Pure Appl. Geophys. 170 (2013), 1229–1248

DOI 10.1007/s00024-012-0492-6

Pure and Applied Geophysics

Observations, Effects and Real Time Assessment of the March 11, 2011 Tohoku-oki Tsunami in New Zealand

JOSE C. BORRERO,[1,2,8] ROB BELL,[3] CLAUDIA CSATO,[1] WILLEM DELANGE,[4] DEREK GORING,[5] S. DOUGAL GREER,[1,8] VERNON PICKETT,[6] and WILLIAM POWER[7]

Abstract—The great Tohoku-oki earthquake of March 11, 2011 generated a devastating tsunami in the near field as well as substantial far-field effects throughout the Pacific Ocean. In New Zealand, the tsunami was widely observed and instrumentally recorded on an extensive array of coastal tidal gauges and supplemented by current velocity data from two sites. While the tsunami's first arrival was on the morning of March 12 in New Zealand, the strongest effects occurred throughout that afternoon and into the following day. Tsunami effects consisted primarily of rapid changes in water level and associated strong currents that affected numerous bays, harbors, tidal inlets and marine facilities, particularly on the northern and eastern shores of the North Island. The tsunami caused moderate damage and significant overland flooding at one location. The tsunami signal was clearly evident on tide gauge recordings for well over 2 days, clearly illustrating the extended duration of far field tsunami hazards. Real time analysis and modelling of the tsunami through the night of March 11, as the tsunami crossed the Pacific, was used as a basis for escalating the predicted threat level for the northern region of New Zealand. A comparison to recorded data following the tsunami shows that these real time prediction models were accurate despite the coarse near-shore bathymetry used in the assessment, suggesting the efficacy of such techniques for future events from far-field sources.

[1] ASR Ltd. Marine Consulting and Research, 1 Wainui Road, Raglan, New Zealand. E-mail: jose@ecoast.co.nz
[2] Tsunami Research Center, University of Southern California, 3620 S. Vermont Avenue, Los Angeles, CA 90089-2531, USA.
[3] National Institute of Water and Atmospheric Research, PO Box 11115, Hamilton 3251, New Zealand. E-mail: r.bell@niwa.co.nz
[4] Department of Earth and Ocean Sciences, University of Waikato, Private Bag 3105, Hamilton 3240, New Zealand. E-mail: delange@waikato.ac.nz
[5] Mulgor Consulting, PO Box 9320, Tower Junction, Christchurch 8149, New Zealand. E-mail: d.goring@mulgor.co.nz
[6] Environment Waikato, Waikato Mail Centre, Private Bag 3038, Hamilton 3240, New Zealand. E-mail: Vernon.Pickett@waikatoregion.govt.nz
[7] GNS Science, 1 Fairway Drive, Avalon 5010, PO Box 30-368, Lower Hutt 5040, New Zealand. E-mail: W.Power@gns.cri.nz
[8] eCoast Ltd, PO Box 151, Raglan, New Zealand. E-mail:d.greer@ecoast.co.nz

Key words: Tsunami, New Zealand, Japan, tide gauge, field survey, numerical modeling.

1. Introduction

The great Tohoku-oki earthquake ($M_w = 8.9$, USGS) of March 11, 2011 (0546 UTC), occurred along the northern east coast of Honshu Island in Japan, generated a devastating tsunami with the strongest effects observed in the near field close to the earthquake source and ultimately resulted in nearly 20,000 casualties and billions of dollars in damage (IOC/UNESCO, 2011). The first warning message from the Pacific Tsunami Warning Center (PTWC) was issued 9 min after the event (0555 UTC), and listed the earthquake as a Magnitude 7.9. The message established a tsunami warning for the region close to the earthquake source and put the western Pacific under a tsunami watch. It is important to note that this initial message severely underestimated the size of the earthquake; this is common since the analysis techniques for determining the magnitudes of very large earthquakes require additional time. A second advisory from the PTWC issued at 0643 UTC, approximately 1 h after the earthquake, increased the estimated magnitude to 8.8 and confirmed that a tsunami had been generated based on instrumental recordings of the tsunami on a DART tsunameter located near the source region. At this time the warning and watch areas were expanded to cover the central and western North Pacific Ocean.

Approximately 45 min later, at 0730 UTC (8:30 PM, 11-March NZDT), New Zealand was officially put under a tsunami warning by the PTWC. By this time news reports showing the extensive destruction in Japan were widely available and the tsunami had been recorded on several tsunameter stations and coastal tide gauges. This message also provided predicted first arrival times for the tsunami for sites throughout the Pacific. Warning messages and updates were issued regularly by the PTWC for the next 24 h until the warning was cancelled at 0636 UTC on March 12 (7:36 PM March 12th NZDT, 24 h 50 min after the earthquake). Because the earthquake and tsunami occurred in the middle of the day (2:46 pm Japan Standard Time), the effects of the tsunami were recorded by many individuals in Japan and transmitted quickly via news outlets and broadcast around the world. The timing of these broadcasts also coincided with the evening news hour in New Zealand, making the nation aware of the magnitude of the disaster as it happened.

With a travel time of approximately 12 h to the northern parts of New Zealand, emergency procedures were initiated including the activation of the Tsunami Experts Panel (TEP). Members were alerted by text message and other means (phone call, email) at 7:42 pm NZDT (0642 UTC) and the first group meeting was set for 8:15 pm (0715 UTC). At the first meeting the TEP drafted an advisory message to New Zealand's Ministry of Civil Defence and Emergency Management (MCDEM) indicating the anticipated effects from the tsunami. The TEP advised that a minimum of a 'Marine Threat' level be established for the central and northern North Island and that the computed first arrival times would coincide with low tide. Based on historical events and existing numerical models, the general consensus of the TEP was that the tsunami would not be destructive in New Zealand; however, it would be significant and the potential effects warranted caution, particularly in areas known to be vulnerable to tsunami. These assessments were backed up by real-time numerical modelling using a tsunami source model derived from observed waveforms on DART tsunameters located in the western Pacific. A modelling assessment, completed several hours before the tsunami arrival, was used as a basis for upgrading the warning messages and predicted threat levels for the northern region of the country.

1.1. Tide Gauge Data

Tsunami waves first arrived in New Zealand on the morning of 12 March. The tsunami was recorded on a number of different instruments located in and around New Zealand, including Raoul Island and the Chatham Islands (Fig. 1). Most of the gauges are operated and maintained by either New Zealand's National Institute of Water and Atmospheric Research (NIWA) or Institute of Geological and Nuclear Science (GNS). Additional water level records were also recovered from gauges maintained by: (a) port companies at Tauranga, Taranaki (New Plymouth), Lyttleton (Christchurch) and Timaru; and (b) local government agencies (Northland and Waikato Regional Councils and Tasman District Council); and (c) the National Tide Center—Bureau of Meteorology, Australia (Jackson Bay gauge). Data collected from these stations were processed to remove the tidal signal and extract arrival times and water level statistics. Figure 2a, b and Tables 1, 2 provide an overview of this information. In Fig. 2a, b we see the onset of the tsunami arrival as it moves from north to south down the length of New Zealand. The time series plots also show the extended duration of the tsunami effects, as they are clearly visible for at least 2.5 days after tsunami arrival. It is also evident that some of the highest wave heights occurred well after the tsunami's first arrival [see Gisborne (GIST) in Fig. 2a]. Arrival times and summary statistics for the tide gauge data are listed in Tables 1, 2. The processed data shows arrival times across the New Zealand gauge array ranging from 12 h in the north (North Cape–NCPT) to nearly 18 h in the far south (Dog Island). Maximum positive amplitudes ranged from 0.2 to 0.85 m with maximum peak to trough (P2T) wave heights of 0.4–2.0 m. The highest values were recorded in the Chatham Islands followed by Whitianga. At Port Charles, just north of Whitianga, there is strong evidence that the maximum positive amplitude was even higher at $\sim$1.5 m, as the deck of a jetty with a known elevation was photographed as it was temporarily overtopped. The data also show that the occurrence of both the maximum positive amplitude and the maximum peak to trough wave height generally occurred 5 or more hours after the first arrival times. A more complete discussion of the New Zealand time series data and summary statistics is provided in Borrero and Greer (2012, this volume).

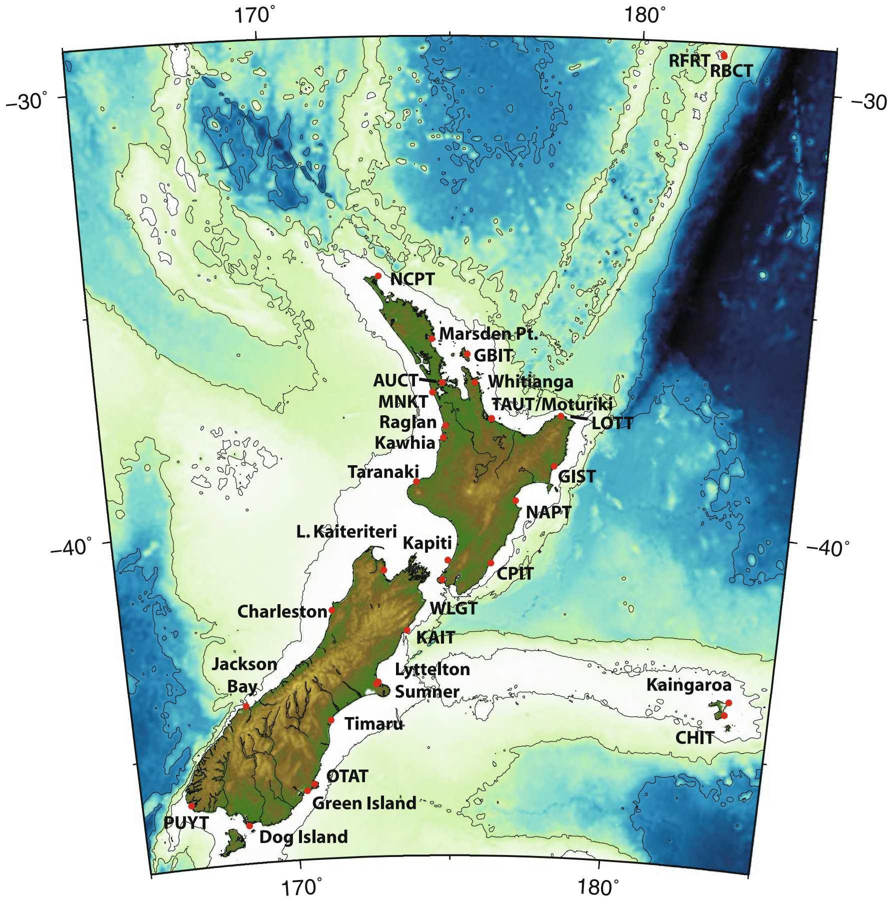

Figure 1
Locations of sea level gauge stations around New Zealand and other locations mentioned in the text. Station codes are as follows *RFRT* Raoul Island Fishing Rock, *RBCT* Raoul Island Boat Cove, *NCPT* North Cape, *GBIT* Great Barrier Island, *AUCT* Auckland, *TAUT* Tauranga, *LOTT* Lottin Point, *GIST* Gisborne, *NAPT* Napier, *CPIT* Castlepoint, *WLGT* Wellington, *MNKT* Manukau Harbor, *KAIT* Kaikoura, *SUMT* Sumner Heads, *CHIT* Chatham Islands, *OTAT* Port of Otago, *PUYT* Puysegur Point

1.2. Water Levels and Currents at Tauranga and Lyttelton

At Tauranga, the tsunami was recorded on six separate instruments located both inside and outside the harbor (Fig. 3). These include the GNS GeoNet station TAUT, NIWA's Moturiki tide gauge and three pressure sensors (A Beacon, Tug Berth and Sulphur Point) maintained by the Port of Tauranga. An acoustic Doppler current meter at the entrance to the harbor recorded current speeds. The water level measurements shown in Fig. 4 indicate that the tsunami height was attenuated by approximately 40 % between the Moturiki gauge, which sits outside of the harbor near shore, and the TAUT station located inside the harbor.

Currents measured at the entrance to Tauranga Harbor are shown in Fig. 5. Peak raw current speeds exceeded 4 knots while peak residual (tsunami only, tidal component removed) current speeds reached a maximum of approximately 2 knots. The peak residual current speed occurred just before high tide in the late morning of March 12 NZDT, while the peak raw current speed (with tidal current included) occurred a few hours later on the outgoing tide. For large container ships (>220 m in length and >11.7 m draft), navigation through the mouth of the harbor is restricted to times when the currents are less than 1.5 knots. This criterion was exceeded during the four slack waters on two consecutive tidal cycles after the tsunami arrived. Despite the water level changes and

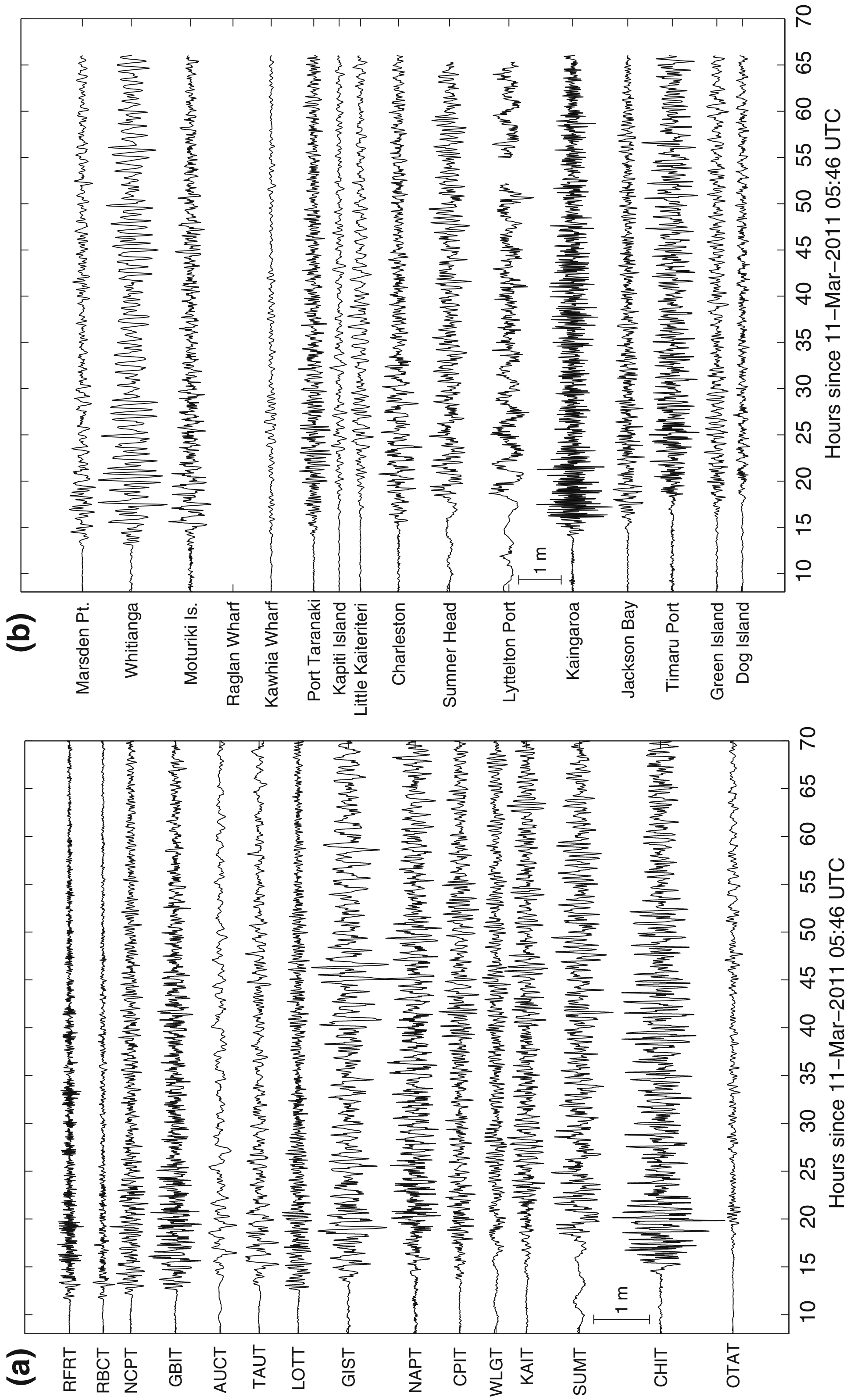

Figure 2

a Time series plots of de-tided sea level records at GNS Geonet stations locations around New Zealand. Locations are ordered from north (*top*) to south (*bottom*). **b** Time series plots of de-tided sea level records at gauges within a network around New Zealand coordinated by NIWA. Locations are ordered from north (*top*) to south (*bottom*)

Table 1

Summary statistics of the Tohoku-oki tsunami in New Zealand as recorded on the GNS Geonet tide gauges

Station	Arrival Time (h after EQ)	Max Amp	Assoc. trough	Height	Hrs after quake	Hrs after arrival	Max P2T	Hrs after quake	Hrs after arrival	Max SL	Hrs after quake	Hrs after arrival
RFRT	11.52	0.21	−0.13	0.34	17.34	5.82	0.42	19.27	7.75	0.72	17.34	5.82
RBCT	11.60	0.18	−0.21	0.39	13.37	1.77	0.39	13.37	1.77	0.62	17.28	5.68
NCPT	12.06	0.38	−0.21	0.58	19.20	7.14	0.58	19.20	7.14	1.01	19.20	7.14
GBIT	12.61	0.48	−0.45	0.93	16.11	3.50	0.93	16.11	3.50	1.02	18.21	5.60
AUCT	14.01	0.2	−0.08	0.28	18.55	4.54	0.44	17.00	2.99	1.18	18.55	4.54
TAUT	13.00	0.25	−0.11	0.36	47.72	34.72	0.59	16.05	3.05	0.85	18.57	5.57
LOTT	12.52	0.29	−0.23	0.51	20.67	8.15	0.51	20.67	8.15	0.84	17.06	4.54
GIST	13.44	0.66	−0.72	1.38	46.30	32.86	1.38	46.30	32.86	0.95	18.73	5.29
NAPT	13.99	0.53	−0.34	0.87	45.10	31.11	0.94	49.36	35.37	0.86	30.52	16.53
CPIT	13.69	0.38	−0.31	0.69	41.67	27.98	0.69	41.67	27.98	0.84	41.67	27.98
WLGT	16.31	0.25	−0.15	0.39	45.22	28.91	0.48	44.71	28.40	0.68	53.41	37.10
KAIT	15.96	0.4	−0.38	0.78	45.93	29.97	0.78	45.93	29.97	0.89	28.50	12.54
SUMT	16.86	0.51	−0.14	0.65	24.85	7.99	0.91	47.93	31.07	1.16	28.58	11.72
CHIT	14.16	0.86	−1.15	2.01	20.13	5.97	2.01	20.13	5.97	1.05	28.80	14.64
OTAT	16.19	0.15	−0.04	0.18	47.07	30.88	0.24	20.55	4.36	0.7	52.65	36.46

See Fig. 1 for station locations

Table 2

Summary statistics of the Tohoku-oki tsunami in New Zealand as recorded on gauges within a network around New Zealand coordinated by NIWA

Station	Arrival Time (hrs. after EQ)	Max Amp	Assoc. trough	Height	Hrs after quake	Hrs after arrival	Max P2T	Hrs after quake	Hrs after arrival	Max SL	Hrs after quake	Hrs after arrival
Marsden Pt.	12.89	0.31	−0.28	0.59	16.92	4.03	0.59	16.92	4.03	1.05	18.4	5.51
Whitianga	13.04	0.78	−0.85	1.63	17.68	4.64	1.63	17.68	4.64	1.28	17.68	4.64
Moturiki Is.	13.03	0.52	−0.38	0.90	15.60	2.57	0.92	17.07	4.04	1.17	18.55	5.52
Raglan Wharf	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Kawhia Wharf	14.04	0.16	−0.11	0.27	26.35	12.31	0.27	26.35	12.31	0.92	21.12	7.08
Port Taranaki	13.94	0.36	−0.21	0.57	32.12	18.18	0.73	23.07	9.13	1.12	21.08	7.14
Kapiti Island	15.59	0.22	−0.17	0.39	32.27	16.68	0.39	32.27	16.68	0.62	32.27	16.68
Little Kaiteriteri	16.03	0.3	−0.15	0.45	37.82	21.79	0.51	24.28	8.25	1.11	20.70	4.67
Charleston	14.83	0.47	−0.39	0.85	20.75	5.92	0.88	23.13	8.30	1.10	20.77	5.94
Sumner Head	16.94	0.49	−0.17	0.66	49.42	32.48	0.92	47.93	30.99	1.18	28.58	11.64
Lyttelton Port	17.24	0.47	−0.22	0.69	18.67	1.43	0.79	50.42	33.18	1.11	28.75	11.51
Kanigaroa	13.81	0.84	−0.65	1.50	17.47	3.66	1.50	17.47	3.66	1.21	16.23	2.42
Jackson Bay	14.43	0.35	−0.33	0.68	19.08	4.65	0.69	18.00	3.57	0.80	21.82	7.39
Timaru Port	16.44	0.72	−0.43	1.14	56.60	40.16	1.24	50.6	34.16	1.13	53.62	37.18
Green Island	16.13	0.3	−0.16	0.46	23.12	6.99	0.52	25.65	9.52	0.78	52.55	36.42
Dog Island	18.13	0.21	−0.14	0.34	27.13	9.00	0.34	27.13	9.00	0.80	49.83	31.70

Figure 3
Locations of the water level and current meters in and around Tauranga Harbor

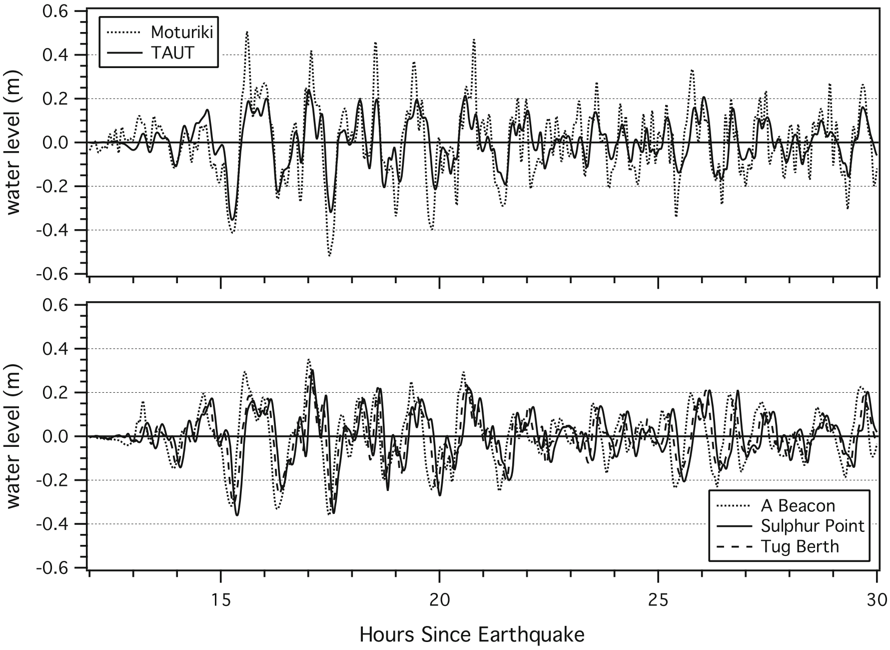

Figure 4
Recorded water sea levels at five locations in Tauranga Harbor during the 2011 Japan tsunami. *Upper panel* is the NIWA and GNS tide stations, *lower plot* is the three pressure sensors maintained by the Port of Tauranga

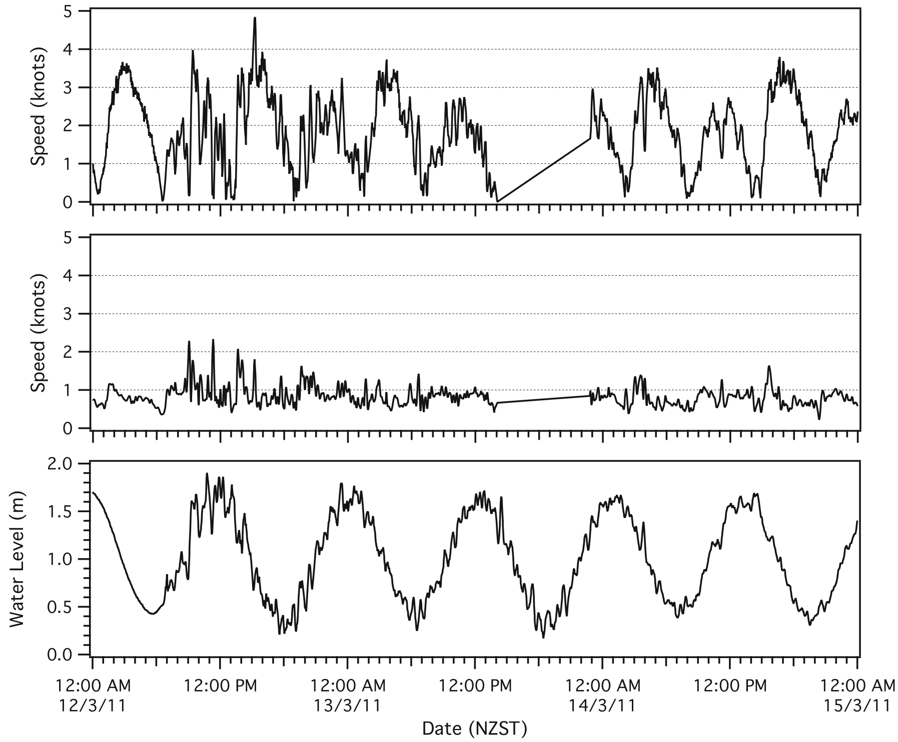

Figure 5
Raw current speed (*top*), residual current speed (*middle*) and water level (*bottom*) measured at Tauranga Harbour. The highest current speed corresponds with the falling tide in the afternoon of March 12, 2011 (New Zealand Standard Time)

Table 3

Constituent seiche modes in Lyttelton Harbor

Seiche mode	Period (min)
Transverse harbor seiche	10
Longitudinal harbor seiche (2nd mode)	40
Longitudinal harbor seiche (fundamental mode)	99
Pegasus Bay seiche	205

currents in the Port of Tauranga, normal operations were not disrupted.

Like Tauranga, there were several concurrent water level recordings and current data collected from the Christchurch and Lyttelton Harbor area. These included NIWA's Sumner Head tide station, the GNS SUMT gauge and a tide gauge maintained by Lyttelton Port Company. Current data was recorded using a drogue tracer study conducted on the day of the tsunami. Goring (2009a) previously described several different seiche periods for Lyttelton Harbor (Table 3). Through the technique of orthogonal wavelet decomposition (Misiti *et al.*, 2000), the tide gauge data from Lyttelton can be decomposed to reveal these modes in the signal (Fig. 6). The Pegasus Bay seiche identified by Goring and Henry (1998) is the oscillation of the whole of Pegasus Bay from the shoreline to the continental shelf. Under normal conditions, the seiche is driven by the interaction of tide and weather systems as they propagate over the continental shelf and into the bay. Inspection of the decomposed signal shows that this seiche was active at Lyttelton prior to tsunami arrival and was amplified by the tsunami for several cycles before settling back to pre-tsunami levels, an effect also seen in the Sumner Head (SUMT) data (Fig. 7). Long waves with periods from 3 to 24 min are also an important component of the water level signal in Lyttelton Harbor as they are commonly present, being generated by groups of swells propagating northward from the Southern Ocean or from moving low pressure systems to the east of New Zealand (Goring, 2009b). Prior to the tsunami arrival, there was no significant

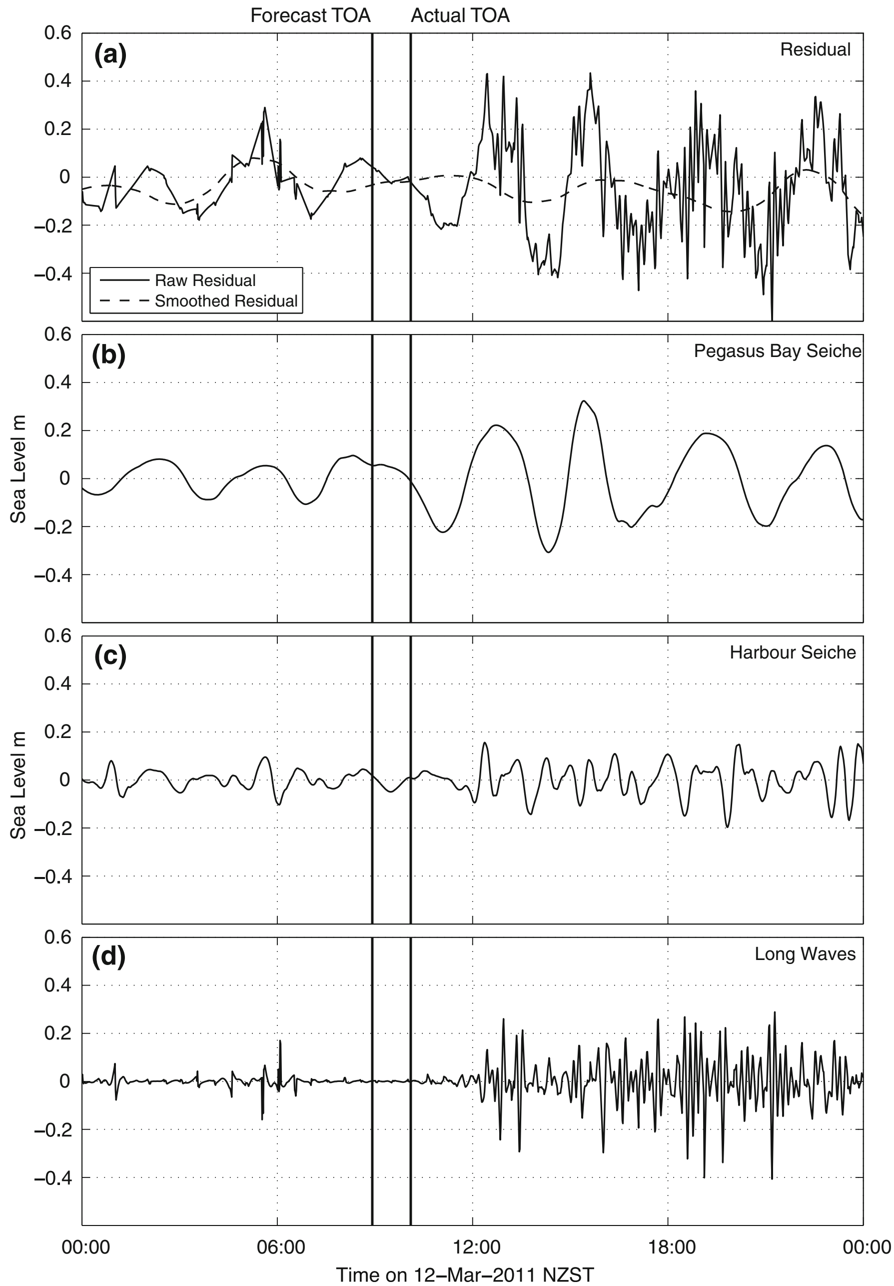

Figure 6
Raw residual water level from the Port of Lyttelton tide gauge (**a**) and its decomposition into Pegasus Bay seiche (**b**), with timescales of 192 min; harbor seiche (**c**), with timescales of 48–96 min; and long waves (**d**), with timescales from 3 to 24 min. *Vertical bars* are the forecast and actual times of arrival (TOA)

long wave signal present at Lyttelton. However at 11:43 am NZST (12:43 pm NZDT), nearly 2 h after the forecast tsunami arrival time, the long waves suddenly increased in amplitude. The peak of the long wave signal (0.8 m) occurred the next day at 05:00 on 13-Mar NZST (Fig. 8). The long wave signal then tapered off slowly over the next 3 days.

In summary, the Pegasus Bay seiche, harbor seiche and long waves were all present in the water level signals recorded in Lyttelton Harbor. The

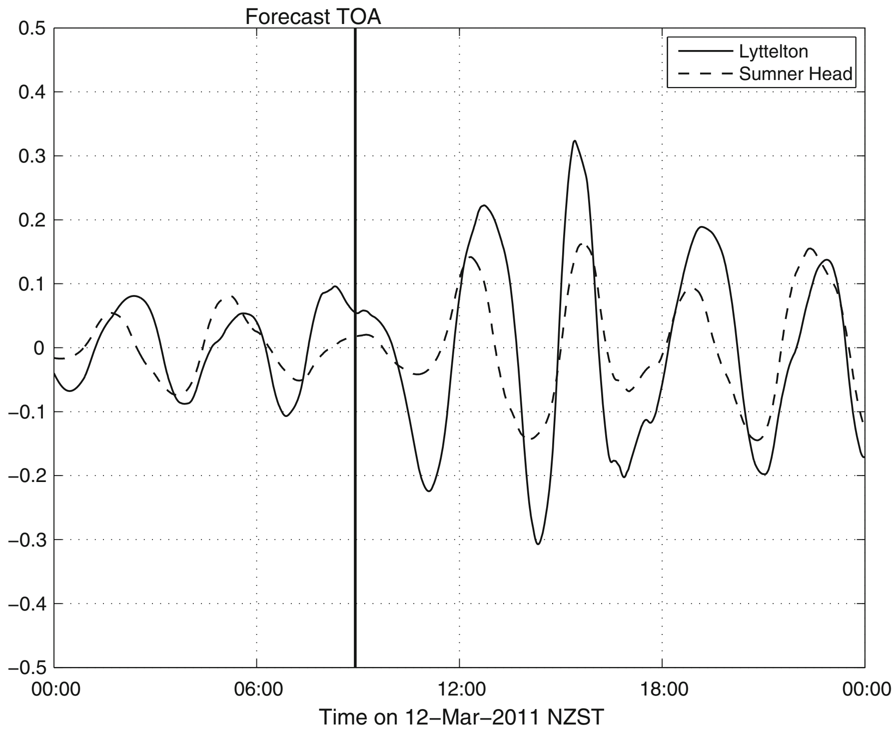

Figure 7
A comparison of the Pegasus Bay seiche at Lyttelton and Sumner Head (SUMT)

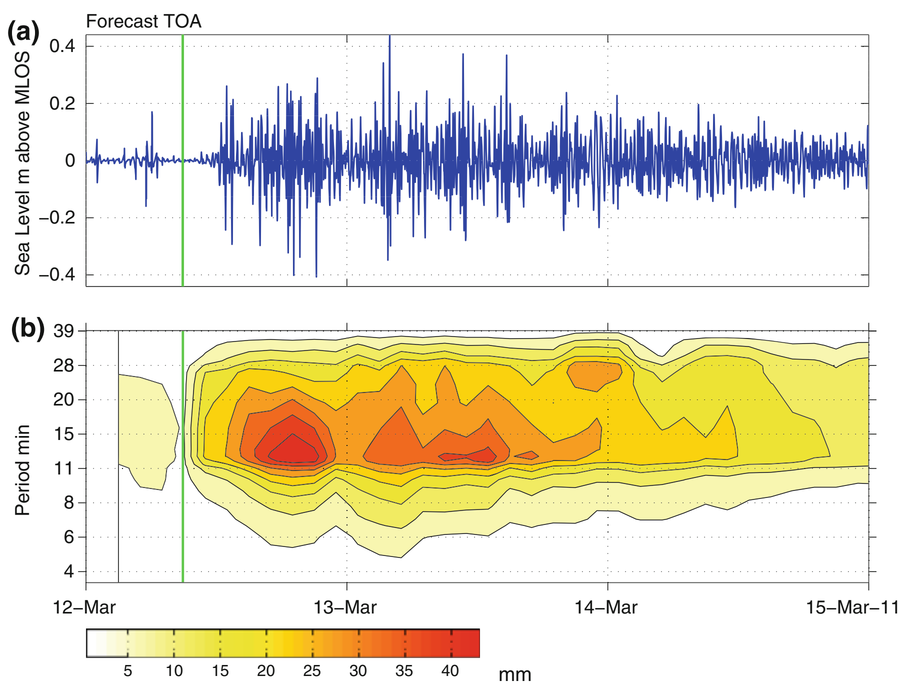

Figure 8
Long wave record from the Port of Lyttelton tide gauge (*upper*) and contour plot of wave height with time and period (*lower*)

Table 4

Summary of maximum wave heights and timing in Lyttelton Harbor on March 12, 2011

Wave type	Height (m)	Time (NZDT)
Pegasus Bay Seiche	0.530	14:22
Harbor Seiche	0.345	21:09
Long waves	0.698	22:14

maximum heights of these components are listed in Table 4. The Pegasus Bay seiche increased in amplitude just after the forecast time of arrival of the tsunami, while harbor seiche and long waves began at about noon and peaked in the evening, by which time the Pegasus Bay seiche had receded to normal levels. Detailed analysis of the data suggests that the issue of tsunami arrival is not well defined. While the Pegasus Bay seiche appears to have responded at about the forecast time of arrival, the harbor seiche and long waves did not become active until approximately 3 h later. This may correspond to one or two leading waves of a very long period (an order of hours), followed by shorter period waves that excited the harbor seiche and long waves.

Currents were measured in Lyttelton Harbor through the deployment of 15 drogues near the entrance to the Port (Goring, 2011). Initial drogue positions were recorded by GPS and using a small speedboat, the drogues were located and their positions recorded approximately every 30 min. These data were processed to give the position and velocity at the midpoint between each recording, yielding snapshots of the velocity field (Figs. 9, 10). The tidal currents were estimated using tidal constituents (MetOcean Solutions, 2009) and subtracted from the raw measurements to obtain the net velocities due to the tsunami. Figure 9 shows the time bands for each snapshot, and the snapshots themselves are presented in Fig. 10a, b. The snapshots show that the incoming tsunami currents were sufficient to reverse the ebbing tidal flow, while at other times, the outflow of the tsunami waves combined with the ebb-tide flow to produce currents as high as 1.1 knots. Comparing the tsunami waves shown in Fig. 9 with

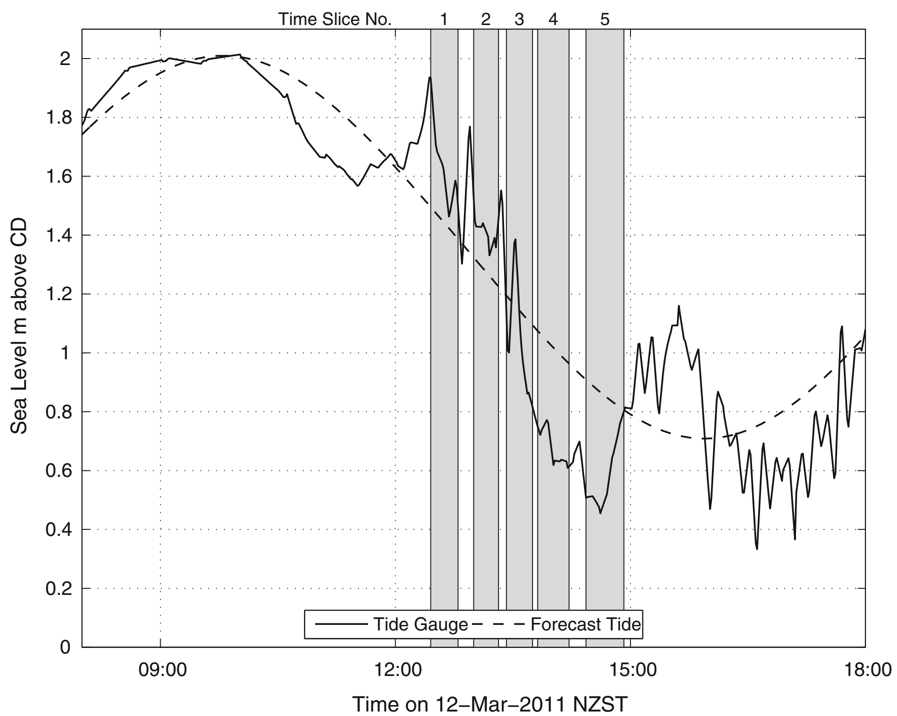

Figure 9

Measured and predicted water levels at the Port of Lyttelton. The *vertical grey bars* indicate the time intervals over which the drogue velocity data was recorded (Fig. 10)

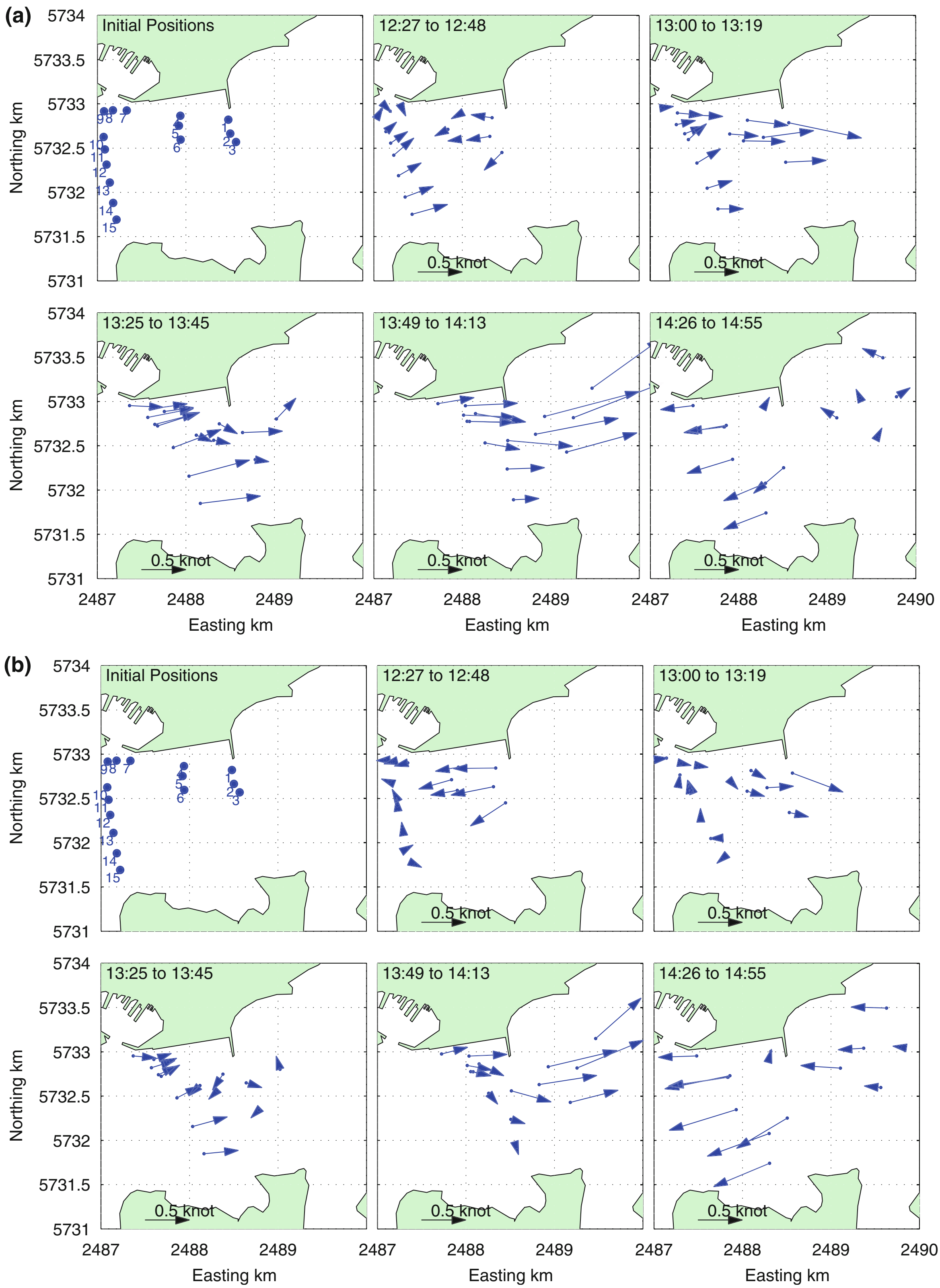

Figure 10
Raw (**a**) and residual (**b**) current speeds as recorded by a drogue deployment in Lyttelton Harbor during the Tohoku tsunami

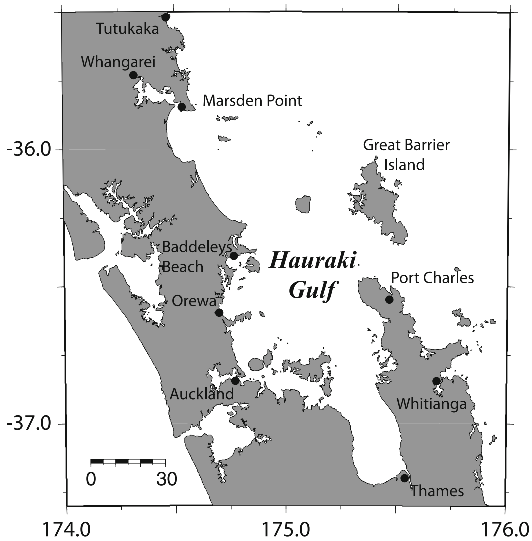

Figure 11
Locations mentioned in the text in the central North Island of New Zealand

the net currents in the snapshots suggests that the most significant flows occurred when the amplitude of the tsunami wave was largest (i.e., when the departure from the forecast tide was largest).

1.3. Port Charles

Port Charles, located at the northern tip of the Coromandel Peninsula (Fig. 11), was strongly affected by the Tohoku-oki tsunami (Fig. 12). A temporary water level gauge at that location also recorded the tsunami, although the signal appears to have been damped by the stilling pipe used to filter out wave activity. A field survey of the area conducted on 21 March, 9 days after the tsunami, gathered information on the tsunami effects. Based on this survey, photographs and eyewitness accounts, the tsunami overtopped a jetty and flooded the low lying areas at the head of the bay with surges inundating up to 100 m inland. The highest absolute water levels were recorded around the time of high tide when overtopping of the jetty deck occurred (Fig. 12). The height of the jetty deck has been measured at +2.3 m relative to the Moturiki Vertical Datum-1953 (MVD53). Inspection of the measured time series shows a damped tsunami wave signal, with a mean high tide level of 0.8 m MVD53, which implies the maximum positive amplitude was ~1.5 m. Videos recorded at Port Charles during the event showed that the waves overtopped small dunes, and flowed inland, flooding vehicles and inundating a small residential area (Fig. 12). Surges also propagated up nearby stream channels overflowing the banks. Flow depths and velocities reported by witnesses suggested conditions too dangerous for wading with water depths up to 'thigh level' and maximum speeds estimated to be about 0.5–1 m/s. Surging occurred approximately every 20–40 min with the largest surges between 12 and 1:10 pm (NZDT) based on sea level gauge measurements with tsunami surges propagating 250–600 m up local streams. Eight households lodged the first-ever claims for tsunami-related damage of houses under New Zealand's Earthquake Commission (EQC) government-operated insurance scheme since tsunami cover was introduced in 1993 (PENINSULA POST, 2011).

1.4. Accounts from Maritime Facilities

In the weeks following the Tohoku-oki tsunami, several ports, marinas and other marine facilities were contacted to gather information regarding the tsunami event. Using a questionnaire developed for sites in California (WILSON *et al.*, this volume) as a basis for our investigation, we inquired about observations of the physical effects of the tsunami as well as about the flow of information from the media and government sources and about actions taken to protect life and property. The questions contained in the questionnaire were as follows:

- How did they hear about the tsunami?
- Was it clear which actions to take?
- What action did they take?
- How did the public respond?
- When and why did you give the all clear?
- Character of the tsunami
- Timing of largest surge?
- Damage?
- General notes about the tsunami
- How did it compare to the Samoan and Chilean tsunamis of 2009 and 2010?

The questions were asked in a conversational manner and not every respondent provided an answer

Figure 12
Tsunami effects at Port Charles: (*top*) inundation into a neighborhood and (*bottom left* and *right*) tsunami induced currents and surface agitation. The *small jetty* indicated with the *arrow* is overtopped in the second image (indicated by the *oval*)

for every question. While a summary of the responses at important sites is described below, the full set of responses is summarised graphically in Fig. 13.

Starting in the north, a worker at the Marsden Point Oil Refinery reported observable surges, no stronger than typical strong tidal currents, late in the day on March 12, after the official all clear had been posted. However, normal operations were not disrupted. Staff at Whangarei Marina, noted that they received a text message from New Zealand's Ministry of Civil Defence and Emergency Management (MCDEM) but otherwise obtained most of their information from the TV or radio. The only effect was a small surge on the order of 10 cm at approximately 1:30 pm on March 12. The situation was substantially different at Tutukaka Marina, just north of Whangarei where strong currents and surges damaged dock piles and nearly damaged several moored vessels. During the event, staff members received an advisory text message from MCDEM. After being warned, several boat owners took their boats out for the day, causing problems later as people returned to the marina while the strongest surges were affecting the area.

In the Auckland region, staff at the Bayswater Marina obtained information from television news reports and advised boat owners verbally and via email. The tsunami was observed as a small surge that arrived much later than expected based on the official reports. At the Bucklands Beach Yacht Club and Marina, the dock master received his information from the radio and subsequently went to the docks to warn residents. He reported that there were no discernible tsunami effects. Most sites in the Auckland area did not report any observable tsunami effects; however, the Orakei Marina reported a strong

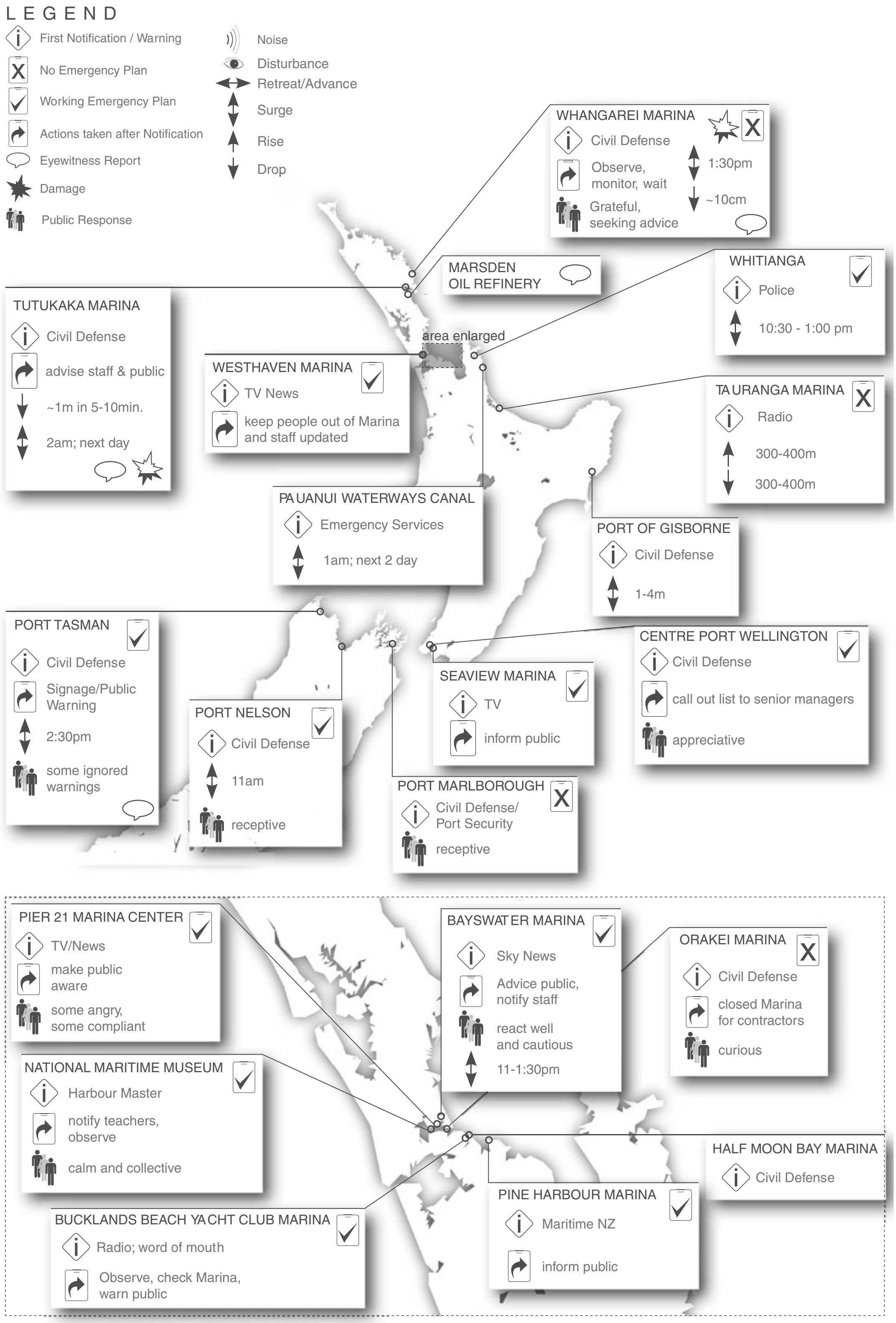

Figure 13
A graphical summary of eyewitness accounts from maritime facilities throughout New Zealand. The Auckland region (shaded in the *upper panel*) is enlarged in the *lower panel*

current on the next day and at the Westhaven Marina, there was a noticeable water level change of about 30 cm and some agitation of the water surface.

In the Coromandel Peninsula, the site manager at the Pauanui Waterways Canal reported that she was first alerted by a phone call from her son, which was followed by a call from emergency services. The manager reported that surges were evident throughout the day Saturday and Sunday with the strongest effects at about 1 pm on Saturday (12 March). At Whitianga, known to be particularly vulnerable to tsunami, the existing tsunami response plan was not implemented because the harbormaster was away and the message was not delivered to the next point of contact. There were several close calls in Whitaianga as the public boat ramp near the inlet entrance became unusable due to the strong currents. The situation was made worse by a high volume of boating traffic associated with a fishing competition and a boat race held that day. The respondent reported 10 surges in approximately 4 h on Saturday, some of which were ‘horrific’ and ‘quite alarming’. Standing waves were observed at the marina entrance and the water levels came very close to overtopping the piles of the floating docks. Three boats dragged their moorings and there was a near collision with a catamaran. The tsunami surge moved sand in to the marina and deposited black silt into the entrance channel. All in all it was reported that they were ‘very close to serious issues’. Interestingly, during the 2010 Chilean tsunami, the Whitianga Marina was closed for 48 h and resulted in stronger and longer lasting effects than in this event.

At Tauranga Harbor, a witness reported surges and water level fluctuations in the order of 30–40 cm throughout 11 and 12 March, consistent with the tide gauge records. At Eastland Port in Gisborne, the harbor master received a text message from MCDEM and subsequently initiated their emergency response plan. While the tsunami was not damaging, there were strong currents and water level changes much larger than expected. The surges lasted for several days and the largest surges happened *after* the official ‘all clear’ had been issued. Similar effects were observed in Gisborne during the 2010 Chilean tsunami.

On the South Island, Port Nelson was advised by MCDEM via text message. The respondent noted that the emergency plan for tsunami was basic and could be improved. The reaction from the public and civil defence was much less than in the 2009 Samoa tsunami when local beaches were evacuated. In Marlborough, the Waikawa, Picton and Havelock Marinas share a tsunami response plan. Port Security who had been notified by MCDEM notified the operations manager for the marinas. In preparation, the staff posted warnings, notified members of the public and mobilised additional staff; however, the effects were minimal with the strongest surges noticed on 13 March at the entrance to Picton Harbor. On 14 March, 48 h after the tsunami arrival, unusually low water levels caused mussel farm moorings to become tangled with some resultant damage.

On the east coast of the South Island, the Ports of Lyttelton and Timaru were notified by MCDEM with additional information coming from media sources. Each of the ports has a tsunami plan; at Timaru it involves putting out extra moorings and alerting all ships in the port. At Lyttelton, all relevant marine interests were notified, but the public was not notified since the tsunami was expected to be small. Both ports reported stronger than normal currents and moderate water level changes in the order of 1 m. At Timaru the surging was exceptionally persistent lasting approximately 1 week. It was reported that the water turned a different colour during the tsunami surges. The regional harbormaster reported that one of the pilot boats struck bottom during a tsunami withdrawal and may have sustained some damage. During the 2010 Chilean tsunami, vessels at Lyttelton were moved to the middle of the Harbor whereas during the 2009 Samoan event, some vessels were moved out to sea.

It is clear from many of these reports, that while there was adequate notification on the part of MCDEM, there was not an adequate appreciation for the extended duration of the tsunami maritime hazard. The fact that the arrival time coincided with the morning of a sunny Saturday may have provided a good excuse to ‘take out the boat and wait for the tsunami to pass’. Unfortunately at these locations some of the strongest effects occurred in the afternoon, when people were returning to port after a day on the water. The fact that many respondents received information through unofficial channels could be a related to the event occurring in the afternoon in Japan, where the graphic images were extensively broadcast to the world and coincided with the evening news hour in New Zealand. Additionally, there were some inconsistencies in the actions taken at different locations. While most responded appropriately, there were instances, particularly on the east coast of the North Island, where little action was taken yet the tsunami effects were most severe. Apart from a few locations where strong currents often occur during tsunamis (e.g., Tutukaka Harbor), there is generally little appreciation by the boating public of the magnitude of currents that can be generated even for small tsunami heights.

1.5. *Additional Reports from the General Public*

Following the tsunami the GNS Geonet program established an online survey for members of the public to report observations of the event. In total there were 67 usable reports submitted, of which 52 reported observations of tsunami-related phenomena and 15 were null reports, i.e. no unusual behaviour noted at the specified time and location (Fig. 14). The locations of observations are quite widely distributed around New Zealand, with the greatest number of reports coming from the more densely populated northeast coast of the North Island. Similarly the absence of observations along the west coast of the South Island should be viewed in the context of the low population and rugged nature of this coast.

Respondents were asked to estimate the observed vertical change in water level. These should be viewed with caution due to the difficulty in making such estimates. In most cases the reports detailed the difference in water level between the trough of one wave (a withdrawal) and the peak of the subsequent wave (or occasionally vice versa), which we label the 'tsunami surge height'. It is therefore relevant to the provision of tsunami warning information to the public that casual observers notice the change in water level over a tsunami wave cycle; that is, the tsunami *height* as opposed to the *amplitude*. Several of the observations were expressed in terms relative to the tidal range, e.g. 'from low tide mark to two thirds of high tide'. The largest estimated surge heights were observed along the east coast north of Auckland (2.2 m at Orewa 'water level varied between the low tide and high tide marks over a period of about 8 min', and 1.95 m at Baddeleys Beach in Millon Bay (near Omaha) also equated to the tidal range). A similarly large range was reported at Mercury Bay on the Coromandel Peninula (1.85 m). The largest horizontal movement of the shoreline was estimated at 650 m at Baddeleys Beach in Millon Bay, which is a shallow inter-tidal embayment.

1.6. *Real Time Assessment of Tsunami Effects in New Zealand*

During the evening of 11 March, as the tsunami propagated across the Pacific Ocean, a real time assessment of the tsunami effects was carried out using the Community Model Interface for Tsunamis (ComMIT) numerical modelling tool (Titov *et al.*, 2011). The ComMIT model interface was developed by the United States government National Oceanic and Atmospheric Administration's (NOAA) Centre for Tsunami Research (NCTR) following the December 26, 2004 Indian Ocean tsunami as a way to efficiently distribute assessment capabilities amongst tsunami prone countries. The backbone of the ComMIT system is a database of pre-computed deep water propagation results for tsunamis generated by unit displacements on fault plane segments positioned along the worlds subduction zones. The database is used in conjunction with real time recording of the tsunami waveforms on one or more of the deep ocean tsunameter stations deployed throughout the oceans to fine tune details of the earthquake source mechanism. The resulting trans-oceanic tsunami propagation results stored in the ComMIT database are then used as boundary inputs for a series of nested nearshore grids covering a coastline of interest. Given the long travel time for the tsunami to reach New Zealand from Japan and the serendipitous location of several DART stations close to the tsunami source, this provided an excellent opportunity to test the system under emergency conditions.

The model runs conducted during the tsunami event, were set up and executed in an ad-hoc manner and focussed on the northern region of New Zealand, extending from north of Auckland to North Cape. Due to the limited time available, model bathymetry grids for near shore regions were constructed from

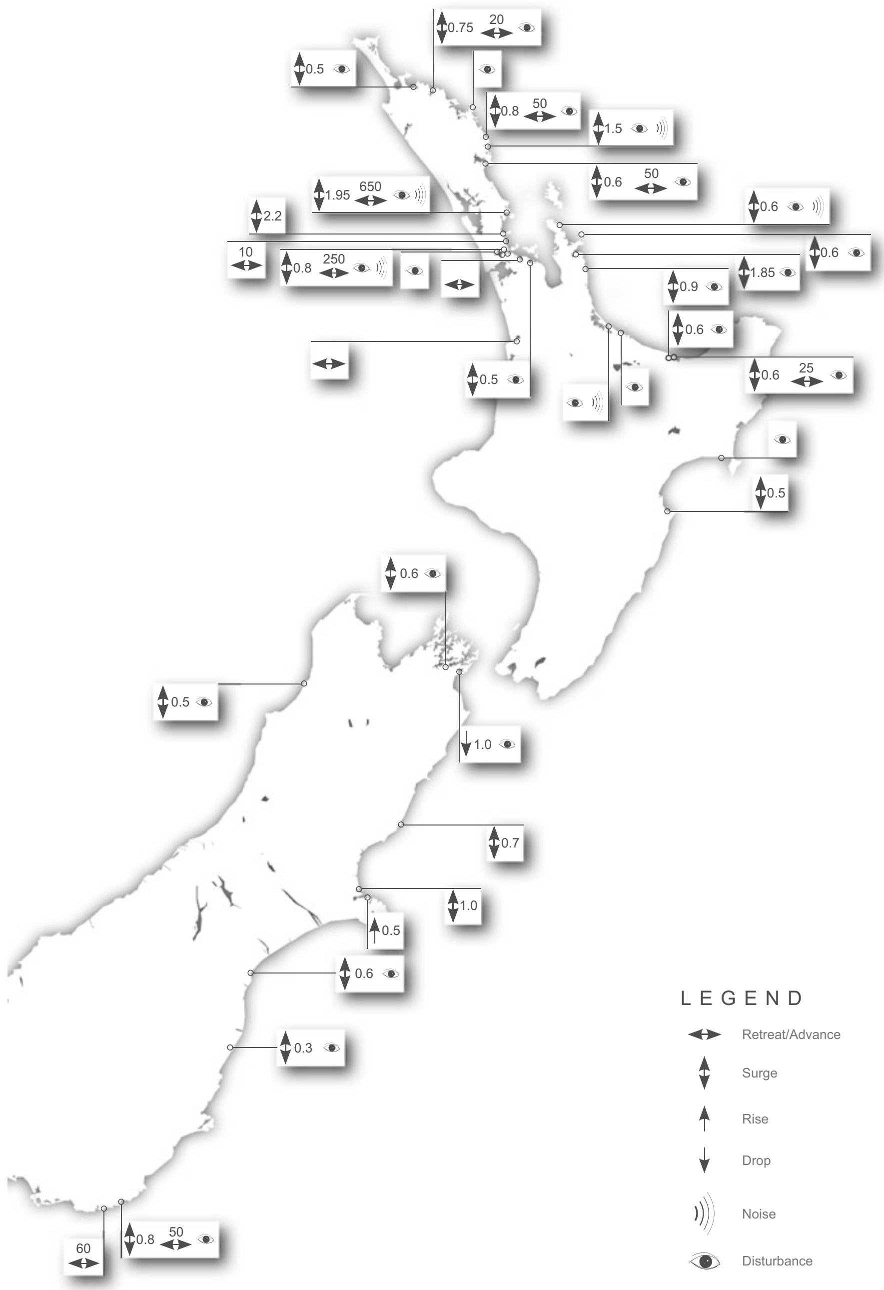

Figure 14
A symbolic summary of observations of the Tohoku tsunami in New Zealand as reported by the general public in a survey conducted by Geonet. Null observations, those in which no unusual behaviour was noted, are not shown

the relatively coarse, yet readily available 0.5 min GEBCO global bathymetry data set interpolated to 2, 1 and 0.5 arcmin (approximately 3.6, 1.8 and 0.9 km). The first real time simulations used a uniform slip earthquake model based on the reported magnitude and geographic location of the earthquake alone. A few hours later, once the DART tsunameter data had been analysed, an updated source model was made available by NOAA/PMEL and used to update the simulations.

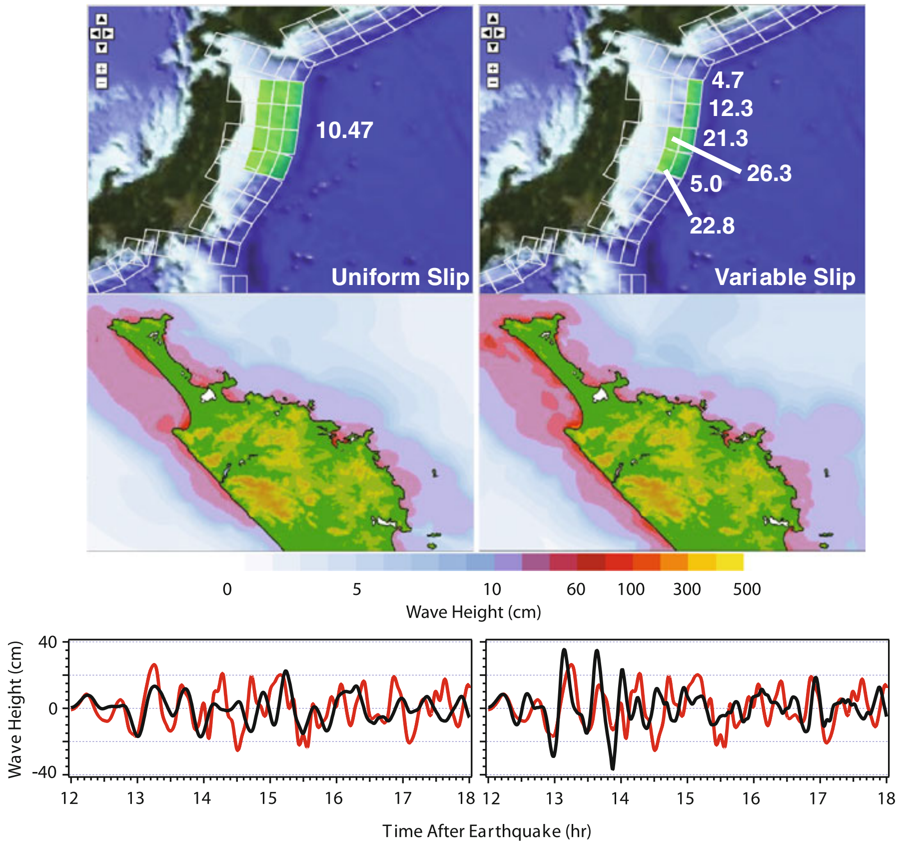

Figure 15
(*Top*) Initial conditions for the real time tsunami assessment conducted on the evening of March 11, 2011. The uniform slip scenario assumed average slip of 10.47 m over all fault segments, while the DART-constrained source used variable slip amounts (*middle*). The DART constrained source predicted slightly elevated wave heights in the northern region of New Zealand. (*Bottom*) Model output (*black*) is compared to the North Cape (NCPT) tide gauge record (*red*)

The ComMIT model results are shown in Fig. 15 and compared to the tide gauge record at North Cape (NCPT). The DART-constrained source predicted larger wave heights and based on these results the advisory level for the tsunami was raised by MCDEM for the northern regions of the country. For the rectangular source, the model generally under-predicted the measured water levels. While there is a good fit to the first wave arrival time and amplitude for the DART-constrained source, the model over predicts subsequent waves. Despite the mismatch, the general range of predicted wave heights is close to observed and slightly conservative. It must be stressed however that in this first simulation the innermost modelling grid had a resolution of 0.5 min (approx 1 km), and in light of this we contend that the model result are quite good and fit the measured data reasonably well. These results illustrate the effectiveness of the database driven ComMIT tsunami modelling tool for real time tsunami hazard assessment. Used in conjunction with observations and anecdotal accounts, these results can provide a framework for anticipating the effects from future tsunami events.

2. Conclusion

The March 11, 2011 Tohoku-oki earthquake generated a devastating and far-reaching tsunami with damaging effects throughout the Pacific Ocean (see Wilson *et al.*, 2012; Lynett *et al.*, 2012; Reymond *et al.*, 2012, this volume). In New Zealand the tsunami was widely observed as it caused overland flooding in some areas as well as strong currents and surges that lasted for several days. While this event was not overly damaging, it was the strongest tsunami to affect New Zealand since the 1960 Chilean tsunami and highlights the nationwide hazard posed by far field sources, particularly in light of the dramatic increase in exposed coastal population and maritime infrastructure over the intervening years.

This event has provided an opportunity to learn from a near disaster. Post-event interviews, field surveys and data analysis have provided a wealth of qualitative and quantitative data. Questionnaires seeking data from the public can provide informative responses; however, such initiatives need to undertaken promptly to recover the most useful information. While some of the qualitative reports simply reinforced what was already known about site-specific vulnerabilities, quantitative data from tide gauges and current meters can be used to assess local and maritime hazards. Together this information provides an opportunity to modify warning and evacuation procedures and protocols when another event takes place.

Of particular importance is the extended duration of the hazard during a far field tsunami, a fact that was clearly illustrated in this event with the highest water levels and strongest surges occurring many hours after the anticipated tsunami arrival. The potential for this was not fully grasped by the general public nor did the emergency management community adequately convey this message. This resulted in many close calls, particularly at small boat harbors, as those who chose to take their vessels out in anticipation of the tsunami arrival were affected by strong surges as they returned to port later in the day. This emphasizes the need to keep tsunami alerts active for longer and for the advisory messages from far field events to downplay first arrival times while emphasizing the extended hazard duration.

Numerical modelling results from simulations conducted as the tsunami traversed the Pacific Ocean suggest the utility of a modelling prediction system designed to assess the impact of a distant source event before it arrives. The continued development and refinement of this system and distribution of such capability across New Zealand's emergency response community could improve hazard assessments and aid in the fine tuning of warning messages and targeted evacuations.

Finally, the Tohoku-oki tsunami highlights the importance of tsunami-induced currents in ports and harbors even for relatively small tsunami wave heights. While the tsunami induced currents were significant, the end effects were fortunately minor. However, this event was much smaller than the tsunamis caused by the South American earthquakes of 1868, 1877 or 1960. Should a repeat of those events occur, the effects would be much more severe. The tsunami also excited coastal-trapped waves, long waves and seiche activity around New Zealand, which along with reflections off continental shelf plateaus probably contributed to the delayed onset of the strongest effects. This highlights the need for research efforts targeted at an improved understanding of the tsunami response characteristics of New Zealand's intricate coastline and economically vital maritime infrastructure.

Acknowledgments

The Port of Tauranga provided water level and current data in Tauranga Harbor. Lyttelton Port of Christchurch provided water level data for Lyttelton Harbor. Other sources of sea level data are listed in the Tide Gauge Data section. ASR Intern Cole Cannon conducted numerous phone interviews with employees and operators of maritime facilities throughout New Zealand. The authors would like to acknowledge the valuable information provided by the operators and employees of various marine facilities who were interviewed for this report. Rob Eaton of OCEL Consultants Ltd and staff from En-Viro Consultants conducted the drogue tracking study at Lyttelton Harbor. John Black provided photographs of the tsunami at Port Charles.

References

Borrero, J., and Greer, S.D. (2012). *Comparison of the 2010 Chile and 2011 Japan Tsunamis in the Far-Field*. Pure Appl. Geophys, in review.

Goring, D. (2009a). *Seiche in Lyttelton Harbor*, Mulgor Technical Note, October 2009.

Goring, D. (2009b). *Meteotsunami resulting from the propagation of synoptic-scale weather systems*. Phys. Chem. Earth *34*, 1009–1015.

Goring, D. (2011). *Honshu Tsunami 12-March-2011*, Report to the Lyttelton Port Company, 17 pp.

Goring, D., and Henry, R. (1998). *Short period (1–4 h) sea level fluctuations on the Canterbury coast, New Zealand*. New Zeal. J. Mar. Fresh. *32*, 119–134.

IOC/UNESCO (2011). IOC/UNESCO Japan Tsunami Bulletin No. 29, 30 September, 2011, 2 pp.

Lynett, P., Weiss, R., Renteria, W., Morales, G., and Don, S. (2012). *Coastal Impacts of the March 11th Tsunami in the Galapagos Islands*. Pure Appl. Geophys, accepted for publication.

MetOcean Solutions (2009) *Waves and Currents in Lyttelton Harbor*. Report for Lyttelton Port of Christchurch, December 2009.

Misiti, M., Misiti, Y., Oppenheim, G., and Poggi, J.-M. (2000). *Wavelet Toolbox User's Guide*. The Mathworks Inc., Natick, Mass.

Peninsula Post (2011) 'EQC's first tsunami claims from Port Charles', 8 September 2011, p 4.

Reymond, D., Hyvernaud, H., and Okal, E. (2012). *The 2010 and 2011 tsunamis in French Polynesia: Operational aspects and field surveys*. Pure Appl. Geophys, accepted for publication.

Titov, V., Moore, C, Greenslade, D., Pattiaratchi, C., Badal, R., Synolakis, C., and Kânoğlu, U. (2011). *A new tool for inundation modeling: community modeling interface for tsunamis (ComMIT)*. Pure Appl. Geophys., *168*, 2121–2131.

Wilson, R., Admire, A., Borrero, J., Dengler, L., Legg, M., Lynett, P., Miller, K., Ritchie, A., Sterling, K., and Whitmore, P. (2012). *Observations and Impacts from the 2010 Chilean and 2011 Japanese tsunamis in California*. Pure Appl. Geophys., submitted.

(Received December 23, 2011, revised April 10, 2012, accepted April 11, 2012, Published online June 9, 2012)