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Earthquake Prediction : Algorithms

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Earthquake prediction: Algorithms

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Outline

- Earthquake prediction definition
- Intermediate-term middle-range earthquake prediction algorithm M8
- How to reduce earthquake prediction uncertainty from middle-range to narrow? Algorithm MSc
- Global Test of M8-MSc

What is earthquake prediction?

The United States National Research Council, Panel on Earthquake Prediction of the Committee on Seismology suggested the following definition (1976, p.7):

"An earthquake prediction must specify the expected magnitude range, the geographical area within which it will occur, and the time interval within which it will happen with sufficient precision so that the ultimate success or failure of the prediction can readily be judged. Only by careful recording and analysis of failures as well as successes can the eventual success of the total effort be evaluated and future directions charted. Moreover, scientists should also assign a confidence level to each prediction."

Stages of earthquake prediction

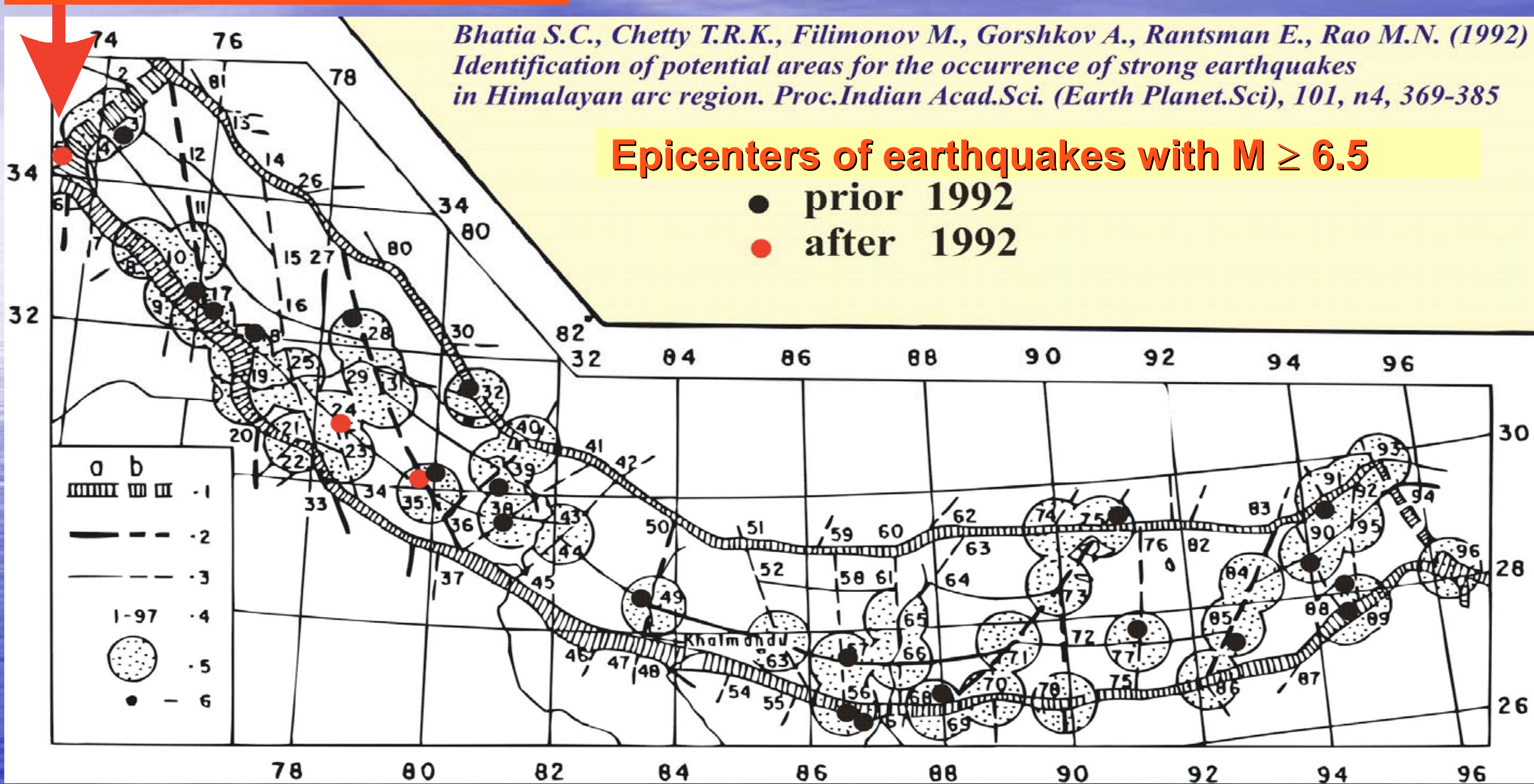
- Term-less prediction of earthquake-prone areas
- Prediction of time and location of an earthquake of certain magnitude

Temporal, ***in years***		Spatial, ***in source zone size L***	
Long-term	10	Long-range	up to 100
Intermediate-term	1	Middle-range	5-10
Short-term	0.01-0.1	Narrow	2-3
Immediate	0.001	Exact	1

- Moreover, the Gutenberg-Richter law suggests limiting magnitude range of prediction to about one unit. Otherwise, the statistics would be essentially related to dominating smallest earthquakes.

Region: **PAKISTAN 14 km off Muzaffarabad**
Date Time: **2005/10/08 03:50:36.4 UTC**
Location: **34.47 N ; 73.50 E**
Depth: **10 km**
Magnitude: **7.7**

An example of term-less prediction

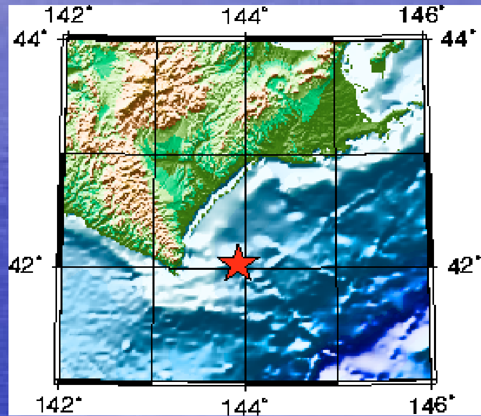


PLANETS ALIGN:
On Wednesday morning, September 24th, 2003 a lovely trio appeared in the eastern sky: **Jupiter, the crescent moon and Mercury…**

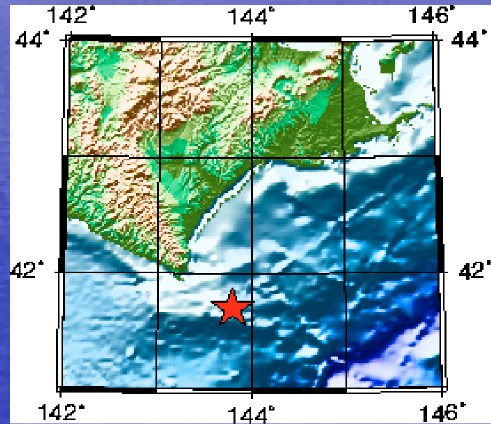
Is it a coincidence or a law?

Two days later …

防災科研Hi-net暫定処理による震源位置



本震
2003年9月26日04時50分11秒
北緯42.0度
東経143.9度
深さ25km
M7.7



最大余震
2003年9月26日06時08分03秒
北緯41.8度
東経143.9度
深さ35km
M7.4

Statistical significance and effectiveness of predictions

A statistical conclusion about the effectiveness and reliability of an earthquake prediction algorithm could be attributed in the following way.

Let **T** and **S** be the total time and territory considered; A_t is the territory covered by the alarms at time t; τ×μ is a measure on **T**×**S** (we consider here a direct product measure τ×μ reserving a general case of a time-space dependent measure ν for future more sophisticated null-hypotheses); **N** counts the total number of large earthquakes with $M \geq M_0$ within **T**×**S** and **n** counts how many of them are predicted. The time-space occupied by alarms, $\mathbf{A} = \bigcup_T A_t$, in percentage to the total space-time considered equals

$$\boldsymbol{p} = \int_A d(\tau \times \mu) \; / \int_{T \times S} d(\tau \times \mu) \, .$$

The statistical significance level of the prediction results equals

$$1 - B(\mathbf{n-1}, \mathbf{N}, \boldsymbol{p}),$$

where B is the cumulative binomial distribution function.

Measure τ×μ: For time we assume the uniform measure τ, which corresponds to the Poisson, random recurrence of earthquakes. For space we assume the measure μ proportional to spatial density of epicenters. Specifically, the measure μ of an area is proportional to the number of epicenters of earthquakes from a sample catalog.

Seismic Roulette

Consider a roulette wheel with as many sectors as the number of events in a sample catalog, a sector per each event.

- Make your bet according to prediction: determine, which events are inside area of alarm, and put one chip in each of the corresponding sectors.
- Nature turns the wheel.
- If seismic roulette is not perfect…

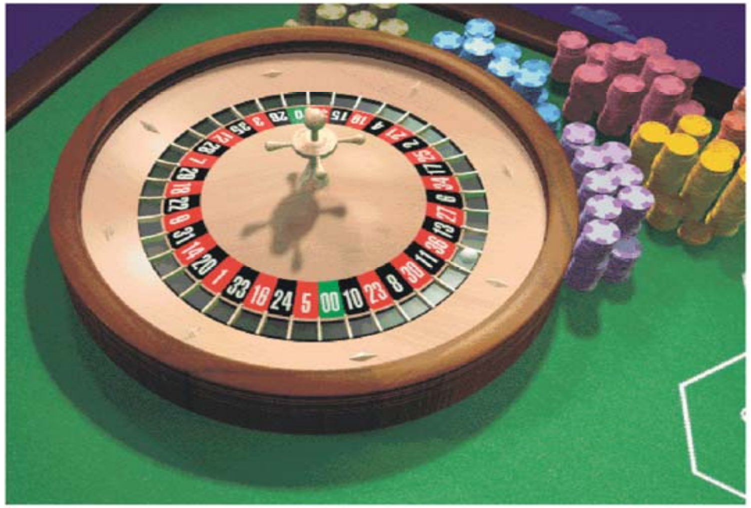
then ***systematically*** you can win! ☺

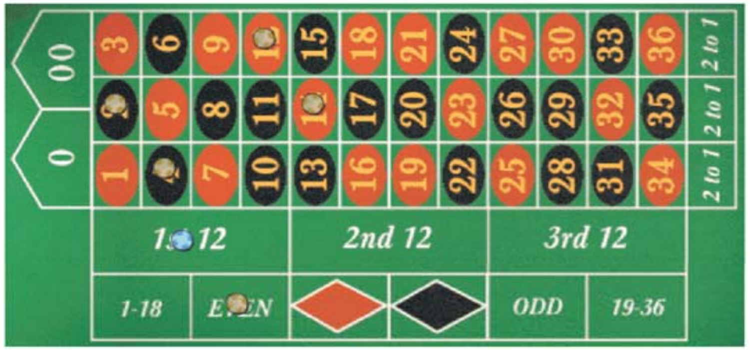
and lose … ☹

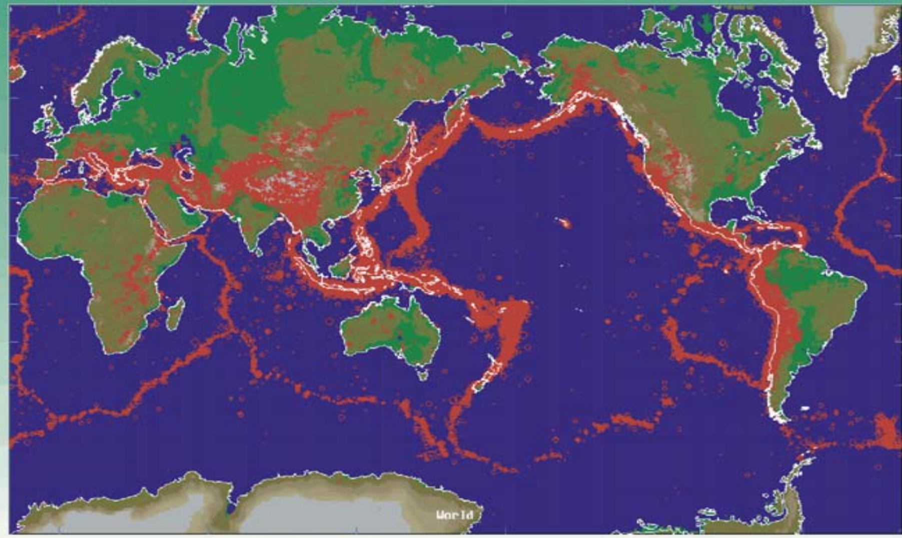
If you are smart enough and your predictions are effective ------

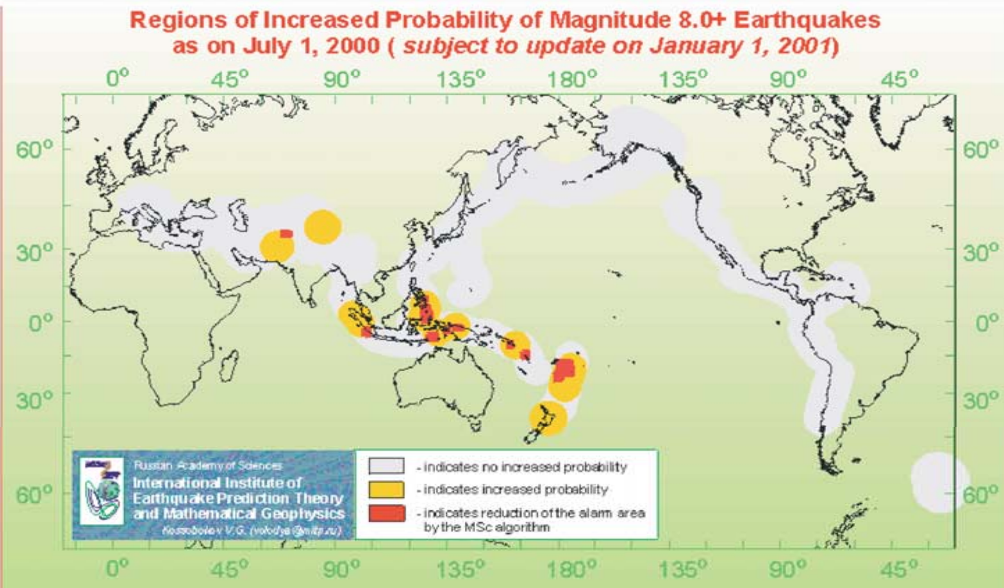
the first will outscore the second! ☺ ☺ ☹ ☺ ☺ ☺ ☹ ☺ ☺ ☺

Seismic Roulette









How earthquake prediction methods work?

"Predicting earthquakes is as easy as one-two-three.

- Step 1: Deploy your precursor detection instruments at the site of the coming earthquake.

  Routine seismological data bases, e.g. US GS/NEIC

- Step 2: Detect and recognize the precursors.

  Reproducible intermediate-term algorithms, e.g. M8

- Step 3: Get all your colleagues to agree and then publicly predict the earthquake through approved channels."

  Number of earthquakes have been predicted

Scholz, C.H., 1997. Whatever happened to earthquake prediction. *Geotimes*, **42**(3), 16-19

(available from *IASPEI Software Library, Vol. 6. Seismol. Soc. Am., El Cerrito, CA, 1997*)

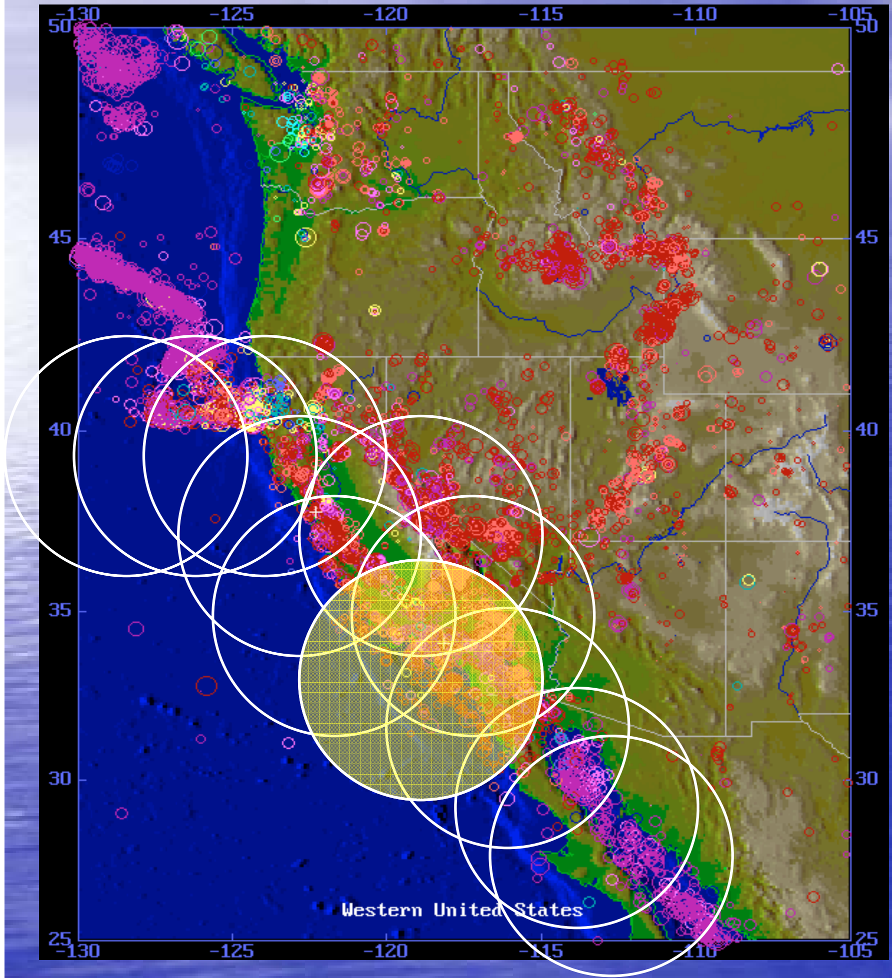
M8 algorithm

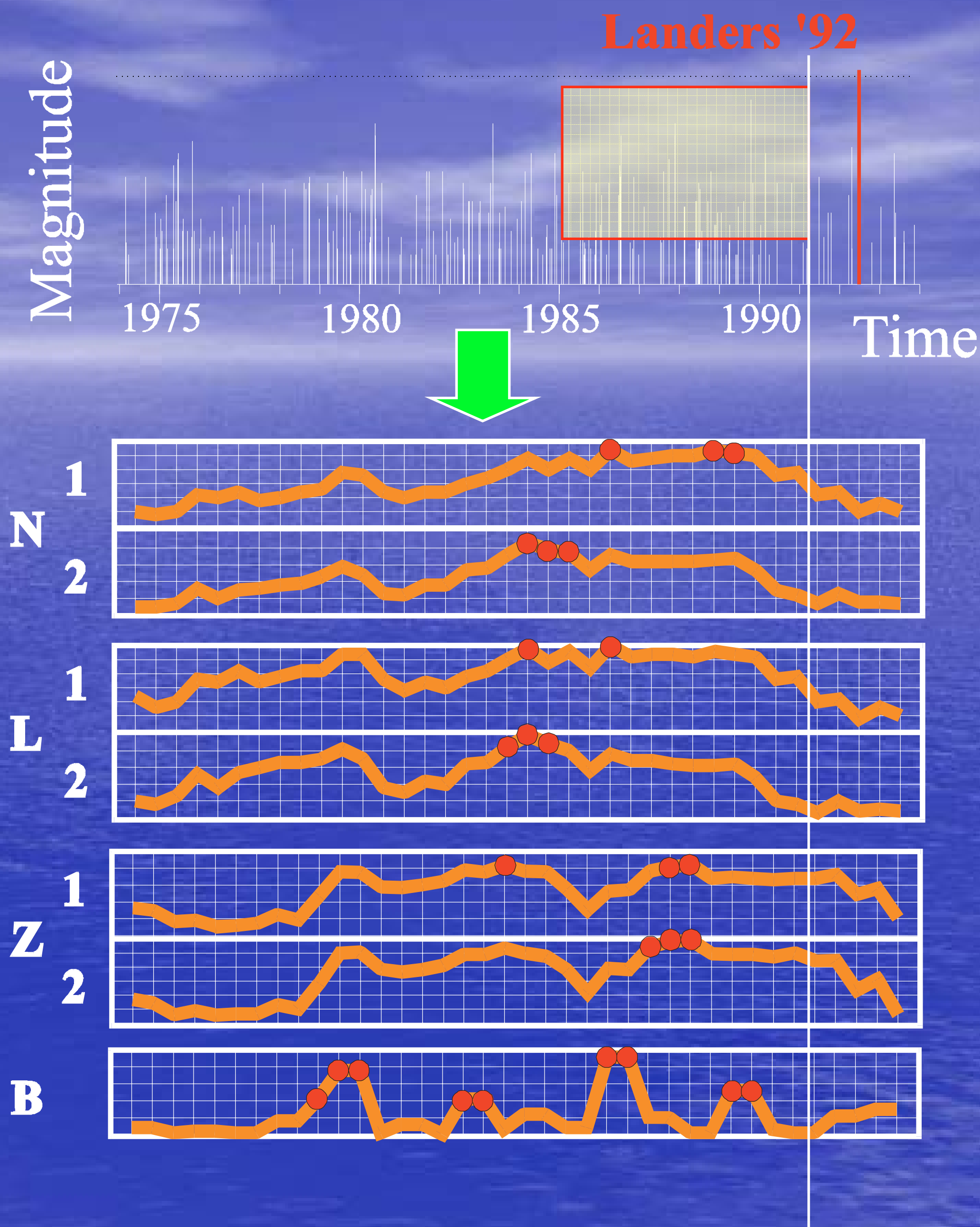
This intermediate-term earthquake prediction method was designed by retroactive analysis of dynamics of seismic activity preceding the greatest, magnitude 8.0 or more, earthquakes worldwide, hence its name.

Its prototype (***Keilis-Borok and Kossobokov, 1984***) and the original version (***Keilis-Borok and Kossobokov, 1987***) were tested retroactively at 143 points, of which 132 are recorded epicenters of earthquakes of magnitude 8.0 or greater from 1857-1983.

The algorithm is based on a simple physical scheme…

General scheme



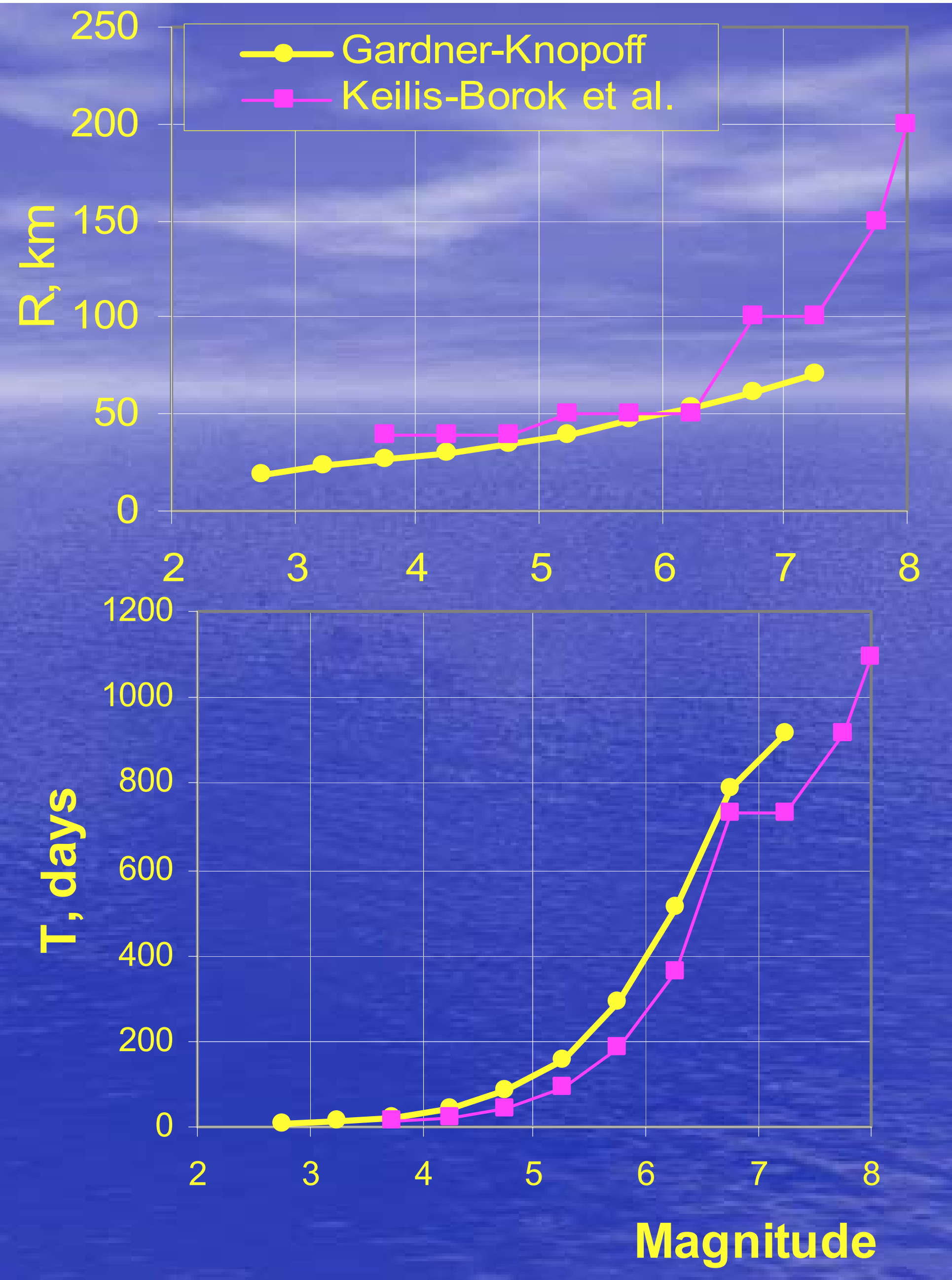


Data

- Catalog of main shocks:

  $\{t_i, m_i, h_i, b_i(e)\}$, i = 1, 2 ...

Here t_i is the origin time, $t_i \le t_{i+1}$; m_i is the magnitude, h_i is focal depth, and $b_i(e)$ is the number of aftershocks with magnitude M_{aft} or more during the first *e* days.



Prediction aimed at magnitude M_0

- Prediction is aimed at earthquakes of magnitude M_0 and larger from the range $M_0+ = [M_0, M_0+\Delta M]$ (where $\Delta M < 1$). Magnitude scale should reflect the size of earthquake sources (accordingly, MS usually taken for larger magnitudes, while mb is used for smaller ones).
- If the data permits, we set different M_0+ with a step 0.5.
- Overlapping circles, with the diameter

  $D(M_0) = (exp(M_0 - 5.6)+1)^0$ in degrees of the Earth meridian, scan the seismic region under study.
- The sequence is normalized by the lower magnitude cutoff m = $M_{min}(\tilde{N})$, Ñ being the standard value of the average annual number of earthquakes in the sequence.

Trailing averages

- Several running averages are computed for this sequence in the trailing time window (t - s, t) and magnitude range $M_0 > M_i \geq m$.
- They depict different measures of intensity in earthquake flow, its deviation from the long-term trend, and clustering of earthquakes.

The averages include:

Rate and acceleration of activity

$N(t \mid m, s)$ - the number of earthquakes

with $M \geq m$ in time interval from $(t\text{-}s)$ to t, i.e., the number of events of certain size per unit time,

***rate of activity*.**

$L(t \mid m, s, t_0)$ - deviation of activity from a longer-term trend over the period from t_0 to t:

$$L(t \mid m, s, t_0) =$$

$$N(t \mid m,s) - N(t \mid m,t\text{-}s\text{-}t_0) \times s/(t\text{-}s\text{-}t_0)$$

i.e. differential of the rate of activity

Linear concentration of main shocks

$Z(t) = Z(t \mid m, M', s, \beta, \gamma) = \Sigma 10^{\beta M_i} / N^{\gamma}$ is a linear concentration of the main shocks {i} from the magnitude range $m \le M_i < M'$ and

interval $t - s \le t_i < t$ estimated as the ratio of the average diameter of the source, $l \sim \Sigma 10^{\beta(M_i - \alpha)}/N$ **(when β=0.46)**, to the average distance, $r \sim N^{1/3}$, between them **(that implies γ = 2/3)**

Characteristic of clustering

$B(t \mid m, M', s, m_{aft}, e) = \max b_i(e, m_{aft})$ is the maximum calculated over the main shocks with $m \le M_i < M'$ and time interval $(t-s, t)$.

Vector of description

- Each of the functions N, L, Z is calculated twice for $m = M_{min}(\tilde{N})$, $\tilde{N} = 20$ and $\tilde{N} = 10$.
- As a result, the earthquake sequence is given a robust averaged description by seven functions: N, L, Z (twice each), and B –

N1, N2, L1, L2, Z1, Z2, B

Criterion – abnormal values

"Very large" values are identified for each function using the condition that they exceed *Q* percentiles (i.e., they are higher than *Q* percent of the encountered values).

That is another local normalization of function values according to the natural empirical distribution.

Rules for issuing an alarm

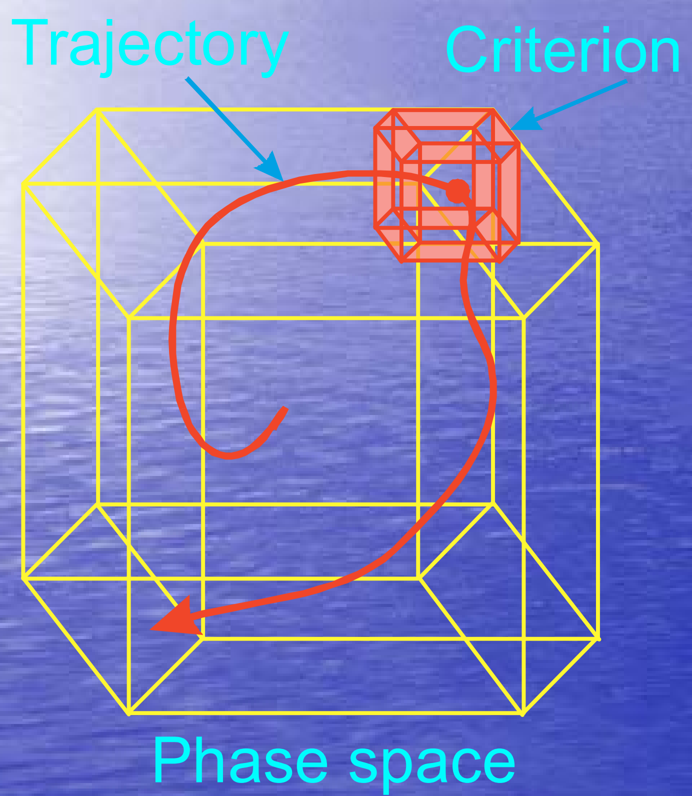
- An alarm or a TIP, "Time of Increased Probability", is declared for five years, when at least six out of seven functions, including B, become "very large" within a narrow time window (t - u, t).
- To stabilize prediction, this criterion is required for two consecutive moments, t and t+0.5 years.

In course of a forward application, the alarm may extend beyond or be terminated before five years in case the updating causes changes in determination of the magnitude cutoffs and/or the percentiles.

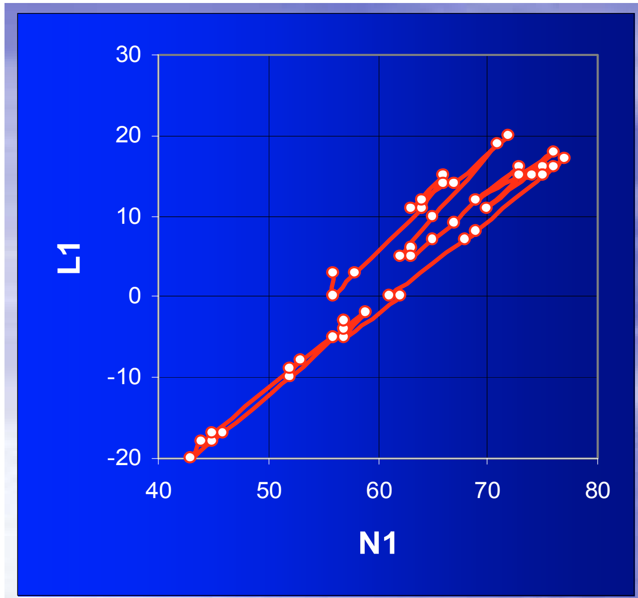
Standard values of parameters

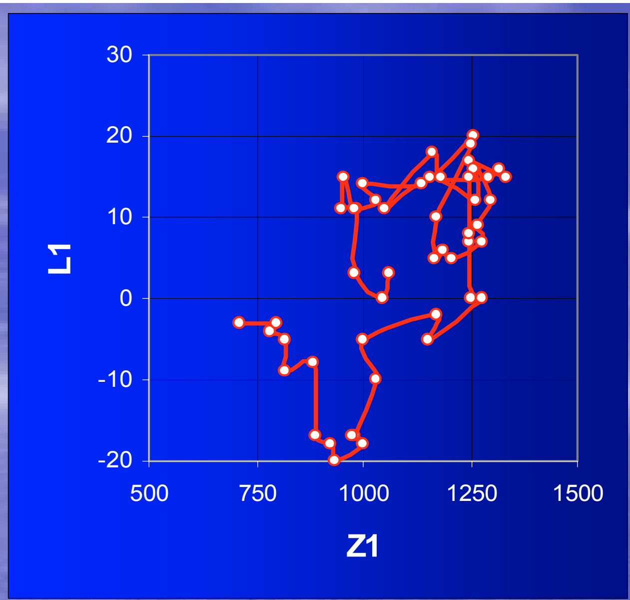
The following standard values of parameters indicated above are prefixed in the algorithm M8: $D(M_0)=\{\exp(M_0 - 5.6)+1\}^0$ in degrees of meridian (*this is 384 km, 560 km, 854 km and 1333 km for M_0 = 6.5, 7.0, 7.5 and 8 respectively*), s = 6 years, s' = 1 year, g = 0.5, p = 2, q = 0.2, u = 3 years, β=0.46, γ = 2/3, and Q = 75% for B and 90% for the other six functions.

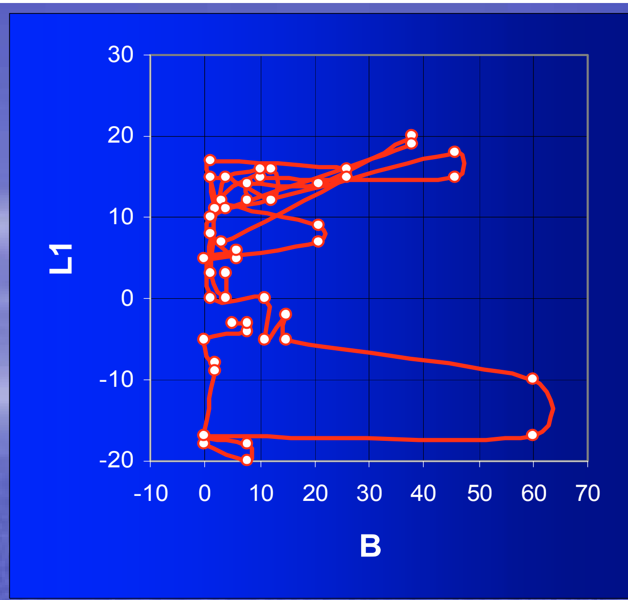
Criterion in the phase space



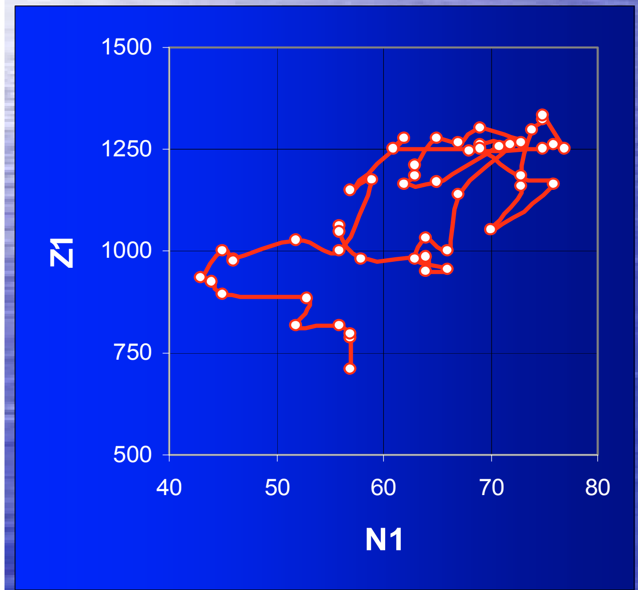
- The algorithm M8 uses traditional description of a dynamical system adding to a common phase space of rate (N) and rate differential (L) dimensionless concentration (Z) and a characteristic measure of clustering (B).
- The algorithm recognizes *criterion*, defined by extreme values of the phase space coordinates, as a vicinity of the system singularity. When a trajectory enters the criterion, probability of extreme event increases to the level sufficient for its effective provision.

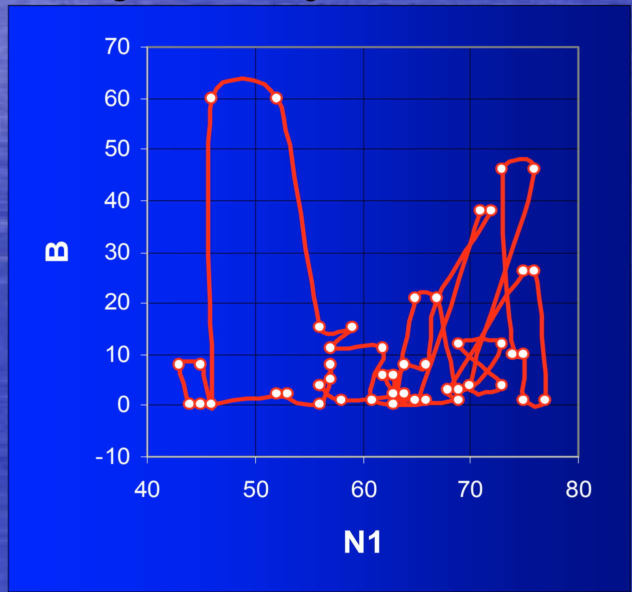


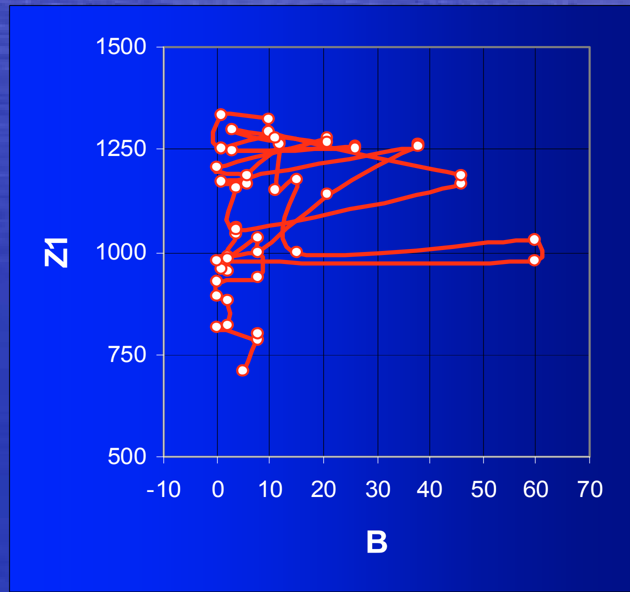




Trajectory in CI#116, Central California







M8 algorithm performance

- Retrospectively (*Keilis-Borok and Kossobokov, 1990*) the standard version of the algorithm was applied to predict the largest earthquakes (with M_0 ranging from 8.0 to 4.9) in 14 regions.

25 out of 28 predicted in 16% of the space-time considered.

- Modified versions in 4 regions of lower seismic activity predicted

all the 11 largest earthquakes in 26 % of the space-time considered.

Second approximation prediction method

The algorithm for reducing the area of alarm (*Kossobokov, Keilis-Borok, Smith, 1990*) was designed by retroactive analysis of the detailed regional seismic catalog prior to the Eureka earthquake (1980, M=7.2) near Cape Mendocino in California, hence its name abbreviated to MSc.

Qualitatively, the MSc algorithm outlines such an area of the territory of alarm where the activity, from the beginning of seismic inverse cascade recognized by the first approximation prediction algorithm (e.g. by M8), is continuously high and infrequently drops for a short time. Such an alternation of activity must have a sufficient temporal and/or spatial span.

The phenomenon, which is used in the MSc algorithm, might reflect the second (possibly, shorter-term and, definitely, narrow-range) stage of the premonitory rise of seismic activity near the incipient source of main shock.

Given a TIP…

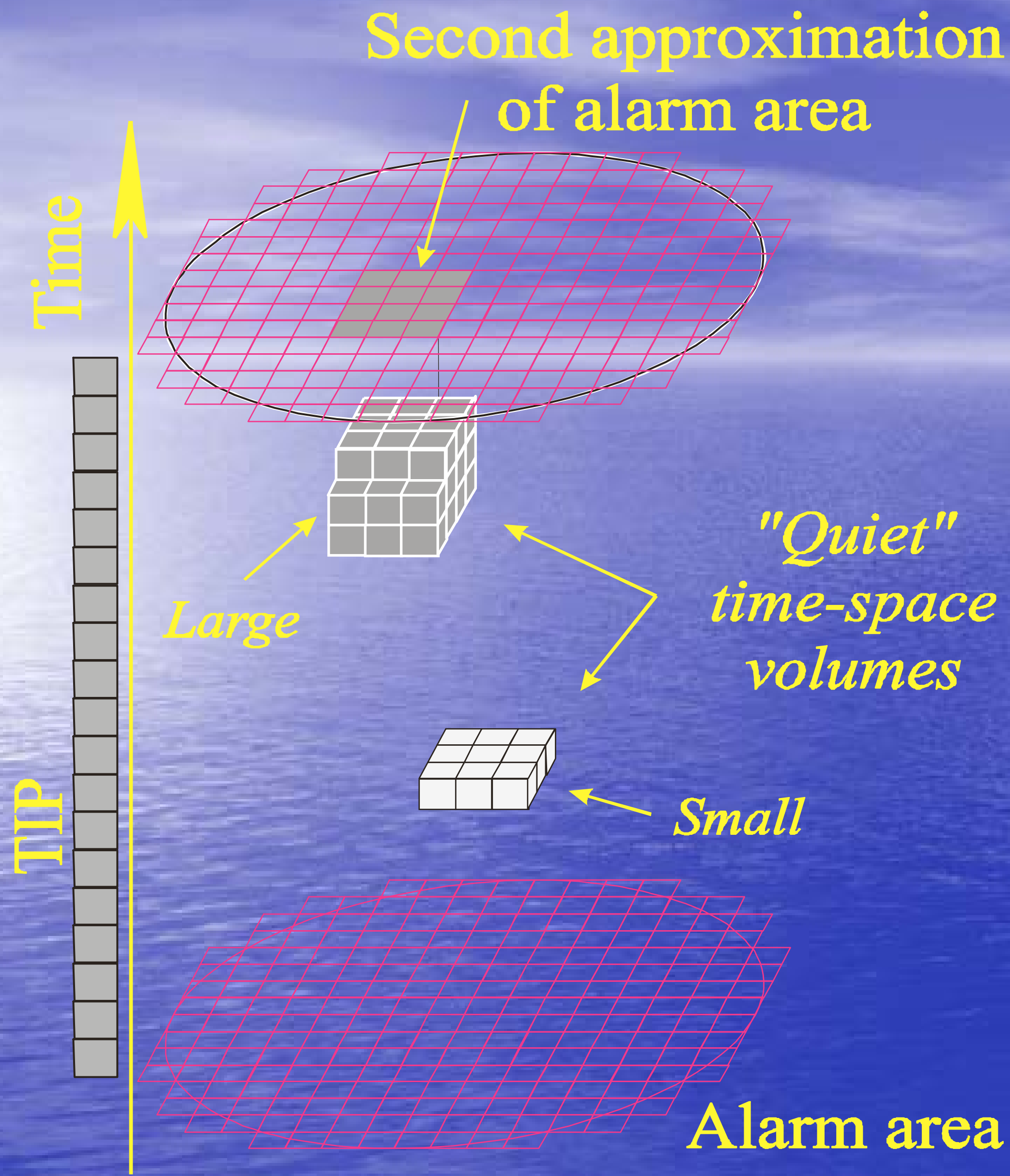
- Given a TIP diagnosed for a certain territory U at the moment T, the algorithm attempts to find within U a *smaller* area V where the predicted earthquake can be expected.
- The algorithm requires a reasonably complete catalog of earthquakes with magnitudes $M \geq (M_0 - 4)$, which is lower than the minimal threshold usually used by M8.

The essence of MSc

- Territory U is coarse-grained into small squares of $s \times s$ size. Let (i,j) be the coordinates of the centers of the squares.
- Within each square (i,j) the number of earthquakes $n_{ij}(k)$, aftershocks included, is calculated for consecutive, short time windows, *u* months long, starting from the time t_0 = (T-6 years) onward, to allow for the earthquakes, which contributed to the TIP's diagnosis; here k is the sequence number of a trailing time window.

The essence of MSc (cont.)

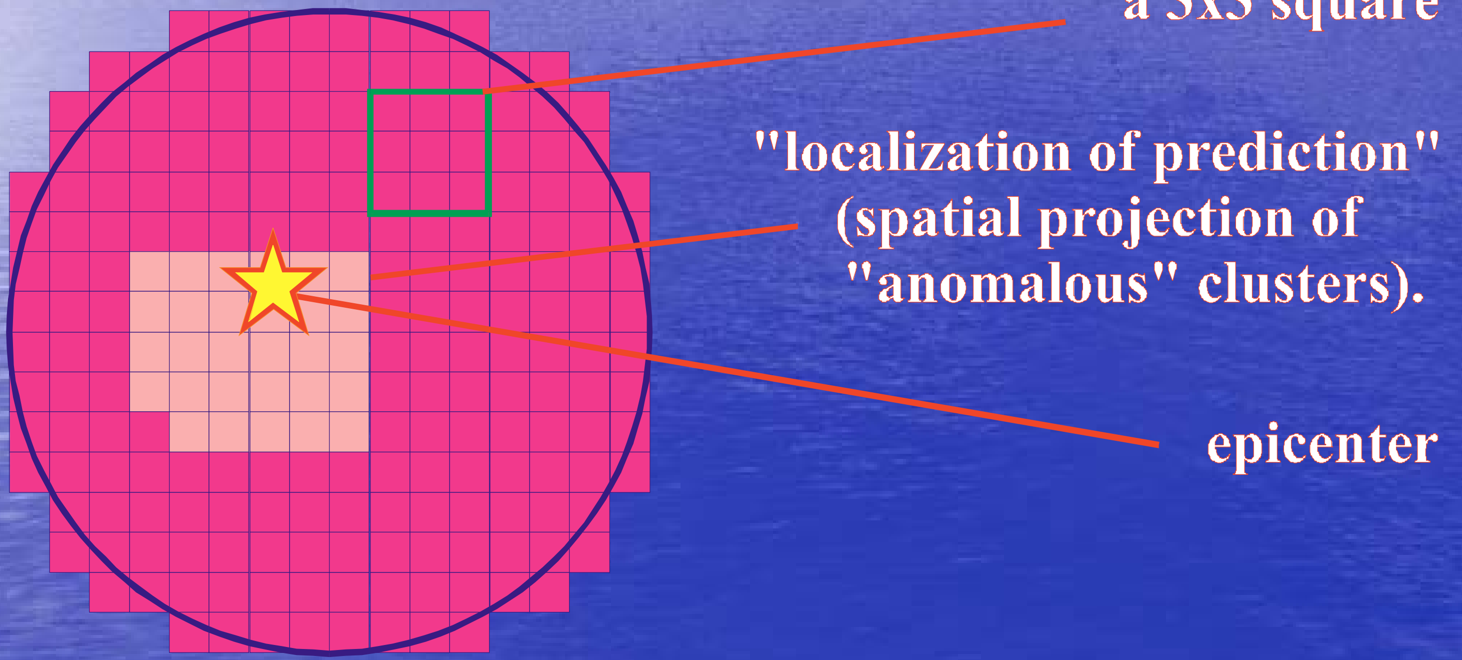
- Finally, the time-space considered is divided into small boxes (i,j,k) of the size ($s \times s \times u$).
- "*Quiet" boxes* are singled out for each small square (i,j); they are defined by the condition that $n_{ij}(k)$ is below the Q percentile of n_{ij}.
- The clusters of q or more quiet boxes connected in space or in time are identified.
- Area V is the territorial projection of these clusters.



The prediction is localized to a spatial projection of all recent "sufficiently large" clusters of squares being in state of "anomalous quiescence".

"Anomalous quiescence" suggests high level of seismic activity during formation of a TIP and after its declaration. "Sufficiently large" size of clusters suggests large scale correlations in recent seismicity.

Eureka 1980, M7.2 earthquake

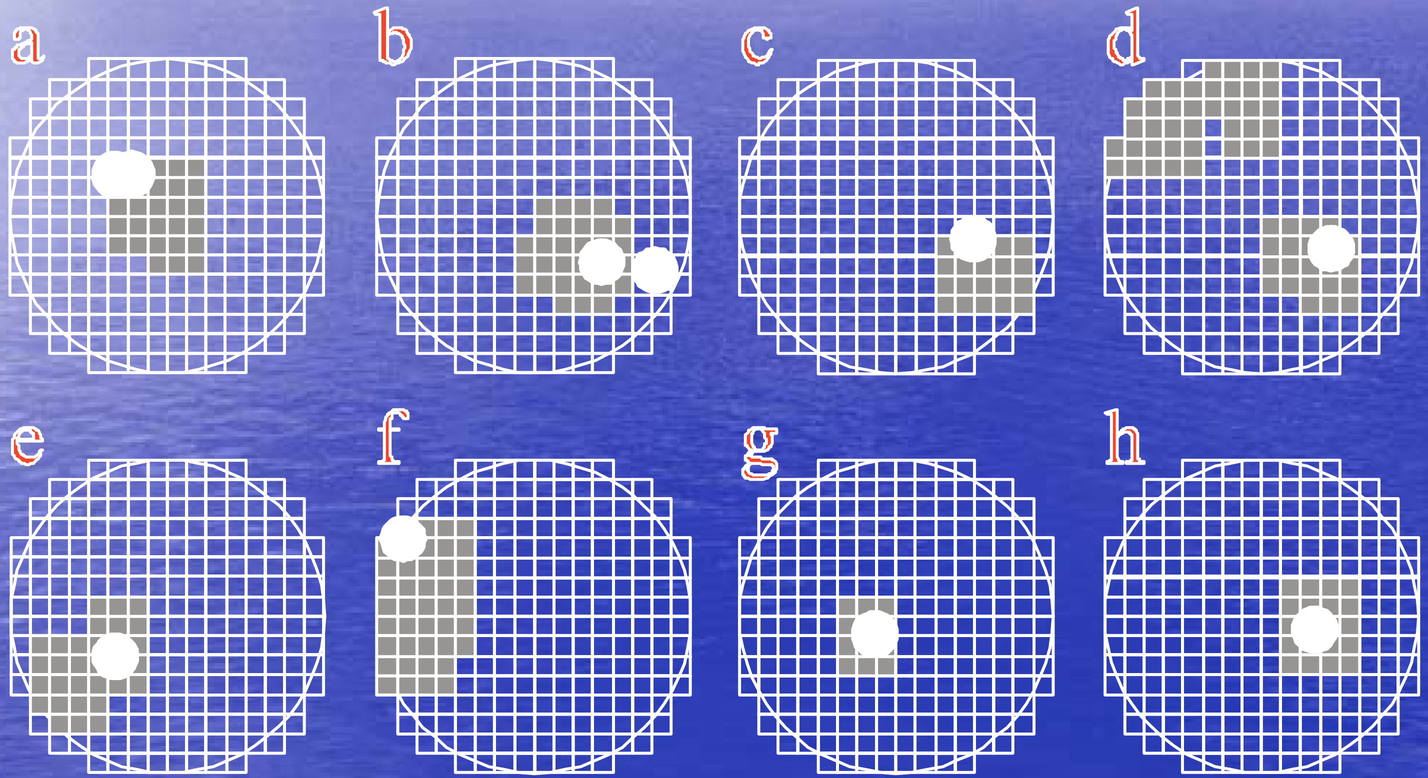


The standard version of MSc

- *The standard values of parameters* adjusted for the case of the 1980 Eureka earthquake are as follows:

u = 2 months, Q = 10%, q = 4, and $s = 3D/16$, D being the diameter of the circle used in algorithm M8.

(a) Santa Cruz Is, 11/28/1985 & 12/21/1985; (b) New Guinea, 02/08/1987 & 10/16/1987; (c) Costa Rica, 04/22/1991; (d) Landers, CA, 06/28/1992; (e) Guam, 08/08/1993; (f) Fiji, 03/09/1994; (g) Shikotan Is, 10/04/1994; (h) Samoa, 04/07/1995.



MSc vs. Activity

MSc outscores simple alternatives of narrowing down the area of first approximation alarm –

- Nonempty Cells (NeC);
- Most Active Cells (MAC) that contain (a) 1/8, (b) 1/4, (c) 1/3 of the recent seismic activity.

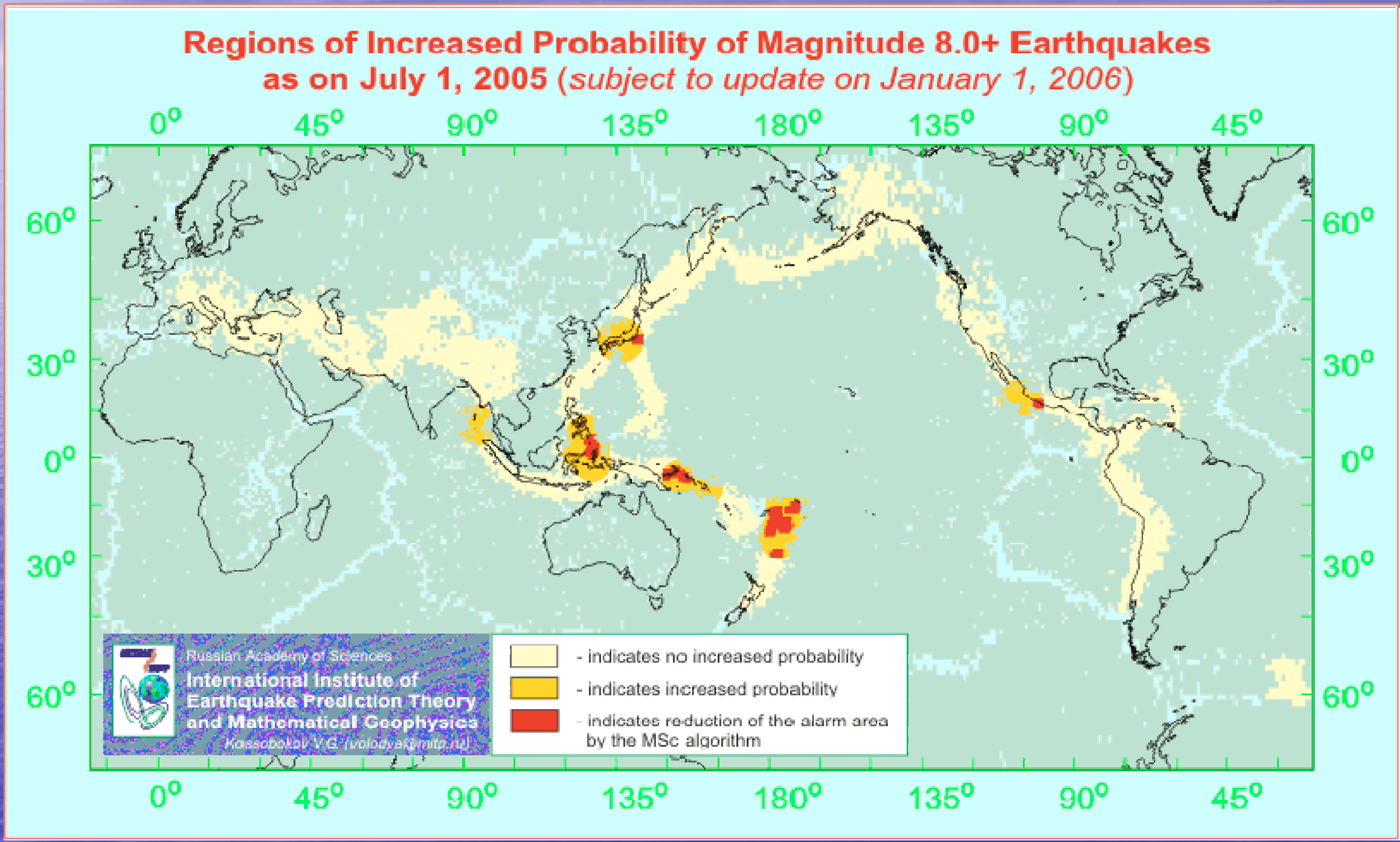
The same number of correct localizations, as obtained with MSc, is achieved also by MAC(1/3), which narrows down the alarm area to 28%, while MSc outperforms it with 14%.

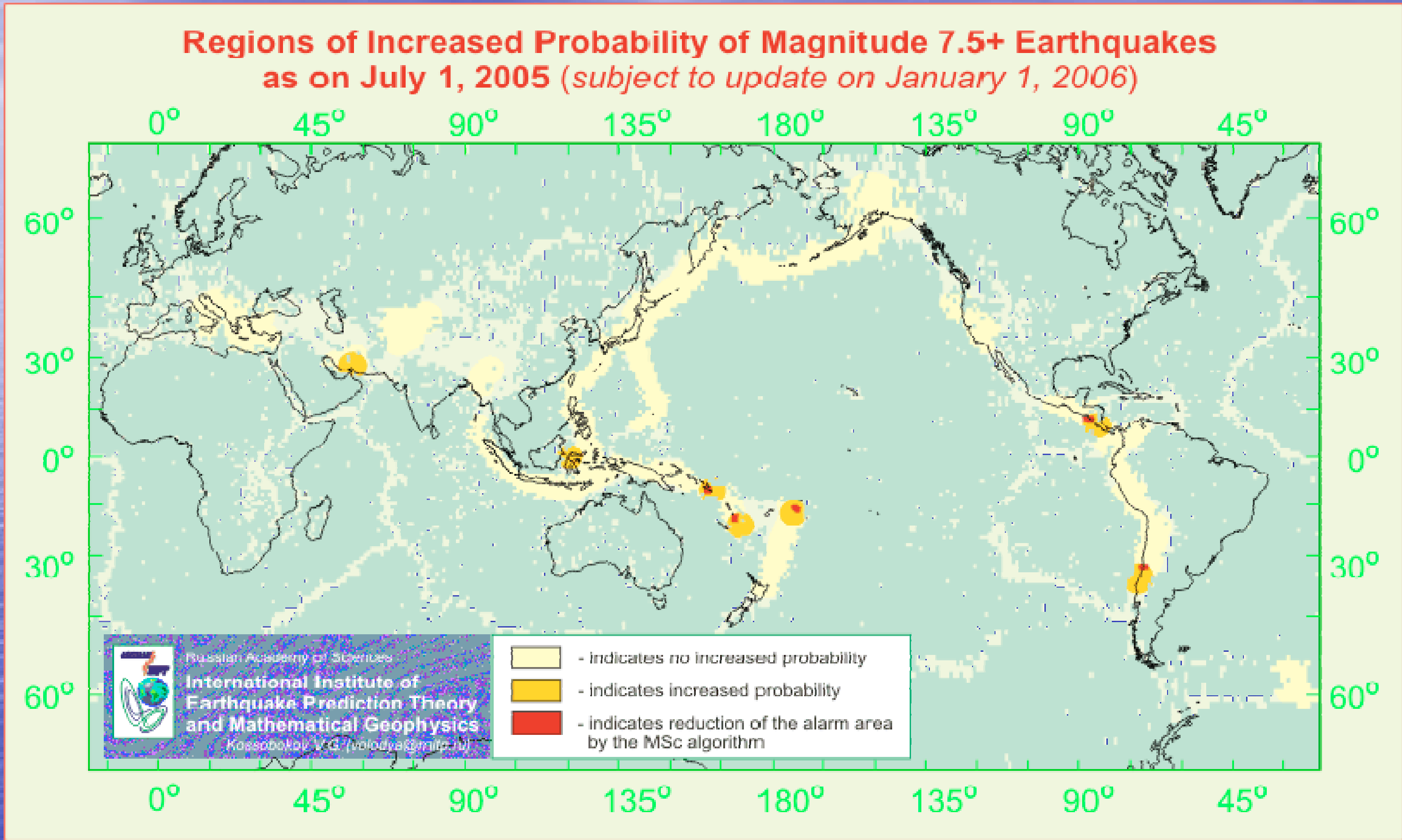
By 1992 all the components necessary for reproducible real-time prediction, i.e., an unambiguous definition of the algorithms and the data base, were specified in publications

- Algorithm M8 (*Keilis-Borok and Kossobokov, 1984, 1987, 1990*) was designed by retroactive analysis of seismic dynamics preceding the greatest ($M \geq 8$) earthquakes worldwide, as well as the MSc algorithm for reducing the area of alarm (*Kossobokov,Keilis-Borok, Smith, 1990*)
- The National Earthquake Information Center Global Hypocenters Data Base (*US GS/NEIC GHDB, 1989*) is sufficiently complete since 1963.
- This allowed a systematic application of M8 and MSc algorithm since 1985.

Real-time prediction of the world largest earthquakes

(http://www.mitp.ru or http://www.phys.ualberta.ca/mirrors/mitp)





Regions of Increased Probability of Magnitude 7.5+ Earthquakes
as on July 1, 2005 (*subject to update on January 1, 2006*)
0° 45° 90° 135° 180° 135° 90° 45°
60° 30° 0° 30° 60°
Russian Academy of Sciences
International Institute of Earthquake Prediction Theory and Mathematical Geophysics
Kossobokov V.G. (volodya@mitp.ru)
- indicates no increased probability
- indicates increased probability
- indicates reduction of the alarm area by the MSc algorithm

Although the M8-MSc predictions are intermediate-term middle-range and by no means imply any "red alert", some colleagues have expressed a legitimate concern about maintaining necessary confidentiality. Therefore, the up-to-date predictions are not shown here, although available on web-pages of restricted access provided to about 150 members of the Mailing List.

Worldwide performance of earthquake prediction algorithms M8 and M8-MSc: Magnitude 8.0+.

Test period	Large earthquakes Total	Predicted by M8	Predicted by M8-MSc	Measure of alarms,% M8	Measure of alarms,% M8-MSc	Confidence level, % M8	Confidence level, % M8-MSc
1985-present	11	9	7	33.24	17.14	99.87	99.92
1992-present	9	7	5	28.42	14.37	99.69	99.54

The significance level estimates use the most conservative measure of the alarm volume accounting for empirical distribution of epicenters.

To drive the achieved confidence level below 95%, the Test should encounter four failures-to-predict in a row.

Worldwide performance of earthquake prediction algorithms M8 and M8-MSc: Magnitude 7.5 or more.

Test period	Large earthquakes Total	Large earthquakes Predicted by M8	Large earthquakes Predicted by M8-MSc	Measure of alarms,% M8	Measure of alarms,% M8-MSc	Confidence level, % M8	Confidence level, % M8-MSc
1985-present	53	30	16	34.35	11.05	99.93	99.98
1992-present	40	19	10	28.77	10.45	99.07	99.31

The significance level estimates use the most conservative measure of the alarm volume accounting for empirical distribution of epicenters.

The prediction for M7.5+ is less effective than for M8.0+. Nevertheless, we continue testing the algorithms for this and smaller magnitude ranges.

Conclusions – The Four Paradigms

Statistical validity of predictions confirms the underlying paradigms:

- Seismic premonitory patterns exist;
- Formation of earthquake precursors at scale of years involves large size fault system;
- The phenomena are similar in a wide range of tectonic environment…
- … and in other complex non-linear systems.

Conclusions – Seismic Roulette is not perfect

Are these predictions useful?

- Yes, if used in a knowledgeable way.
- Their accuracy is already enough for undertaking earthquake preparedness measures, which would prevent a considerable part of damage and human loss, although far from the total.
- The methodology linking prediction with disaster management strategies does exist (*Molchan, 1997*).

Kofi Annan:

Introduction to Secretary-General's Annual Report on the Work of the Organization of United Nations, 1999 - A/54/1

"More effective prevention strategies would save not only tens of billions of dollars, but save tens of thousands of lives. Funds currently spent on intervention and relief could be devoted to enhancing equitable and sustainable development instead, which would further reduce the risk for war and disaster. Building a culture of prevention is not easy. While the costs of prevention have to be paid in the present, its benefits lie in a distant future. Moreover, the benefits are not tangible; they are the disasters that did NOT happen."

Conclusions – Implications for Physics

- The predictions provide reliable empirical constrains for modeling earthquakes and earthquake sequences.
- Evidence that distributed seismic activity is a problem in statistical physics.
- Favor the hypothesis that earthquakes follow a general hierarchical process that proceeds via a sequence of inverse cascades to produce self-similar scaling (*intermediate asymptotic*), which then truncates at the largest scales bursting into direct cascades (*Gabrielov, Newman, Turcotte, 1999*).

What are the Next Steps?

- The algorithms are neither optimal nor unique (CN, SSE, Vere-Jones "probabilistic" version of M8, etc.). The accuracy could be improved by a systematic monitoring of the alarm areas and by designing a new generation of earthquake prediction technique ("Seismic Reversal" - SR, ROC, Accord, RTP, etc.).

… and an obvious general one -

- More data should be analyzed systematically to establish reliable correlations between the occurrence of extreme events and observable phenomena.

Some References

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