Three tsunamis (and earthquakes) ... in one day

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March 5 2021 was a busy day for New Zealand's emergency management and tsunami response community. It all began at approximately 2:30 am on Friday March 5 2021 (New Zealand Daylight Time-NZDT) when a magnitude 7.3 earthquake located some 175 km northeast of Gisborne shook people awake across the North Island. The relatively strong and long-lasting shaking felt by residents in Gisborne and along the East Cape alerted many to the possibility of an ensuing tsunami prompting numerous people to spontaneously evacuate coastal areas.

This was particularly the case for the coastal settlements north of Gisborne city where the Tolaga Bay, Tokomaru Bay, Te Araroa and Hick's Bay communities self-evacuated to higher ground. In Gisborne city, self-evacuation was more sporadic, but areas prone to shake amplification such as Sponge Bay did evacuate. Muriwai also evacuated to Muriwai school and in the absence of a local coordinator, a Council staff member who lived in the area informally took over local coordination. The Gisborne Emergency Co-ordination Centre (ECC) mobilised and was operational by 2:45 am and continued until 2:45 pm.

Video taken by Claudia Maaki of Tokomaru Bay showed a pronounced bore at Tokomaru from the 8.1 Kermadec event. The Te Araroa web cam was accessed by the ECC to assess tsunami and strong wave seiche was observed along the Te Araroa beach front.

Post event information gathering was initiated but found no evidence of tsunami at Tokomaru Bay above the normal high tide mark. At Hick's Bay deeper water seaweeds were found thrown up at the high tide mark.

The tsunami monitoring response for the first event began immediately after the earthquake thanks to the 24/7 operations at New Zealand's National Geohazards Monitoring Centre (NGMC). Additionally, several members of New Zealand's Tsunami Experts Panel (TEP) were awakened by the shaking and quickly began responding to the event. Determining whether or not a large tsunami was generated by this earthquake was of critical importance due to the fact that the region offshore of New Zealand's East Cape is known to produce earthquakes capable of generating tsunami much larger than the magnitude alone would suggest (discussed in more detail below). As such, the teams worked for several hours after the earthquake monitoring coastal tide gauges for any signs of a large tsunami.

With no indication that a large wave was generated, response activities were winding down when, at 6:40 am, a second earthquake struck on the Tonga-Kermadec Trench, the enigmatic subduction zone that runs from Wellington to Samoa. However, this earthquake was located 1100 km north of Gisborne and with a magnitude (M_W) of only 7.4 it was immediately clear that it did not pose a significant tsunami threat to New Zealand. Nevertheless, members of the NGMC and TEP convened another series of conference calls to discuss the event and provide information to New Zealand's National Emergency Management Agency (NEMA) who are in charge of providing official tsunami warning information to the public.

As discussions related to the second event continued, the third and largest earthquake occurred in nearly same location as the second. With a magnitude of 8.1, this earthquake presented more of a concern for New Zealand, as historical predecessors such as the 15 January 1976 earthquake which occurred in nearly the same location, caused strong currents and damage to boats and docks in Tutukaka Harbour, a well-known tsunami 'hot spot' on the New Zealand coast (Borrero and O'Neill, 2019).

With the first arrival of tsunami waves from the third earthquake not due in New Zealand for at least two hours, the focus of the assessments quickly shifted. Rapid assessment tools suggested that tsunami heights would exceed 30 cm, the threshold for a 'beach and marine' threat, for all of the North Island and the west coast of the South Island.

Later assessments increased the threat level to the lowest of the 'marine and land' threat levels along the Northland coast near Tutukaka, Great Barrier Island and the northern and eastern sections of East Cape. These advisory levels proved to be accurate as surges in that size range were observed in those areas, including dramatic video posted on social media of a tsunami bore propagating in to Tokomaru Bay (see Figure 1) and of the strong currents rushing in and out of Tutukaka Harbour. Monitoring of this event continued through the day and, by 3:30 pm, it was apparent that the peak of the tsunami activity had passed and the advisories were lifted. The overlapping tsunami signals from the three tsunamis were clearly recorded on tide gauges in New Zealand as shown in Figure 2.

Figure 1: A tsunami bore, generated by the third earthquake, entering Tokomaru Bay at 11:27 am. Image sourced from the internet.

Event	Time (NZDT)	Mag. (M_W)	Long. (deg W)	Lat. (deg S)	Depth (km)
1	0227	7.3	180.556	37.563	20.8
2	0641	7.4	177.834	29.665	53.1
3	0828	8.1	177.282	29.735	26.5

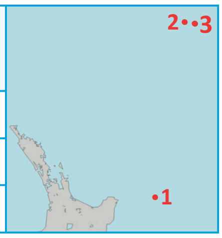

Table 1: Details of the three significant earthquakes near New Zealand on 5 March 2021 (Source: USGS).

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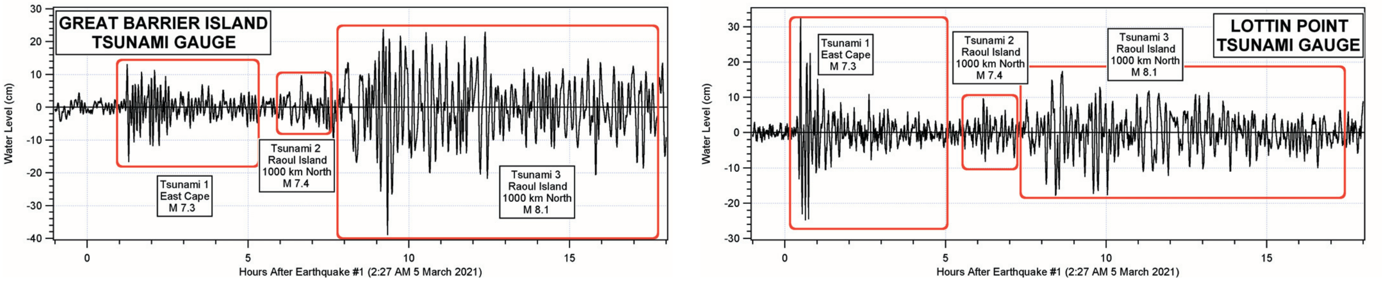

Figure 2: The three overlapping tsunami signals as seen on the Great Barrier Island and Lottin Point sea level gauges.

Discussion

With a magnitude of 7.3, the first earthquake was on the small end of the spectrum for producing highly destructive tsunami – even in the nearfield. However, as noted above, the East Cape region is known to produce tsunamis much larger than would be expected based on earthquake magnitude alone.

These so called 'tsunami earthquakes' (Kanamori, 1972) generate larger tsunami due to their relatively slow earthquake rupture, which is more efficient at transferring seismic energy into wave energy, as well as greater deformation of the sea bed related to the presence of mechanically weaker material.

Indeed, on March 25 1947 a magnitude ~7 earthquake offshore of Gisborne generated a tsunami with runup heights in excess of 10 m at sites along the open coast north of Poverty Bay. This event was followed a few months later (17 May) by a slightly smaller earthquake that also generated an anomalously large tsunami with runup heights of up to 6 m along the coast from Gisborne to Tolaga Bay (Eiby, 1982).

However, the M 7.3 event on March 5 2021 did not exhibit any characteristics of a tsunami earthquake. Instead, the focal mechanism suggests that it was an intraplate event which occurred on a steeply dipping fault in the over-riding Australasian tectonic plate on the western side of the subduction zone. The sense of motion of the earthquake was mostly strike-slip with a slightly oblique component that provided sufficient vertical motion to generate a small tsunami.

In contrast, the 6:41 am and 8:28 am events were classic interplate subduction zone earthquakes, meaning that they ruptured on the plate boundary itself and they had a pure thrust mechanism where the overriding plate moves upwards relative to the subducting plate. While these types of earthquakes are the classic tsunami generators, the ultimate size of the tsunami was muted by two factors: the relatively small magnitude of the event and the fact that the greatest amount of dislocation occurred some 100 km down the fault plane itself at a depth of ~30 km in to the earth, thereby reducing the amount of seafloor deformation and the amplitude of the subsequent tsunami.

The tsunamis generated by these earthquakes were recorded on New Zealand's newly installed DART buoy array (Fry et al., 2020; Borrero, 2020). Six DART sensors were operational during the events and recorded the tsunami. The data were used in real time by the Tsunami Experts Panel to assess the tsunami threat and have since been used to calibrate numerical models of the event (Gusman, 2021).

An example of this modelling is shown in Figures 3 and 4 where Borrero (2021) used

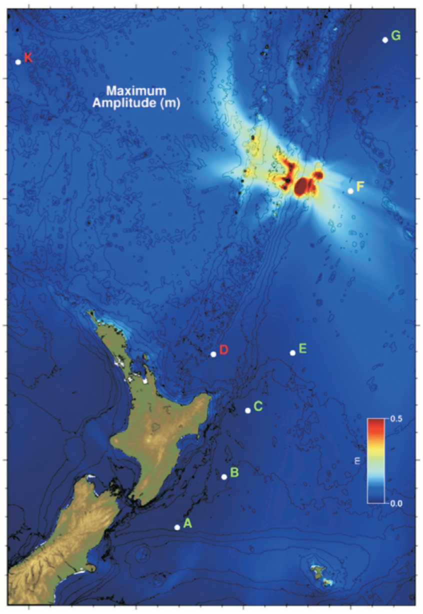

Figure 3: Maximum computed tsunami amplitude from the 8:28 am, M_W 8.1 earthquake and locations of New Zealand's DART sensors.

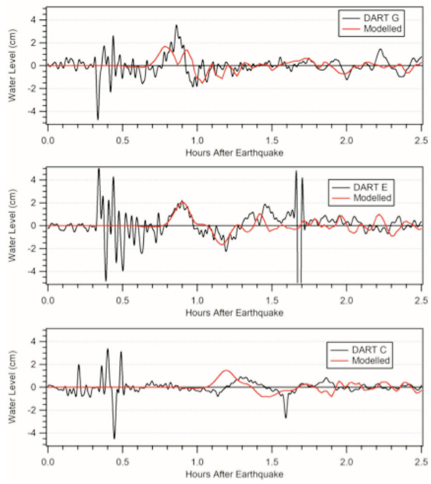

Figure 4: A comparison of modelled to measured tsunami water levels at DART stations C, E and G. Dart data provided by Aditya Gusman, GNS Science.

the USGS fault solution to initialise a hydrodynamic model. The model output shows a particularly good fit to the measured data at Site E, a good fit for timing and total wave energy at Site G and accurate amplitude with early arrival at Site C. Unfortunately DART F, located closest to the rupture zone, was offline during the event. However, the presence of multiple sensors gave the overall system the redundancy needed to be useful.

Conclusion

The early morning earthquakes of March 5th 2021 were – quite literally – a wakeup call for New Zealand's disaster management community. The long and strong shaking of the first event prompted people to self-evacuate and to act without an official warning, behaviour that is important to save lives. This was followed by two earthquakes a few hours later located approximately 1000 km north of New Zealand. These events each generated a tsunami, however neither was big enough to generate a damaging tsunami in New Zealand. Nevertheless the events tested New Zealand's emergency and disaster response capabilities and the experience gained and lessons learned will serve to improve these systems in future events.

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