Real-Time Community Internet Intensity Maps and ShakeMaps for Australian Earthquakes

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Abstract

Geoscience Australia provides 24/7 monitoring of seismic activity within Australia and the surrounding region through the National Earthquake Alerts Centre (NEAC). Recent enhancements to the earthquakes@GA web portal now allow users to view felt reports, submitted online – together with reports from other nearby respondents – using the new interactive mapping feature. Using an updated questionnaire based on the US Geological Survey's Did You Feel It? System, Geoscience Australia now calculate Community Internet Intensities (CIIs) to support near-real-time situational awareness applications. Part of the duty seismologists' situational awareness and decision support toolkit will be the production of real-time "ShakeMaps." ShakeMap is a system that provides near-real-time maps of shaking intensity following significant earthquakes. The software ingests online intensity observations and spatially distributed instrumental ground-motions in near-real-time. These data are then interpolated with theoretical predictions to provide a grid of ground shaking for different intensity measure types. Combining these predictions with CIIs provides a powerful tool for rapidly evaluating the likely impact of an earthquake. This paper describes the application of the new felt reporting system and explores its utility for near-real-time ShakeMaps and the provision of situational awareness for significant Australian earthquakes.

Keywords: Did You Feel It?, Community Internet Intensity Maps, ShakeMap, situational awareness

INTRODUCTION

The rise of the internet has accelerated the impact and utility of "citizen science" in the government sector. In parallel, the demand for rapid earthquake information, delivered via the internet on a range of desktop and mobile platforms, has climbed sharply in the past two decades. End-users, including emergency response managers, the media and general public, expect the delivery of rapid, high-quality information and data products that provide situational awareness for an earthquake.

Since the commencement of 24/7 operations at Geoscience Australia, felt reports have been used to provide notification for events in regions where real-time (telemetered) seismic monitoring networks are sparse. Since 2017, the spatial distribution of felt reports has been displayed in real-time on the earthquakes@GA website. Geoscience Australia can now incorporate data from public felt reports, into real time earthquake information products that provide emergency managers with important contextual and situational information that is not available from earthquake parametric data, alone. To do this, Geoscience Australia has taken proven, open-source software developed by the U.S. Geological Survey (USGS), and has adapted it for Australian earthquakes. Geoscience Australia is using USGS's Did You Feel It? (DYFI?) software (Wald *et al.* 1999a; Wald *et al.* 2011) to generate Community Internet Intensity Maps (CIIMs) from felt reports submitted through the earthquakes@ga website. Individual geocoded responses can be aggregated to a Community Internet Intensity

(CII) for a predefined spatial extent. In responding to earthquakes, these CIIs provide critical, ground-truthed information on the extent and degree of shaking in regions at risk.

ShakeMap is another system developed by the USGS and adapted by Geoscience Australia for Australia's earthquakes and seismic monitoring conditions. ShakeMap combines observational data (instrumental and macroseismic) with theoretical models to generate real-time maps of ground motion and shaking intensity following significant earthquakes (Wald *et al.* 1999b). The primary purpose of ShakeMap is the provision near-real-time situational awareness in regions affected by earthquakes, with the system being implemented by many seismological observatories globally (e.g., Michelini *et al.* 2008; Cauzzi *et al.* 2015; Horspool *et al.* 2015; Pramono *et al.* 2017).

This contribution discusses the development and implementation of the DYFI? and ShakeMap systems within Geoscience Australia's National Earthquake Alerts Centre (NEAC) and provides some early outputs from these applications.

COMMUNITY INTERNET INTENSITY MAPS

The DYFI? System operating at Geoscience Australia is an automated application for rapidly collecting information on earthquake shaking intensity and potential damage from internet users to support near-real-time situational awareness. Through the responses of an online questionnaire, a Community Internet Intensity Map (CIIM) can be generated for earthquakes felt by the public.

To calculate a CII, numerical values are assigned to responses provided through the online questionnaire (e.g., Wald *et al.* 1999a). For each predefined spatial area, the geocoded values assigned to each question are subsequently averaged across the "community." Following the methodology of Dengler & Dewey (1998) and Wald *et al.* (1999a), a decimal CII value is calculated at the pre-defined aggregation level. The CII value has been calibrated to be approximately equivalent to traditional Modified Mercalli Intensity (MMI) levels. Geoscience Australia aggregates and averages the felt reports over regular geocoded grids at four spatial scales: 1, 5, 10 and 20 km. These data are useful for situational awareness in that they define where people and assets at risk are located. Figure 1 shows an example of a CIIM from the 8 November 2018 M_W 5.2 Lake Muir, Western Australia, earthquake (Clark *et al.* 2019).

The aggregated CII data provide constraints on the observed shaking intensity levels and are used by Geoscience Australia analysts and duty officers to identify those communities that felt earthquakes and to understand the degree of shaking. The CII data can be viewed at a regional scale (as shown in Figure 1), or at the scale of significant population centres if the data is of sufficient quality and quantity (Figure 2). The data collected at a specific location can be used to calibrate ShakeMaps, which combine modelled ground-motion predictions with community-supplied intensity data to calibrate the expected ground shaking from any given earthquake.

HOW ACCURATE ARE COMMUNITY INTERNET INTENSITIES?

Given the short duration the Geoscience Australia DYFI? System has been in operation, we are not able to quantitatively assess the accuracy of the reported intensities[1]. However,

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[1] A modified DYFI questionnaire was introduced by Geoscience Australia in 2016. A different online questionnaire was in effect prior to this. Pre-dating this are other tailored questionnaires such as that circulated by the Newcastle Police Department and University of Queensland, following the 1989 Mw 5.4 earthquake which impacted Newcastle.

qualitatively, the calculated CIIMs are generally as expected for any given earthquake occurring within Australia. The use of the DYFI? application has enabled Geoscience Australia to rapidly convert large numbers of felt reports into CIIs for the first time, and to deliver these data to emergency managers in a form, and time-frame, that is relevant for post-event analysis and decision-making (e.g., Williams *et al.* 2019).
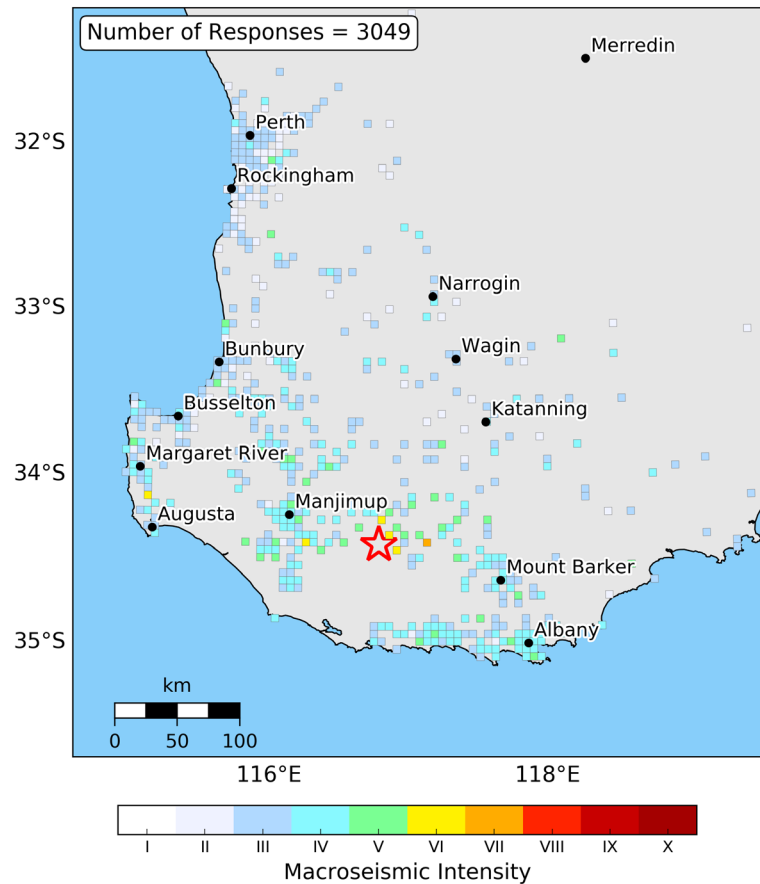

Figure 1: A Community Internet Intensity Map (CIIM) for the 8 November 2018 M_W 5.2 Lake Muir earthquake, with felt reports aggregated across 5-km grid cells. This example uses a minimum of one response per cell. The red star indicates the earthquake epicentre.
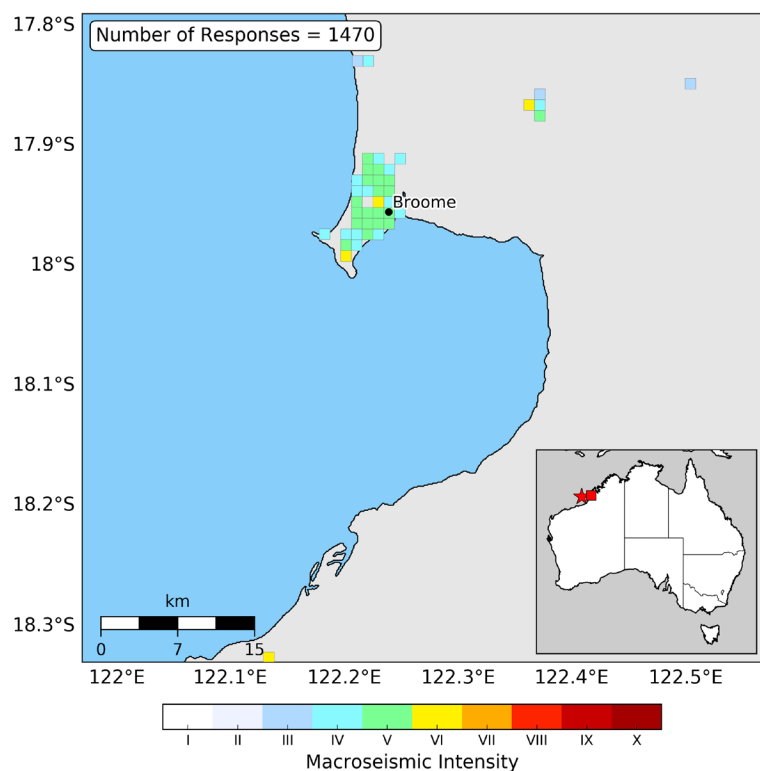

Figure 2: Example of CII data observed from the 14 July 2019 M_W 6.6 offshore Broome earthquake, aggregated across a 1×1 km grid for the Broome, WA, regional area. The red star indicates in the inset map shows the epicentre of the earthquake relative to the mapped extent (red square) – these symbols are almost co-located for this example. This example uses a minimum of one response per cell.

Experience in the US suggests that the large number of responses from most communities make the intensities surprisingly robust (Wald *et al.* 2006; Atkinson & Wald 2007). Early experience with the Geoscience Australia system generally concurs with this assessment. However, the automated collection of data from the public via the internet will invariably result in outliers, which may be either intentional or unintentional. There is a small risk that "lone actors" may provide nefarious information in the DYFI? questionnaire to game the system following a felt earthquake. Nonetheless, experience shows that overwhelmingly, the community will provide an honest assessment of their experience and value the opportunity to contribute through citizen science. Filters can be developed that will automatically remove malicious (or erroneous) responses and the Geoscience Australia system will be trained to do this over time. Furthermore, the aggregated intensity values within any grid cell represent the average across a "community." Therefore, any erroneous intensity observations from malicious responses will be moderated by contributions of other nearby responders.

One potential limitation of DYFI? data is that following a significant earthquake, communications systems and other lifelines may be disrupted. This could create a so-called "doughnut effect" in the felt responses (Bossu *et al.* 2017), where the regions of maximum damage potential near an earthquake's epicentre may not be able to communicate through standard methods. Nevertheless, this effect can be used by as a diagnostic tool for first responders to prioritise resources following a significant earthquake. Another factor causing the lower response levels is that people within the regions of highest shaking intensities will often have more important priorities than completing an online questionnaire (Wald *et al.* 2011). This demonstrates that felt reports alone are unlikely to be able to provide a complete assessment of potential earthquake impacts for strong-to-severe shaking levels (i.e., MMI $\geq$ VI). Therefore, the CII data from internet users further afield coupled with the ShakeMap system, discussed below, will have significant utility in being able to rapidly map ground shaking in zones of potential damage.

Finally, it is intended that newly collected CII data will be compared against historical intensity data points digitized from Australian isoseismal maps (e.g., Everingham *et al.* 1982) to evaluate the quality and continuity of these new data.

CII DATA COLLECTED TO DATE

Geoscience Australia have been collecting and analysing CII data through the updated web questionnaire since September 2018. Through the end of September 2019, this has resulted in more than 12,100 individual responses that can be associated to 199 earthquakes (including aftershocks from recent earthquake sequences) at the time of writing.

Figure 3 shows a map of the maximum observed intensities across Australia since September 2018. The maps are generated using a 35 × 35 km grid. These "super-cells" are subdivided into 49 5 × 5 km-sized grid cells, and the maximum observed intensity within the super-cell is plotted (see Figure 4). Consequently, this represents an exaggerated view of shaking intensities on a national scale. However, this map is useful in that it demonstrates the spatial extent of data that can be collected for any Australian earthquake through crowdsourcing. In particular, Figure 3 shows the density of reported CIIs following the 2018 Lake Muir earthquake sequence (Clark *et al.* 2019), as well as other moderate shaking-intensity events such as the 24 June 2019 Banda Sea and 14 July 2019 offshore Broome earthquakes. Figure 5 is plotted at a similar resolution, but shows the number of earthquakes felt in any super-cell. This figure is dominated by felt reports relating to the Lake Muir earthquake sequence in southwest Western Australia in addition to a number of felt events in the Broome, WA, region. However, other patterns begin to emerge, such as the number of felt events in Darwin, NT (from plate margin earthquakes in the Banda Sea), Kalgoorlie, WA and in the eastern

highlands region, near Canberra. Over time, it is expected that the CII dataset will expand, as will the extent over which earthquakes are felt within Australia. Furthermore, there is potential to reprocess raw data to derive CIIs from online felt reports that pre-date September 2018. However, it should be noted that the extent over which earthquakes are felt within the continent will be limited to populated regions and the lack of responses in remote regions should not be interpreted as low rates of seismicity elsewhere.
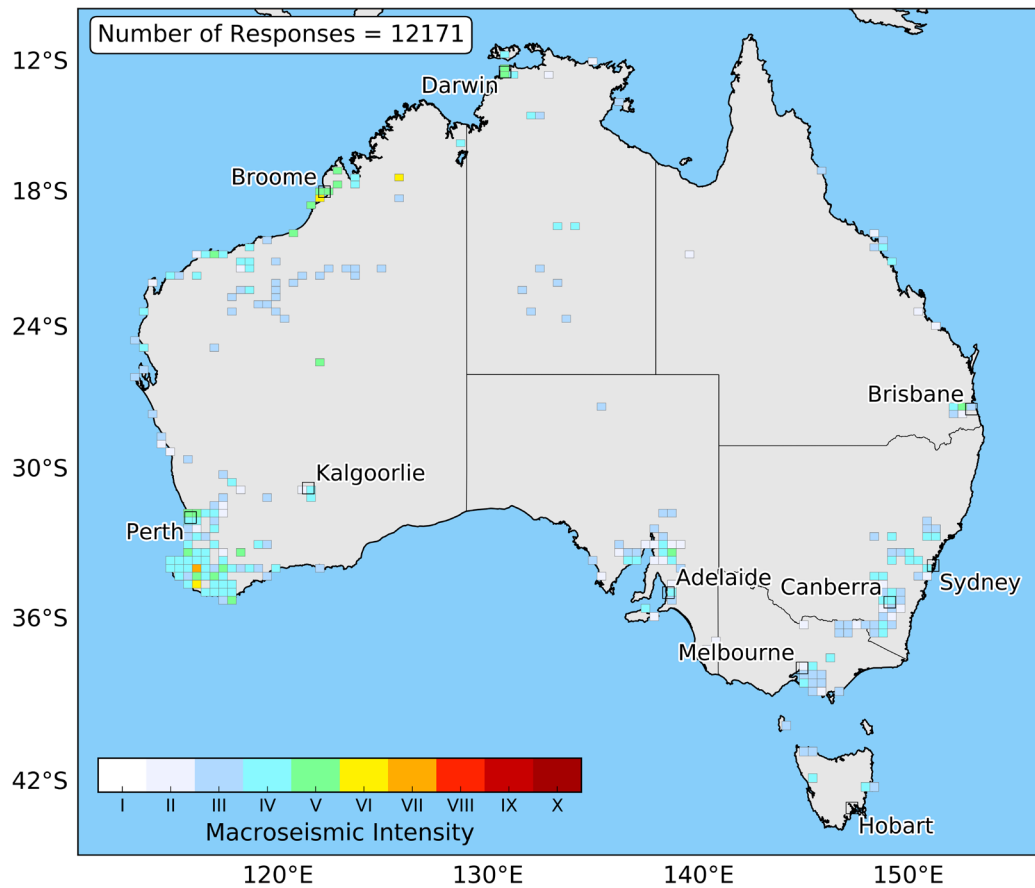

Figure 3: "Exaggerated" map of maximum macroseismic intensities observed for all earthquakes from the DYFI? System at Geoscience Australia since September 2018. The maximum shaking intensity from a 49-cell region of 5 × 5 km-sized grid cells is assigned to a 35 × 35 km super-cell for mapping (see Figure 4).
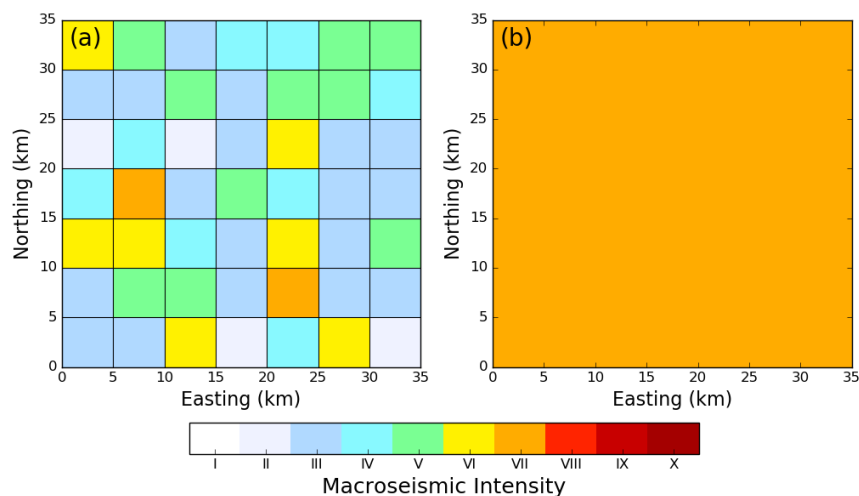

Figure 4: Schematic diagram illustrating how (a) the maximum shaking intensity from a 49-cell region of 5 × 5 km-sized grid cells is assigned to (b) a 35 × 35 km "super-cell" for mapping the maximum shaking intensities observed across Australia since the launch of the DYFI? System at Geoscience Australia.
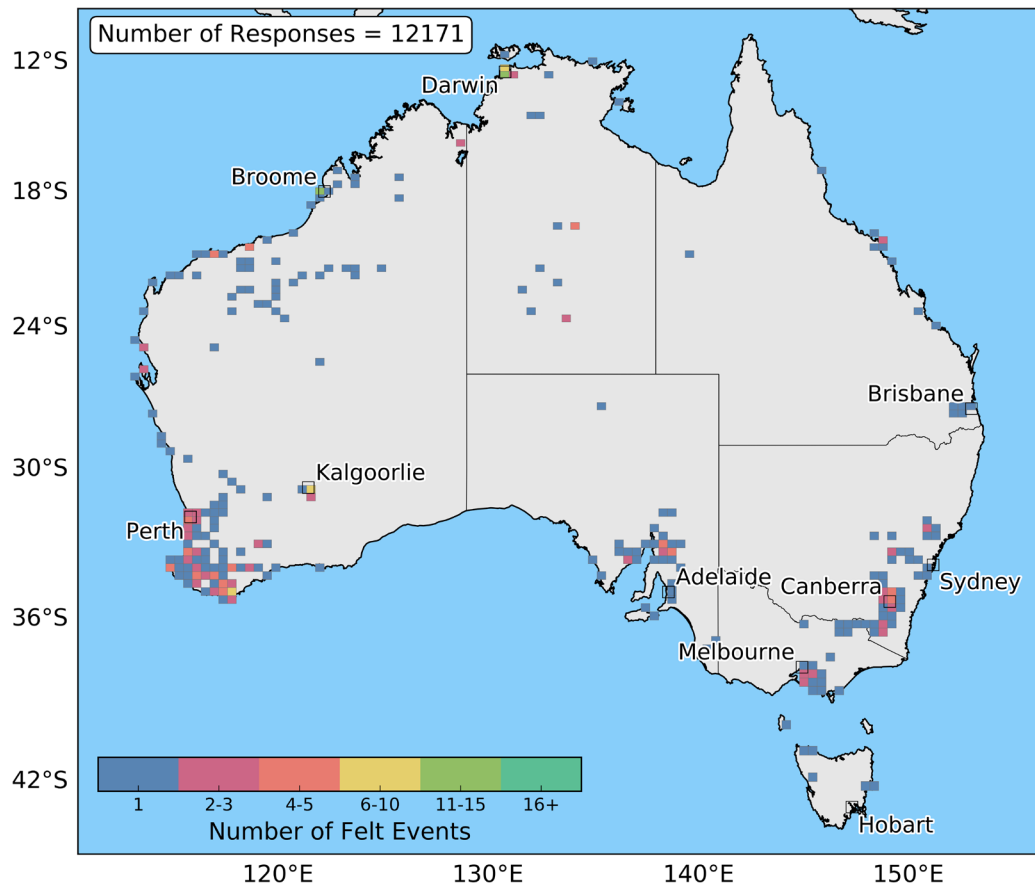
Figure 5: Map showing the number of unique earthquakes felt in any 35 × 35-km super-cell region since September 2018.

REAL-TIME SHAKEMAPS

ShakeMap provides near-real-time maps of shaking intensity following significant earthquakes (Wald *et al.* 1999b). The software ingests near-real-time peak ground motions from spatially distributed instruments and interpolates these data with theoretical predictions to provide a grid of ground shaking of different intensity measures (e.g., peak ground acceleration [PGA] and velocity [PGV], spectral acceleration at a range of spectral periods and macroseismic intensities)(Worden *et al.* 2018). The system can also ingest CII data to provide additional calibration to the ground-motion intensity field. Combining the predicted ground-motion fields with CIIs provides a powerful tool for rapidly evaluating the likely impact of an earthquake and allows for more timely decision-making for emergency management and response.

In Geoscience Australia's implementation of ShakeMap, the maps are calculated for all Australian earthquakes with magnitudes of M_{La} 3.5 and above. Once the magnitude and location of an earthquake are determined by the NEAC and the magnitude threshold is met, the analysis system will undertake the following processes (see Figure 6):

1. If the preferred magnitude is not a moment magnitude, M_W, convert M_{La} to M_W using conversions published in Allen *et al.* (2018);
2. Extract seismic waveform data for the event and calculate the instrumental peak ground-motion levels;

3. Associate available CII data to the earthquake and assign geolocated intensities with three or more responses per cell[2];
4. Calculate an initial grid of shaking intensities using a suite of ground-motion attenuation models (GMMs) for instrumental data, calibrated to Australian geological conditions (e.g., Somerville *et al.* 2009; Allen 2012);
5. Modify initial shaking predictions by site amplification factors (e.g., Seyhan & Stewart 2014) depending on the local geology according to the Australian Seismic Site Conditions Map (McPherson 2017);
6. Convert instrumental ground-motion intensity measures to macroseismic intensities (e.g., Worden *et al.* 2012);
7. Adjust predicted shaking intensities and interpolate over observed instrumental and CII data.

Fundamental to the data-calibrated ShakeMaps is the "bias correction," which provides an inter-event adjustment to the median GMM predictions, or corrects for an incorrect magnitude assignment relative to the observed data (Wald *et al.* 2011). The bias is applied by adjusting the median ground-motion estimates so as to reduce the misfit between the observed data and the estimated ground motions determined from GMMs (Worden *et al.* 2017). The minimisation of the model misfit is weighted by the number of observations used to calibrate the shaking, such that only when the number of observations is very large does the bias term effectively minimise the misfit between the observations and the model (Bruce Worden, pers. comm., 2019). Data used to calculate this bias correction is limited by a user-defined maximum distance from the earthquake's epicentre. Presently, the Geoscience Australia system only considers data within 150 km of the epicentre to generate the bias term and specifies a maximum range of ±1.5 standard deviation units relative to the median GMM uncertainty model (Step 7 above). Individual data points are screened from the ground-motion interpolation and inter-event bias calculation if they are beyond ±3 standard deviations relative to the GMM uncertainty model.

Within the Geoscience Australia operations system, ShakeMaps are generated and updated at fixed time intervals following the earthquake: 20 min, 1 hour, 2 hours, 4 hours, 24 hours and 48 hours. The ShakeMaps require updating because the CIIs, used to calibrate the shaking levels, will gradually be submitted by the public over a period of several hours to days following an earthquake. Therefore, estimates of ground shaking from crowdsourced data will continue to improve as more CII data are submitted. Furthermore, ongoing improvements in magnitude and location estimates will also affect the estimated distribution of ground shaking. Figure 7 shows an example of a ShakeMap for the 14 July 2019 M_W 6.6 offshore Broome earthquake, which is calibrated by both instrumental data from the Australian National Seismic Network (ANSN) and crowdsourced CIIs.

Key to ShakeMap's success is its ability to provide ground-truthed constraints on shaking. Additionally, ShakeMap applies scientific best practices for providing event-specific estimates of shaking in areas where observations are sparse or non-existent. Detailed background on all aspects of ShakeMap can be found online in the ShakeMap Manual (Worden *et al.* 2017). At present, Geoscience Australia only generate ShakeMaps for earthquakes within Australia, or for earthquakes that are likely to be widely felt within the continent (i.e., the Banda Sea region).

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[2] The cell resolution (1, 5, 10, or 20 km) used in ShakeMaps is that which has the greatest number of cells that meet the minimum number of responses per cell (three). To date, this is most commonly the 1 × 1 km grid for significant earthquakes.
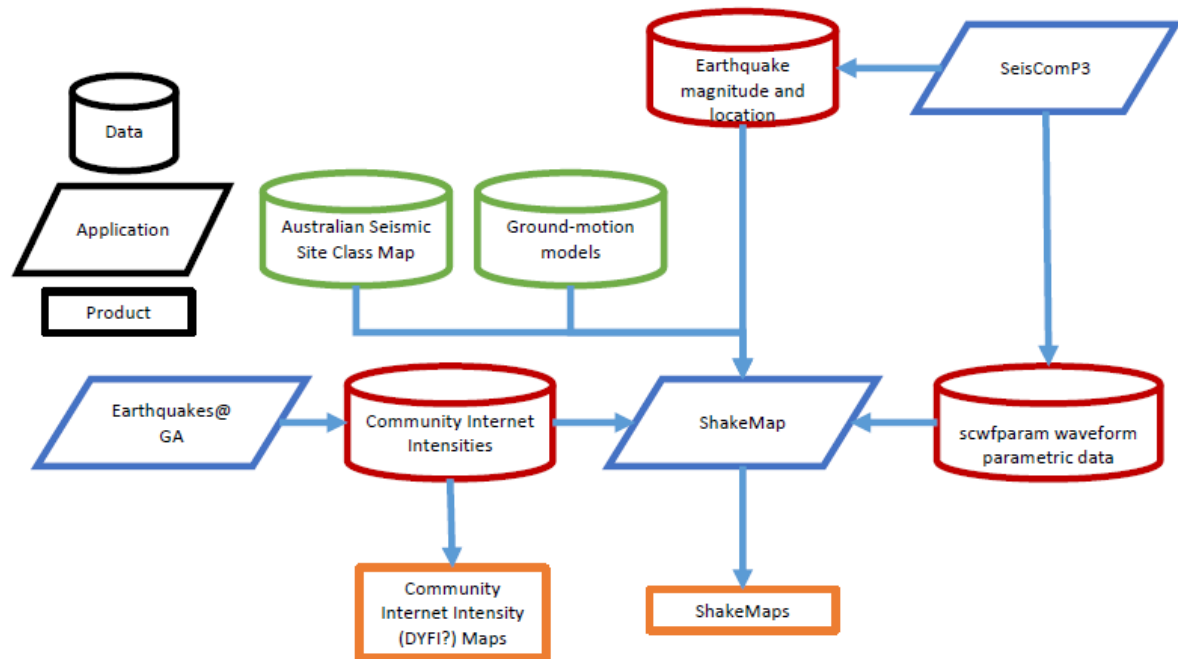
Figure 6: Geoscience Australia ShakeMap workflow. Green objects are static model inputs and are consistent for all earthquakes. Red objects are versioned datasets that can be updated over several hours or days. Orange objects are versioned outputs that are dependent on model inputs. These outputs may vary over time. SeisComP3 (Weber *et al.* 2007) is the processing system Geoscience Australia uses to process seismic data.
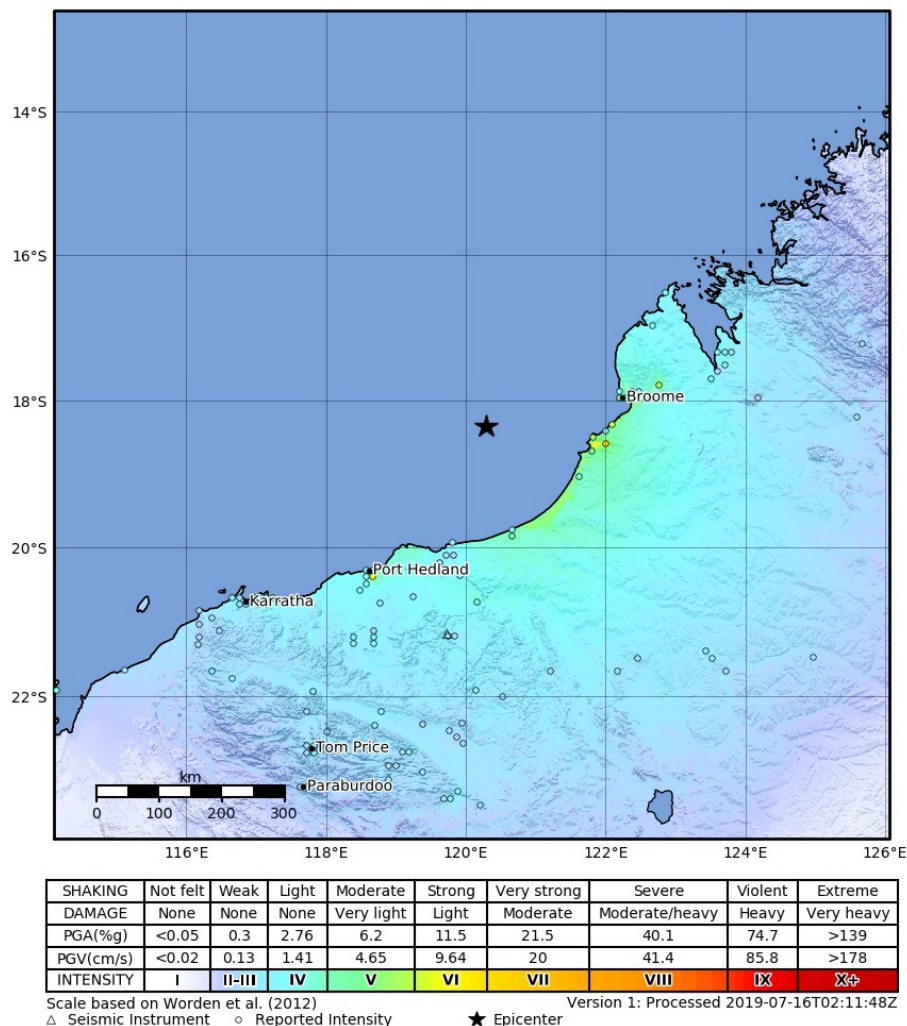

SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.05	0.3	2.76	6.2	11.5	21.5	40.1	74.7	>139
PGV(cm/s)	<0.02	0.13	1.41	4.65	9.64	20	41.4	85.8	>178
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Worden et al. (2012)   Version 1: Processed 2019-07-16T02:11:48Z
△ Seismic Instrument   ○ Reported Intensity   ★ Epicenter

Figure 7: ShakeMap for the 14 July 2019 M_W 6.6 offshore Broome earthquake. The ShakeMap is calibrated by the CII data collected through Geoscience Australia's DYFI? System, as well as data from the sparse instrumental ANSN.

CURRENT SHAKEMAP LIMITATIONS

The are several known limitations with the current ShakeMap implementation at Geoscience Australia and these limitations are intended to be addressed in time as more calibration data is collected. The preferred ground-motion models that underpin the shaking distribution are not well calibrated for ground motions at large distances. The reason for this is two-fold: firstly, several of the models are based on simulations that rely on earthquake source and attenuation properties from smaller earthquakes (e.g., Allen 2012). Due to limitations in the signal-noise ratios for the original data used, the models should generally not be extended beyond the distance range of the original datasets (i.e., 400 km). Secondly, these low-intensity ground motions in the far-field are generally not of engineering significance. Consequently, they are generally not considered important to ground-motion modellers for seismic hazard applications. Over time, the augmentation of instrumental and macroseismic datasets will enable Geoscience Australia assess the utility of different GMMs and intensity conversions for use in ShakeMap in the Australian context (e.g., Allen & Wald 2009; Cua *et al.* 2010). For example, the current intensity conversion equation selected in Geoscience Australia's ShakeMap implementation is Worden *et al.* (2012), which was developed based on California data. Presently there are no systematic studies to conclude whether this conversion (or any others) is most appropriate for Australia and this will be reviewd in the fullness of time.

The other factor is that many felt intensities at large distances from earthquakes are commonly felt within deep sedimentary basins by observers in medium-to-high-rise buildings (e.g., Gregson *et al.* 1979)(Figure 8). Whilst these observers genuinely feel the earthquake shaking, these motions likely occur at long ground-motion periods and are unlikely to be representative of the median free-field ground motions for which GMMs are calibrated. Therefore, we may see CIIMs demonstrating felt effects in regions far away from the earthquake epicentres that are not well-calibrated in the ShakeMaps.
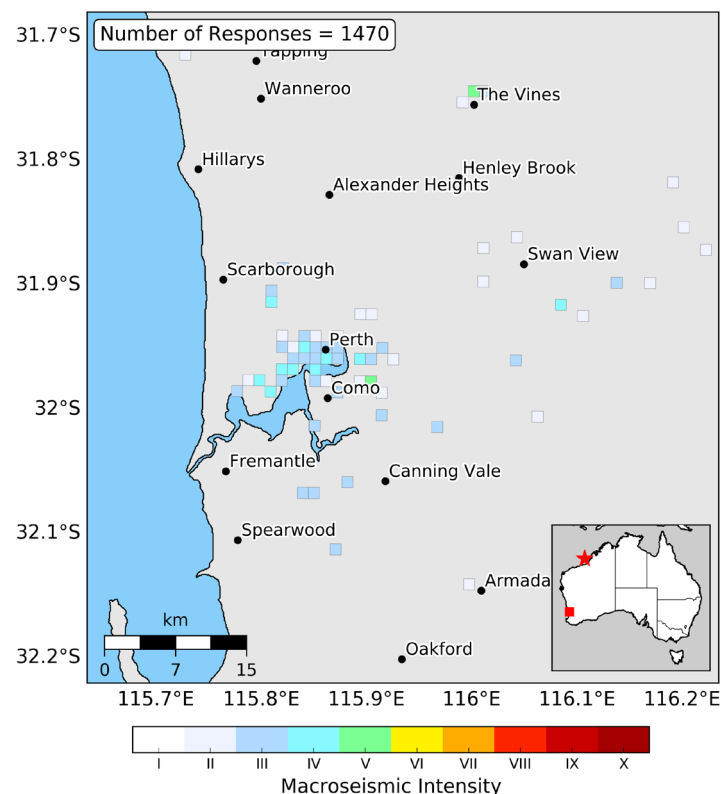

Figure 8: Example of CII data observed from the 14 July 2019 M_W 6.6 offshore Broome earthquake, aggregated across a 1 × 1 km resolution grid for the city of Perth, WA and surrounding regions. The shaking in this region was felt most strongly for sites on the alluvial plains of the Swan River Valley within the Perth Basin. The red star indicates in the inset map shows the epicentre of the earthquake relative to the mapped extent (red square).

For emergency response, end-users are mostly concerned with the near-source ground-motion estimates because this is vital for assessing potential earthquake impacts. Whilst it is useful to measure the felt extent of ground shaking, this is a second-order concern relative to being able to better identify communities in near-source regions that may have been impacted by earthquake ground shaking.

Another limitation of the current system is that Geoscience Australia does not routinely calculate moment magnitudes for small-to-moderate-magnitude earthquakes. The GMMs used by ShakeMap are all calibrated to M_W and the use of an inappropriate magnitude type will result in systematic biases in the estimation of the ground-motion field. In contrast, if enough near-source CII data are available from any one earthquake, then the calculated magnitude of an earthquake becomes of lesser importance because the shaking intensities will be adjusted up or down by observations rather than the earthquake source parameters.

Finally, the instrumental ground-motion data, ingested from the SeisComP3 system (Weber *et al.* 2007; Cauzzi *et al.* 2013) as used by Geoscience Australia as it's earthquake analysis system, currently only processes down-sampled waveform data (typically at 40 samples per second) for calculation of PGA, PGV and response spectral ordinates in real-time. Given the potential for aliasing, Geoscience Australia does not recommend the use of PGA values calculated by this system, until such time that high-sample-rate data are processed in real-time for input into ShakeMaps. Given the very sparse station locations of the ANSN and other open networks (i.e., Balfour *et al.* 2014), the utility of instrumental data for calibrating ShakeMaps in remote regions will be limited. This is where "human seismometers" have the advantage over instrumental networks in being able to fill the gaps in the observed ground-motion field (e.g., Atkinson & Wald 2007).

DATA DELIVERY AND FORMAT

The data content and format delivered by the Geoscience Australia felt report and ShakeMap system will continue to evolve as the system becomes more frequented and end-users suggest alternative delivery mechanisms or data products. Currently, Geoscience Australia is delivering a range of web-rendered products, static maps and geospatial products that include:

- Web-rendered CII gridded intensity data on earthquakes@GA that possesses multiple resolutions depending on zoom level;
- Static CIIMs, generated at four spatial scales with 1, 5, 10 and 20-km grid cells;
- Web-rendered ShakeMaps in terms of macroseismic intensity (MMI) on earthquakes@GA;
- Static ShakeMaps produced for MMI, PGA, PGV;
- Web Map Service (WMS) of ShakeMap layers for geospatial information systems;
- info.json file that contains all ShakeMap metadata (i.e., GMMs, intensity conversion equations, inter-event bias, etc.) on the generation of the maps.

CONCLUSIONS

The combination of CIIMs and ShakeMaps on the earthquakes@GA webpage, launched in late 2019, will significantly improve the NEACs ability to provide more quantitative, evidence-based information to emergency responders to assess the potential impacts of earthquakes within Australia. The systems provide critical ground-truthed information in near-real time that can be used to plan and expedite emergency relief efforts to potentially affected communities.

The data collected through the GA DYFI? System is already yielding benefits in terms of calibrating updated intensity attenuation models for Australia. The ongoing operation of these systems will only improve and augment these datasets for future scientific studies. The CIIMs also provide an important perspective on human behaviour during earthquakes, providing in insight into the way people respond, and how they perceive earthquake risk (e.g., Celsi *et al.* 2005; Williams *et al.* 2019). These data will therefore have utility in earthquake scientists and science communicators develop improved strategies to raise awareness of earthquake risk and the actions to take during an earthquake in order to mitigate the potential for potential human casualties.

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