Development of Products and Procedures for the Mitigation Tsunami Hazards at Maritime Facilities in Northland

Appendices 1-5

eCoast Limited
Marine Consulting and Research
P.O. Box 151
Raglan, New Zealand

jose@ecoast.co.nz

<BLANK PAGE>

Development of Products and Procedures for the Mitigation Tsunami Hazards at Maritime Facilities in Northland

Appendices 1-5

Report Status

Date	Status	Approved By:
30 June 2019	Final Report	JCB

Jose C. Borrero Ph.D.


Cover Picture: Marsden Point at the entrance to Whangarei Harbour, Northland.

<BLANK PAGE>

CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

1 APPENDIX 1: EFFECTS IN PORTS FROM DISTANT SOURCE TSUNAMI OCURRING BETWEEN 2004 – 2012

The text below is reproduced from the report:

"Decision Making Tools for the Real-Time Assessment of Far-Field Tsunami Hazards in New Zealand Ports and Harbours. Part 1: Background Information and Preliminary Analysis" by Jose Borrero, Derek Goring, Dougal Greer, Aggeliki Barberopoulou and William Power. This report was submitted to the Ministry of Science and Innovation (MSI) as part of the Natural Hazard research Platform project entitled "Improving tsunami warnings and real time hazard assessment in New Zealand's ports and harbours." This project ran from July 1, 2012 through 31 December 2014.

1.1 Tsunami Currents during the 2004 Indian Ocean Tsunami

During the 2004 Indian Ocean tsunami, three occurrences of ships being torn from their moorings were detailed in field survey reports by Okal (2006, a,b,c; Figure 1.1).

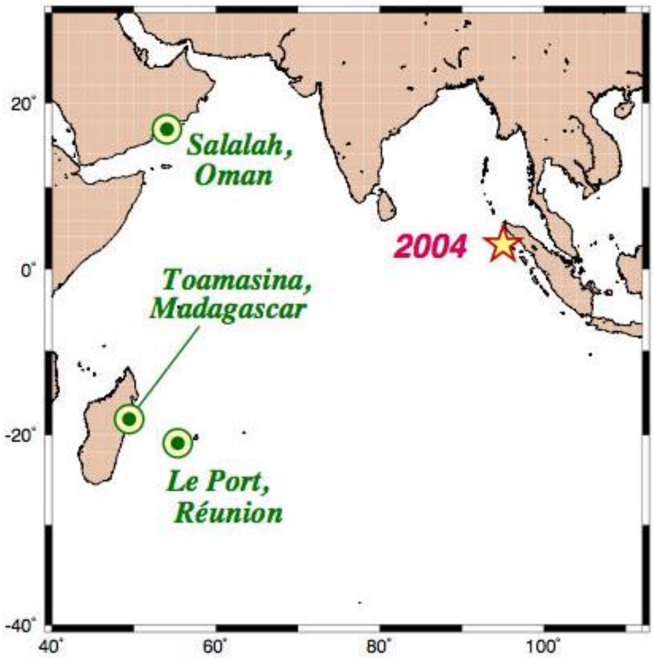


Figure 1.1 Locations where ships were broken free from their moorings due to tsunami surges induced by the 2004 Indian Ocean tsunami (image provided by Prof. Emile Okal).

In the first case, at the port of Toamasina, Madagascar tsunami waves began affecting the port some 8 hours after the earthquake, consistent with tsunami travel times from Sumatra to Madagascar, with maximum water levels measured to be approximately 0.6 m above mean sea level. The initial tsunami activity was observed for 4 or 5 hours and then abated. Approximately two hours after this, currents in the harbor increased dramatically, eventually causing a 50 m freighter to break her mooring lines and wander through the harbor for the next 3 hours until it was grounded on a sand bar. Luckily the free-floating ship did not collide with any other vessels or wharf structures.

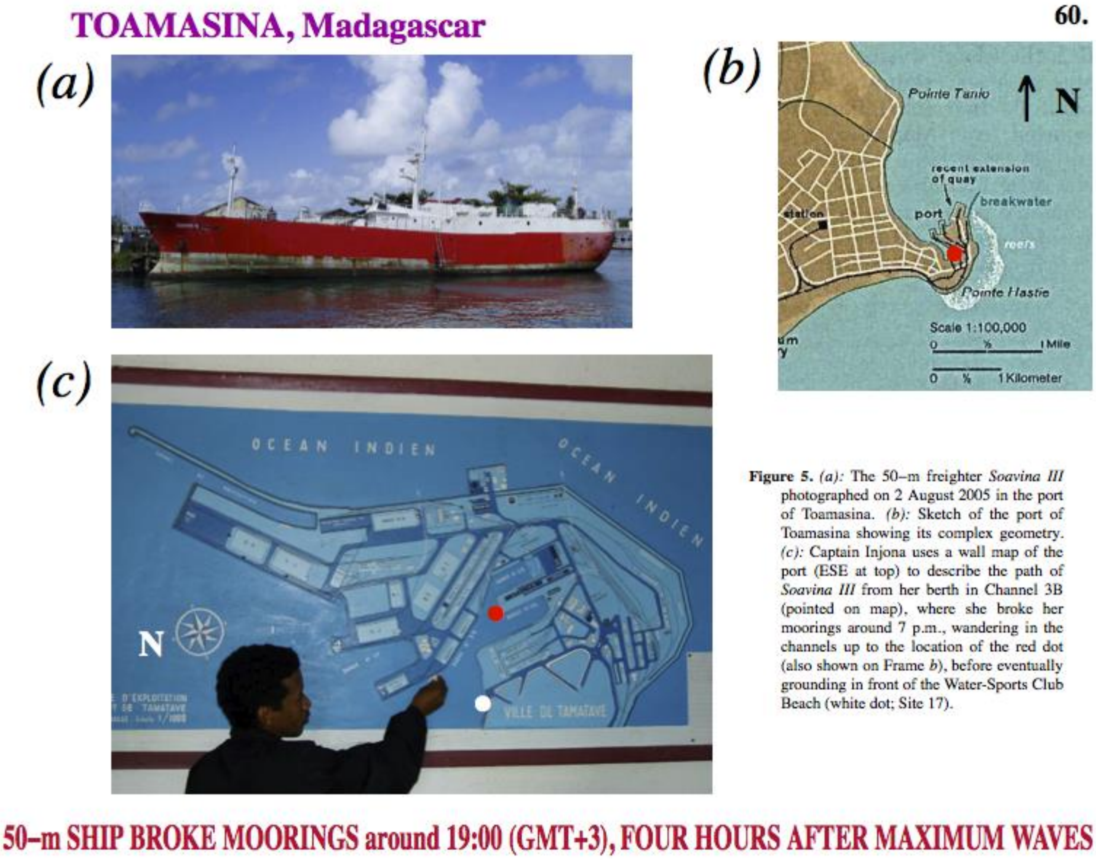


Figure 1.2 Description of the occurrence in Toamasina, Madagascar (reproduced from Okal et al., 2006a).

The situation was somewhat different at Le Port on Reunion Island. At 15:30 local time, four hours after the arrival of the tsunami, strong currents in the port broke all of the mooring lines securing the 196 m container ship *MSC Uruguay*. The ship then became uncontrollable as it was pushed around the harbor by the tsunami currents. During this time it struck and damaged gantry cranes on nearby docks. The ship was secured, but then at 1820 local time (~6.5 hours after tsunami arrival) it once again broke free before it was finally secured.

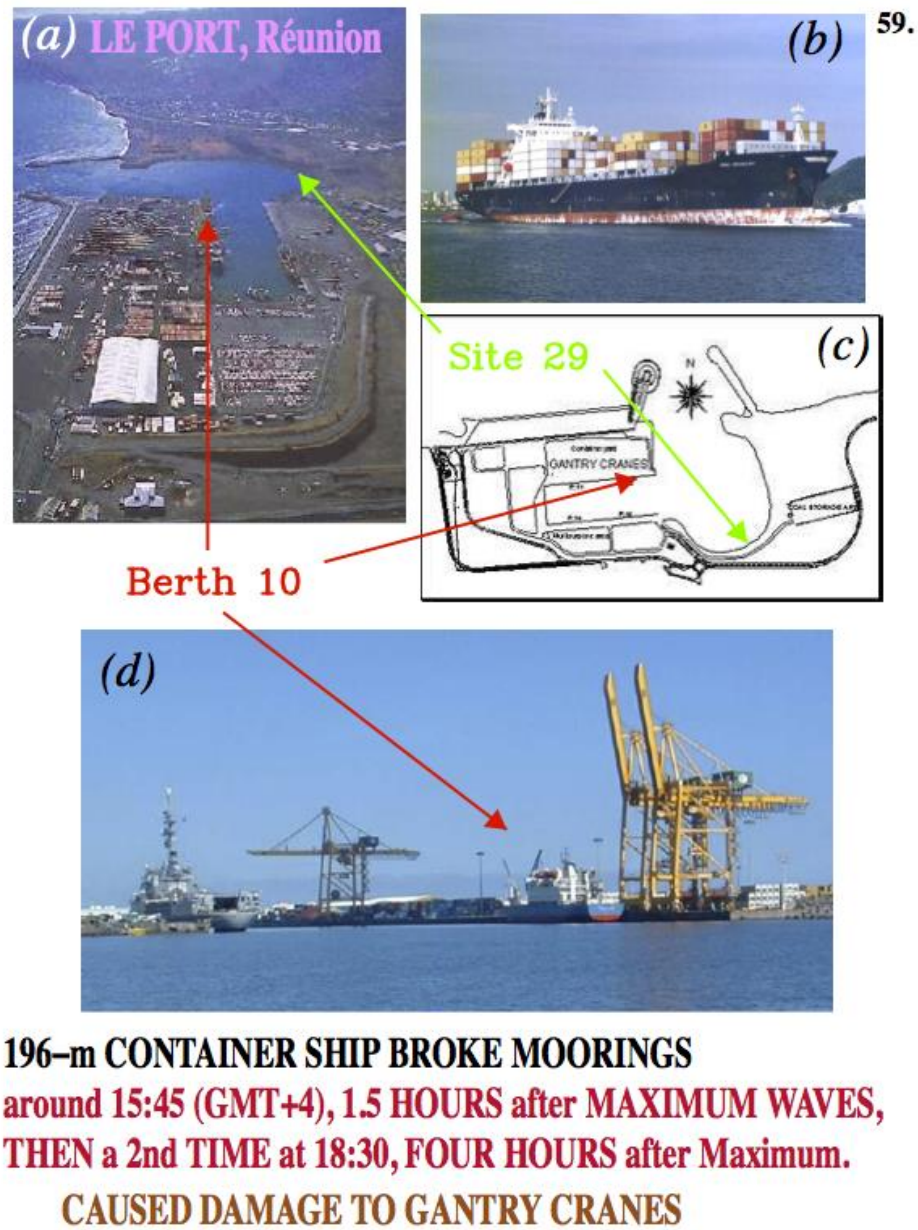


Figure 1.3 Description of the occurrence in Le Port, Reunion Island (reproduced from Okal et al., 2006c).

The third of these events occurred in the Port of Salalah, Oman, an important shipping container terminal servicing the Indian Ocean. At Salalah, approximately 90 min after tsunami first arrival, strong currents near the most offshore unloading berth broke all of the mooring lines of the 285 m freighter *Maersk Mandraki* and pulled it away from the terminal. The ship was reportedly caught in a system of eddies and could not be brought under control even with the use of tugboats. The currents eventually pulled the freighter out of the harbor and beached it on a nearby sandbar. At the same time, the 292 m freighter *Maersk Virginia* was rocked by the tsunami as it entered the harbor. The captain delayed the entry into the harbor and waited outside for several hours during which time strong currents caused the freighter to collide with the breakwater resulting in minor damage to the ship's fuel tank.

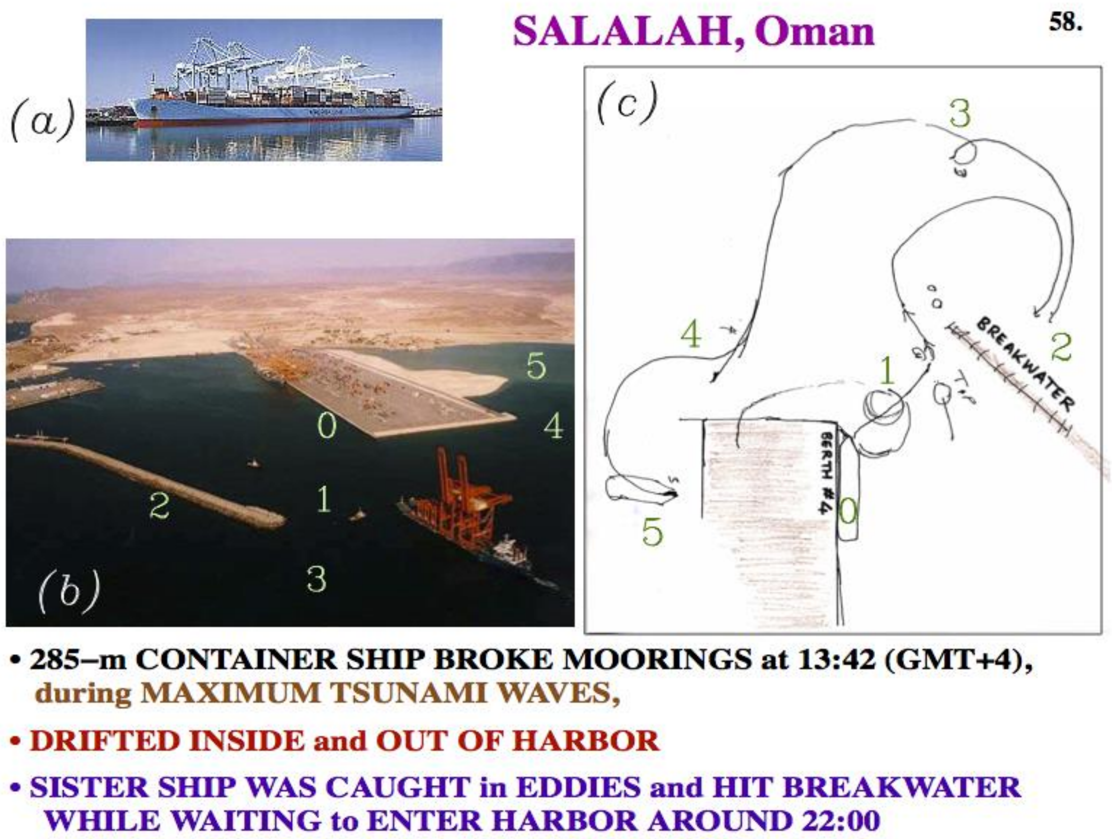


Figure 1.4 Description of the occurrence in Port of Salalah, Oman (reproduced from Okal et al., 2006b).

1.2 The 2006 Kuril Islands Tsunami in Crescent City, CA

Dengler et al. (2008) described the effects in Crescent Harbor as a result of the 15 November 2006 tsunami generated by an M 8.3 earthquake located in the Kuril Islands. The size of the earthquake prompted the issuance of tsunami warnings, watches and advisories for different regions of the Pacific Ocean. Crescent City itself was only placed under a tsunami advisory. Due to relatively small wave heights recorded on near-source tide gauges, the watches and warnings were cancelled by the West Coast Alaska Tsunami Warning Centre (WCATWC) approximately three and a half hours after the earthquake. Continued monitoring of oceanic tide gauges however suggested that the tsunami could be larger on the US west coast and prompted the WCATWC to contact emergency managers in northern California to warn them of the possible danger. As a result, the beaches and harbor areas were cleared to remove people from possible danger. The first tsunami waves reached Crescent City just before noon on November 15th, and surges steadily increased until mid-afternoon when a maximum surge of 1.76 m (peak to trough) affected the harbor between 2:00 and 2:30 PM PST (Figure 1.5), some three hours after the initial wave.

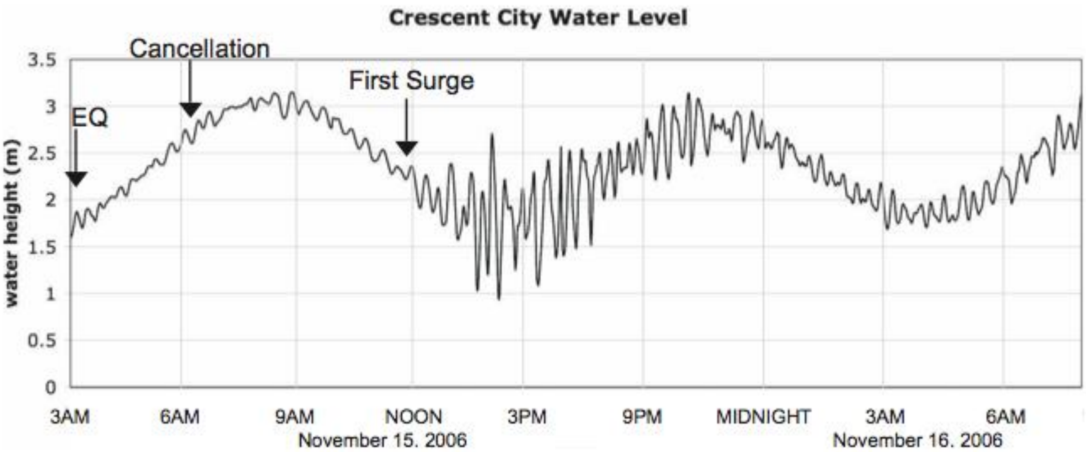


Figure 1.5 Water level data from the National Ocean Services (NOS) tide gauge in Crescent Harbor. The earthquake occurred at 3:15 am PST (first arrow). Warning and watch were cancelled by WCATWC at 6:42 am PST (second arrow), and the first surge arrives at about 11:40 am PST (third arrow). The gauge is located on Citizens Dock at 41.745 N, 124.185 W. (image reproduced from Dengler et al., 2008).

It should be noted that these peak surges occurred around low tide and this may have mitigated the overall effects. Nevertheless, very strong and damaging currents were reported beginning with the initial waves and intensifying as the larger surges came through. The design of the docks in used in Crescent City connects the floating platforms to the metal pilings by a metal pile ring. Since the strong currents pushed the docks laterally pinning the pile ring against the pilings, the docks were unable to adjust to the changing water level allowing water to flow over the top. The increased hydrodynamic forces resulted in severe damage to several docks, particularly those located nearest to the entrance of the inner harbor (Figure 1.6).

Figure 1.6 Small-boat basin. Docks F, G, and H were either completely or severely damaged during the 2006 tsunami (from Dengler et al., 2008).

1.3 The 2009 Samoa Tsunami in New Zealand

In September 2009 a series of powerful earthquakes struck the northern end of the Tonga-Kermadec trench between Tonga and Samoa. While the precise seismology of the event is still a matter of debate (Beavan et al., 2010, Lay et al., 2010), the event was unique in that it involved two large (M~8) earthquakes occurring nearly simultaneously – a rupture along the main subduction plate boundary as well as an outer rise normal fault rupture to the east of the subduction interface (Satake, 2010). The net result was a large and deadly tsunami that claimed 189 lives in Samoa and Tonga and produced runup of greater than 17 m in American Samoa (Okal et al., 2010, Fritz et al., 2011).

The tsunami propagated throughout the Pacific Ocean (Figure 1.7) and was recorded on tide gauges throughout New Zealand. Fortunately, due to the fact that tsunami energy is spread perpendicular to the strike of the earthquake source, most of the tsunami energy was radiated to the east and west with relatively little energy pushed to the south towards New Zealand (Figure 1.7). Nevertheless the tsunami caused peak to trough wave heights of 0.9 m in the Chatham Islands and approximately 0.5 m at several sites in both the North and South Islands (Figure 1.2, Rob Bell, *pers. comm.)*.

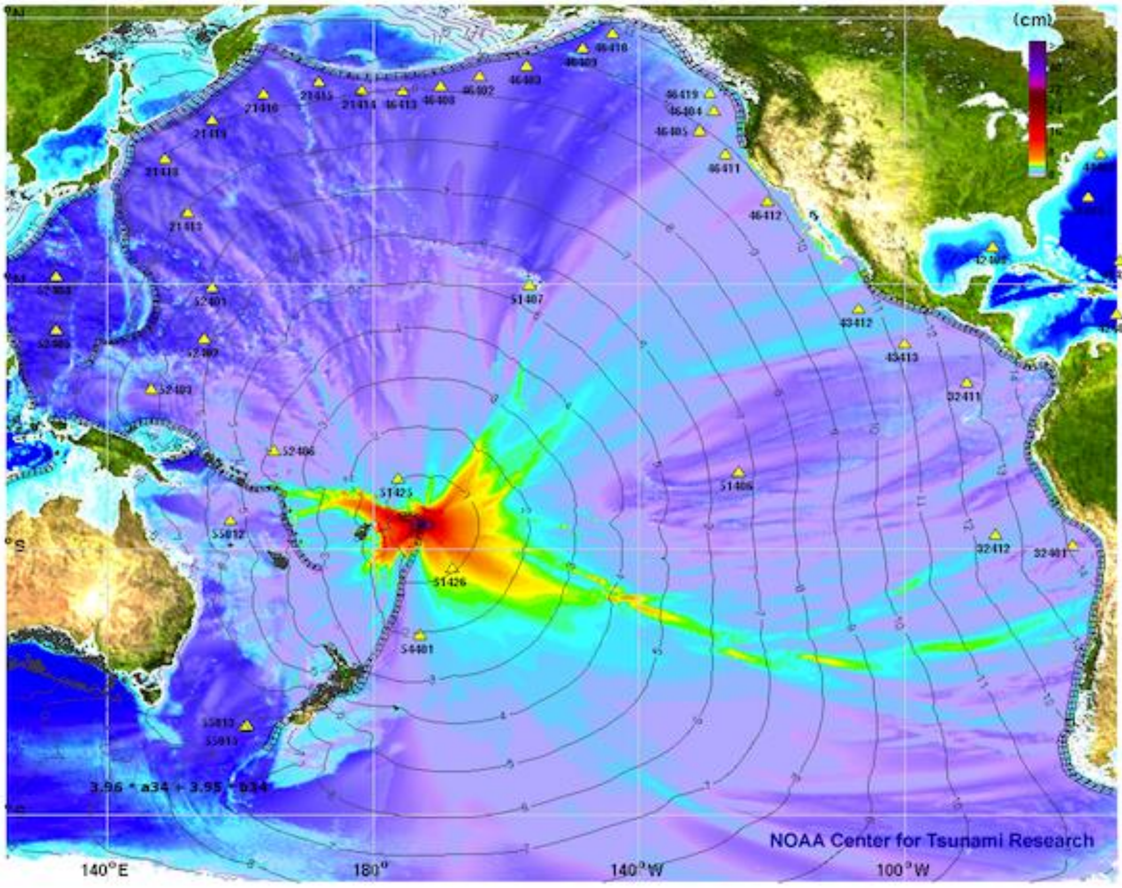


Figure 1.7 Maximum computed wave heights across the Pacific from the September 29, 2009 Samoa earthquake and tsunami. It is clear from this plot that New Zealand was not affected by the largest wave heights produced by this tsunami (credit: NOAA/PMEL Tsunami Research Centre).

Table 1.1 Tsunami arrival time and timing of highest waves at select tide gauges from New Zealand's GEONET network from the 2009 Samoa tsunami. (Source: Derek Goring)

Station	First Waves	Highest Wave		
	TOA (h)	Height (m)	Period (min)	TOA (h)
Raoul Is. Fishing Rock	3.1	0.365	6.1	4.6
Raoul Is. Boat Cove	3.2	0.195	8.1	7.3
North Cape	4.7	0.212	16.8	6.8
Waitemata Harbour	7.2	0.034	14.0	8.8
East Cape	4.5	0.218	9.4	9.9
Tauranga	6.3	0.205	53.4	15.3
Gisborne	5.9	0.145	13.6	7.5
Napier	7.4	0.156	11.0	37.1
Wellington	9.4	0.108	27.7	35.6
Chatham Islands	5.1	0.414	12.6	5.7

Table 1.2 Measured parameters of recorded tsunami waves in New Zealand, with all elapsed times relative to the time of the earthquake (at 17:48 29 September 2009 UTC) and other times in UTC. (Source Rob Bell, NIWA)

Station	Elapsed arrival time [hrs]	Arrival time [UTC 29 Sept]	Peak wave height (crest-to-trough) [m]	Peak wave height above tide level [m]	Wave period for peak wave [min]	Elapsed Time of Peak [hrs]	Time at peak wave [UTC 30 Sept]
Kaingaroa Chatham Is.	4.22	22:01	0.89	0.39	11	5.37	23:10 [29 Sept]
Moturiki Is.	5.23	23:02	0.54	0.37	8	9.18	02:59
Marsden Pt.	5.95	23:45	0.13	0.08	8	11.57	05:22
Whitianga	5.53	23:20	0.27	0.17	21	12.28	06:08
Sumner Head	7.00	00:48 [30 Sept]	0.24	0.14	14	18.97	12:46
Lyttelton Port	7.22	01:01 [30 Sept]	0.43	0.24	11	13.53	07:20
Timaru Port	7.20	01:00 [30 Sept]	0.55	0.32	11	12.88	06:41
Green Island	7.00	00:48 [30 Sept]	0.21	0.12	10	8.92	02:43
Charleston	8.02	01:49 [30 Sept]	0.41	0.23	12	11.75	05:33
Jackson Bay	7.93	01:44 [30 Sept]	0.61	0.26	9	11.85	05:39
Port Taranaki	6.77	00:34 [30 Sept]	0.31	0.16	11	19.93	13:44
Kapiti Island	–	–	negligible	negligible	–	–	–
Scott Base, Ross Sea*	~10.2	~04:00 [30 Sept]	0.02	0.01	10–15	19.0	12:50

1.4 The Trans-Pacific Tsunamis of 2010 and 2011

Two major tsunamis occurred in the Pacific Ocean the 2010 and 2001. First, on 27 February 2010, a $M_w = 8.8$ earthquake occurred in southern central Chile along South American Subduction Zone (SASZ), known to generate great earthquakes and transoceanic tsunamis. This event, the largest from the SASZ in half a century, originated some 230 km north of the source for the largest ever instrumentally recorded earthquake, the great Chilean earthquake of May 22, 1960. While the 2010 event was a big earthquake, it nucleated relatively deep along the plate interface, causing the bulk of the energy release (20 m slip at 30 km depth) to occur at depth, minimizing its tsunami generation potential (Delouis et al., 2010; Fujii and Satake 2012). Nevertheless the earthquake produced a locally devastating tsunami with runup heights approaching 30 m near Constitución (Fritz et al., 2011).

This was followed just over 1 year later by, the 11 March 2011 Tohoku, Japan earthquake. This earthquake released nearly twice the energy of the 2010 Chilean earthquake, resulting in nearly 30 m of co-seismic slip at 20 km depth and rupture extending to the trench axis (Ozawa et al., 2011) resulting in tsunami runup of over 40 m in the near field (Mori et al., 2011). Numerical modelling results from the US National Oceanic and Atmospheric Administration Centre for Tsunami Research (NOAA/NCTR) showing maximum computed tsunami wave heights across the Pacific are reproduced in Figure 1.8. Both of these earthquakes generated a significant far-field tsunami observed and recorded throughout the Pacific Basin.

As reported in Borrero and Greer (2012), the tsunamis generated by the 2010 Chile and 2011 Tohoku earthquakes present a unique opportunity to examine the effects of major tsunamis in the far field. These tsunamis complement each other for a number of reasons. First, the events occurred just 1 year apart with source regions located on opposite corners (northwest and southeast) of the Pacific Basin, thus providing an interesting juxtaposition of the distributed effects. Second, the tsunamis were recorded on a large number of coastal tide gauges and deep-ocean tsunameters. Of particular interest are the recordings from the relatively dense arrays of tide gauges near New Zealand and California, located at the alternate opposite corners of the Pacific (northeast and southwest) relative to the source regions (northwest and southeast), as well as the recordings of the tsunami wave forms on the Pacific-wide array of Deep-ocean Assessment and Recording of Tsunamis (DART) tsunameters. Third, the Pacific Ocean has not experienced a significant transoceanic tsunami since the 1960 Chile and 1964 Alaska events; thus the 2010 and 2011 tsunamis represent the best source of information on the effects of transoceanic tsunamis on all scales of modern maritime infrastructure. Furthermore, New Zealand and California represent excellent case studies for such an investigation in that both industrial and recreational marine activities are of primary importance to the economies of each region and have expanded dramatically over the past five decades.

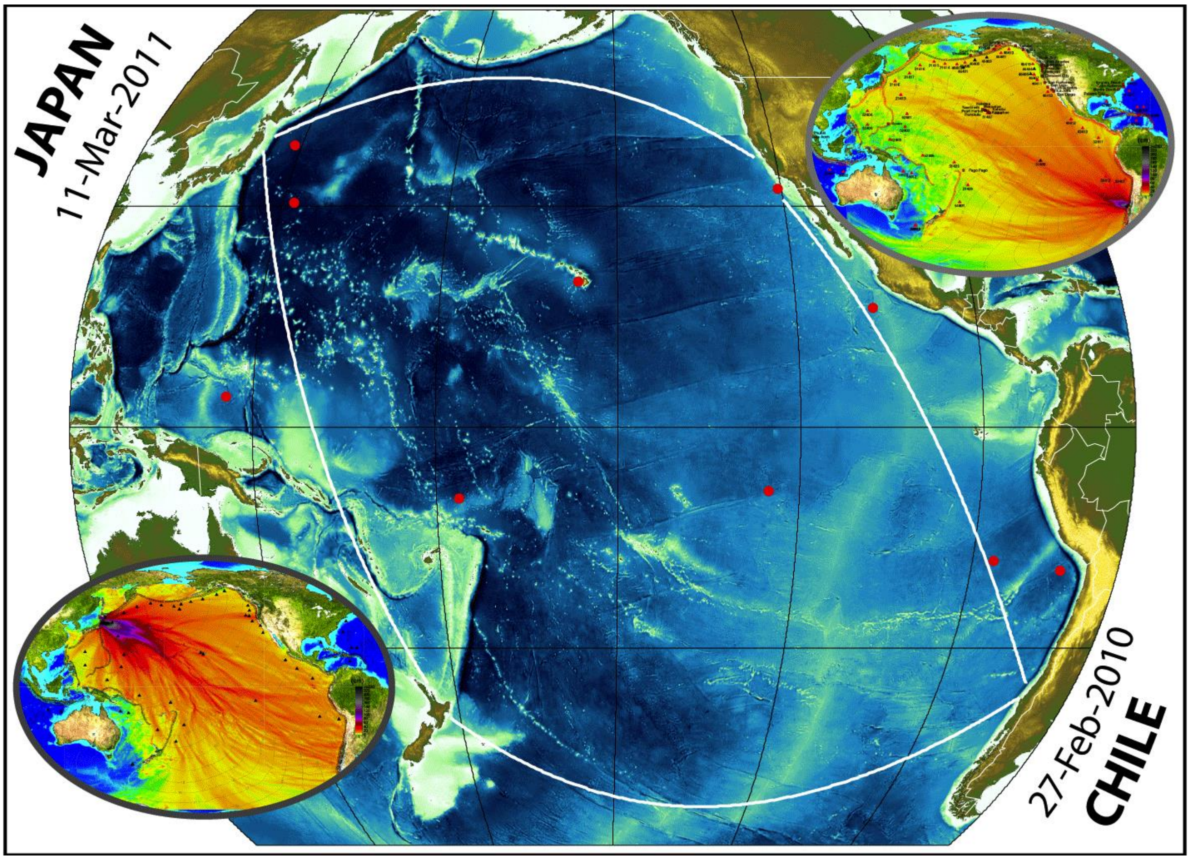


Figure 1.8 The tsunamis of 2010 and 2011 across the Pacific and relative to New Zealand and California.

1.5 The 2010 Chile Tsunami

1.5.1 Effects in California

In California, the Chile tsunami began affecting San Diego, CA around mid-day on February 27 and steadily moved northward over the next several hours. The surges caused currents of up to 8 m/s (~16 knots) according to eyewitness accounts, although these values may be overestimated. Nevertheless, strong and damaging currents were observed, particularly in San Diego, Ventura and Santa Cruz Harbours (Figure 1.9).

In San Diego a sailboat was swamped by standing waves at the entrance to Mission Bay. These waves formed as a result of the interaction between the ebbing tsunami current and incoming swells. At Shelter Island in San Diego Bay, strong currents, estimated at 5 m/sec (10 knots) caused damage to docks and pulled a 25 m fishing boat and the dock it was attached to off of the concrete piles to which it was secured.

The strongest effects from the Chile tsunami occurred in Ventura Harbor where several docks were damaged and current speeds were estimated at 6-7 m/s by the local harbor master. To the north at Santa Barbara strong currents (~5 m/s) were also reported, however there was no damage reported. At Santa Cruz, currents were also estimated to be on the order of 5 m/s, strong enough to force boats that had previously been evacuated to stay outside of the harbor for over 6 hours until the surges abated.

Two large boats broke free from their moorings and caused minor damage in collisions with other boats and harbor structures.

Figure 1.9 Photos from the February 27, 2010 tsunami in California. (A) is a still image of a boat that floats loose during the tsunami in Santa Cruz Harbor (source: YouTube video). (B) A photo of docks damaged during the 2010 tsunami in Ventura Harbor (source: Dale Carnathan). (C) and (D) Pictures showing flooding and damage to dock taken during and after the 2010 tsunami, northern Shelter Island, San Diego Bay (sources: (C) is still image from YouTube video; (D) is by Rick Wilson). (Reproduced from Wilson et al., 2012).

1.5.2 Effects in New Zealand

In New Zealand, the effects were limited mostly to strong currents and surges with no reports of significant damage. Borrero and Greer (2013) reported extensively on the tsunami signature on New Zealand tide gauges and noted the extended duration of the tsunami effects in New Zealand waters. This is clearly evident on the residual tide gauge data shown in Figure 1.11 (reproduced from Borrero and Greer, 2012).

1.6 The 2011 Tohoku Tsunami

Understanding the effects of the 2011 Tohoku tsunami in California are particularly important to understanding the potential effects from a large far-field tsunami in New Zealand. The orientation and distance between the subduction zone responsible for the 2011 earthquake and tsunami relative to California is roughly analogous to the location and orientation of the South American Subduction Zone of northern Chile and

Southern Peru. This region is known to have produced at least two very large and destructive tsunamis responsible for damaging and deadly tsunami waves in New Zealand. However, these events occurred in the late 1800's (1868 and 1877), when New Zealand was much less developed and dependent on maritime infrastructure than today.

1.6.1 Effects in California

Virtually every port, harbor and maritime facility in California was adversely affected by surges and currents induced by the 2011 Tohoku tsunami. The strongest effects and most severe damage occurred in northern California at Crescent City close to the Oregon border. Tsunami surges caused very strong currents in the inner small boat harbor resulting severe damage to the docks and to the boats that were present at the time of the tsunami. Fortunately, most of the commercial fishing vessels was evacuated from the harbor before the tsunami arrived and were therefore spared the destruction. In Santa Cruz, strong currents – up to 7 m/s – accompanied the surges that penetrated deep into the rectangular harbour basin, the largest of which occurred some 3 hours after the tsunami first arrival. These surges caused considerable damage throughout the harbor. At Ventura, the effects from the 2011 tsunami were less than what was experienced during the 2010 Chile tsunami. However, the currents were still significant and caused problems for boaters trying to dock during the tsunami and were blamed for one injury to harbor personnel working during the event. It is worth noting that the strongest and most damaging surges occurred at 0100 PST on March 12th, some 15 hours after the tsunami first arrival.

Figure 1.10 Photos from the March 11, 2011 tsunami in California. (A) Aerial view of heavy damage within Crescent City small boat basin. (B) A tsunami bore in east San Francisco Bay. (C) A tsunami bore damaging boats in Santa Cruz Harbor. (D) A boat sinking and damage to docks in southern Shelter Island, San Diego Bay (Reproduced from Wilson et al., 2012).

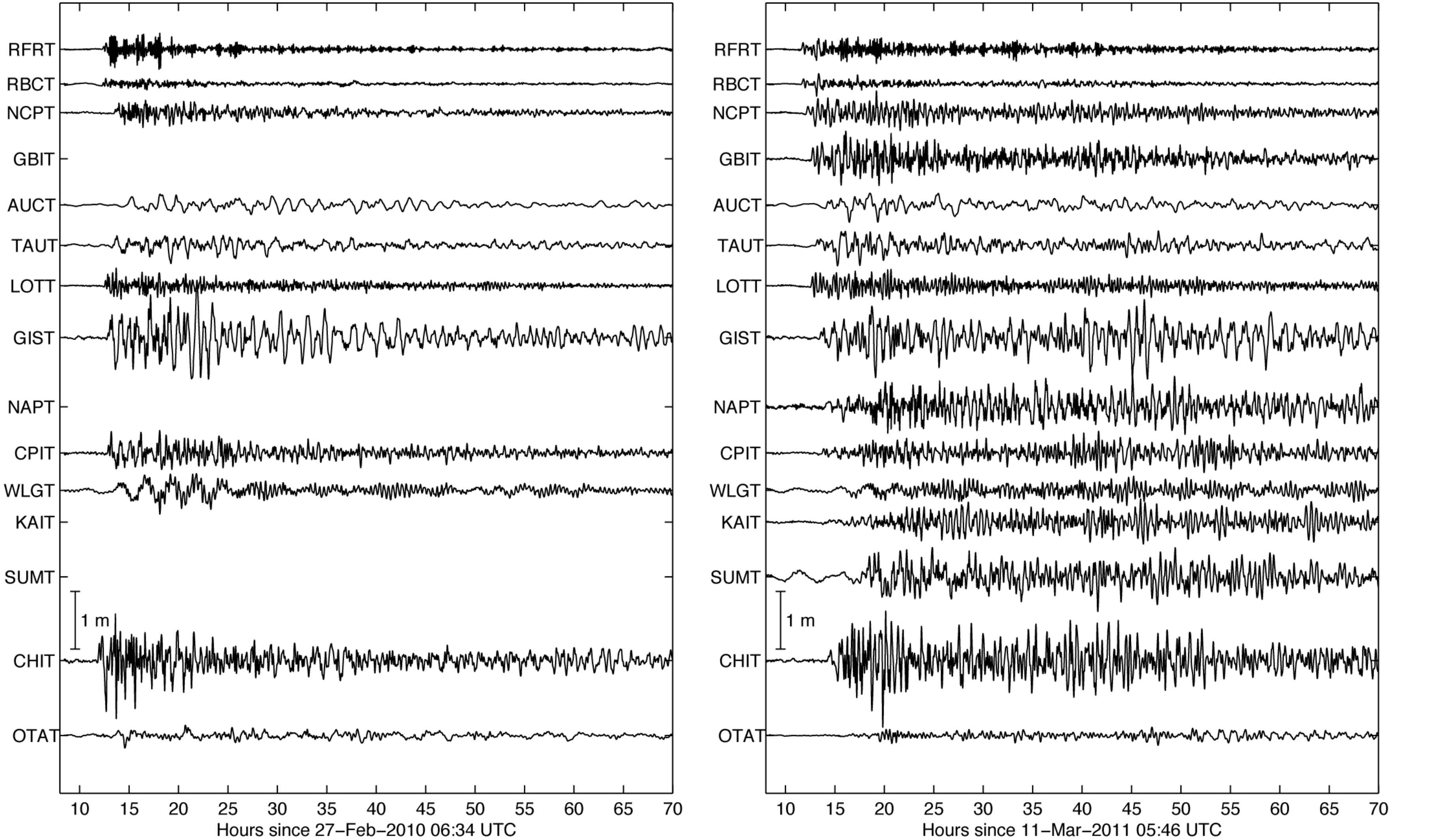
1.6.2 Effects in New Zealand

The effects of the Tohoku tsunami in New Zealand were detailed extensively in a report by Borrero et al. (2012). In that study they analysed the variety of data collected in New Zealand following that event. This included water level measurements on tide gauges around the country, instrumental velocity data from the Port of Tauranga, tsunami currents recorded by floating drogues in Lyttelton Harbour, runup and inundation information from the Coromandel Peninsula, and photographs, videos and eyewitness information from around the country. The authors also conducted a series of interviews with owners and operators of several maritime facilities (ports, small boat harbours) to learn more about their experiences during the event and to provide feedback on how the 2011 event compared to the 2010 tsunami and how warning messages and information were received and disseminated.

Some of the important findings from that study included:

- Tsunami induced current speeds at the entrance to Tauranga Harbour exceeded the 1.5 knots threshold for safe navigation of large ships on 4 separate wave cycles. The peak tsunami induced current speeds exceeded 2 knots on two separate wave cycles.
- New Zealand experienced moderate overland flooding in some areas including moderate flooding damage to several houses in Port Charles on the Coromandel Peninsula.
- Although tsunami first arrival was early in the morning on March 12th (Saturday), the strongest tsunami surges did not occur until 2 or 3 in the afternoon when many were just returning from a day's activities on the water.
- Ports and marinas on the east coast of the north Island were most strongly affected, this included Whitianga and Tutukaka where strong currents caused difficulties in navigation, some near-collisions and minor damage to docks.
- Several maritime related activities (i.e. boat races and fishing tournaments) were allowed to carry on as scheduled despite the impending tsunami.
- The extended duration of a major trans-oceanic tsunami was generally not accounted for and most warning messages – and the reaction of the general public – focussed primarily on the predicted tsunami arrival time and not for how long hazardous conditions might last.

Overall, the Tohoku tsunami in New Zealand should serve as a wake-up call to New Zealand's maritime community and emergency planners to better understand tsunami effects and to be better prepared for future events.


RFRT
RBCT
NCPT
GBIT
AUCT
TAUT
LOTT
GIST
NAPT
CPIT
WLGT
KAIT
SUMT
1 m
CHIT
OTAT
10 15 20 25 30 35 40 45 50 55 60 65 70
Hours since 27–Feb–2010 06:34 UTC
Hours since 11–Mar–2011 05:46 UTC

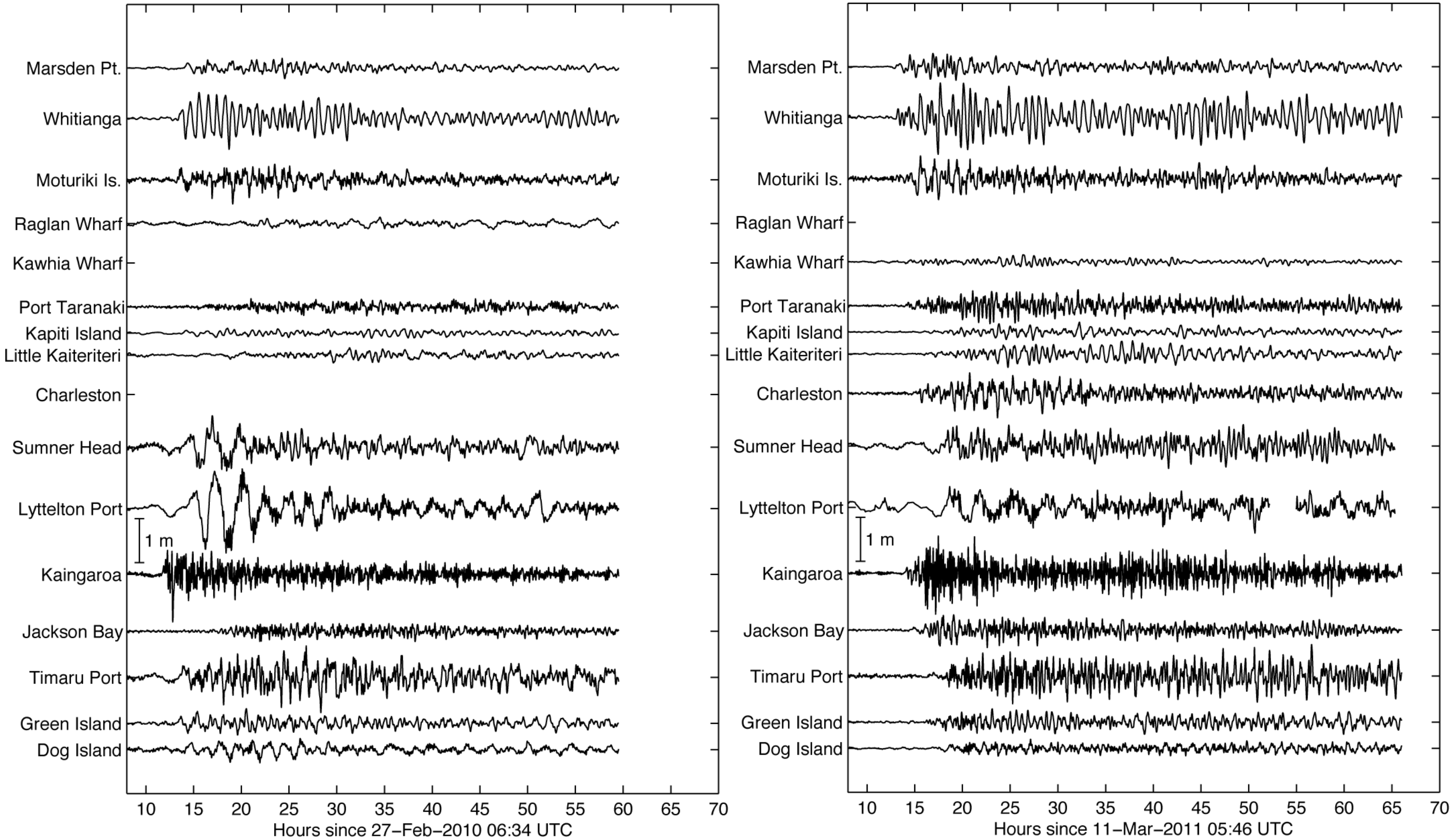


Figure 1.11 Residual water levels at New Zealand tide gauges from the 2010 Chile (previous page) and 2011 Japan (this page) tsunamis. The extended duration of the tsunami signal (more than 2 days) is clearly evident. Location and station names are referenced in Error! Reference source not found.**.**

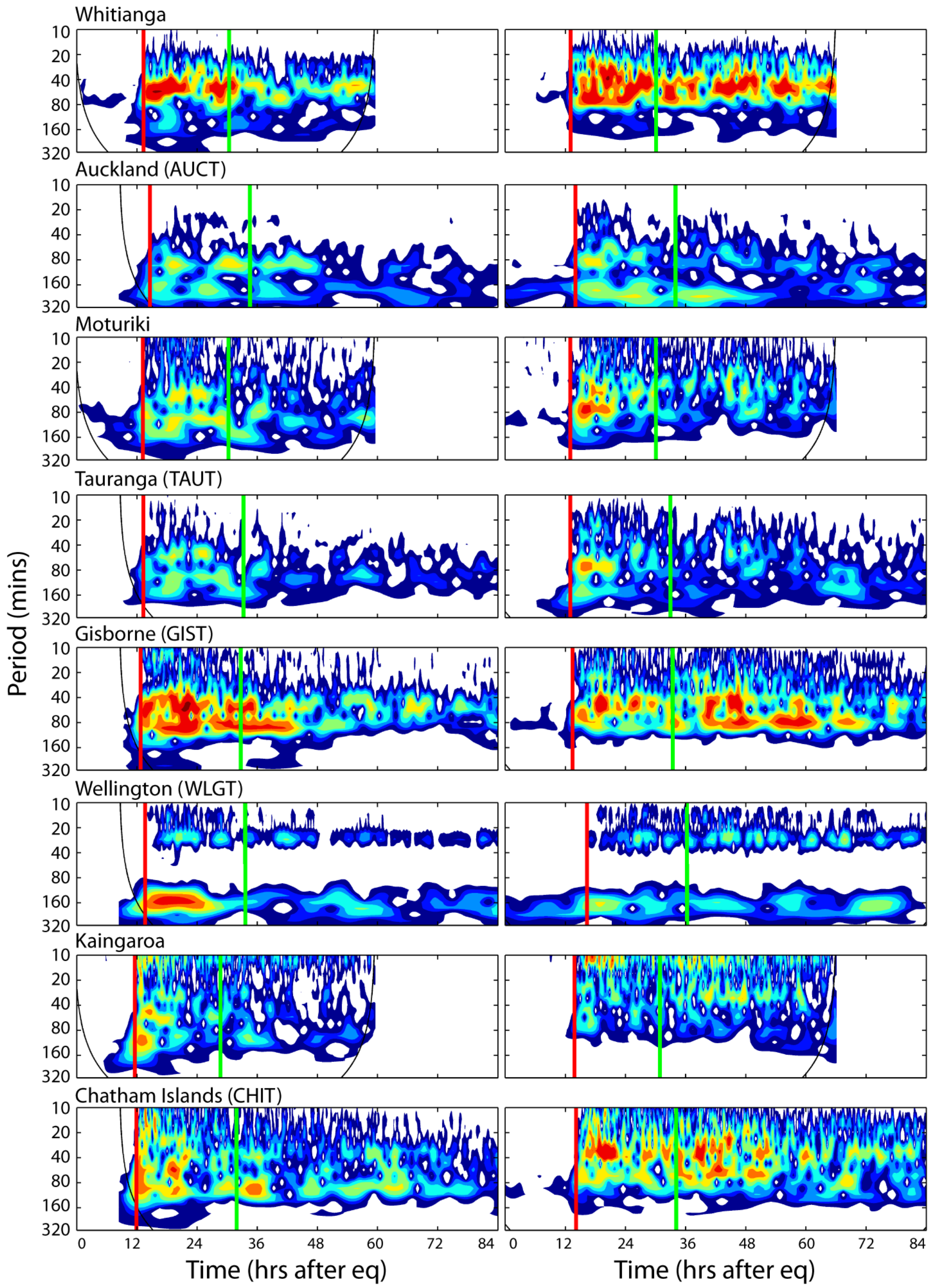


Figure 1.12 Wavelet spectrograms at select ports and tide gauges in new Zeeland for the 2010 and 2011 tsunamis. Vertical axis is wave period in minutes, horizontal axis time after earthquake in hours. Vertical red bar indicates tsunami arrival time. Hot colours indicate higher energy levels at that particular time/frequency combination. Location and station names are referenced in Error! Reference source not found. **(reproduced from Borrero and Greer, 2012).**

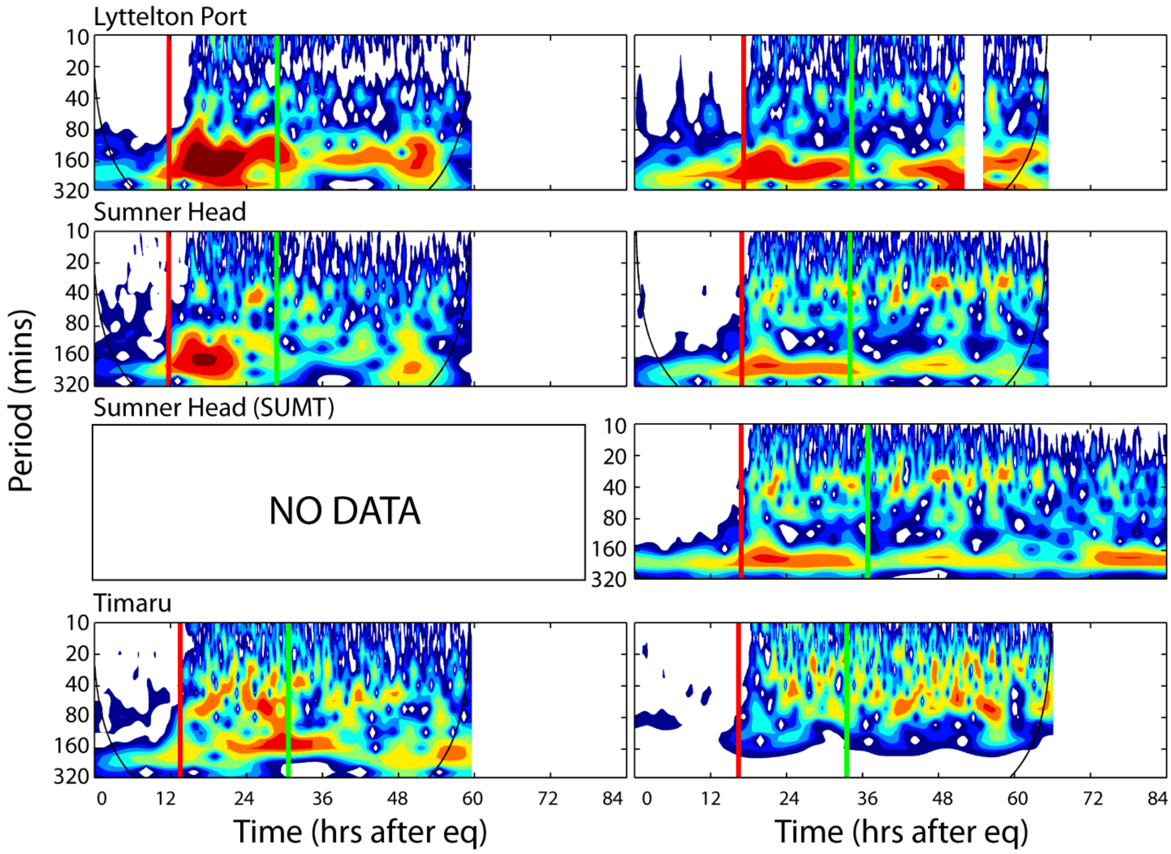


Figure 1.13 Wavelet spectrograms at select ports and tide gauges in New Zealand for the 2010 and 2011 tsunamis. Vertical axis is wave period in minutes, horizontal axis time after earthquake in hours. Vertical red bar indicates tsunami arrival time. Hot colours indicate higher energy levels at that particular time/frequency combination. Location and station names are referenced in Error! Reference source not found. **(reproduced from Borrero and Greer, 2012).**

1.7 Tsunami Arrival Times in New Zealand for the 2010 and 2011 Tsunamis

An important factor in tsunami hazard in ports is the timing of wave maxima. While emergency response messages and media reports generally focus on the arrival time of a tsunami, for far-field events, the largest waves and strongest effect invariably occur several hours after the tsunami waves begin to arrive. This was clearly the case in New Zealand during the 2010 and 2011 tsunamis.

For both the 2010 and 2011 events, the tsunami arrival to the main islands of New Zealand was generally between 12 and 16 hours after the earthquake. Peak wave heights however did not occur until 2 to 13 hours after arrival for Chile and as much as 30 hours after arrival during the Japan tsunami (Borrero and Greer, 2012).

Table 1.3 Timing of basic tsunami wave properties at select locations for three historical events. P2T: Peak to trough tsunami height, SL: Sea level. Data from Borrero and Greer 2012 and Rob Bell *pers. comm.*

Marsden Point

	Arr. Time	Max. Amp.	Assoc. Trough	Height	Hrs after arrival	Max P2T	Hrs After arrival	Max SL	Hrs After Arrival
2009 Samoa	5.95	0.08				0.13			5.64
2010 Chile	14.0	0.22	-0.24	0.46	10.3	0.46	10.3	1.34	23.4
2011 Japan	12.9	0.31	-0.28	-0.59	4.0	0.59	4.0	1.05	5.5

Port Taranaki

	Arr. Time	Max. Amp.	Assoc. Trough	Height	Hrs after arrival	Max P2T	Hrs After arrival	Max SL	Hrs After Arrival
2009 Samoa	6.8	0.16				0.31			13.16
2010 Chile	16.1	0.19	-0.06	.25	4.9	0.38	16.4	2.0	23.1
2011 Japan	13.9	0.36	-.21	-.57	18.2	0.73	9.1	1.12	7.1

Port of Tauranga (TAUT)

	Arr. Time	Max. Amp.	Assoc. Trough	Height	Hrs after arrival	Max P2T	Hrs After arrival	Max SL	Hrs After Arrival
2009 Samoa	6.3	.21			9.0				
2010 Chile	13.3	0.17	-0.21	0.38	11.2	0.48	5.4	0.97	24.2
2011 Japan	13.0	0.25	-.11	0.36	34.72	0.59	3.1	0.85	5.57

Moturiki Island (Tauranga)

	Arr. Time	Max. Amp.	Assoc. Trough	Height	Hrs after arrival	Max P2T	Hrs After arrival	Max SL	Hrs After Arrival
2009 Samoa	5.2	0.37				0.54			3.95
2010 Chile	13.2	0.35	-0.42	0.77	10.3	0.77	10.3	1.29	10.3
2011 Japan	13.0	0.52	-0.38	0.9	2.6	0.92	4.0	1.17	5.52

Port of Lyttleton

	Arr. Time	Max. Amp.	Assoc. Trough	Height	Hrs after arrival	Max P2T	Hrs After arrival	Max SL	Hrs After Arrival
2009 Samoa	7.22	.24				0.43			6.31
2010 Chile	11.8	0.91	-0.77	1.68	8.3	1.86	5.4	1.74	8.3
2011 Japan	17.24	0.47	-0.22	0.69	1.4	0.79	33.2	1.11	11.5

Sumner Head

	Arr. Time	Max. Amp.	Assoc. Trough	Height	Hrs after arrival	Max P2T	Hrs After arrival	Max SL	Hrs After Arrival
2009 Samoa	7.0	.14				.24			11.97
2010 Chile	11.7	0.72	-0.48	1.2	5.3	1.2	5.3	1.44	22.9
2011 Japan	16.9	0.49	-0.17	0.66	32.5	0.92	31.0	1.18	11.6

Sumner Head (SUMT)

	Arr. Time	Max. Amp.	Assoc. Trough	Height	Hrs after arrival	Max P2T	Hrs After arrival	Max SL	Hrs After Arrival
2009 Samoa									
2010 Chile	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
2011 Japan	16.9	0.51	-.14	0.65	7.99	0.91	31.1	1.16	11.7

2 APPENDIX 2: DETAILS OF THE MARITIME FACILITIES AT THE STUDY SITES

2.1 Whangaroa

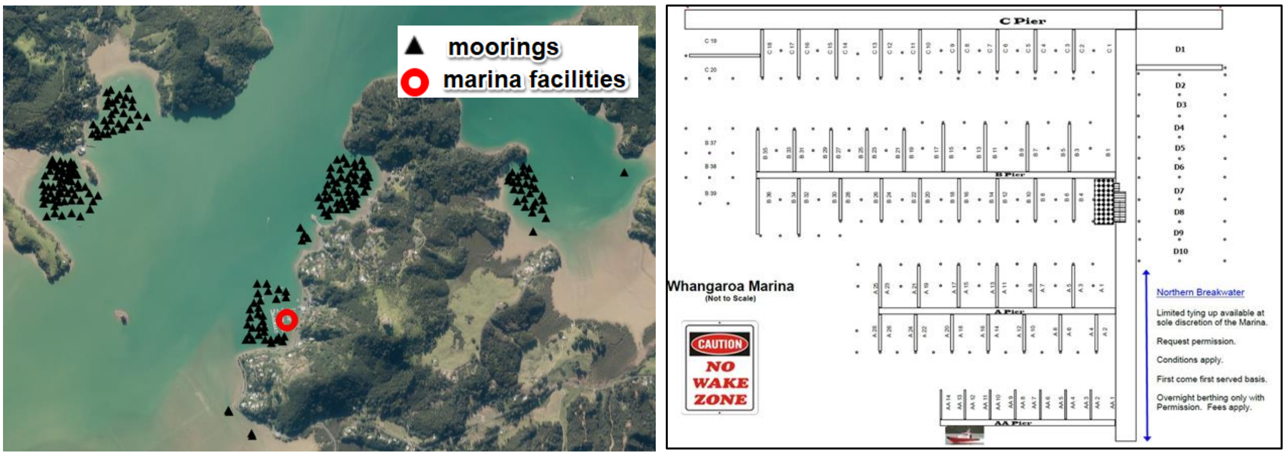


Figure 2.1 Locations and layout of moorings and berths at Whangaroa.

Table 2.1 Berths and moorings at Whangaroa

Whangaroa Marina	
Berths	109
Berth Length Min	8m
Berth Length Max	20m
Moorings	219
Amenities	Fuel, Power, Toilets

2.2 Dove's Bay

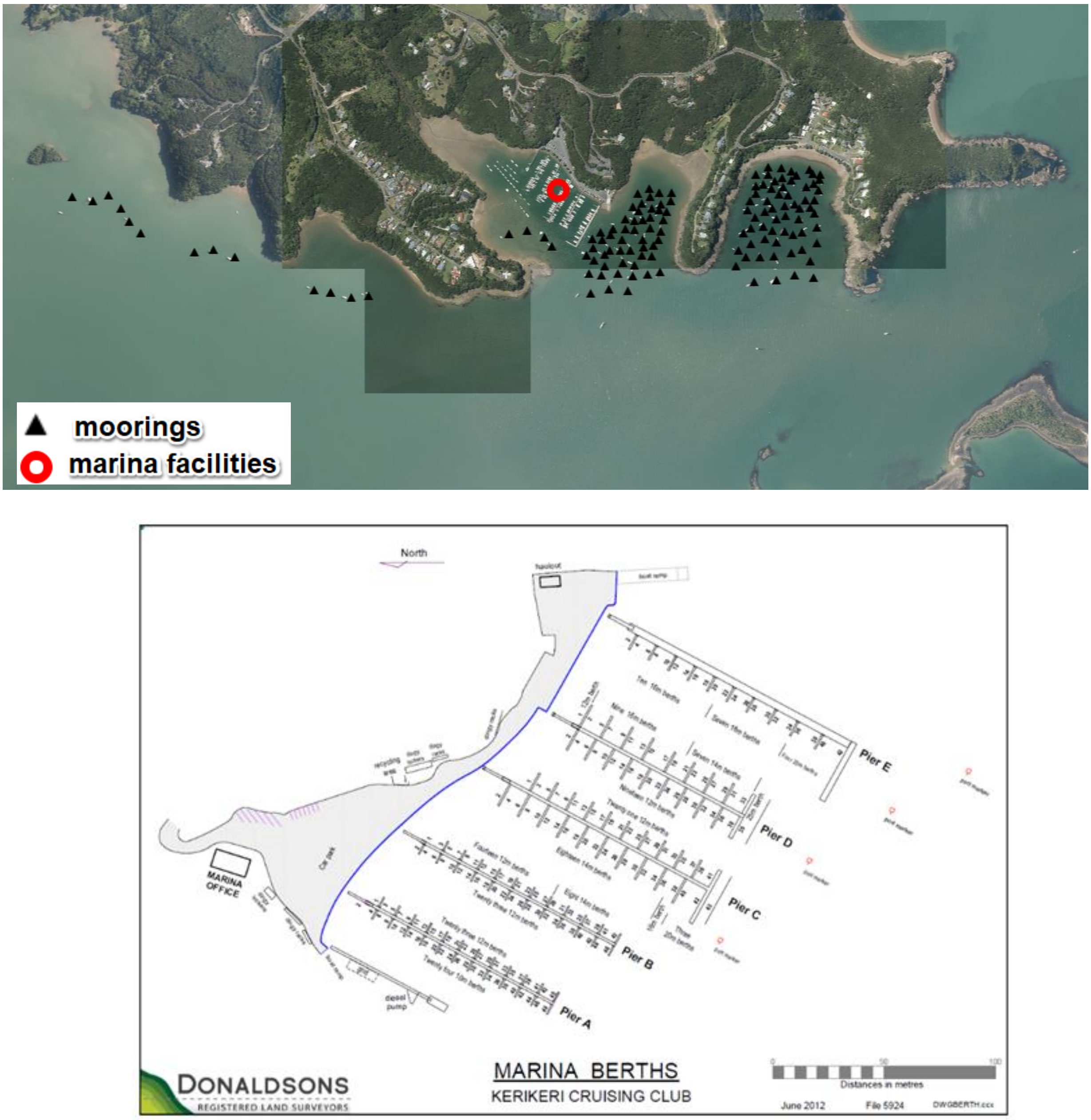


Figure 2.2 Locations and layout of moorings and berths at Dove's Bay.

Table 2.2 Berths and moorings at Doves's Bay

Kerikeri Cruising Club	
Berths	193
Moorings	134
Amenities	Fuel, Power, Toilets, Sewage pump out, Boat Ramp
Berth Length	**Quantity**
10m	24
12m	100
14m	33
16m	20
18m	7
20m	7
25m	1
27m	1

2.3 *Waitangi*

Figure 2.3 Locations of moorings at Waitangi.

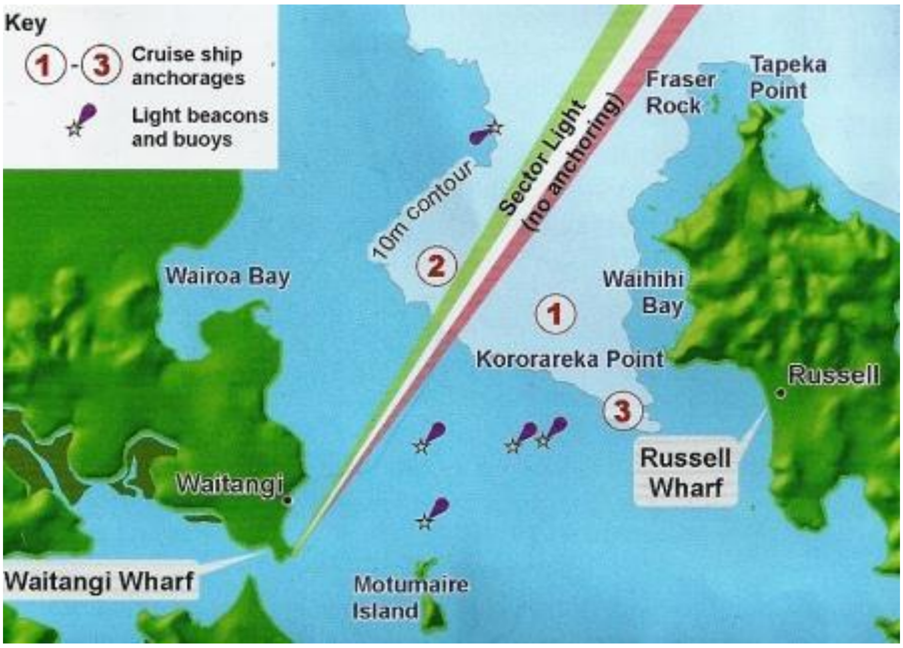
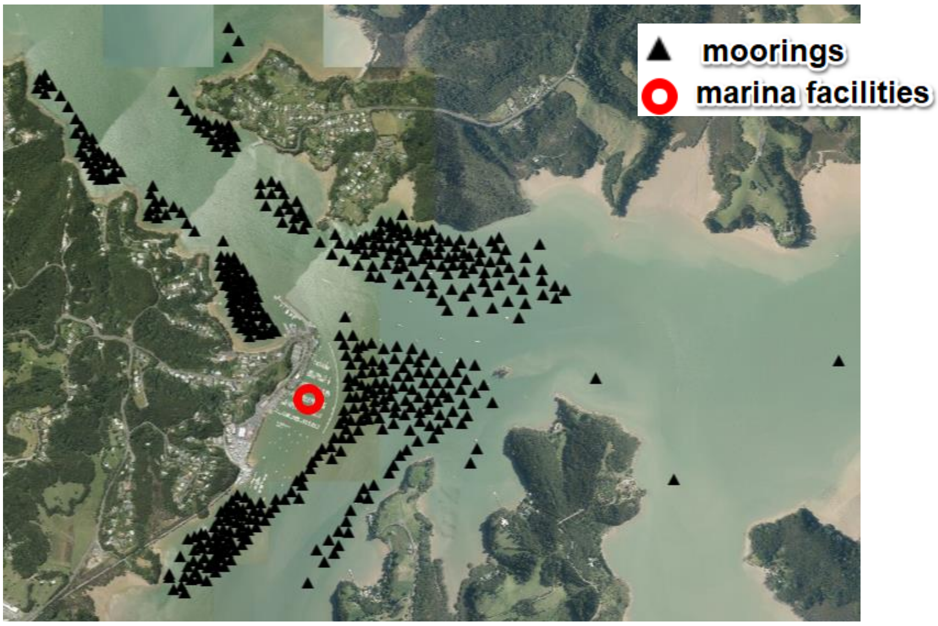


Figure 2.4 (top) A cruise ship moored offshore of Waitangi. (bottom) the cruise ship mooring locations.

2.4 Opua



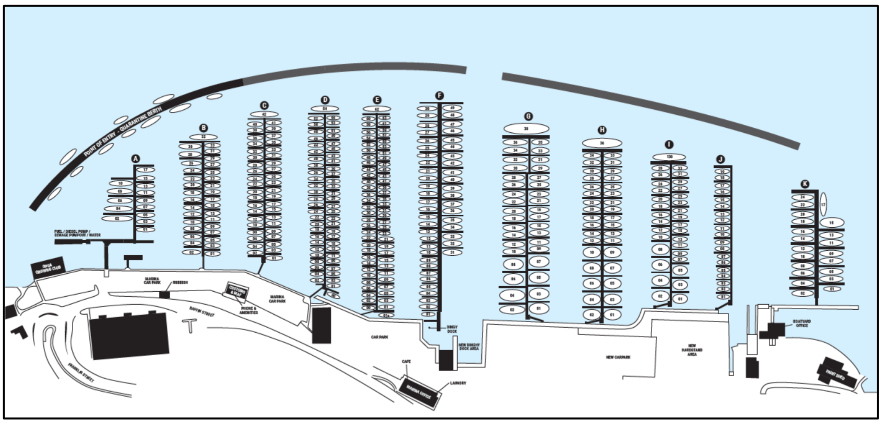


Figure 2.5 Locations and layout of moorings and berths at Dove's Bay.

Table 2.3 Berths and moorings at Opua Marina

Bay of Islands Opua Marina	
Berths	400
Berth Length Min	10.5m
Berth Length Max	50m
Moorings	481
Amenities	Fuel, Power, Toilets, Sewage pumpout, Boat Ramp, Cruise ship anchorage

2.5 *Tutukaka*

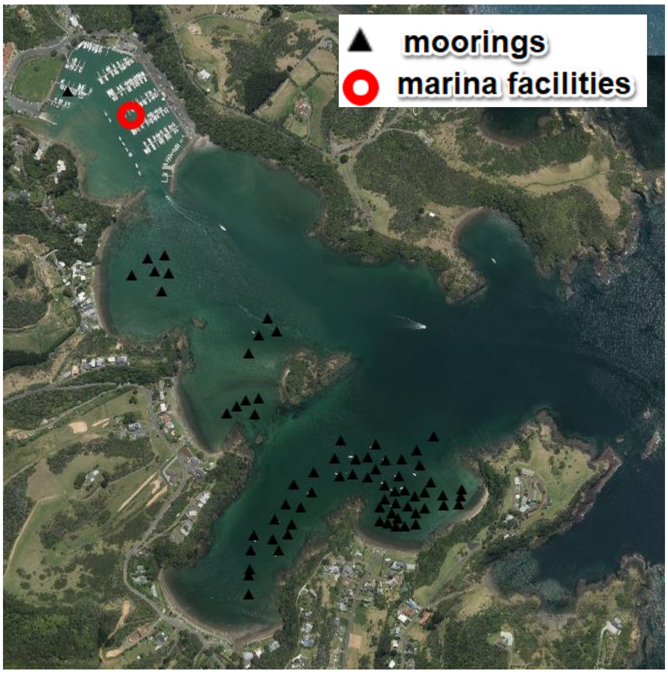


Figure 2.6 Locations and layout of moorings and berths at Tutukaka.

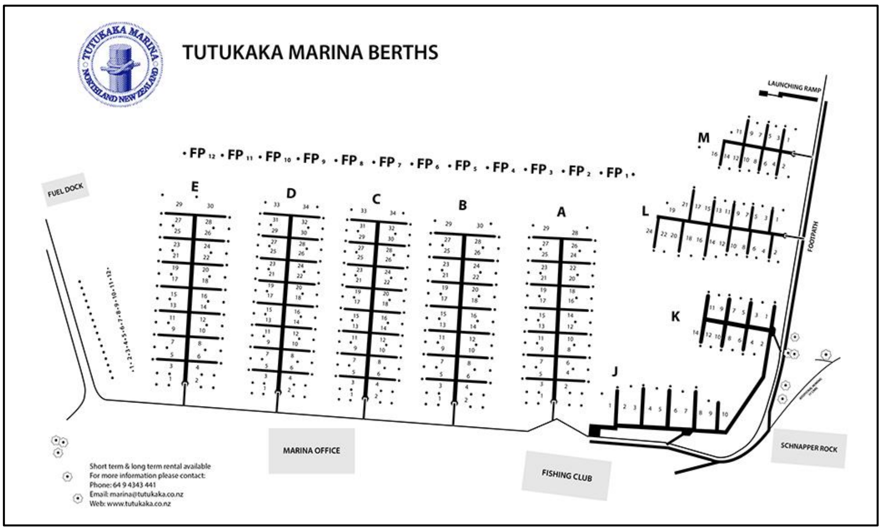


Figure 2.7 Layout of Tutukaka.

Table 2.4 Berths and moorings at Tutukaka Marina

Tutukaka Marina	
Berths	207
	12m
Berth Length Max	26m
Moorings	70

2.6 Marsden Point

Figure 2.8 Locations and layout of facilities at Marsden Point (figures reproduced from Popovich, 2015).

Table 2.5 Berths and moorings at Marsden Cove Marina

Marsden Cove Marina	
Berths	230
Moorings	220
Amenities	Fuel, Power, Toilets, Sewage pumpout, Boat haulout
Berth Length	**Quantity**
44m	1
33m	2
25m	8
25m CAT	1
20m	16
18m	16
18m CAT	7
16m	17
16m CAT	7
14m	59
14m CAT	5
12m	47
10.5m	36

3 APPENDIX 3: HISTORICAL TSUNAMI INFORMATION

The information below has been directly reproduced from the on line GNS historical tsunami database: http://data.gns.cri.nz/tsunami/index.html (Downes et al., 2017). It is presented here for completeness with minimal editing.

3.1 The 1835 Central Chile Event

3.1.1 Tsunami Impact Summary

Following the 1868 August tsunami (q.v.), which caused damage and disruption throughout the east coast of the North and South Islands and in the Chatham Islands (where there was one death), there was some discussion of previous events. During one such discussion at the Auckland branch of the NZ Institute, one of the members states that he had made many inquiries amongst the old inhabitants about “a wave that reached the Bay of Islands shortly after the great earthquake at Concepcion in 1835”, but he had not been able to “glean many particulars”. The inference is that the 1835 event was observed at the Bay of Islands, but no old inhabitants were found who could give details. This is not surprising as organised European settlement of New Zealand did not begin until 1840. The majority of the Europeans in New Zealand in 1835 were missionaries in the north of the North Island, and whalers and sealers at scattered locations in both main islands and the Chatham Islands. Few diaries exist for this period in New Zealand history. Unfortunately, one of the few known day-to-day journal writers, Henry Williams, a missionary at the Bay of Islands, was at an inland location at the head of the Hauraki Gulf at the time the tsunami would have occurred. Not only was he unable to observe the tsunami on the coast, but the first expected arrival would have been during the evening. Nevertheless, it is credible that the tsunami reached New Zealand.

3.1.2 Source Parameters

Time UTC: 16:22 20th February 1835

Source Location (longitude, latitude): -73.00, -36.80

The 1835 February 20, 16:22 UTC M8.2 Chile earthquake was strongly felt in the central Chile area. Epicentral locations, the time of the earthquake and estimates of magnitude, which are probably based on the distribution of felt intensities, vary between various catalogues. The earthquake generated a tsunami, which reached its greatest height above sea level at the time, 24 m, at Coelemu, with an estimated 18 m at Concepcion. There are only reports of this tsunami being experienced beyond Chile, in Peru and in the Hawaiian Islands. (NGDC Tsunami Database, March 2009)

3.1.3 Effects in Waitangi

During discussion about the 1868 Peru tsunami at the Auckland branch of the NZ Institute, "Mr. J. A. Wilson said he had made many inquiries amongst the old inhabitants about a wave that reached the Bay of Islands shortly after the great earthquake at Concepcion, but he had not been able to glean many particulars." (Daily Southern Cross, 7 July 1869)

3.2 The 1868 Southern Peru Event

3.2.1 Tsunami Impact Summary

The tsunami from the 1868 August 13 M_W 8.8-9.3 Southern Peru earthquake first arrived at the main islands of New Zealand early am on August 15. Observations of the tsunami were reported from nearly 90 locations, mainly on the eastern seaboard from Mangonui, in Northland, to Riverton, in Southland, as well as at Nelson and Motueka and at Westport and Greymouth on the West Coast of the South Island and at Wanganui on the west coast of the North Island. It was also observed throughout the Chatham Islands, arriving just after midnight, the greatest water height above sea level at the time reaching 10 m at Owenga on the east coast, washing away several huts and damaging boats. At Tupuanga (Tupuangi) on the northwest coast of Chatham Island, the dwellings of entire Maori village were washed away, the 60-70 residents escaping after the first of three large waves reached the floor of their dwellings. One death occurred nearby at Waitangi West when a person tried to rescue a boat between waves. A European-style house was completely destroyed at Te Raki Bay, the two occupants barely escaping. Damage occurred at other locations on Chatham Island, and an inundation map, dated September 1868, showing water heights as broad or narrow bands of yellow dependent on height, indicates water heights from 1.8 m to over 6 m generally. The areas most affected in the North and South islands were around Great Barrier Island, eastern Bay of Plenty, Napier, Canterbury, especially Bank’s Peninsula, and Oamaru. Fifteen locations reported water heights above sea level at the time of 2 m or more. The greatest reported heights were at Little Akaloa (4.5-5.0 m), and Le Bons Bay (5.8-7.6 m), although the latter may have been overestimated by observers. At Westport, water levels of 1.2-1.5 m above normal were experienced. Bores were observed in the Waimakariri, Heathcote and Avon Rivers, in Canterbury, the Awatere River in Marlborough, and in eastern Bay of Plenty, the greatest distance from the coast being in the Awatere River (15 km). The tsunami damaged boats and moved moorings and buoys at many places. Around Bank’s Peninsula, many wharves, bridges, and fences were damaged or destroyed, and several houses were inundated. The effects may have been significantly greater, had some of the largest waves occurred at higher tide levels, particularly about Bank’s Peninsula. Along much of the South Island and southern half of the North Island east coast the first few hours of waves occurred when the tides were below MSL. This and the arrival of the first waves during the night contributed to the first waves not being well observed and, in many cases, the first observed waves being many hours after the forecast arrival time (calculated using ITDB, 2004). On the West Coast, the tsunami was first noticed about 10 hours after the first observed arrivals on the east coast. The waves were greatest within the first 12-20 hours of arrival, and sea level did not return to normal for at least 2-3 days.

3.2.2 Source Parameters

Time UTC: 21:30 13th August 1868

Source Location (longitude, latitude): -71.60, -17.7

The 1868 August 13 southern Peru earthquake was a very large plate interface earthquake, which was destructive in the towns of Arequipa, Moquegua, Mollendo and Ilo in Southern Peru. It generated a tsunami, which was devastating locally, and which was observed over a large part of the Pacific Rim. (NGDC Tsunami Database) There is much uncertainty about the earthquake's location and magnitude, with locations ranging over two degrees latitude and magnitudes ranging from 8.5 to 9.5, two of the more recent estimates of which are: MW9.3, Okal et al. (2006); MW8.8, Comte & Pardo (1991). Other magnitude and location estimates are available for example, in the NGDC Tsunami Database and Dorbath et al.

(1990). Careful consideration should be given to choosing the most appropriate earthquake parameters for tsunami propagation models and for scenario development by Emergency Management for response in a Tsunami Warning situation.

3.2.3 Effects in Dove's Bay

At Kemp's, at head of navigation in river, water rose and fell about 4 ft several times in succession at about 15:00 on 15 Aug. On 16 Aug tide was higher by 1œ ft than ever before known, and disturbance observed all day as at Paroa. (Judd, A. 1868)

Estimated run-up for MCDEM: 1.5

Max. observed effective peak-through (m): 1.2

3.3 The 1877 Northern Chile Event

3.3.1 Tsunami Impact Summary

The tsunami from the 1877 May 10 M_W 8.8 Northern Chile earthquake first arrived on the main islands of New Zealand early on the morning of 1877 May 11 NZMT. The tsunami was reported observed from nearly 50 locations, from Mangonui, in Northland, to Riverton, in Southland, and at Westport on the West Coast. It was also observed at Waitangi (est. 3-3.5 m water height above sea level at time) in the Chatham Islands, where a house and bridge were washed away, and another house inundated, and at Perseverance Harbour, Campbell Island, where it did some damage and reached an estimated 3-4 m above MSL. The data are probably incomplete for the Chatham Islands. The areas most affected areas in the North and South Islands were Northland, Coromandel, Banks Peninsula, and Oamaru, with water heights above sea level at the time reaching just over 3 m at Little Akaloa, possibly Pigeon Bay, and Akaroa. Heights of 1-1.5 were common, with 8 locations only experiencing heights of 2 m or more. Westport experienced waves with a peak-to-trough of 1.8 m, i.e. the height above sea level at the time of about 0.9-1.0 m. The tsunami was not observed at Hokitika, nor reported from other west coast North or South Island locations. Bores were observed in the Piako and Waihou Rivers near Thames, in the Waimakariri and Avon Rivers, in Canterbury. Generally, the tsunami was less pronounced than the 1868 tsunami and it did not cause as much concern or damage, probably because some of the largest waves about Bank's Peninsula and Oamaru, and along much of the South Island and southern North Island east coast occurred when the tides were below MSL. On the other hand, the Coromandel and Northland were impacted close to high tide. The first waves of the tsunami generally arrived not long after the forecasted arrival time, (calculated using ITDB, 2004), and were greatest within the first 6-12 hours. The tsunami was first observed at Westport about 10 hours after the first arrivals on the east coast.

3.3.2 Source Parameters

Time UTC: 00:59 10th May 1877

Source Location (longitude, latitude): -70.20, -19.60

The 1877 May 10 M_W 8.8 (Comte & Pardo, 1991) Northern Chile earthquake was most strongly felt between Iquique and Antofagasta. Uplift and subsidence of the coast occurred at various points along the coast. Most of the loss of life and damage is attributed to the tsunami, which reached a maximum of 24 m above sea level at the time. (Principally from

NGDC Tsunami Database, April 2009) The earthquake followed nine years after the disastrous 1868 Southern Peru earthquake and tsunami, immediately to the north along the plate boundary. As with many of the historical earthquakes there is much uncertainty about the earthquake's location and magnitude, with locations ranging over three degrees latitude and magnitudes ranging from 8.3 (NGDC Tsunami database) to 8.8 (Comte & Pardo, 1991). Other magnitude and location estimates are available on the NGDC Tsunami Database. The extent of tsunami effects in New Zealand suggests that the magnitude of the earthquake was greater than the M_W 8.3 in the NGDC Tsunami database, and more consistent with Comte & Pardo (1991) M_W 8.8. More recent estimates may be available. Hence, careful consideration should be given to choosing the most appropriate earthquake parameters for tsunami propagation models and for scenario development by Emergency Management for response in a Tsunami Warning situation.

3.3.3 Effects in Waitangi

Felt very strongly up the Waitangi River at about 05:00 May 11. (Macfarlane 1877); Tide falling when captain of ship Iona went ashore in morning. Soon after a wave rushed in and drove boat and passenger onto shore above HWM. (Martin & Edwin 1877); [The following is Bay of Islands in general] A large tidal wave into the Bay and surrounding harbours, rising 6ft in as many minutes. (Evening Star 11 May 1877); Maoris from some of the islands in the bay reported that at about 17:00 May 11 water rose over 8 ft in as many minutes. Rushed in & out at intervals of about 20 min until late in evening. (Martin & Edwin 1877)

According to NIWA Tide Forecaster (www.niwa.co.nz/services/free/tides) high tide (0.73 m at Waitangi, Russell, etc) was at about 05:10 and again at just before 18:00 on May 11 (all times are NZMT, the standard time in use in 1877.

Estimated run-up for MCDEM: 1.5

Max height reached at inundation limit (m): Observed

Damage built/marine/environmental: boat swept above HWM

3.3.4 Effects in Tutukaka

Wave broke over beach at daybreak with tremendous roar, then rolled up river rapidly, receded swiftly, sweeping away timber stored above HWS. Vessel at anchor driven with force onto bank and left high & dry. Half of Tutukaka Harbour was left dry, and large quantities of fish left on beach. Each succeeding wave decreased in size and force. (Evening Star 18 May 1877).

According to NIWA Tide Forecaster (www.niwa.co.nz/services/free/tides) high tide (0.7 m) was at about 04:55 NZMT, low at 11.15 NZMT (-0.78) and high at 17:30 NZMT (0.71 m)on May 11 (all times are NZMT, the standard time in use in 1877)

Estimated run-up for MCDEM: 2

Max height reached at inundation limit (m): 1.6

Damage built/marine/environmental: timber washed away, boat beached

3.4 The 1946 Aleutians Event

3.4.1 Tsunami Impact Summary

The April 1, 1946 earthquake (1228 UTC, 0028 April 2 NZST; M_S 7.3, M_W 8.1 M_m 8.6), occurred south of Unimak in the Aleutian Islands. The earthquake caused a devastating tsunami near-source and in Hawaii, as well as strong effects in the Marquesas Islands and South America. The effects were also experienced in New Zealand, albeit somewhat patchily. The greatest impact on the main islands was from Ngungaru, just north of Whangarei Harbour, to Mangonui, with water heights above sea level at the time reaching 1.2 m and causing minor damage to a bridge at Tutukaka. Great Barrier Island, Tolaga Bay and Stewart Island were also affected with inundation heights of about 1-1.2 m. Other than these locations the tsunami caused little effect and was little noticed by the public. Tide gauges at Bluff, Wellington, and Auckland reported minor fluctuations while on Dunedin, Oamaru, Nelson and Greymouth tide gauge records, the tsunami was not observable. A report of large waves, inundation of the shore and some damage at Tuapeka on the northern coast of Chatham Island is unconfirmed, but credible. Some damage was also caused at Perseverance Harbour on Campbell Island.

3.4.2 Source Parameters

Time UTC: 12:28 1st April 1946

Source Location (longitude, latitude): -163.19, 53.32

The 1946 April 01 1228 UTC April 02 0028 NZST M_S 7.3 M_W 8.1 M_m 8.6 earthquake, centred south of Unimak Island in the Aleutians, caused a devastating tsunami near source, where maximum water height above sea level at the time of over 35 m is estimated and a lighthouse was destroyed. The tsunami was recorded at many distant locations around the Pacific. The maximum height reached in Hawaii was over 11 m, while at Juan Fernandez Island, Chile, and in the Marquesas Islands, over 9 m heights were reached (NGDC, November 2008). The devastating effects in Hawaii provided the impetus for the development of the Pacific Tsunami Warning System and Center, at first for US territories but now with many members around the Pacific, including New Zealand. The earthquake has been identified as a "tsunami earthquake", a type of event that was first identified by Kanamori (1972) and characterised by a number of key features relating to the source (including slow rupture velocity, long source time duration, slow initiation, location close to the trench with slip and dip being compatible with slip on the plate interface), and to the large size of the tsunami in relation to the earthquake magnitude, as well as large discrepancies between the different magnitude measures because energy is released at the low frequencies. Tsunami earthquakes are often not strongly felt on land and because of this, pose a problem to warning authorities in the near-field (as people don't feel a particularly strong earthquake), as well as in far-field because of the difficulty in forecasting wave heights from a non-standard source, which is generally not well understood. Numerical tsunami propagation and source modelling has been used to better understand the strong "beaming" effect of the tsunami across the Pacific, which produced high wave heights across a narrow zone from the source towards the Marquesas Islands and South America. Fryer et al. (2004) suggest that no earthquake source can simultaneously explain the narrow beam of large waves in the far field and the rapid variation in near-source runup and propose a landslide source rather than purely tectonic source. On the other hand, Lopez & Okal (2006) maintain that the unusual earthquake source is sufficient to explain the beaming across the Pacific. They also re-evaluate the moment magnitude using mantle waves, obtaining a mantle magnitude of M_m 8.6. Until recently (~2000), the tsunami was not known to have been observed in New Zealand.

3.4.3 Effects in Tutukaka

Disturbances like those at Matapouri noted in the creek on night of 2 April. "Waves several feet high followed one another in rapid succession, creating a swift current where normally there is none, and roaring under the bridge." Similar conditions continued to next day, although the sea was "flatly calm, the wind being offshore". Water muddy, when usually clear. On the ebb, the tide did not reach the usual low water mark, and people watched "a succession of small tidal waves rising from the calm sea and sweeping up the beach". No damage reported. (Northern Advocate 3 April 1946); Waves continuing on morning of 4 April although diminishing. Where the waves swept up the creek and back again with a rise of about 4ft, the stone facings of the bridge were damaged, one corner of the facing holding the spoil washed out completely. Tides at their peak were highest ever known, while normal low water was not reached. Other Northland coastal centres also affected (no detail.) (Northern Advocate 4 April 1946); also in Waikato Times 4 April 1946);

According to NIWA Tide Forecaster (http://www.niwa.co.nz/services/free/tides), HW was at 19:33 NZST (0.97) at Tutukaka Harbour.

Estimated run-up for MCDEM: 1.2

Max height reached at inundation limit (m): 1.2

Damage built/marine/environmental: minor damage to stone facings on bridge

3.5 The 1952 Kamchatka Event

3.5.1 Tsunami Impact Summary

The tsunami from the 1952 November 4, 1658 UT November 5 0458 NZST MS8.3 MW9.0 earthquake reached New Zealand shores late in the evening of November 5. The most affected areas were parts of Northland, Gisborne, Wellington, Greymouth and Lyttelton. However, the effects were mostly minor with the largest zero-to-peak measurements or water heights above sea-level at the time generally less than 1 m. At many places the tsunami seems to have been too small to be observable on tide gauges or by the casual observer. Severe weather conditions and flooding in South Canterbury and Southland would have prevented small effects being noticed there. The lack of observable effects in Napier, however, cannot be attributed to this. The tsunami was observed in several rivers and in estuaries, tearing nets in the Ashley River and throwing a dinghy on the rocks at Greymouth. One person was slightly injured at Matapouri when a 0.9 m surge hit the boat he was in. A key feature of the data is the occurrence of unexpectedly strong effects at Greymouth, given the path through New Caledonia, Vanuatu etc. The largest waves seem to have occurred late in the series, but the first waves arrived very shortly after the calculated first arrival. On the other hand, the first observed arrivals, and strongest effects, at Gisborne were well after the expected first arrivals, and the largest amplitude at Wellington was some 24 hours after the first arrival. The effects in the Chatham Islands are unknown.

3.5.2 Source Parameters

Time UTC: 16:58 4th November 1952

Source Location (longitude, latitude): 159.50, 52.75

The 1952 November 4, 1658 UT November 5 0458 NZST M_S 8.3 M_W 9.0 Kamchatka earthquake generated a tsunami that reached a maximum water height above sea level at the time of 13 m locally. The tsunami was widely observed around the Pacific, the NGDC Tsunami Database recording nearly 300 wave height measurements.

3.5.3 Effects in Tutukaka

(per PA) Two hours before the observed wave at 9.30 p.m at Matapouri., a person at Tutukaka heard a roaring noise and saw a wave about 1 ft high coming swiftly up the Tutukaka river. The wave was observed to take 15 minutes to run in from the bay entrance and the same time to run out. The tide rose 30 in with each wave and dropped again as the wave receded. Waves were still coming in when the observer retired at 11 p.m. . The water was still surging the next morning [6 November]. Another Tutukaka resident said he heard a roaring at 9 p.m. and saw a 3 ft wave coming in. Every 10 minutes the water would settle down and then the wave would run back. This went on until he retired. (Gisborne Herald 7 November 1952; similar in many other papers)

Estimated run-up for MCDEM: 0.9

Max. observed effective peak-through (m): 0.75

3.6 The 1960 Chile Event

3.6.1 Tsunami Impact Summary

Observations of the tsunami generated by the great 1960 May 22, 1911 UT May 23 0711 NZST M_W 9.4-9.6 Chile earthquake were reported at more than 120 locations In New Zealand. The most affected locations occurred along the whole eastern seaboard of New Zealand from Cape Reinga to west of Bluff and to Stewart Island, but the tsunami was also observed at locations on the west coast of the North Island, notably as far as south as Ahipara in Northland, at Wanganui and Paremata but not at New Plymouth, Foxton or Himatangi Beach. Ion the western and north-western seaboard of the South Island, the tsunami was observed at Nelson, Motueka, as well as several West Coast towns. The tsunami was also experienced on the Chatham Islands, and Campbell Island, where water heights above sea level at the time were from 3 m to over 5 m at locations only a few kilometres apart in Perseverance Harbour. In the Chatham Islands, heights of 1.8 m (Waitangi) to over 3.6 m (Pitt Island) were reported, with damage to a wharf on Pitt Island, but the heights are only known at three locations. In the North Island, heights of 2 m or more were reported from a few locations in Northland and Coromandel, from Tokomaru Bay to south of Gisborne, at Napier, Te Awanga and Clifton in Hawke’s Bay, and at Lake Ferry in Palliser Bay, with the greatest heights around Poverty Bay and northwards (3-4 m) and Napier, Clifton and Te Awanga (3-4.5 m). In the South Island, heights of 2 m or more were experienced at Wairau (2-2.5 m), Sumner area (3-3.6 m), around Banks Peninsula (max. 3.2-3.6 m, at Lyttelton) and possibly at Oamaru (estimated 1.5-2.1 m). On the West Coast, Hokitika reported a height of 0.9 m. The first arrivals on the east coast were at night, and in general, only noticed where the larger waves occurred or where smaller waves arrived on top of high tide. The first arrivals that were unmistakeable were within a short time of predicted time. As with the 1868 and 1877 tsunami, the largest waves at Lyttelton and Sumner occurred within 1.5-3 hrs of low tide. The time of the largest surges varied around the Peninsula, and some (e.g. Okains Bay) seem to have been closer to high tide, but the earlier waves at a lower tide level may not have reached significantly above high tide mark. Similarly, the largest surges at Gisborne occurred closer to low tide than to high tide, although there were also large surges some hours later nearer high tide, whereas in Napier, the largest surges seem to have occurred at the later time i.e. within an hour or so of high tide. The largest surges generally occurred within 12-15 hours after the first arrival, some within the first 2-4 hours. In the most affected areas, houses, roads sheds, and paddocks were inundated, bridges, fences, and sheds damaged, and stock killed. De Lange & Healy (1986) record that the Earthquake and War Damage Commission (1961) recorded 69 claims for tsunami damage. Most were reported from Banks Peninsula and Napier, although damage claims extended from the mouth of the Catlins River in the South Island to Whangarei in the North Island. The value of the claims was not specified in the Earthquake and War Damage Commission report. The absence of a Pacific-wide Tsunami Warning System at the time meant that the tsunami arrived without an official warning being issued, although some ports seem to have notified each other, and one person heard of the tsunami on short wave radio. Several days after the main event, another large earthquake occurred in Chile (possibly an event listed in ITDB/PAC (2004) M7.5 May 25 0834 UT), about which the Air Department in Wellington received a message suggesting that a tsunami could possibly reach New Zealand. This initiated the broadcast of a nationwide warning on radio. The warning resulted in the evacuation of many east coast towns. In other places, people ignored the warnings and went down to the sea to watch. The response to the warning is discussed in Johnston et al. (2008). Interestingly, many people interviewed about the 1960 tsunami remember the warning and evacuation and the fact that no tsunami occurred, and recall nothing of the significant effects of the main event a few days earlier.

3.6.2 Source Parameters

Time UTC: 19:11 22th May 1960

Source Location (longitude, latitude): -74.50, -39.50

The 1960 May 22, 1911 UT May 23 0711 NZST M_W 9.4-9.6 Chile earthquake, the largest earthquake instrumentally recorded (up to May 2009), occurred in southern Chile. The series of large earthquakes that followed ravaged southern Chile and ruptured over a period of days a 1,000 km section of the fault (the plate interface), one of the longest ruptures ever reported. The mainshock generated a tsunami that was not only destructive along the coast of Chile, but also caused numerous casualties and extensive property damage in Hawaii and Japan and was noticeable along the shorelines throughout the Pacific Ocean area. (NGDC Tsunami Database, May 2009) The magnitude of the earthquake was underestimated at the time, primarily because the surface magnitude scale saturates at magnitudes greater than about 8, and the moment magnitude scale, which can determine the magnitude of earthquakes beyond this limit, was not introduced until the late 1970s. More recent calculations of the moment magnitudes are: M_W 9.4-9.6 (Pacheco & Sykes, 1992); M_W 9.5 (Barrientos & Ward, 1990).

3.6.3 Effects in Whangaroa

Boat suddenly left high and dry. (NZ Herald May 25, 1960); At Whangaroa a boat owned by a commercial fisherman, was suddenly left high and dry. When it was re-floated by a returning “tide,” A boat that set off up harbour at half-throttle could hardly make way against the tide, which should have been running with it. (Northern Advocate (Whangarei) 25 May 1960)

Estimated run-up for MCDEM: OBS

Max height reached at inundation limit (m): OBSERVED

3.6.4 Effects in Opua

At 0930 May 24, tide receded leaving car ferry/barge stranded on the concrete ramp at Deeming's Point. As the barge was approaching the Opua end, run of water so fierce that the barge was almost forced into the ramp stanchions. The pilot managed to edge the barge away and run it aground on the small shingle beach beside the Opua wharf. At 0630 May 25 the tide was full in at Opua. Less than an hour later it had fallen 2 feet. Force of the waves worked free a flashing–beacon channel pile off Okiato point, near Opua. The recurring surge am on May 25 made it hazardous to load the Bay of Islands Harbour Board's 30ft pile frame on to a barge and the task of replacing the broken pile has been deferred. By 0800 tide was full in again. (Northern Advocate (Whangarei) 25 May 1960); Opua, Bay of Islands, NZ – From local reports of small boat owners the first effects of the tsunami were noticed at Waitangi River entrance at 2230 May 23, 1960, when the river was subjected to strong flow and ebb currents in rapid succession. At Opua the same effect occurred at 2200. Normal tidal currents in the harbor ceased. Flood and ebb changes occurred at intervals of 20-40 minutes, with shorter periods in Opua Basin. Change of direction of current was suddenly accompanied by formation of whirlpools. Water level changed 3-4 feet in a matter of minutes; however, the highest level was not unusual. (Berkman & Symons, 1964); Ferry with two cars on board left high and dry when water surged out. (NZ Herald May 25 1960)

According to NIWA Tide Forecaster (http://www.niwa.co.nz/services/free/tides)), HW at 18:22 May 23 NZST (0.79), LW at 00:25 (-0.72), HW at 06:30 (0.82), LW at 12:49 (-0.92), HW at 19:07 (0.83) May 24 NZST at Opua. Tsunami waves could have been higher at the time of low tide during the night of May 23-24, i.e. with a tidal range to HWS approaching 1.9 m this zero-peak at low tide would not have exceeded HW.

Estimated run-up for MCDEM: 1.5

Max. observed effective peak-through (m): 2.0-3.0

Max height reached at inundation limit (m): 1-1.5

Max observed height of inundation (m): 1

Damage built/marine/environmental: flashing beacon channel pile moved, ferry grounded

3.6.5 Effects in Tutukaka

Water rose over the bridge at Tutukaka at 0700 May 24. Parts of its stone facing on bridge carried up to 80 yards up the tidal creek. Bridge closed to heavy traffic. Surges kept rushing up the basin from 2100 May 23. Big surges hit at 2200 May 23 and 0400 May 24, rose 9 ft up to the decking of the jetty. Waves eased off at ~2400 May 23. Regular surges every 15 to 30 minutes swept up the creek am May 24. NZBS broadcast of the tidal wave in Chile heard at 2100 May 23, and almost immediately the surges started at Tutukaka, according to witness. An "outboard motor had been picked up out of the tide" [?]; two boats dragged their anchors. Tutukaka's fleet of big-game fishing boats is remaining in harbour. Boatmen were awake all night watching mooring lines. Pleasure fishing trips cancelled because of conditions. Before the first wave came, the water receded, then came back in a slow wave that mounted 9 ft within minutes. Surges continued at 20-minute intervals, the waves dying down to about 3 ft, before growing again to 9 or 10 feet as high tide approached and the water swept across the low filling beside the estuary bridge. PHOTO AVAILABLE. (Northern Advocate (Whangarei) 24 May 1960); Early pm May 25, tidal surges still occurring. Tide at a low ebb surged in every 20 minutes or so and reached high water mark. Boats moored in shallow water heeled over as their keels rested on the bottom. (Northern Advocate (Whangarei) 25 May 1960)

According to NIWA Tide Forecaster (http://www.niwa.co.nz/services/free/tides)), HW at 18:04 May 23 NZST (0.76), LW at 00:08 (-0.68), HW at 06:12 (0.78), LW at 12:31 (-0.88), HW at 18:50 (0.80) May 24 NZST at Tutukaka Harbour.

Estimated run-up for MCDEM:

Max. observed effective peak-through (m): 2.7-3.0

Max. water elevation at shore (m): 1.5

Max observed height of inundation (m): 1.8

Damage built/marine/environmental: bridge abutment damaged

3.6.6 Effects in Marsden Point

Water came over the road at Urquhart's Bay during the night and swirled round Mr Fred Reynolds' house at Taurikura, but no damage was reported. (Northern Advocate (Whangarei) 24 May 1960)

Max height reached at inundation limit (m): 1-2

Max observed height of inundation (m): 2

3.7 The 1964 Alaska Event

3.7.1 Tsunami Impact Summary

Although the tsunami from the 1964 March 28 0336 UT 1536 NZST MW9.2 Prince William Sound, Alaska reached New Zealand, it was relatively small, with minor damage and disruption in Northland, where estimated onshore water heights above sea level at the time did not exceed 1.3 m. Mangonui appears to have been the most affected location in the area. It is notable that the tsunami was observed at least as far south as Ahipara on the west coast of Northland. Noticeable effects, strong currents and surges, with elevations of up to 1 m were experienced in Lyttelton, a few other Banks Peninsula bays, and in the Waimakariri River, as well as isolated parts of Coromandel and Great Barrier Island. Picton was surprisingly strongly affected with minor flooding of the shoreline, which surrounded a house to 0.3 m depth and covered low jetties. This occurred twice, at high tide, 27 and 39 hours after the expected first arrival. Although it was the time of spring tides, they were not exceptionally high and cannot account for the inundation However, the NIWA Tide Forecaster, which has been used here for hindcasting tide heights, may be inappropriate for calculating tides at a location far from the open sea. Nothing is known of the effects in the Chatham Islands.

3.7.2 Source Parameters

Time UTC: 3:36 28th March 1964

Source Location (longitude, latitude): -147.50, 61.10

The 1964 March 28 0336 UT 1536 NZST M_W 9.2 Prince William Sound, Alaska, earthquake, the largest earthquake in Northern America in historical time, was a subduction zone event occurring within the islands of Prince William Sound in Alaska. The earthquake caused 15 deaths; the tsunami caused 124 deaths (106 in Alaska, 13 in California and 5 in Oregon). Significant earth deformation occurred, and many landslides. Twenty landslide tsunamis were generated; the tectonically generated tsunami devastated towns along the Gulf of Alaska, left serious damage in British Columbia, Hawaii and along the west coast of the US. The tsunami was recorded throughout the Pacific. (NGDC Tsunami and large earthquake databases (March 2009)

3.7.3 Effects in Whangaroa

In Whangaroa Harbour a fisherman anchored in about three feet of water in the morning found his boat suddenly high and dry. He walked to the shore and then looked back, seeing his boat was afloat again. (Northland Age 31 March 1964; similar in Northern Advocate 30 March 1964); + No boats were damaged. (Northern Advocate 30 March 1964)

Estimated run-up for MCDEM: 0.45

Max. observed effective peak-through (m): 1

3.7.4 Effects in Waitangi

"In the Bay of Islands tides of 10 knots were estimated where they usually run at three knots. The effect was most noticeable in the Waitangi Estuary and at Opua wharf. Three times during the day the tide began to ebb and then come in again, and at Opua the noise of the upsets was quite noticeable. Only damage was to the navigational beacon at Okiato Point but it was not put out of action." (Northland Age 31 March 1964); Tides of up to 10 knots were experienced in the Bay of Islands on March 29. The morning tide started ebbing half an hour earlier than scheduled, and the level of the tide then dropping very suddenly by two feet. The effect was most noticeable in the Waitangi estuary and at the Opua wharf. Three times during the day the tide began to ebb, stopped and became a flood tide. The noise of the tidal upsets was most noticeable at Opua. The navigational beacon off Okiato Point was damaged but not put out of action. No damage to boats. (Northern Advocate 30 March 1964)

According to NIWA Tide Forecaster (http://www.niwa.co.nz/services/free/tides), HW occurred at about 08:22 NZST (0.95 m) LW at 14:36 NZST (-0.93) 29 March 1964.

Estimated run-up for MCDEM: 0.45

Max height reached at inundation limit (m): 0.6

Damage built/marine/environmental: navigational beacon damaged

3.7.5 Effects in Opua

"In the Bay of Islands tides of 10 knots were estimated where they usually run at three knots. The effect was most noticeable in the Waitangi Estuary and at Opua wharf. Three times during the day the tide began to ebb and then come in again, and at Opua the noise of the upsets was quite noticeable. Only damage was to the navigational beacon at Okiato Point but it was not put out of action." (Northland Age 31 March 1964)

Estimated run-up for MCDEM: 0.45

Max height reached at inundation limit (m): OBSERVED

3.7.6 Effects in Marsden Point

"There was about a foot variation in the tide at Marsden point in Whangarei Harbour at 10 am on Sunday [March 29]." (Northland Age 31 March 1964); "In the Whangarei harbour there was about one foot variation in the morning tide observed about 10 o'clock yesterday at the Whangarei harbour Board's marine terminal at Marsden Point. There was little or no variation up harbour at Port Whangarei." (Northern Advocate 30 March 1964)

Estimated run-up for MCDEM: 0.45

Max height reached at inundation limit (m): 0.3

3.8 The 1976 Kermadec Islands Event

3.8.1 Tsunami Impact Summary

The 1976 January 15 0447 NZST M_W 7.9 Kermadec Islands earthquake caused a small tsunami that was observed at Tutukaka, Whangarei, Auckland, and Mount Maunganui. Fluctuations at the last three locations were small (probably <0.3 m), while at Tutukaka, the tsunami waves reached their greatest height above sea level at the time of about 0.2-0.75 m (newspaper reports are inconsistent), but given the fact that several yachts were damaged, the larger figure is probably correct.

3.8.2 Source Parameters

Time UTC: 7:10 15th January 1976

Source Locations (longitude, latitude): -176.75, -28.72

In 1976, early in the morning of January 15 NZST, there were two large earthquakes located near the Kermadec Islands within an hour of each other (1976 January 14, 1556 UT January 15 0356 NZST [0456 NZ Daylight Saving Time] M_W 7.8 & 1976 January 14 1647 UT January 15 0447 NZST [0547 NZ Daylight Saving Time] M_W 7.9 earthquakes). Their locations differed by less than a degree in latitude and longitude. The second earthquake was slightly larger (M_W7.9) and shallower than the first (M_W 7.8), and so more likely to have generated the small tsunami that was observed as far away as Mexico, and in Fiji, Australia, Samoa, and American Samoa, as well as New Zealand. (NGDC Tsunami database, April 2009) Effects are listed in the database entry for the second event.

3.8.3 Effects in Tutukaka

Surge at 08:40 [NZ Daylight Saving Time; 07:40 NZST] broke loose a yacht from its anchorage, sweeping it into other boats, breaking some mooring ropes. An 0.2 m rise lasting 5-6 minutes came in as a "great big whirlpool" that moved at an estimated 8 knots. Second surge at 09:20 [08:20 NZST]. (NZ Herald 16 January 1976); Several yachts were damaged in a 0.75 metre tidal surge at the Tutukaka boat harbour at about 8 am [07:00 NZST] on 15 January. (Bay of Plenty Times 15 January 1976).

Max height reached at inundation limit (m): 0.2-0.75

Damage built/marine/environmental: Yachts damaged

3.9 The 1977 Tonga Event

3.9.1 Tsunami Impact Summary

The 1977 June 22, 1209 UT June 23 0009 NZST MW8.0 Tonga Trench earthquake caused a small tsunami, which was observed on tide gauge records at Opua, Whangarei, Auckland and Tauranga. The maximum recorded water height above normal tide level was less than 0.15 m. As the tsunami arrived during the night it is unlikely to have been observed by people at the shore.

3.9.2 Source Parameters

Time UTC: 12:09 22nd June 1977

Source Location (longitude, latitude): -174.91, -22.86

The 1977 June 22, 1209 UT June 23 0009 NZST M_W 8.0 Tonga Trench earthquake, located near the Tonga Trench south of the Tonga Islands, caused damage and injuries on the Islands. The earthquake generated a small tsunami (max. recorded water height above normal tide levels, 0.4 m), which was recorded on tide gauges as far away as the west coast of the US. (NGDC Tsunami Database, April 2009) Note that there is a degree of longitude difference in NGDC and Global CMT Catalogue epicentres (latitude similar), and a significant difference in magnitude (NGDC: M_S=M_b=M 7.2; Global CMT, M_W 8.0).

3.9.3 Effects in Opua

Maximum reported wave height of 0.15 m. (De Lange & Healy (1986) citing IOC Tsunami Report 1977-79 and NZ Seismological Bulletin E-159.); Max water height: 0.15 (Type 2= tide gauge measurement); Travel time: 04:02; period of first cycle: - (NGDC Tsunami Database, April 2009)

This measurement is identified in NGDC Tsunami Database (April 2009) as a tide gauge measurement, and the given " maximum water height" is defined as "half the maximum height (minus the normal tide) of a tsunami wave recorded at the coast by a tide gauge".

Estimated run-up for MCDEM: 0.15

Max. observed effective peak-through (m): 0.15

3.10 The 1994 Kuril Islands Event

3.10.1 Tsunami Impact Summary

The great earthquake of 1994 October 10 M_W 8.3 earthquake occurred at the southern end of the Kuril Islands, northeast of Hokkaido, Japan. The earthquake generated a tsunami, which was recorded around the Pacific as far as South America. The tsunami reached sub-metre peak-trough wave heights only, except near the source in the Kuril Islands and in Hokkaido, where it reached damaging levels. (International Tsunami Information Center (ITIC) Tsunami Newsletter (march, 1995), and 1994 summary of events). In New Zealand, Fraser (1998) reports run-ups (peak-trough or zero-peak uncertain) of less than 0.1 m at eastern seaboard tide gauges at Marsden Point, Auckland Port, Tauranga, Gisborne, Napier, Wellington, Lyttelton and Pegasus Point (location unknown). Although Fraser (1998) cites de Lange & Hull (1994) as the source of information on the measurements, only one location (Auckland Port) is in fact listed in this publication.

3.10.2 Source Parameters

Time UTC: 13:23 4th October 1994

Source Location (longitude, latitude): 147.63, 43.60

3.10.3 Effects in Marsden Point

Fraser (1998) reports run-ups (peak-trough or zero-peak uncertain) of less than 0.1 m at eastern seaboard tide gauges at Marsden Point, Auckland Port, Tauranga, Gisborne, Napier, Wellington, Lyttelton and Pegasus Point (location unknown). Although Fraser (1998) cites de Lange & Hull (1994) as the source of information on the measurements, only one location (Auckland Port) is in fact listed in this publication.

Estimated run-up for MCDEM: 0.1

3.11 The 2001 Southern Peru Event

3.11.1 Tsunami Impact Summary

The 2001 June 23, 2034 UT June 24 0834 NZST M_W 8.4 southern Peru earthquake was the largest plate interface earthquake in over 25 years. Earthquake destruction cantered inland around the towns of Arequipa, and Moquegua with at least 102 killed, and 1,368 injured. Twenty-one people are known to have died with over 60 missing from the tsunami that occurred along the coast of Peru between Atico and Ilo. Most of the damage was limited to 30 km of coastline, cantered on Camaná (International tsunami Information Center (ITIC), 2001-2002) The tsunami was recorded in New Zealand on 10 of the 13 digitally recorded tide gauge stations operated by NIWA and various Port and Regional Authorities. The maximum peak-to-trough height (~0.6 m) was recorded at Lyttelton. The tsunami could not be identified on three stations located on the west coast of the North and South Islands. Other stations, from Northland to Foveaux Strait, recorded sub-metre peak-to-trough heights. (Goring, 2002) A New Zealand team conducted a post-earthquake and -tsunami survey in Peru reported in Stirling et al. (2003).

3.11.2 Source Parameters

Time UTC: 20:34 23rd June 2001

Source Location (longitude, latitude): -72.71, -17.28

3.11.3 Effects in Marsden Point

Goring (2002) gives a figure (5) showing high pass filtered sea level records at 13 digitally recorded tide gauge stations. Maximum zero-to-peak is given for Lyttelton only.

Maximum peak-to-trough and zero-to-peak measurements have been interpreted from Goring's Figure 5. The diagram is not a high enough resolution to interpret accurate arrival times and times of maximums.

Max. observed effective peak-through (m): 0.18

3.12 The 2006 Tonga Event

3.12.1 Tsunami Impact Summary

The large size and shallow depth of the 2006 May 03 1527 UT May 04 0327 NZST M_W 8.0 Tonga Islands Region earthquake meant that a Tsunami Warning was initiated by the Pacific

Tsunami Warning System. It was later withdrawn when nearby sea-level records indicated that only a small tsunami had been generated. The earthquake occurred at 68 km deep (Global CMT Catalog, October 2008), and questions have been raised as to whether it was a plate interface event or a steep rupture in the subducting slab (i.e. beneath the interface) (for example, Beavan et al 2006; Heeszel et al. 2006). Tsunami waves were distinguishable on some sea-level gauge records in New Zealand and there were two observations of small surges and recessions at Whangamata and in the Chatham Islands. The maximum wave height (i.e. peak-to-trough) only reached around 0.35 m. The greatest peak-to-trough measurements were observed at Kaingaroa-Chatham Island (0.35 m), , 0.25 m Gisborne (0.30 m) and Lyttelton and Moturiki Island-Mt Maunganui (0.25 m), and probably Timaru (0.3 m), Napier (0.2 m) and Marsden Point (0.15 m). Most other gauge sites experienced smaller waves that were <0.2 m (crest-to-trough) and barely distinguishable from background seiching or weather-related long waves. In many cases, the tsunami was obscured on Port tide gauges to a greater or lesser extent by long waves (infra-gravity or far-infragravity) produced by weather systems and swell. The first arrival at Kaingaroa, 3.5 hours after the earthquake, is close to the predicted travel time. The first detectable arrivals recorded in the North and South Islands at Moturiki Island-Mt Maunganui (5.1 hours) Marsden Point (5.5 hours), Gisborne (6.0 hours), Otago Harbour Entrance and Lyttelton (~ 6 hours), Napier (~ 6.4 hours), Port Taranaki (~ 8 hours) and Timaru (~8-9 hrs) are all quite late compared to the predicted first arrivals, suggesting that the fast Kermadec Trench path carried little energy for these locations. It is sometimes difficult to pinpoint the initial arrival time in the sea-level record with such a small tsunami signal as from this event, and there needs to be an awareness that larger waves may occur several hours after an apparent small or non-arrival of a tsunami at the estimated first arrival time. For the Tonga event, the largest recorded wave at Gisborne (0.3 m) was the 4th distinguishable wave that arrived approximately 9 hours after earthquake and at Chathams it was the 3rd wave. While the first waves arrived at Lyttelton around 6 hrs after the earthquake, the peak was about 18 hrs after the earthquake. (Downes et al. 2006)

3.12.2 Source Parameters

Time UTC: 15:27 3rd May 2006

Source Location (longitude, latitude): -173.47, -20.39

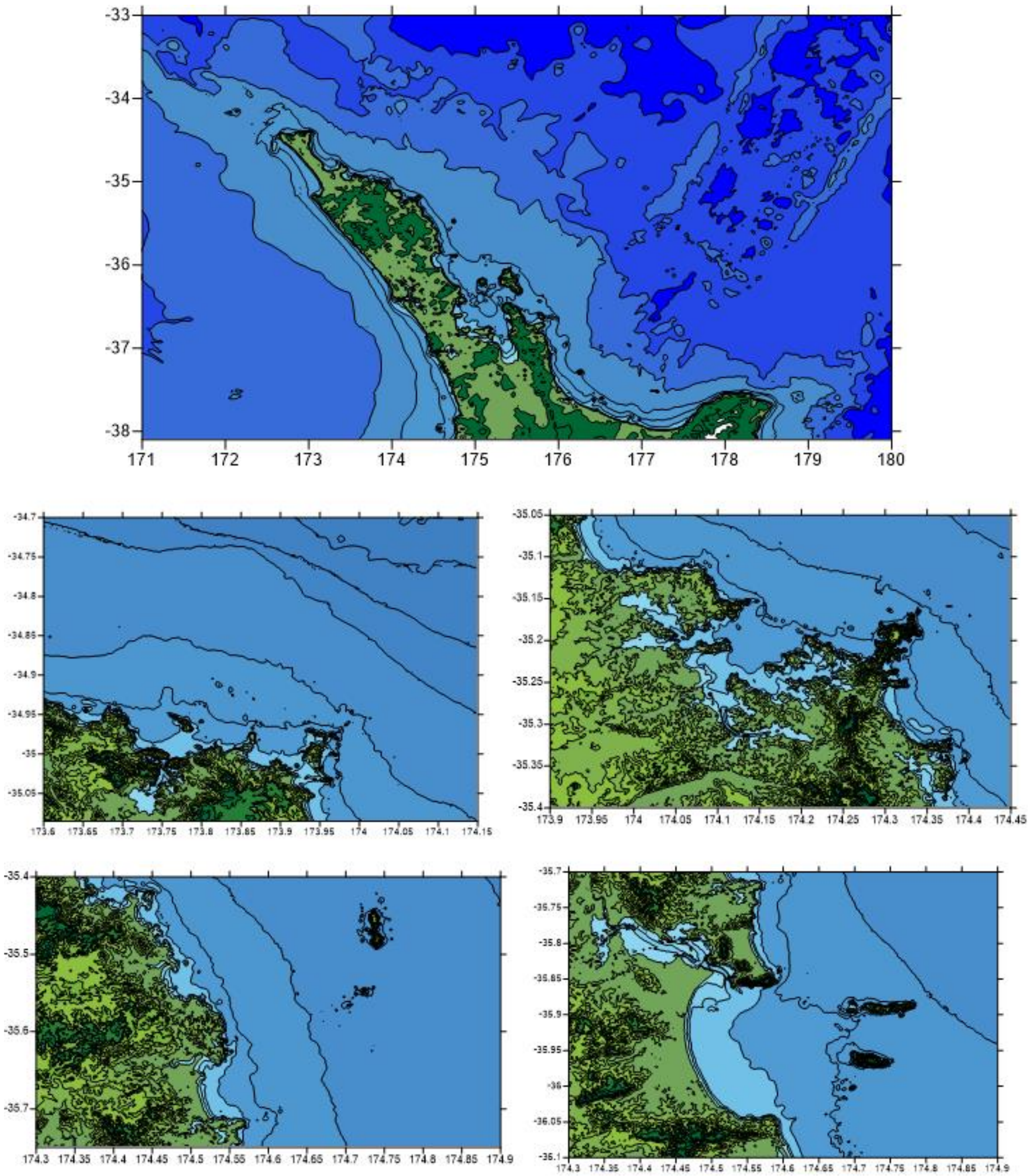
3.12.3 Effects in Marsden Point

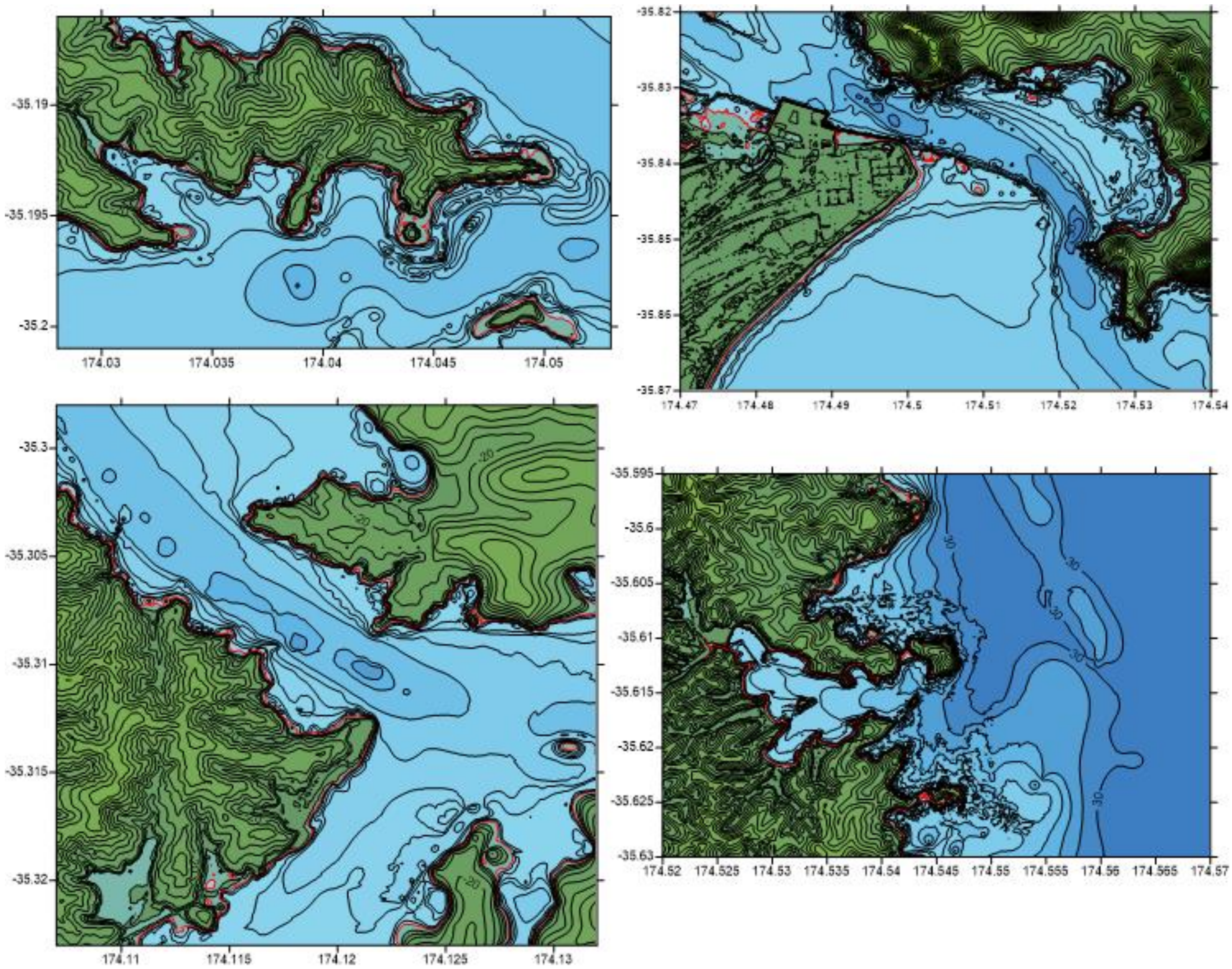
Marsden Point is strongly affected by far infra gravity waves, which are modulated with the tide, being higher at high tide. However, FIG waves tend to have periods of 6 to 20 min, so the very long waves in mid-morning of 4 May, may be the first tsunami waves. The large waves at high tide could be a superposition of FIG and tsunami waves. Marsden Point is in direct line with Tonga, so for the sites under consideration, the tsunami would be expected to reach here first. (www.mulgor.co.nz/TongaTsu06/); "Derek Goring, of Mulgor Consulting, who monitors tide gauges at some NZ ports, has posted his analysis of the records for tsunami for 4-5 May on www.mulgor.co.nz/TongaTsu06/ Derek notes that he has excluded some where nothing apparently happened, and that in many cases, the tsunami was obscured to a greater or lesser extent by long waves (infra-gravity or far-infragravity) produced by weather systems and swell. The greatest peak-to-trough measurements were observed at Kaingaroa-Chatham Island (0.35 m), Gisborne (0.30 m) and Lyttelton (0.25 m), and probably Timaru (0.3 m), Napier (0.2 m) and Marsden Point (0.15 m). The first arrival at Kaingaroa, 3.5 hours after the earthquake, is consistent with William Power's movie (see below). The first arrivals recorded in the North and South Islands were at Moturiki-Mt

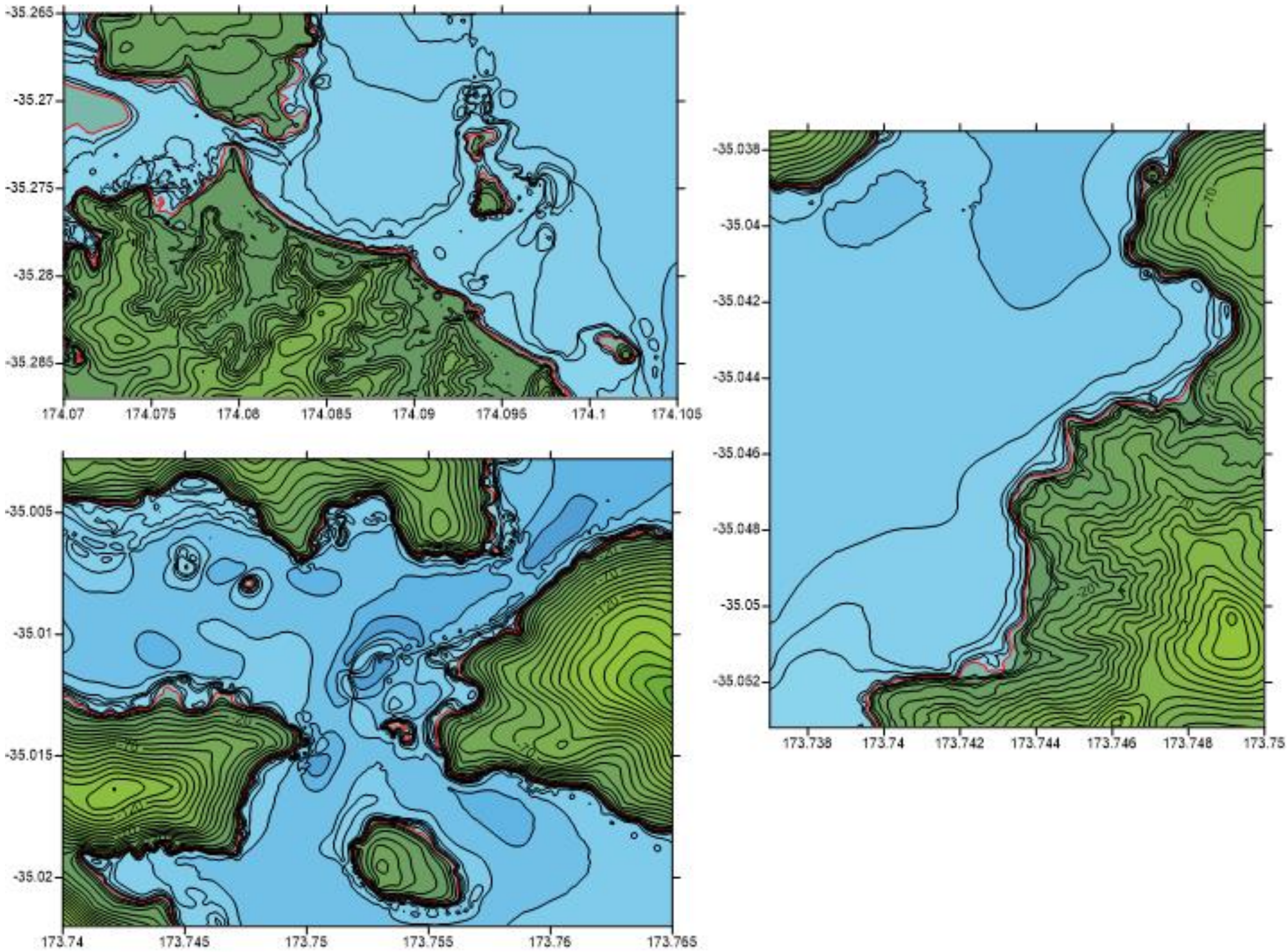
Maunganui (5.1 hours) Marsden Point (5.5 hours), Gisborne (6.0 hours), Otago Harbour Entrance and Lyttelton (~ 6 hours), Napier (~ 6.4 hours), Port Taranaki (~ 8 hours). The Timaru waves arrived quite late at 9 hrs after the earthquake. While the first waves arrived at Lyttelton around 6 hrs after the earthquake, the peak was at about 18 hrs after the earthquake – this very late peak is interesting, and its cause probably requires investigation" (Downes et al, 2006).

Max. observed effective peak-through (m): 0.15

4 APPENDIX 4: NUMERICAL MODELLING GRIDS




-35.19
-35.195
-35.2
174.03
174.035
174.04
174.045
174.05
-35.82
-35.83
-35.84
-35.85
-35.86
-35.87
174.47
174.48
174.49
174.5
174.51
174.52
174.53
174.54
-35.3
-35.305
-35.31
-35.315
-35.32
174.11
174.115
174.12
174.125
174.13
-35.595
-35.6
-35.605
-35.61
-35.615
-35.62
-35.625
-35.63
174.52
174.525
174.53
174.535
174.54
174.545
174.55
174.555
174.56
174.565
174.57


-35.265
-35.27
-35.275
-35.28
-35.285
174.07
174.075
174.08
174.085
174.09
174.095
174.1
174.105
-35.005
-35.01
-35.015
-35.02
173.74
173.745
173.75
173.755
173.76
173.765
-35.038
-35.04
-35.042
-35.044
-35.046
-35.048
-35.05
-35.052
173.738
173.74
173.742
173.744
173.746
173.748
173.75

5 APPENDIX 5: PLOTS OF MAXIMUM MODELLED TSUNAMI HEIGHTS AND CURRENT SPEEDS BY SOURCE

Each of the following plots indicates the source region responsible for the maximum water level or current speed at each model grid node. The models are broken up into the regional sets indicated in **Error! Reference source not found.**. Maximum height plots are presented f or each level of the modelling grids which maximum current speed plots are presented only for the fine scale detailed grids.

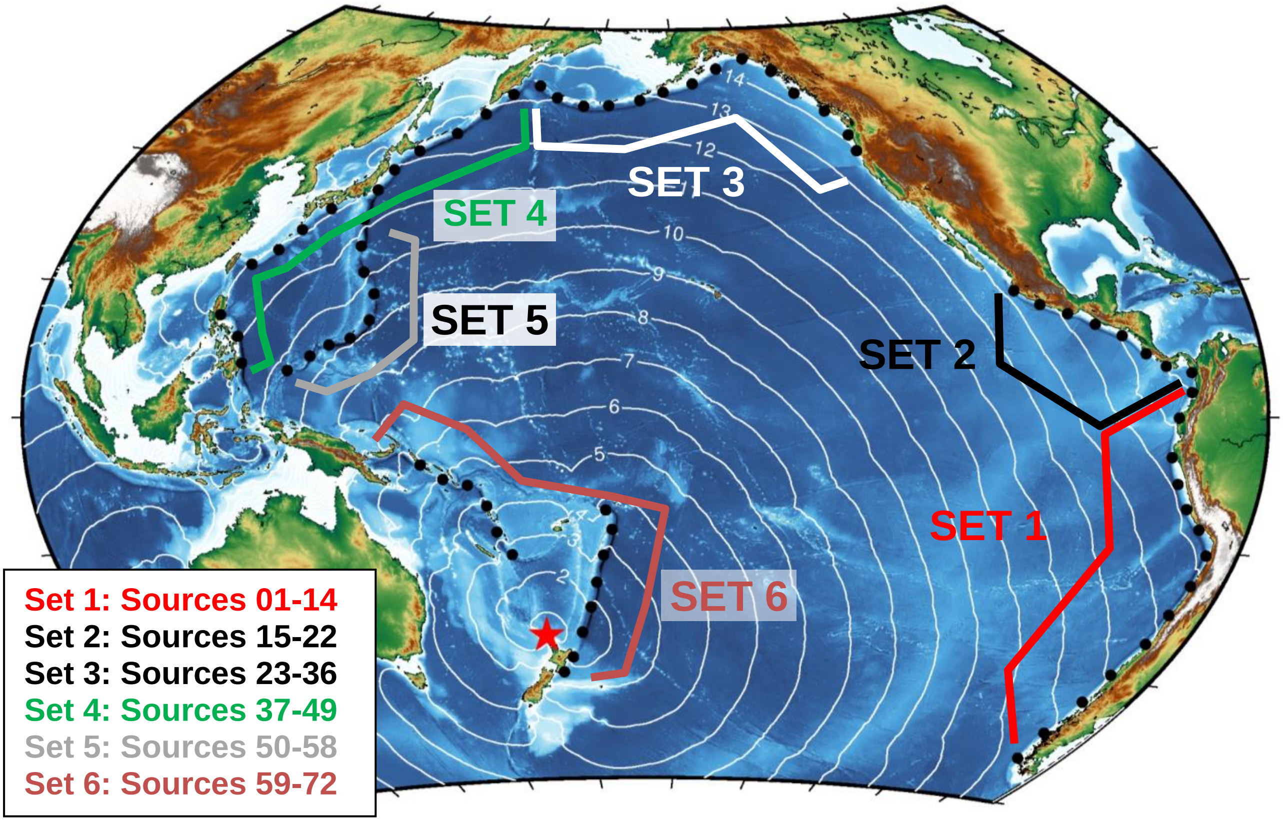
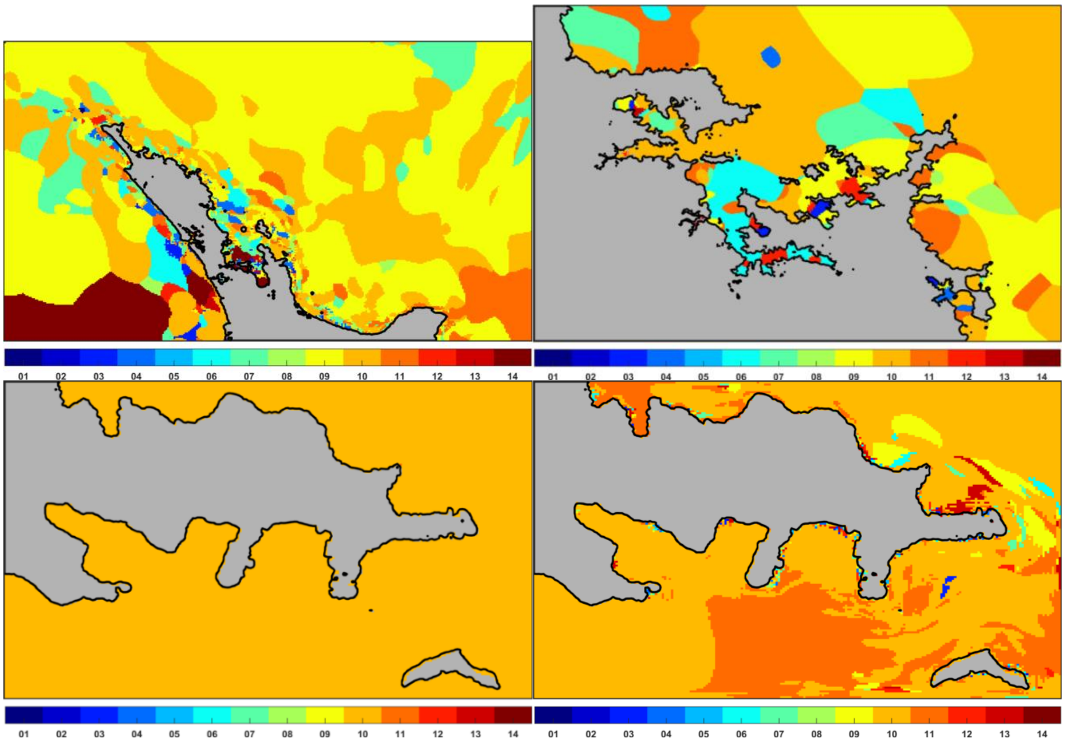


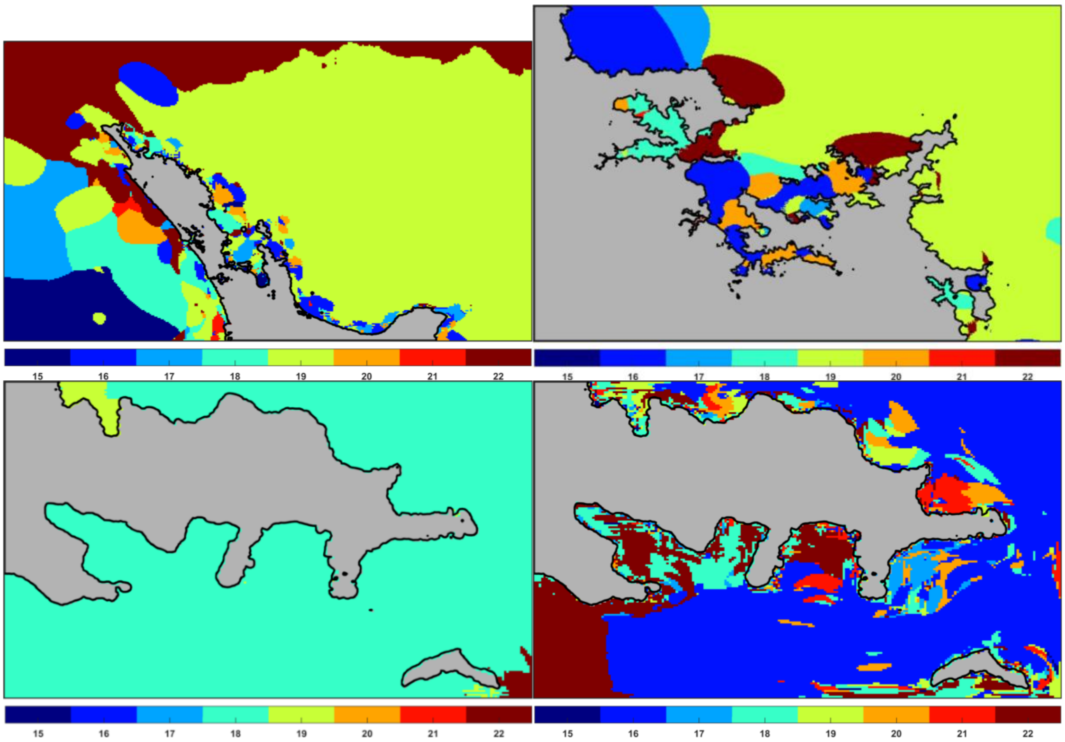
Figure 5.1 Tsunami source regions Black dots denote the centre of each individual tsunami source.

5.1 Dove's Bay

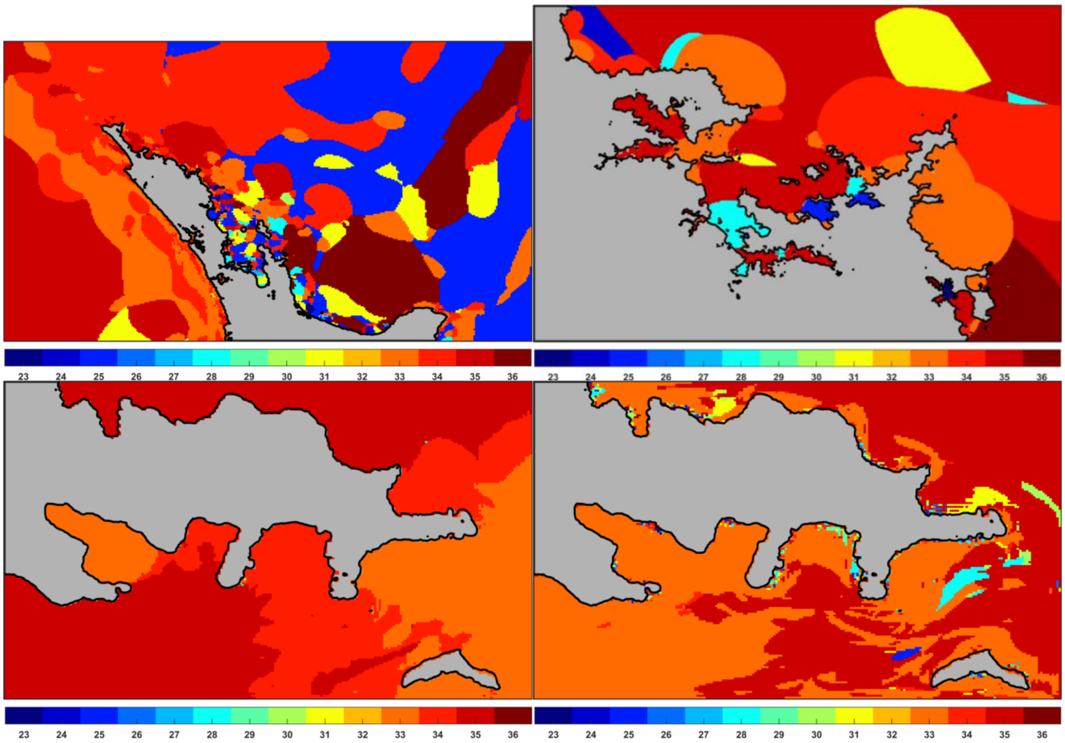
Set 1



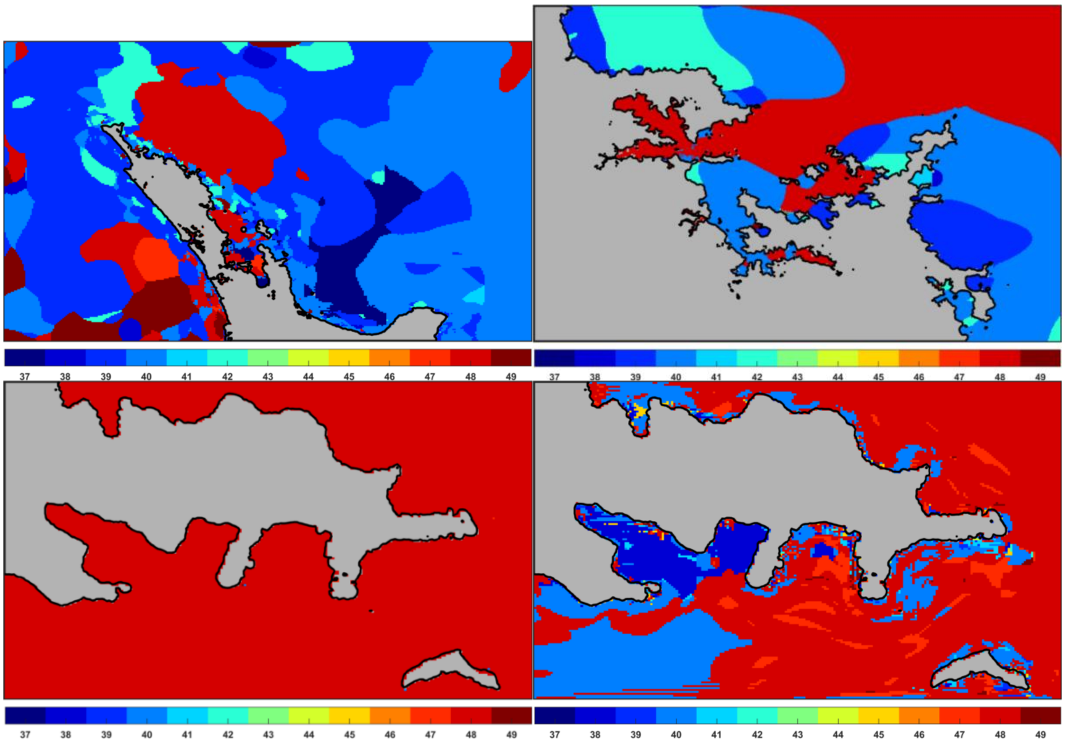
Set 2



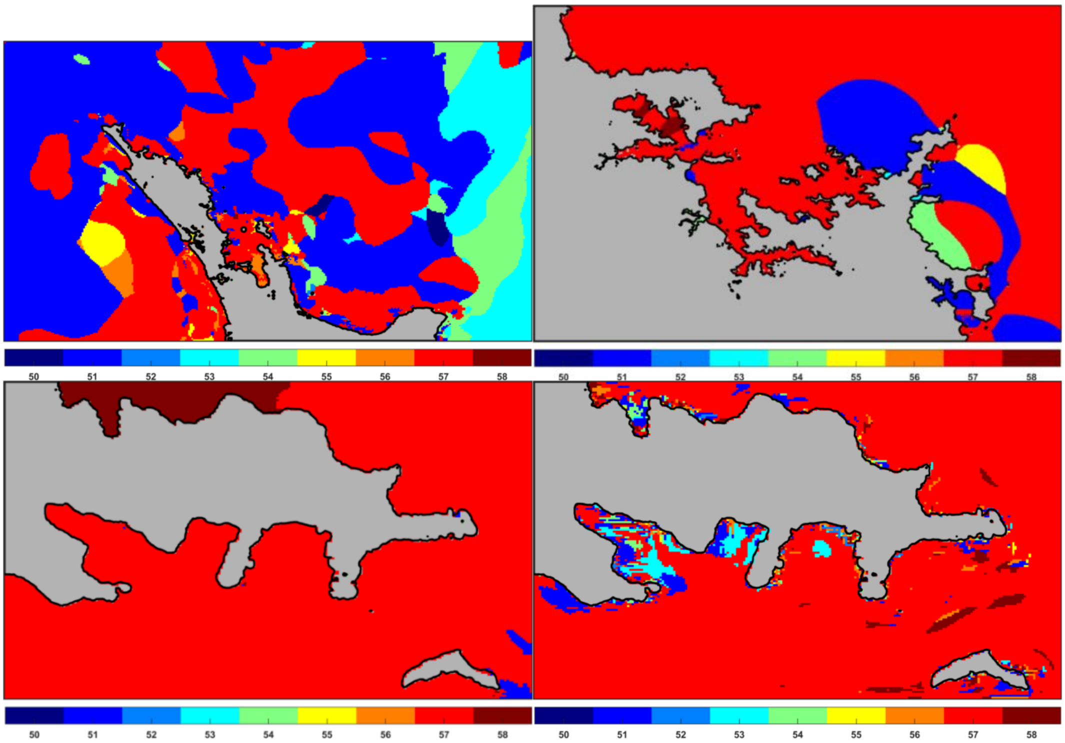
Set 3


23 24 25 26 27 28 29 30 31 32 33 34 35 36

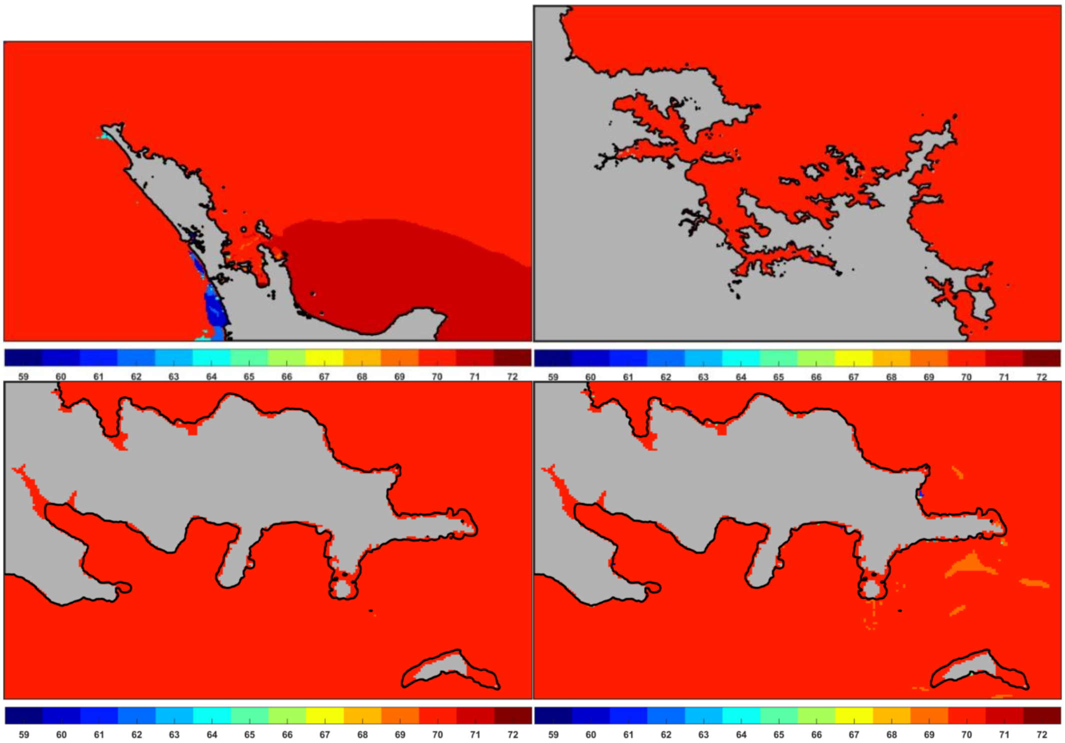
Set 4


37 38 39 40 41 42 43 44 45 46 47 48 49

Set 5

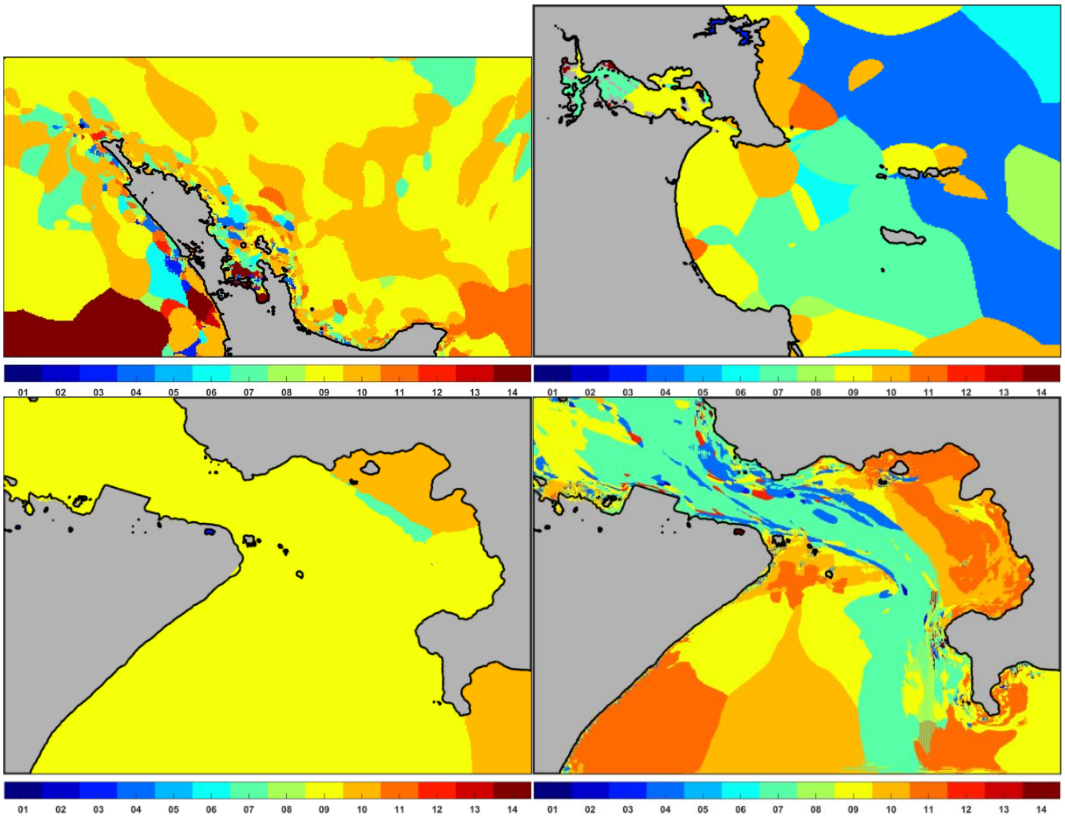


Set 6

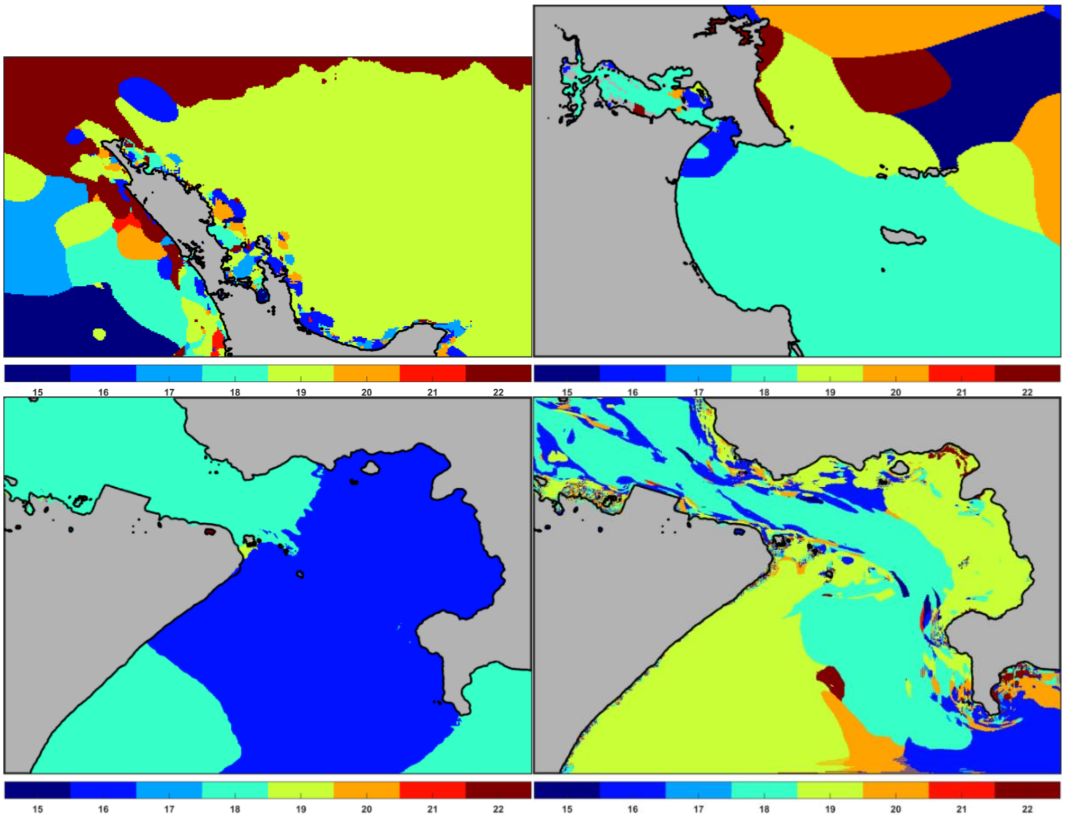


5.2 Marsden Point

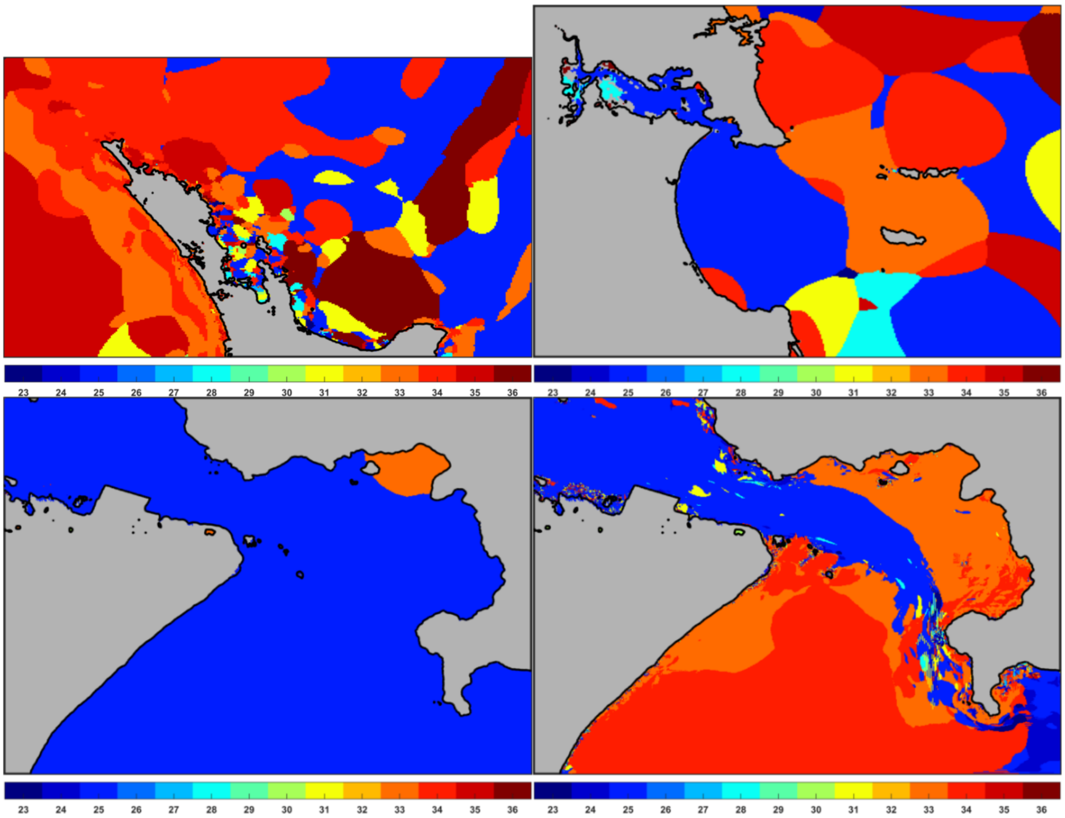
Set 1



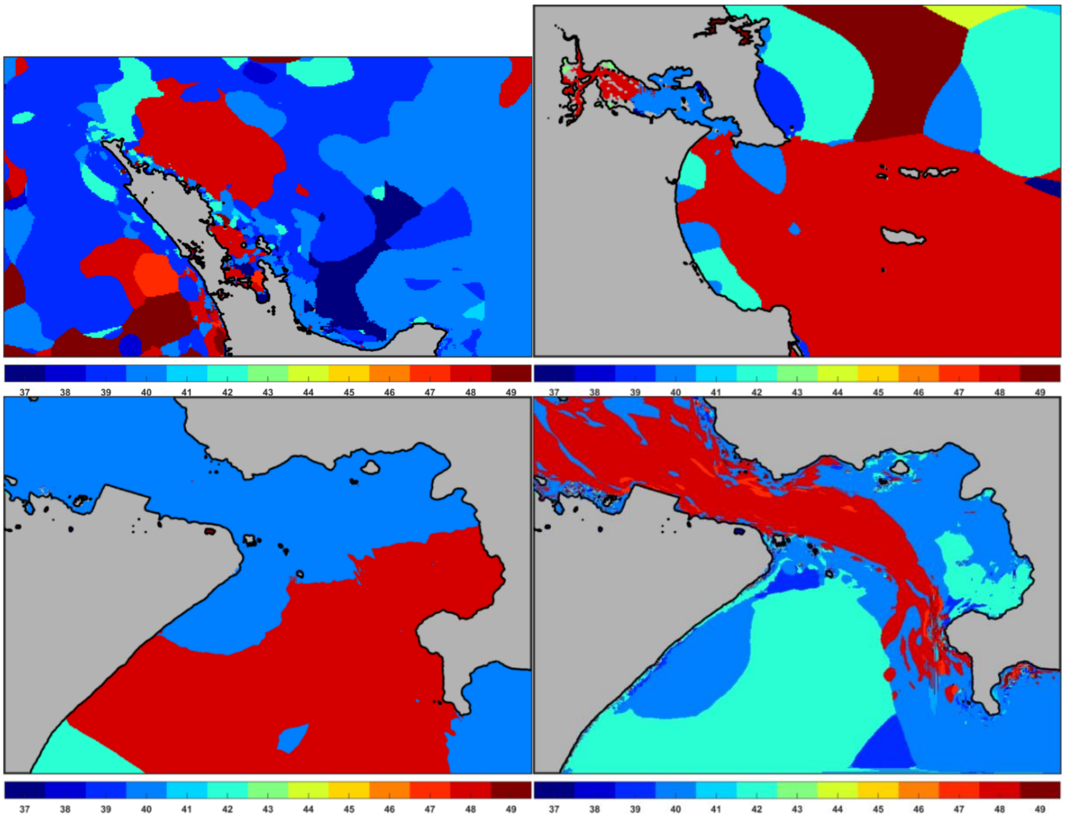
Set 2



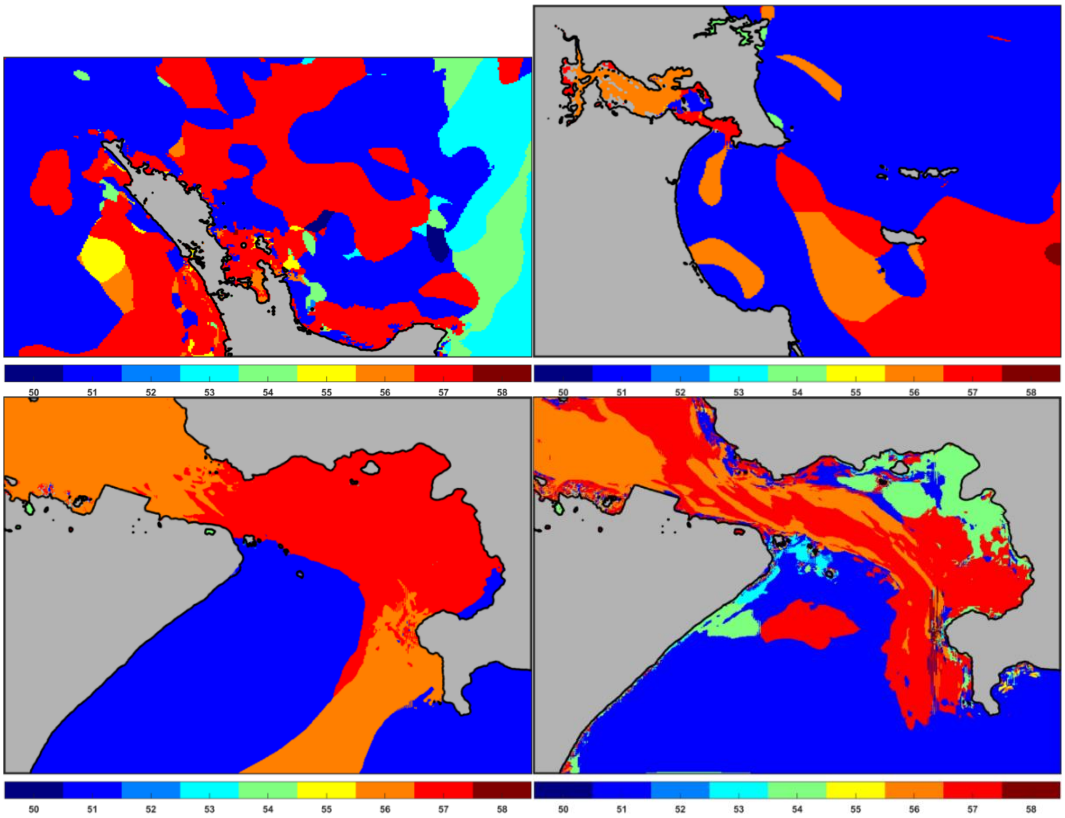
Set 3


23 24 25 26 27 28 29 30 31 32 33 34 35 36
23 24 25 26 27 28 29 30 31 32 33 34 35 36
23 24 25 26 27 28 29 30 31 32 33 34 35 36
23 24 25 26 27 28 29 30 31 32 33 34 35 36

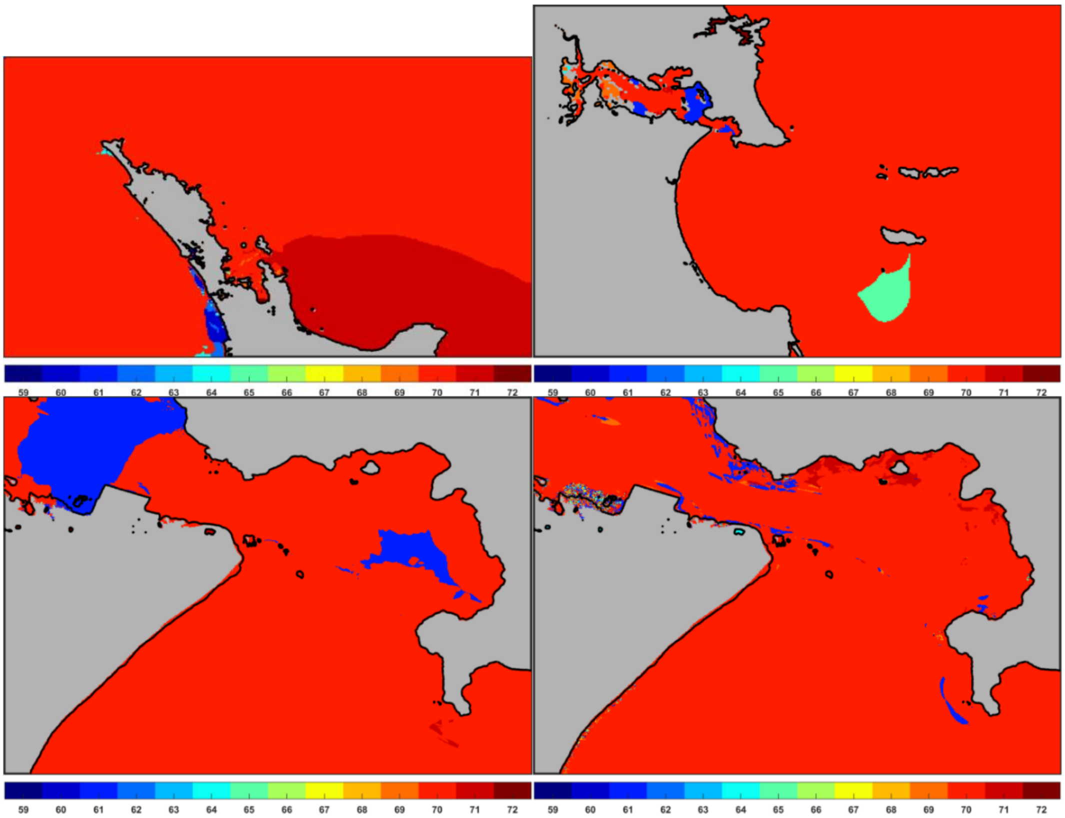
Set 4


37 38 39 40 41 42 43 44 45 46 47 48 49
37 38 39 40 41 42 43 44 45 46 47 48 49
37 38 39 40 41 42 43 44 45 46 47 48 49
37 38 39 40 41 42 43 44 45 46 47 48 49

Set 5

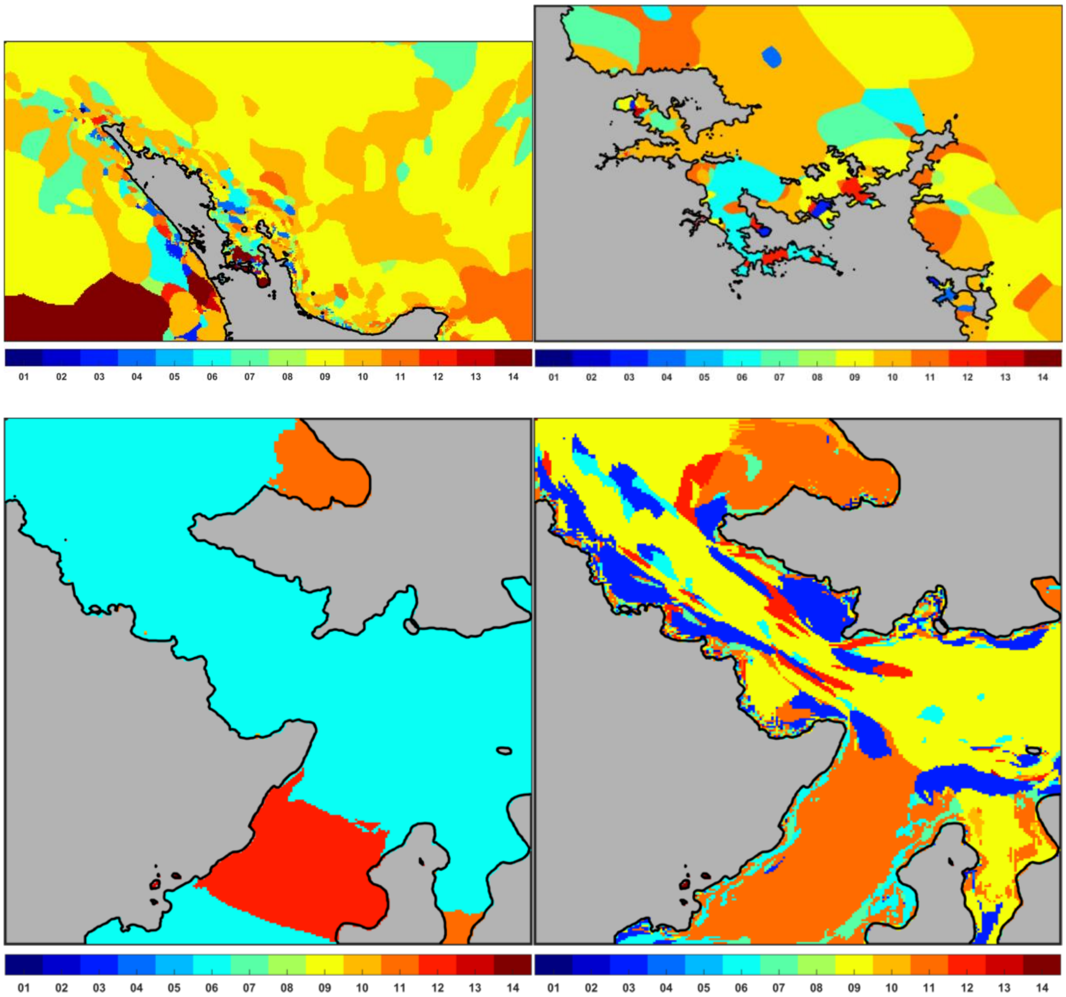


Set 6

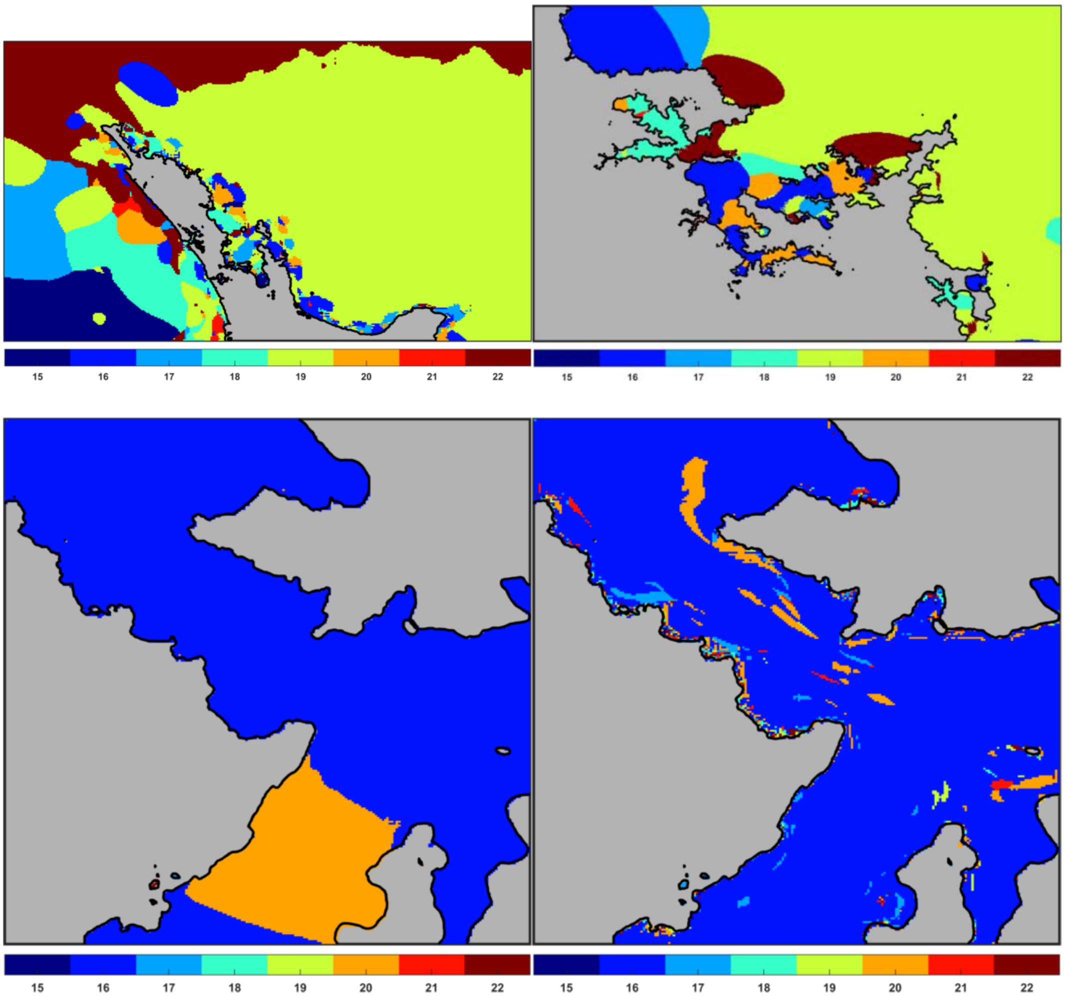


5.3 *Opua*

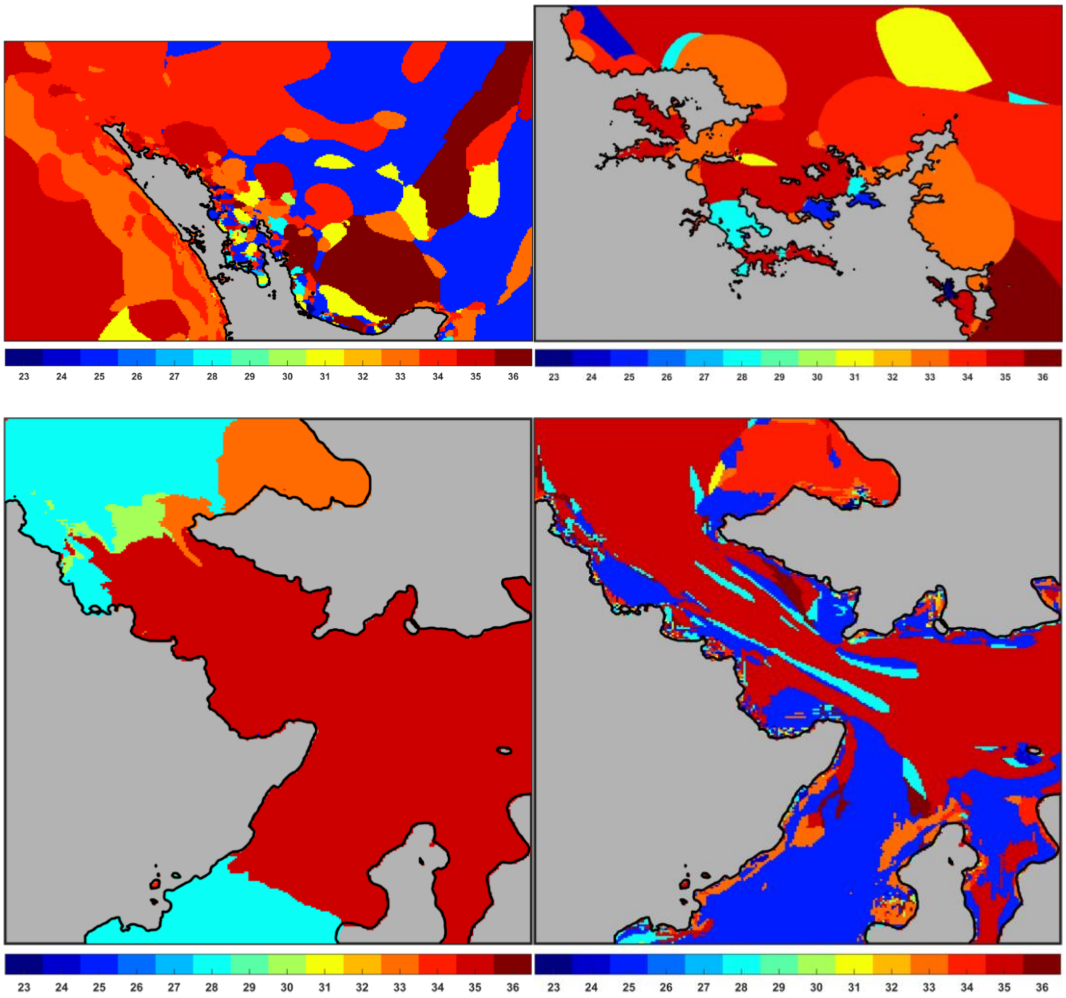
Set 1


01 02 03 04 05 06 07 08 09 10 11 12 13 14
01 02 03 04 05 06 07 08 09 10 11 12 13 14
01 02 03 04 05 06 07 08 09 10 11 12 13 14
01 02 03 04 05 06 07 08 09 10 11 12 13 14

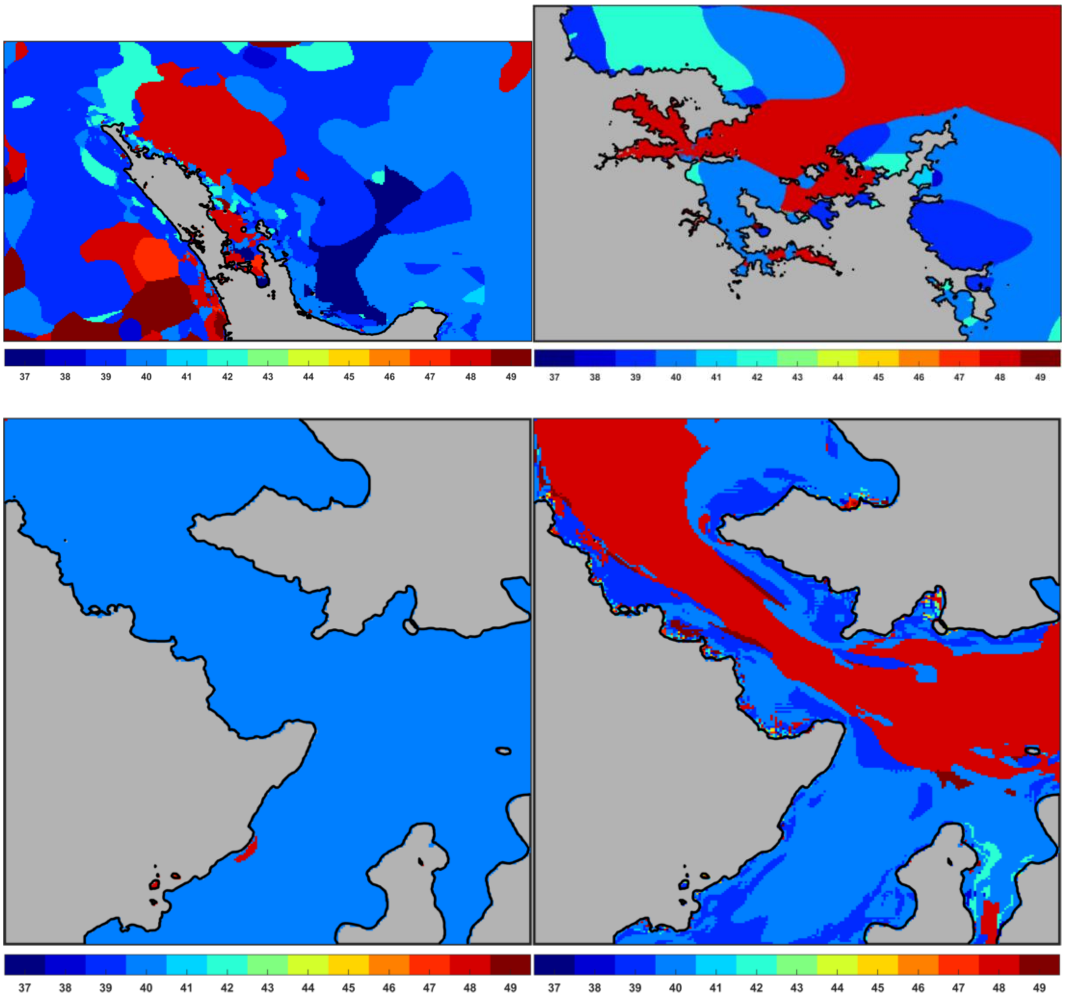
Set 2


15 16 17 18 19 20 21 22
15 16 17 18 19 20 21 22
15 16 17 18 19 20 21 22
15 16 17 18 19 20 21 22

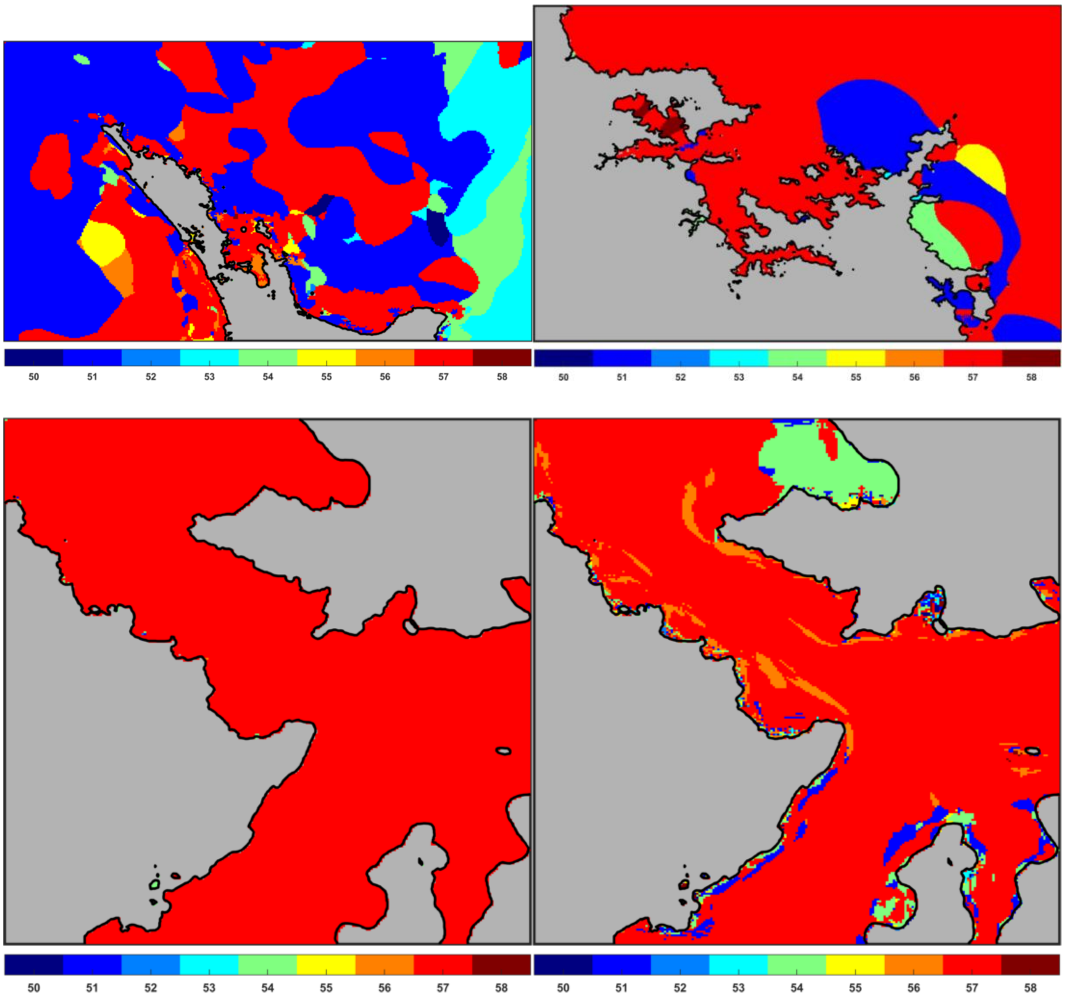
Set 3


23 24 25 26 27 28 29 30 31 32 33 34 35 36
23 24 25 26 27 28 29 30 31 32 33 34 35 36
23 24 25 26 27 28 29 30 31 32 33 34 35 36
23 24 25 26 27 28 29 30 31 32 33 34 35 36

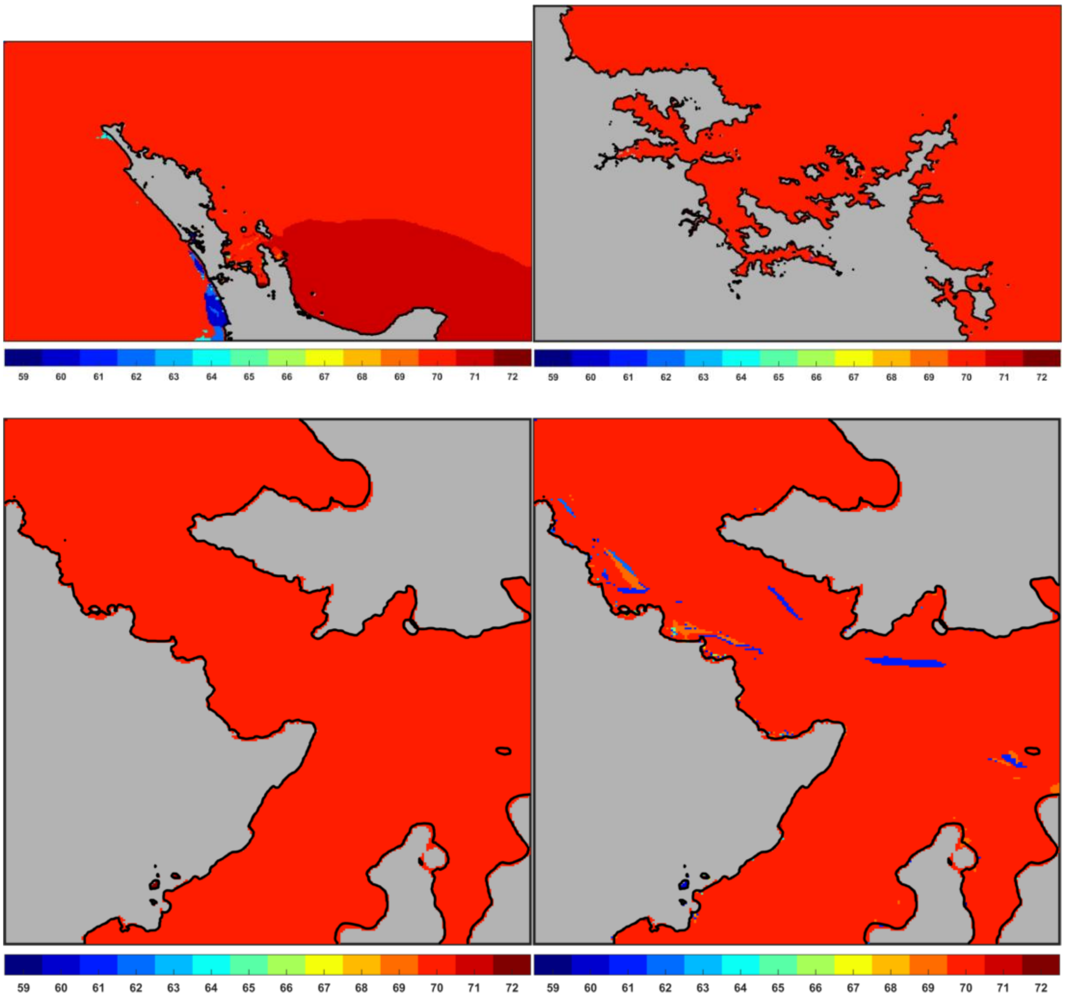
Set 4


37 38 39 40 41 42 43 44 45 46 47 48 49
37 38 39 40 41 42 43 44 45 46 47 48 49
37 38 39 40 41 42 43 44 45 46 47 48 49
37 38 39 40 41 42 43 44 45 46 47 48 49

Set 5

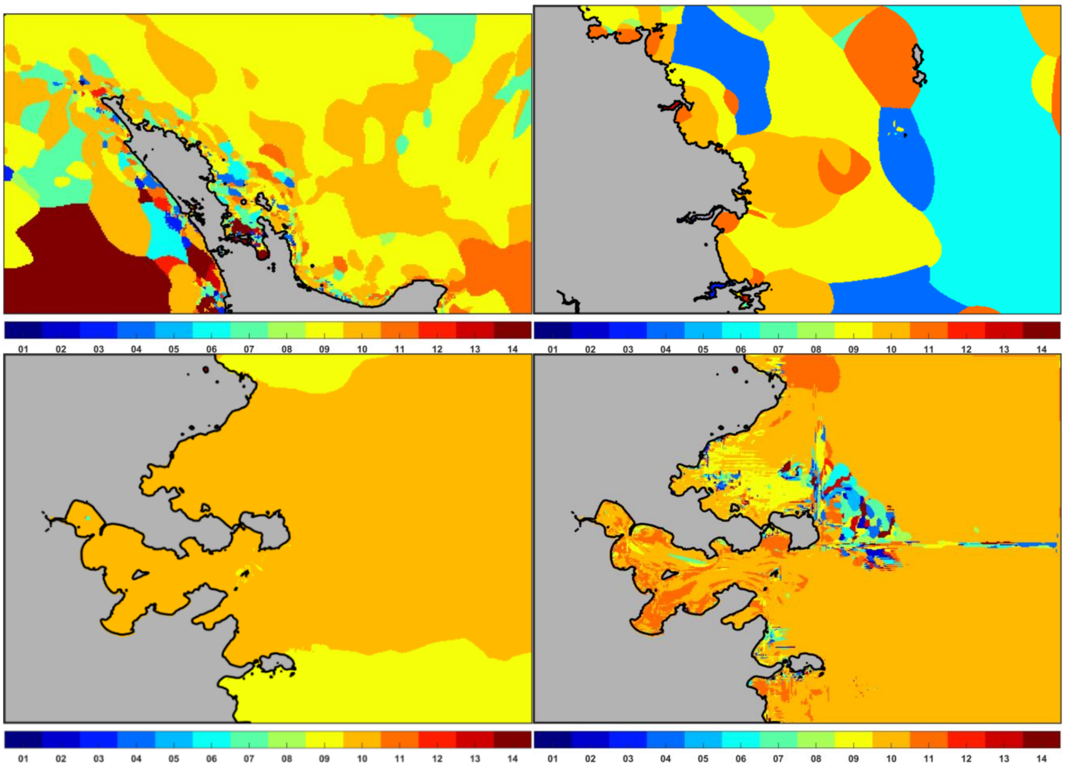

50 51 52 53 54 55 56 57 58
50 51 52 53 54 55 56 57 58
50 51 52 53 54 55 56 57 58
50 51 52 53 54 55 56 57 58

Set 6

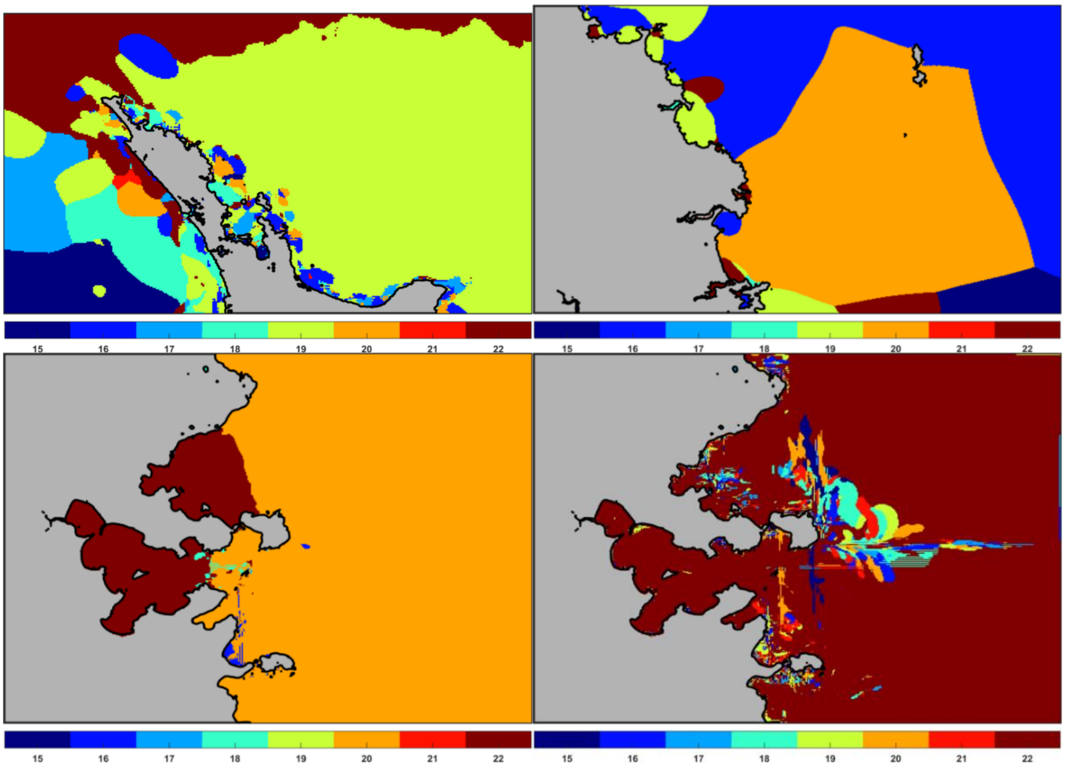

59 60 61 62 63 64 65 66 67 68 69 70 71 72
59 60 61 62 63 64 65 66 67 68 69 70 71 72
59 60 61 62 63 64 65 66 67 68 69 70 71 72
59 60 61 62 63 64 65 66 67 68 69 70 71 72

5.4 *Tutukaka*

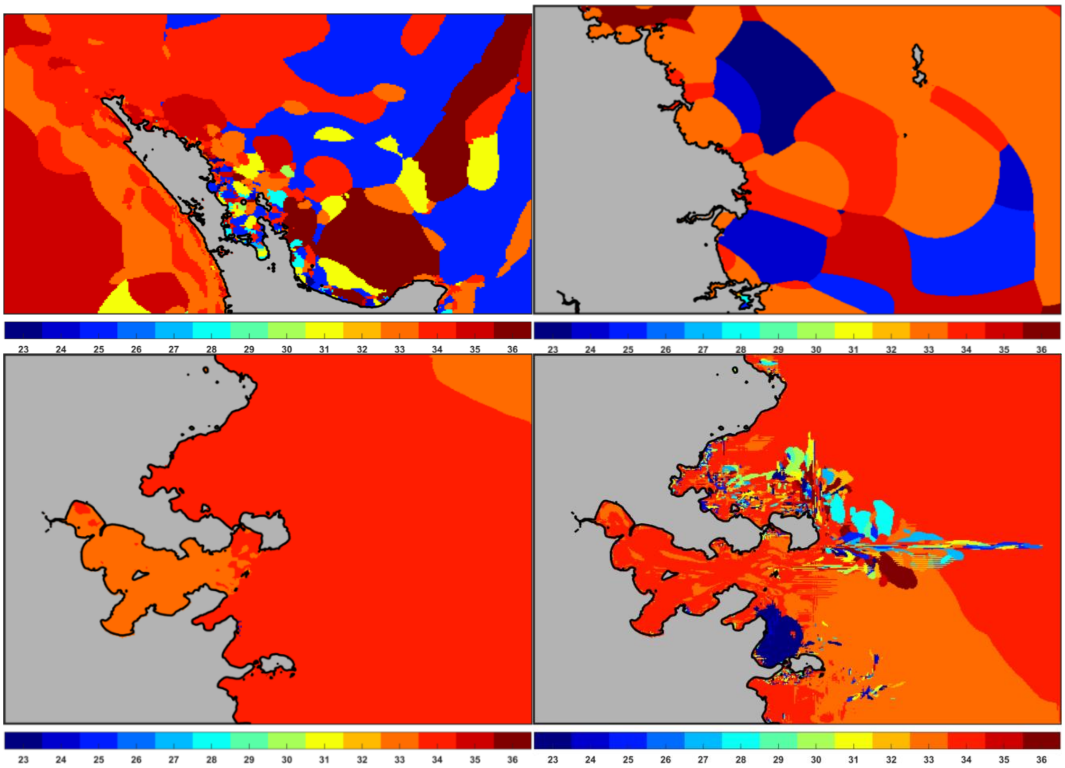
Set 1



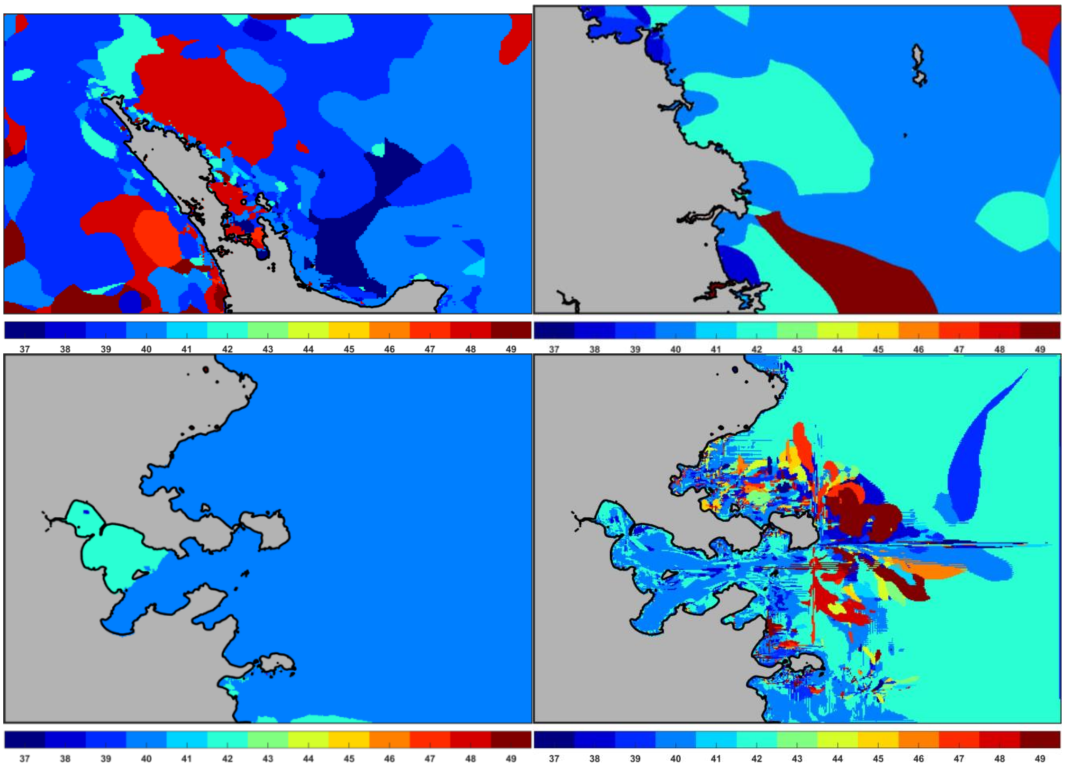
Set 2



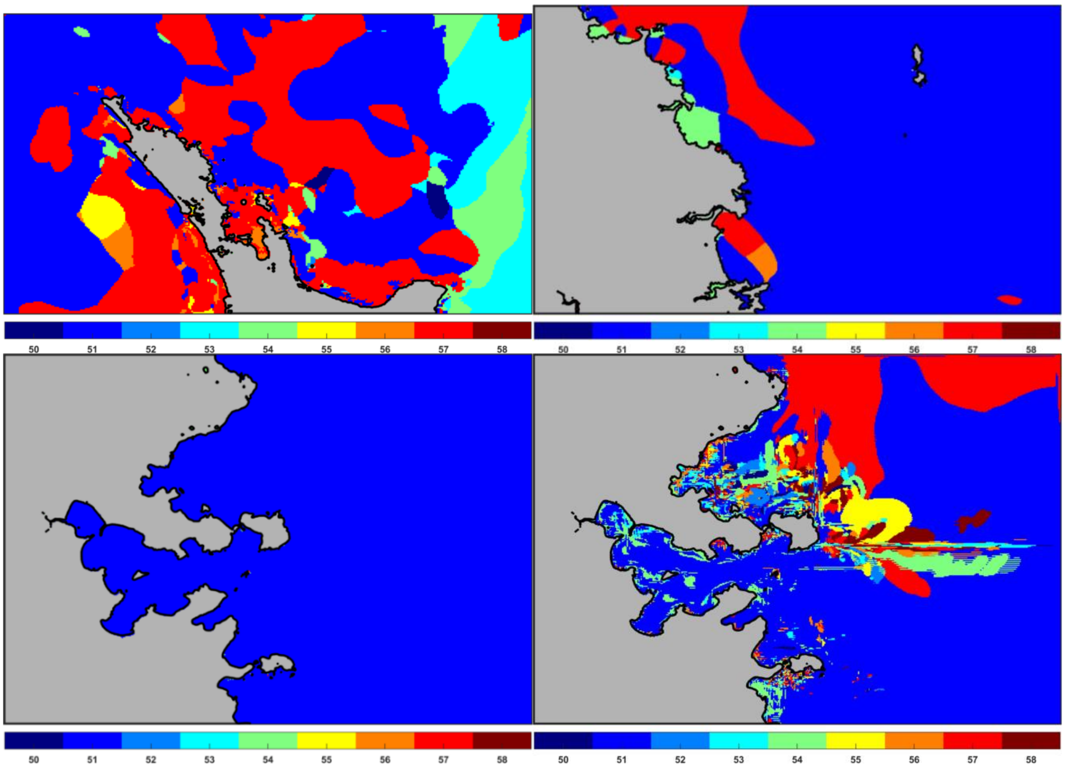
Set 3


23 24 25 26 27 28 29 30 31 32 33 34 35 36
23 24 25 26 27 28 29 30 31 32 33 34 35 36
23 24 25 26 27 28 29 30 31 32 33 34 35 36
23 24 25 26 27 28 29 30 31 32 33 34 35 36

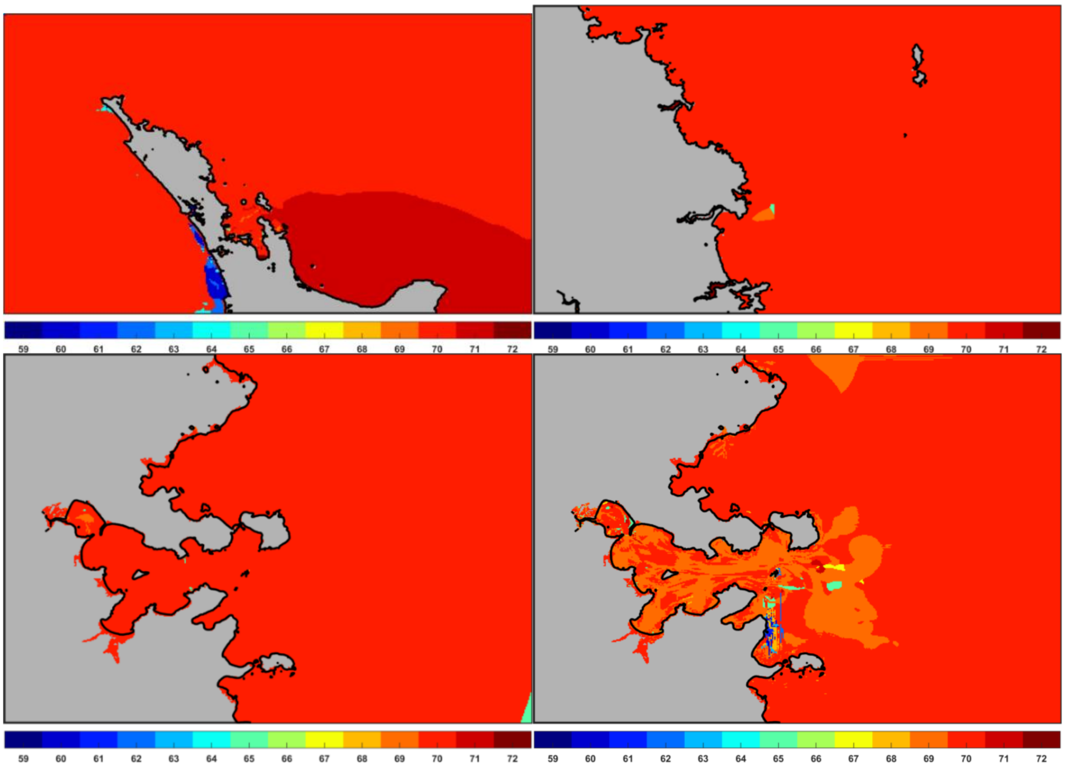
Set 4


37 38 39 40 41 42 43 44 45 46 47 48 49
37 38 39 40 41 42 43 44 45 46 47 48 49
37 38 39 40 41 42 43 44 45 46 47 48 49
37 38 39 40 41 42 43 44 45 46 47 48 49

Set 5

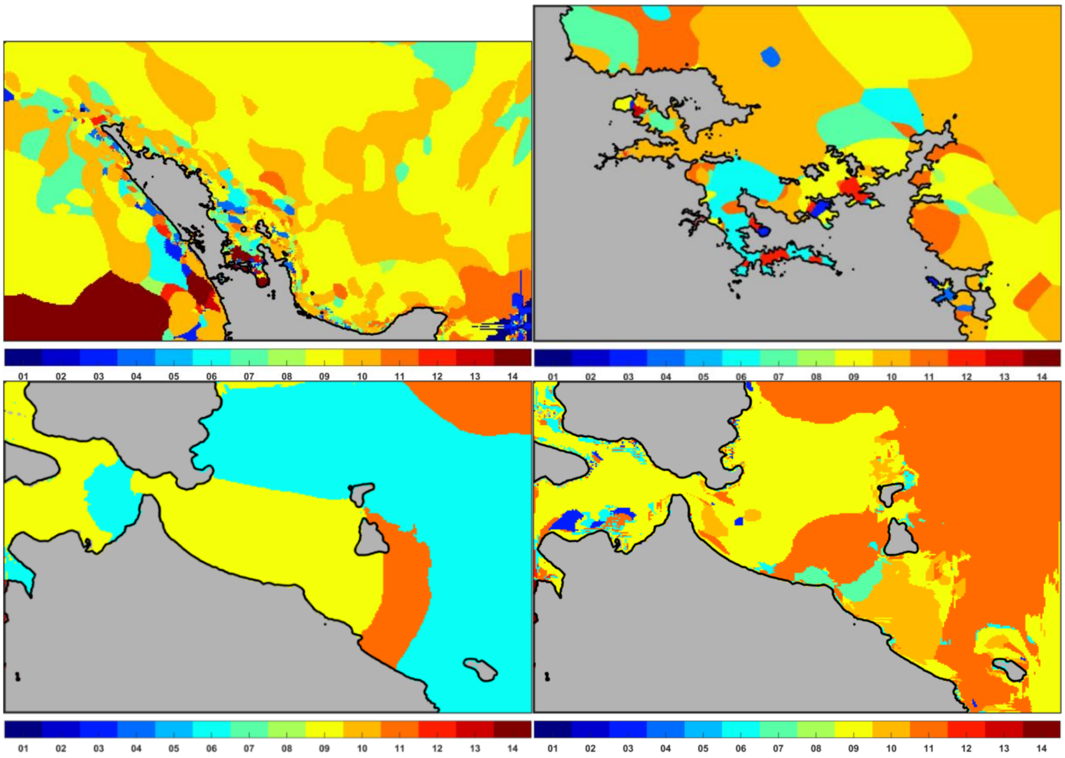


Set 6

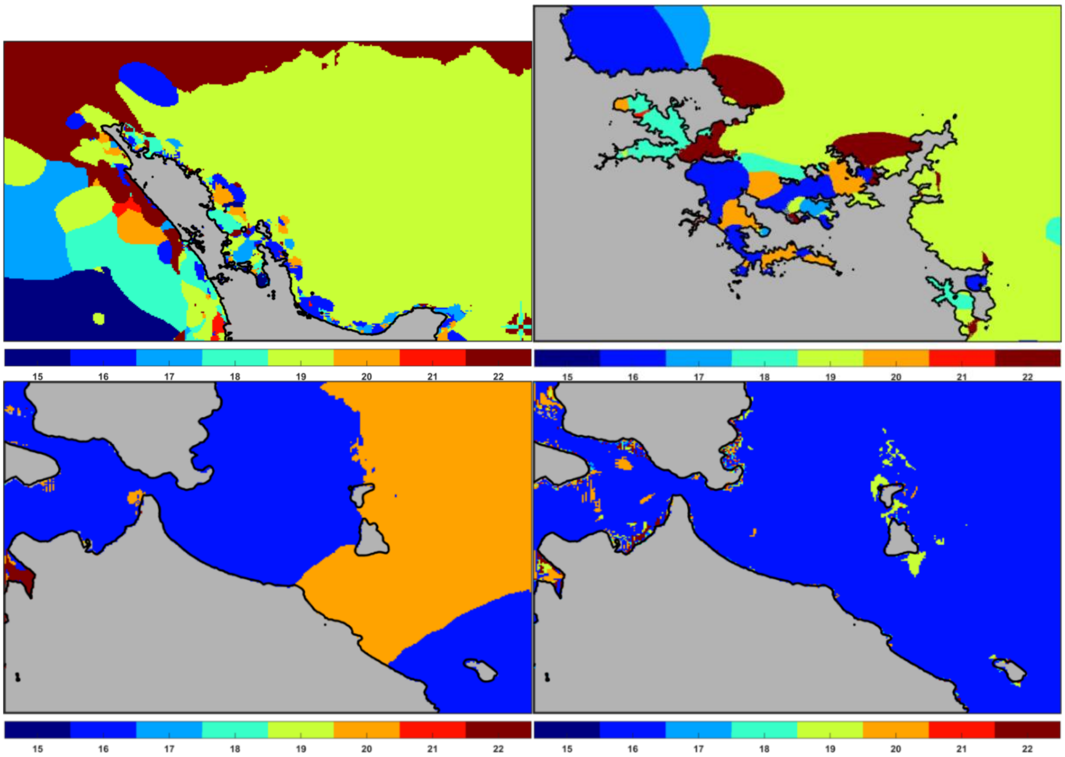


5.5 *Waitangi*

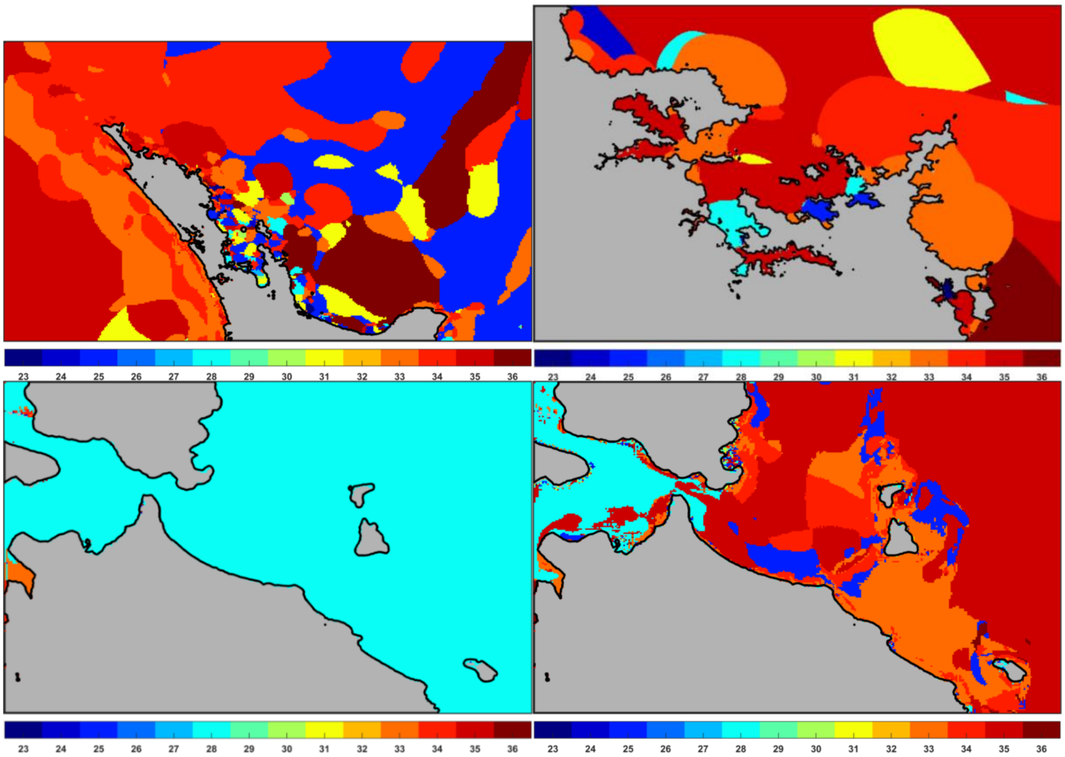
Set 1



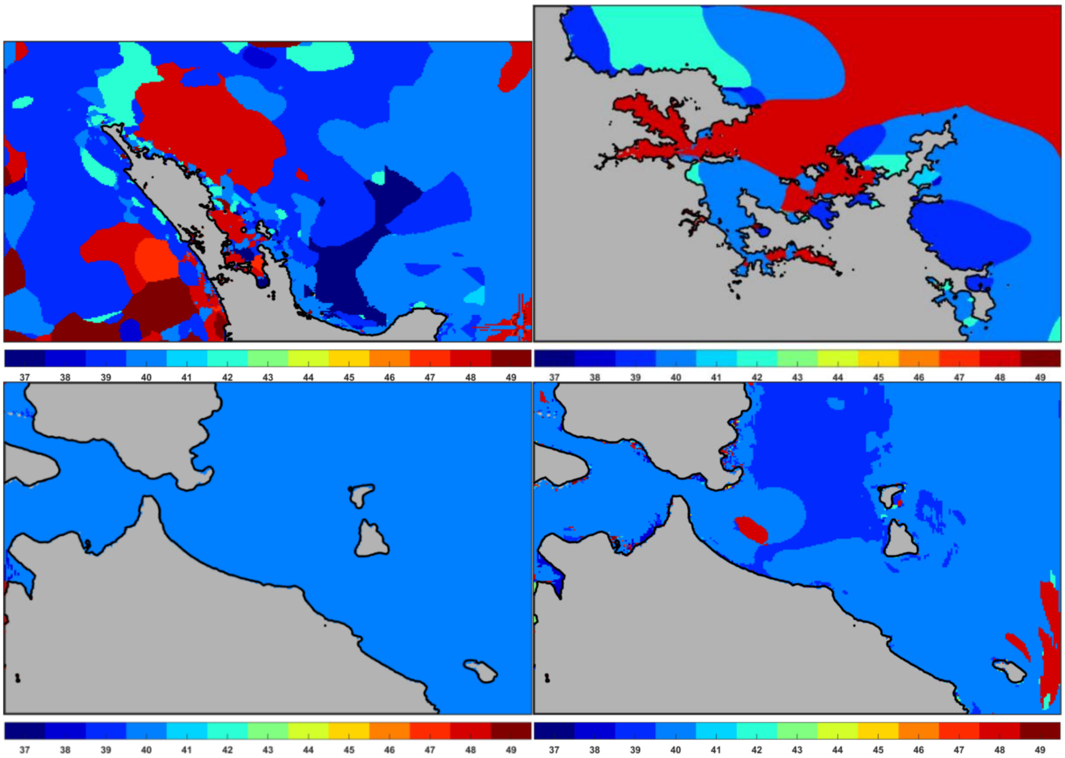
Set 2



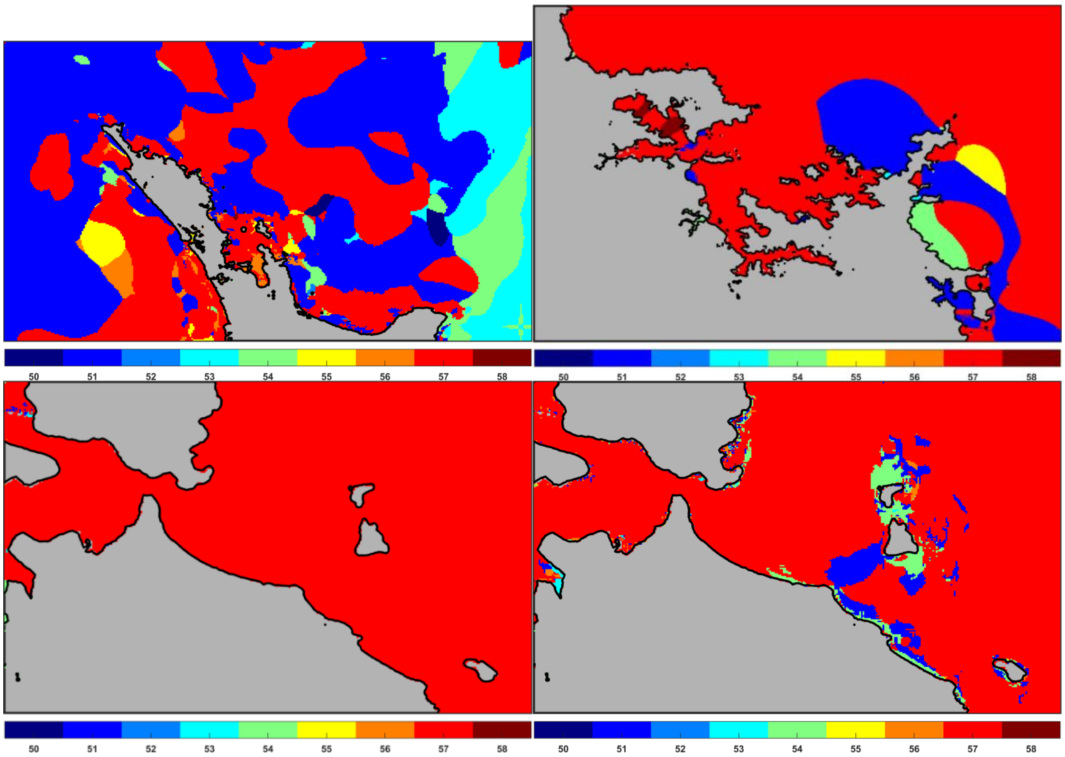
Set 3


23 24 25 26 27 28 29 30 31 32 33 34 35 36
23 24 25 26 27 28 29 30 31 32 33 34 35 36
23 24 25 26 27 28 29 30 31 32 33 34 35 36
23 24 25 26 27 28 29 30 31 32 33 34 35 36

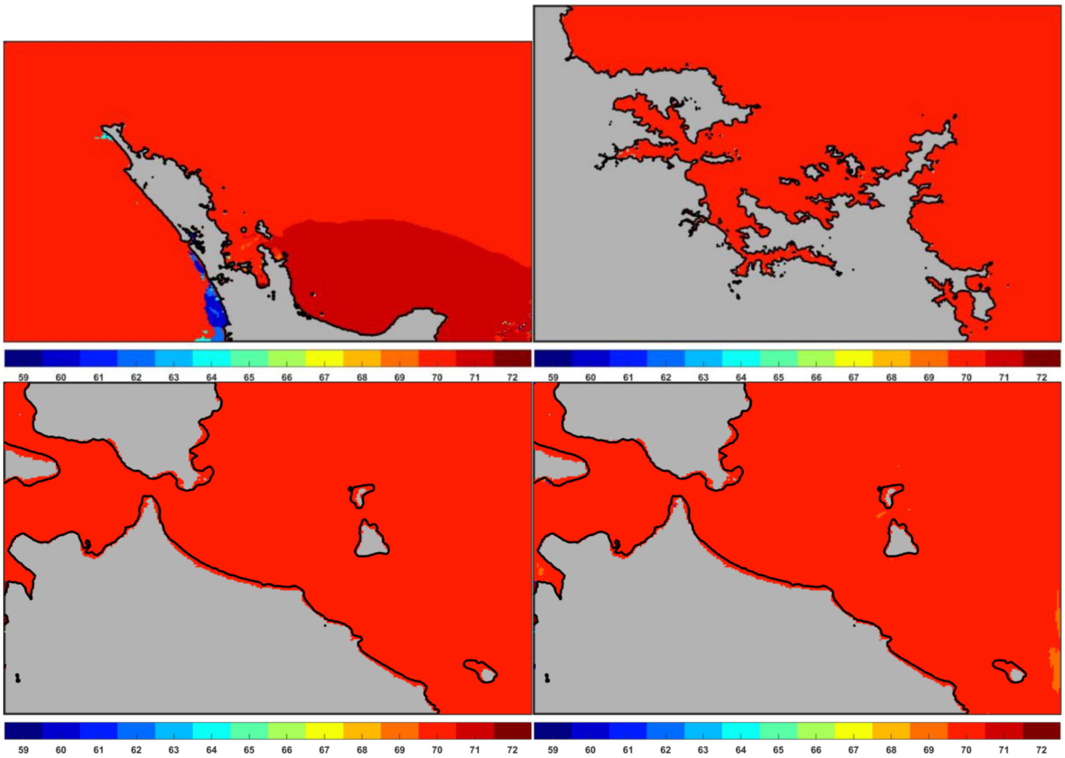
Set 4


37 38 39 40 41 42 43 44 45 46 47 48 49
37 38 39 40 41 42 43 44 45 46 47 48 49
37 38 39 40 41 42 43 44 45 46 47 48 49
37 38 39 40 41 42 43 44 45 46 47 48 49

Set 5

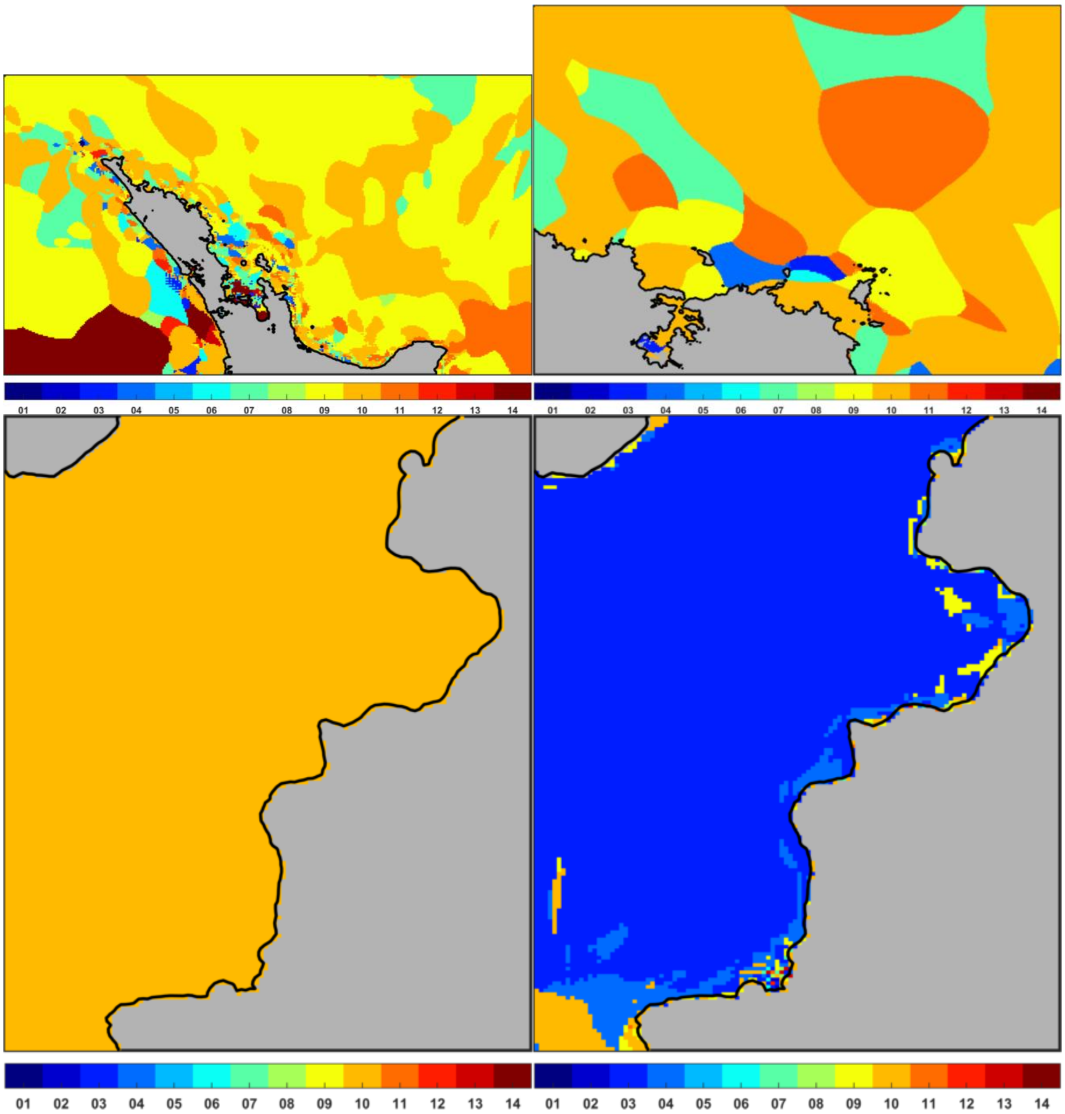

50 51 52 53 54 55 56 57 58
50 51 52 53 54 55 56 57 58
50 51 52 53 54 55 56 57 58
50 51 52 53 54 55 56 57 58

Set 6

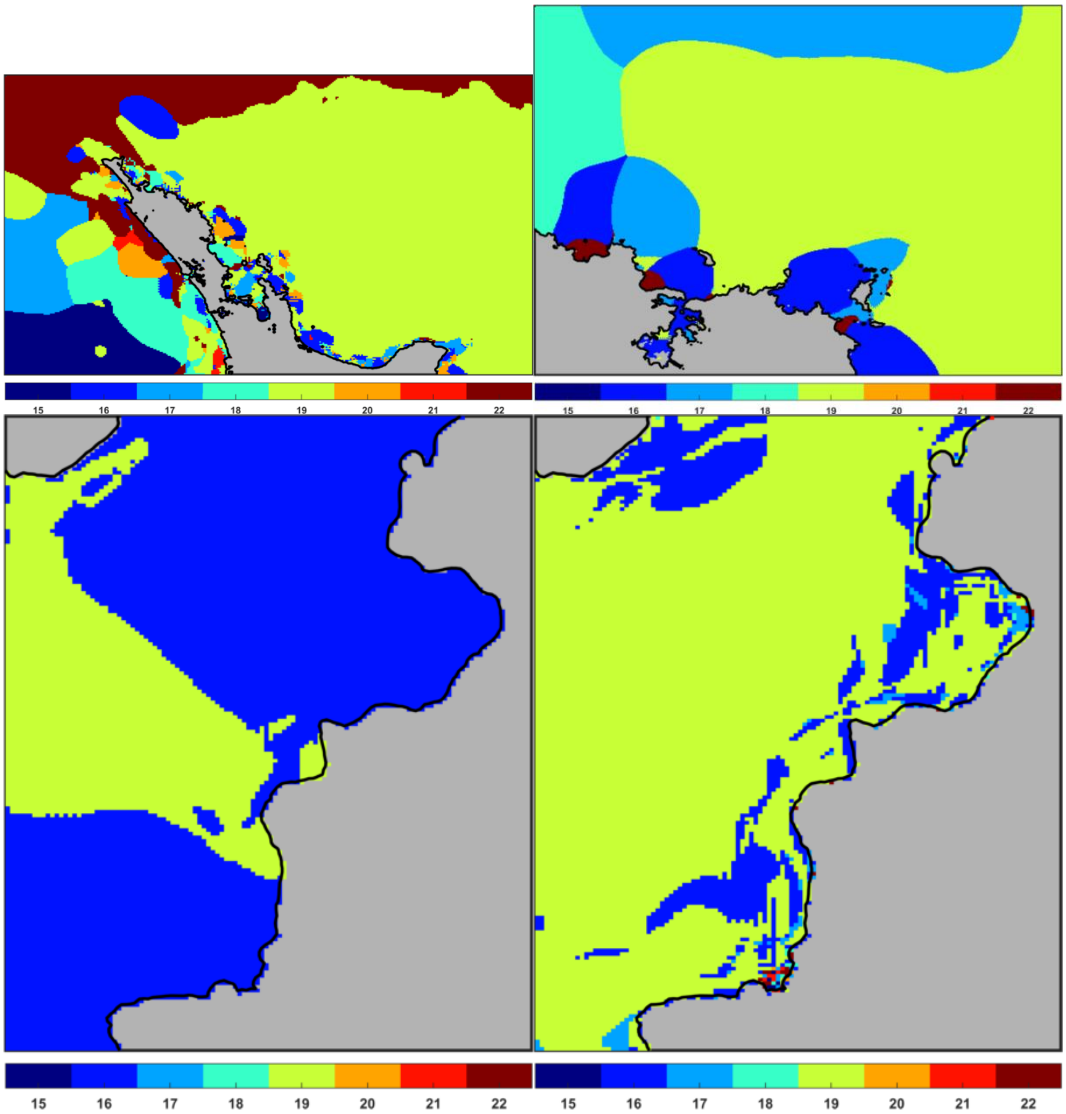

59 60 61 62 63 64 65 66 67 68 69 70 71 72
59 60 61 62 63 64 65 66 67 68 69 70 71 72
59 60 61 62 63 64 65 66 67 68 69 70 71 72
59 60 61 62 63 64 65 66 67 68 69 70 71 72

5.6 Whangaroa

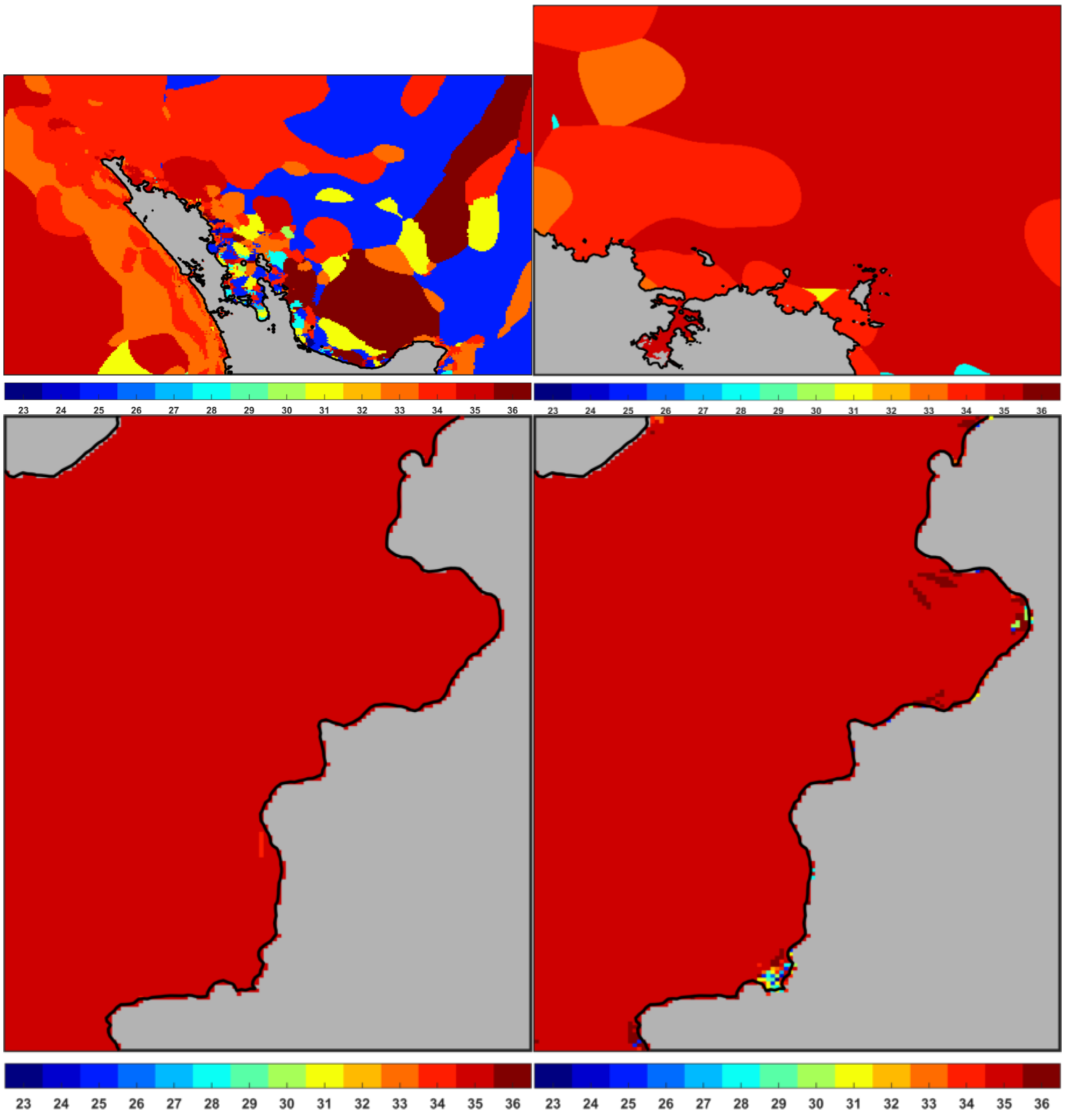
Set 1



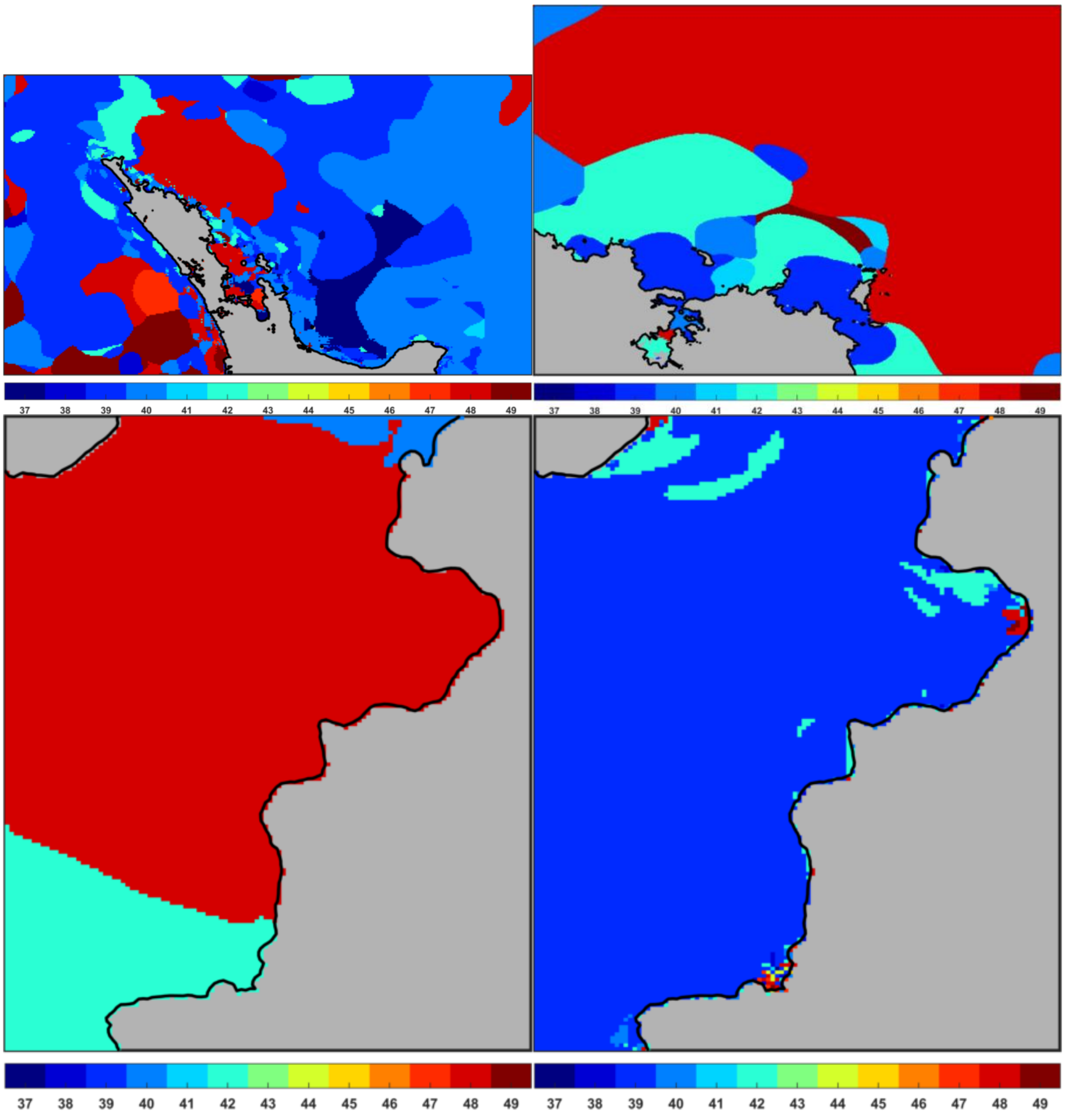
Set 2



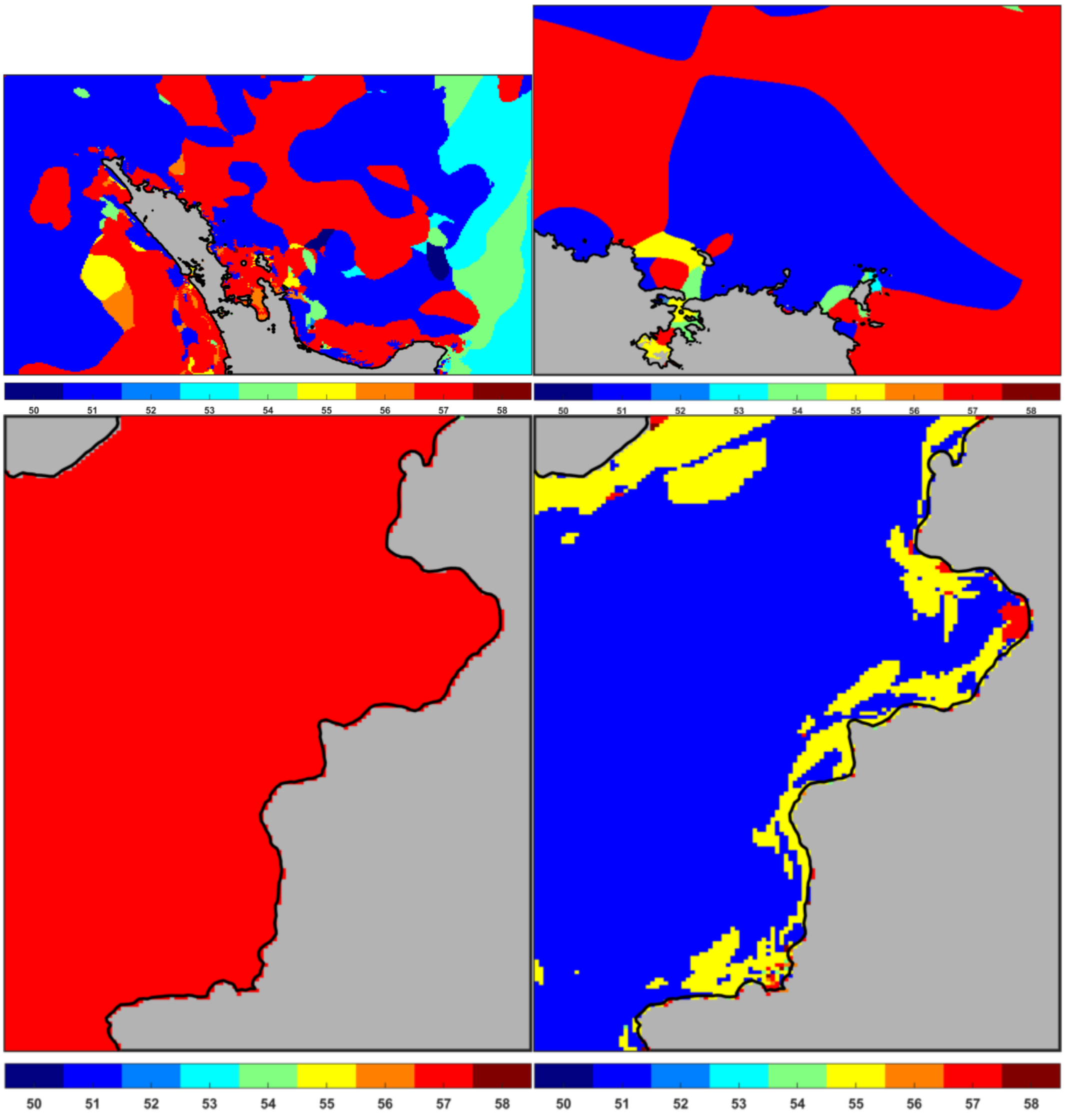
Set 3


23 24 25 26 27 28 29 30 31 32 33 34 35 36
23 24 25 26 27 28 29 30 31 32 33 34 35 36
23 24 25 26 27 28 29 30 31 32 33 34 35 36
23 24 25 26 27 28 29 30 31 32 33 34 35 36

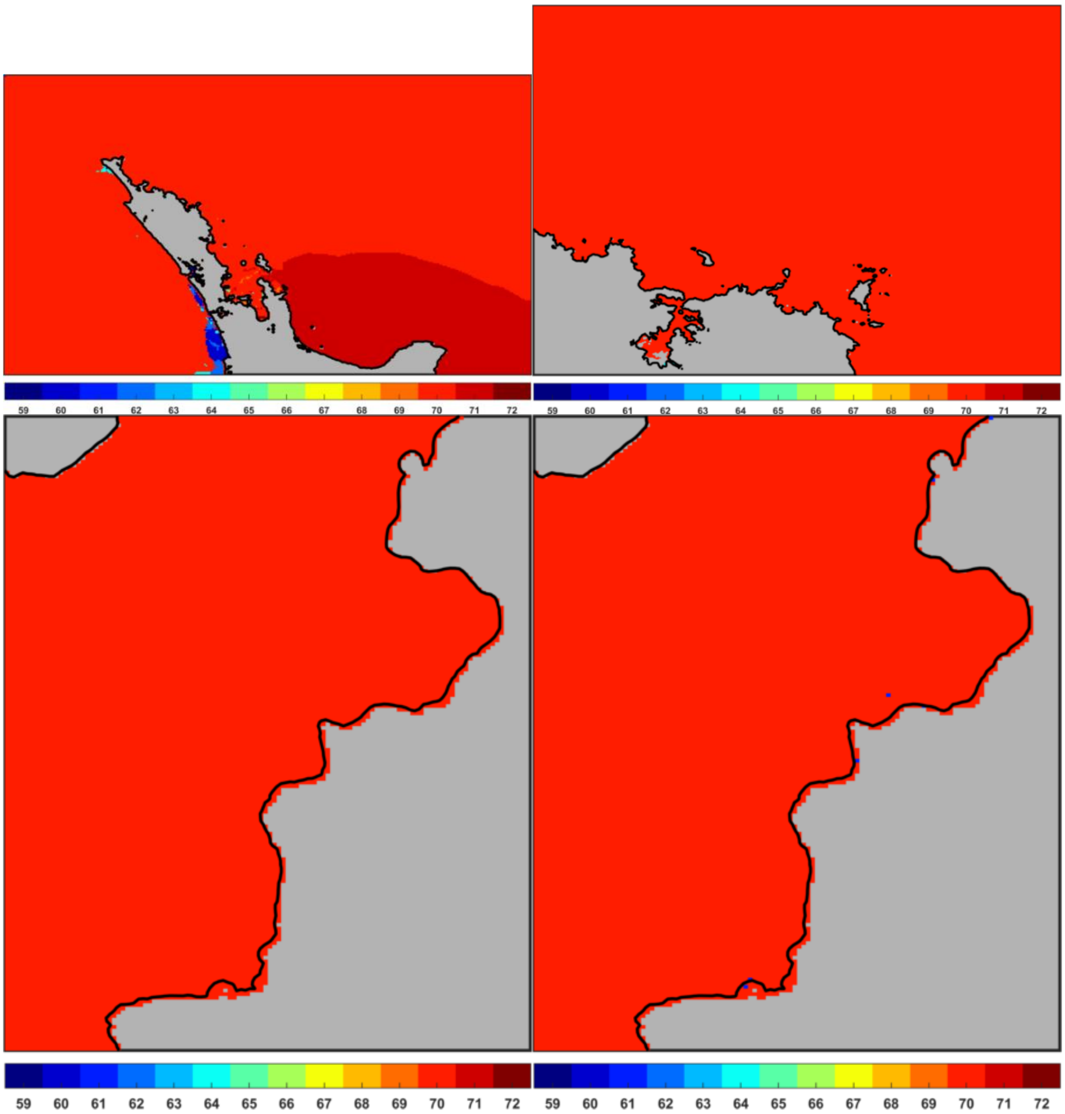
Set 4


37 38 39 40 41 42 43 44 45 46 47 48 49
37 38 39 40 41 42 43 44 45 46 47 48 49
37 38 39 40 41 42 43 44 45 46 47 48 49
37 38 39 40 41 42 43 44 45 46 47 48 49

Set 5

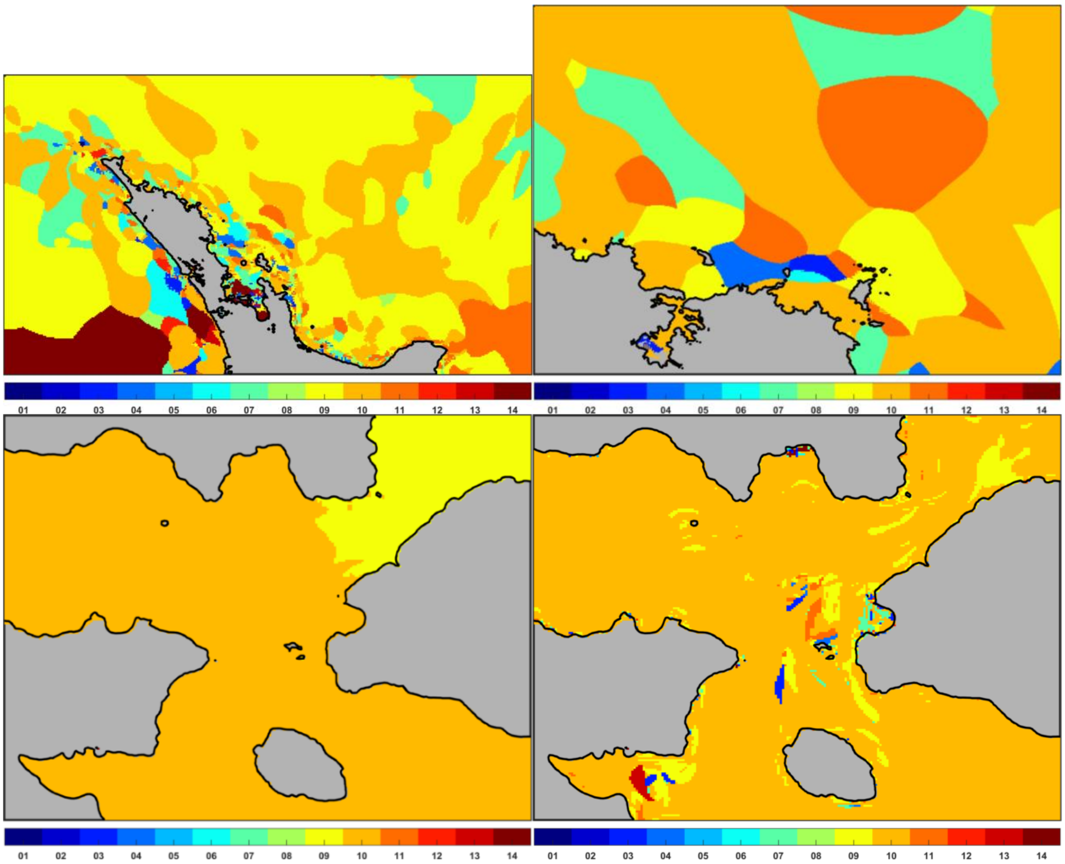


Set 6

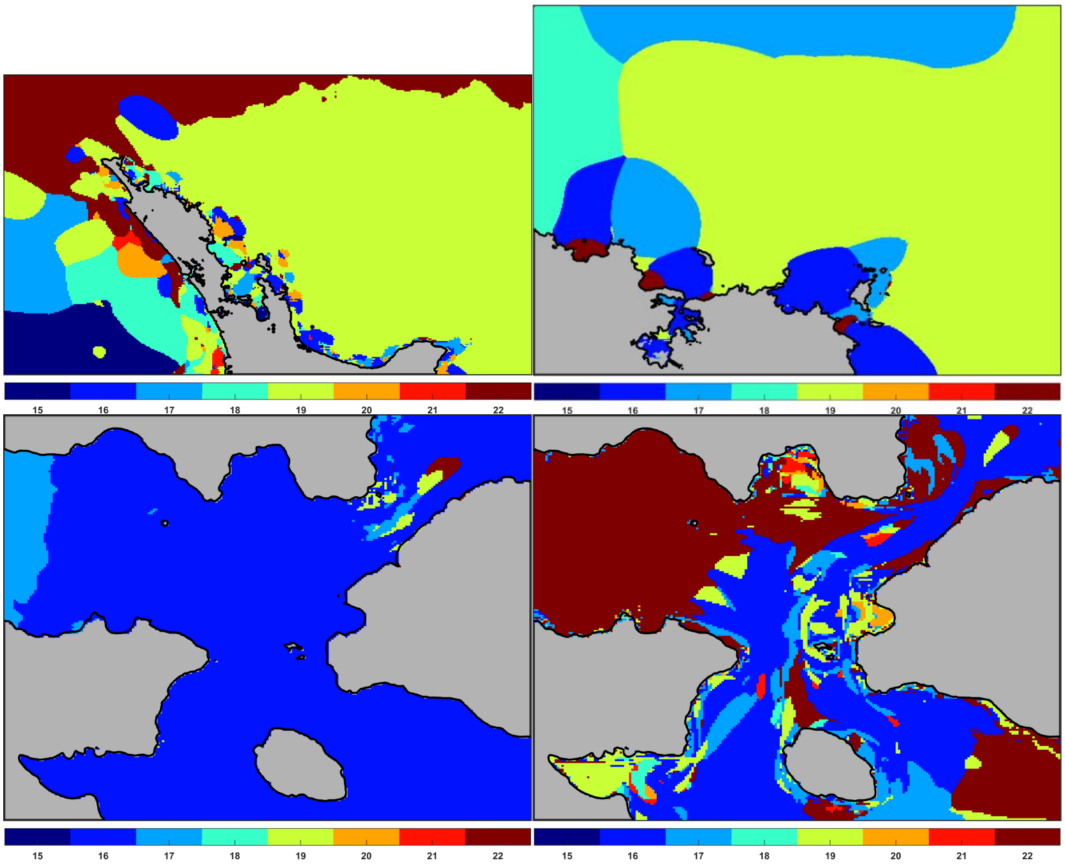

59 60 61 62 63 64 65 66 67 68 69 70 71 72
59 60 61 62 63 64 65 66 67 68 69 70 71 72
59 60 61 62 63 64 65 66 67 68 69 70 71 72
59 60 61 62 63 64 65 66 67 68 69 70 71 72

5.7 *Whangaroa Entrance*

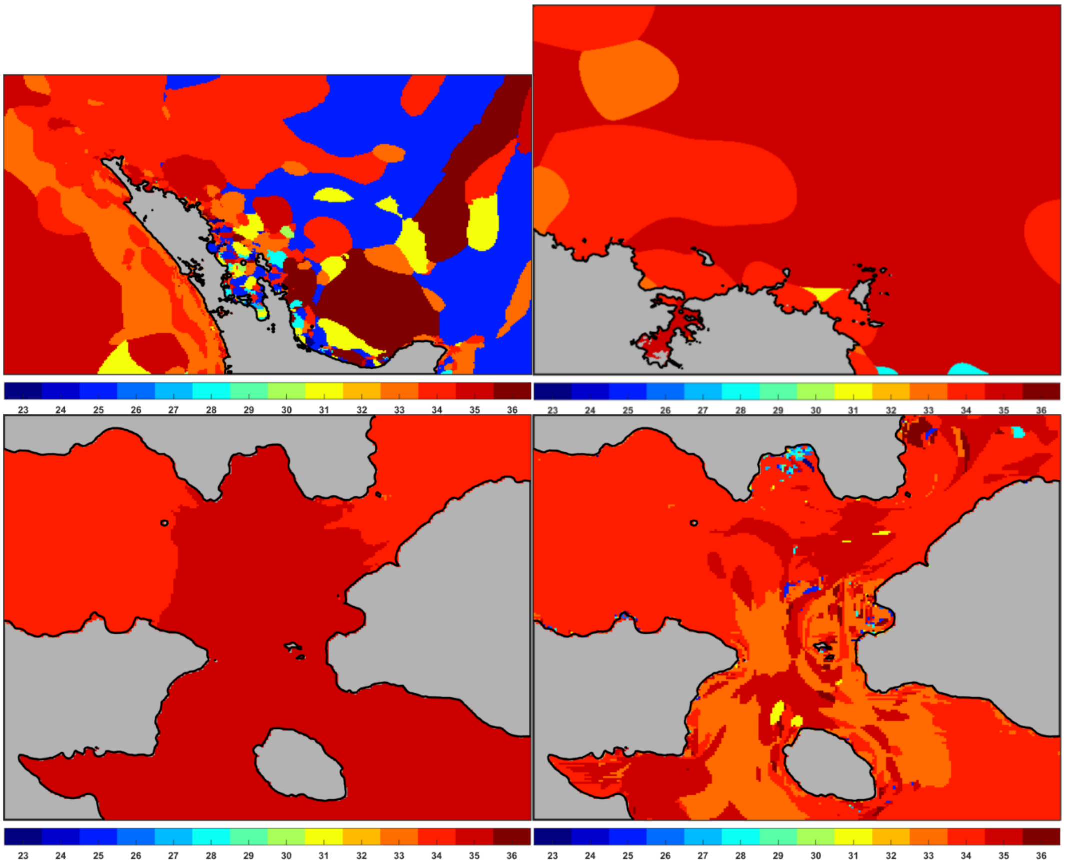
Set 1



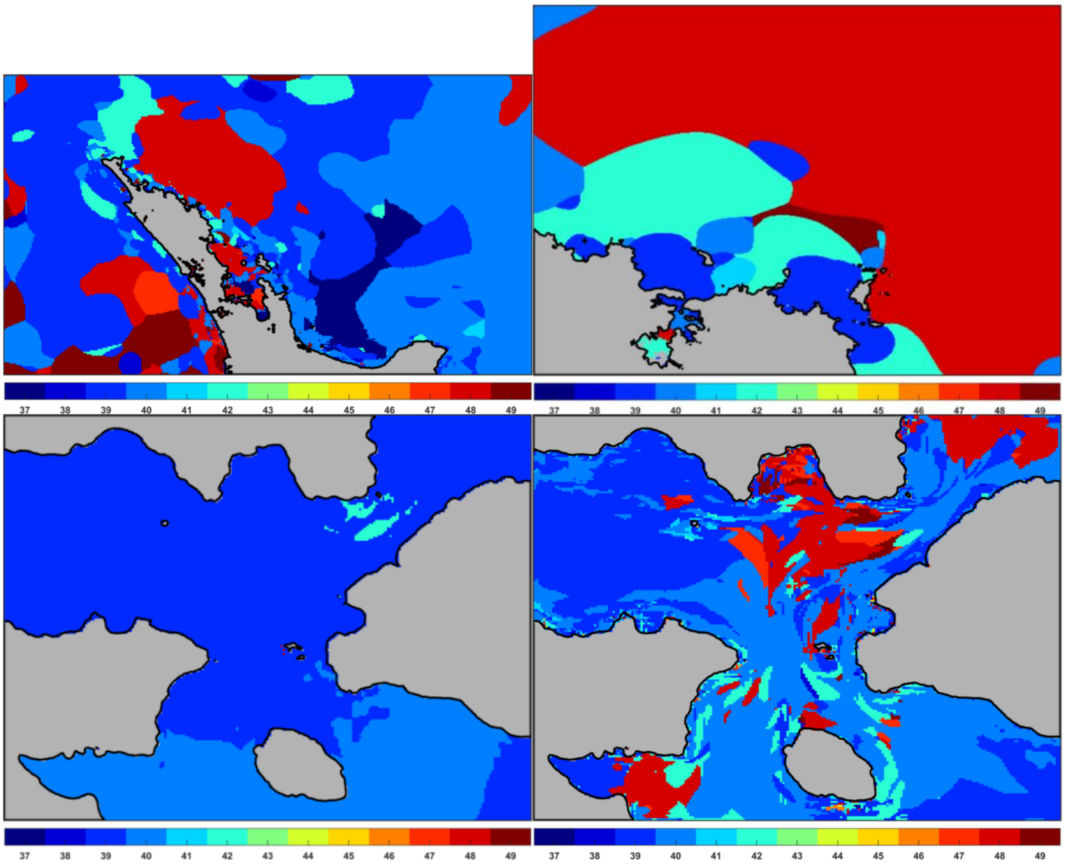
Set 2



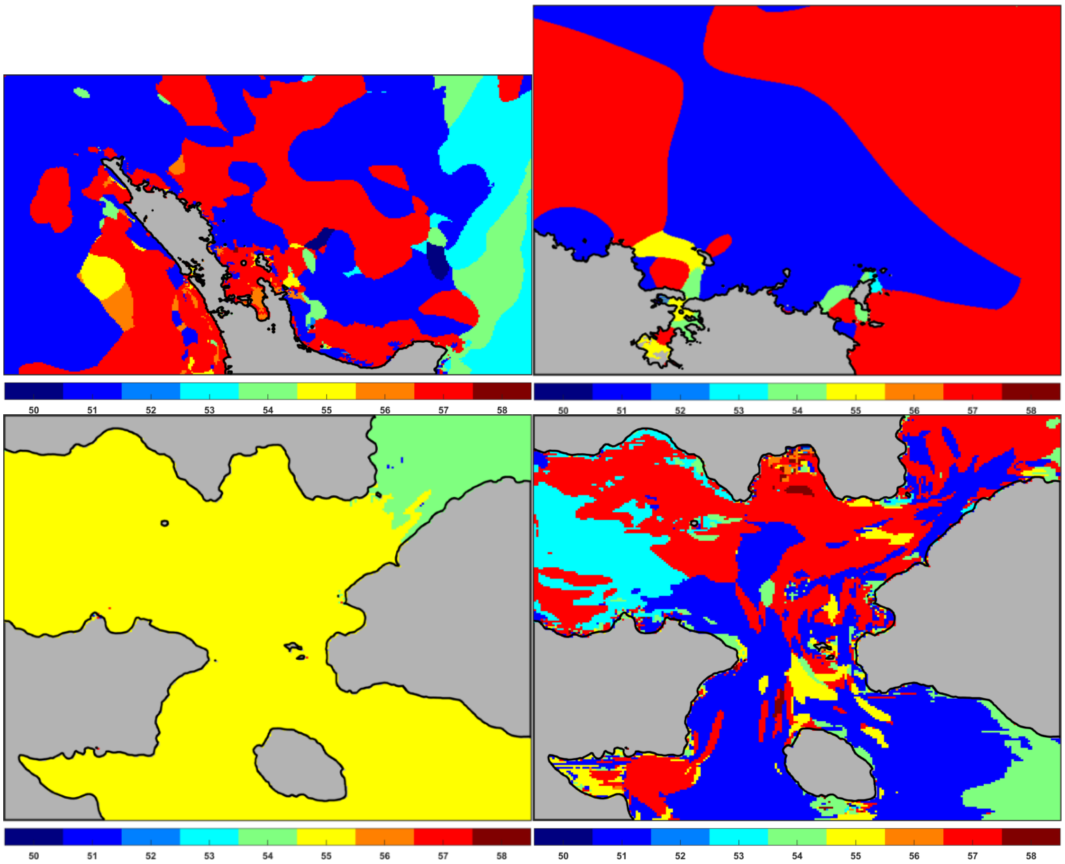
Set 3


23 24 25 26 27 28 29 30 31 32 33 34 35 36

Set 4


37 38 39 40 41 42 43 44 45 46 47 48 49

Set 5



Set 6