# Blurring the line between earthquake forecasting and seismic hazard

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GNS SCIENCE
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# Learning from the Canterbury Earthquake Sequence

I will draw heavily from what we have learned from Canterbury (and numerous more recent strong shaking events), but two key points to set the context:

**Moving beyond short-term (1-day 1-week 1-month) forecasting is necessary**

This has been particularly necessary for technical end-users and decision makers.

**Consistency between the OEF forecasts and long-term hazard is important**

This has been necessary for technical end-users and helpful for communication across all levels of users.

# The time-dependent hazard model for Canterbury

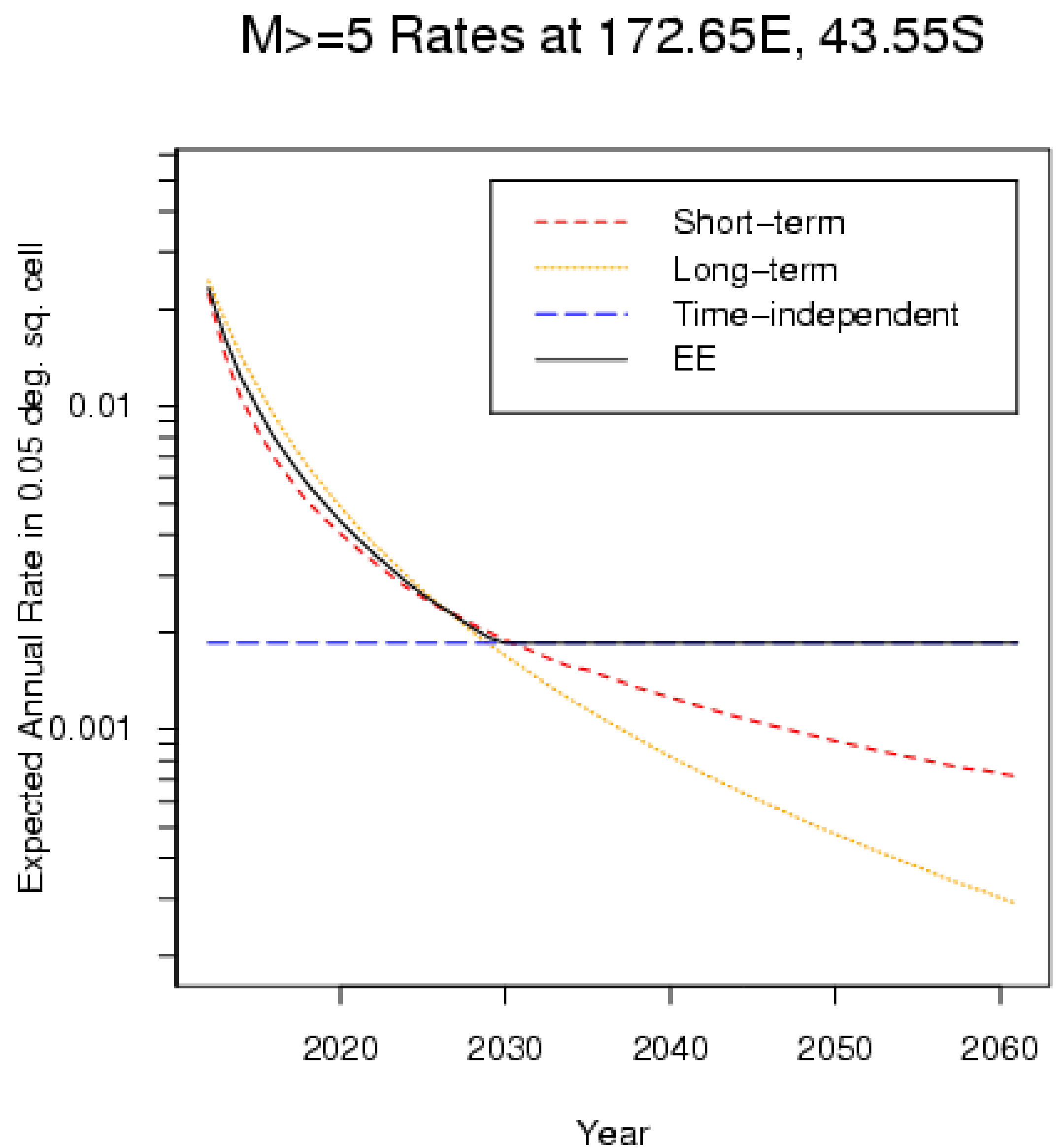
Requested by Government

For revision of building design standards & rebuild planning

Ultimately subjective (constructed by expert panel)

Aimed to capture uncertainty in our understanding of short-term and long-term rates

1yr to 50-yr forecast: hybrid combination of multiple models on three different time scales



# The time-dependent hazard model

Increasing time scale

***Short***-term clustering

- **STEP & ETAS (aftershocks)**

***Medium***-term clustering

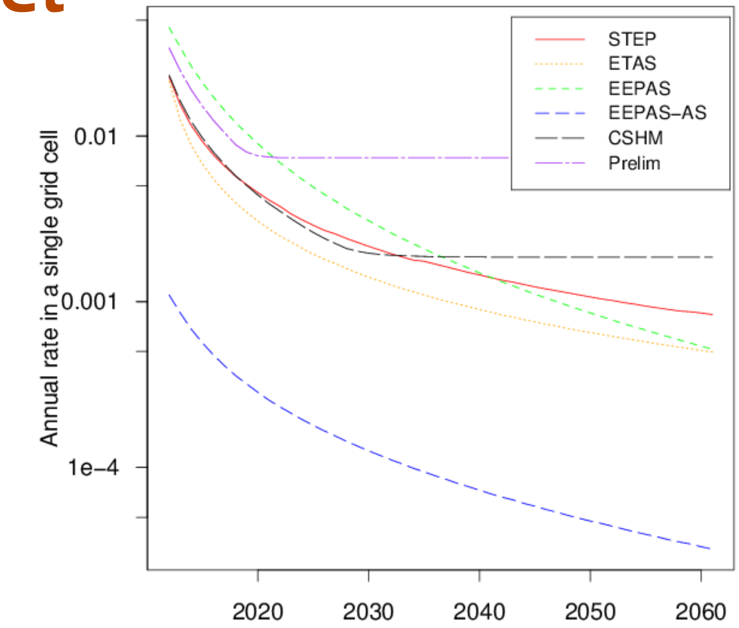
- **EEPAS 1&2 (years–decades )**

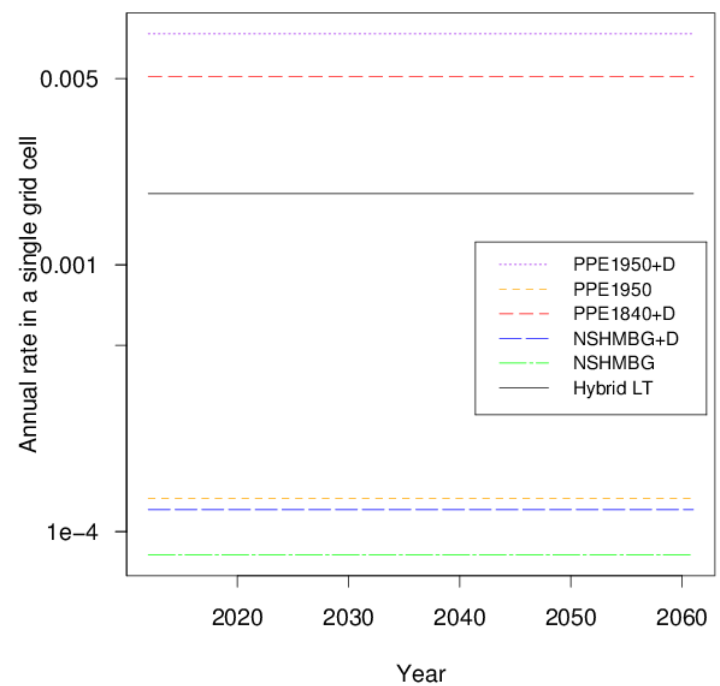
***Long***-term smoothed seismicity

- **PPE, NSHM (Gaussian), Helmstetter**

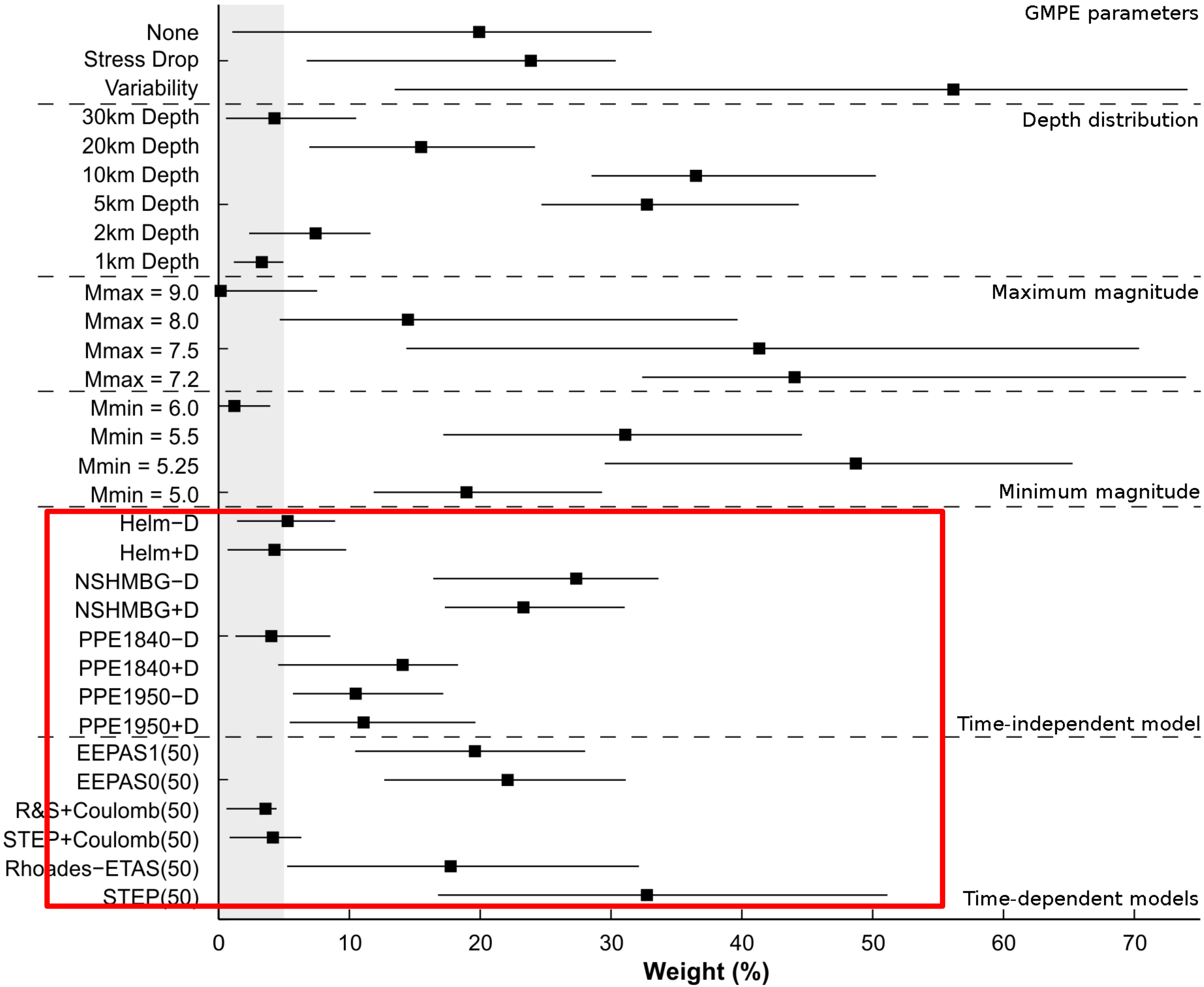
All models were implemented in CSEP testing centres prior to their use in the ensemble

Subsequent testing has shown the combined Model outperforms any individual model



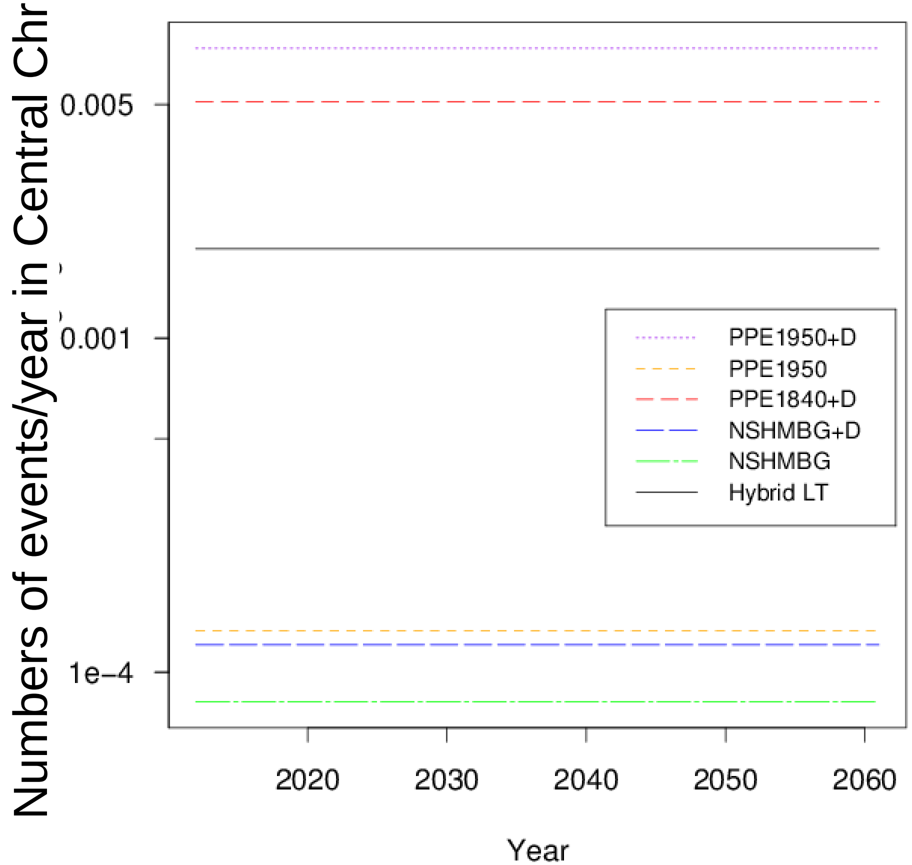



# Expert uncertainty (and not pursing consensus)

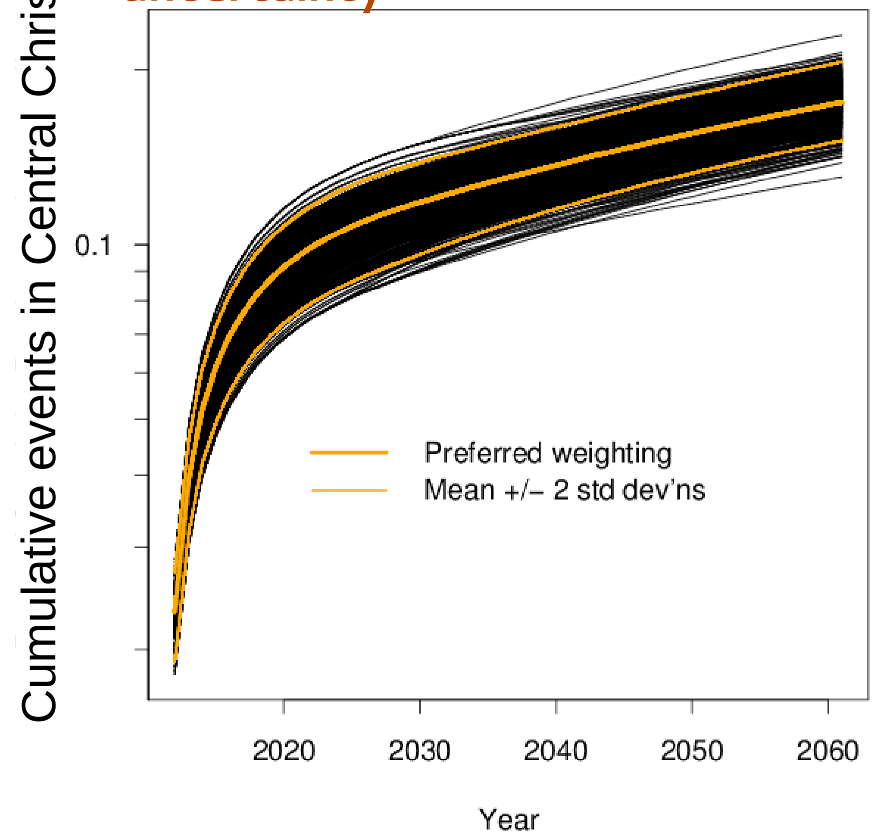


# Exploring the epistemic uncertainty

**Individual models**: Range of long-term rate across models

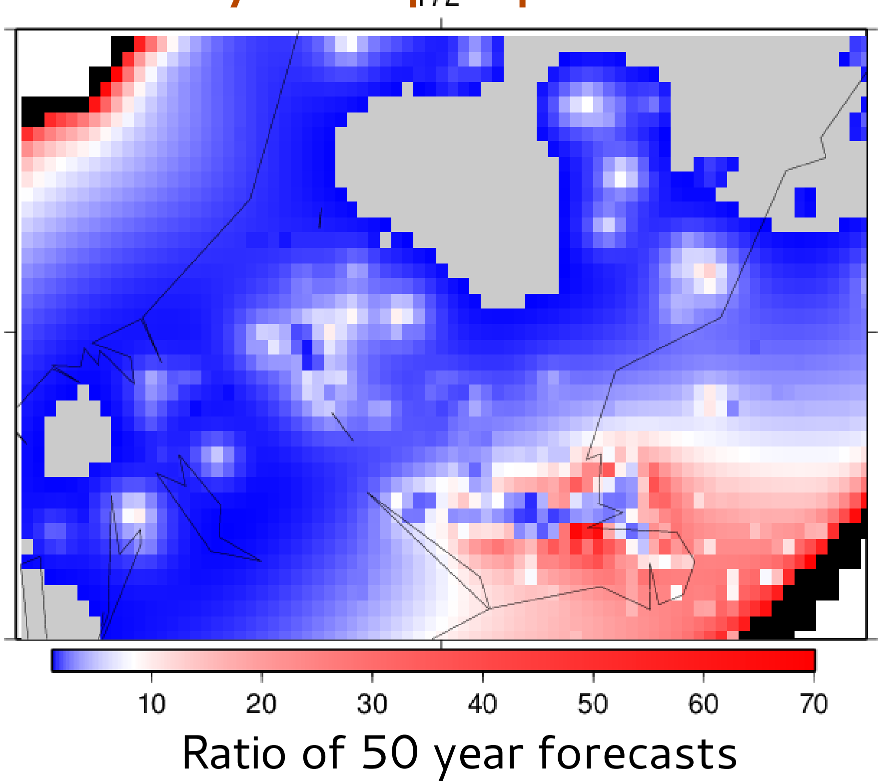



**Combined model**: Plausible range of rates based on expert weights with uncertainty

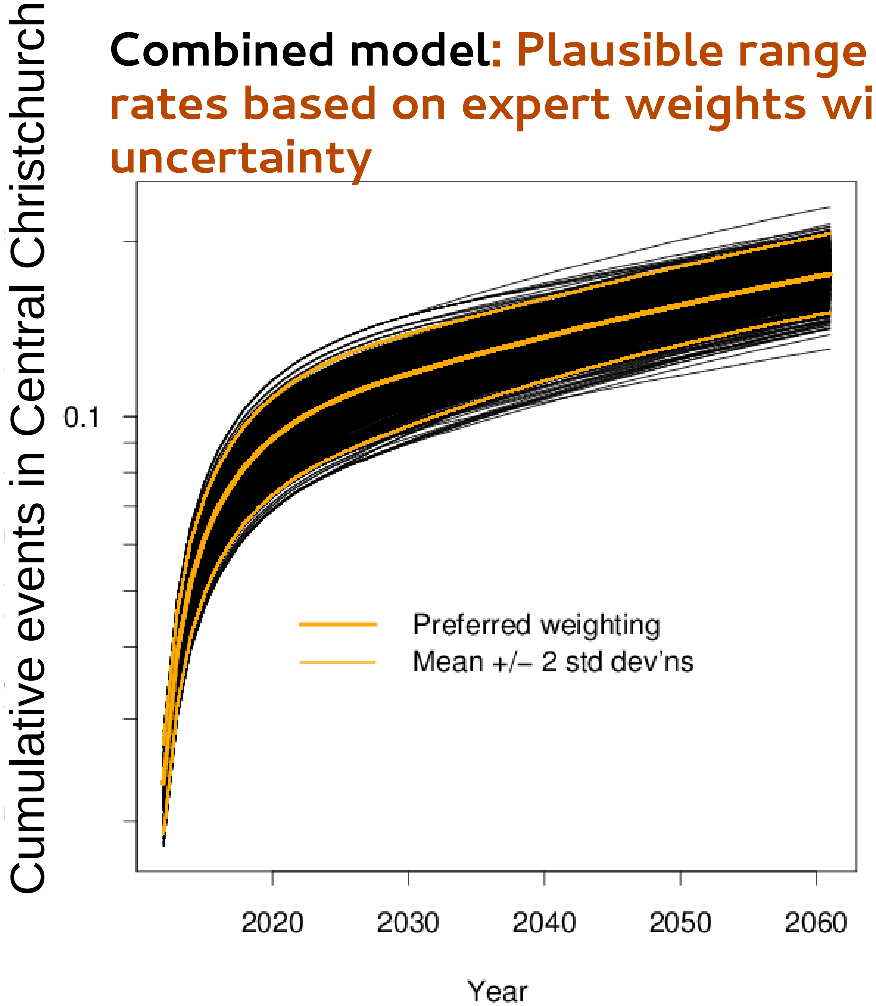


# Exploring the epistemic uncertainty

**Ratio of 50 year rate forecasts** between two model realisations considered plausible by the expert panel




**Combined model**: Plausible range of rates based on expert weights with uncertainty



# Spatial resolution

1) what are the primary sources of uncertainty that contribute to reduction in forecast skill as spatial resolution increases

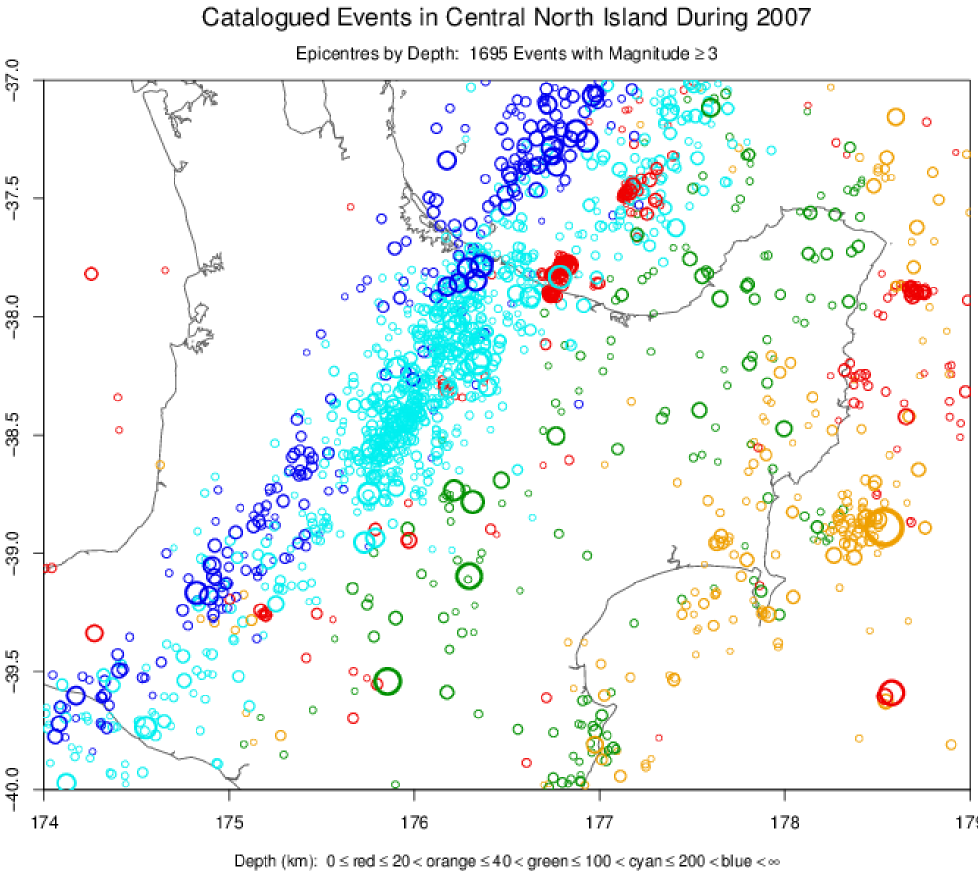
2) can we quantify or reduce these uncertainties

3) what is, and how do we determine, the optimal resolution for applications such as the building design standards

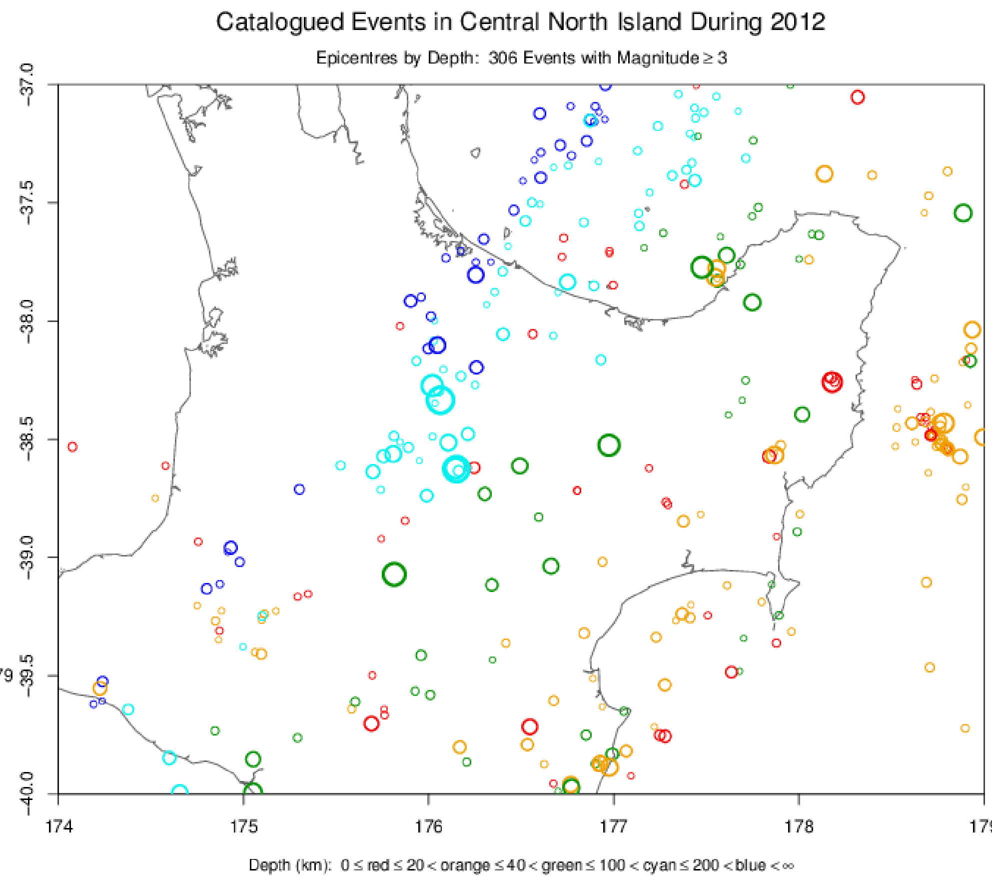
**A focus on uncertainty**

**5 examples of source model uncertainty**

# Ex. 1 Magnitude isn't magnitude, isn't magnitude, isn't magnitude, ...




2012: **306** Ml>3.0 (SeisComp3)

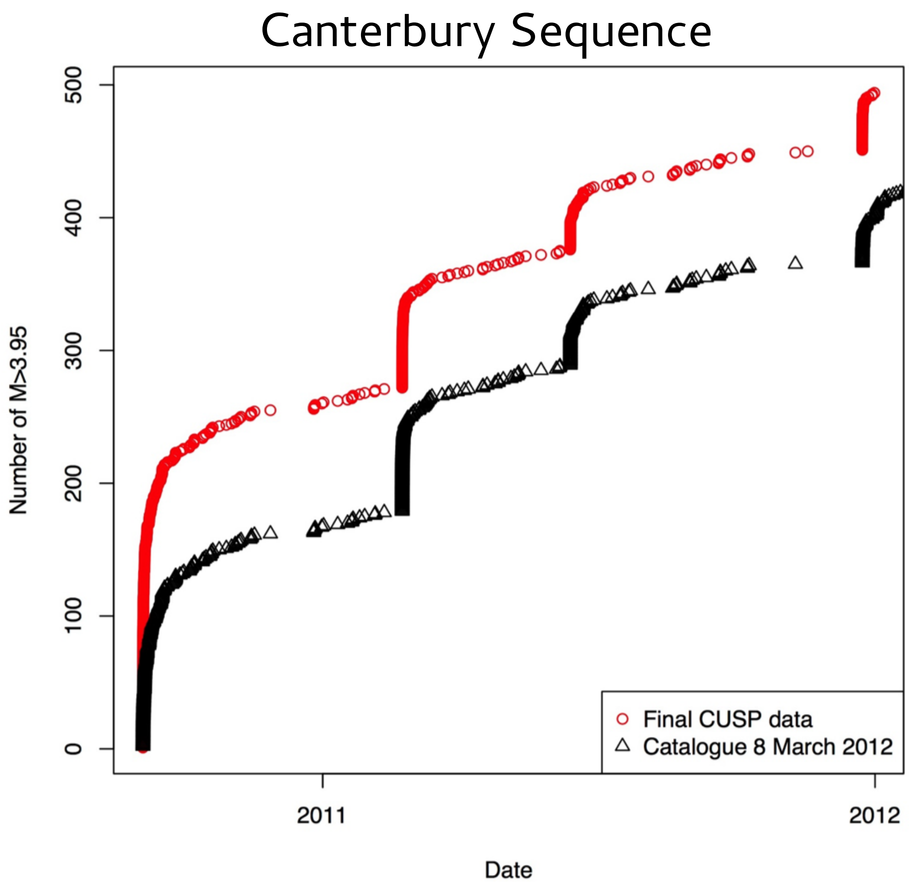


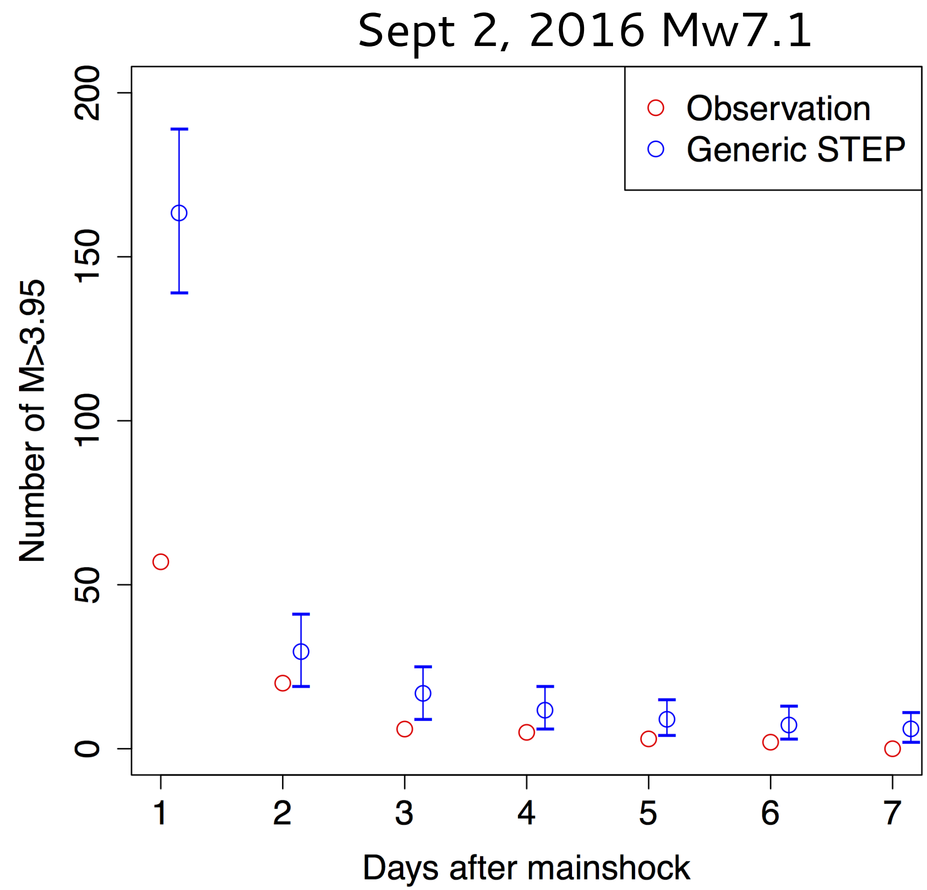

2007: **1,695** Ml>3.0 (CUSP)

Gutenberg-Richter is a powerful thing. A **ΔM of 0.25 = doubling of rates** and 20%-30% increase in hazard

For hazard we need to forecast Mw. **We don't have Mw to small magnitudes**

# Understanding catalog quality impacts

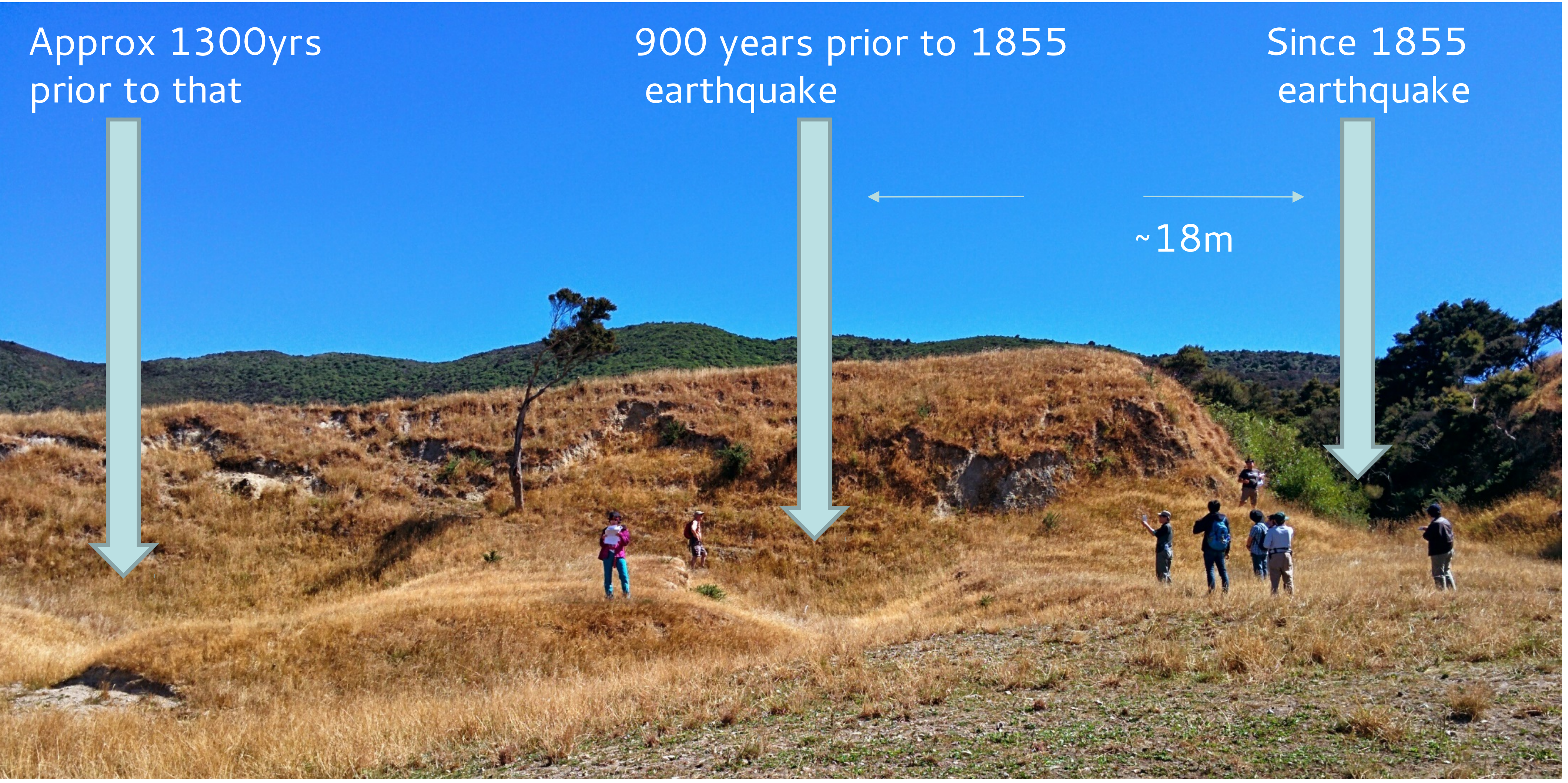



Models are developed on best quality catalogs
OEF doesn't necessarily have available best quality catalogs
The impact of this can be significant

See **Annemarie Christophersen's** poster for more details

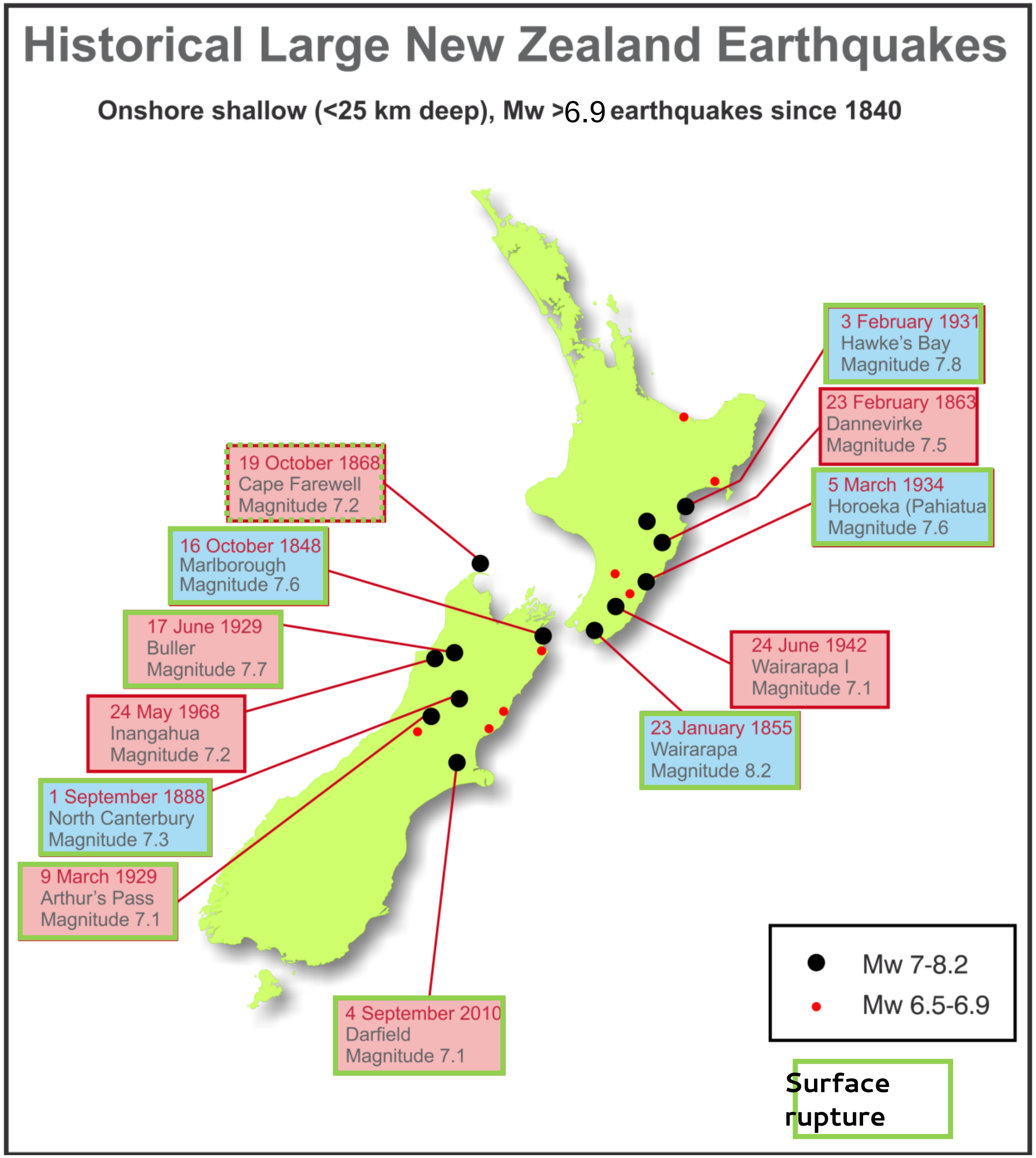
# Ex. 2: Fault model completeness, a thought experiment




**Wairarapa Fault, New Zealand, M8.1 1855**

**Max horizontal offset ~18m; vertical ~7m**

# Ex. 2: Fault model completeness, a thought experiment

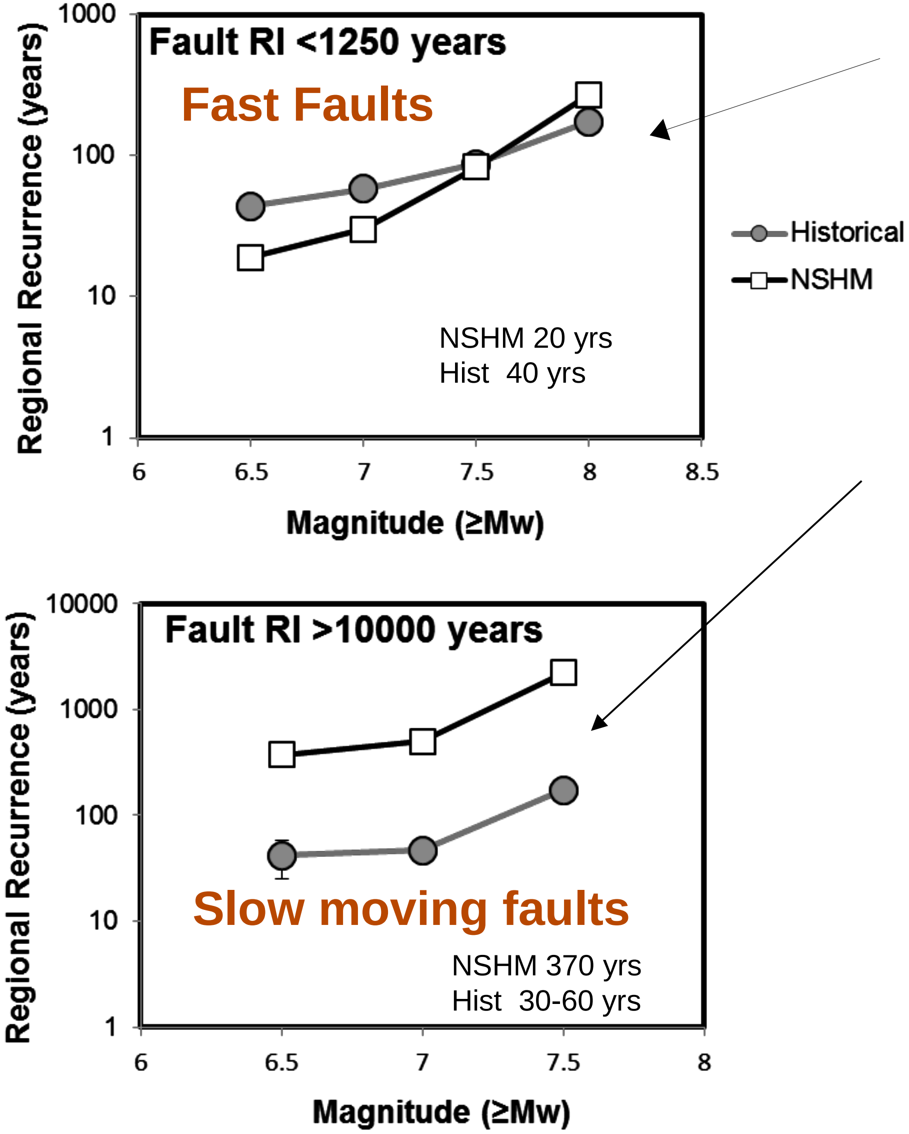



If we had today's geological methods & tools in 1840, how many earthquakes since 1840 would have occurred on faults we would have included in the source model?

| | | |
|---|---|---|
| **YES!** | 5 events | 42%-50% |
| **NO...** | 5-7 events | 50%-58% |

(Nicol, et al, 2016)

# Ex. 2: Fault model completeness, a thought experiment




Fast moving faults are "well" represented in the model

Slow moving faults: ~400 additional Mw ≥6.5 earthquake sources (faults) are *required* to account for this in the NSHM

Does the smoothed seismicity model fully account for this difference? *Possibly*.

(Nicol, et al, 2016)

# Ex. 3: Clustering & the Poisson Assumption

## Traditional PSHA

-Future clustering is difficult to model.

- In the NSHM, earthquakes are assumed to be random and independent in time.
- The uncertainty is larger than what is modelled

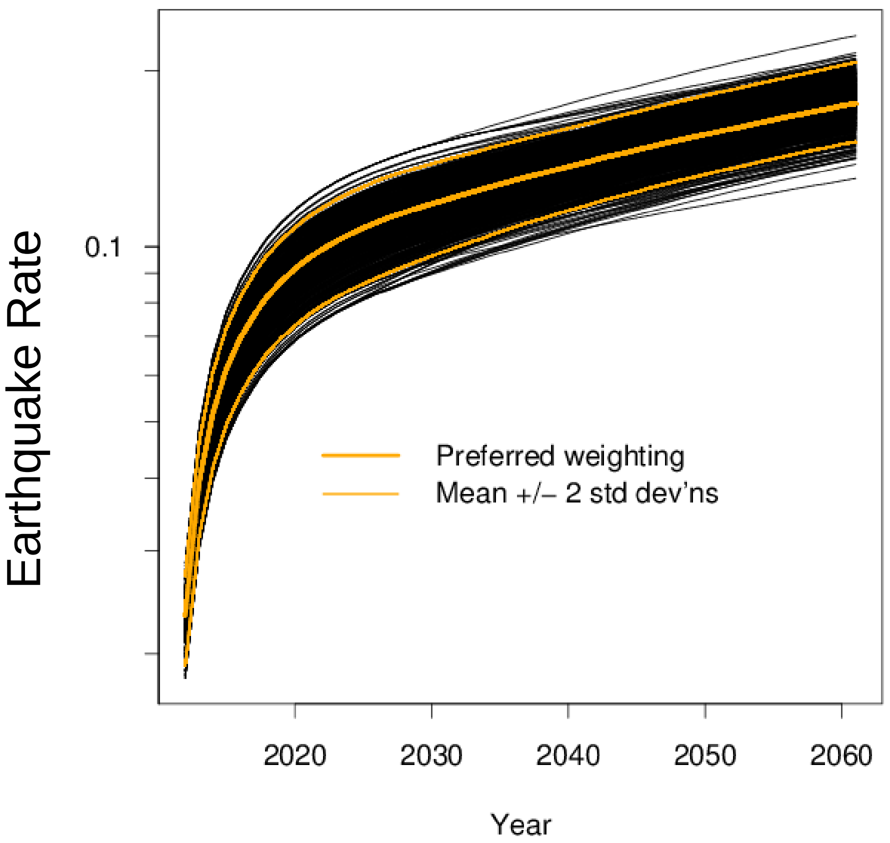
## Earthquake Clustering

- Occurrence rates are best understood during an aftershock sequence (due to knowledge of clustering)

## Declustering

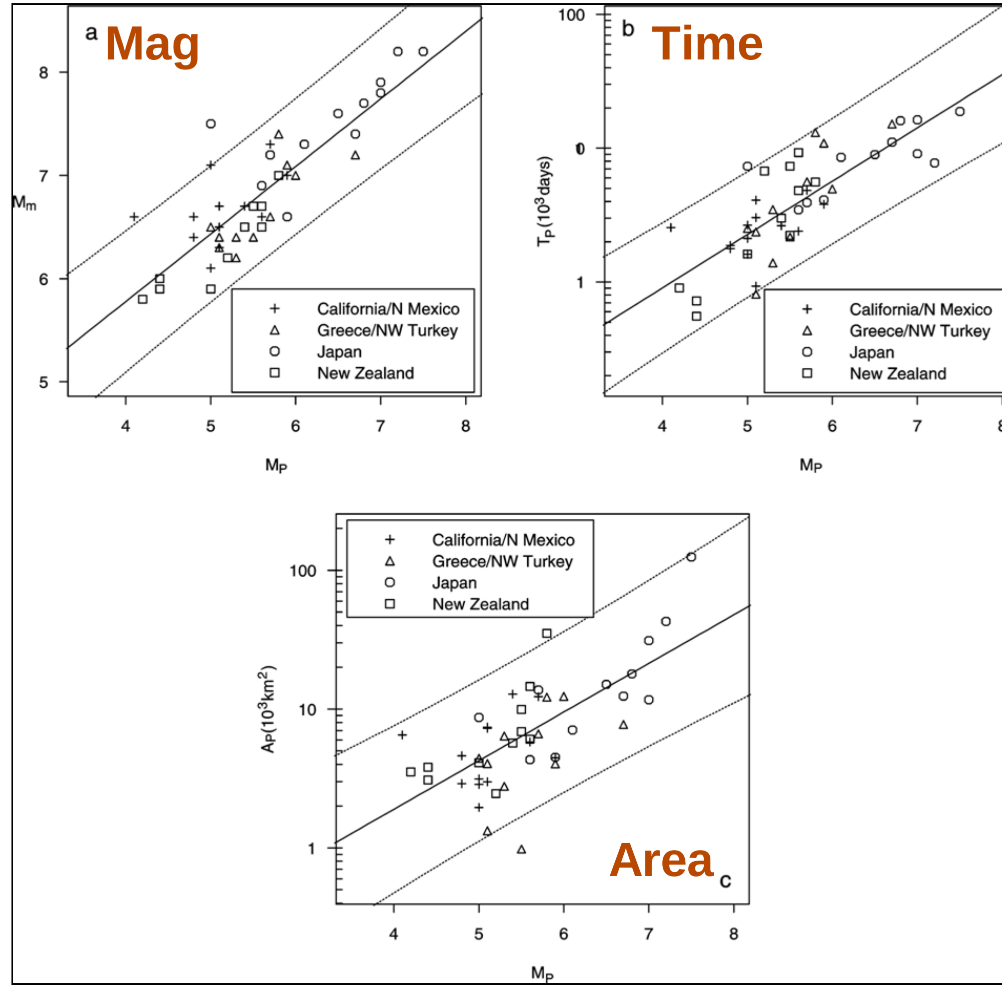
- the method of declustering can add significant variability to the hazard

Aftershock Rates with Uncertainty



# The EEPAS Model

- Every earthquake contributes to probabilities for future quakes. Swarms tend to contribute more
- Probability increases are only for larger events (unlike ETAS) "***main shocks", not aftershocks***
- Three scaling relations with *observed regional avg magnitude* with **forecast**:
  - **Magnitude (non-GR)**
  - **Time**
  - **Area**
- Dominates from 2~15yrs
- Tested globally and within CSEP




Rhoades & Evison 2004

$$M_m = a_M + b_M M_P$$

$$\log T_P = a_T + b_T M_P$$

$$\log A_P = a_A + b_A M_P$$

# Medium–term EEPAS Clustering
# Two Examples:

**New Zealand**: Arthur's Pass Region 1970-2015

- 1970s 5 M>5
- 1990s 2 M>6.5
- 2015 M6.0

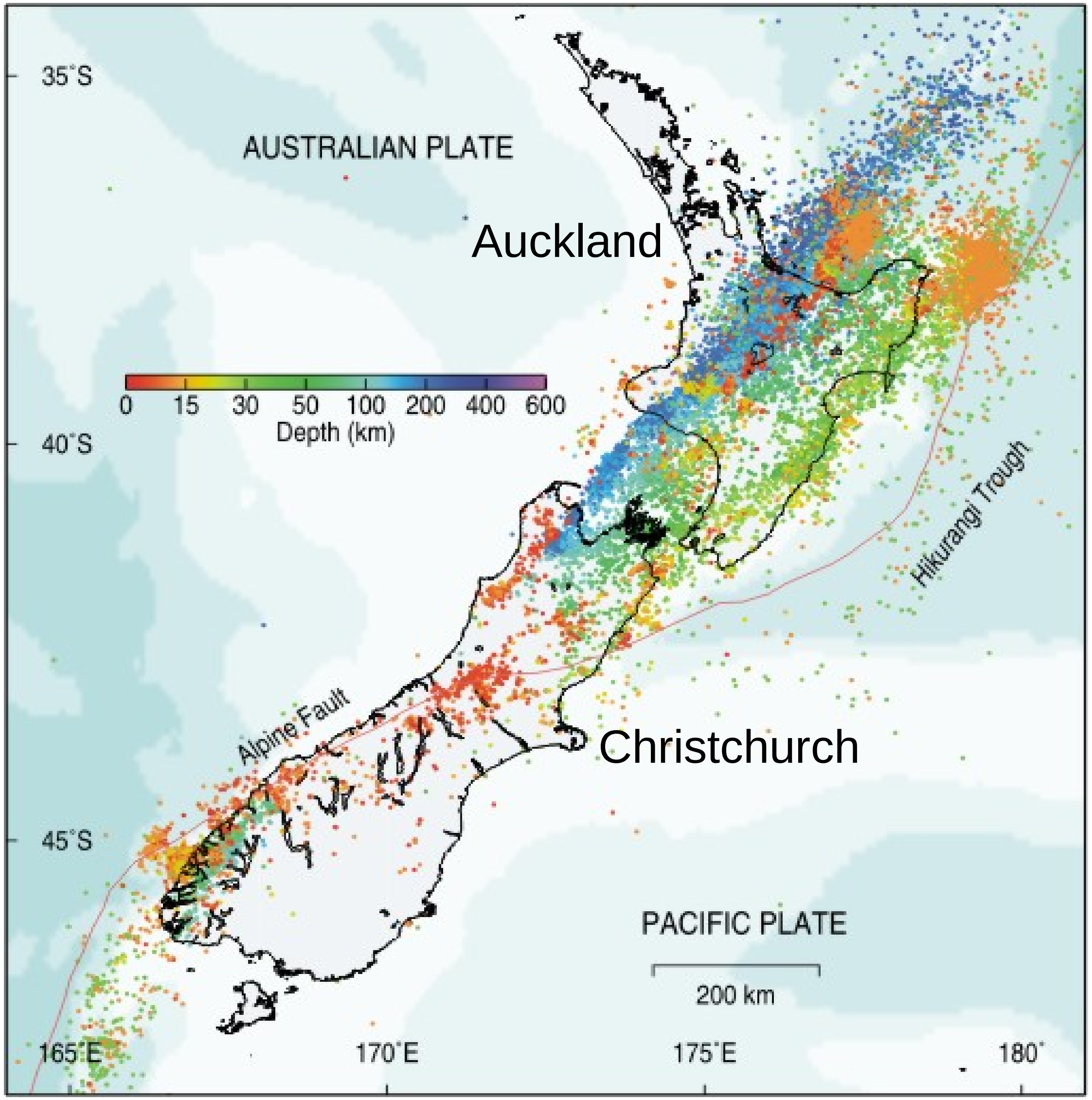
**California**: Mojave Desert 1992- 1999

- 1992 Joshua Tree M6.1
- 1992 Landers M7.3 + M6.5 (Big Bear)
- 1999 Hector Mine M7.1

# Ex. 4: Low Seismicity Regions & Lack of Data

## Current PSHA is built upon knowledge of faults, and recent earthquake occurrence

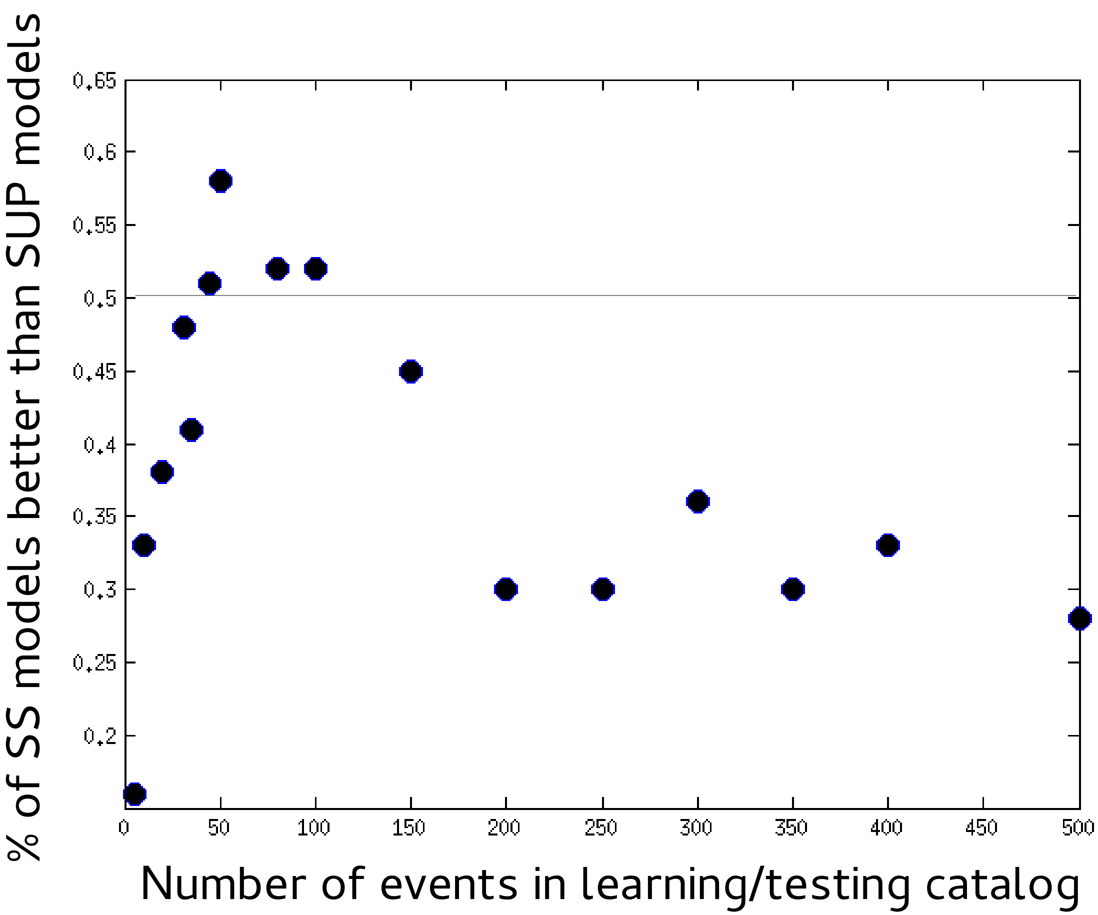
- Particularly for low seismicity areas (e.g., Auckland) with few data: are the last 50-150 years of earthquakes representative of the next 50?
- With less data, uncertainty is necessarily higher, but is unquantified
- *Quantifying* uncertainty requires a model or data

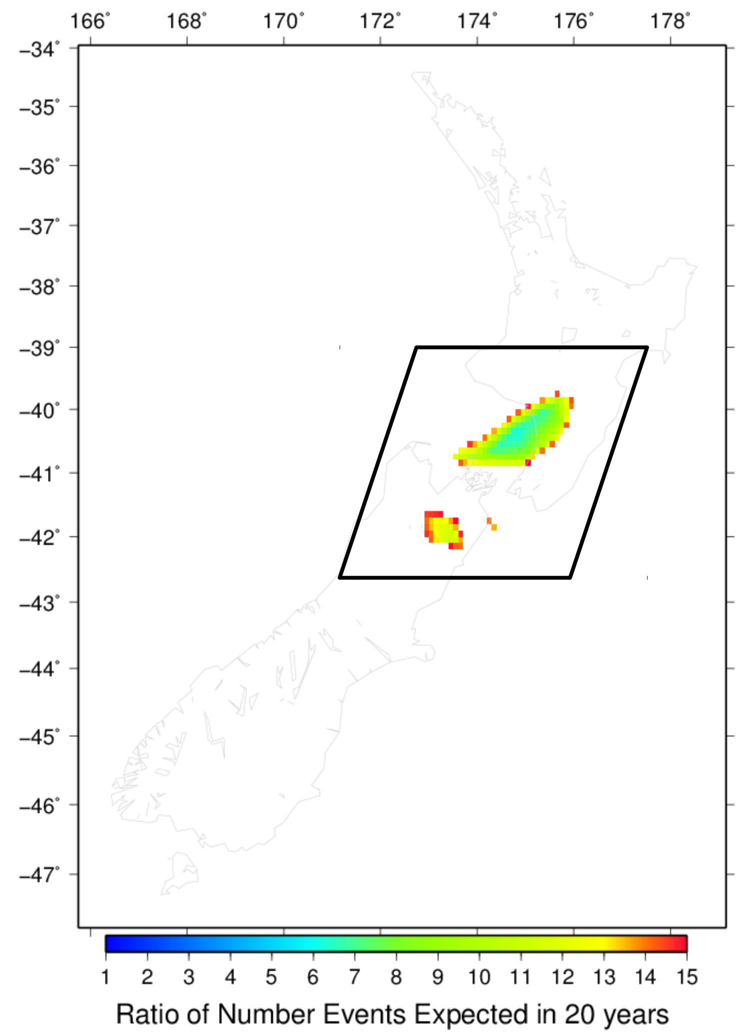


# Learning from high seismicity regions

**What can we learn by testing models created from subsets of data selected from high seismicity regions?**

- Create multiple smoothed seismicity (SS) models from block bootstrapped catalogs of 5, 10, 20 … up to 500 M>4 events
- Test against the M>5 events selected from the ***next*** X M>4 events (e.g., 5, 10 … 20) against a Spatially Uniform Poisson (SUP) model



# Hybrid models

The goal is to use multiple models in combination and to not be restricted by model type or input data type (**clustering, time-periods, smoothing, fault data, subduction interface, strain**)

**Multiplicative** combinations of models are more dynamically adaptive than additive combinations

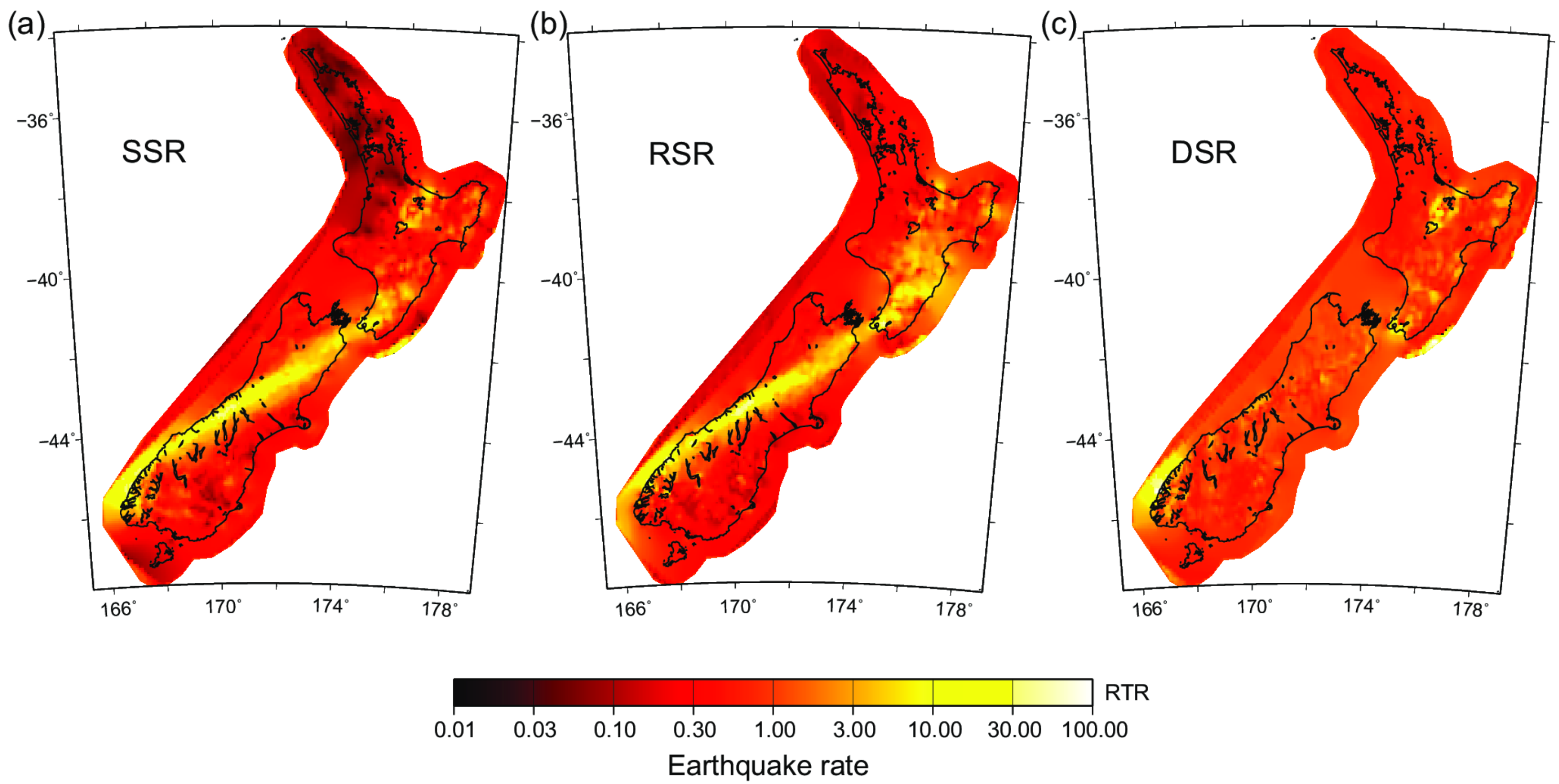
**Optimised scaling functions** are applied to each model in the combination based on fitting to data

A two step procedure:

- **Optimisation** of the hybrid combination (e.g., the scaling functions) during a learning period

- **Testing** the combination during an independent testing period. The best model during optimisation is not always the best model during testing

# Hybrid models including geodetric strain




Beavan model based on Haines and Holt
Shear strain (SSR)
Rotation strain (RSR)
Dilatational strain (DSR)

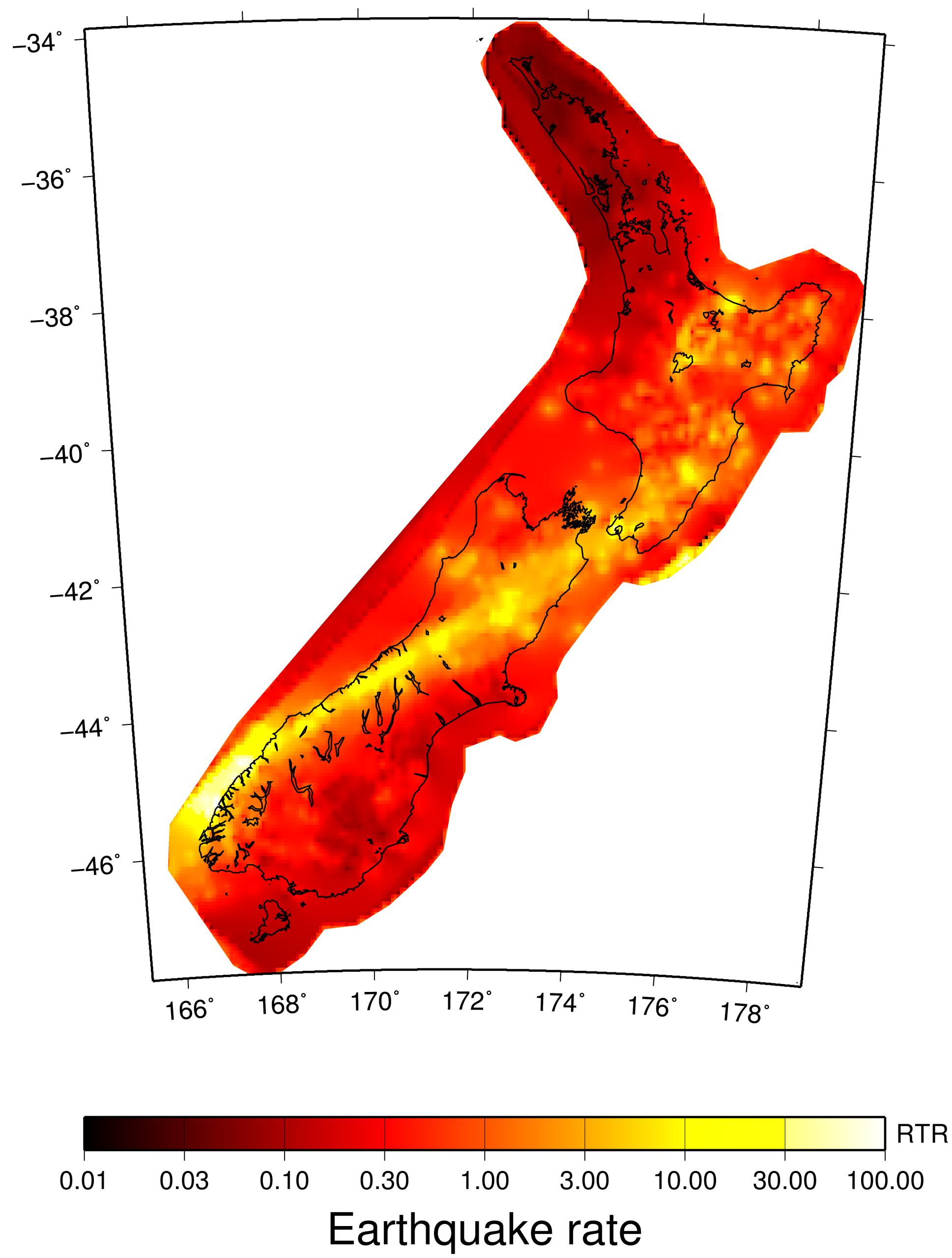
In the time frames optimised and tested, strain rate information gives the most significant improvement of all models

*Optimisation Period*

**Spatially Uniform Poisson * Smoothed Seismicity * Shear Strain * Dilatational Strain**

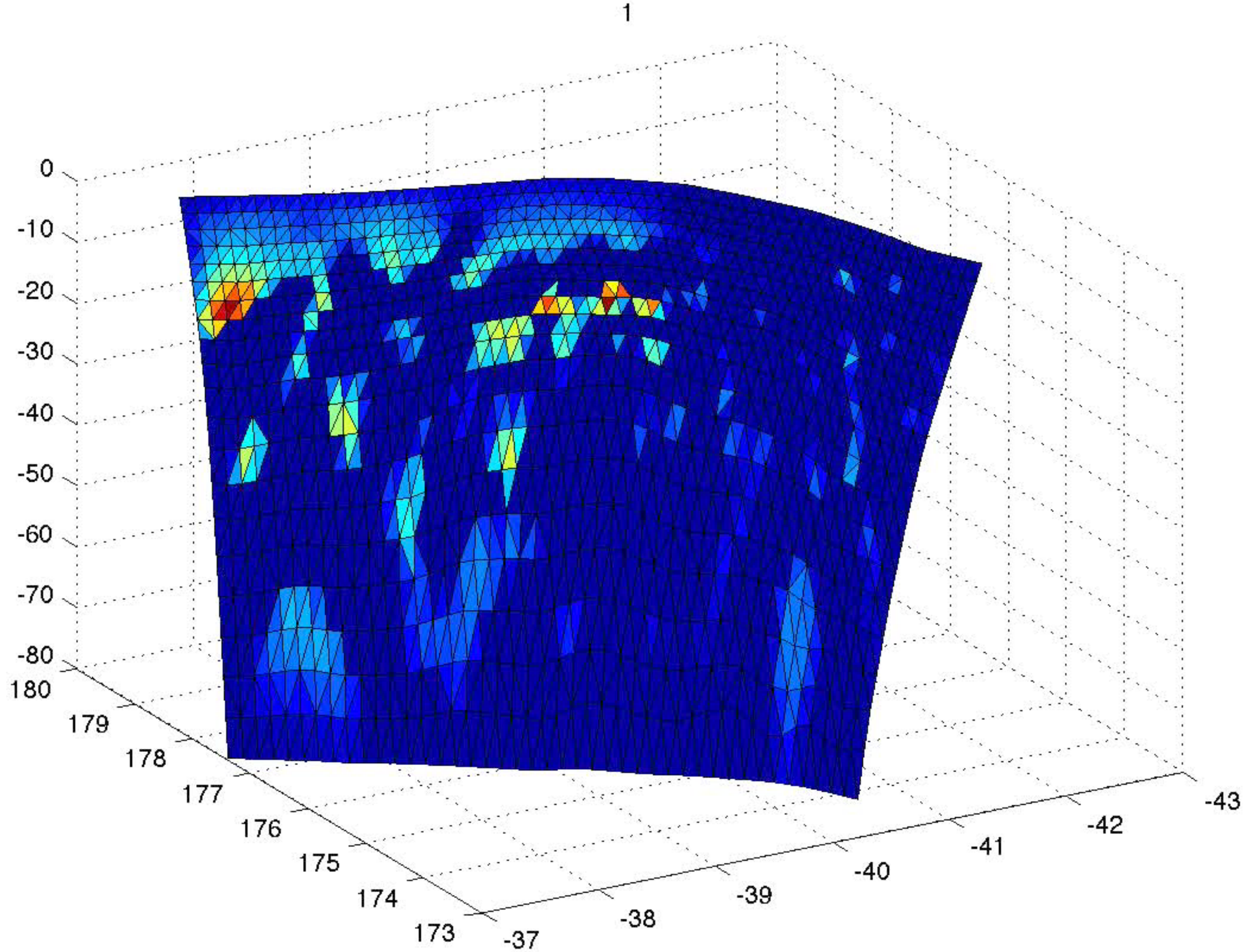
*Testing Period*

**Spatially Uniform Poisson * Smoothed Seismicity * Shear Strain**



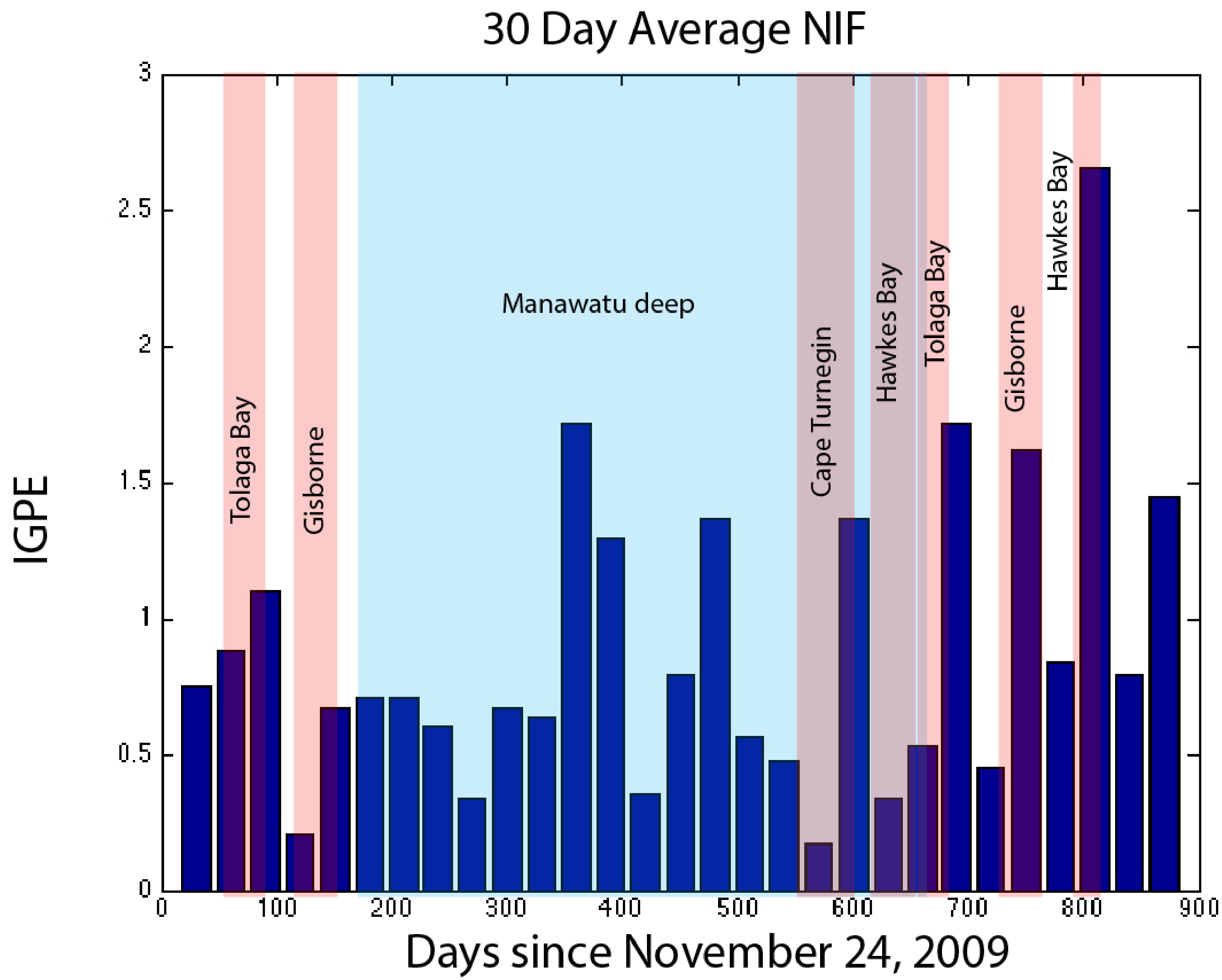
# A hybrid based on slow slip events and PPE

Network Inversion Filter (NIF) results showing SSE on the Hikurangi Margin




**We only use data from 40km upward**

**Bartlow et al., 2014**

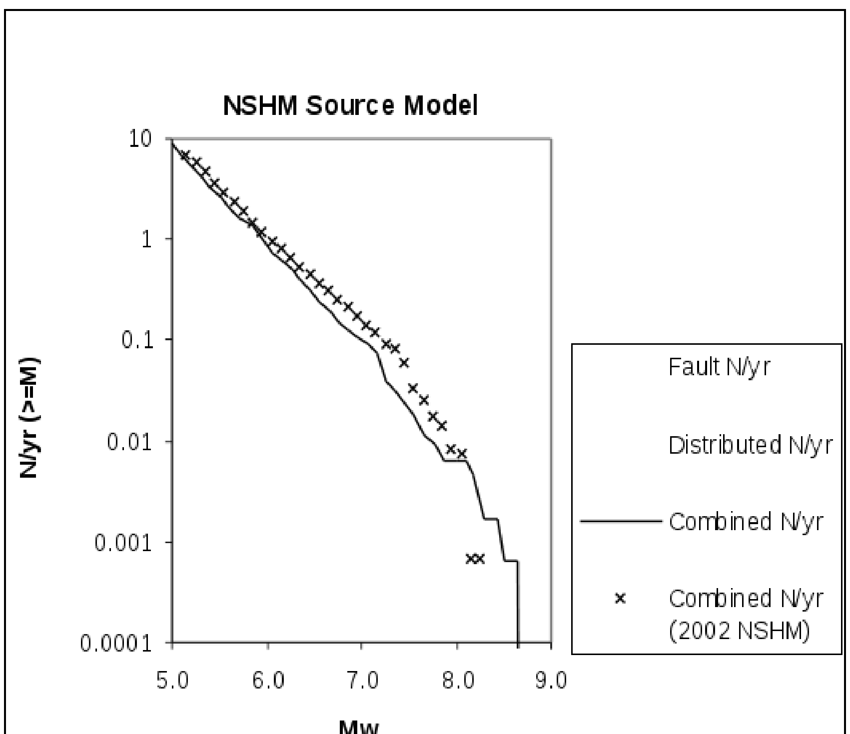


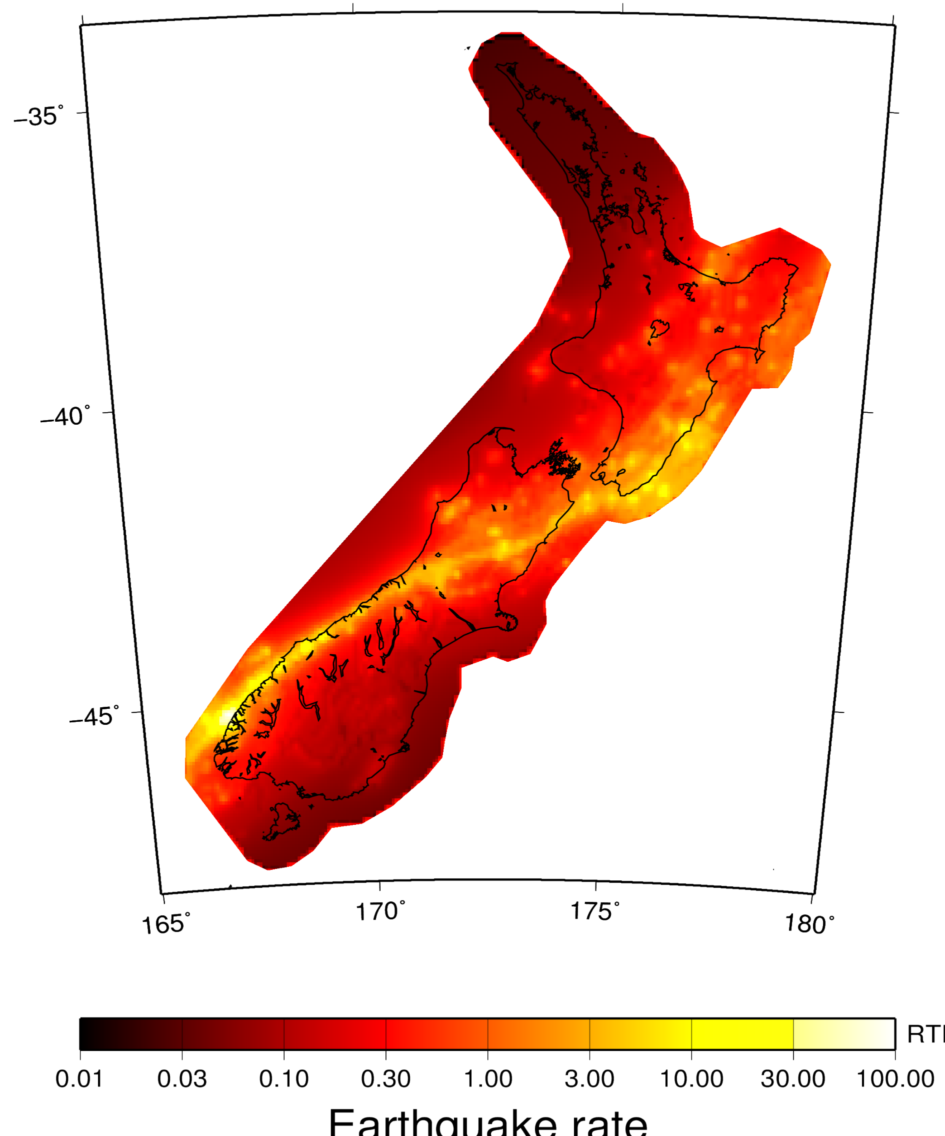

**Multiplicative hybrid testing results (against PPE)**

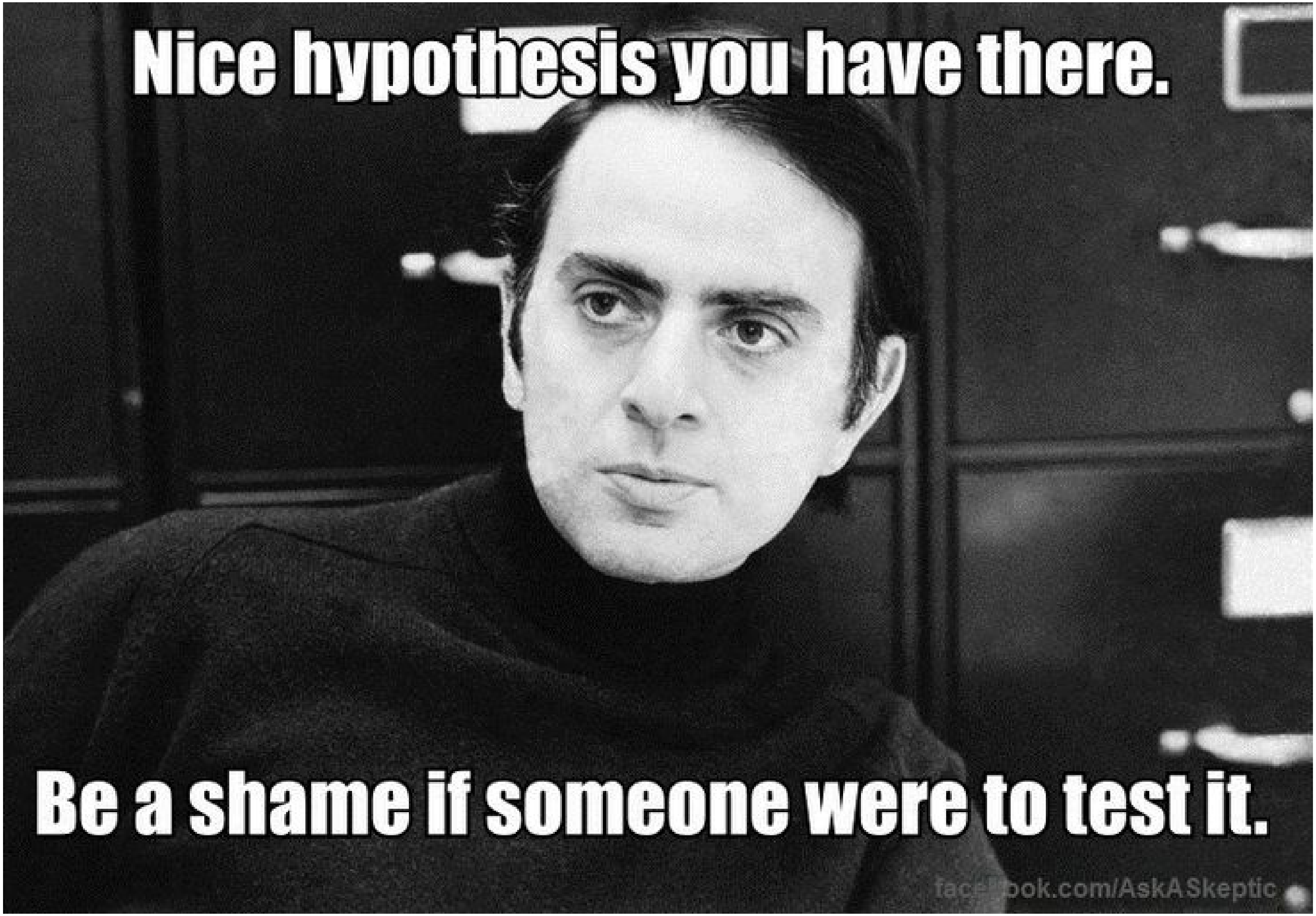
# Ex. 5: Spatial Resolution

- If we predict the earthquake rate distribution for the next 50-years for all of NZ collectively, we do pretty well.
- If we predict it for this 10km$^2$ region, we are less informative.

- **What is the best resolution for the most useful information for regulation and planning? Risk based optimisation?**




Nice hypothesis you have there.
Be a shame if someone were to test it.
facebook.com/AskASkeptic

- Carl Sagan

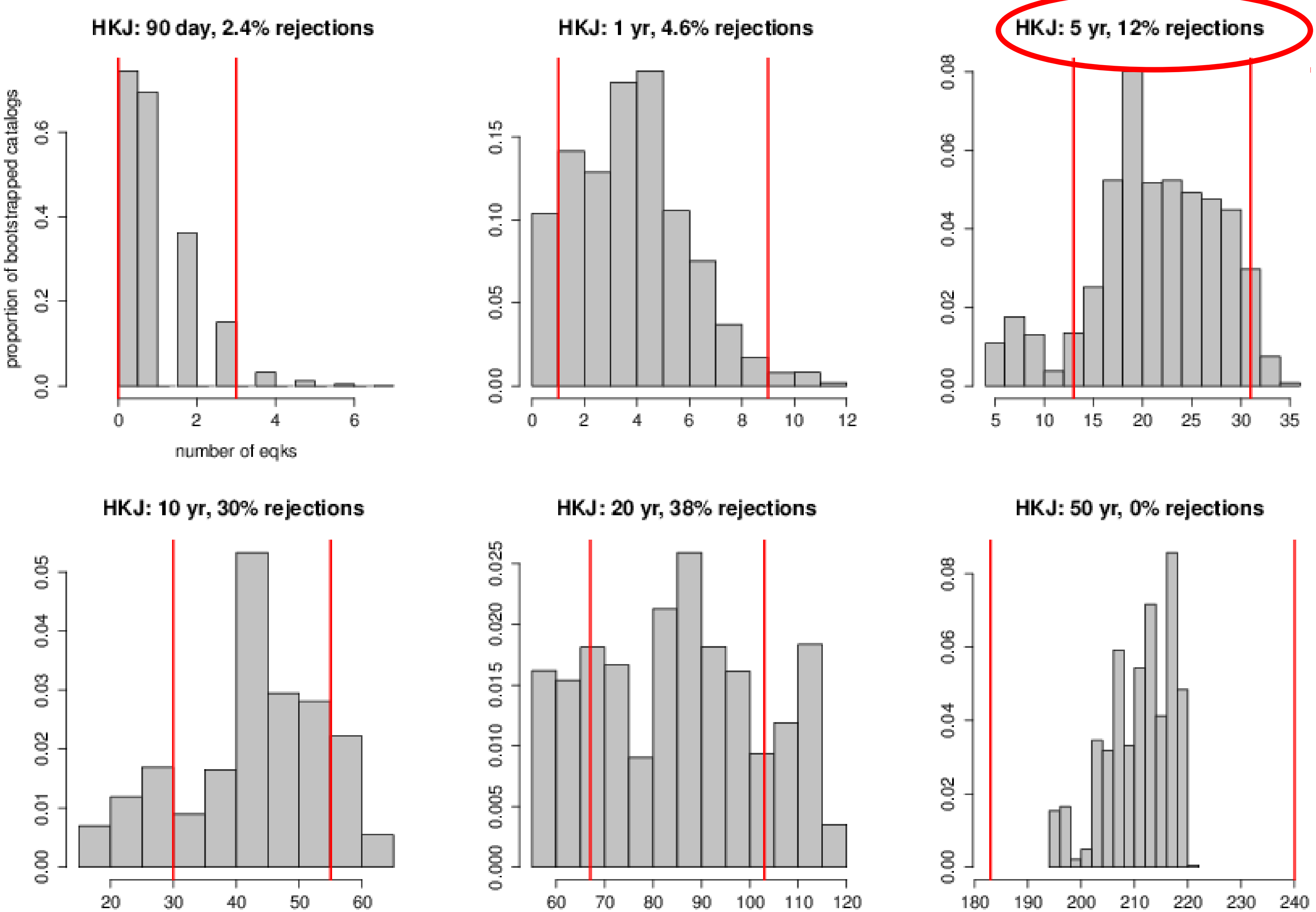
# How much information is in any 5 year test?

CSEP “long-term” model testing is based on 5 year tests on so called time-independent models.

## What does one five year testing period tell us about any other five year period?

- Use California earthquake catalog data from 1940
- Create hundreds of block bootstrapped catalogs of length 90 days, 1yr, 5yrs, 10yrs, 20yrs and 50yrs
- Evaluate the variability of the forecast skill of the models across the bootstrapped catalogs

# How much information is in any 5 year test?




Results for all time periods for Helmstetter Kagan Jackson (HKJ): best performing RELM model

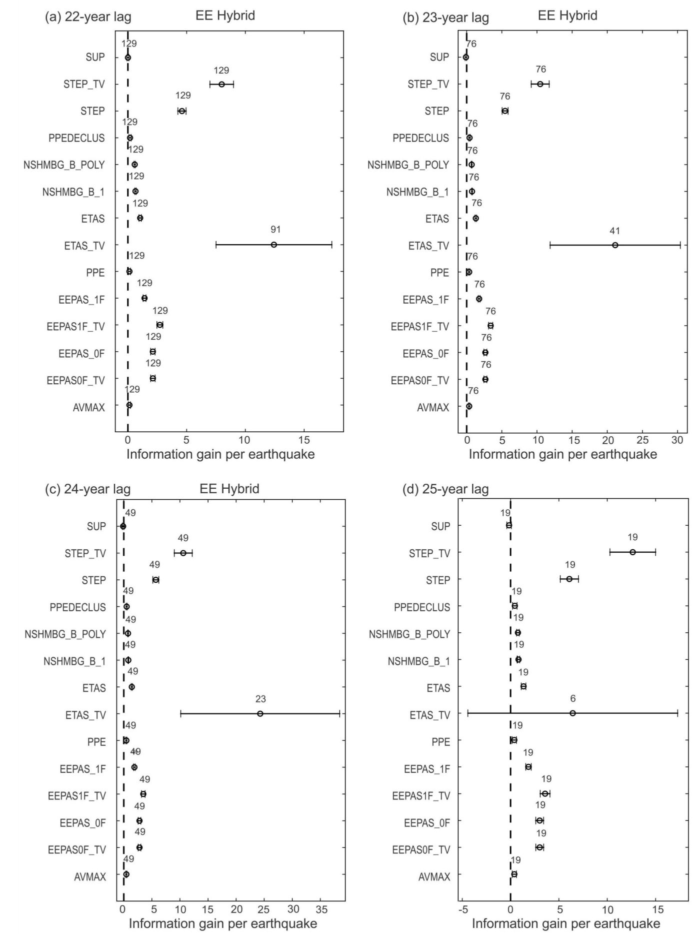
# The Value of Testing and Gut-Feeling

All parts of the Canterbury model have been tested against NZ and global data:

- Against past data
- Ongoing against future data

Results indicate that:
The combined model out performs all of the individual models

The model provides informative forecasts for its current uses



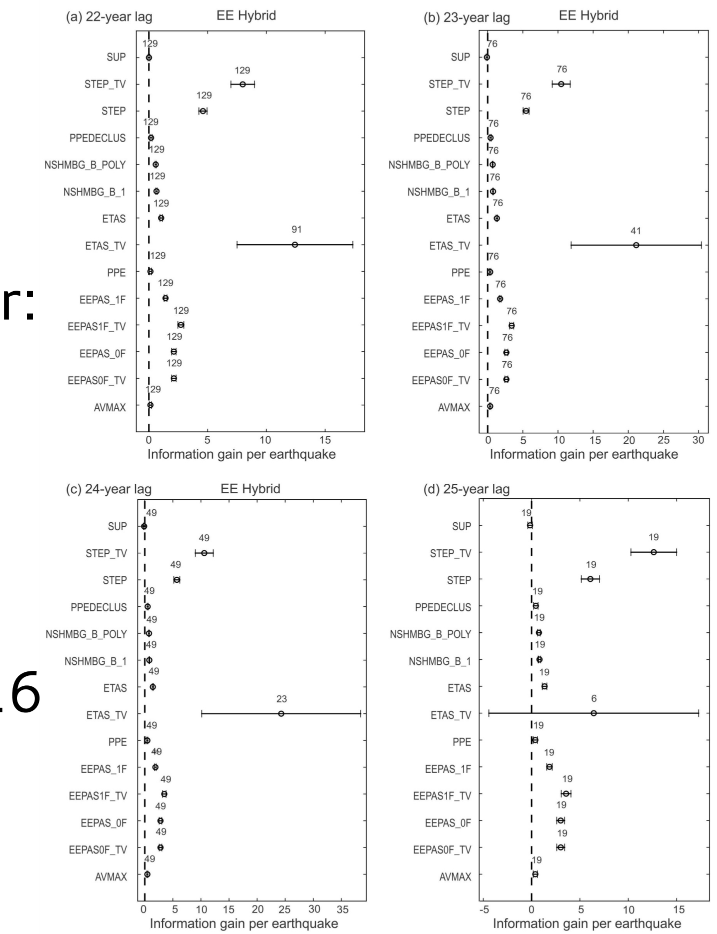

Canterbury model vs other models *(models to the right of line perform worse than hybrid model)*

# The Value of Testing and Gut-Feeling

Test results are not of interest and are not understood by decision makers and end-users, including the NZ engineering community

New Zealand has **no official body responsible** for:
1) delivering forecasts
   -or-
2) commenting on the validity of publicly available forecasts (e.g., **CEPEC/NEPEC**)

"***The sequence is over***" - Many People 2012-2016 (14/2/2016 Mw5.7 Christchurch CBD)




Canterbury model vs other models (*models to the right of line perform worse than hybrid model*)

# Communicating Forecasts & Hazard

# Challenges to communication

- Complexities of meeting the needs/perceptions of many different groups (e.g. forecasters, social scientists etc…)
- Communication guidance that does not address uncertainty in the models
- Internal actors who may want to "not panic the public".
- Putting the needs of the public first

# What works

- Providing maps, images, story (scenario), tables and figures to communicate forecasts
- Simple, straight forward, include multiple agency messages

## M7.1 East Cape Earthquake: what we think will happen next

**Scenario One – Very Likely (up to 95 percent within the next 30 days)**

The most likely scenario is that aftershocks will continue to decrease in frequency as expected (and in line with forecasts). Aftershocks of the M7.1 earthquake will continue to be felt in the East Cape area. This includes the potential for aftershocks of between M6.0 – 6.9 (50 percent chance within the next 30 days). A similar earthquake occurred on Waitangi Day 1995 (M7.1) just to the south-east of the M7.1 East Cape earthquake; that particular earthquake had felt aftershocks which continued for more than two years.

**Scenario Two – Unlikely (5 percent or less within the next 30 days)**

An unlikely scenario is another quake between M7.0 – M7.9. This earthquake may be onshore or offshore but close enough to cause severe shaking on land. Also there is a possibility of an earthquake either north or south of the M7.1 mainshock area e.g., in the Hikurangi Subduction Zone. Such large earthquakes have the potential to generate tsunami.

**Scenario Three - Very Unlikely (within the next 30 days)**

A much less likely scenario than the previous two scenarios is that recent earthquake activity will trigger a significantly larger earthquake (M8 or greater). This scenario is very complex and when combined with the current uncertainty in our models, we can't confidently put a probability estimate on it occurring. However, even with such a large "triggered" earthquake on the 'plate interface' (where the Pacific Plate meets the Australian Plate) being very unlikely, we cannot discount the possibility. This scenario is similar to what occurred in the Tohoku Earthquake in Japan in 2011. Although it is still very unlikely, the chances of this occurring have increased slightly since the M7.1 earthquake.

### Aftershock Forecasts

**East Cape region long-term aftershock probabilities**

| | M5.0-5.9 | | | M6.0-6.9 | | | M ≥7.0 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average number | Range | Probability of one or more | Average number | Range | Probability of one or more | Average number | Range | Probability of one or more |
| **Within 30 days** | 4 | 1 - 9 | 99% | 0.4 | 0 - 2 | 32% | 0.04 | 0 - 1 | 4% |

*Issued at noon, 12 September 2016 for coming month.*

***Aftershock probabilities read from the table:***

# Guidance from social science

- People may still be confused, no matter what you say or how you say it. That is okay.
- Research does not always work in practice (probability wording table).
- Timing is everything. Get out the information quickly.
- 8 PhDs reviewing the article does not guarantee that the story will be without typos.

# Communicating OEF Forecasts

# Short Summary: Some Overarching Principles & Goals

- Accounting for *uncertainty* in the forecasts

- Moving *beyond* simple *aftershocks*

- Using *tested* models

- *Consistent* information across all needs from short-term forcasting to long-term hazard
- Providing *context* for the forecast numbers
- *Responsive* to the needs of the end users
- Adaptable to changing/improving *communication* needs

# What I would like to see from the Forecasting/CSEP Community

- Moving beyond ETAS
- Medium/long-term model development
- Testing of long-term models
- Alternative methods & data sets
- Improved spatial modelling
- Spatial resolution/optimisation: trading off precision and uncertainty
- Alternative end-user metrics (e.g. Risk based)
- Consideration of hazard & PSHA needs
- Improved communication and interpretation of testing results within science and end-user communities

- More students in statistical model development and testing.