Rapid earthquake rupture characterisation for New Zealand using the FinDer algorithm

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ABSTRACT

For large and damaging earthquakes, rupture location and extent are critical inputs for impact forecasts and response decision-making. This information has the potential to significantly improve estimates of ground shaking, as well as subsequent estimates of impact or loss, or secondary hazards such as landslides and tsunami. The R-CET programme (Rapid Characterisation of Earthquake and Tsunami) is implementing and testing a set of near real-time tools for use in event response, aiming to reduce the time taken to determine these critical input parameters from days or hours, to minutes or seconds.

One of these tools is FinDer, the Finite-fault Rupture Detector, which aims to characterise the location, extent, and orientation of rupture in the seconds to minutes following an earthquake, by matching spatial distributions of high-frequency seismic amplitudes with pre-computed templates. During real-time, and systematic and historic offline testing, we have found that FinDer performs reliably in the New Zealand setting for onshore crustal earthquakes, providing reasonable magnitude and location estimates for M6+ earthquakes, and also strike estimates for M7+ events.

FinDer was also created, and is used elsewhere, as an earthquake early warning (EEW) algorithm, and while neither the national GeoNet seismic network nor the New Zealand FinDer configuration are currently designed for EEW, we can begin to test its capability and performance. We present a summary of the testing and performance of FinDer for New Zealand, and the opportunities and challenges it offers for earthquake response.

1 INTRODUCTION

New Zealand's tectonic hazard includes the occurrence of onshore, complex, large magnitude ruptures, such as the 2016 Kaikōura earthquake (e.g. Kaiser et al., 2017a) and the 2010-2011 Canterbury sequence (Bannister & Gledhill, 2012). Such events have the potential for significant economic and societal impact (e.g. Potter et al., 2015) due to ground shaking, and secondary hazards such as landslides and tsunami. Rapid and reliable earthquake source information that can provide situational awareness, guide response decision-making, inform impact modelling, or even mitigate impact, is therefore highly valuable.

FinDer is designed to output the timeseries of rapid, simplified earthquake line-source or fault-plane models as the earthquake rupture evolves (Böse et al., 2012, 2015, 2018a, 2023). This fills the information gap before more detailed rupture modelling or mapping can be carried out, which is typically on the order of hours (e.g. for automatic kinematic rupture models) to days or weeks (e.g. for field studies or remote sensing) (Goldberg et al., 2023).

Distance to rupture is a controlling factor on ground shaking, making inclusion of even a simple extended rupture source a critical input to improve ground shaking estimates (Wald et al., 2021), and other downstream forecasts such as loss estimates or landslide forecasting (Horspool et al., 2023; Kaiser, 2023). Furthermore, FinDer's timeseries of solutions can also be used to indicate additional strong ground-shaking hazard due to rupture directivity (Andrews et al., 2023).

In this paper we report on offline and real-time testing of FinDer in New Zealand over the past 12 months, and demonstrate the performance for source characterisation and improvement of rapid shaking estimates. We also compute EEW performance metrics for a sub-set of historic earthquakes to begin to explore the potential of the GeoNet network and algorithms such as FinDer to deliver EEW in New Zealand.

2 FINDER FOR REAL-TIME CHARACTERISATION AND RESPONSE

FinDer has been running real-time in New Zealand since January 2023, ingesting high-rate broadband and strong motion seismic data from the GeoNet permanent monitoring network (500+ seismic sensors), and delivering results via email and web dashboards to GNS response scientists. The results are also formatted for input to the Shaking Layers platform (https://shakinglayers.geonet.org.nz/) allowing response scientists to use FinDer solutions in shaking estimates, and make them publicly available, when appropriate. Ongoing testing to review and optimise performance is guiding the integration of FinDer into automatic and manual response processes and products.

2.1 New Zealand Configuration

FinDer's performance can be optimised by using region-appropriate ground motion templates. For New Zealand we have currently created two template sets: one for onshore crustal earthquakes using the scaling relation of Leonard (2014) for intraplate strike-slip earthquakes, a mixed GMPE model set (equally weighted between the active crustal models of Abrahamson et al. (2014), Boore et al. (2014), Campbell and Bozorgnia (2014), Chiou and Youngs (2014), and Bradley (2013)) and a fixed V_{s30} of 400 m/s (approximate median of values in Kaiser et al., 2017b); and one for offshore interface earthquakes using the scaling relation of Strasser (2010) for interface dip-slip events, a mixed GMPE model set (a weighted combination of the subduction interface models of Atkinson and Boore (2003, 2008), Zhao et al. (2016), and Abrahamson et al. (2016)) and the same fixed V_{s30} of 400 m/s. This provides one set of symmetric ground motion templates and one set of asymmetric ground motion templates, but clearly does not capture the full range of seismic sources present in New Zealand's complex tectonic environment. In the interests of computational efficiency we choose to run with just these two template sets, and seek to observe the impact on FinDer's earthquake parameter estimates. Furthermore, the selection of 400 m/s for the V_{s30} is expected to contribute to FinDer's magnitude estimate errors for cases when this poorly reflects the site condition of most stations used to compute a FinDer solution. Quantifying these errors during ongoing testing will inform future revisions of FinDer's New Zealand configuration. For event detection, FinDer is configured to require four spatially-close stations to exceed 2 cm/s/s within 90 seconds.

2.2 Historic Data Testing

FinDer has the greatest potential for benefit when the effects of source extent are significant, beginning around magnitude 6.0. We therefore test FinDer using historic data replays for the three most recent M 7+ onshore events in New Zealand: 2016 M 7.8 Kaikōura (Kaiser et al., 2017a), 2010 M 7.2 Darfield (Gledhill et al., 2010), and 2009 M 7.8 Dusky Sound (Fry et al., 2010). These replays use GeoNet waveform data (Geonet, 2022) and mimic the real-time system with the exception of acquisition and data telemetry latencies. Final FinDer rupture solutions are shown in Figure 1.

For the two onshore crustal events, Kaikōura (Figure 1a) and Darfield (Figure 1b), FinDer's performance is excellent, with rapid first detection (7 and 3 s after origin respectively) and good agreement with catalogue values (GeoNet, 2023) for event epicenter (9.5 and 11.3 km error respectively), rupture length (+35 km and +15 km overestimated compared to published values respectively), rupture orientation (within ranges of published values) and magnitude (both 0.2 underestimated compared to GeoNet catalogue M_w(mB) and M_w values respectively). Furthermore, the timeseries of solutions captures the north-eastward propagation of the Kaikōura rupture and eastward propagation of the Darfield rupture, indicating the additional directivity hazards for the events.

The offshore interface Dusky Sound event (Figure 1c) poses a particular challenge for FinDer, with a rupture that nucleated on the edge of, and propagated away from, the onshore monitoring network. FinDer significantly underestimates the rupture length (by approximately 100 km) and therefore magnitude (by 1.2 magnitude units), and although the epicentral error is reasonable (3.1 km), the rupture centroid is incorrectly placed close to or within the instrument network. Similar behaviour has been observed during testing with synthetic offshore events (Böse et al., 2022) and real edge- or out-of-network events (Böse et al., 2023).

2.3 Impact Estimates

We assess the effect of incorporating FinDer's rupture solutions into shaking estimates using the same events tested in historic replay (Section 2.2) by comparing ShakeMaps (Worden et al., 2020) computed using point source and FinDer rupture solutions. We observe that FinDer has the potential to noticeably improve early shaking estimates for events with significant source extension and limited epicentral station coverage, and even where FinDer source characterisation is poor it does not significantly degrade shaking estimates, since by design the peak ground motions are still well matched by the FinDer solution (Andrews et al., 2023).

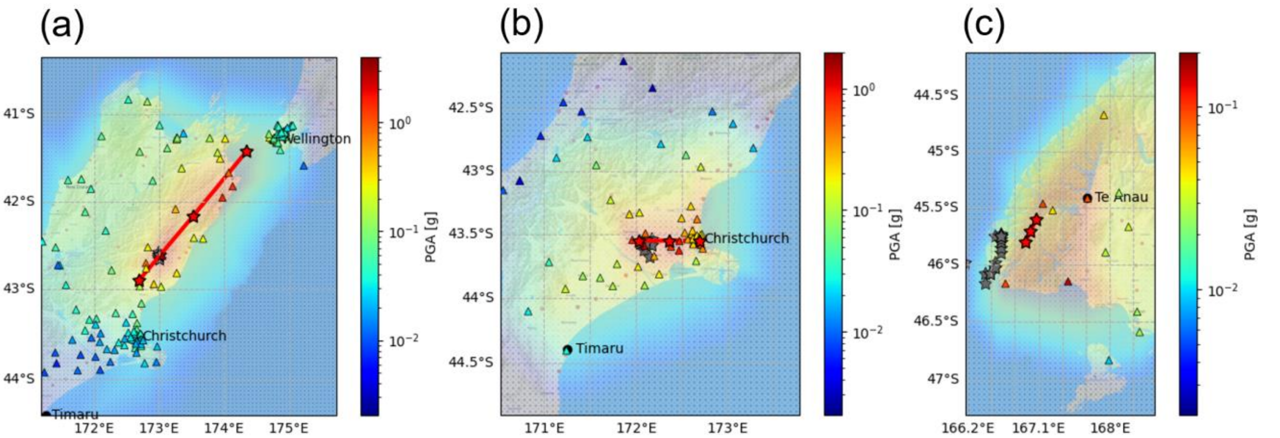

Figure 1: Final rupture source solutions for FinDer replays of the a) M7.8 2016 Kaikōura, b) M7.2 2010 Darfield and c) M7.8 2009 Dusky Sound events. The red stars indicate the endpoints and centroid of the final FinDer rupture model, shown by the red line. Grey stars mark the centroid solutions for earlier timesteps. Triangles indicate GeoNet stations coloured by PGA in %g according to the colour bar. The interpolated PGA data is shown as the transparent colour overlay.

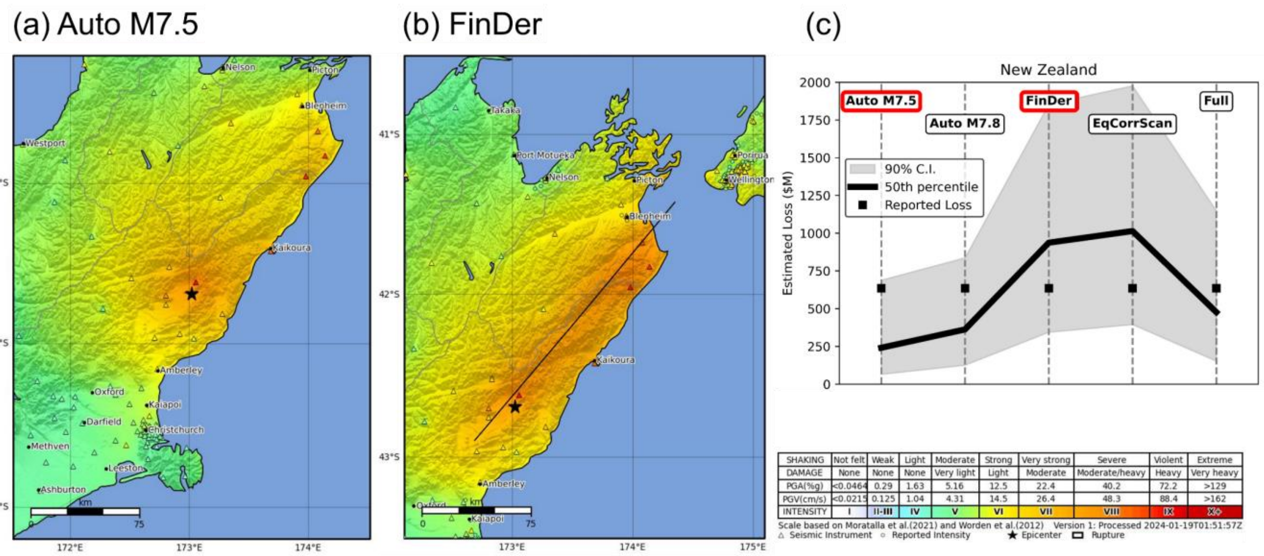

Figure 2: Shaking estimates (MMI, colour scale shown) calculated using ShakeMap for the M7.8 2016 Kaikōura earthquake using (a) the M7.5 GeoNet first real-time point source solution (computed approximately 90 seconds after the event) and (b) the FinDer rupture solution and M7.8 obtained during replay (approximately 2 minutes after the event). (c) Shows the estimated economic losses (in millions of dollars, $M) computed using RiskScape for different input shaking estimates, with the Auto M7.5 and FinDer solutions indicated in red, as well as the reported loss value.

Shaking estimates can be further used for loss estimation within the RiskScape software (Paulik et al., 2022), and an example for the 2016 M 7.8 Kaikōura event is shown in Figure 2. Inclusion of the extended FinDer rupture source noticeably increases the forecast losses, most significantly in the Wellington region and somewhat in the Marlborough region, due to the north-eastward propagation of the rupture. Ongoing testing will guide the appropriate use of FinDer solutions in downstream impact forecasts during response.

2.4 Real-time Data Testing

Real-time testing of FinDer allows us to explore its detection sensitivity, source parameter recovery, behaviour within different tectonic regimes (e.g. slab, geothermal/volcanic, crustal, interface), sensitivity to noise in the GeoNet network, and timeliness of results. FinDer's current event detection settings are more sensitive than is needed for the targeted purpose of rupture characterisation (i.e. M6+ events), but allow system operation and performance to be monitored through regular event detection.

In the period 25 January 2023 to 15 January 2024, FinDer has detected 48 events in the magnitude range 2.9 to 6.0 (GeoNet catalogue magnitudes) which are shown in Figure 3. Minimum detected magnitudes vary predominantly with the heterogeneous station distribution. Excluding offshore and subducting slab events, there were nine M 4.5+ events not detected by FinDer during the same period, and none above M 5.0. Most are not unexpected, as they are on the limit of likely detection based on the expected sensitivity of the instrument network (station spacing and FinDer event detection settings), but the lack of detection of a M 4.7 event near Kawerau during a swarm may be the result of strongly attenuated high frequency energy in the geothermal area, suggesting a similar reduction in sensitivity may occur in other active volcanic and geothermal regions in New Zealand.

For event location and magnitude errors, we compare GeoNet catalogue values with FinDer's last reported solution (this neglects some late updates that our notification system ignores), and location error is computed using the FinDer epicenter (which is set as the centroid of the early FinDer solutions).

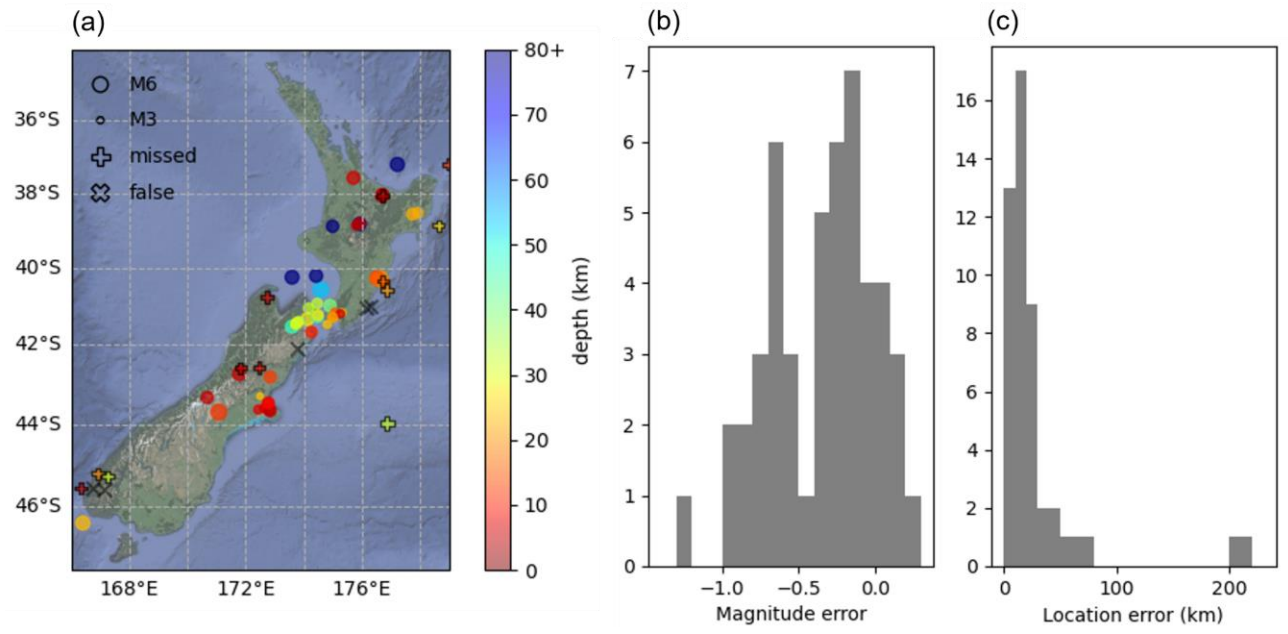

Figure 3: (a) Map of events detected by FinDer in real time between 25 January 2023 and 15 January 2024, sized by catalogue magnitude and coloured by catalogue depth according to the legends shown. Events FinDer did not detect with catalogue magnitude of 4.5 or greater (plus sign), and false detections with maximum FinDer magnitude of 4.5 or greater (cross) are also shown. (b) Histogram of the magnitude errors given as M_{FinDer}-M_{cat} such that FinDer underprediction gives a negative error. (c) Histogram of the epicentral location errors.

Location errors (Figure 3c) range between 1 and 220 km (mean 27 km; median 15 km), and include the 5 km resolution for the FinDer templates. Very large location errors (> 100 km) are only observed for a small number of deep slab events, due to the strong waveguide effect of the subducting slab, which causes FinDer to mislocate events closer toward the subduction trench.

Magnitude errors range from 1.3 underprediction to 0.3 overprediction (Figure 3b), with a bias toward underprediction (mean 0.3 and median 0.2 underprediction). The systematic underprediction, and a slight increase in underprediction as catalogue magnitude increases, may indicate that the parameters used in the creation of the New Zealand FinDer templates should be reviewed.

FinDer had six false detections with maximum magnitude of M 4.5 or greater during the period 25 January 2023 to 15 January 2024. These can generally be automatically identified as false (and therefore not notified to response scientists) using alert behaviour criteria, but are an indication of the noise levels in the GeoNet network. Notably, clusters of false detections occurred during high wind events.

3 FINDER POTENTIAL FOR EARTHQUAKE EARLY WARNING IN NEW ZEALAND

FinDer was originally developed as an earthquake early warning (EEW) algorithm, in response to the observed limitations of point-source-based methods during the 2011 M_w9 Tohoku-Oki earthquake in Japan (Hoshiba & Aoki, 2015; Kodera et al., 2021). It is currently running as part of public EEW systems on the US West Coast (Kohler et al., 2020; Böse et al., 2023) and in Central America (Porras et al., 2021), and is part of prototype systems or has been tested offline in a range of tectonic settings (e.g. Switzerland (Massin et al., 2021); central Italy (Böse et al., 2018b); Japan (Meier et al., 2020); China (Li et al., 2020)). Offline and real-time testing of the FinDer algorithm with New Zealand data allows us to explore the potential for delivering earthquake early warning using the existing GeoNet sensor network.

3.1 Real-time Data

For the real-time data set from the period 25 January 2023 to 15 January 2024, FinDer's real-time first detections are in the range from 7 to 100 s after origin (mean 19 s; median 13 s). Detection times greater than 25 seconds only occur for slab events, which have hypocentral depths reaching 200 km. For crustal events, first detection time is predominantly controlled by local station density, with values below 10 seconds (comparable to performance in other EEW systems, e.g. Böse et al., 2023) achieved in dense networks regions such as Christchurch and Wellington. First detection times within EEW systems are generally improved by optimising data network infrastructure (e.g. data packetization and telemetry), which if undertaken for the GeoNet network could reduce first alert times by several seconds.

3.2 Historic Data Testing

We also test FinDer for potential EEW performance using historic event replays with the same setup as for the M7 testing in Section 2.2. The timeseries of FinDer solutions is turned into a timeseries of alert polygons using the criteria that FinDer's magnitude is 4.5 or greater, and the region expected to experience median shaking of MMI 3.5 or greater (i.e. likely felt) is alerted. An alert radius around FinDer's rupture solution is computed for a fixed 400 cm/s V_{s30} using the same GMPE set used to create FinDer templates (Section 2.1) plus the GMICE of Moratalla et al. (2020). We then compute the EEW performance metrics following Meier (2017) for a target MMI of 5.0 (i.e. potentially damaging) for all stations in the replay data, such that warning times are computed relative to the onset of MMI 5.0 shaking, and we issue alerts for potential MMI 3.5 shaking with the aim of alerting all sites that experience MMI 5.0. To account for the data, telemetry, computation and alert latencies not present in our replays, we add a 10 second delay to the FinDer alert time.

Sites are assigned the following classifications: 'TP timely' sites have maximum observed MMI of 5.0 or greater and receive an alert before that shaking intensity is reached (i.e. true positive, timely); 'TP timely < MMI_tw' sites have maximum observed MMI between MMI 3.5 and 5.0 and receive an alert before the S-wave arrives; 'TP untimely' sites have maximum observed MMI of 3.5 or greater but receive an alert after that shaking intensity is reached; 'FP' sites receive an alert but have a maximum observed MMI below 3.5 (i.e. false positive); 'FN' sites do not receive an alert but have a maximum observed MMI above 3.5 (i.e. false negative); 'TN' sites do not receive an alert and have a maximum observed MMI below 3.5 (i.e. true negative). Note that this performance is computed for station locations, so cannot be interpreted in terms of vulnerable population or infrastructure.

Due to the larger affected area with potential damage, EEW performance should be better for larger (M7+) earthquakes than for moderate (M6 – M7) events. Results for a replay of the 2016 M7.8 Kaikōura event are shown in Figure 4, and indicate that even some areas with high observed MMI (7 – 9) could receive 10s of seconds of warning, and a very high proportion of sites with potentially damaging MMI (5-6) could receive long warning times of 1 to 2 minutes (Figure 4c). This very successful outcome results from a combination of the nature of the earthquake and FinDer performance, where rupture directivity increased shaking in a region with long warning times, and FinDer's accurate characterisation of the event leads to few false or missed alerts.

The same analysis for the 2010 M7.2 Darfield event is quite different (Figure 5), with almost all sites with high observed intensity (MMI 5+) receiving alerts after strong shaking has started (i.e. untimely). However, a significant group of sites with high predicted intensity have low observed intensity, and we need to carry out further analysis of the waveforms to understand the cause of the discrepancy since the FinDer solutions are good for this event. The majority of sites are correctly alerted for this scenario, the challenge is to alert before strong shaking arrives.

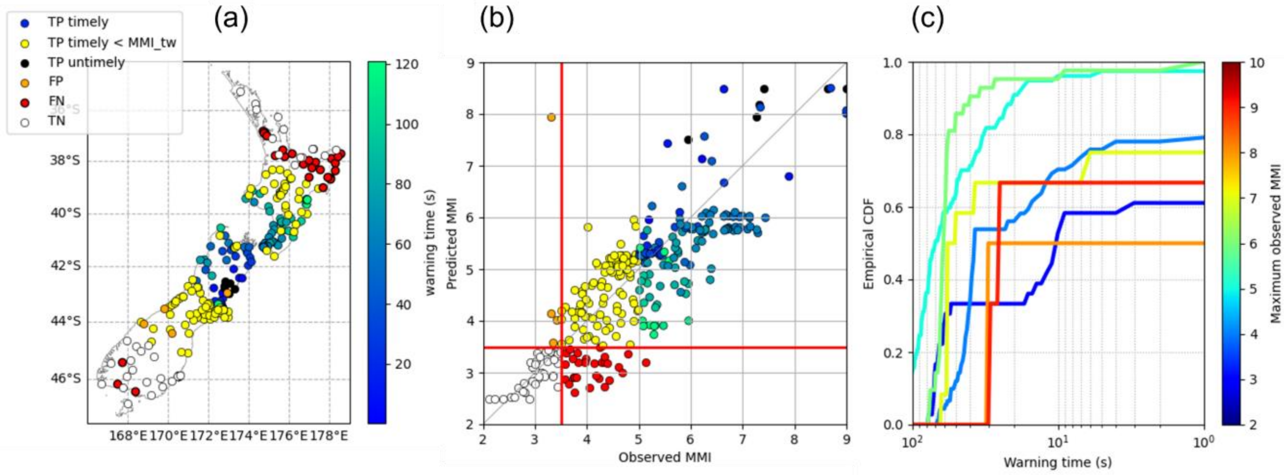

Figure 4: EEW performance metrics for a FinDer replay of the M7.8 2016 Kaikōura earthquake, using an alert magnitude threshold of 4.5, an alert MMI threshold of 3.5 and a target MMI of 5.0. An assumed alert delay of 10 seconds has been added. (a) Map of alerts, categorised according to the legend, with sites that have timely alerts coloured by the warning time colour scale. Site classifications are explained in the text. (b) Scatter plot of the observed and maximum predicted MMI, with sites coloured following the map in (a). (c) Cumulative density functions for warning times grouped by observed MMI (according to colour scale shown). Sites with no warning time are included in the calculation such that the intersection of each trend line with the right axis gives the percentage of sites with a timely warning.

We perform the same analysis for four M6 – M7 events: M6.2 2011 Christchurch, M6.2 2014 Eketahuna, M6.5 2013 Cook Strait and M6.6 2013 Lake Grassmere; which provide a greater challenge for timely EEW due to the smaller magnitude and impacted area. These lower magnitude events also provide a greater challenge for FinDer, where the rupture dimension is closer to, or smaller, than the station spacing. However, we observe that even lower accuracy FinDer solutions can result in reasonable EEW behaviour, where speed is important as well as accuracy. For these four tested events, timely EEW alerts could still be received by a good proportion (50% or higher) of sites with maximum observed intensity of MMI 5.0 with warning times between 1 and 20 seconds, and up to a few 10s of seconds for sites with maximum observed intensity between MMI 3.5 and 5.0.

National earthquake early warning systems involve the installation, implementation and maintenance of significant infrastructure (e.g. Given et al., 2018), and this is not considered in our analysis on potential EEW alert delivery. Further work would be needed to assess optimisation of the sensor network, data delivery and telemetry, as well as implementation of EEW algorithms and processing infrastructure, and alert delivery pathways. Furthermore, deciding whether EEW is feasible depends upon the required performance of such a system (i.e. alert accuracy and warning time), including any potential technical uses (e.g. automated protection of infrastructure) or public alert mechanisms (e.g. cell phone alerting).

4 CONCLUSIONS

The ongoing work within the R-CET program to implement a suite of real-time tools has the potential to change the timescales and type of information delivered during response to a damaging earthquake or tsunami. The real-time implementation of FinDer for New Zealand provides rapid rupture characterisation that can improve situational awareness and aid response decision-making in the critical minutes and hours following a large earthquake. When appropriate, GNS response scientists can use the solutions in downstream products such as rapid shaking estimates, loss calculations or earthquake induced landslide forecasts.

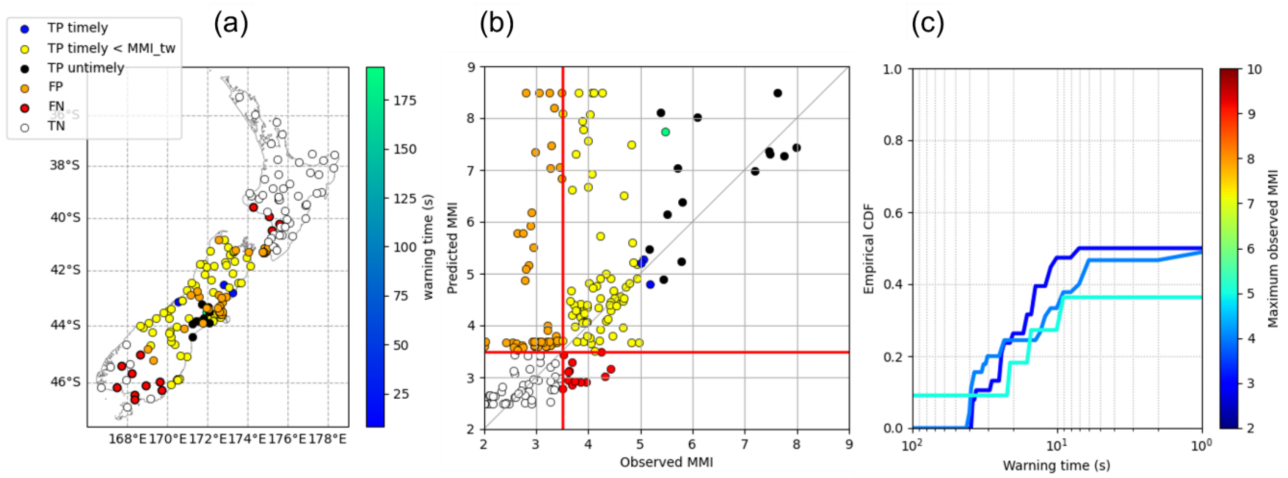

Figure 5: EEW performance metrics for a FinDer replay of the M7.2 2010 Darfield earthquake. Details follow Figure 4.

Testing shows reliable performance for onshore, crustal earthquakes, with FinDer delivering solutions that well characterise the rupture location, size and orientation within a few minutes of origin time. Ongoing work will further test and optimise FinDer for the New Zealand setting, with a particular focus on the performance for offshore and tsunamigenic events.

The implementation and testing of earthquake early warning methods, such as FinDer, allows us to explore the potential of such systems for New Zealand using the existing GeoNet sensor network. Initial results in this study suggest that successful alerting should be possible, however many of the components of such a system are not yet in place. Both the costs and benefits of implementation need to be understood, as well as the expectations of, and desire for, a national EEW system in New Zealand.

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