Space-Time Trade-off of Precursory Seismicity in the EEPAS Medium-Term Forecasting Model Optimized for New Zealand Earthquakes

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Abstract

'Every Earthquake a Precursor According to Scale' (EEPAS) is a model to forecast earthquakes within the coming months, years and decades, depending on magnitude. EEPAS performs well for seismically active regions including New Zealand (NZ) and has been formally evaluated in Collaboratory for the Study of Earthquake Predictability (CSEP) centres in NZ and California, USA. It has been used for practical forecasting in NZ for nearly a decade. An EEPAS forecast is formed by accumulating the contributions from past earthquakes to the expectation of future earthquakes. It uses the precursory scale increase (Ψ) phenomenon along with three predictive spatial, temporal and magnitude scaling relations. For a particular mainshock, Ψ is identified as a prior sharp increase in the occurrence of minor earthquakes. Each identification is represented by a value of precursor magnitude MP, precursor time TP and precursory area AP. An algorithm to automatically identify Ψ was developed and applied to real and synthetic earthquake catalogs. Multiple identifications of Ψ were obtained for most mainshocks. A trade-off between AP and TP was observed among such multiple identifications. Here, we examine the implications of the trade-off for the EEPAS temporal and spatial scaling parameters aT and σA. The EEPAS parameters were initially fitted to the NZ earthquake catalog from 1986-2006. The EEPAS parameters are now refitted with a sequence of fixed values for aT and then for σA. The range of fixed values constrain the respective temporal and spatial scales to vary by a factor of a hundred. Results confirm the existence of a similar space-time trade-off in EEPAS as in Ψ, with large aT values being associated with small σA values and vice versa. We conclude that the space-time trade-off is an intrinsic feature of precursory seismicity. This exists independently of other influences, such as the local strain rate, that may contribute to scatter in the predictive scaling relations. Mixing EEPAS models with parameters along the trade-off line should improve forecasting.

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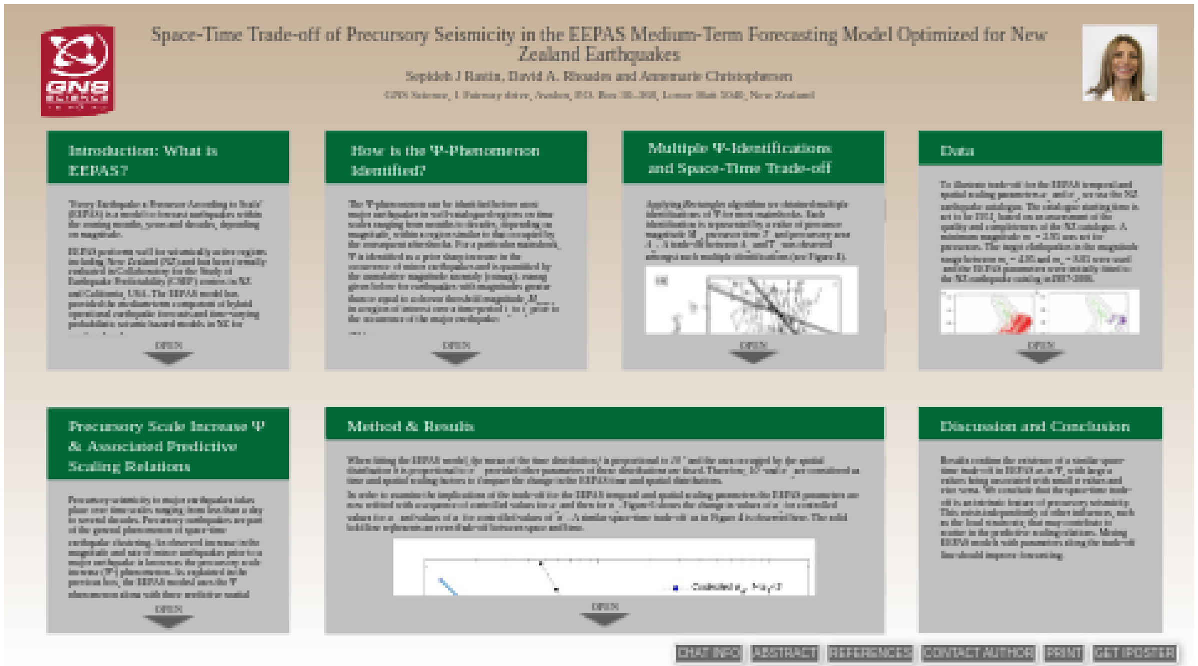

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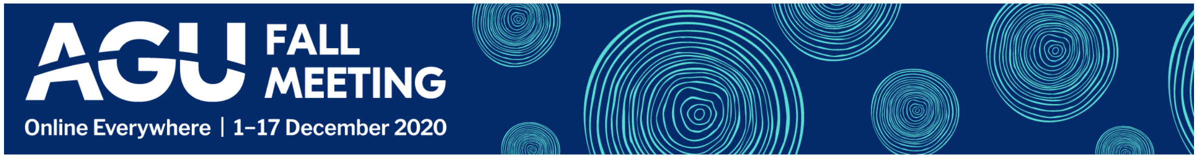


INTRODUCTION: WHAT IS EEPAS?

'Every Earthquake a Precursor According to Scale' (EEPAS) is a model to forecast earthquakes within the coming months, years and decades, depending on magnitude.

EEPAS performs well for seismically active regions including New Zealand (NZ) and has been formally evaluated in Collaboratory for the Study of Earthquake Predictability (CSEP) centres in NZ and California, USA. The EEPAS model has provided the medium-term component of hybrid operational earthquake forecasts and time-varying probabilistic seismic hazard models in NZ for nearly a decade.

An EEPAS forecast is formed by accumulating the contributions from past earthquakes to the expectation of future earthquakes. The rate density of the EEPAS model is obtained by summing over all past occurrences, including earthquakes outside *R*, that could affect the rate density within *R*:

$$\lambda(t,m,x,y) = \mu\lambda_0(t,m,x,y) + \sum_{(t_i \geq t_0, m_i \geq m_0)} \eta(m_i)\lambda_i(t,m,x,y)$$

where $\lambda(t,m,x,y)$ is the rate densitiy of earthquake occurrence within a chosen depth range is defined for any time, t, magnitude, m, and location (x,y), where m exceeds a target threshold magnitude, m_c, and (x,y) is a point in a region of surveillance, R. Mixing parameter μ representing the proportion of the forecast contributed by the background model component, λ_0 is the rate density of a background Poisson model with a location distribution based on proximity to the epicentres of past earthquakes (PPE), t_0 is the starting time of the earthquake catalogue and η is a normalising function.

Each earthquake with time origin and epicenter coordinates (t_i,m_i,x_i,y_i), with t_i greater than a starting time, t_0, and m_i greater than a minimum magnitude, m_0, contributes a transient increment $\lambda_i(t,m,x,y)$ to the future rate density in its vicinity given by $\lambda_i(t,m,x,y) = w_i f(t|t_i,m_i) g(m|m_i) h(x,y \,|\, x_i,y_i,m_i)$

where w_i is a weighting factor to emphasise earthquakes that are most likely to be precursors, and f, g and h are densities of the probability distributions for time, magnitude and location, respectively.

The magnitude density, g, is a normal density of the form $g(m|m_i) = \frac{1}{\sigma_M\sqrt{2\pi}} exp[\frac{-1}{2}(\frac{m-a_M-b_M m_i}{\sigma_M})^2]$

The time density, f, is a lognormal density of the form $f(t|t_i,m_i) = \frac{H(t-t_i)}{(t-t_i)\sigma_T ln(10)\sqrt{2\pi}} exp[\frac{-1}{2}(\frac{log(t-t_i)-a_T-b_T m_i}{\sigma_T})^2]$

where $H(s) = 1$ if $s > 0$ and 0 otherwise.

The location density, h, is a bivariate normal density of the form $h(x,y|x_i,y_i,m_i) = \frac{1}{2\pi\sigma_A^2 10^{b_A m_i}} exp[\frac{-(x-x_i)^2+(y-y_i)^2)}{2\sigma_A^2 10^{b_A m_i}}]$

Parameters of f,g and h are derived from the Ψ-predictive scaling relations. Ψ-predictive scaling relations are explained in the box below.

HOW IS THE Ψ-PHENOMENON IDENTIFIED?

The Ψ-phenomenon can be identified before most major earthquakes in well-catalogued regions on time scales ranging from months to decades, depending on magnitude, within a region similar to that occupied by the consequent aftershocks. For a particular mainshock, *Ψ* is identified as a prior sharp increase in the occurrence of minor earthquakes and is quantified by the cumulative magnitude anomaly (cumag). cumag given below for earthquakes with magnitudes greater than or equal to a chosen threshold magnitude, M_{thres} , in a region of interest over a time-period t_s to t_f prior to the occurrence of the major earthquake:

$$C(t) = \sum_{(t_s \le t_i < t)} [M_i - (M_{thres} - 0.1)] - k(t - t_s)$$

with

$$k = \sum_{(t_s \le t_i < t_f)} [M_i - (M_{thres} - 0.1)]/(t_f - t_s)$$

A large increase in seismicity leads to a sharp minimum of *C(t)*. The minimum of *C(t)* is taken to mark the onset of *Ψ*. A recent example of the *Ψ*-phenomenon from the 2019 Ridgecrest, California, earthquake sequence is shown in Figure 2.

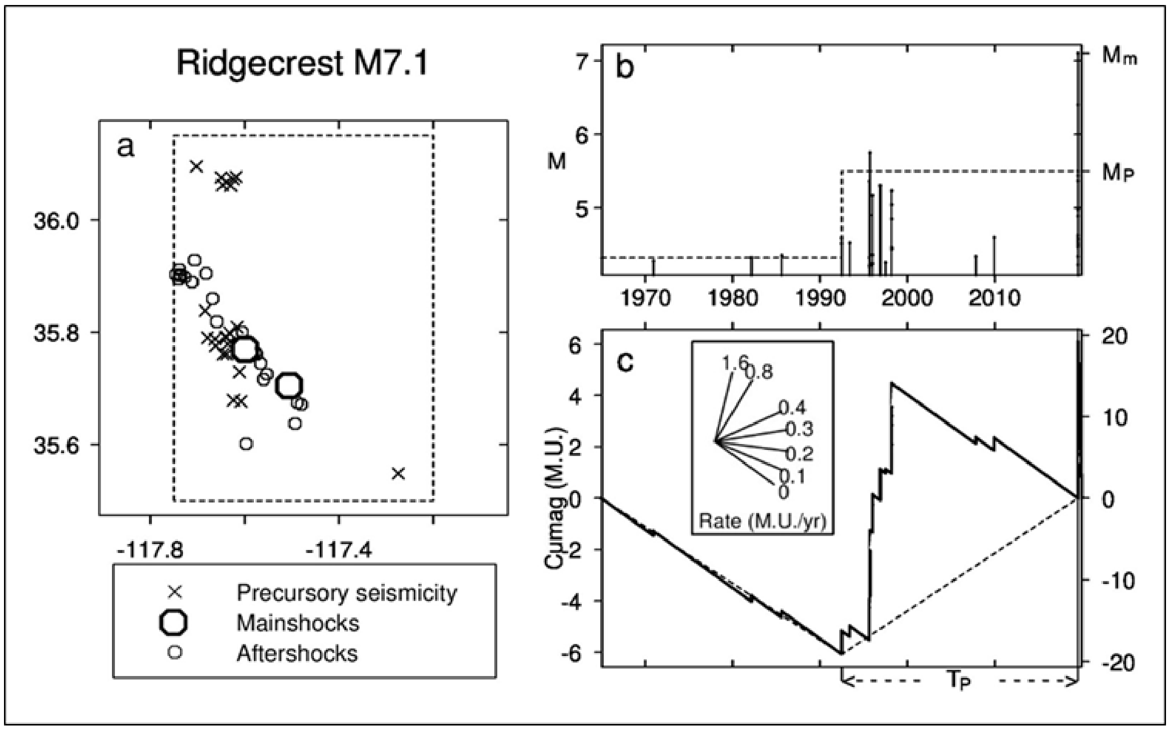


Figure 2: *Ψ*-phenomenon for the 2019 Ridgecrest earthquake, July 2019, M 6.4 and 7.1. (a) Epicentres of the precursory seismicity, mainshocks and aftershocks. (b) Magnitude versus time of prior and precursory earthquakes with the onset of *Ψ* in 1992. (c) Changes in cumag with time.

We developed an algorithm for automatic identification of *Ψ*- phenomenon as shown in Figure 3.

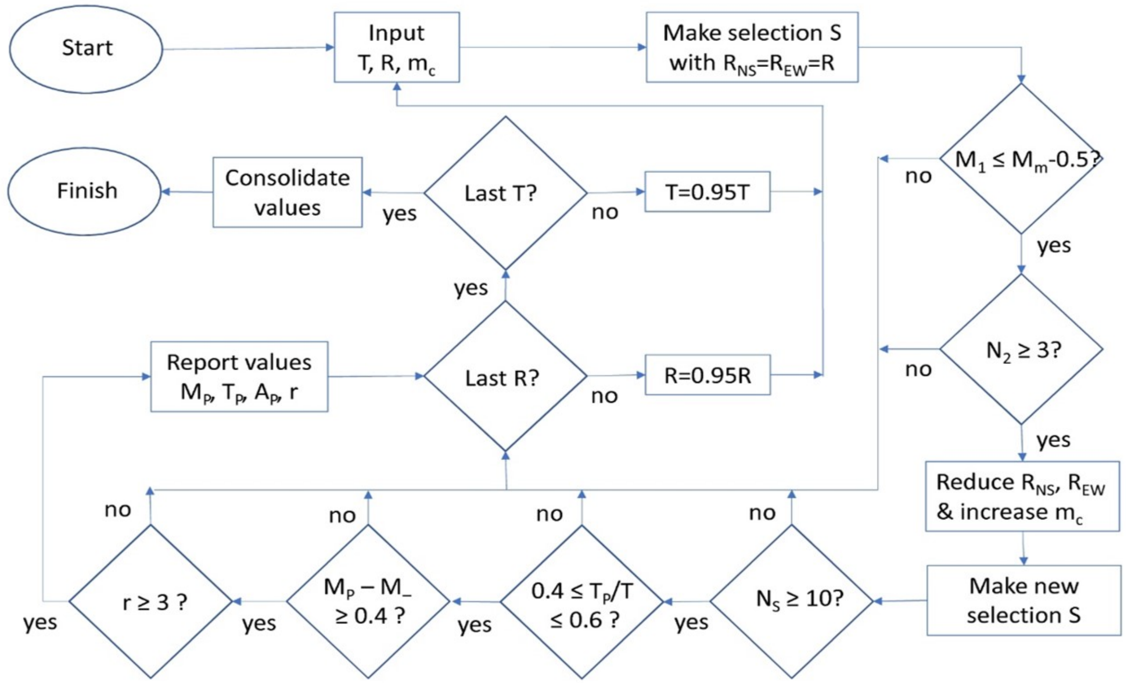
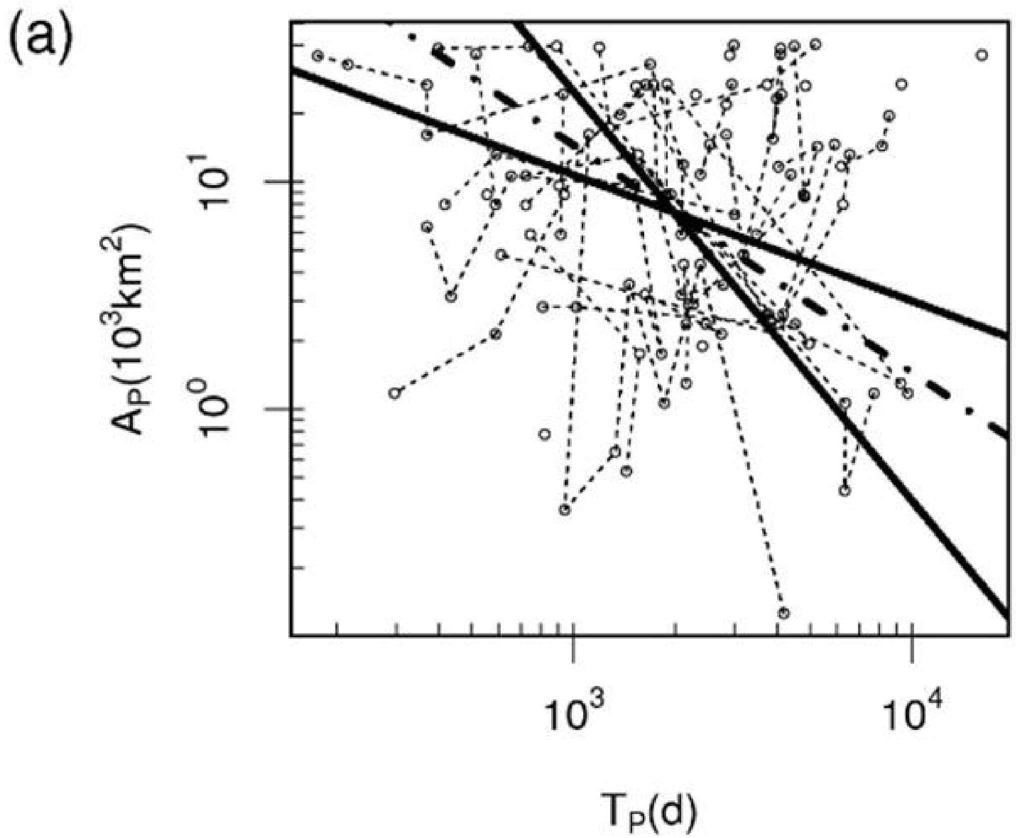
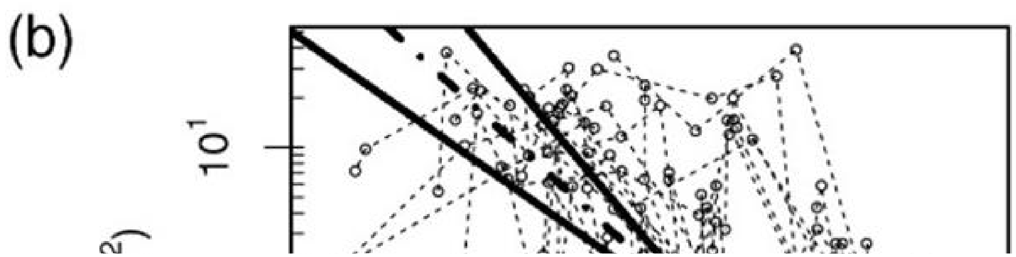


Figure 3. The applied algorithm for automatic *Ψ*- phenomenon identification.

MULTIPLE Ψ-IDENTIFICATIONS AND SPACE-TIME TRADE-OFF

Applying *Rectangles* algorithm we obtained multiple identifications of Ψ for most mainshocks. Each identification is represented by a value of precursor magnitude M_P, precursor time T_P and precursory area A_P. A trade-off between A_P and T_P was observed amongst such multiple identifications (see Figure 4).





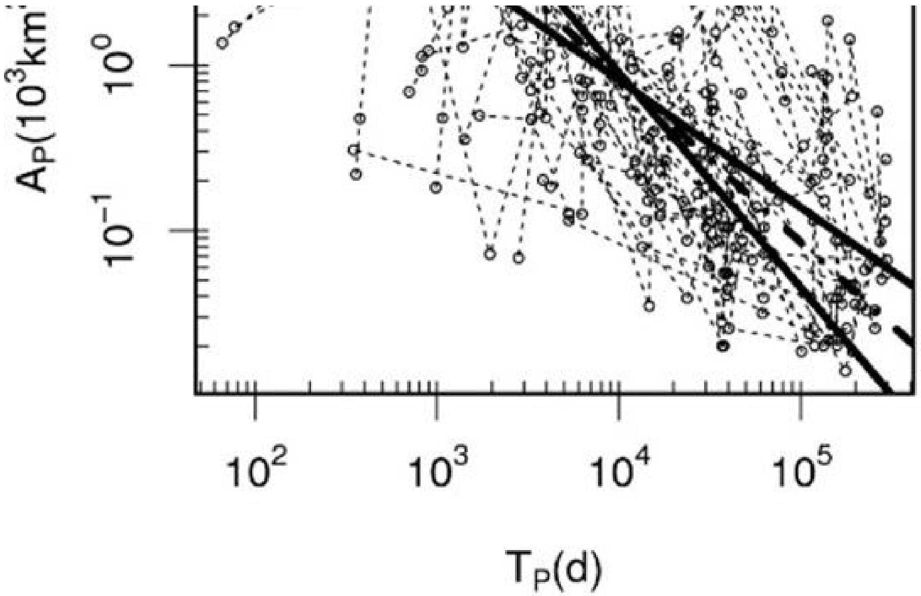


Figure 4. Plot of precursory area A_P against precursor time T_P in algorithmic identifications of Ψ by the "*rectangles*" algorithm for (a) 34 of 47 real mainshocks in four regions (Evison and Rhoades, 2004); (b) randomly selected subset of 34 of 376 mainshocks with $M_m \geq 7.0$ in a synthetic catalogue of Wellington region.

Dotted lines link the identifications corresponding to a single mainshock. The slope of the bold solid lines represent the slope of a set of parallel lines (one for each earthquake) fitted through the data of Figure 4, to minimize the least square errors in the *x* and *y* directions respectively.

The bold solid lines in Figure 4 (b) were fitted using all 376 mainshocks. Bold dashed line has slope -1 representing an even trade-off between precursory area and precursor time.

DATA

To illustrate trade-off for the EEPAS temporal and spatial scaling parameters a_T and σ_A, we use the NZ earthquake catalogue. The catalogue starting time is set to be 1951, based on an assessment of the quality and completeness of the NZ catalogue. A minimum magnitude $m_0 = 2.95$ was set for precursors. The target earthquakes in the magnitude range between $m_c = 4.95$ and $m_u = 8.05$ were used and the EEPAS parameters were initially fitted to the NZ earthquake catalog in1987-2006.

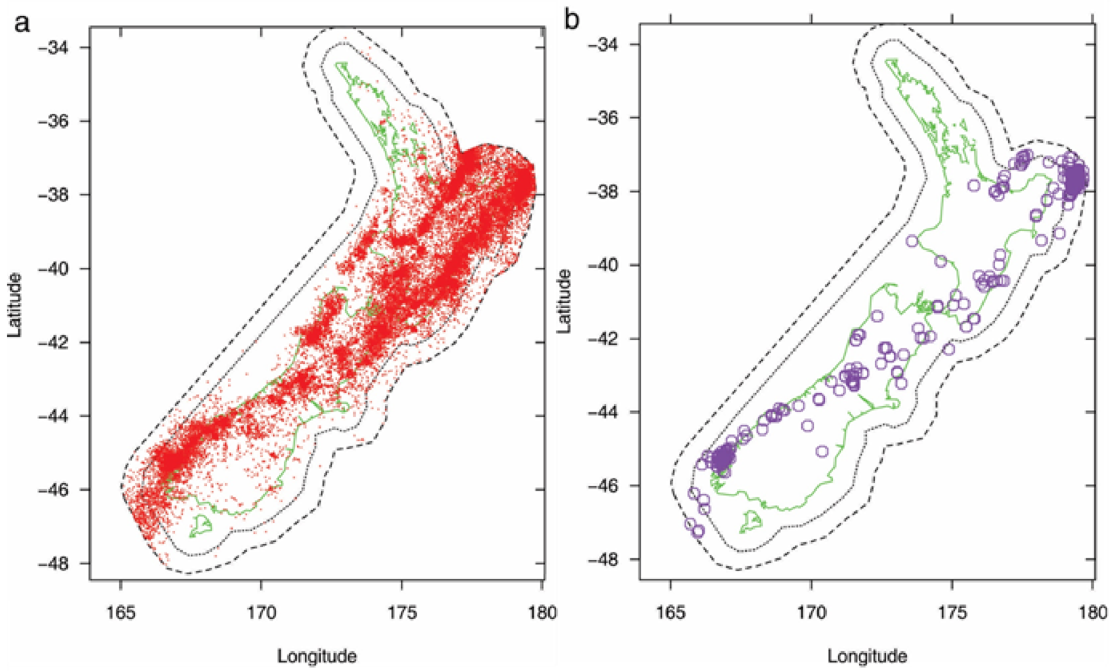


Figure 5. Maps of NZ seismicity including test region (dotted inner polygon) and data collection region (dashed outer polygon), and earthquakes of magnitude (a) M > 2.95 from 1951 to 2006 with hypocentral depth ≤ 45 km , and (b) M > 4.95 from 1987 to 2006, with depth ≤ 40 km.

The region of surveillance is the NZ Earthquake Forecast Testing Centre test region of Figure 5. The depth is set to 0–40 km and the selection of data is consistent with previous model fittings. The target set of 158 earthquakes in the test region are shown in Fig 5.

PRECURSORY SCALE INCREASE Ψ & ASSOCIATED PREDICTIVE SCALING RELATIONS

Precursory seismicity to major earthquakes takes place over time scales ranging from less than a day to several decades. Precursory earthquakes are part of the general phenomenon of space-time earthquake clustering. An observed increase in the magnitude and rate of minor earthquakes prior to a major earthquake is known as the precursory scale increase (Ψ-) phenomenon. As explained in the previous box, the EEPAS modesl uses the Ψ phenomenon along with three predictive spatial, temporal and magnitude scaling relations. The scaling relations are:

$$M_m = a_M + b_M M_P$$

$$logT_P = a_T + b_T M_P$$

$$logA_P = a_A + b_A M_P$$

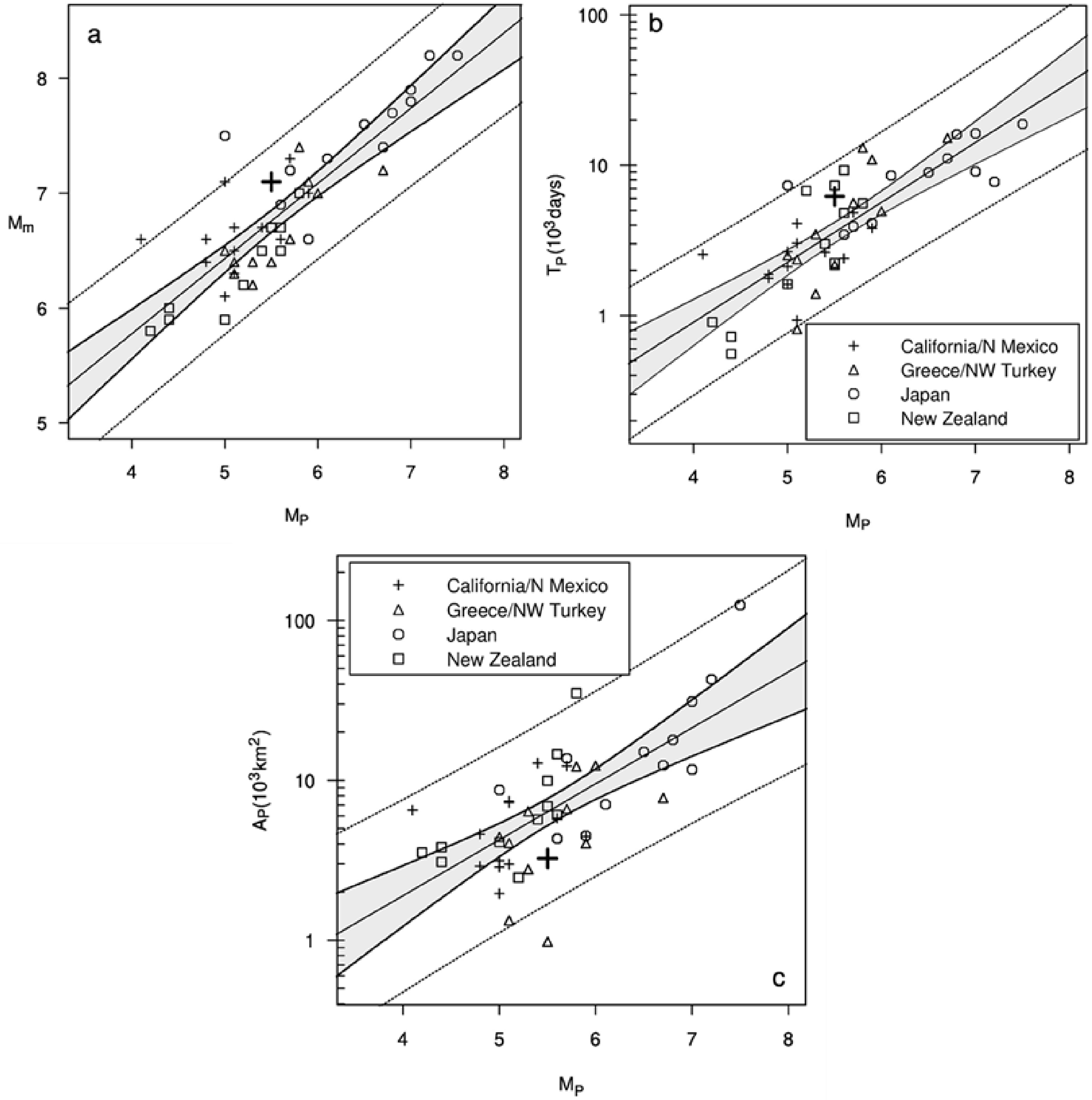


Figure 1. Ψ-predictive scaling relations between (a) mainshock and precursor magnitudes, M_m and M_P (b) precursor time, T_P and M_P and (c) precursor area, A_P and M_P for 47 major earthquakes and the recent Ridgecrest sequence (large symbols).

METHOD & RESULTS

When fitting the EEPAS model, the mean of the time distribution *f* is proportional to 10^{a_T} and the area occupied by the spatial distribution *h* is proportional to σ^2_A provided other parameters of these distributions are fixed. Therefore, 10^{a_T} and σ^2_A are considered as time and spatial scaling factors to compare the change in the EEPAS time and spatial distributions.

In order to examine the implications of the trade-off for the EEPAS temporal and spatial scaling parameters the EEPAS parameters are now refitted with a sequence of controlled values for a_T and then for σ_A. Figure 6 shows the change in values of σ_A for controlled values for a_T and values of a_T for controlled values of σ_A. A similar space-time trade-off as in Figure 4 is observed here. The solid bold line represents an even trade-off between space and time.

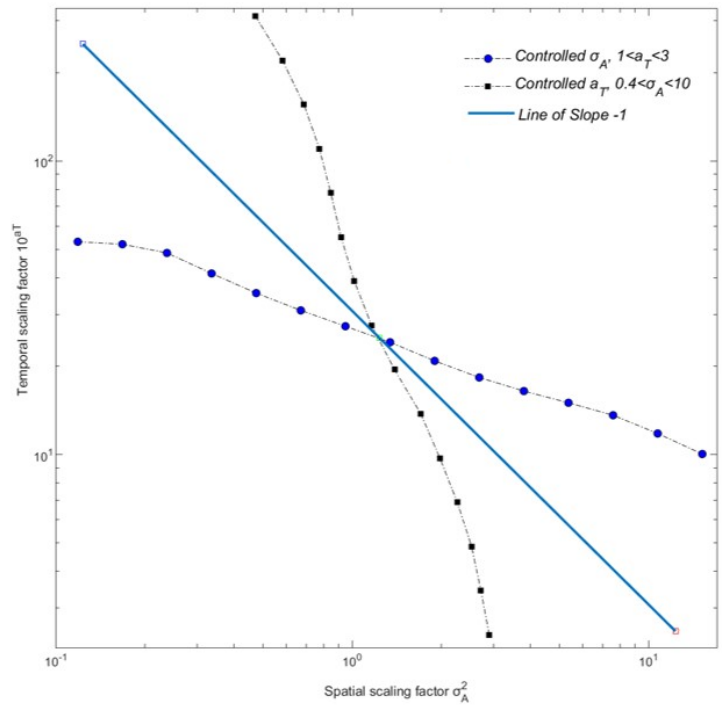


Figure 6. Implication of Space-Time trade-off for the temporal and spatial scaling parameters a_T and σ_A in the EEPAS-1F with downweighed aftershocks .

DISCUSSION AND CONCLUSION

Results confirm the existence of a similar space-time trade-off in EEPAS as in Ψ, with large a_T values being associated with small σ_A values and vice versa. We conclude that the space-time trade-off is an intrinsic feature of precursory seismicity. This exists independently of other influences, such as the local strain rate, that may contribute to scatter in the predictive scaling relations. Mixing EEPAS models with parameters along the trade-off line should improve forecasting.

ABSTRACT

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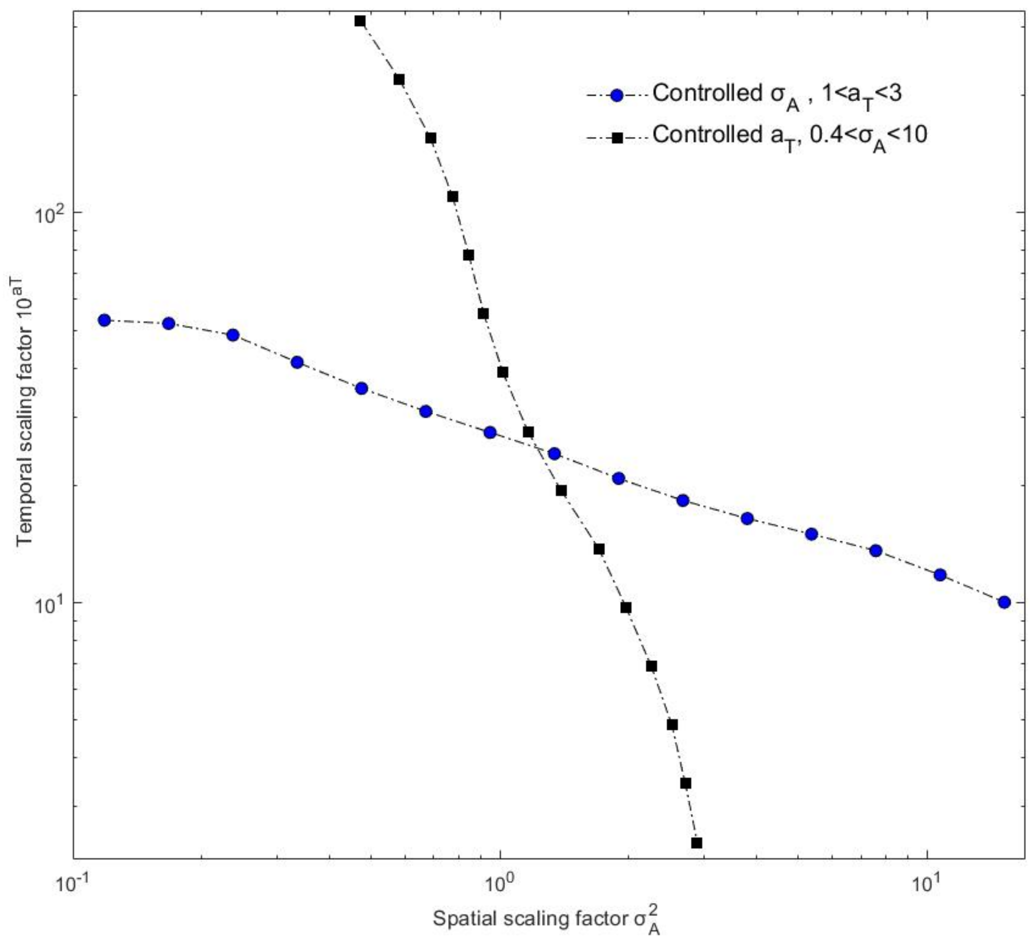

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