NATURAL HAZARDS RESEARCH PLATFORM

# Kaikōura Earthquake Short-Term Project

## Title: Probabilities of Large Earthquakes in Central New Zealand


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**Organisation: GNS Science**


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# Probabilities of Large Earthquakes in Central New Zealand

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## ABSTRACT

In this project, we have estimated the 1-year and 10-year probabilities for the occurrence of large earthquakes in central New Zealand. Following the November 14th, 2016 Kaikoura Mw7.8 earthquake, there was widespread triggering of slow slip earthquakes (SSE) on the Hikurangi subduction zone. At that time, little research had been done to understand the implications of SSE for the occurrence of future larger earthquakes. In December, 2016 initial modelling was done to estimate the probabilities of larger earthquakes within the next year in central New Zealand; this was the first time such work had been done anywhere. In this project, we have improved upon the initial models and have constructed new physical and statistical forecast models that account for the interaction of SSE and crustal earthquakes. Part of this process included two international workshops. In the first workshop, preliminary models were reviewed by the international panel and revisions and recommendations for new models were discussed. In the second workshop, a non-consensus structured expert elicitation procedure was used to evaluate the models and observations and to estimate the revised probabilities as shown in the table below. The best estimates for the next year for M7.0+ and M7.8+ represent increases of 20% and 100% respectively over the long-term estimates from the National Seismic Hazard Model. The upper bounds for both of these magnitude range estimates are a significantly greater increase. Similarly, the upper bounds on the decade estimates are a significant increase over the long-term estimates.

Probabilities of large earthquakes in the coming year and decade

| | **Magnitude Range** | **Chance of occurrence:** **Range** (best estimate) |
|---|---|---|
| **Within the *next year*** | **M7.8** or greater | **0.3% to 3%** (1%) |
| | **M7.0** or greater | **2% to 14%** (6%) |
| **Within the *next decade*** | **M7.8** or greater | **2% to 20%** (7%) |
| | **M7.0** or greater | **10% to 60%** (30%) |



## KEYWORDS

earthquake forecast, slow slip, Hikurangi subduction, expert elicitation

# 1.0 INTRODUCTION

The Mw 7.8 Kaikōura earthquake occurred on November 14, 2016 on the northeastern part of the South Island. It ruptured a complex network of mostly-on-land faults in proximity to the Hikurangi megathrust. By November 25th it became apparent, through continuous GPS observations, that wide spread slow slip events (SSE) had begun to occur on the Hikurangi margin. Based on the timing of the onset of the SSE, it was assumed that they were likely dynamically triggered by the passing main shock energy and locally increased stress.

At that time, three regional SSE were modelled to be occurring: East Cape, Hawke Bay and Kapiti (Figure 1). While SSE in these regions have been observed numerous times in the past 20 years, the behaviour of the triggered SSE were believed to be unique for two reasons:

1) all three events had never been observed to occur simultaneously;

2) The apparent larger than usual slip rate at which slip was occurring on the Kapiti SSE.

These observations raised concern in the seismological community about the impact of the SSE on future earthquake occurrence for several reasons:

- A locked segment of the Hikurangi megathrust, beneath the lower North Island, has not been observed to have slipped since geodetic observations began in the early 2000s. This segment is largely surrounded by the SSE, and the impact of the SSE on the locked patch was unknown;

- The apparent and likely triggering of the SSE by the Kaikōura main shock, and the likely loading of portions of the locked segment by the main shock;

- On November 23rd, a Mw 6.1 occurred on the Hikurangi megathrust at the transition from the Hawke Bay SSE to the locked segment.

On November 25th, the Ministry of Civil Defense and Emergency Management (MCDEM) was notified of the concerns, and on November 26th, information about the SSE and the potential for it to impact future earthquake occurrence was disseminated via the GeoNet website (http://www.geonet.org.nz/news/3V1CSAmmLuaYa2sYoue2O0).

Following the briefing with MCDEM on the 25th, it became apparent that there was an expectation of more formal advice from GNS Science on the likelihood of future M≥7.8 events in central New Zealand, including any potential impact of the ongoing SSE on this likelihood. At this point, GNS began informal discussion with overseas experts on this topic and on possible ways to model this impact. Concurrent to these discussions, GNS began compiling multiple streams of “evidence” to help inform the development of probabilities of future large earthquakes. Little existing research was available to guide the determination of a quantitative expectation of future events and international research to explicitly model the impact of SSE on future earthquake probabilities is immature (e.g., Mazzotti and Adams, 2004; Beeler, et al, 2014; Leptokaropoulos, et al, 2014; Segall and Bradley, 2012; Dixon, et al, 2014) with most research focussed on detecting and modelling of SSE.

## 1.1 DECEMBER 2016 FORECAST WORKSHOP

Between November 26th and December 1st several datasets and model outputs were compiled. These results were used to inform a discussion (December 1st) between 11 NZ scientists who

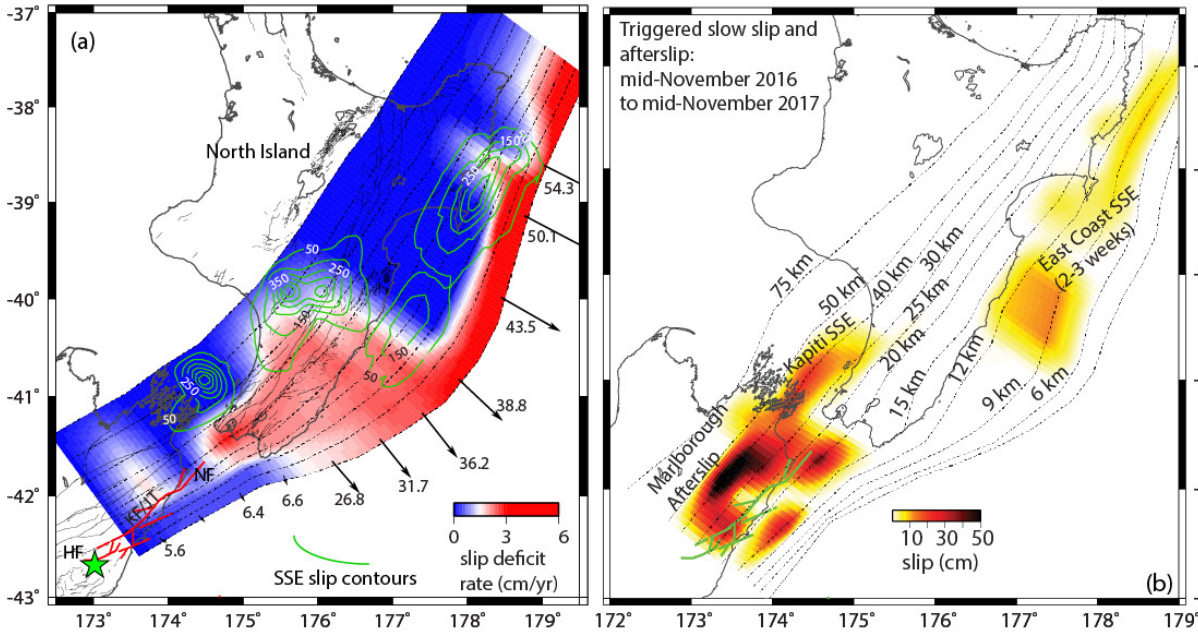


Figure 1: (a) Tectonic setting of the northern South Island and the North Island of New Zealand. Red to blue colors show the degree of interseismic locking on the Hikurangi subduction thrust, and past slow slip events there (after Wallace et al., 2012a, 2012b). Black arrows show motion of the overriding plate relative to the Pacific Plate at the Hikurangi trench (labeled in mm/yr). Green star shows epicenter of the Kaikōura earthquake, and red lines show traces of the faults that ruptured during the Kaikōura earthquake (from Hamling et al., 2017). HF=Hope Fault; KF/JT=Kekerengu Fault and Jordan Thrust; NF=Needles Fault (b) Total slip on the Hikurangi subduction interface during the year following the Kaikōura earthquake (yellow to hot colors) estimated from time-dependent inversions of GPS timeseries and InSAR line of sight change data. Kapiti slow slip and Marlborough Afterslip is still ongoing one year on, while the East Coast SSE lasted 2-3 weeks (Wallace et al., 2017).

were tasked with estimating the probability for a M≥7.8 (i.e., equal to or greater than the Kaikoura main shock) within the next year. For this discussion, five strands of evidence were compiled and will be discussed in detail in later sections:

- **Statistical forecasting models**: GeoNet has regularly published earthquake forecasts for the Kaikōura and other regions (Gerstenberger et al, 2014, 2016; Rhoades, et al, 2016) using a collection of models that represent clustering on different time scales.

- **Rate increases during past New Zealand SSE:** this consisted of an analysis of seismicity rate changes during 23 large SSE since 2003. We also included an analysis that included the 30 days following SSE. On average an increase in rates by a factor of 1.4 is seen.

- **Synthetic seismicity simulations:** We have analysed a synthetic seismicity catalogue that contains many millions of years of events (Robinson, et al, 2011). The catalogue was developed using a fault model for central New Zealand based on the National Seismic Hazard Model source model (NSHM; Stirling, et al, 2012). In this catalogue there is a 2% probability of a M≥7.8 earthquake within 1 year following any other M≥7.8.

- **Paleoseismic observations:** Paleoseismic observations related to past large earthquake on the Hikurangi is sparse. There may be some suggestion of a temporal correlation of past Hikurangi earthquakes and large crustal earthquakes; however, this is preliminary and the uncertainties are large.

- **National Seismic Hazard Model (long-term expectation).** The long-term time-independent rate of large events in this region from the NSHM is 0.5% to 0.8%. This is dominated by the Hikurangi and is poorly constrained based on the sparse paleoseismic observations.

Using this information as guidance and through an informal and unstructured elicitation process, each expert was asked to independently provide their best estimate, and 90% confidence bounds for the probability for an M≥7.8 within the next year (from December 1st, 2016). The region was loosely defined as "as the Lower half of North Island and Kaikōura Aftershock zone as presented on the GeoNet webpages today". Results were collected from each expert by the day following the workshop and we did not aim to reach consensus on the probability as we wanted to capture the potentially wide range in views across experts; we also do not feel it is reasonable to achieve consensus on this or other similar problems (Gerstenberger, et al 2016). To obtain the final result, we averaged the best estimates and confidence bounds across all experts.

The final estimate was a 5% probability (2% to 8%) of a M≥7.8 within the next year (from December 1st, 2016). The estimates from all experts can be seen in Figure 2. Across experts, the best estimates ranged from 3% to 7% with the 90% confidence bounds ranging from 1% to 12%. This was the first time such a modelling exercise for SSE had been undertaken anywhere in the world.

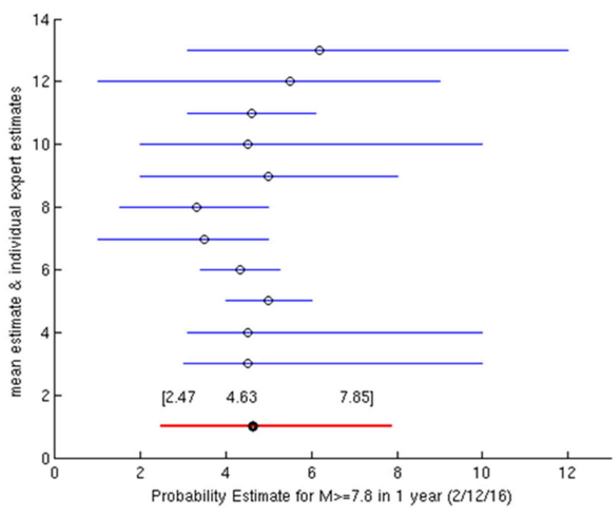


Figure 2: Probabilities from across the range of experts in December 2016, prior to this NHRP project. The blue lines represent each expert's estimates and the red represents the average of all experts.

On May 1st a new Natural Hazards Research Platform project was started with the goal of further developing the research from December, 2016. This project had an overall goal of revising the probability of a M≥7.8 within the next year with two main steps to achieve that: 1) re-evaluate and extend the December 2016 modelling done on in the impact of SSE on future earthquake probabilities; 2) conduct an international expert panel to evaluate the modelling and to determine the revised probability.

In remainder of this report we discuss the development of those probabilities.

## 2.0 REVISING THE PROBABILITIES

In this project, we had two main goals:

1) *revise the model from the 2016 elicitation exercise, and develop new models that specifically address the role of SSE in future earthquake occurrence;*
2) *conduct a sequence of expert workshops:*
    a. *September 9th, 2017: preliminary model international peer review and suggestions for improvements and alternative models;*
    b. *November 14th-15th: an international expert elicitation workshop to estimate the revised probabilities;*

There are no well-established and tested models that explicitly account for the role of SSE in earthquake forecasts. With the government expectation of providing quantitative probabilities, we had to understand what SSE influence was in existing models, and to establish what other evidence could be established that would help guide the estimation of the probability of large events in central New Zealand. It was not possible to rely directly on model probabilities of future events, however the established and tested models played a central role in the probability estimation. The aim was to use expert-judgment to assess the available models and to determine the final outcomes.

### 2.1 MODELS AND OBSERVATIONS

As with almost any area of seismology, no single model or observation was expected to fully capture the process we wished to model: the SSE and earthquake-occurrence interaction process. By using and developing a range of models, we aimed to explore as many parts of this process as possible (during the short time we had available). The specific types of models and observations that we targeted were developed in a series of meetings, informal discussions and finally, at the first expert workshop in September.

The models and observations will be discussed in detail in Section 4.

## 3.0 THE EXPERT WORKSHOPS

Two workshops were held throughout the process of estimating the probabilities. The first was an informal workshop held on September 9th, 2017 in Palm Springs, California. It was held in Palm Springs to take advantage of the numerous scientists already present for the Southern California Earthquake Center 2017 Annual Meeting; however, our workshop was not associated with the meeting. Prior to this workshop, the GNS research team had been meeting and individually working on preliminary models and observations. The goal of the September workshop was to present the preliminary work for peer review and to discuss any new approaches that should be considered. Present at this workshop were: M. Gerstenberger, L. Wallace, B. Fry, and D. Rhoades (all from GNS Science); M. Stirling (University of Otago); E. Brodsky (UC Santa Cruz, USA); N. Van der Elst and N. Beeler (USGS, USA); B. Shaw (Lamont-Doherty, USA); K-F Ma (NCU Taiwan); W. Marzocchi (INGV, Italy); J. Vidale (USC/SCEC, USA); H. Houston (University of Washington, USA); Present on video conference from New Zealand were Y. Kaneko and S. Bannister (GNS) and J. Townend (VUW). This was an approximately four-hour workshop with a series of presentations by: M. Gerstenberger, L. Wallace, Y. Kaneko, D. Rhoades and B. Fry. Specific outcomes of this workshop were a range of improvements for each of the individual models presented, and the formulation of an alternative baseline model to be constructed by GNS.

In the 9 weeks following the September workshop final versions of the models and observations were developed by GNS Scientists.

A formal workshop to estimate the probabilities was held at GNS Science on November 14th and 15th. Similar to the September workshop, there was a series of presentations on each model or observation. Following each model presentation there was time allowed for detailed discussion of the model and its implications. Each day also had time allotted for general discussion.

Because the goal of this workshop was to elicit specific probabilities, the workshop design was more formal than for the first workshop. Two components of this were: 1) the selection of experts; and 2) the use of a structured expert elicitation procedure. Both of these components followed similar procedures as laid out in previous work by the authors (Gerstenberger, et al, 2014, 2015, 2016; Gerstenberger & Christophersen, 2016). The experts were selected to cover the diverse range of topics necessary for modelling the impact of SSE on forecast probabilities. With an aim to minimise bias, experts from early to late career and experts independent of the process prior to the second workshop were selected. Other specific aims were to have experts with the ability to challenge traditional thinking and basic assumptions of the group, and to have experts who were not committed to pre-existing ideas. Due to a scheduling conflict (i.e., a major international paleoseismology meeting happening in New Zealand at the same time), paleoseismology was missing direct representation; however, care was taken to best represent relevant paleoseismology knowledge at the workshop.

The experts on the panel in workshop 2 who contributed to the final probability estimates include: E. Brodsky (University of California, Santa Cruz), D. Dempsey (University of Auckland), B. Fry (GNS Science), I. Hamling (GNS Science), N. Hirata (ERI, University of Tokyo), C. Holden (GNS Science), H. Houston (University of Washington, Y. Kaneko (GNS Science, K-F Ma, D. Rhoades, B. Shaw, J. Townend, J. Vidale, and L. Wallace. M. Gerstenberger (GNS Science) facilitated the workshop. A. Christophersen (GNS Science) and C. Williams (GNS Science) developed the calibration questions.

## 3.1 THE ELICITATION PROCEDURE

Structured expert elicitation is the process of using expert judgment like scientific data (Colson and Cooke, 2017). There are two fundamental different approaches to combine expert judgment, behaviourally (e.g. O'Hagan, 2006) and mathematically (e.g. Cooke, 1991). Mathematical methods are generally more objective and better auditable. In particular, the Classical Model of Cooke (1991) aims to capture the uncertainty across experts. At the heart of this method is the acknowledgement that it is not reasonable to expect scientific consensus on a problem as challenging as the one faced in this workshop. The method aims to capture the uncertainty across experts, and asks the experts to agree with the process, but not necessarily the final result.

The Classical Model is a performance-based approach to mathematically combine expert judgments and has been developed with the aim to use expert judgement like scientific data (Cooke, 1991; Colson and Cooke, 2017). An integral part of the method is the weighting of the experts' answers to the target questions according to their performance on so-called seed or calibration questions. These are questions that are similar in nature to the target questions and their answers are known to the analyst or will be known within the timeframe of the study (Aspinall, 2010). The experts provide a subjective uncertainty distribution for each question. We asked for a $10^{th}$, $50^{th}$ and $90^{th}$ percentile to capture the uncertainty in the answers. To avoid anchoring it is useful to encourage the experts to think about their upper and lower boundaries before providing their best estimate (Quigley et al., 2018)

One example calibration question asked of the experts is as follows:

*Bartlow et al (2014) performed time-dependent inversions of continuous GPS data on the Hikurangi from late 2009 to early 2012 using the Network Inversion Filter (Segall and Matthews, 1997; McGuire and Segall, 2003; Miyazaki et al., 2006). During this time-period, they observed 12 major slow slip events, with equivalent moment magnitude ranging from 5.9 to 6.9. Assuming a shear modulus of 30GPa and a Poisson's ratio of 0.25, what was the total cumulative moment release (in Nm) over the entire two-year period? Please give your best estimate and 80% confidence bounds. (answer: 1.25E20 Nm)*

## 3.2 DEFINING THE PROBABILITIES TO BE ASSESSED

From the onset of the project the goals were loosely defined as revising the forecasting probabilities including the impact of SSE. Therefore, the preliminary target was to revise the probability of M≥7.8 in central New Zealand, within the next year. Over the course of the project, the details of the specific elicitation questions were defined. The questions were defined with consideration for: 1) the existing Scenario 3 from December 2016; 2) the variability in the detail in the forecasts produced by the models (e.g., Hikurangi Megathrust specific vs regional); 3) a desire to communicate the temporal change in the probabilities; and 4) a desire to be able to communicate a comparison of the probabilities for different magnitude thresholds. Because the end result of this project was information for government, public and industry consumption, it was important that the final results could be communicated in a meaningful way.

All definitions were allowed to be changed during the workshop if they were determined to be inappropriate by the experts. In practice, this did not happen despite discussion around some of the definitions.

## 3.3 UNCERTAINTY ON A PROBABILITY

Although the elicitation results were expected to be heavily informed by quantitative model results, it was ultimately a subjective process driven by the best estimates provided by each expert. To determine their best estimate, the experts were asked to consider all models and observations presented to them, as well as any particularly knowledge they brought with them or developed during the workshop discussions. Given the difficulty and hence uncertainty involved in determining this subjective best estimate we asked all experts to provide their 80% confidence bounds on their best estimate to allow a confidence in the final result to be communicated to the end users.

## 3.4 MAGNITUDE RANGE AND TIME WINDOWS

For consistency with the December 2016 scenario, the exercise was repeated for M≥7.8. To aid in communication of the results, probabilities were also elicited for M≥7.0. No upper bound magnitude for either of these imposed.

Also for consistency with the previous scenario, a time-period of 1 year from November 15$^{th}$, 2017 was used. Additionally, a second time-window of 10 years from November 15$^{th}$, 2017 was used. This second time-window was selected largely based on decadal scale rate increases from the statistical clustering forecast models (see Section 4). The window was used to develop an understanding of the probability on this time-scale, and to also allow for communication of the time-dependence of the probabilities and that earthquake rates would likely remain increased beyond the 1-year time-window.

## 3.5 THE REGION

The region for the elicitation is show in red Figure 3. A polygon was selected for the region that encompassed the locked patch of the Hikurangi Megathrust below the lower North Island and that also included the SSE directly surrounding the locked patch. The Alpine Fault was specifically excluded from the region to avoid complication in estimating the probabilities and also to avoid complication in communicating the results. The region is defined for hypocentres occurring within the region and at depths of 40km or shallower; in other words, while the forecast region could not accommodate a M9 rupture, such an event is not necessarily excluded from the forecast as it could initiate within the region and rupture beyond its borders. The region defined for this elicitation reflects some expectation of a northward progression of seismicity from both the models and the experts. For comparison, the standard GeoNet Kaikōura forecast region is shown in blue.

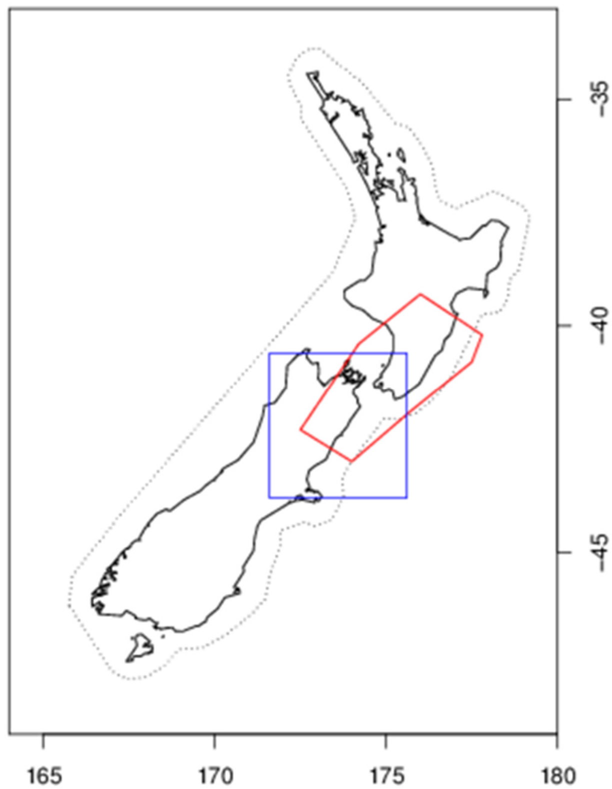


Figure 3: The elicitation region in red as compared to the GeoNet Kaikōura aftershock forecast region in blue.

### 3.5.1 The elicitation questions.

The four elicitation questions as asked to the experts are as follows:

**Q1:** What is the probability of occurrence of a magnitude 7.8 earthquake or larger with hypocentre in the region of interest and shallower than 40 km within **one year** from 15 November 2017?

10%________50%________90%_________

**Q2:** What is the probability of occurrence of a magnitude 7.8 earthquake or larger with hypocentre in the region of interest and shallower than 40 km within **ten years** from 15 November 2017?

10%________50%________90%_________

**Q3:** What is the probability of occurrence of a magnitude M7 or larger earthquake with hypocentre in the region of interest and shallower than 40 km within **one year** from 15 November 2017?

10%________50%________90%_________

**Q4:** What is the probability of occurrence of a magnitude M7 or larger earthquake with hypocentre in the region of interest and shallower than 40 km within **ten years** from 15 November 2017?

10%________50%________90%_________

## 4.0 THE MODELS AND OBSERVATIONS

In this section, we present the models, observations and results that were calculated between July and workshop 2 in November. All models, observations and figures are presented in the exact state and formulation as used for workshop 2. This is done to preserve the record of what was available for informing the expert judgement in workshop 2.

### 4.1 OBSERVATIONS OF EARTHQUAKE RATES DURING SSE IN NEW ZEALAND

Using observed SSE, since 2003, we have quantified some basics aspects of earthquake activity that is spatially and temporally correlated with SSE and compared that to seismicity that is not directly correlated with SSE.

To accomplish this, we have formulated a catalogue of 30 SSEs of M6.3 and greater since 2003, when GPS observations first became available. We compared this to the GeoNet earthquake catalogue from the same time period.

We calculated seismicity rates changes by comparing the daily rate of events during SSEs to the daily rate of events during all times when an SSE had not been identified for the same region. We compared the rate changes in four different time windows. In each time-window we apply one of four lookahead times for calculating the SSE related seismicity rate changes: 0 days, 30 days, 365 days and 730 days. For example, for 365 days lookahead time, SSE related seismicity rates are calculated from the start of the SSE to 365 days beyond the end. These results indicate that earthquake rates approximately double during SSE and decay back to the long-term rate over the next two years.

### 4.2 TEMPORAL EARTHQUAKE MOMENT-RELEASE DISTRIBUTION

To gain insight into the question of whether SSE are more likely to trigger earthquakes late in their evolution, we looked at the temporal distribution of earthquake related moment release across all SSE, where moment is the amount of energy released during an earthquake (Figure 4). These results show, that since 2003, large earthquakes are no more likely to occur late in an SSE than at any other time.

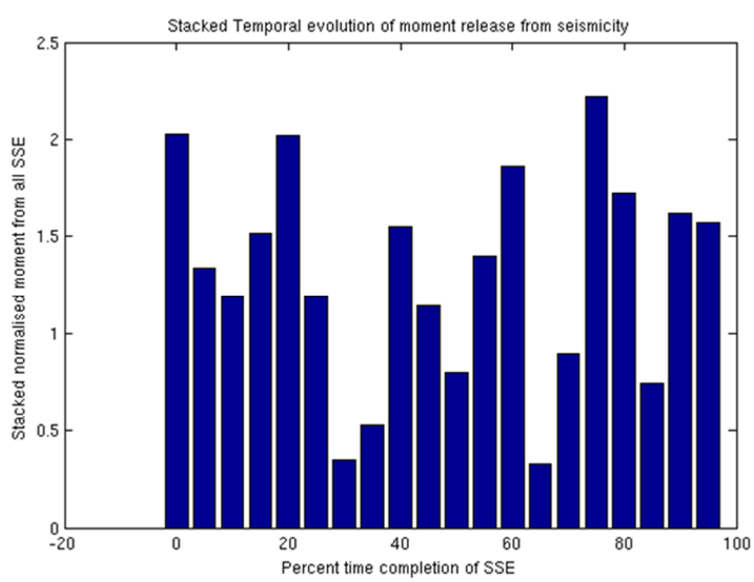


Figure 4: Relative time-distribution of energy released from earthquakes during all SSE.

## 4.3 A SIMPLE MODEL BASED ON RECURRENCE

To explore a model of least information, i.e., a simple and potentially baseline model, we ran multiple simulations using a model with a few basic assumptions. The assumptions were as follows: the megathrust will rupture with a single characteristic magnitude and the earthquake is always coincident with a SSE; the characteristic earthquake has a range of plausible recurrence intervals (100 – 1500 years); the occurrence rate of SSE is 0.5/year to 2.5/year. Since observations began, the rate is approximately 2/year; the impact of concurrent SSE is additive and we explored from 1 to 4 concurrent SSEs. This simple model suggests that the largest probabilities of 2% and greater and are only seen for extremely short recurrence intervals of around 100 years, and for four concurrent SSEs. Probabilities of 1% are seen for 2 to 4 concurrent SSEs and for recurrence intervals of less than 300 years.

## 4.4 MAGNITUDE CONVERSION MODELS

Subduction related SSEs in New Zealand are commonly coeval with elevated rates of earthquakes. However, when the SSE and related earthquakes are treated as mainshock-aftershock sequences, standard equations that forecast aftershocks over-predict the number of subsequent events; for a given magnitude main shock, standard earthquakes produce more aftershocks than SSEs. We must therefore treat SSE differently than normal earthquakes during forecasting. In an effort to model increased rates associated with SSE, we have analysed them using 1) a statistical model that describes the occurrence of aftershocks following large earthquakes and 2) a physical model that describe the physical earthquake process in terms of stress changes and varying frictional properties of faults. In the following, we will discuss each of these individually.

### 4.4.1 Statistical Magnitude Conversion

In the first model, we convert the standard SSE magnitude (Wallace, et al, 2017), to an equivalent magnitude using standard aftershock models (Reasenberg & Jones, 1989, 1994). To do this, we apply the aftershock model backwards in comparison to normal forecasting. In other words, we say: if we have observed this many aftershocks, what does the aftershock model predict the main shock magnitude to have been? For all 30 SSEs, we find the number of M≥4.0 earthquakes associated with the SSE and then calculate what the average New Zealand main shock magnitude is that would produce the same number of aftershocks. We then assign that magnitude to the SSE. In all cases the equivalent magnitude is smaller than the standard SSE magnitude.

### 4.4.2 Physics-based Magnitude Conversion

Based on laboratory experiments meant to simulate earthquake cycles, equations have been established to model earthquake occurrence in terms of stress-transfer processes. Rate-state is one such approach (Dietrich, 1996). We apply the fundamental equations of rate-state to first define the background stressing rate of the Hikurangi Margin (Dietrich, 1996, equation 5 and 6). We then use the number of earthquakes following the Southern Hawke's Bay triggered SSE (Figure 5) to quantify the increased stressing rate imposed by the SSE using equations 4 and 8 from Segall et al., (2006). We find that the ratio of stressing rate during the SSE to the background rate is about 4:1. This equates to a stressing rate of about 0.3MPa per fortnight. Based on this, we have estimated the SSE-driven increased probabilities of M≥7 in 1 year (0.1%), M≥7.8 in 1 year (0.01%), M≥7.0 in 10 years (3.2%) and M≥7.8 in 10 years (0.39%).

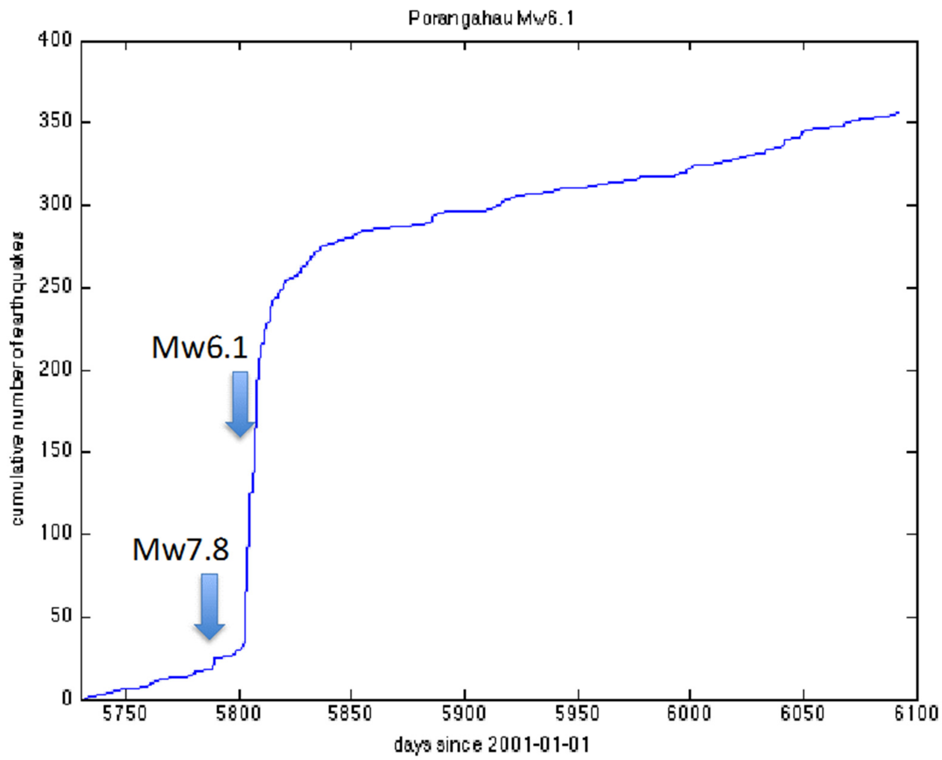


Figure 5. Plot showing the cumulative number of earthquakes in the region of the Southern Hawke's Bay triggered SSE before, during, and after the Mw7.8 earthquake. Note, the largest increase in seismicity occurred almost 2 weeks after the Mw7.8. This correlates to the onset of the triggered SSE. We use this sequence for stress analysis with rate-state theory.

## 4.5 STATISTICAL CLUSTERING MODELS

This class of models represents the models used for the standard GeoNet earthquake forecast models as used for the Kaikōura earthquake sequence, the Canterbury earthquake sequence and numerous other earthquakes since 2010. The hybrid model is the model used for construction of the Kaikōura Seismic Hazard Model (Gerstenberger, et al, in prep.). For each model, a 1-year and 10-year forecast was calculated.

The model is similar in many ways to the hybrid forecasting model that was constructed for Canterbury following the 2010 Darfield and 2011 Christchurch earthquakes (Gerstenberger et al., 2014, 2016; Rhoades et al., 2016). However, the model now has separate short-term and medium-term time-varying components instead of just a single time-varying component. Also, the long-term component now includes information on strain rates as well as past earthquakes. This is the first time that geodetic observations have been included in such a direct way in operational earthquake forecasts in New Zealand.

The models used are short-term aftershock clustering models: STEP (Gerstenberger, et al, 2005), ETAS model (Ogata, 1988; Harte, 2013; 2015; 2016); medium-term clustering models: EEPAS0 and EEPAS1 (Rhoades and Evison, 2004); and long-term models: PPE-Strain rate and PPE (Rhoades, et al, 2016) and the background from the NSHM (Stirling, et al, 2012). Additionally, various statistically optimised combinations of the models (i.e., hybrids) were created. Hybrid models have been demonstrated to provide significantly improved forecasts over any individual model (e.g., Rhoades et al, 2016).

New forecasts were created that use augmented catalogues where SSE were added to the GeoNet catalogue data set with four methods of calculating the equivalent SSE magnitude: 1) standard SSE magnitude based on the area of the SSE and how much it slipped (Wallace, et al, 2017); 2) calculating a magnitude based directly on reduced numbers of aftershock when compared to normal New Zealand aftershock sequences (Section 4.4; Reasenberg & Jones, 1989, 1994); 3) a regression between numbers of aftershocks and standard SSE magnitudes; and 4) calculating a magnitude based on the earthquake rate in the first 30 days after the start of the SSE using standard aftershock scaling (Section 4.4; Reasenberg & Jones, 1989, 1994).

All forecast earthquake rates and probabilities are shown in Table 1.

Table 1: Forecast earthquake rates and probabilities from statistical clustering models

| | **1 year** | | **10 years** | |
|---|---|---|---|---|
| **Model** | **M≥7.0** | **M≥7.8** | **M≥7.0** | **M≥7.8** |
| Long-term PPE-Strainrate | 0.0093 (0.93%) | 0.0011 ((0.11%) | 0.093 (8.9%) | 0.011 (1.1%) |
| Long-term time-invariant hybrid | 0.014 (1.4%) | 0.001649 (0.16%) | 0.14 (13%) | 0.016 (1.6%) |
| STEP aftershocks only | 0.059 (5.7%) | 0.0082 (0.81%) | 0.19 (17%) | 0.027 (2.7%) |
| ETAS aftershocks only | 0.0091 (0.9%) | 0.0011 (0.11%) | 0.036 (3.5%) | 0.0043 (0.42%) |
| EEPAS0 | 0.024 (2.4%) | 0.0016 (0.16%) | 0.22 (20%) | 0.017 (1.7%) |
| EEPAS1 | 0.020 (2.0%) | 0.0017 (0.17%) | 0.19 (17%) | 0.017 (1.7%) |
| Max hybrid | **0.051 (5.0%)** | **0.0061 (0.61%)** | **0.32 (27%)** | **0.036 (3.5%)** |
| Max hybrid EEPAS catalog augmented with SSE Mw (Wallace) | **0.054 (5.2%)** | **0.0080 (0.80%)** | **0.35 (30%)** | **0.058 (5.6%)** |
| Max hybrid EEPAS catalog augmented with SSE $M_{Rate}$ (Fry) | **0.056 (5.4%)** | **0.0071 (0.71%)** | **0.36 (30%)** | **0.044 (4.3%)** |
| Max hybrid EEPAS catalog augmented with SSE $M_{N30}$ (Fry) | **0.054 (5.2%)** | **0.0063 (0.63)** | **0.35 (29%)** | **0.037 (3.7%)** |
| Max hybrid EEPAS catalog augmented with SSE $M_{Nreg}$ (Rhoades) | **0.054 (5.3%)** | **0.0066 (0.66%)** | **0.34 (0.29)** | **0.039 (3.8%)** |

#### 4.5.1 Simulations using stress changes from SSE and megathrust events

In this model, we develop a relatively simple simulation-based model for estimating the probability of a large subduction-zone earthquake following SSEs in places where there is no or little record of the timing and size of historical large earthquakes, such as the Hikurangi subduction zone. The model relies on estimates of stress changes on a subduction interface due to nearby SSEs and large earthquakes, combined with a local geodetic slip deficit rate and stress drops of global subduction earthquakes inferred from seismological observations. We apply this model to the locked portion of the southern Hikurangi subduction megathrust, which has been loaded by the M7.8 Kaikōura earthquake and surrounding SSEs since November 2016.

In this approach, estimating the probability of a large subduction earthquake involves following three steps: (i) Calculating stress changes due to the Kaikōura earthquake and SSEs on the locked portion of the Hikurangi megathrust; (ii) Constructing a synthetic earthquake-time history expressed in terms of shear stress evolution on the megathrust over millions of years; (iii) Computing the probability of triggering of a large earthquake based on the concept of clock advance, that is, a positive stress perturbation shortens the time of an earthquake that would have happened eventually under background tectonic loading alone (Harris, 1998). A simple cartoon of the model is shown in Figure 6.

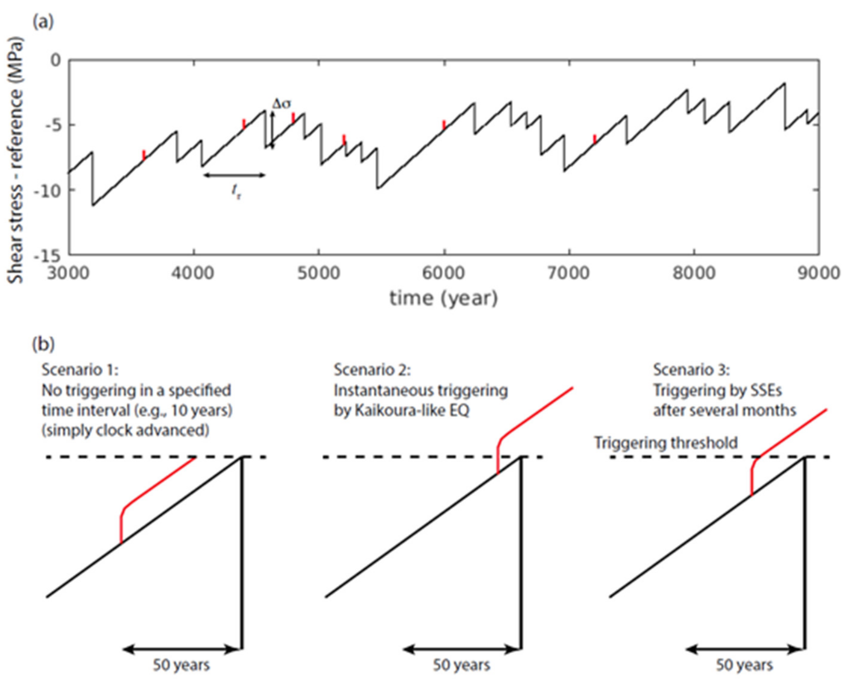


Figure 6. (a) An example of synthetic earthquake-time history represented by stress evolution on the locked portion of the Hikurangi megathrust. Δσ is the stress drop of earthquakes and $t_r$ is the inter-event time. Red line corresponds to a total time-dependent stress perturbation Δτ from the Kaikōura earthquake and SSEs (exaggerated for illustration). (b) Sketch illustrating possible scenarios following stress perturbation.

The results of this model suggest the probabilities of a M>7.8 subduction earthquakes are in the range of 0.3 - 1.4% for November 2017 - November 2018 and 3.2 - 11% for November 2017 - November 2027. The equivalent probabilities of a M>7.0 subduction earthquake ares in the range of 1.5 - 2.5% for 12 November 2017 - 12 November 2018 and 13 - 18% for

November 2017 – November 2027. Probabilities of a large subduction earthquake are mainly controlled by the ratio of the total stressing rate to the mean stress drop of large earthquakes, which can provide a back-of-envelope estimate consistent with the results of the statistical analysis

## 5.0 RESULTS

The probabilities estimated by the experts are show in Table 2. They can be summarized as follows:

a. Within the next year there is between a 0.3% and 3% chance of a M7.8+ earthquake (best estimate: 1%) and between a 2% and 14% chance of a M7.0+ earthquake (best estimate: 6%).

b. Within the next decade, there is a 2%-20% chance of a M7.8+ earthquake (best estimate of 7%) and a 10%-60% chance of a M7.0+ earthquake (best estimate of 30%).

c. The best estimates for the next year for M7.0+ and M7.8+ represent increases of 20% and 100% respectively over the long-term estimates from the National Seismic Hazard Model. The upper bounds for both of these magnitude range estimates are a significantly greater increase. Similarly, the upper bounds on the decade estimates are a significant increase over the long-term estimates.

d. The range of probabilities show the experts' uncertainty around what we can expect. For example, small ranges mean they are more certain of the probability, large ranges mean they are less certain.

Table 2: Probabilities of large earthquakes in central New Zealand within the next year and decade

| | **Magnitude Range** | **Chance of occurrence: Range** (best estimate) |
|---|---|---|
| **Within the *next year*** | **M7.8** or greater | **0.3% to 3%** (1%) |
| | **M7.0** or greater | **2% to 14%** (6%) |
| **Within the *next decade*** | **M7.8** or greater | **2% to 20%** (7%) |
| | **M7.0** or greater | **10% to 60%** (30%) |

Figures 7-10 show the probabilities as estimated by each of the experts for the four questions. These figures show the preferred combined results based on the calibration questions results, and also the average of all experts.

The general consensus across all of the models and data examined was that the impact of the SSE on the probability of future earthquakes was most significant in the first year following the Kaikōura earthquake. One year following the earthquake, the Kaikōura-triggered SSE have mostly stopped and their influence on future earthquakes is likely to be largely reduced.

The statistical clustering models appeared to be the core of the probabilities, with the other models and observations used to explore deviations and uncertainties in the estimates of the statistical clustering models.

The results of the study were publicly released via GeoNet on December 19th, 2017 (http://www.geonet.org.nz/news/5JBSbLk9qw8OU4uWeI86KG) and further announced in numerous media articles.

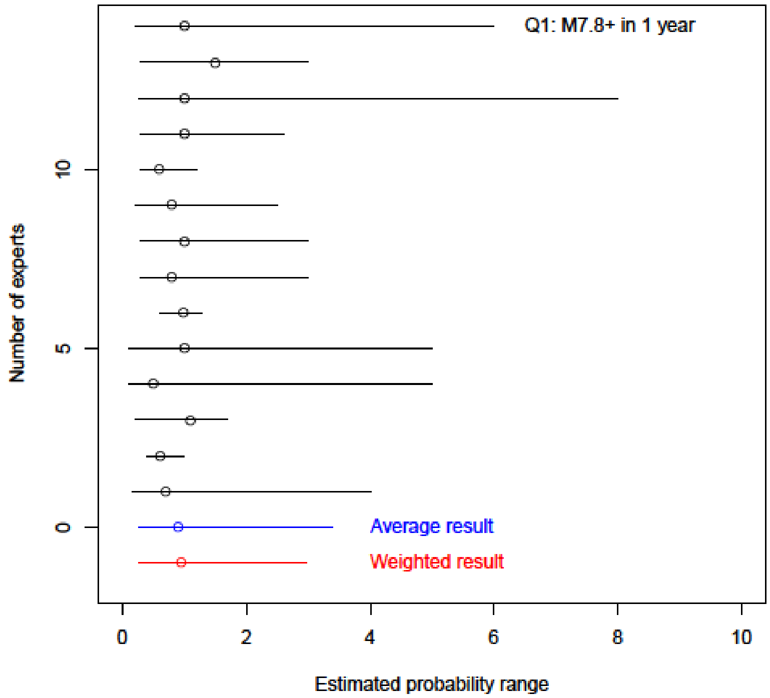


Figure 7: The range of expert probabilities for M≥7.8 within one year. Both the average result and the weighted result are shown. The weighted result is uses the calibration question weighting and is the preferred answer.

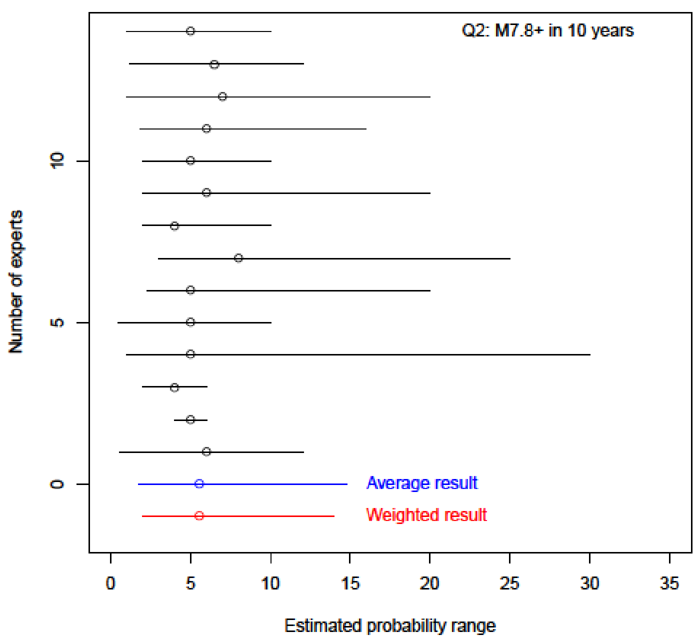


Figure 8: The range of expert probabilities for M≥7.8 within 10 years. Both the average result and the weighted result are shown. The weighted result is uses the calibration question weighting and is the preferred answer.

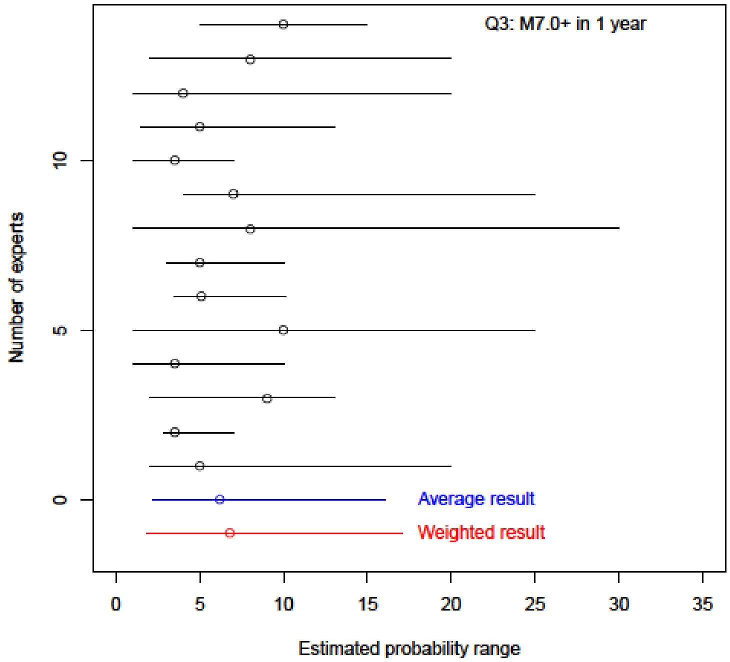


Figure 9: The range of expert probabilities for M≥7.0 within one year. Both the average result and the weighted result are shown. The weighted result is uses the calibration question weighting and is the preferred answer.

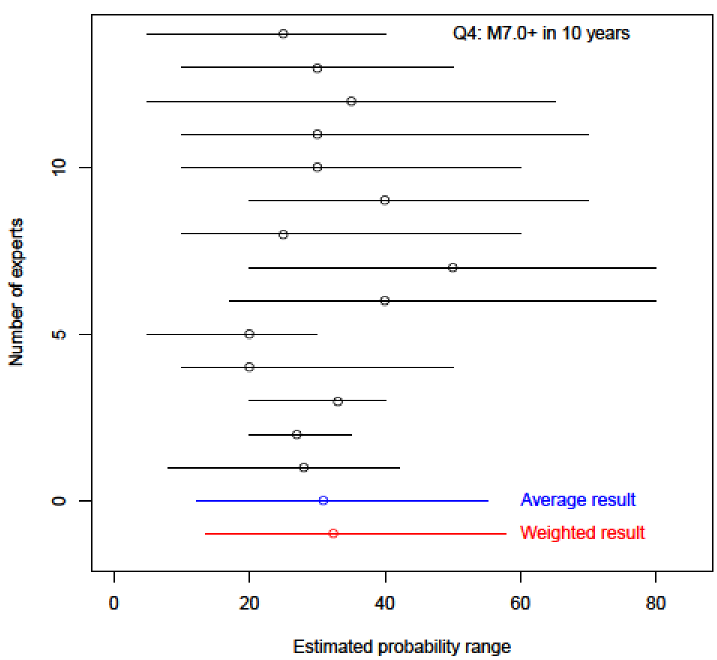


Figure 10: The range of expert probabilities for M≥7.0 within 10 years. Both the average result and the weighted result are shown. The weighted result is uses the calibration question weighting and is the preferred answer.

## 6.0 CONCLUSIONS AND FUTURE WORK

The exercise in December 2016 represented the first time forecast probabilities had been estimated that included the specifics of an ongoing SSE. In this work, we have developed new SSE specific forecast models that, again, represent the first attempt globally at doing so. This range of models and observations, when coupled with expert judgment have resulted in revised and credible probabilities for large events in central New Zealand within the next decade.

The models were developed within a very short time-frame, but have laid the groundwork for future more sophisticated models that will hopefully be able to better constrain forecast probabilities with reduced uncertainty. A number of research priorities were identified by the expert panel in workshop 2.

At the close of the workshop, the experts were asked to rank the models with the following question: *Please score the following models/methods on a scale from 1 (not useful at all) to 10 (extremely useful) for their potential to contribute to future earthquake rate estimates when adjusting a hybrid model earthquake forecast to the occurrence of SSE.*

The results are shown in Table 3. The models receiving the most confidence from the panel were the standard hybrid forecast model as used by GNS and GeoNet, the strain-rate based hybrid, the equivalent magnitude conversions, and the simple physical simulator.

Table 3: usefulness of models for future SSE forecasting related research

| STEP | ETAS | EEPAS | Standard Hybrid | Strain-rate hybrid | Rate-state | Equivalent Magnitudes | Physical stress simulations |
|---|---|---|---|---|---|---|---|
| 5.6 | 6.2 | 6.0 | 7.8 | 7.2 | 5.8 | 7.1 | 7.2 |

A key priority for future research was identified as the development of an international working group focused on the topic understanding the role of SSE in earthquake occurrence. Initial ideas for setting up a working group were discussed. Other key priorities and quesitons were identified as follows:

- Disaggregation of EEPAS to understand what earthquakes contribute in different forecast scenarios
- Interface locking time: physical and statistical models
- What is the prior stress of the interface and what methods (e.g., paleo methods) can be used to better understand it
- Developing a better record of clustering of earthquake in New Zealand, both in the long-term paleo record and the historical record (e.g. the Dusky Sound earthquake to now)
- How to measure triggerability of the interface (i.e., its potential to rupture given the occurrence of other earthquakes)
- Understanding of late and large aftershocks
- Physical controls on low productivity sequences
- Spatial distribution of triggered earthquakes by SSE
- Template matching for more complete catalogues

- Analogues from around the world of earthquakes triggered by SSE
- Rate and state modelling
- What is the impact of multiple concurrent SSE?
- Mechanism of delayed triggering
- Synthetic seismicity modelling
- Full time-dependent inversions of slip, continuous estimates of strain/slip
- Formulate a testable model
- Non-stationary ETAS versus EEPAS and geodetic model
- A More complete catalogue of SSE including historical seismicity (e.g., ETAS)
- Quantification of uncertainty in SSE modelling
- Characterisation of megathrust, Mmax on Hikurangi?
- Effective magnitude of SSE
- What observations would have helped our response post Kaikōura?
- Re-evaluate southwest extent of Hikurangi subduction interface beneath the northern South Island in light of SSE evidence

## 7.0 ACKNOWLEDGMENTS

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