School for Young Scientists

Methods for Integrated Seismic Hazard Assessment

EARTHQUAKE PREDICTION PROBLEM IN A BIG DATA WORLD

VLADIMIR G. KOSSOBOKOV

Institute of Earthquake Prediction Theory & Mathematical Geophysics,
Russian Academy of Sciences, Moscow, Russian Federation
Institut de Physique du Globe de Paris, Paris, France
International Seismic Safety Organization (ISSO)
E-mail: volodya@mitp.ru

How earthquake prediction methods work?

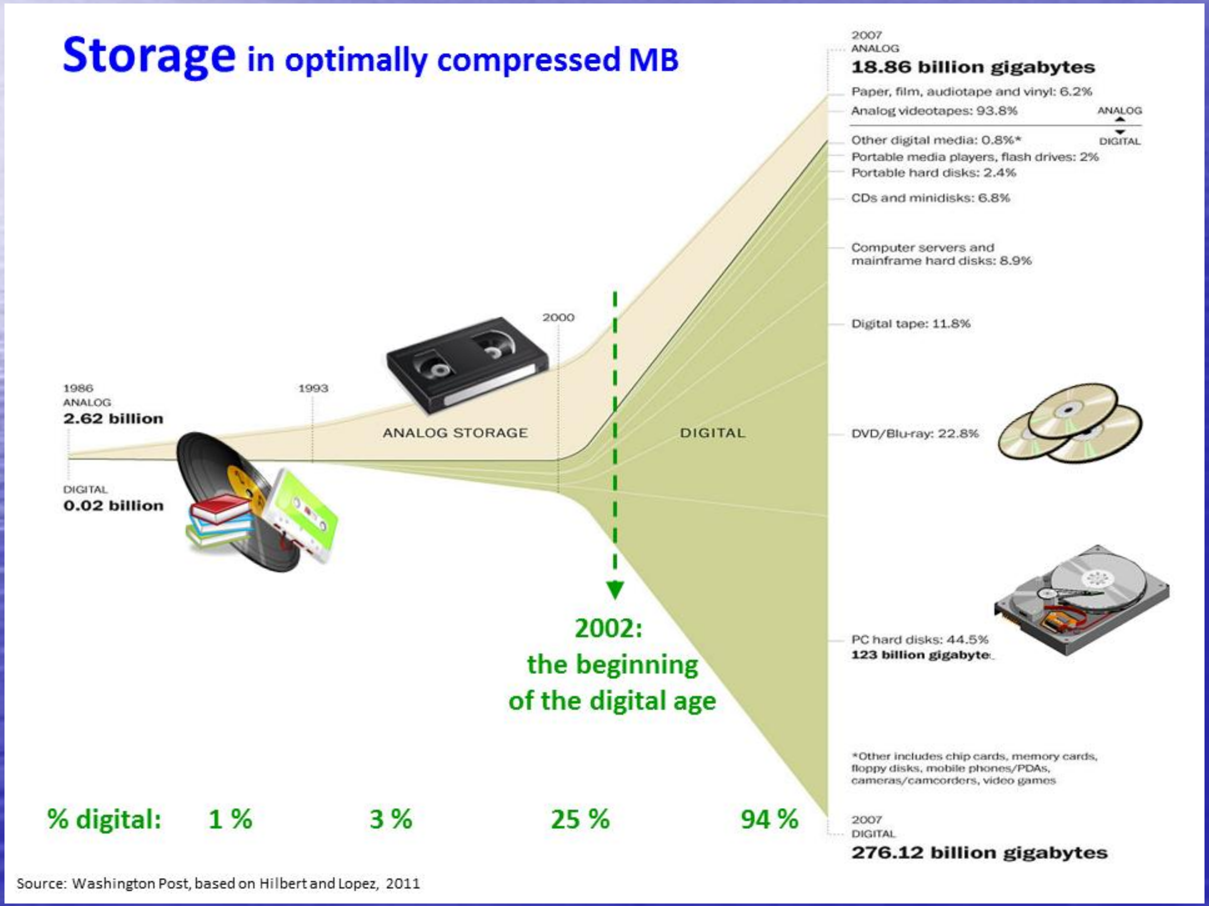
"Predicting earthquakes is as easy as one-two-three.

- Step 1: Deploy your precursor detection instruments at the site of the coming earthquake.
- Step 2: Detect and recognize the precursors.
- Step 3: Get all your colleagues to agree and then publicly predict the earthquake through approved channels."

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

The digital revolution started just about 15 years ago has already surpassed the global information storage capacity of more than 5000 Exabytes (5×10^{21} in optimally compressed bytes) per year.

http://www.martinhilbert.net/wp-content/uploads/2015/01/10HilbertLopezGrowthStorage.png



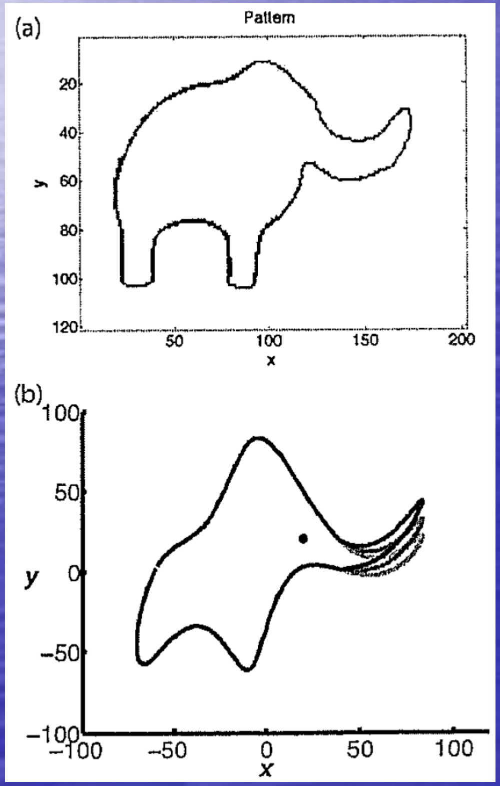
"BIG DATA IS NOT ABOUT THE DATA !"

Gary King, Harvard University, making the point that while data is plentiful and easy to collect, the real value is in the analytics.

https://www.cscollege.gov.sg/knowledge/knowledge/gary%20king/prof%20gary%20king.mp4

Open data in a Big Data World provides unprecedented opportunities for enhancing scientific studies and better understanding of the Earth System. At the same time, it opens wide avenues for deceptive associations in inter- and transdisciplinary data misleading to erroneous predictions, sometimes, unacceptable for implementation.

Mayer et al. (2010) Drawing an elephant with four complex parameters. *Am. J. Phys.* 78(6): 648-649; doi: 10.1119/1.3254017

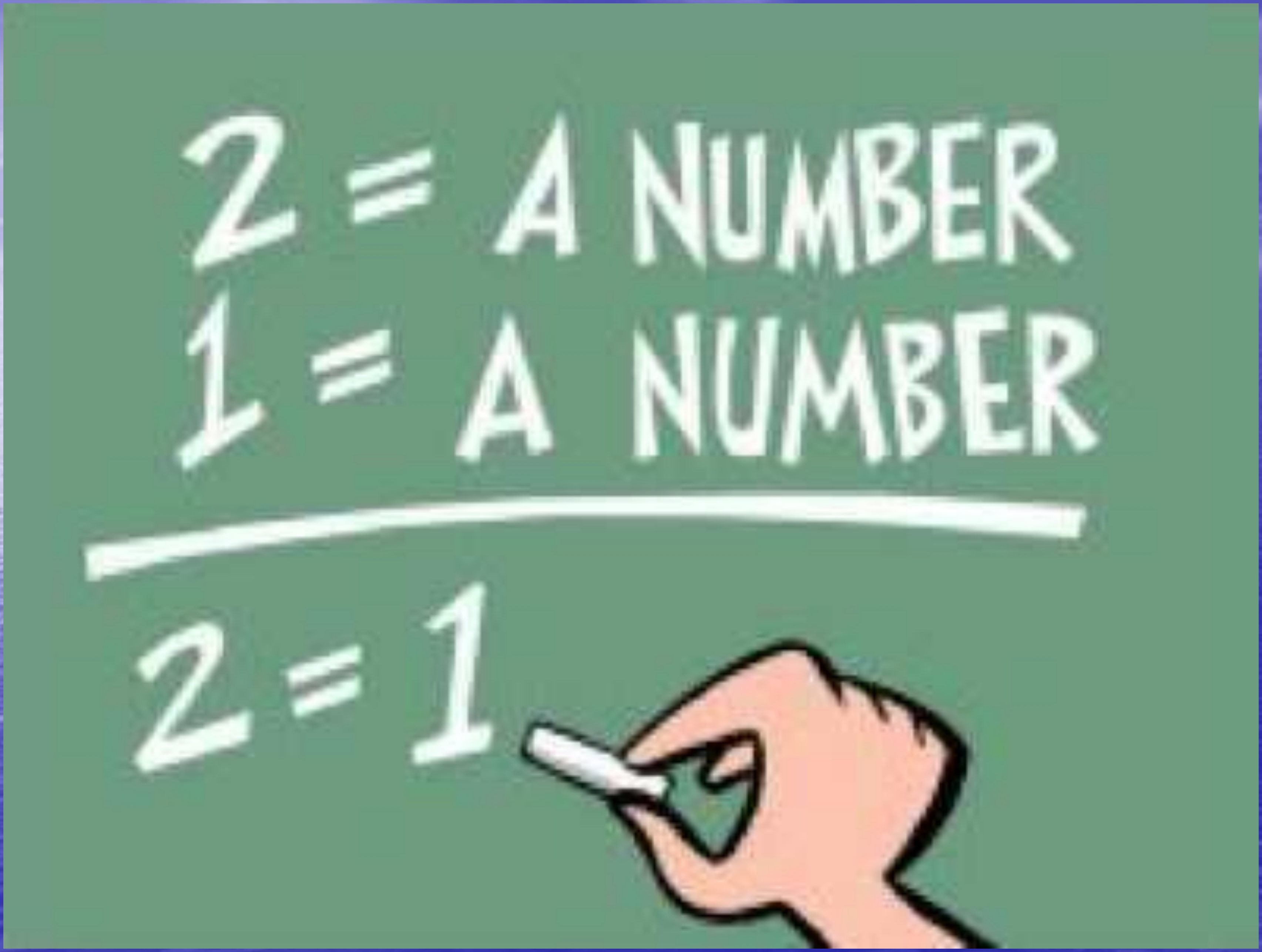


'A turning point in Freeman Dyson's life occurred during a meeting in the Spring 1953 when Enrico Fermi criticized the complexity of Dyson's model by quoting Johny von Neumann: "With four parameters I can fit an elephant, and with the five I can make him wiggle his trunk."'

$$p_1 = 50 - 30i \qquad p_2 = 18 + 8i$$

$$p_3 = 12 - 10i \qquad p_4 = -14 - 60i$$

$$p_5 = 40 + 20i$$


2 = A NUMBER
1 = A NUMBER
2 = 1

Even the advanced tools of data analysis may lead to wrong assessments when inappropriately used to describe the phenomenon under consideration. A (self-) deceptive conclusion could be avoided by verification of candidate models in experiments on empirical data and in no other way. Seismology is not an exception.

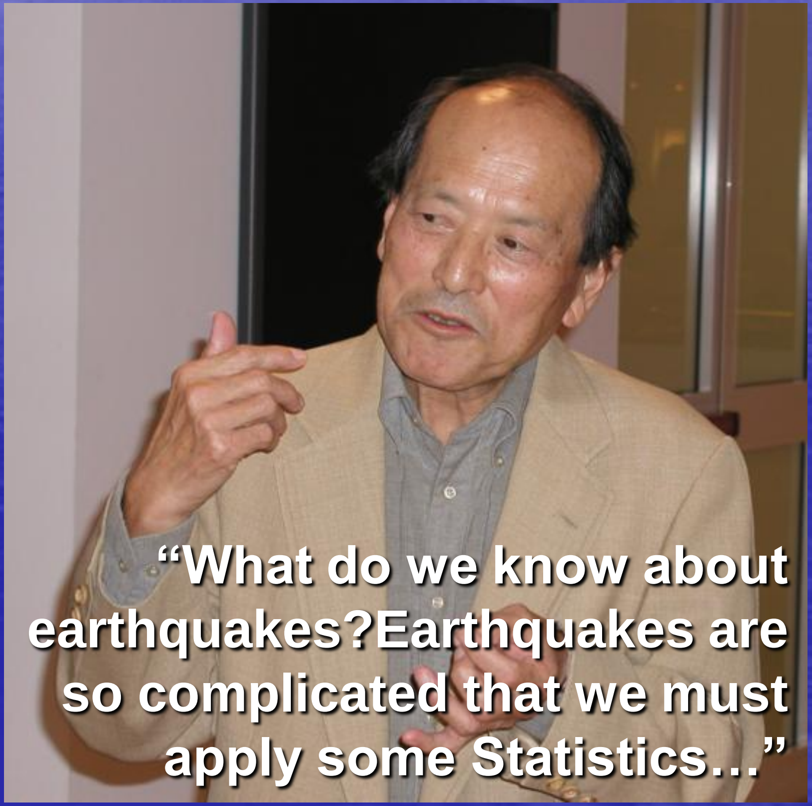
‘ SCIENCE SHOULD be able to warn people of looming disaster, Vladimir Keilis-Borok believes.
“My main trouble,” he says, “is feeling of responsibility.” ‘
(Los Angeles Times, 9 July 2012)

Vladimir Isaacovich Keilis-Borok (1921-2013)

Moreover, seismic evidences accumulated to-date demonstrate clearly that most of the empirical relations commonly accepted in early history of instrumental seismology can be proved erroneous when subjected to objective hypothesis testing. In many cases of seismic hazard assessment (SHA), either probabilistic or deterministic, term-less or short-term, the claims of a high potential of a model forecasts are based on a flawed application of statistics and, therefore, are hardly suitable for communication to decision makers, which situation creates numerous deception points and resulted controversies.

Earthquake prediction is not an easy task that implies a delicate application of statistics.

So far, none of the proposed short-term precursory signals showed sufficient evidence to be used as a reliable precursor of catastrophic earthquakes. Regretfully, in many cases of seismic hazard assessment (SHA), from term-less to time-dependent (probabilistic PSHA or deterministic DSHA), and short-term earthquake forecasting (StEF), the claims of a high potential of the method are based on a flawed application of statistics and, therefore, are hardly suitable for communication to decision makers.



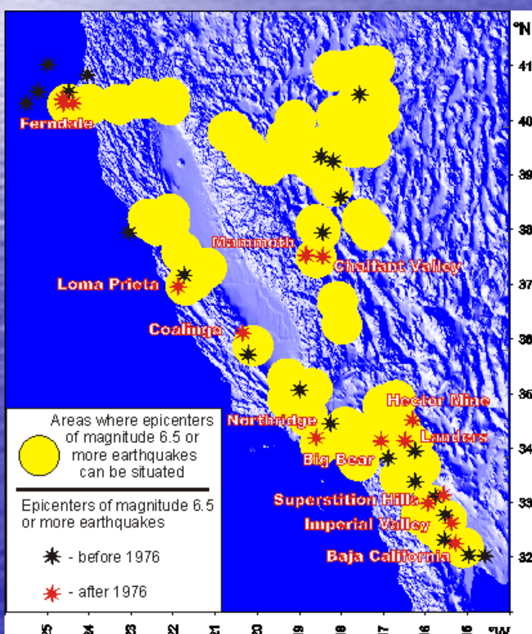
Keiiti **Aki** (1930-2005)

Definition of *Earthquake Prediction*

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

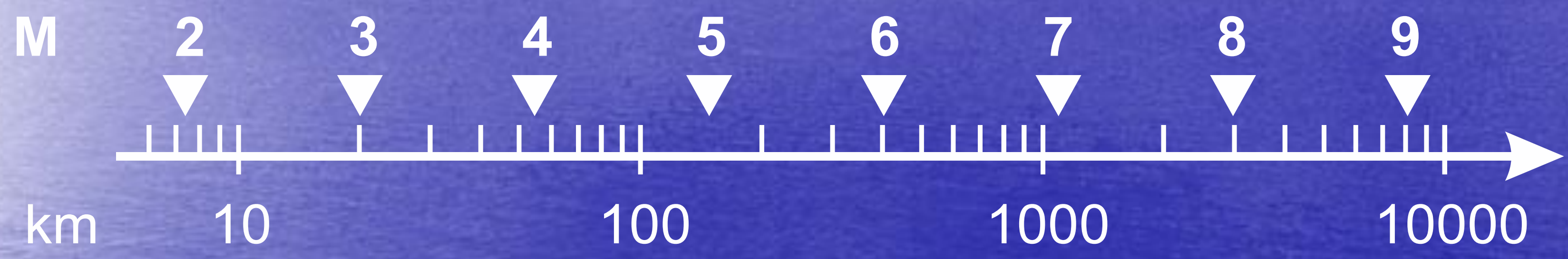
"An earthquake prediction must specify the expected magnitude range, the geographical area within which it will occur, and the time interval within which it will happen with sufficient precision so that the ultimate success or failure of the prediction can readily be judged. Only by careful recording 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."

Usually, earthquake prediction is classified in respect to duration of expectation time while overlooking term-less identification of earthquake prone areas, as well as the spatial accuracy of an earthquake prediction method.



- The 73 D-intersections of morphostructural lineaments in California and Nevada determined by *Gelfand et al.* (1976) as earthquake-prone for magnitude 6.5+ events. Since 1976 fifteen magnitude 6.5+ earthquakes occurred, all in a narrow vicinity of the D-intersections

The linear dimensions of the target earthquake preparation zone of $R = 10^{0.43\,M}$ km (*Dobrovolsky et al., 1979*) are independently confirmed by *Bowman et al.* (*1998*), who claimed $\log_{10}R \sim 0.44$ M. **[$\log_{10}e = 0.434\ldots$]**



The forecasts are often made for a "cell" (Schorlemmer et al., 2010; Lee et al., 2011) or "seismic region" (McCann et al., 1979; Kagan and Jackson, 1991, 1995) whose area is not linked to the size of the target earthquake. This might be another source for making a wrong choice in parameterization of a forecast / prediction method and, eventually, for unsatisfactory performance in real-time applications.

NATURAL ACCURACY IN EARTHQUAKE FORECASTING

Prediction of time and location of an earthquake of a certain magnitude range can be classified as follows -

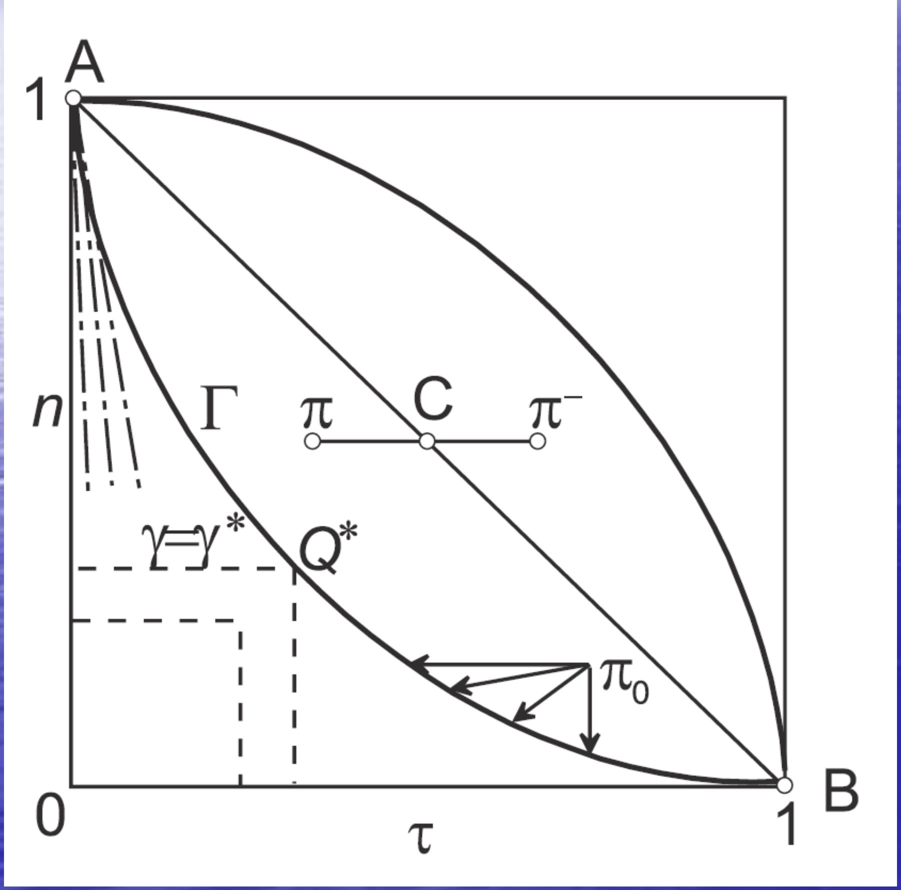
- Term-less prediction of areas prone to earthquakes of certain magnitude
- Prediction of time and location of an earthquake of certain magnitude

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

- The Gutenberg-Richter law suggests limiting magnitude range of prediction to about one unit of magnitude.

Otherwise, the statistics would be essentially related to dominating smallest earthquakes.

Accurate testing against real observations must be done in advance claiming seismically hazardous areas and/or times. The set of errors of the first and second kind in such a comparison permits evaluating the SHA method effectiveness and determining the optimal choice of parameters in regard to a user-defined cost-benefit function.



ERROR DIAGRAM

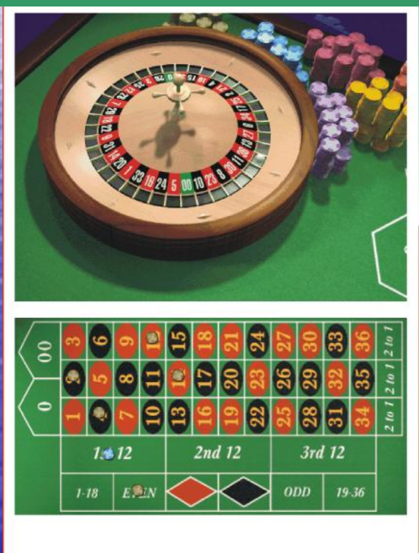
Molchan, G.M. Earthquake Prediction as Decision-making Problem. *Pure Appl. Geoph*, **149**, 233-247, 1997.

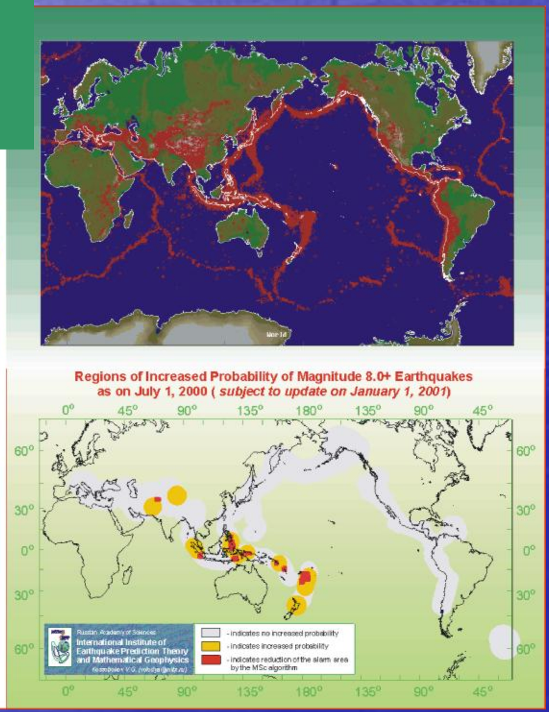
Molchan, G.M. Chapter 5. Earthquake Prediction Strategies: a theoretical analysis. In: Keilis-Borok, V.I., and A.A. Soloviev, (Editors). *Nonlinear Dynamics of the Lithosphere and Earthquake Prediction*. Springer, Heidelberg, 208-237, 2003.

The necessity and possibility of applying simple tools of **Earthquake Prediction Strategies**, in particular, **Error Diagram** and **Seismic Roulette** null-hypothesis as a metric of the alerted space, is evident.

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

SEISMIC ROULETTE





- 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! ☺

or lose … ☹

If you are smart enough to know "antipodal strategy" (Molchan, 1994; 2003), make the predictions efficient ------

and your wins will outscore the losses! ☺

☺ ☹ ☺ ☺ ☺ ☹ ☺ ☺ ☺

Note that statistics can never prove things, but disprove them.

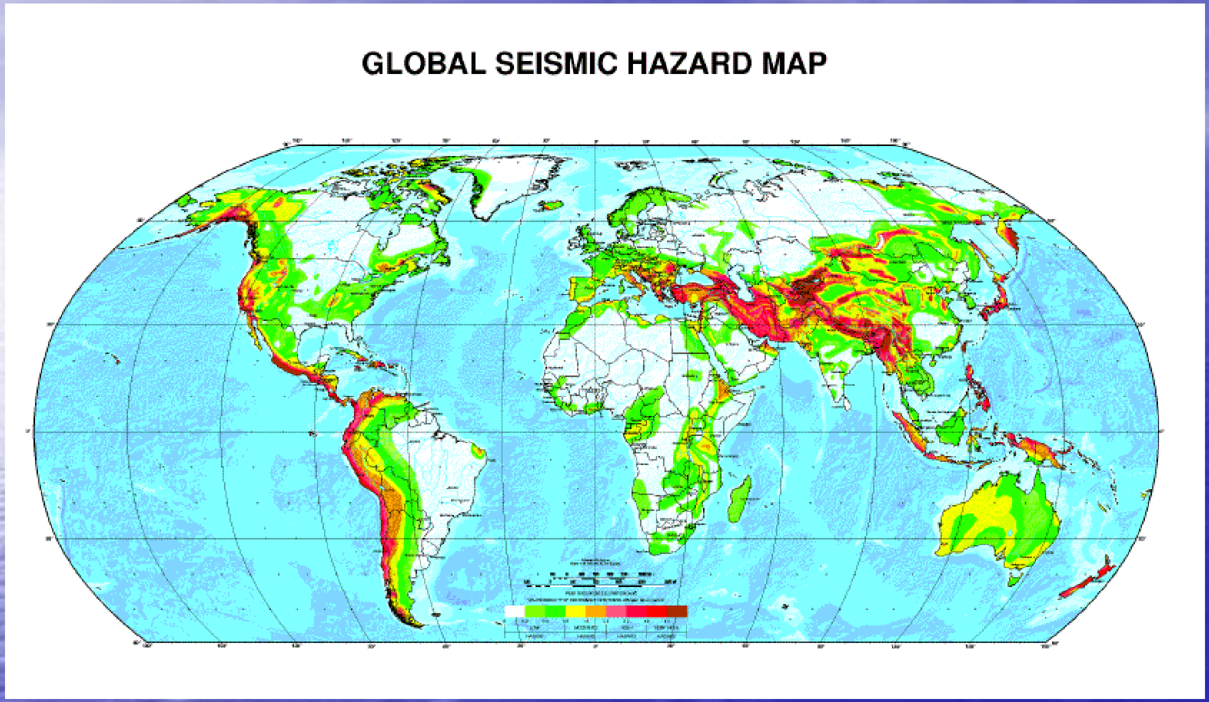
The set of errors, i.e. the rates of failure and of the alerted space-time volume, can be easily compared to random guessing, which comparison permits evaluating the SHA method effectiveness and determining the optimal choice of parameters in regard to a given cost-benefit function. These and other information obtained in such a simple testing may supply us with a realistic estimates of confidence and accuracy of SHA predictions and, if reliable but not necessarily perfect, with related recommendations on the level of risks for decision making in regard to engineering design, insurance, and emergency management.

Note that earthquake related observations are limited to the recent most decades or centuries in just a few rare cases.

Getting, experimentally, reasonable confidence limits on an objective estimate of recurrence rate of an earthquake requires a geologic span of time which is unreachable for instrumental, or even historical, seismology (see, e.g., *Beauval et al., 2008*). That is why **PROBABILITY ESTIMATES BY PROBABILISTIC SEISMIC HAZARD ANALYSIS REMAIN SUBJECTIVE VALUES RANGING FROM 0 TO 1**, derived from analytically tractable hypothetical models of seismicity.

Making SHA claims, either termless or time dependent (t-DASH), quantitatively probabilistic in the frames of the most popular objectivists' viewpoint on probability requires a long series of "yes/no" trials, which cannot be obtained without an extended rigorous testing of the method predictions against real observations.

"One is well advised, when traveling to a new territory, to take a good map and then to check the map with the actual territory during the journey" [Wasserburg, 2010].



The Global Seismic Hazard Assessment Program (GSHAP) was launched in 1992 by the International Lithosphere Program (ILP) with the support of the International Council of Scientific Unions (ICSU), and endorsed as a demonstration program in the framework of the United Nations International Decade for Natural Disaster Reduction (UN/IDNDR). The GSHAP project terminated in 1999 .

A systematic comparison of the GSHAP peak ground acceleration estimates with those related to actual strong earthquakes discloses gross inadequacy of this "probabilistic" product, which appears **unacceptable for any kind of responsible seismic risk evaluation and knowledgeable disaster prevention.**

- Kossobokov, V.G., 2010. Scaling Laws and Earthquake Predictability in Assessment of Seismic Risk. Advanced Conference on Seismic Risk Mitigation and Sustainable Development. The Abdus Salam International Centre for Theoretical Physics (Trieste - Italy, 10 - 14 May 2010). http://cdsagenda5.ictp.trieste.it/full_display.php?ida=a09145)
- Kossobokov, V. G. ; A. K. Nekrasova, 2010. Global Seismic Hazard Assessment Program Maps Are Misleading. Eos Trans. AGU, 91(52), Fall Meet. Suppl., Abstract U13A-0020.
- Kossobokov, V., Nekrasova, A., 2011. Global Seismic Hazard Assessment Program (GSHAP) Maps Are Misleading. *Problems of Engineering Seismology*, 38 (1), p. 65-76 (in Russian).

Each of 1181 strong crustal earthquakes in 2000-2009 has from 6 to 58 values of GSHAP PGA in the $\frac{1}{4}° \times (\frac{1}{4} \cos \phi)°$ cell centered at its epicenter (ϕ, λ).

We count a "surprise" when the observed value, $I_0(M)$, is larger than the GSHAP expected maximum, $I_0(mPGA)$, $\Delta I_0 = I_0(M) - I_0(mPGA) > 0$

We found (i) about 50% of strong earthquakes surprised the GSHAP map (ii) each of the 59 magnitude 7.5 or larger earthquakes in 2000-2009 was a "surprise" for GSHAP Seismic Hazard Map; the minimum of the 59 values of ΔI_0 is 0.6. The average and the median of ΔI_0 are about 2.

INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy

"Top Twelve Deadliest Earthquakes, 2000-2011"

The average and the median of ΔI_0 is around two units of underestimated intensity.

Region	Date	M	Fatalities	ΔI_0
Sumatra-Andaman "Indian Ocean Disaster"	26.12.2004	9.0	227898	4.0
Port-au-Prince (Haiti)	12.01.2010	7.3	222570	2.2
Wenchuan (Sichuan, China)	12.05.2008	8.1	87587	3.2
Kashmir (North India and Pakistan border region)	08.10.2005	7.7	~86000	2.3
Bam (Iran)	26.12.2003	6.6	~31000	0.2
Bhuj (Gujarat, India)	26.01.2001	8.0	20085	2.9
Off the Pacific coast of Tohoku (Japan)	11.03.2011	9.0	15824 (3847 missing)	3.2
Yogyakarta (Java, Indonesia)	26.05.2006	6.3	5749	0.3
Southern Qinghai (China)	13.04.2010	7.0	2698	2.1
Boumerdes (Algeria)	21.05.2003	6.8	2266	2.1
Nias (Sumatra, Indonesia)	28.03.2005	8.6	1313	3.3
Padang (Southern Sumatra, Indonesia)	30.09.2009	7.5	1117	1.8

"Men han har jo ikke noget paa," sagde et lille Barn. "Herre Gud, hør den Uskyldiges Røst," sagde Faderen; og den Ene hvidskede til den Anden, hvad Barnet sagde.
"Men han har jo ikke noget paa," raabte tilsidst hele Folket. Det krøb i Keiseren, thi han syntes, de havde Ret, men han tænkte som saa: "nu maa jeg holde Processionen ud". Og Kammerherrerne gik og bar paa Slæbet, som der slet ikke var.

Hans Christian Andersen, 1837. Keiserens nye Klæder

Kossobokov V., Peresan A., Panza G.F. (2015)

REALITY CHECK: SEISMIC HAZARD MODELS YOU CAN TRUST. EOS 96(13): 9-11

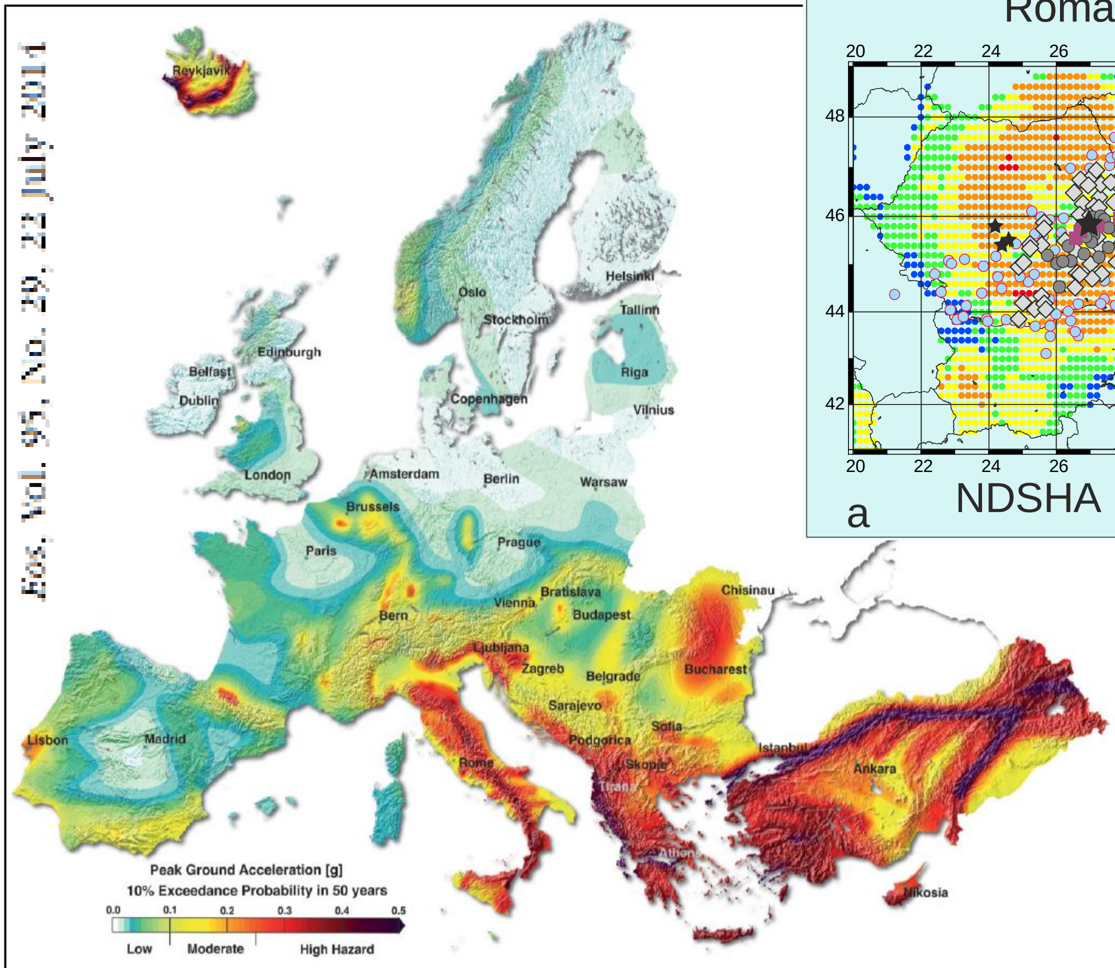
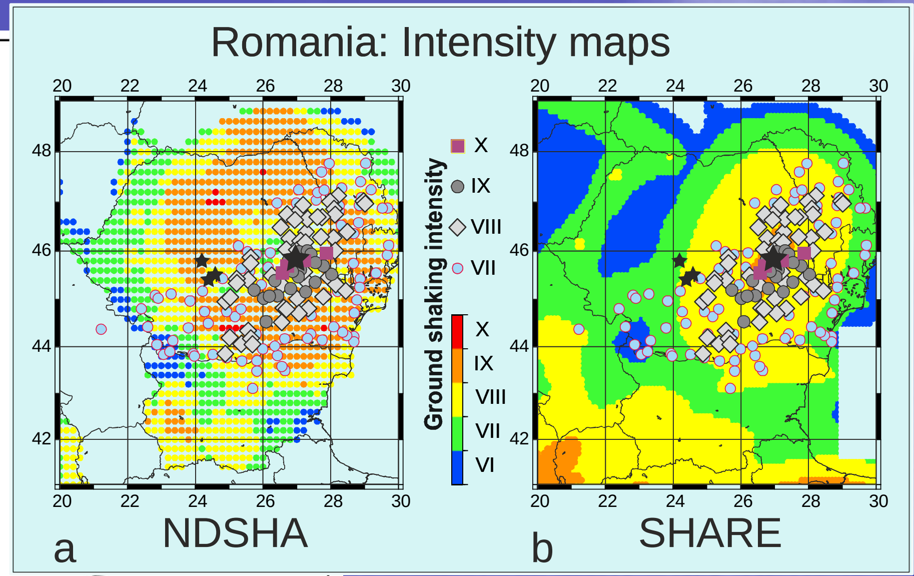
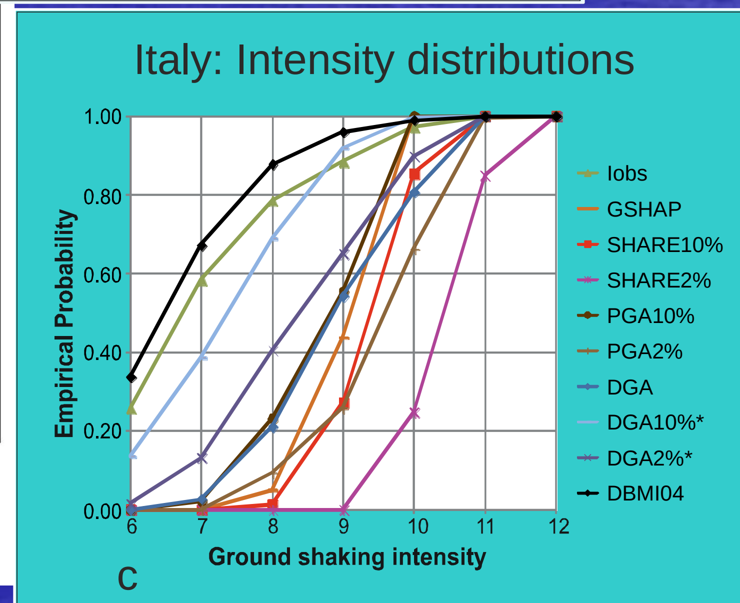


Fig. 1. European Seismic Hazard Map (ESHM13) displaying the 10% exceedance probability in 50 years for peak ground acceleration (PGA) in units of gravity (g). Cold colors indicate comparatively low hazard areas (PGA ≤ 0.1g), yellow and orange indicate moderate-hazard values (0.1g < PGA ≤ 0.25g), and red colors indicate high-hazard areas (PGA ≥ 0.25g).

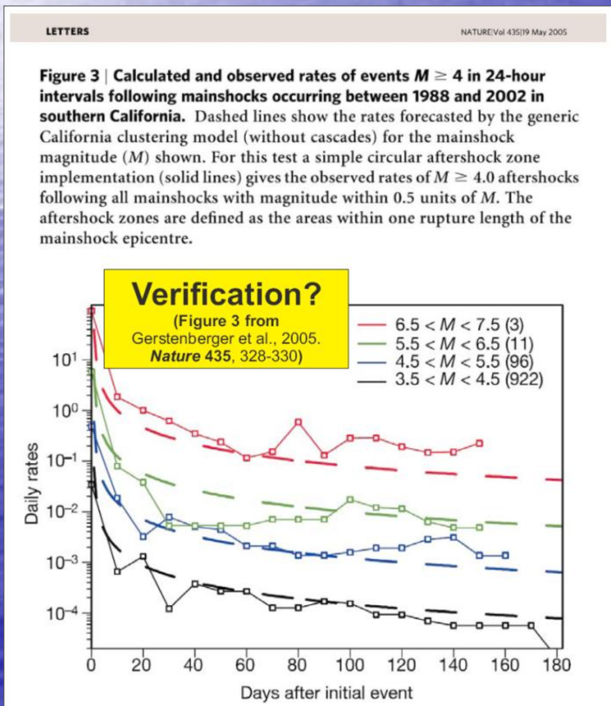




Gerstenberger, M. C., Wiemer, S., Jones, L. M. & Reasenberg, P. A. Real-time forecasts of tomorrow's earthquakes in California. *Nature* 435, 328-331 (19 May 2005)

…Is misleading Californians.

PROOF: Normalised by condition that the total integral of the p.d.f. (probability density function) increments equals 1, each of the four plots provides the minimum of positive p.d.f. increments, which are by definition either 1/N or its integer multiple (e.g., 2/N, 3/N, etc.). These are about 0.0012, 0.0008, 0.0025, and 0.0015, which values imply the sample sizes about 846, 1250, 401, and 665 or integer multiples of these values.



LETTERS NATURE|Vol 435|19 May 2005

Figure 3 | Calculated and observed rates of events $M \geq 4$ in 24-hour intervals following mainshocks occurring between 1988 and 2002 in southern California. Dashed lines show the rates forecasted by the generic California clustering model (without cascades) for the mainshock magnitude (M) shown. For this test a simple circular aftershock zone implementation (solid lines) gives the observed rates of $M \geq 4.0$ aftershocks following all mainshocks with magnitude within 0.5 units of M. The aftershock zones are defined as the areas within one rupture length of the mainshock epicentre.

The probability of a smaller value of the Kolmogoroff-Smirnoff statistic D than that for the two samples used to plot the daily rates after 5.5 < M < 6.5 (green plot in Figure 3) event and after 3.5 < M < 4.5 (black plot) event (which D accounts to the value

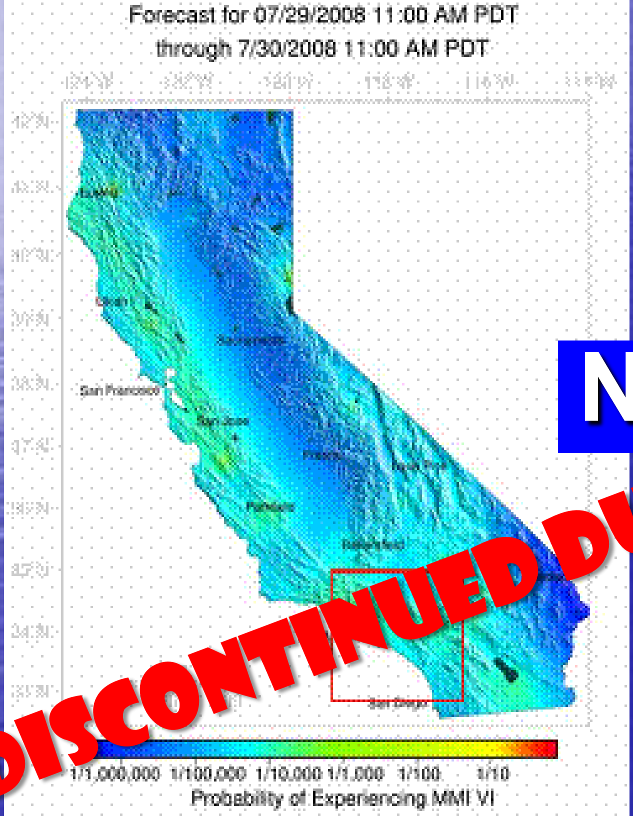
$D = \max | F_{green}(t) - F_{red}(t) | \cdot (N_1 N_2/(N_1+N_2))^{1/2} \geq 2.12$)

is larger than 97%.

Therefore, the hypothesis that these two samples are drawn from the same distribution can be rejected at significance level of 0.03. ■

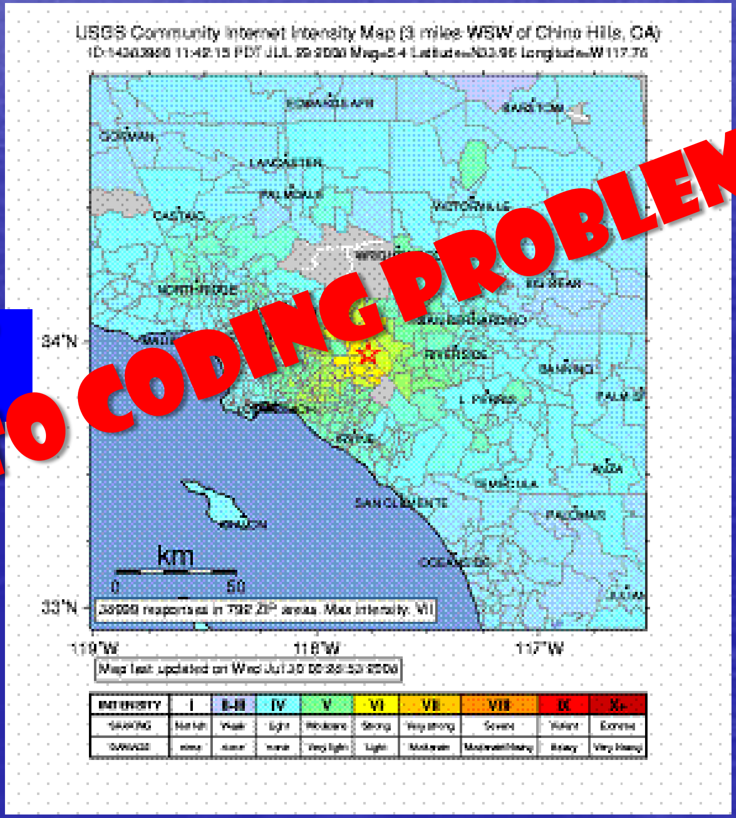
In 1200 days since publication all the seven earthquakes of MMI = VI or larger in California occurred in the areas of the lowest risk (p<1/10000), while the extent of the observed areas of intensity VI or larger is by far less than the one expected from the calculations (a crude low bound estimate of the ratio was above a factor of 8.5)...

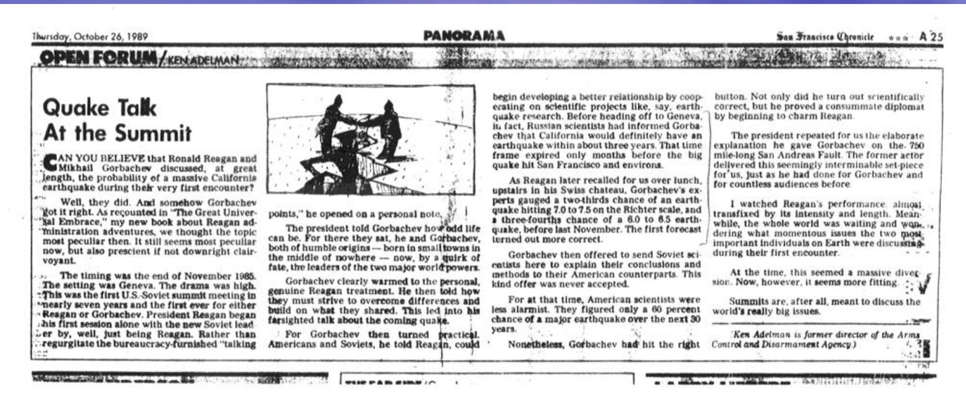
№ 7 (29 Jul 2008, M5.4 WSW of Chino Hills)



№ 7

DISCONTINUED DUE TO CODING PROBLEM





Thursday, October 26, 1989 — PANORAMA — San Francisco Chronicle ★★★ A 25

OPEN FORUM / KEN ADELMAN

Quake Talk At the Summit

CAN YOU BELIEVE that Ronald Reagan and Mikhail Gorbachev discussed, at great length, the probability of a massive California earthquake during their very first encounter?

Well, they did. And somehow Gorbachev got it right. As recounted in "The Great Universal Embrace," my new book about Reagan administration adventures, we thought the topic most peculiar then. It still seems most peculiar now, but also prescient if not downright clairvoyant.

The timing was the end of November 1985. The setting was Geneva. The drama was high. This was the first U.S.-Soviet summit meeting in nearly seven years and the first ever for either Reagan or Gorbachev. President Reagan began his first session alone with the new Soviet leader by, well, just being Reagan. Rather than regurgitate the bureaucracy-furnished "talking points," he opened on a personal note.

The president told Gorbachev how odd life can be. For there they sat, he and Gorbachev, both of humble origins — born in small towns in the middle of nowhere — now, by a quirk of fate, the leaders of the two major world powers.

Gorbachev clearly warmed to the personal, genuine Reagan treatment. He then told how they must strive to overcome differences and build on what they shared. This led into his farsighted talk about the coming quake.

For Gorbachev then turned practical. Americans and Soviets, he told Reagan, could begin developing a better relationship by cooperating on scientific projects like, say, earthquake research. Before heading off to Geneva, in fact, Russian scientists had informed Gorbachev that California would definitely have an earthquake within about three years. That time frame expired only months before the big quake hit San Francisco and environs.

As Reagan later recalled for us over lunch, upstairs in his Swiss chateau, Gorbachev's experts gauged a two-thirds chance of an earthquake hitting 7.0 to 7.5 on the Richter scale, and a three-fourths chance of a 6.0 to 6.5 earthquake, before last November. The first forecast turned out more correct.

Gorbachev then offered to send Soviet scientists here to explain their conclusions and methods to their American counterparts. This kind offer was never accepted.

For at that time, American scientists were less alarmist. They figured only a 60 percent chance of a major earthquake over the next 30 years.

Nonetheless, Gorbachev had hit the right button. Not only did he turn out scientifically correct, but he proved a consummate diplomat by beginning to charm Reagan.

The president repeated for us the elaborate explanation he gave Gorbachev on the 750 mile-long San Andreas Fault. The former actor delivered this seemingly interminable set-piece for us, just as he had done for Gorbachev and for countless audiences before.

I watched Reagan's performance, almost transfixed by its intensity and length. Meanwhile, the whole world was waiting and wondering what momentous issues the two most important individuals on Earth were discussing during their first encounter.

At the time, this seemed a massive diversion. Now, however, it seems more fitting.

Summits are, after all, meant to discuss the world's really big issues.

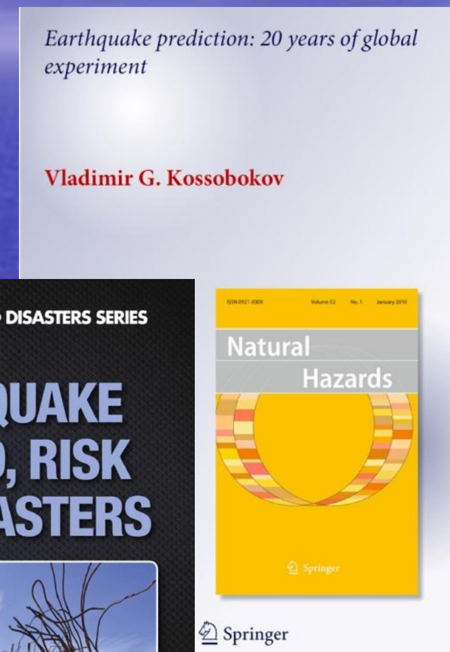
(Ken Adelman is former director of the Arms Control and Disarmament Agency.)

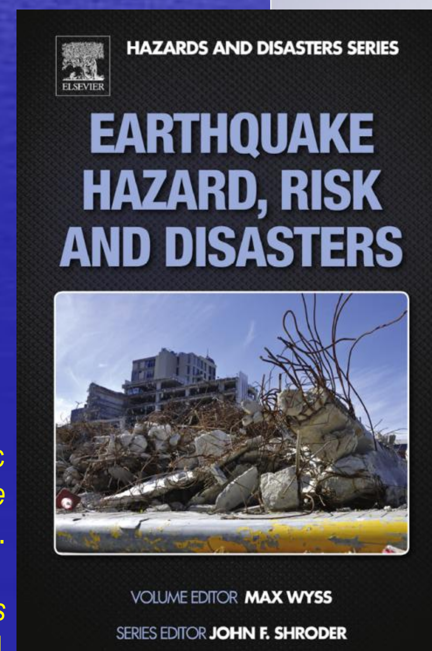
M8-MSc Algorithms

Healy, J. H., V. G. Kossobokov, and J. W. Dewey (1992) *A test to evaluate the earthquake prediction algorithm, M8,* U.S. Geol. Surv. Open-File Report 92-401, 23 p. with 6 Appendices

The results of truly global 25-year old experiment are indirect confirmations of the existing common features of both the predictability and the diverse behavior of the Earth's naturally fractal lithosphere.

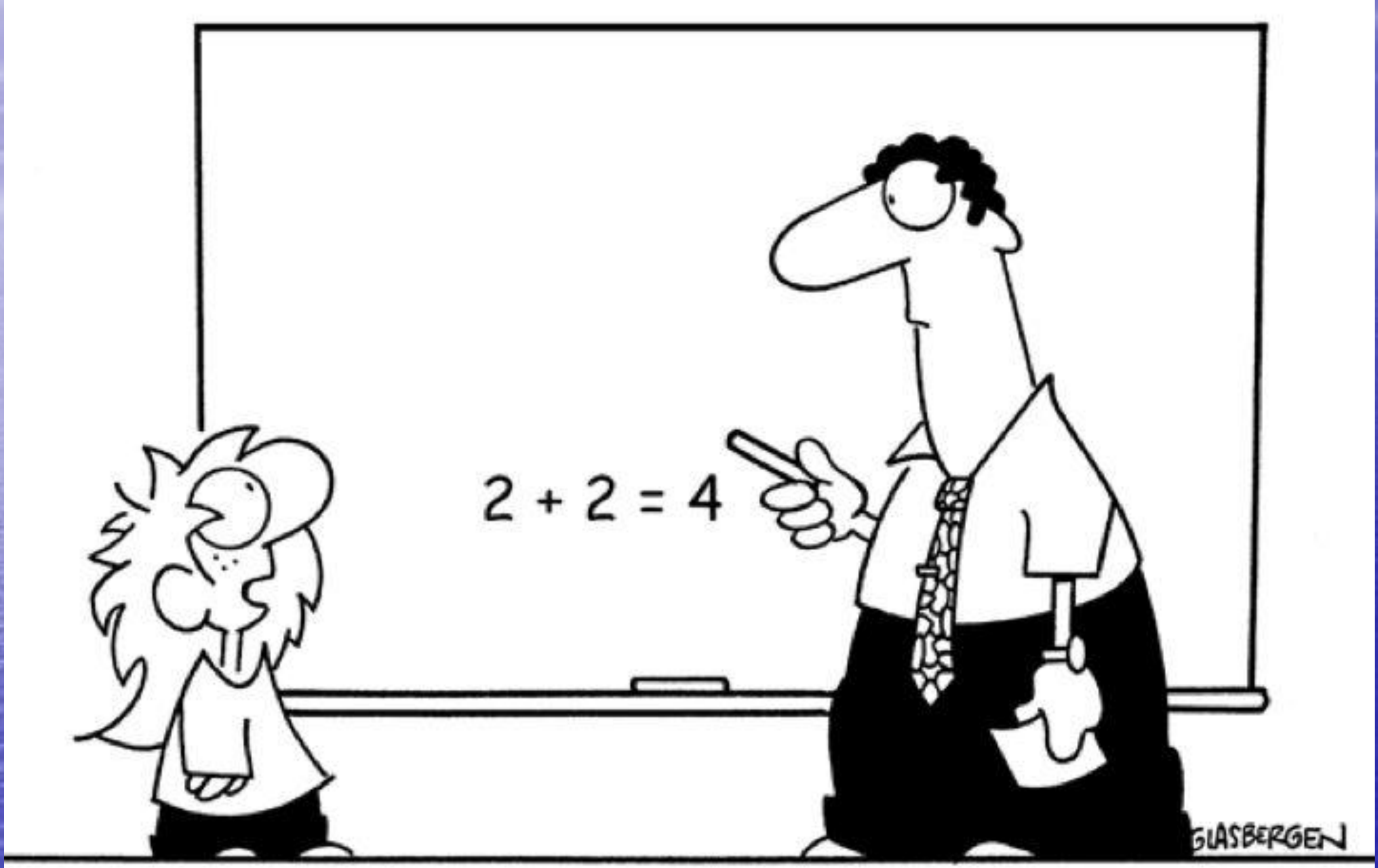
The statistics achieved to date prove (with confidence above 99%) rather high efficiency of the M8 and M8-MSc predictions limited to intermediate-term middle- and narrow-range accuracy.





Kossobokov V (2014) Chapter 18. Times of Increased probabilities for occurrence of catastrophic earthquakes: 25 years of hypothesis testing in real time. In: Wyss M, Shroder J (eds) *Earthquake Hazard, Risk, and Disasters*. Elsevier, London, 477-504.

Kossobokov VG (2013) Earthquake prediction: 20 years of global experiment. *Natural Hazards* **69**(2):1155–1177; doi: 10.1007/s11069-012-0198-1



"How can I trust your information when you're using such outdated technology?"

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

Kossobokov, V. G. (1997). Chapter 4. User Manual for M8. In Healy, J.H., Keilis-Borok, V. I., Lee, W. H. K. (Eds), *Algorithms for earthquake statistics and prediction*. IASPEI Software Library, Vol. 6. Seismol. Soc. Am., El Cerrito, CA, 167–221, with Disk #4: M8 Programs and Test Data Files

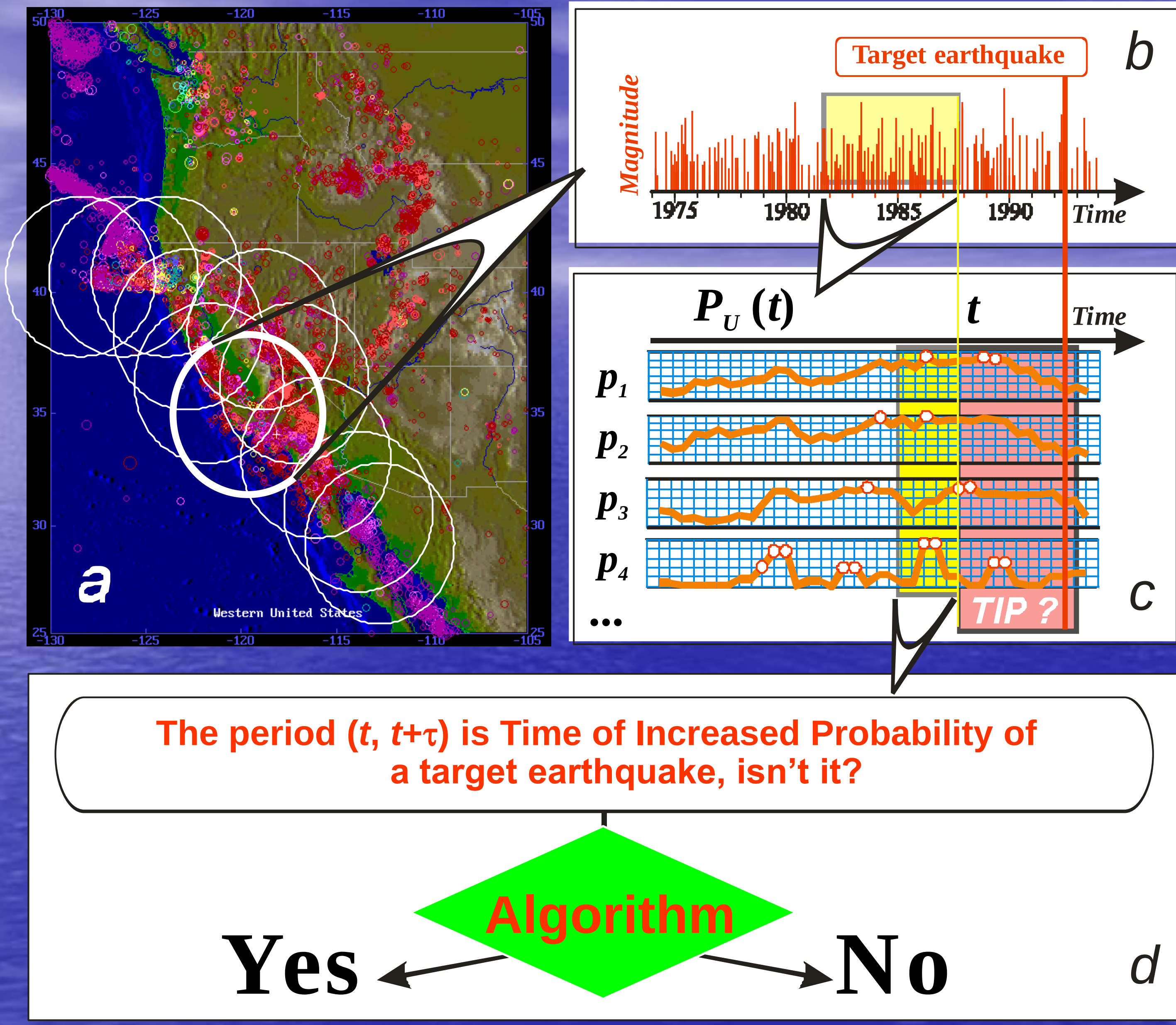
M8 algorithm

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 of prediction



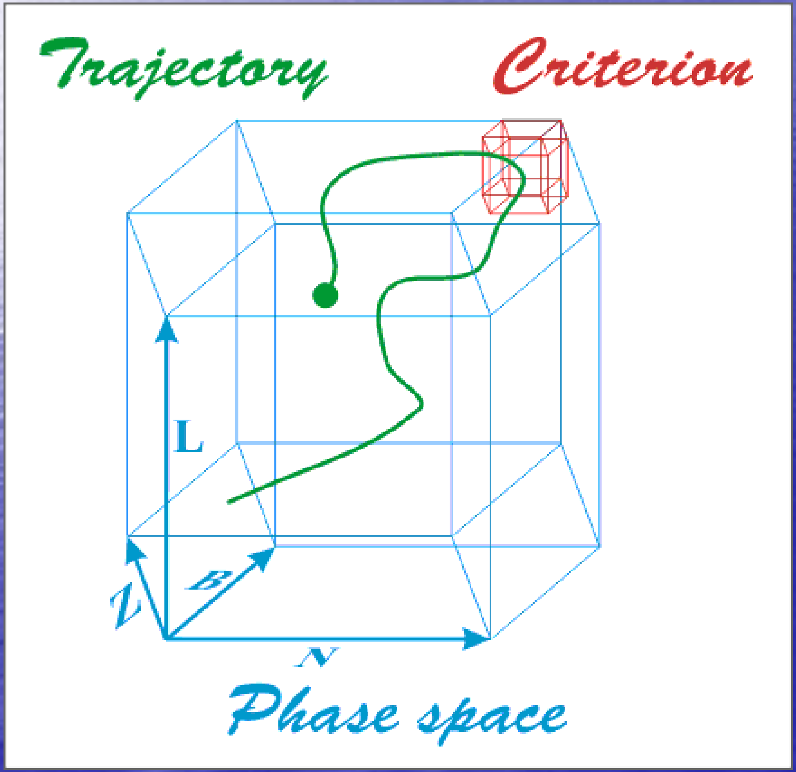
Algorithm M8 (Keilis-Borok and Kossobokov, 1990a; Healy et al., 1992; Kossobokov, 2013). The M8 predictions aim at earthquakes from magnitude range MM_0+ = [M_0, M_0 + Δ*m*] where Δ*m* < 1. Note that by design of the algorithm the earthquake magnitude scale should reflect the size of earthquake sources. In the present-day, most seismologists would assume that the authoritative magnitude for a large earthquake should be a moment-magnitude; however, this was not routinely available at the beginning of the Global Test of the M8 prediction when Healy et al. (1992) applied the rule of the maximum of the four magnitudes reported in the USGS Global Hypocenters' Database System, i.e., mb, MS, and the two authority magnitudes MA1 and MA2. Overlapping Circles of Investigation, CI's, of the fixed diameter $D(M_0)$ scan seismic locus in the region under study. The sequence of earthquakes with aftershocks removed is considered within each CI. Sequences in different CI's are normalized to about the same pre-fixed average annual number of earthquakes by selecting the lower magnitude cutoff .

For a given sequence several functions are computed in the trailing time window (*t-s, t*) and magnitude range ( ). These functions include (i) the number of earthquakes of magnitude or greater in time window (*t-s, t*); (ii) the deviation of from longer-term trend, *L*(*t*); (iii) linear concentration *Z*(*t*) estimated as the ratio of the average source diameter to the average distance between sources; and (iv) the maximum number of aftershocks *B*(*t*). Each of the functions *N*, *L*, and *Z* is calculated twice with for and . (Note: if the CI is located in the region of low seismicity that does not provide 20 events per year, the M8 program issues a warning of seismic data deficiency, and if there are fewer than 16 events per year the program will not run.) As a result, the earthquake sequence is given a robust description by seven functions *N*1, *N*2, *L*1, *L*2, *Z*1, *Z*2, and *B*. "Anomalously large" values are identified for each function using the condition that they are higher than Q% of the encountered values. An alarm or a TIP is diagnosed for t years from the moment of time t when at least six out of seven functions, including *B*, show up "anomalously large" values within a narrow time window (t - *u*, t). To make prediction more stable this condition is required for two consecutive moments, t - 0.5 and t years. In course of a real-time monitoring, the alarm may extend beyond or be terminated before t years in case the updating causes changes in determination of the magnitude cutoffs and/or the percentiles of the encountered functions.

The following standard values of parameters indicated above are prefixed in the algorithm M8: $D(M_0)=\{\exp(M_0 - 5.6) + 1\}°$ 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, about 5-10 times the length of the target earthquake source), *s* = 1 year for B and 6 years for the other six functions, *u* = 3 years, *Q* = 75% for B and 90% for the other six functions, and t = 5 years. Usually, the average diameter of the source, ***l***, is estimated by , where *N* is the number of main shocks in {i}, b = 0.46 to meet the condition of proportionality to the linear dimension of source, and a = 0 (which does not restrict generality), while the average distance, ***r***, between them is set proportional to . The usage of more accurate estimate of the linear concentration of main shocks may improve the performance of the algorithm. The ultimate unambiguous description of the M8 algorithm with all the prefixed parameters and rules of data processing is published as a computer code in the IASPEI Software Library (*Kossobokov 1997*) and was distributed in 1988-2011 to the participants of the bi-annual workshops on non-linear dynamics and earthquake prediction held at the Abdus Salam International Centre for Theoretical Physics, Miramare-Trieste, Italy.

Kossobokov, V. G. (1997). Chapter 4. User Manual for M8. In Healy, J.H., Keilis-Borok, V. I., Lee, W. H. K. (Eds), *Algorithms for earthquake statistics and prediction*. IASPEI Software Library, Vol. 6. Seismol. Soc. Am., El Cerrito, CA, 167–221, with Disk #4: M8 Programs and Test Data Files

The M8 algorithm's criterion



- 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).

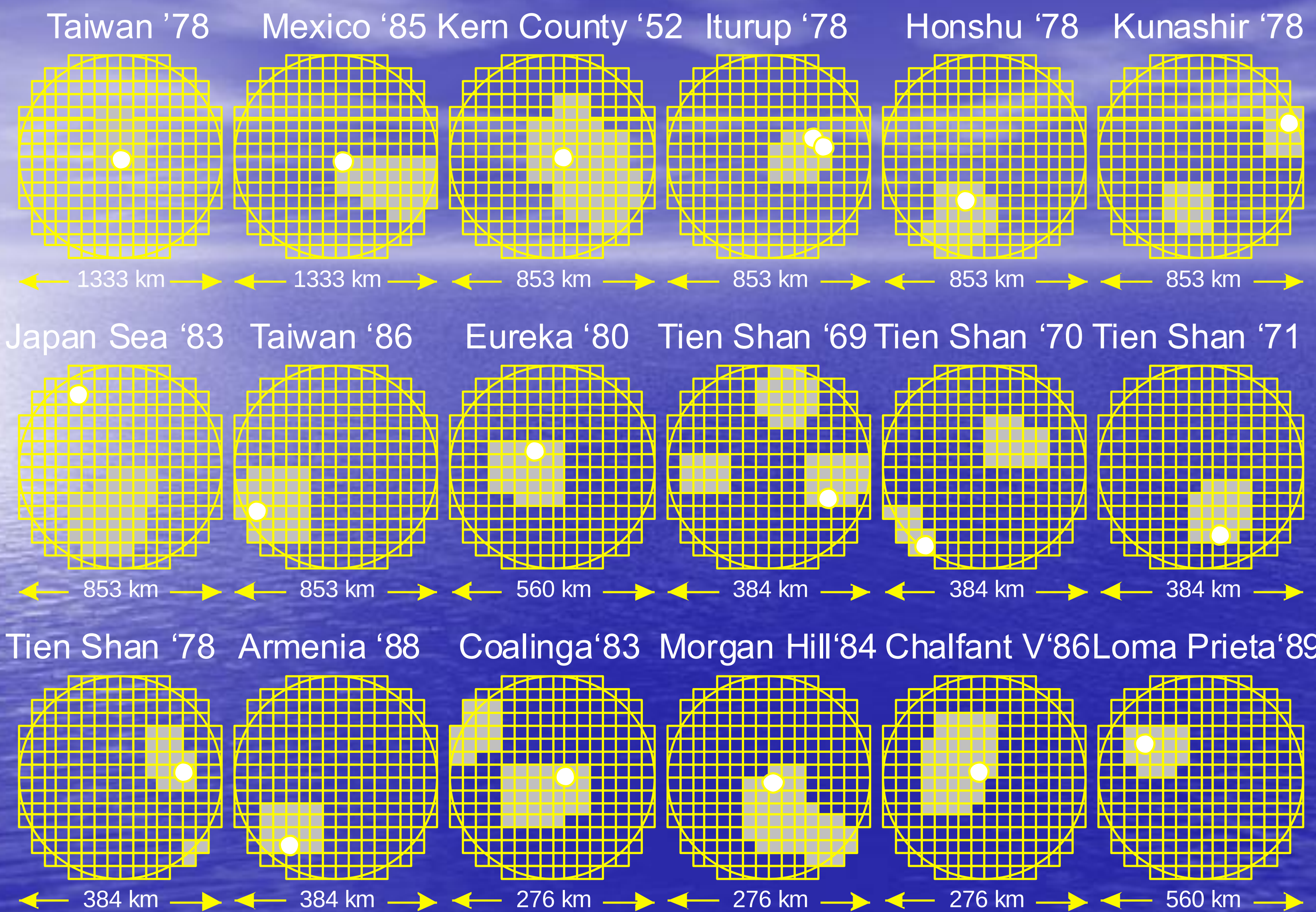
  The algorithm recognizes *criterion*, defined by extreme values of the phase space coordinates, as a vicinity of the system singularity. When a trajectory enters the criterion, probability of extreme event increases to the level sufficient for its efficient provision.

Second approximation prediction method, MSc algorithm

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 source of incipient main shock.


Taiwan ’78
Mexico ‘85
Kern County ‘52
Iturup ‘78
Honshu ‘78
Kunashir ‘78
1333 km
1333 km
853 km
853 km
853 km
853 km
Japan Sea ‘83
Taiwan ‘86
Eureka ‘80
Tien Shan ‘69
Tien Shan ‘70
Tien Shan ‘71
853 km
853 km
560 km
384 km
384 km
384 km
Tien Shan ‘78
Armenia ‘88
Coalinga‘83
Morgan Hill‘84
Chalfant V‘86
Loma Prieta‘89
384 km
384 km
276 km
276 km
276 km
560 km

Summary of TIPs diagnosed by the M8 algorithm

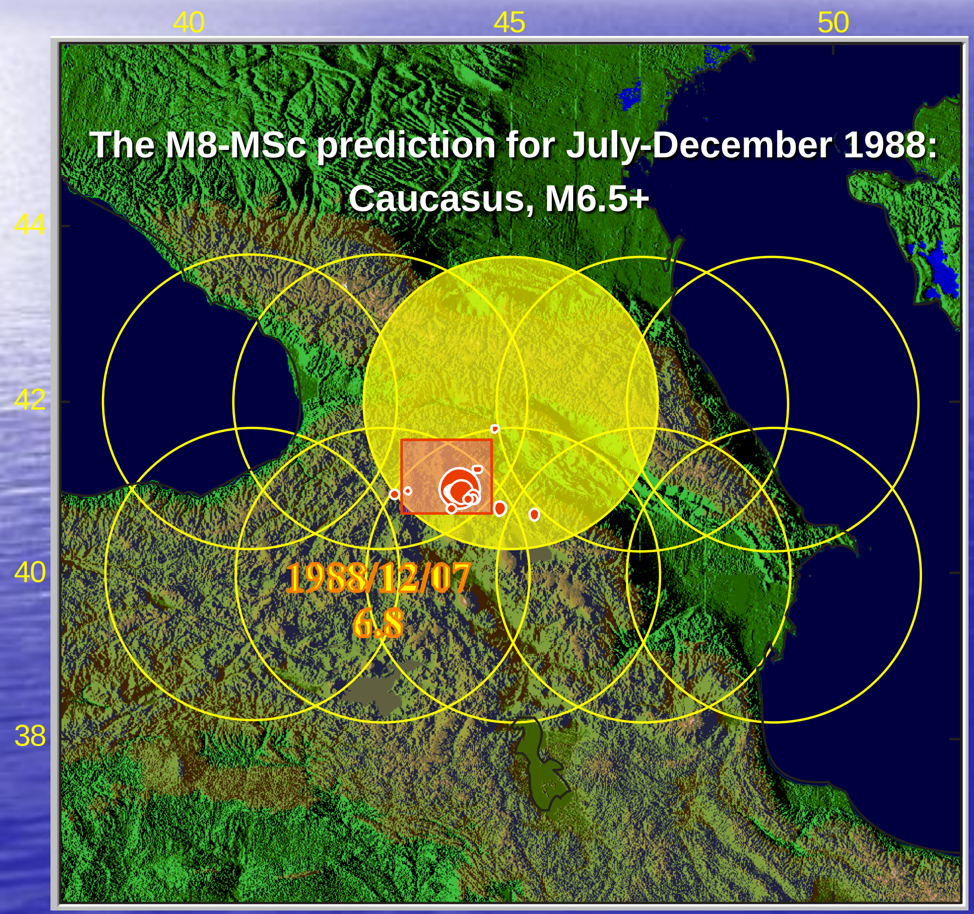
	Region	M_0	Time period	N_T/N^a	V^b_{TIPs}	N_{suc}/N^c_{all}
			Learning			
1.	World	8.0	1967–1982	5/7	5	7/16
			Testing of the Original Version			
2.	Central America	8.0	1977–1986	1/1	16	1/2
3.	Kuril Islands and Kamchatka	7.5	1975–1987	2/2	17	2/3
4.	Japan and Taiwan	7.5	1975–1987	5/6	20	6/8
5.	South America	7.5	1975–1987	3/3	18	3/8
6.	Western U.S.	7.5	1975–1987	-/-	5	0/1
7.	Southern California	7.5	1947–1987	1/1	12	1/1
8.	Western U.S.	7.0	1975–1987	2/2	24	2/2
9.	Baikal and Stanovoy Range	6.7	1975–1986	-/-	0	-/-
10.	Caucasus	6.5	1975–1987	2/3	12	2/2
11.	East Central Asia	6.5	1975–1987	4/5	24	5/6
12.	Eastern Tien Shan	6.5	1963–1987	4/4	27	5/5
13.	Western Turkmenia	6.5	1979–1986	-/-	0	-/-
14.	Apennines	6.5	1970–1986	1/1	10	1/1
15.	Koyna reservoir	4.9	1975–1986	1/1	42	1/1
			Testing of Modified Versions			
16.	Greece	7.0	1973–1987	3/3	18	4/5
17.	Himalayas	7.0	1970–1987	2/2	8	3/4
18.	Vrancea	6.5	1975–1986	2/2	58	2/2
19.	Vancouver Island	6.0	1957–1985	4/4	20	5/7
	Regions 1–19 together			39/44 (89%)	18	49/72
	Regions 2–15 together			25/28 (89%)	16	28/38

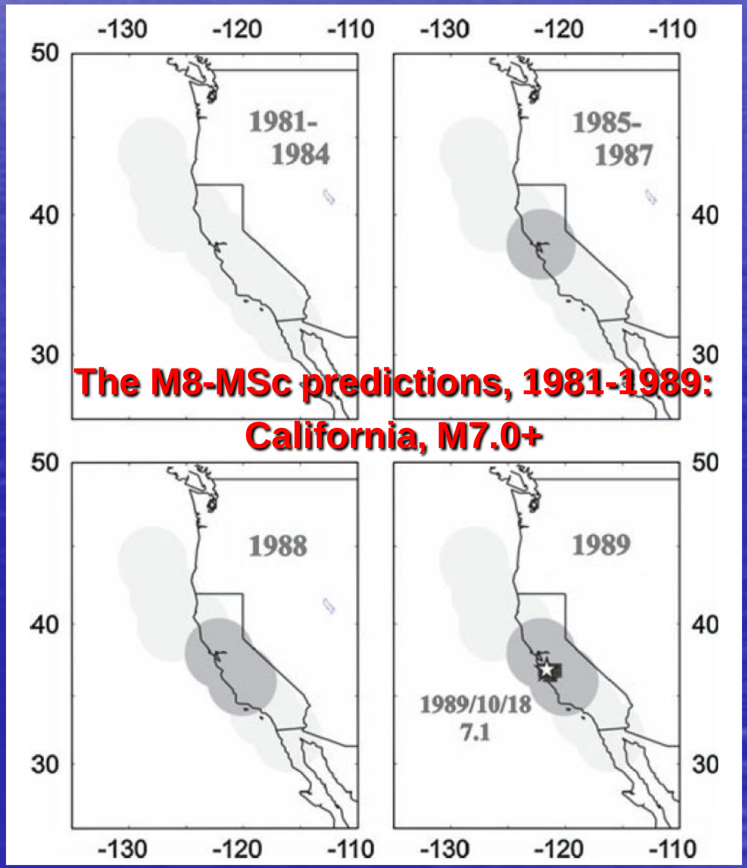
[a] N and N_T are the number of all earthquakes and their number within TIPs.
[b] V_{TIPs} is the space–time fraction of TIPs
[c] N_{all} and N_{suc} are the number of all and successful TIPs, respectively

Keilis-Borok V.I., Kossobokov V.G. (1990) Premonitory activation of seismic flow: algorithm M8. Phys. Earth Planet. Inter., 1990, 61, 73 83.

The pattern recognition algorithm M8, designed in 1984 for prediction of great, magnitude 8, earthquakes, was originally conceived for application targeting other magnitude ranges, so that by 1986 it was already tested in retrospective applications aimed at earthquakes, down to magnitude 5.

After successful early forecasts of the 1988 Spitak (Armenia) and the 1989 Loma Prieta (California) earthquakes, a rigid test to evaluate the efficiency of the reproducible intermediate-term middle-range earthquake prediction technique has been designed.





Testing of an intermediate-term middle-range earthquake prediction algorithm

By 1992, all the components necessary for such a reproducible real-time prediction experiment were specified in publications.

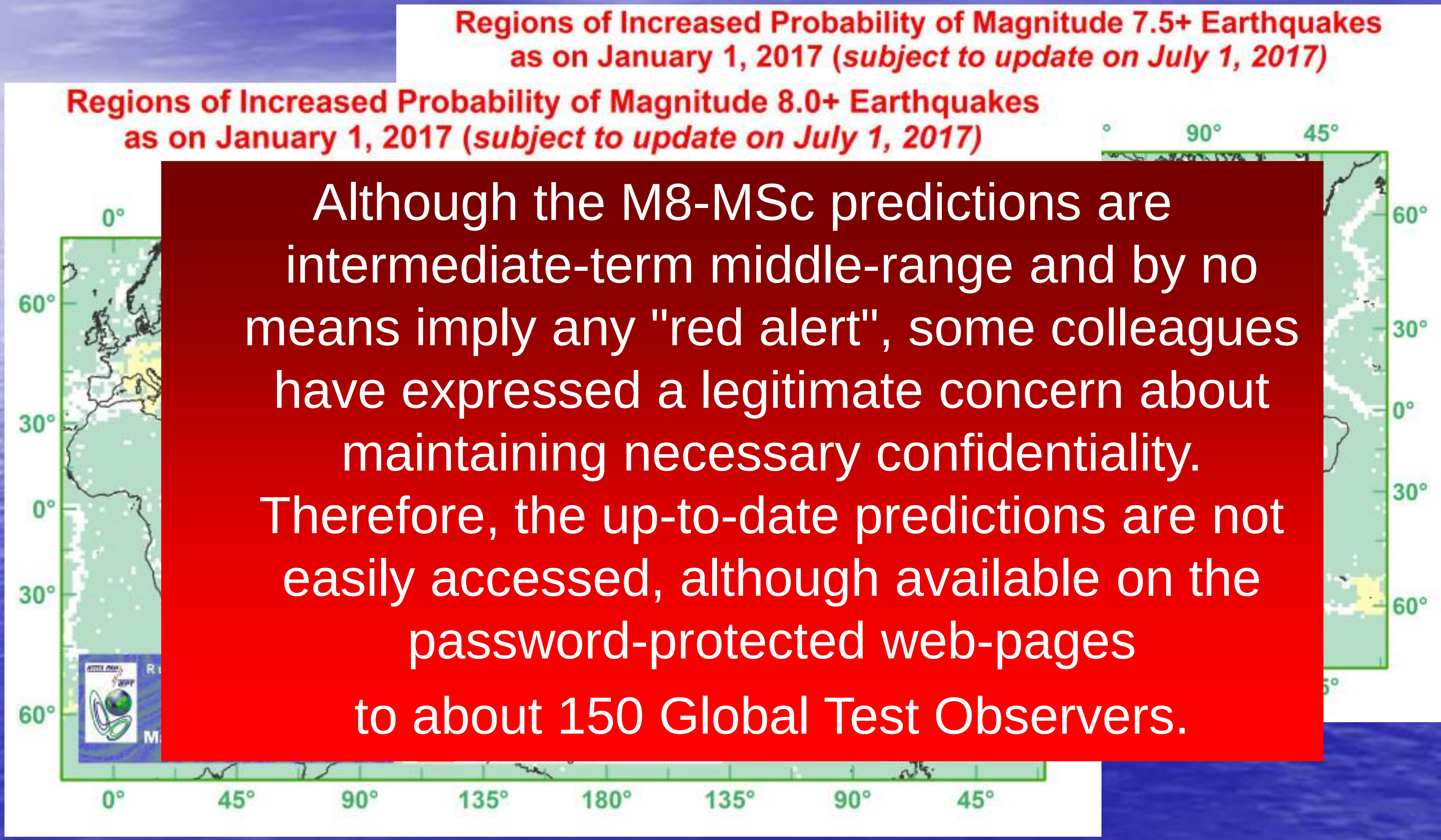
Since 1992 each half-year the algorithm M8 alone and in combination with MSc has been applied in a real-time prediction mode to seismicity of the entire Earth; and this test outlines, where possible, the areas in the two approximations where magnitude 8.0+ and 7.5+ earthquakes are most likely to occur before the next update.

Healy, J. H., V. G. Kossobokov, and J. W. Dewey. A test to evaluate the earthquake prediction algorithm, M8, *U.S. Geol. Surv. Open-File Report* 92-401, 23 p. with 6 Appendices, 1992.

Keilis-Borok, V.I., and Kossobokov V.G. Premonitory activation of seismic flow: algorithm M8. *Phys. Earth Planet. Inter.*, 1990, **61**, 73-83.

Kossobokov, V.G., V.I. Keilis-Borok, and S.W. Smith , Localization of intermediate-term earthquake prediction, *J. Geophys. Res.*, 1990, **95**, No. B12, 19763-19772.

Real-time prediction of the world largest earthquakes: An experiment started in 1992 is going on.



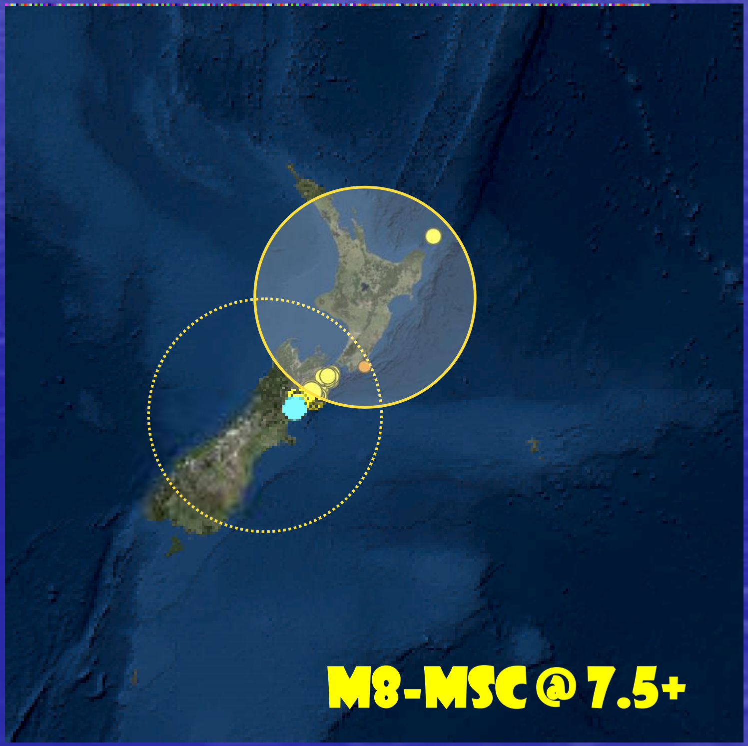
Although the M8-MSc predictions are intermediate-term middle-range and by no means imply any "red alert", some colleagues have expressed a legitimate concern about maintaining necessary confidentiality. Therefore, the up-to-date predictions are not easily accessed, although available on the password-protected web-pages

to about 150 Global Test Observers.

The recent examples of the M8-MSc confirmed predictions for the second half of 2016 suggest intersections of morphostructural lineaments as centers of CI in Italy and expansion of the Global Test to the areas where seismic catalog data was insufficient in 1992 but is enough complete nowadays (like in New Zeeland).

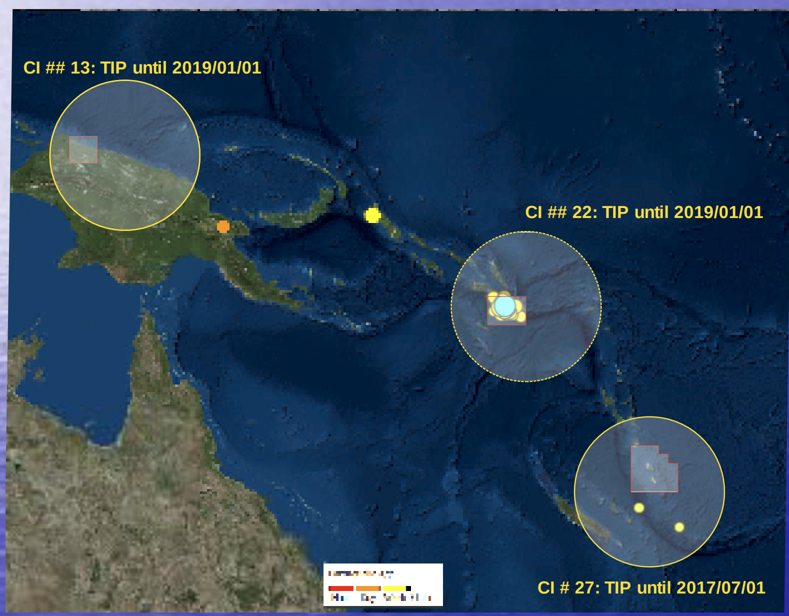
Amatrice, 24th August 2016 (M6.2), Visso, 26th October 2016 (M6.1), and Norcia, 30th October 2016 (M6.6)

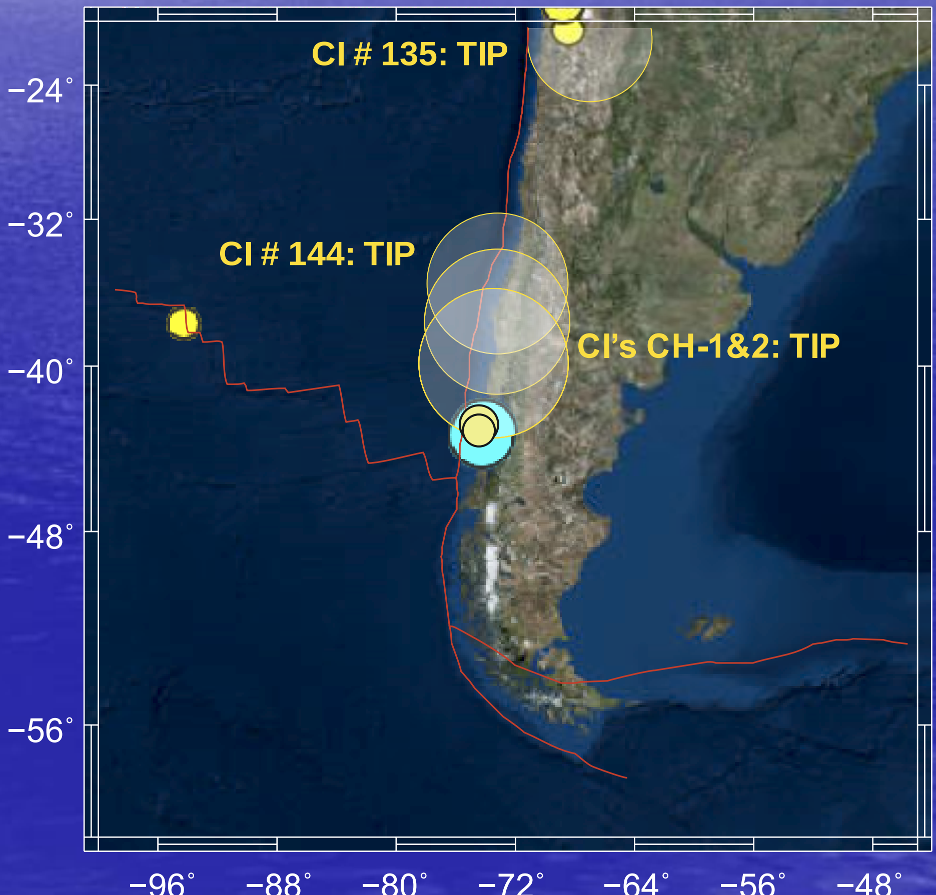
53 km NNE of Amberley, New Zeeland, 13th November 2016 (M7.8)



- 8 December 2016, M7.8, 69km WSW of Kirakira, Solomon Islands

25 December 2016, M7.6, 42 km SW of Puerto Quellon, Chile





M8-MSC @ 7.5+

Kossobokov, V.G. (2017) **Testing an earthquake prediction algorithm: the 2016 New Zealand and Chile earthquakes**. *Pure Appl. Geophys.* 174 (5): 1845–1854; doi: 10.1007/s00024-017-1543-9 (Published online: 08 April 2017).

Worldwide performance of the M8 and M8–MSc prediction results (after Kossobokov 2014, updated as of January 1, 2017)

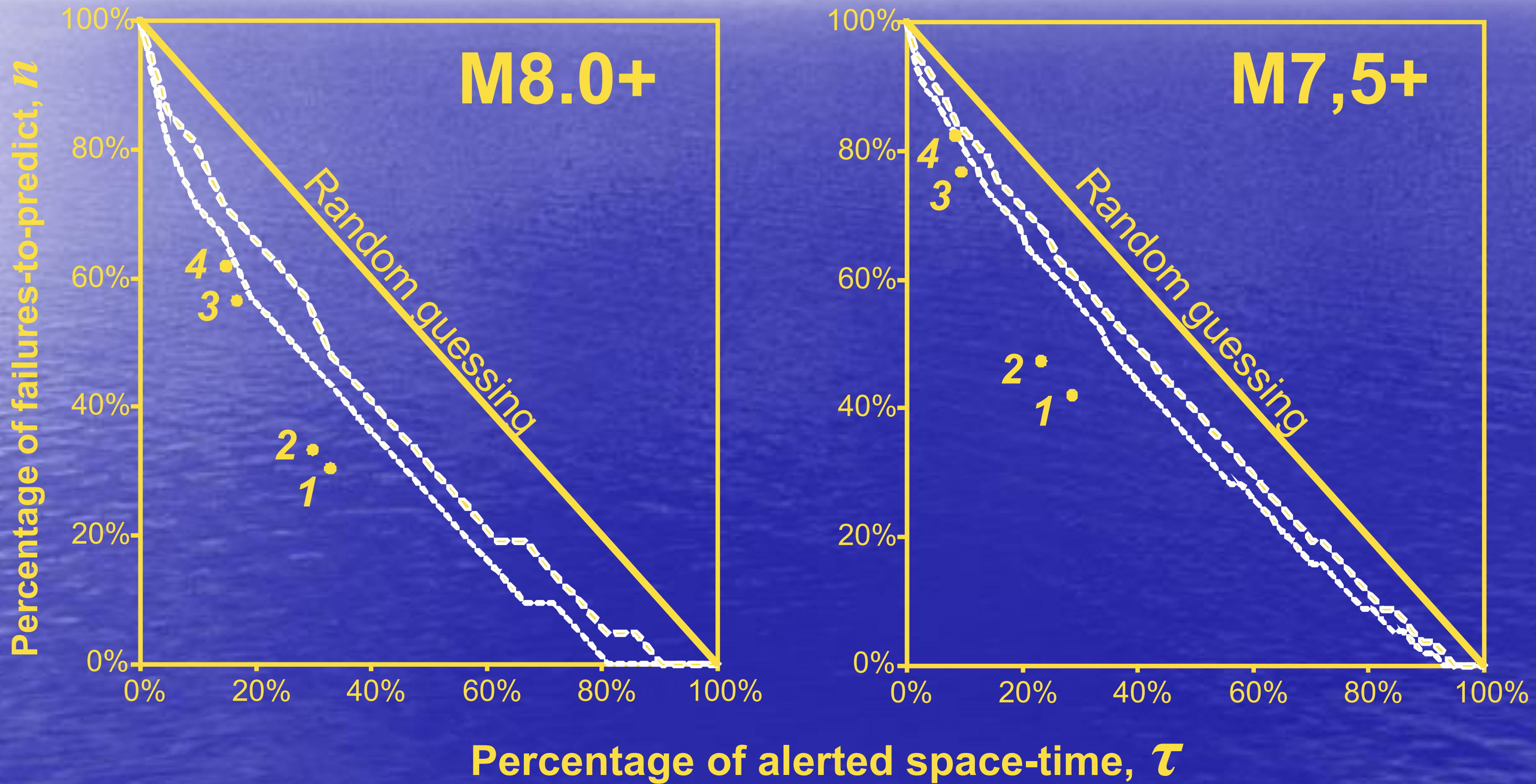
Period	Target earthquakes			Alerted space–time volume		Confidence	
	Total	M8	M8–MSc	M8 (%)	M8–MSc (%)	M8 (%)	M8–MSc (%)
Magnitude range M7.5+							
1985-present	78	41	17	28.54	9.30	>99.99	99.93
1992-present	66	31	11	23.16	8.33	>99.99	98.01
Magnitude range M8.0+							
1985-present	25	17	11	32.84	16.62	99.97	99.88
1992-present	23	15	9	29.80	14.78	99.95	99.62

"Target Earthquakes" are earthquakes of the magnitude range M7.5+ or M8.0+ which "Total" refers to their total number in the union of all CIs during the study "Period", and "M8" and "M8–MSc" refer to the number of those earthquakes that occurred in the space–time volumes covered by the M8 and M8–MSc alerts, respectively. The "Alerted Space–Time Volume" of the M8 and M8–MSc predictions is given in percent to the total space–time volume of all CIs during the study Period. The "Confidence" level tells how sure one can be that the achieved performance is not arisen by chance in the binomial trials (Kossobokov and Shebalin 2003; Kossobokov 2013)

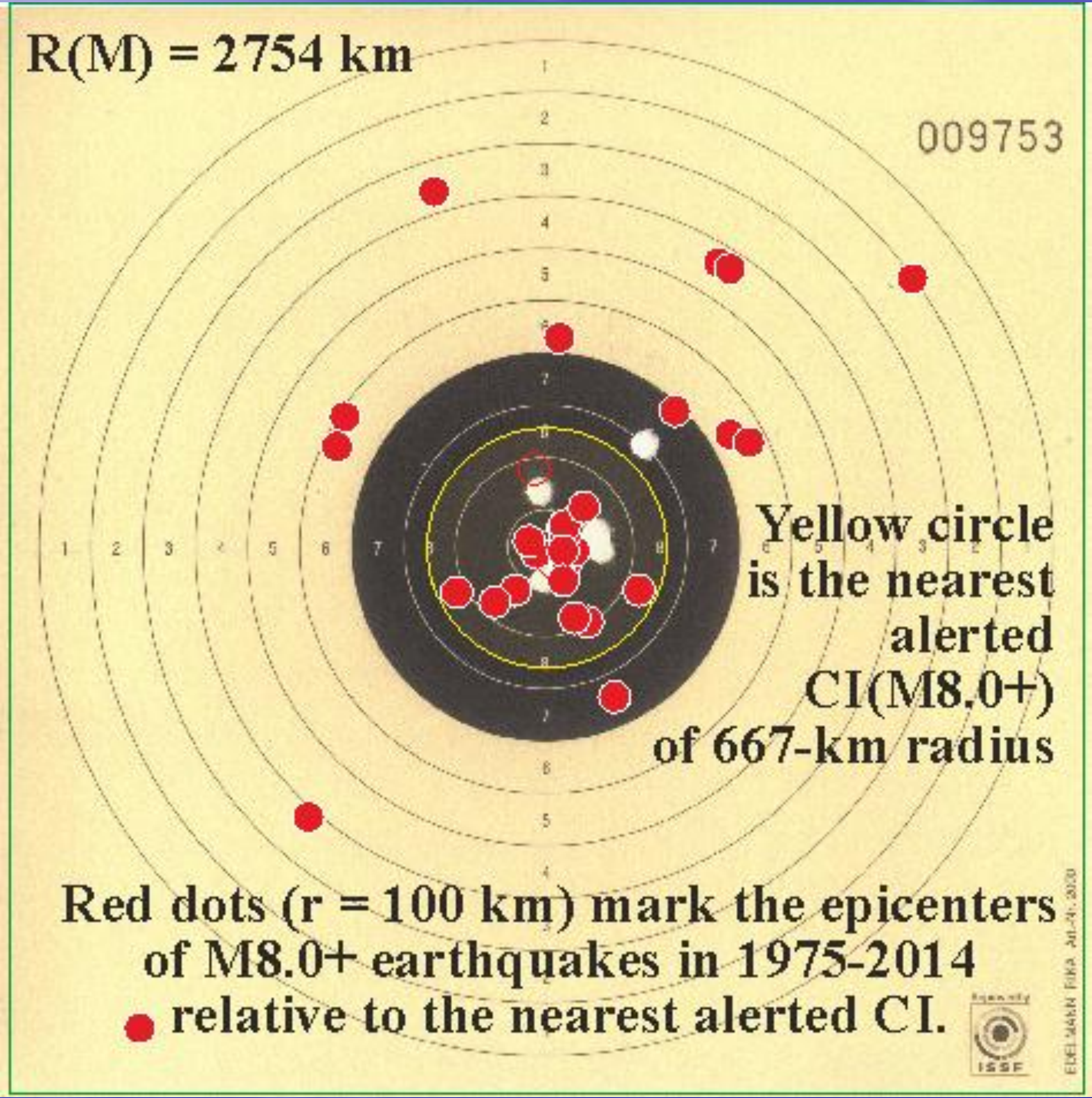
TO DRIVE ANY OF THE ACHIEVED CONFIDENCE LEVELS BELOW 95% THE TEST WOULD NEED TO ENCOUNTER MORE THAN TEN FAILURES-TO-PREDICT IN A ROW.

Error Diagrams for the results of the Global Test of the M8-MSc predictions of the great (M8.0+) and significant (M7.5+):

M8, 1985–2013 (1); 1992–2013 (2); M8–MSc, 1985–2013 (3), and 1992–2013 (4). The “random guessing” is outlined with the 95 and 99% confidence level curves (for 21 and 57 independent tests on the left and right).



Kossobokov V, Soloviev A (2015). Evaluating the Results of Testing Algorithms for Prediction of Earthquakes. *Doklady Earth Sciences, 2015, Vol. 460, Part 2, pp. 192–194*



One may compare the intermediate-term accuracy of earthquake forecast/prediction in time to the next day warning of a coming hurricane, while the middle-range accuracy in location to shooting 8 or more points by an air-pistol from 10 meters.

This kind of accuracy is proved achievable and reliable in the two decades of rigid real-time testing the M8 algorithm (Kossobokov, 2013).

Conclusions –
The Four Paradigms

Statistical validity of predictions demonstrated in 50 semiannual updates of rigorous testing 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

(e.g., Keilis-Borok, Gabrielov, and Soloviev, 2009;
Keilis-Borok,Soloviev, and Lichtman, 2009).

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.

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 (i.e. *intermediate asymptotic*), which then truncates at the largest scales bursting into direct cascades of aftershocks.

Contents lists available at SciVerse ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Advance prediction of the March 11, 2011 Great East Japan Earthquake: A missed opportunity for disaster preparedness

C. Davis [a,*], V. Keilis-Borok [b,c], V. Kossobokov [c,d], A. Soloviev [c]

[a] Geotechnical Engineering Group, Los Angeles Department of Water and Power, 111 North Hope Street, Room 1368, Los Angeles, CA 90012, USA
[b] Department of Earth and Planetary Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA
[c] Institute of Earthquake Prediction Theory and Mathematical Geophysics, Russian Academy of Sciences, 84/32 Profsouznaya, Moscow 117997, Russia
[d] Institut de Physique du Globe de Paris, 1 Rue Jussieu, 75238 Paris Cedex 05, France

The earthquake detection could have been utilized to implement measures and improve earthquake preparedness in advance; unfortunately this was not done, in part due to the predictions' limited distribution and the lack of applying existing methods for using intermediate-term predictions to make decisions for taking action.

Possible actions in response to an intermediate-term prediction

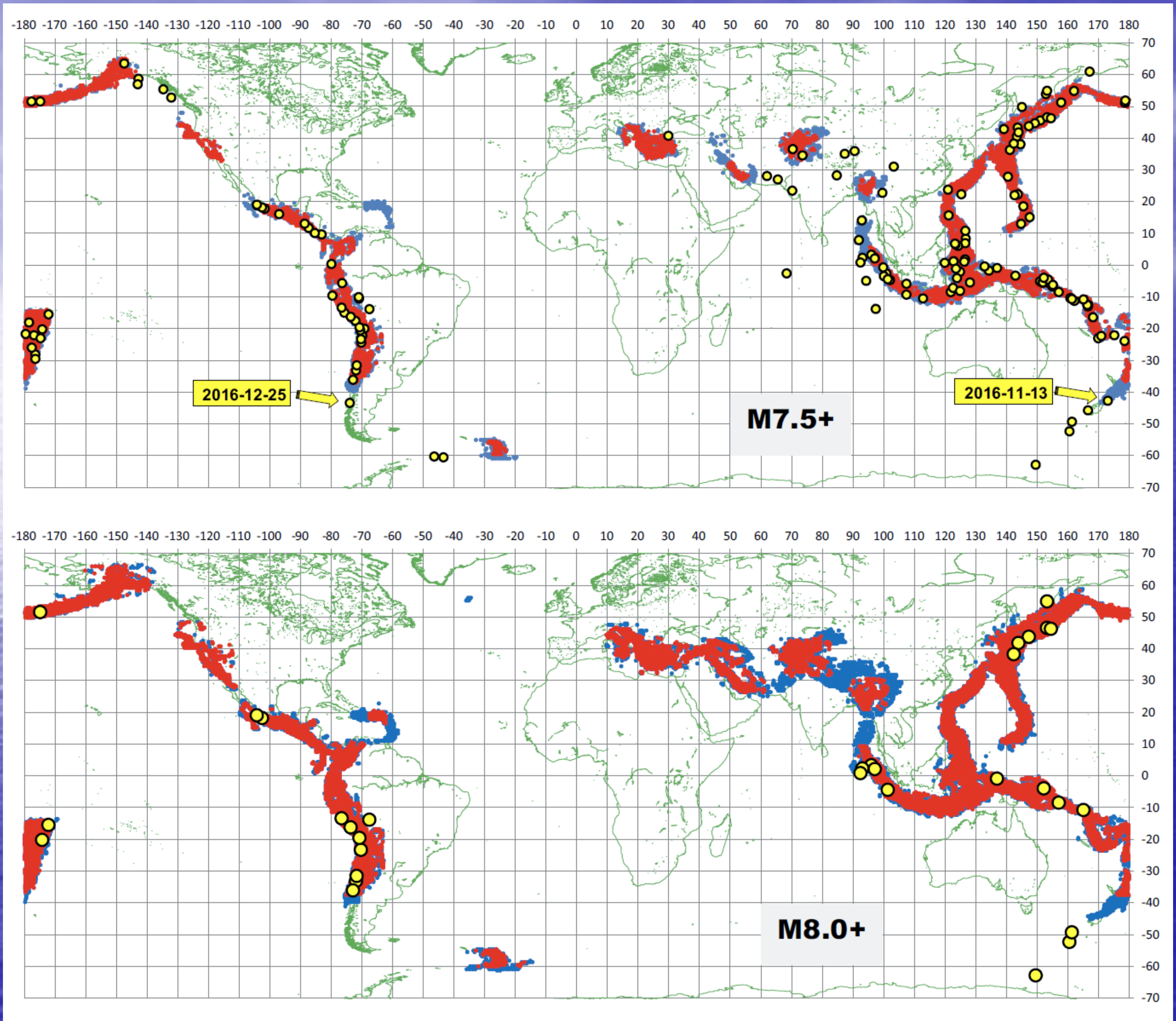
Possible scenario actions to reduce seismic risks in response to alarm. Actions are described in the text.

Item	Action	C_a ($1000)	P ($1000)	Gain, G ($1000) $1-f=20\%$	Gain, G ($1000) $1-f=50\%$
Nuclear power plants					
1a	Raise tsunami wall	10,000	500,000	90,000	240,000
1b	Protective generator housing	1000	500,000	99,000	249,000
1c	Raise wall + protective housing	11,000	500,000	89,000	239,000
Home, office, maintenance, industrial buildings					
2	Anchor furniture, cabinets, computers, equipment, etc.	11	101	9.2	39.5
3a	Relocating out of tsunami inundation area, or	500	1,500	−200	250
3b	Retrofitting structure for tsunami	280	1,500	20	470
Lifeline systems					
4	Railway bridge and track	400	700	−260	−50
5	Water pipe replacement	420	2100	0	630
6	Highway tunnel landslide repair	2000	2000	−1600	−1000
7	Power transformers	1500	10,000	500	3500
8	Roadway bridge	500	1500	−200	250
9	Liquid Fuel Tank	30	2000	370	970
Cultural					
10	Nikko temples	50	100	−30	0
Disregard/Unaware of Prediction					
11	Do nothing	0	−518,401	−103,680	−259,200

Using equation - $G = P(1-f) - Ca$ - to estimate f at the breakeven point when G=0 identifies that it was cost effective to take action for the Fukushima nuclear power plant with a 99.99% probability of false alarm.

What are the next steps?

- The algorithms are neither optimal nor unique (CN, SSE, Vere-Jones "probabilistic" version of M8, stabilized M8S, AZS, etc). The accuracy could be improved by a systematic monitoring of the alarm areas and by designing a new generation of earthquake prediction technique.
- Review the accumulated case-histories of "successes" and "failures-to-predict".
- Expand the Global Test settings.
- More data (including other than seismological) should be analyzed systematically to establish reliable correlations between the occurrence of extreme events and observable phenomena.



The global distribution of all potential centres of CI's where the USGS Global Hypocentre Data Base is enough for running M8 algorithm targeting magnitude ranges M7.5+ (upper panel) and M8.0+ (lower panel) in 1992 (red dots) and 2016 (blue dots). Yellow circles are epicentres of the target earthquakes in 1985-2016.

Conclusion

The confirmed reliability of pattern recognition results, along with realistic and exhaustive scenario modeling and testing against Reality, allow concluding –

Science can disclose Natural Hazards, assess Risks, and deliver the state-of-the-art knowledge of looming disaster in advance catastrophes along with useful recommendations on the level of risks for decision making in regard to engineering design, insurance, and emergency management.

POLICY MAY WISH TO STOP WEARING THE EXPOSED "EMPEROR'S NEW CLOTHES" THAT DO NOT PROTECT FROM NATURAL HAZARDS AND AVOID BUYING SUCH IN THE FUTURE.

Thank you!

"When sorrows come, they come not single spies, but in battalions"
(William Shakespeare, 1564-1616)