A Probabilistic Tsunami Hazard Study of the Auckland Region, Part I: Propagation Modelling and Tsunami Hazard Assessment at the Shoreline

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A Probabilistic Tsunami Hazard Study of the Auckland Region, Part I: Propagation Modelling and Tsunami Hazard Assessment at the Shoreline

William Power,[1] Xiaoming Wang,[1] Emily Lane,[2] and Philip Gillibrand[2,3]

Abstract—Regional source tsunamis represent a potentially devastating threat to coastal communities in New Zealand, yet are infrequent events for which little historical information is available. It is therefore essential to develop robust methods for quantitatively estimating the hazards posed, so that effective mitigation measures can be implemented. We develop a probabilistic model for the tsunami hazard posed to the Auckland region of New Zealand from the Kermadec Trench and the southern New Hebrides Trench subduction zones. An innovative feature of our model is the systematic analysis of uncertainty regarding the magnitude-frequency distribution of earthquakes in the source regions. The methodology is first used to estimate the tsunami hazard at the coastline, and then used to produce a set of scenarios that can be applied to produce probabilistic maps of tsunami inundation for the study region; the production of these maps is described in part II. We find that the 2,500 year return period regional source tsunami hazard for the densely populated east coast of Auckland is dominated by events originating in the Kermadec Trench, while the equivalent hazard to the sparsely populated west coast is approximately equally due to events on the Kermadec Trench and the southern New Hebrides Trench.

Key words: Tsunami, New Zealand, probabilistic, hazard assessment.

1. Introduction

The devastating tsunamis in the Indian Ocean in 2004 (Borrero, 2005) and on the coast of northern Japan in 2011 (Mori *et al.*, 2011) have highlighted the need to mitigate the effects of tsunami. Proposed mitigation measures include evacuation zoning, provision of vertical evacuation structures, restrictions on land use, engineered tsunami defenses and many others (Jonientz-Trisler *et al.*, 2005; Eisner, 2005). To be effective these measures require an accurate estimation of tsunami hazard. Probabilistic tsunami hazard analysis (PTHA, e.g. Rikitake and Aida, 1988; Geist, 2006) provides a method for providing this information, and follows a similar process to that used in probabilistic seismic hazard analysis (PSHA, e.g. Cornell, 1968; McGuire, 2004). PTHA has been applied in New Zealand (Power *et al.*, 2007), northwest USA González (2009), the Mediterranean (Sorensen *et al.*, 2012) and Australia (Burbidge *et al.*, 2008), among others.

Auckland is the most populous city in New Zealand, and is located on an isthmus between the Hauraki Gulf on the Pacific Ocean and the Manukau Harbour on the Tasman Sea. A large proportion of the 1.35 million residents live at less than 20 m asl, which makes effective tsunami hazard mitigation particularly important. At the long return periods used for matters of life safety (>1,000 years), local and regional subduction-zone tsunami sources are expected to be the cause of the largest tsunamis. Power *et al.* (2012) identified the Kermadec Trench subduction zone and the southern New Hebrides subduction margin (Fig. 1) as the most important sources of this type for the northern coasts of North Island, New Zealand.

Substantial epistemic uncertainty [that is, uncertainty due to a lack of knowledge, see Senior Seismic Hazard Analysis Committee (SSHAC) (1997)] exists regarding the true magnitude-frequency distributions of these source regions. For example the maximum magnitude of earthquakes in the Kermadec Trench can only be confidently stated as being between about M_w 8.5, slightly above the largest historical events, and M_w 9.4 if only the length of the subduction zone constrains the possible magnitude (McCaffrey,

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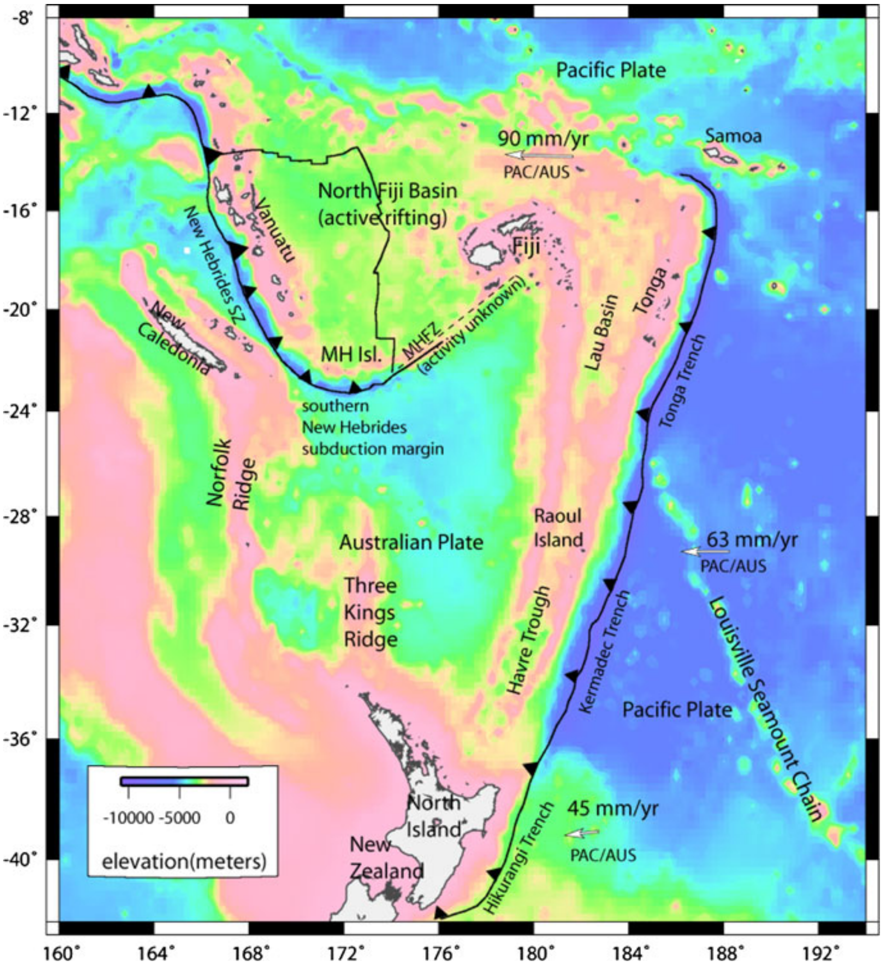

Figure 1

Tectonic setting of the Kermadec and New Hebrides plate margins. *Black triangles* signify the over-riding plate at the regions' subduction margins. *White arrows* show predicted motion of the Pacific Plate relative to the Australian Plate. *MH Isl.* Matthew Hunter Islands, *MHFZ* Matthew Hunter fracture zone, *PAC* Pacific Plate, *AUS* Australian Plate, *SZ* subduction zone

2008). For matters of life safety it is important to take a conservative approach to such uncertainties, and correspondingly we develop techniques for incorporating epistemic uncertainty into the hazard analysis in order to accommodate this in a systematic manner. The logic-tree techniques we apply are similar to those that Annaka *et al*. (2007) used to estimate tsunami hazard at specific sites along the Japanese coast; the authors of that work considered a mixture of tsunami from local and distant earthquake sources to infer the tsunami hazard at the locations of important coastal facilities. Our study differs from that of Annaka *et al*. (2007) in that we seek to estimate a continuous coastal distribution of hazard and to be able to use the coastal hazard model as the systematic basis for probabilistic inundation mapping.

2. Approach

The problem of uncertainty in tsunami sources is a major one if we wish to effectively mitigate the risks that tsunami pose. The magnitude of earthquakes varies naturally from event to event within a source region: if we were able to have a precise history of events over a long enough time frame, it would be possible to empirically establish the true magnitude-frequency distribution for the source. Techniques have been developed for estimating tsunami hazard at the coast once a magnitude-frequency distribution has been determined (e.g. Burbidge *et al*., 2008; Sorensen *et al*., 2012). However, the 2011 Japan tsunami, for which the most recent near-equivalent event was in 869, has highlighted that for many subduction zones, it may be necessary to have an earthquake record spanning more than a 1,000 years before a magnitude-frequency distribution can be empirically estimated with accuracy.

Fortunately, some of the parameters that control the magnitude-frequency distribution can be estimated by other means—for instance the strength of interseismic coupling on a subduction interface can be studied through geodetic techniques (e.g. Wallace *et al*., 2004). Also, the combinations of these controlling parameters are subject to the constraint that they cannot imply a magnitude frequency distribution which is inconsistent with the available catalogue data.

If it is possible to place uncertainty distributions on the set of parameters that control the magnitude-frequency distribution, then this can be used to define an uncertainty distribution for the magnitude-frequency distribution itself. This forms the basis for the logic-tree techniques that have become established in the field of seismic hazard analysis, but are rarely used for tsunami hazard analysis. Notable examples where logic trees have been used for tsunami hazard analysis are given by Annaka *et al*. (2007) and Berryman (2005). Typically a Monte-Carlo technique is used to sample from the branches of the logic tree, but this dictates that the hazard analysis for each branch must be performed quickly. In this study the logic trees that are used are relatively simple; this makes it possible to perform a hazard analysis for each possible branch of the logic tree.

From the set of tsunami hazard estimates and their corresponding logic-tree weights, we can then quantify the uncertainty present in the tsunami hazard. This has important practical applications—for insurance purposes we may be interested in the 'best' (i.e. most likely, given available data) estimate of tsunami hazard, while when designing a critical piece of infrastructure we may wish to have a higher degree of confidence that our estimate of tsunami hazard will not be exceeded because of uncertainties in the source characterisation. By explicitly estimating the hazard at a specified return period and level of confidence, the intention is to provide probabilistic equivalents to established engineering terms such as the 'Maximum Credible Event' [see Bommer (2002) for a helpful discussion of the relationship between deterministic and probabilistic hazard assessment in the context of seismic hazard].

Our measure of tsunami hazard, the maximum amplitude at the coast, is both limited in its practical relevance and constrained by the limitations of our modelling (i.e. linear shallow water equations and reflective boundary conditions). In part II we demonstrate how to go past these limitations by performing a hazard analysis using non-linear tsunami models incorporating inundation, having first established the appropriate magnitude-frequency distribution to use to achieve the required confidence level with the linearised model presented here.

3. *Tsunami Source Regions*

The primary regional sources of interest for the study area are the Kermadec Trench, a subduction zone that extends northwards from East Cape on the North Island of New Zealand to the point where the trench intersects the Louisville Ridge seamount chain, and the southern New Hebrides subduction margin that lies between the southern New Hebrides and Fiji (Fig. 1). These were judged to be the only regional sources capable of influencing the location of the 2,500 year 84th percent confidence inundation line in the Auckland region.

The Kermadec Trench accommodates westward subduction of the Pacific Plate beneath the active Kermadec volcanic arc (Fig. 1). Since $\sim$5 Ma-present, back-arc extension of the overriding plate has occurred along the Havre Trough (Pelletier *et al*, 1998; Wright, 1993; Delteil *et al*., 2002) and Lau Basin (Lawver *et al*., 1976; Weissel, 1977; Parson and Hawkins, 1994). The New Hebrides Trench defines the Australia-Pacific plate boundary zone between the Tonga-Fiji region and New Guinea (Fig. 1). Here the Australian Plate subducts northeastward beneath Vanuatu, and a complex series of rifts and transforms lies to the north and east in the

North Fiji Basin (NFB). GPS data from the Matthew and Hunter Islands (Fig. 1) indicate that up to 5 cm/year of convergence is occurring on the east-west striking portion of the southern New Hebrides Trench (Power *et al*., 2012; Calmant *et al*., 2003), suggesting that active subduction occurs on this segment of the New Hebrides Trench, at least as far east as 172°E. Previous studies that consider the Kermadec Arc as a tsunami source include de Lange and Healy (2001), Walters *et al*., (2006) and Power *et al*. (2012); previous studies that consider the New Hebrides Arc as a tsunami source include Berryman (2005), Goff *et al*. (2006) and Power *et al*. (2012).

Power *et al*. (2012) evaluated the available geodetic, geological and seismic data to produce logic trees for each of the two source zones, and these logic trees were used for this study. The logic trees characterise the range of possible source parameters, encompassing the range of epistemic uncertainty [Senior Seismic Hazard Analysis Committee (SSHAC) (1997)] in these parameters, with weighting according to expert opinion (Figs. 2, 3). An important constraint on the parameter weightings is that the resulting magnitude-frequency distributions should not be inconsistent with the available historical seismic data [see Appendix of Power *et al*. (2012)].

4. *Unit-Source Tsunami Models*

The two source regions were each divided into a set of unit-source 'patches' 100 km long, and either 50 km (Kermadec Arc) or 60 km (New Hebrides) wide (Figs. 4, 5). The position, depth and dip angles of these patches used the values estimated from seismic data by Power *et al*. (2012).

Okada's (1985) elastic finite fault theory was adopted to calculate seafloor displacement of each unit source with 1.0-m "unit" slip; a pure thrust mechanism was assumed. This displacement is considered the source of tsunami generation and is used as the initial condition for tsunami propagation modelling [this is similar to the approach used by Titov *et al*. (2005) to develop tsunami forecast databases]. Using these initial conditions the tsunami propagation time history caused by 1 m of slip on each of the unit sources was estimated using the COMCOT model (Wang, 2008). The nested grid structure used for this modelling is illustrated in Fig. 6. The linear shallow-water tsunami equations were used, which is appropriate for applying the superposition principle to the unit source models. However, this linear approximation limits the accuracy of the models in shallow water.

The generation and propagation of tsunami from the unit sources are modelled with the Cornell Multi-grid Coupled Tsunami model (COMCOT). COMCOT uses a modified leap-frog finite difference scheme to solve (linear and/or nonlinear) shallow water equations in a staggered nested grid system. The model is capable of simulating the generation, propagation, and the subsequent runup and inundation of tsunami from either local or distant sources. It has been systematically validated against analytical solutions, experimental studies and typical benchmark problems (Liu *et al*., 1995; Cho, 1995; Wang, 2008). It has also been successfully used to investigate several historical and recent tsunami events, such as the 1960 Chilean tsunami (Liu *et al*., 1994) and the 2004 Indian Ocean tsunami (Wang and Liu, 2006, 2007; Wang, 2008). With the implementation of two-way nested grid coupling, COMCOT simultaneously calculates the tsunami propagation in the deep ocean with a relatively larger spatial resolution, and the runup and inundation process in the targeted coastal zones with a finer spatial resolution.

In this study three levels of nested grids are implemented to model the propagation of tsunami in the deep ocean, over the continental shelf and near-shore, in order to account for the shortening of tsunami waves as they shoal over the continental shelf. The first level grids (i.e., Layer 01 in Fig. 6) enclose the entire region of New Zealand, the Kermadec-Tonga Trench and south New Hebrides Trench, ranging from 145°E to 190°E in longitude and from 50°S to 4°S in latitude, with a spatial resolution of 2 arc-minutes (about 3.0 km, from NGDC ETOPO2 database). The second level grids (i.e., Layer 02) cover the entire New Zealand, including the continental shelf, and have a spatial resolution of 30 arc-seconds (about 750.0 m, from GEBCO30 database). The third level grids (i.e., Layer 03 and 04) have a spatial resolution of 10 arc-seconds (about 250.0 m, mainly interpolated from Land Information

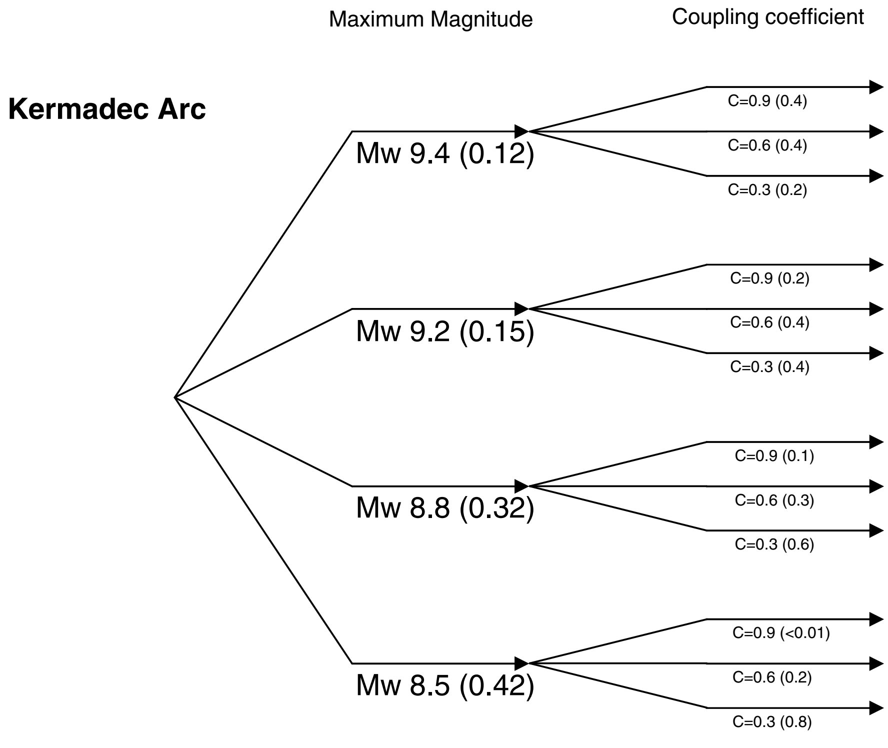

Figure 2
Logic tree for the Kermadec Trench. M_w is the moment magnitude of the largest earthquake that the Kermadec Arc can experience, and C is the interseismic coupling coefficient. Weightings are in *brackets*

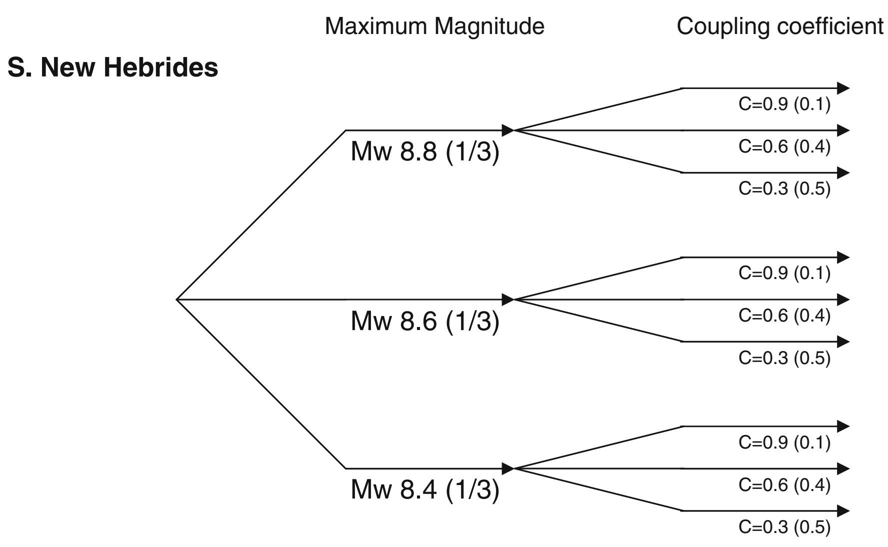

Figure 3
Logic tree for the Southern New Hebrides Trench. M_w is the moment magnitude of the largest earthquake that the Southern New Hebrides Trench can experience, and C is the interseismic coupling coefficient. Weightings are in *brackets*

New Zealand nautical charts), covering the nearshore regions around Auckland and the Northland Peninsula (see Fig. 7 for locations of places referred to in the text). This type of nested grid system guarantees that the grid resolution is sufficient to resolve tsunami wave profiles both in the deep ocean and nearshore.

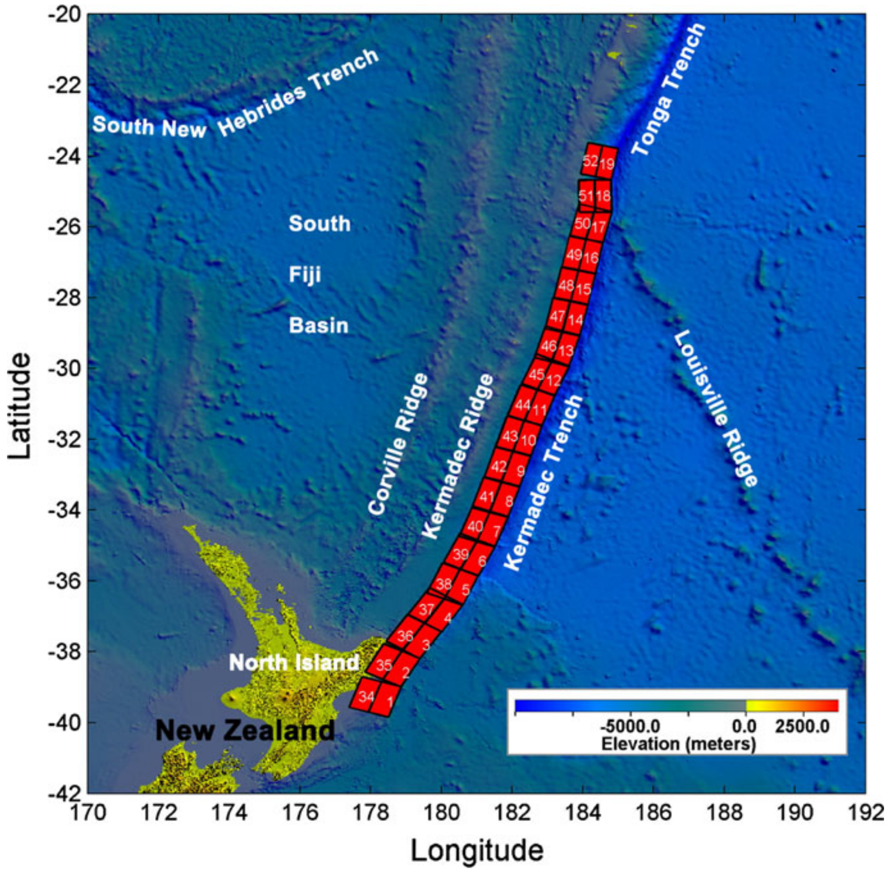

Figure 4
Unit source locations for the Kermadec Trench. Unit sources 20–33 (not shown) extend towards Tonga, but were not used in this study

Time series of model-predicted water level and velocity were stored at 2 arc-minute intervals over the area from 165.6 to 186.0°E and from 48.5 to 23.5°S.

Water level time-series predictions were also stored at 30 arc-second intervals over the area from 172.3 to 176.4°E and from 39.3 to 34.0°S. To conserve disc space only data points within 3 km of the coast were stored.

5. *Monte-Carlo Modelling*

The hazard due to each of the two studied source regions (the Kermadec and southern New Hebrides trenches) was evaluated separately. For each branch of the corresponding logic tree a 100,000 year simulated sequence of earthquakes was generated, according to the statistical source parameters that define the magnitude-frequency distribution for the particular branch. That is, in total there were 12 synthetic earthquake catalogues generated for the Kermadec Trench and 9 for the southern New Hebrides trench. A truncated Gutenberg-Richter magnitude-frequency distribution was assumed, with a *b* value of 1, matching the global magnitude-frequency distribution. The maximum magnitude and the coupling coefficient values from the logic trees were sufficient to parameterise this distribution using moment rate balancing (that is by reconciling the seismic moment rate with the geodetic/geologic moment rate), and the known plate convergence rates and estimated interface dimensions. Earthquake magnitudes were randomly sampled from the truncated Gutenberg-Richter distribution once the necessary parameters were determined. For each simulated earthquake the amount of slip caused by

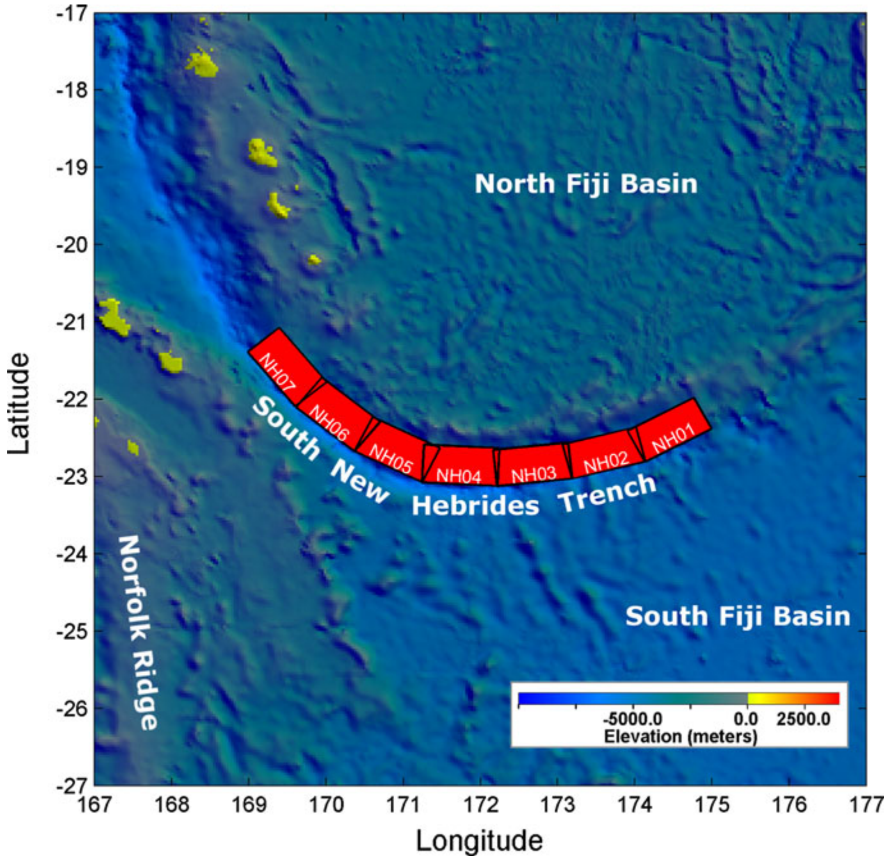

Figure 5
Unit source locations for the southern New Hebrides Trench

that event on each of the unit sources was determined using the scaling relations described in Power *et al.* (2007) and a randomly sampled midpoint (along strike) for each rupture. Using the pre-calculated tsunami responses, a weighted linear superposition of the tsunami time series was used to create time series for the heights of the simulated tsunami within the study area. The maximum water level was recorded for each simulated event on a line around the coasts of Auckland and the Northland Peninsula. Using these maximum water levels for the entire 100,000 year sequence, the greatest height (to the nearest metre) that was exceeded on more than 40 occasions was used to estimate the 2,500 year return period hazard for the branch of the logic tree corresponding to the particular synthetic catalogue.

These maximum water level exceedances were then used as a measure of the hazard to the Auckland region from each of the respective logic tree branches. The spread of hazard results corresponding to the different logic-tree branches represents the spread of uncertainty in the hazard due to our lack of knowledge regarding the magnitude-frequency properties of the source. Analysis of hazard plots such as Fig. 8 allowed the logic-tree branches to be ranked according to the level of hazard in the study region. Then, taking into account the logic-tree weightings, the logic-tree branch corresponding to the 84th percentile of source uncertainty was obtained (the 84th percentile is often used in hazard studies, as it corresponds to the mean plus one standard deviation in a normal distribution). Figure 8 shows the estimated hazard posed by that branch of the logic tree for the Kermadec Trench, and Fig. 9 shows the equivalent 2,500 year 84th percentile hazard from the southern New Hebrides.

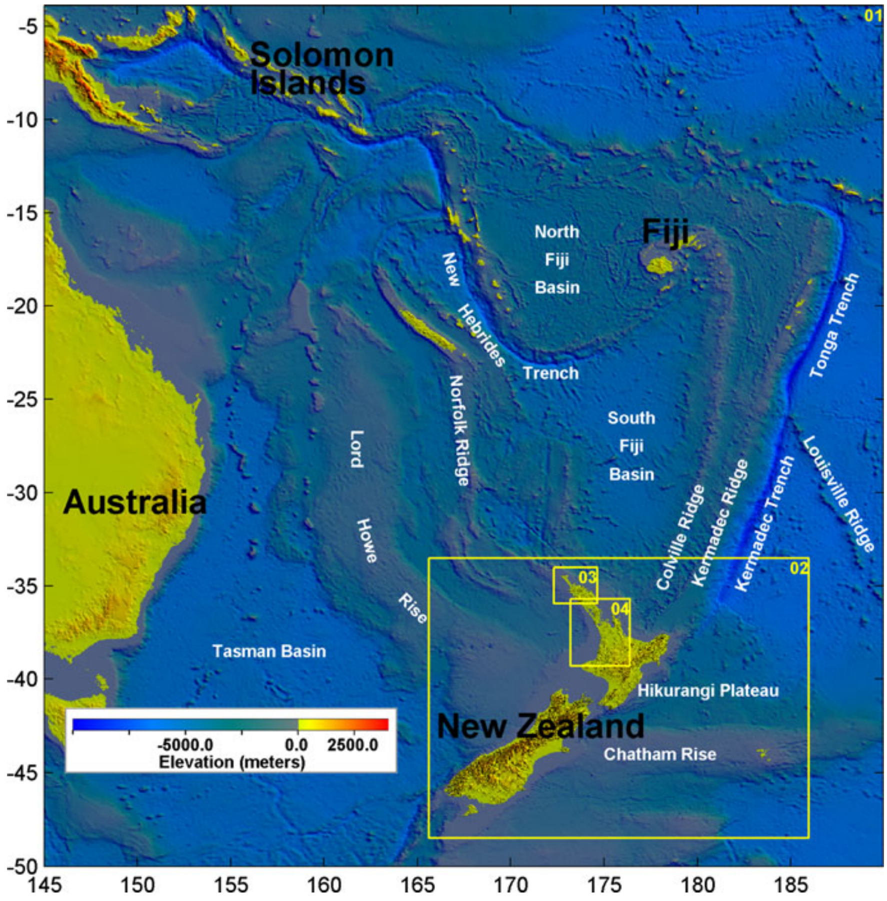

Figure 6
Nested grid structure used for tsunami propagation modelling. Grid resolutions are: 2 arc-minutes (about 3.0 km) for Layer 01, 30 arc-seconds (about 750 m) for Layer 02, and 10 arc-seconds (about 250 m) for Layers 03 and 04. *Yellow boxes* indicate the coverage of nested grid layers

Although the primary purpose of our study is to evaluate tsunami hazard in Auckland, it is useful to examine the results for their wider relevance. Figure 8 shows that the Kermadec Trench poses very high levels of tsunami hazard (>5 m tsunami height at the coast) for portions of the Coromandel Peninsula, Great Barrier Island and the Northland Peninsula north of 36.5°S. These areas are directly in the path of greatest tsunami energy in many simulated events generated on the Kermadec Trench (see Power *et al.*, 2012). Fortunately the densely populated central areas of Auckland are relatively sheltered by the Coromandel Peninsula and Great Barrier Island, though the hazard of the northern coastal suburbs increases the further north you go from central Auckland. Sufficient tsunami energy 'wraps around' the far northern tip of the Northland Peninsula in Kermadec Trench events to pose a high hazard to the west coast, particularly north of 36.7°S.

The hazard shown in Fig. 9, caused by earthquakes on the southern New Hebrides Trench, is typically (with some exceptions) much higher on the west coast of the Northland Peninsula than on the east. This is a consequence of the wave-guiding roles of the Three Kings Ridge and the Norfolk Ridge in directing tsunami energy from this source region towards New Zealand (see Power *et al.*, 2012). There are small areas on the west coast of the Aupouri Peninsula that show a particularly large hazard from the southern New Hebrides; this localised sensitivity appears to be a consequence of the interaction of waves guided along the Three Kings Ridge with the areas in which they initially meet the North Island landmass. This localised effect warrants further investigation.

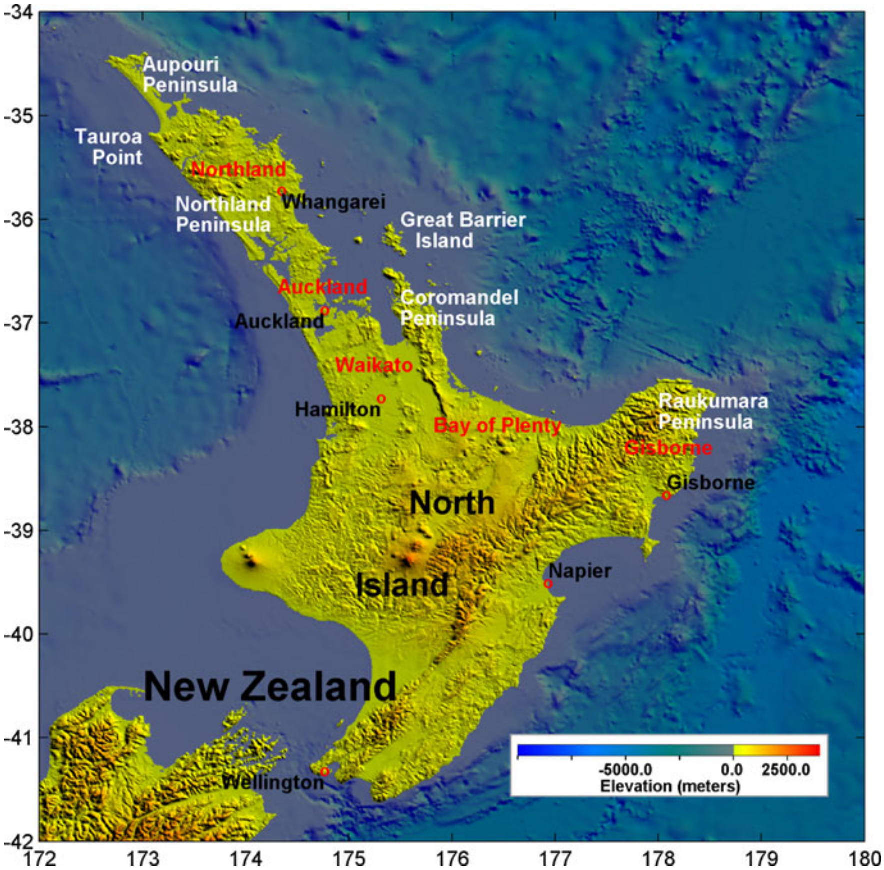

Figure 7
Map of the North Island of New Zealand, showing major cities and locations referred to in the text

Analysis of Figs. 8 and 9 demonstrates that the Kermadec Arc is a significantly greater hazard for the Auckland region east coast, where most of the exposure to tsunami risk is located because the east coast is much more densely populated than the west. For the Auckland region west coast, the hazard from the two source regions is comparable at the 2,500 year 84th percentile level. Because of the reduced hazard on the west coast, and the lower exposure to tsunami risk there, the rest of this study focuses on the tsunami hazard to the Auckland region east coast.

It is important to recognise the limitations of the linear modelling and associated boundary conditions. Nonlinear processes change the shape of large amplitude tsunami waves in shallow water, leading to a more steeply fronted wave. Nonlinearities also change the spectrum of the tsunami wave and may alter resonant interactions with the coast. Comparisons of linear and non-linear models have been made by Satake (1995) and Liu *et al*. (2009) among others. The modelling also assumes a reflective boundary at the coast. This is a fair approximation where the tsunami is not able to travel far inland, but in situations where the tsunami can penetrate significant distances, due to large amplitudes and a gentle slope, the behaviour at the coast may more closely approximate a radiation boundary condition. In the extreme case of very flat topography this may lead to overestimation of the tsunami height at the coast by almost a factor of two. These modelling limitations will be overcome in part II where a nonlinear model is used that includes inundation. What is required from the linear modelling is that it should be sufficient to identify the branch of the logic tree corresponding to the 84th percentile of uncertainty;

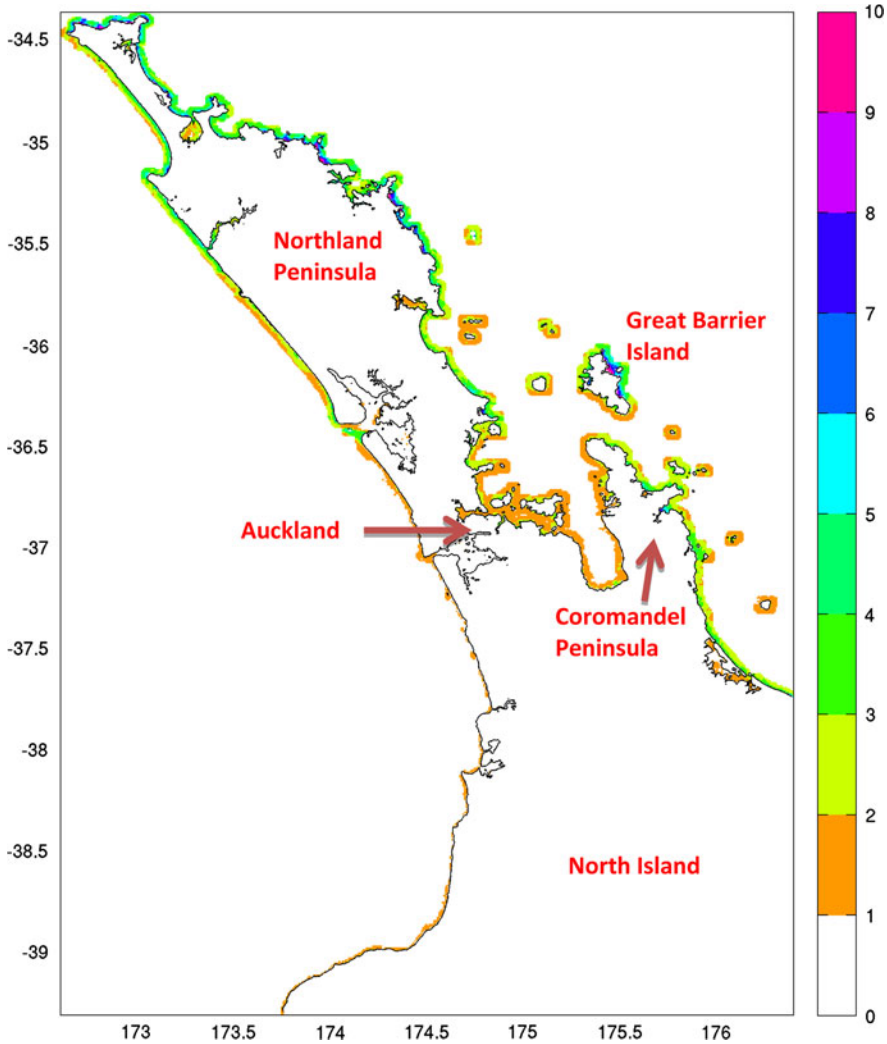

Figure 8
Estimated 2,500 year 84th percentile tsunami hazard from the Kermadec Trench, expressed in terms of the maximum water level in meters. Note that the hazard is estimated with a linear model and reflective boundary conditions (See discussion in Sect. 5)

for this we must assume that the larger the amplitude at the coast estimated with the linear model, the larger the extent of inundation will be in the nonlinear inundation model.

The combined coastal hazard from both source regions cannot, in general, be simply obtained from the hazard plots for each individual source. However, for the Auckland region east coast the hazard from the Kermadec source is significantly higher than from the southern New Hebrides. The 2,500 year 84th percentile water level for the Auckland region east coast is higher than that of the maximum event possible from the southern New Hebrides in our logic tree. Consequently, for the east coast we may assume that most of the regional tsunami hazard comes from the Kermadec Arc and that we can neglect the southern New Hebrides without significantly changing the result. Thus, the maximum water levels in Fig. 8 describe the 2,500 year 84th percentile hazard from all regional sources along the Auckland east coast.

Having determined which branch of the logic tree represents the 84th percentile (which turns out to be that with maximum magnitude $M_w = 9.2$ and coupling coefficient $C = 0.6$), we can now develop a set of scenarios to be used for the Monte Carlo modelling

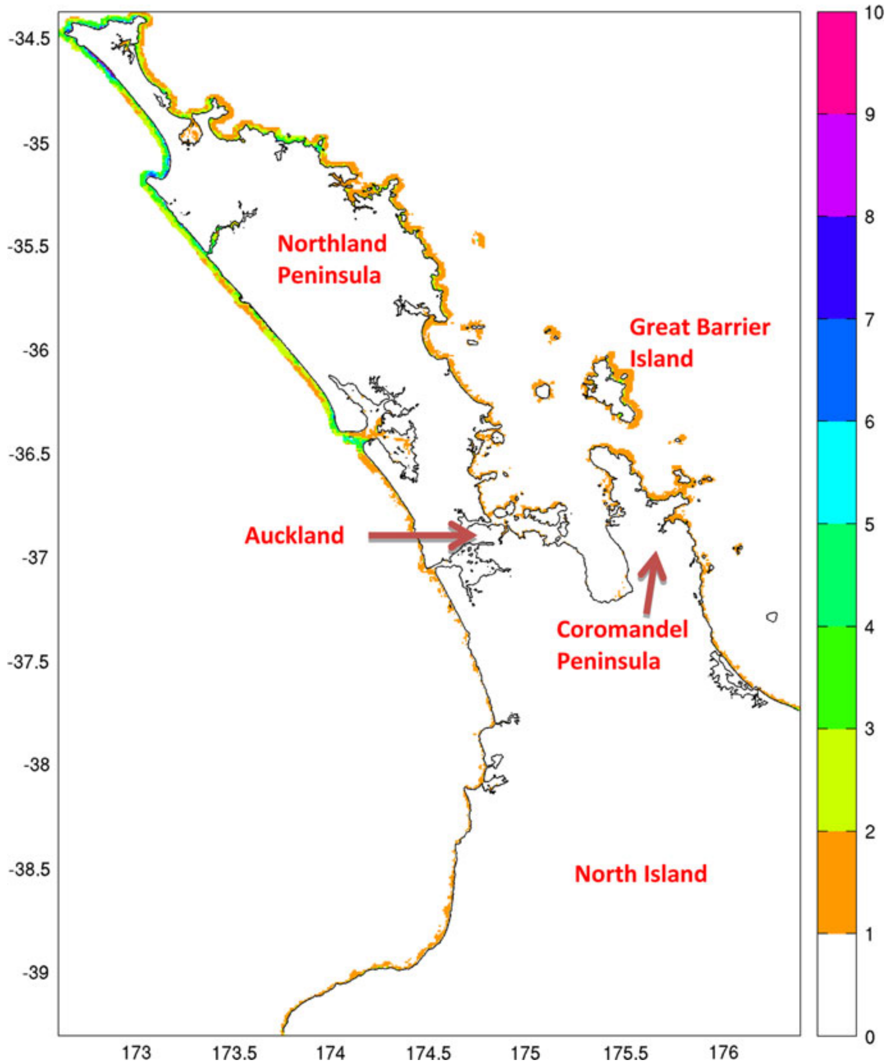

Figure 9

Estimated 2,500 year 84th percentile tsunami hazard from the southern New Hebrides Trench, expressed in terms of the maximum water level in meters. Note that the hazard is estimated with a linear model and reflective boundary conditions (see discussion in Sect. 5)

of inundation. Ideally we would perform inundation modelling for all of the events in the 100,000 year period. This, however, would be computationally infeasible because of the large number of simulated events within that period. Instead we use the linear modelling process previously developed to quickly remove those events too small to contribute to the 2,500 year return period inundation.

Using the logic-tree branch for the Kermadec Trench that was estimated to represent the 84th percentile uncertainty at the 2,500 year return period, a synthetic sequence of tsunamigenic earthquakes was created for a 100,000 year period. The magnitude of each event was randomly selected according to the statistical properties of the chosen branch. The mid-point location of each rupture was randomly selected, and the length of rupture determined according to the scaling laws presented in Power *et al*. (2007), with a maximum source width of 100 km.

Over this 100,000 year period there are approximately 3,000 simulated earthquakes, and for each of these the unit-source models were used to estimate the subsequent maximum water levels around the coast. For each event, the maximum water level was averaged over the Auckland region east coast shoreline. The events were then ranked from that with the highest (average) water level on the Auckland region shoreline to that with the lowest. From this ranking, the 100 largest events were selected for the purpose of inundation modelling.

6. Links to Inundation Modelling

For the purposes of this study it was necessary to go beyond estimates of tsunami hazard at the coast to provide estimates of tsunami inundation at the 2,500 year return period and 84 percent confidence level along the east coast of Auckland. As discussed in Sect. 5, at this return period and confidence level it is only the Kermadec Trench source that is important: even the most severe logic-tree branch for the New Hebrides at a 2,500 year return period produced a lower hazard on the Auckland east coast than the 2,500 year 84th percentile hazard from the Kermadec Trench.

For the inundation modelling the RiCOM model was used (Walters, 2005). To couple COMCOT with the RiCOM model, time series of water level and current velocity describing the tsunami propagation from each unit source (with 1.0-m slip) at the eastern boundary locations of the RiCOM model grid are extracted from COMCOT simulations. The time series data from unit sources are weighted, linearly superimposed together and then used to force the RiCOM model as boundary conditions for the inundation modelling of the 100 most severe scenarios in the 100,000 year simulation period.

The area inundated on a 2,500 year return period was determined by looking for locations that were inundated more than 40 times in 10,000 years. The reason for modelling the 100 most severe scenarios, rather than only the top 40, was to ensure that all events that might contribute to this area were included, as some of the sample tsunami had a relatively stronger impact on some parts of the study region than others. As a validation that 100 events was sufficient for this purpose, a hazard model equivalent to Fig. 8 was constructed using only the 100 selected events; this showed negligible differences to Fig. 8 in the Auckland east coast study area. In other words, events outside our selected sample of 100 had negligible contribution to the 2,500 year return period hazard. The 100 most severe scenarios ranged in magnitude from M_w 8.8 to M_w 9.2, and in latitude of the rupture midpoint from 37.6°S to 27.2°S, with the majority of events being south of 36°S; this is consistent with the observation that the Auckland region is most strongly affected by tsunami caused by earthquakes on the southern portion of the Kermadec Arc (Power *et al*., 2012). The 40 most severe scenarios ranged in magnitude from M_w 9.0 to M_w 9.2, and were more strongly concentrated towards the southern portion of the subduction zone: all had midpoint latitudes south of 33°S. The full details of the inundation modelling and subsequent results are described in part II.

7. Conclusions and Discussion

We have taken the techniques of PTHA and expanded them to systematically account for uncertainty in the magnitude-frequency distribution of the source regions, by evaluating the tsunami hazard for each branch of the logic trees. This has important practical implications, because for many tsunami source regions, including those studied here, there remains a great deal of uncertainty about the magnitude-frequency distributions, and this should be accounted for in order that mitigation measures are appropriate.

In taking this approach it was very helpful that the logic trees were relatively small. There are other areas of uncertainty that could potentially be included, leading to a more complicated tree and a more difficult analysis; to some extent the simplicity of the trees used can be justified by the fact that these are regional sources and that some of the complexities of the source that are relevant in the near-field (i.e for local sources) are 'washed out' with increasing distance (see discussion in Power *et al*., 2012; and Geist, 2002), though a more complete analysis including other effects, such as the roles of non-uniform slip and splay-faulting, would be useful further work to verify this conclusion. The use of uniform slip on relatively large (50 × 100 km) unit sources also limits the range of frequencies present in the modelled tsunami, the effects of which could also be examined when investigating the role of non-uniform slip.

Volcanic and landslide tsunami sources were not included in this analysis [see discussion in Chapter 5 of Berryman (2005)], which assumes that subduction zone earthquakes are the dominant source of regional tsunami on the time frames considered here, although it has been suggested that a collapse of the Healy caldera approximately 600 years ago may have been tsunamigenic (Wright *et al*., 2003), and this has been proposed as a possible source of paleotsunami deposits in northern New Zealand (Goff *et al*., 2010).

The primary site of interest for this study was the east coast of Auckland, and a goal of this work was to be able to provide a set of scenarios from the probabilistic hazard model that could be used to make a probabilistic model of inundation; this later step has been done and is described in part II. For this purpose it was fortunate that, at the requested 2,500 years return period, only one of the two source zones was significant in determining the hazard; simply put, on this time frame the largest tsunamis are all from the Kermadec Trench. Had this not been the case it would have been possible, but onerous, to construct a combined logic tree with $12 \times 9 = 108$ branches and work with that to evaluate the combined hazard at the requested 84 % confidence. In general, as the number of source regions, or the number of logic-tree branches, increases, our method of evaluating the hazard for every branch becomes increasingly impractical. Probably some form of sampling from the set of possible epistemic parameters will be necessary.

While our results demonstrate that the 2,500 year hazard to the densely populated east coast of Auckland is relatively low because of its location in the 'shadow zone' behind the Coromandel Peninsular and Great Barrier Island, there is a demonstrably high tsunami hazard from the Kermadec Trench affecting many other areas of northern New Zealand, particularly the east coasts of the Coromandel Peninsular, Great Barrier Island and the Northland Peninsular north of Auckland. The tsunami hazard from the southern New Hebrides Trench is greatest along the west coast and in the far north (Aupouri Peninsula); in these areas the hazard is typically comparable to that from the Kermadec Trench. These results illustrate an urgent need for tsunami mitigation measures in these regions.

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