 13 July 2007 event, and (c) the 26 February 2008 event. In (a), the thick open arrow indicates the direction of the high-altitude geostrophic wind (jet stream) over northern BC, in (b) and (c) the thick black arrows denote the computed inverted phase velocity vectors taken from Figs. 10 and 15, respectively.

Croatia, where the generation mechanism of meteorological tsunamis is generally similar to that for Ciutadella Harbour (Vilibić and Šepić, 2009), except that some of the events are associated with thunderstorm fronts (Šepić et al., 2009). As with Ciutadella Harbour and the Croatian Adriatic, meteorological tsunamis recorded along the coasts of British Columbia and Washington State are linked to high-frequency air pressure disturbances with a typical range of 1–4 hPa. The phase speed of the disturbances is estimated to have been 24.7 m/s (13 July 2007) and 30.6 m/s (26 February 2008), which is similar to the 22–31 m/s values observed for the Balearic Islands region and in the western Adriatic (cf. Monserrat et al., 1991; Vilibić et al., 2004; Šepić et al., 2009). The typical periods of 8–30 min for the longwave oscillations we observed for the 2007 and 2008 events, are similar to those for the Balearic Islands (cf. Rabinovich and Monserrat, 1996) and bays along the Croatian coast (Vilibić et al., 2004; Vilibić and Šepić, 2009).

There are differences between the Mediterranean and northeast Pacific meteotsunami events. All known rissaga events reported for the Balearic Islands occurred in summer (more precisely, from June to September, with a few occasional events in May). Approximately the same is true for the Croatian coast (Vilibić and Šepić, 2009) and for other sites in the Mediterranean (Malta, Sicily, Greece) (cf. Šepić et al., 2009). In contrast, only one of the three events examined in the present study occurred in summer (13 July 2007), while the two others (9 December 2005 and 26 February 2008) took place in winter. Another important distinction is in the direction of propagation of the atmospheric disturbance generating the meteorological tsunamis. The directions (azimuth) for atmospheric disturbances responsible for significant rissaga events in Ciutadella Harbour are very narrowly confined to ~30–60° (i.e., are from the southwest to the northeast) whereas for the three meteotsunamis examined for the coasts of BC and Washington State, the pressure events propagated in significantly different directions (Figs. 10 and 15). To understand the reason for these different directions, we compared the directions of the events with high-altitude (500-hPa) height contours for the times of the three events (Fig. 17). The results of this comparison (Fig. 17b and c) indicate precise coincidence between high-altitude steering winds (the jet stream) for the events of 13 July 2007 and 26 February 2008 and the estimated velocities of the atmospheric pressure disturbances which produced the anomalous sea level oscillations on the coasts of BC and Washington. Not only the velocity directions but also the wave speeds closely match those of the jet stream. A similar situation is described by Šepić et al. (2009) for the destructive meteotsunami event of 22 August 2007 in Široka Bay in the northern Adriatic.

The 500-hPa height contour map for 9 December 2005 (Fig. 17a) shows a high-gradient air pressure field with a well-defined jet stream over British Columbia. The geostrophic high-altitude winds over northern Vancouver Island were directed toward ~120° (the direction is indicated in Fig. 17a by the large open arrow) with speeds of approximately 30–35 m/s (see wind symbols in the map in Fig. 17a). Although there were no near-surface observations of high-frequency air pressure fluctuations for the 2005 event (in contrast to the 2007 and 2008 events), the start times for the 2005 meteotsunami sea level oscillations along the coast of BC (Fig. 2a) clearly define a propagation direction that is consistent with the direction and speed of the jet stream winds (see Section 1). Moreover, according to sea level observations along the Washington coast, the atmospheric disturbance that generated the anomalous 2005 tsunami-like oscillations on this coast (Fig. 2b) should have been moving slower, with an estimated speed of roughly 20–25 m/s (Rabinovich, 2005). This is highly consistent with the observed air pressure field for this region (Fig. 17a) which was comprised of a high-pressure ridge and wind speeds of only 20 m/s.

The close agreement between the velocity of the propagating pressure pulses and the jet stream winds cannot be accidental. What physical mechanism was responsible for this link is unclear, although there are several obvious candidates:

(1) The BC-Washington disturbances were due to convective cells advected by the high-altitude winds, as was the case for several destructive Adriatic events (Belušić and Mahović, 2009). The measured surface pressure perturbations in the Adriatic case coincided with the appearance of such systems.

(2) The disturbances were associated with gravity wave modes ducted in a stable near-surface layer and linked to a critical layer above the duct, similarly to that reported by Monserrat and Thorpe (1996) for the Balearic Islands. Monserrat and Thorpe (1996) find that, of the wide range of possible generated wave modes, the mode having a phase speed that is equal to the wind speed at some level in an intermediate atmospheric layer, is trapped between the sea surface and this layer, causing the energy to be reflected at this level and to remain confined near the surface. This mechanism appears to explain the observations at Mallorca and reveals the critical role of wind shear in selecting the phase speed of the ducted atmospheric waves that give rise to the generation of rissaga (meteotsunami) waves in Ciutadella Inlet.

(3) The recorded disturbances were small-scale Karman-type vortices rather than freely propagating waves, which were again transported downstream by the high-altitude winds. Such motions might resemble the "vortex streets" in the wake of the Aleutian Islands described by Thomson et al. (1977). In the present case, the Olympic Mountains or the series of volcanoes such as Mount Rainer and Mount Baker that run merdionally along the west coast of North America could play the same role as the volcanoes of the Aleutian Islands Chain.

It is not clear which mechanism was driving the three events examined in the present study; it is also possible that several factors were working together (e.g., topographic effects and convective instability). Further investigation is needed to address this question.

The atmospheric disturbances recorded by the BC and WA instruments had characteristic periods (T) of 15–90 min (Figs. 11 and 15) and propagation speeds (c) of 25–31 m/s. The corresponding wave lengths are then $\lambda = cT \approx 22$–170 km. We can assume that typical across-track scales of these disturbances are of the same order. This explains why particular disturbances are observed at some stations but are not at others (for example, events recorded at Tacoma and Seattle were not recorded at La Push and Neah Bay). In other words, what we observe is not a single disturbance propagating over the entire BC-Washington region but rather a number of individual disturbances with different scales carried as wave-like "packets" within the main airstream. Whether these features are related to atmospheric ducted waves, convective cells or Karman-type vortices remains undetermined. Whatever the cause of the events, it is clear that greater consideration must now be given to these phenomena since they contribute significantly to anomalous sea level variations along the coasts of British Columbia and Washington State.

One of the puzzling questions is how air pressure disturbances of a few hPa may produce sea level oscillations of several tens of centimetres or even several meters. The common consensus is that the strong amplification of the sea level oscillations is due to a combination of Proudman resonance in the open sea and/or on the shelf and harbour resonance within the inner basin (cf. Monserrat et al., 2006; Rabinovich, 2009). Proudman resonance occurs when the propagation speed of the atmospheric disturbance equals the long-wave speed of ocean waves, $c = \sqrt{gh}$, where h is the water depth and g is the gravitational acceleration. The observed speeds of atmospheric disturbances, 25–31 m/s, correspond to a relatively narrow band of surface wave speeds, c, that are resonant for water depths, h, of 60–100 m. In the study region, these depths are confined to relatively small regions (when compared with the larger atmospheric disturbance scales) of the Strait of Georgia, Puget Sound, and Juan de Fuca Strait (Fig. 5). It is apparently for this reason that meteorological tsunamis in the BC-Washington region are not as pronounced as in the vicinity of the Balearic Islands or the Adriatic Sea where areas with "resonant depths" are quite large.

Unlike the Mediterranean, tides are an important factor when considering the impact of meteotsunamis on coastal British Columbia and Washington State. Meteotsunamis generated during times of extreme spring tides in summer and winter, or during high storm surges, could be particularly damaging to moored vessels and harbour infrastructure. With rising coastal population densities, the ability to predict these events may prove critical to the safety of boat harbours in the near future.

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