SCEC NASA

SCEC-NASA Workshop

Evaluating Ground-Based and Space-Based Methods of Earthquake Forecasting

July 26-27, 2011, at the University of Southern California

Organizing Committee: ***Tom Jordan*** **(SCEC/USC; chair)**
Tom Bleier **(Quakefinder; co-chair)**
Andy Michael **(USGS/Menlo Park)**
Friedemann Freund **(NASA Ames)**

Sponsors: ***Southern California Earthquake Center*** **(SCEC)**

National Aeronautics and Space Administration **(NASA)**

World Bank Global Facility for Disaster Reduction and Recovery **(GFDRR)**

United States Geological Survey **(USGS)**

Department of Homeland Security **(DHS)**

SCEC-NASA Workshop

Evaluating Ground-Based and Space-Based Methods of Earthquake Forecasting

- **Arrays of ground-based and space-based sensors observe a variety of earthquake-related phenomena, including seismic, geodetic, electromagnetic, and geochemical signals**
- **This two-day workshop will focus on the use of these signals in earthquake forecasting. It will provide a forum for exchanging views among different research communities about**
  - ***how forecasts are specified (e.g., in terms of location, time, and magnitude)***
  - ***how hypotheses regarding precursory behavior can be tested***
  - ***how the reliability, skill, and net information gain of forecasting methods can be evaluated***
- **The workshop aims to provide a collaborative environment for researchers from different fields to explore common earthquake forecasting issues and compare a variety of research programs on forecast development**
  - ***The objective is not to evaluate specific forecasting methods but to build a consensus about general strategies for forecast evaluation***

SCEC-NASA Workshop

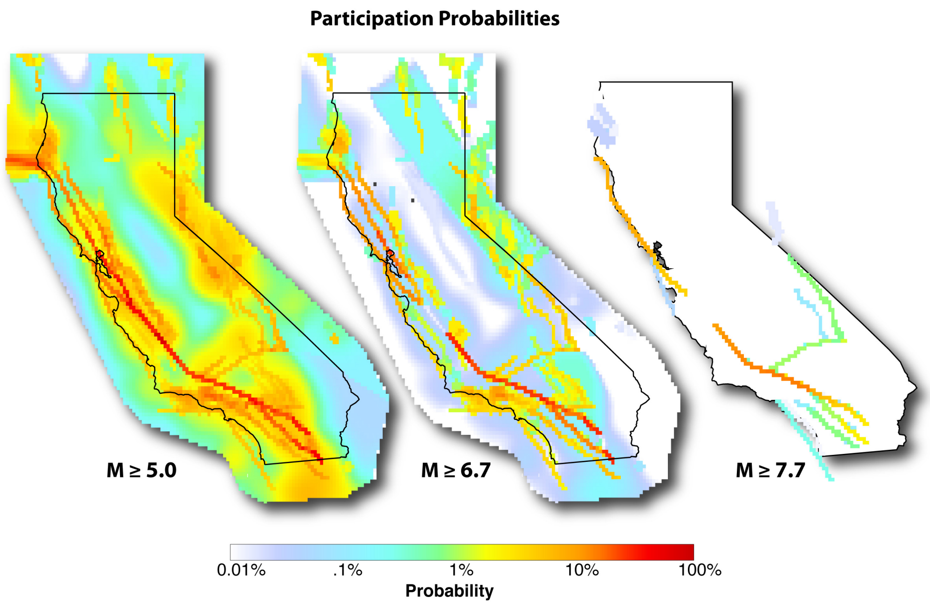
Evaluating Ground-Based and Space-Based Methods of Earthquake Forecasting

- **The goal of the workshop is to chart a course for forecast development that**
  - **begins with exploratory research on earthquake precursors and the casting of testable precursory hypotheses**
  - **proceeds through retrospective and prospective testing of forecasting methods**
  - **leads to the incorporation of significant precursory information into operational earthquake forecasting**

Forecasting Methods

Long-term (centuries to decades)	Medium-term (years to months)	Short-term (weeks to minutes)
Probabilistic Seismic Hazard Analysis (PSHA)	→	***Operational Earthquake Forecasting (OEF)***
"Seismic Climate Forecasting"		***"Seismic Weather Forecasting"***

Probabilistic Seismic Hazard Analysis



SCEC-USGS-CGS Working Group on California Earthquake Probabilities (2007)

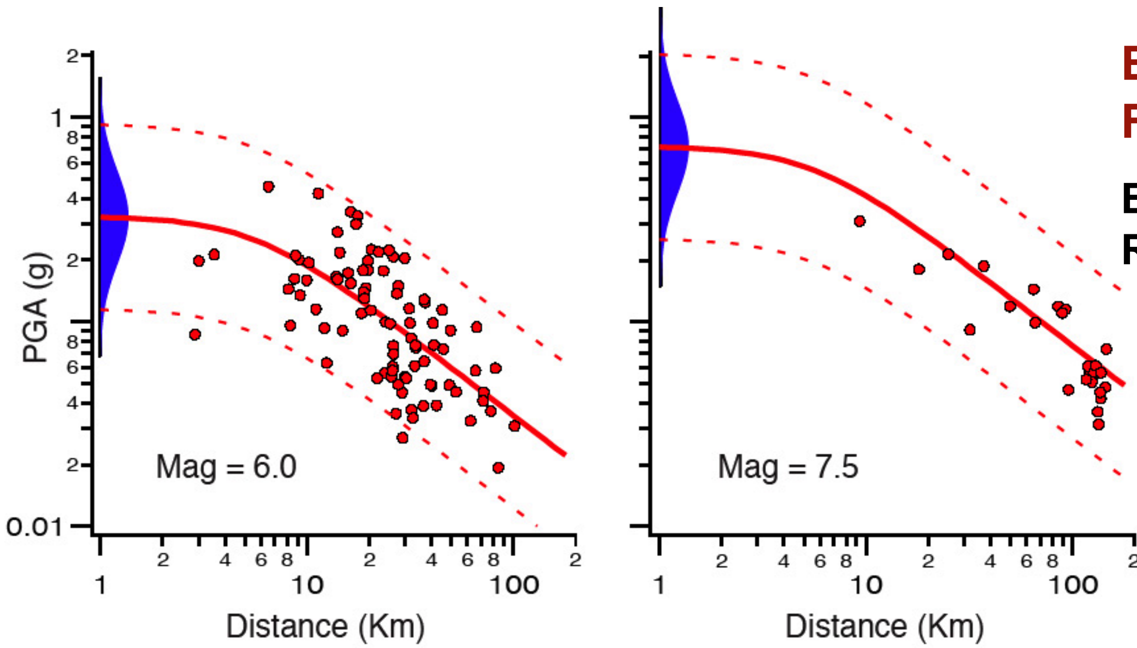
Uniform California Earthquake Rupture Forecast (UCERF2)

Earthquake Rupture Forecast → **Attenuation Relation** → **Intensity Measures**

$P(S_n)$ $P(IM_k \mid S_n)$ $P(IM_k)$

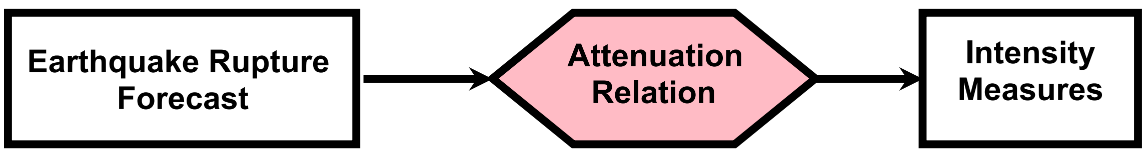
Probabilistic Seismic Hazard Analysis

Probabilistic Seismic Hazard Analysis



Boore, Joyner & Fumal (1997)

Empirical Attenuation Relationship



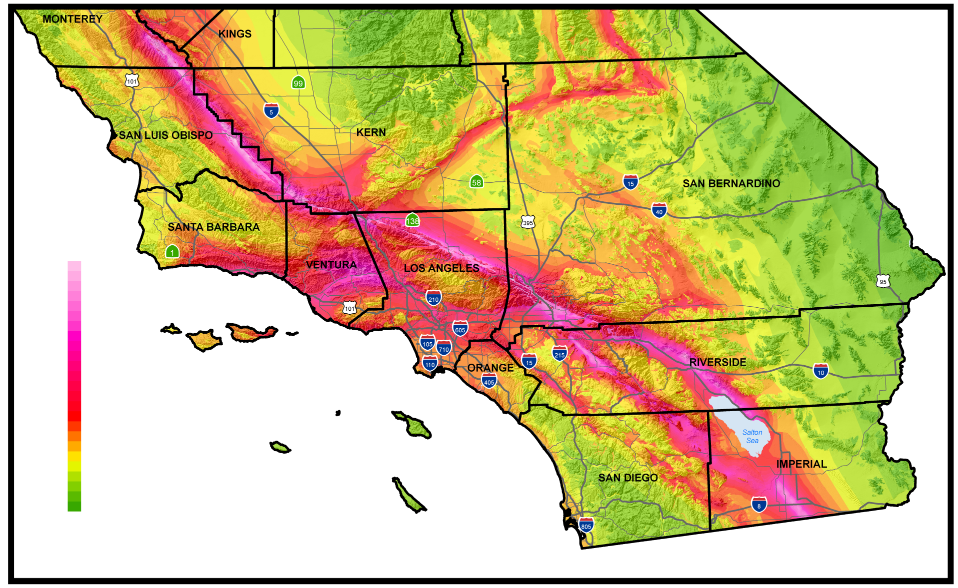
$P(S_n)$ $P(IM_k \mid S_n)$ $P(IM_k)$

Probabilistic Seismic Hazard Analysis

Probabilistic Seismic Hazard Analysis

Hazard Map

PGA (%g) with 2% Probability of Exceedance in 50 years



Earthquake Rupture Forecast → **Attenuation Relation** → **Intensity Measures**

$P(S_n)$ $P(IM_k \mid S_n)$ $P(IM_k)$

Probabilistic Seismic Hazard Analysis

Some Destructive Earthquakes Since 2008

Date	Location	Magnitude	Deaths
2008 05 12	Wenchuan, China	7.9	87,587
2009 04 06	L'Aquila, Italy	6.3	308
2009 09 30	Padang, Indonesia	7.5	1,117
2010 01 12	Port-au-Prince, Haiti	7.0	222,570
2010 02 27	Maule, Chile	8.8	557
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 Science May 31, 2011

Out of the blue. Students at California State University, Northridge, ponder the destruction wrought by a quake on an unrecognized fault.

SEISMOLOGY

Seismic Crystal Ball Proving Mostly Cloudy Around the World

Failing at quake prediction, seismologists tried making fuzzier forecasts, but Japan's megaquake is only the latest reminder of the method's shortcomings

When a devastating megaquake rocked the region north of Tokyo in March, nobody saw such a huge quake coming. "Japanese scientists are among the world's best, and they have the best monitoring networks," notes geophysicist Ross Stein of the U.S. Geologi- 1960s and '70s, seismologists worked on *prediction*: specifying the precise time, place, and magnitude of a coming quake. To do that, scientists needed to identify reliable signals that a fault was about to fail: a distinctive flurry of small quakes, a whiff of radon gas oozing from the ground, some oddly perturbed wildlife. Unfortunately, no one has yet found a bona fide earthquake precursor. By the time the 2004 magnitude-6.0 Parkfield earthquake—the most closely monitored quake of all time—struck the central San Andreas fault without so much as a hint of a precursor (*Science*, 8 October 2004, p. 206), most researchers had abandoned attempts at precise prediction.

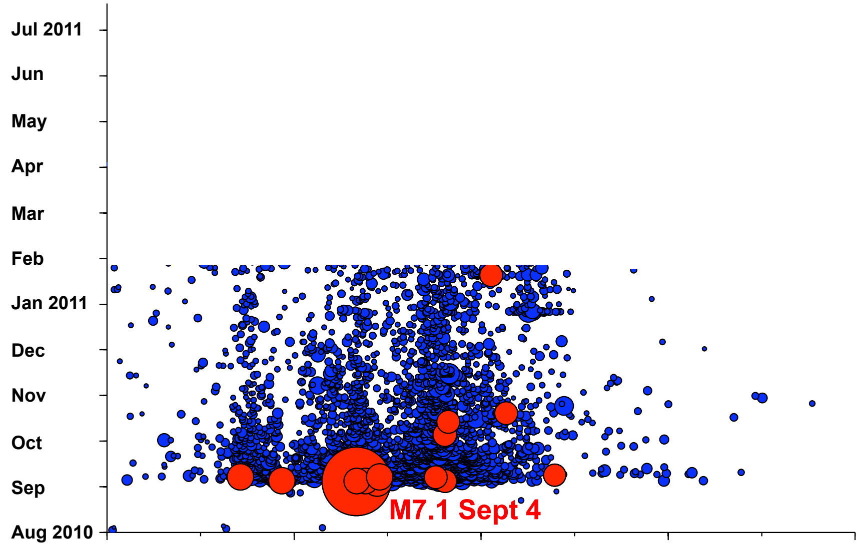
Parkfield did mark an early success of a new strategy: quake *forecasting*. Rather than waiting for a warning sign, forecasters look to the past behavior of a fault to gauge future behavior. They assume that strain on a fault is building steadily and that the same segment of fault that broke in the past will produce a similar break again in the future, once it reaches the same breaking point. Instead of giving the year or range of years when the next quake will strike a particular segment of fault, they express it as a probability.

USGS issued its first official earthquake forecast for the San Andreas in 1988 (*Science*, 22 July 1988, p. 413). Parkfield, which had a long record of similar quakes at roughly 22-year intervals, rated a 99% probability of repeating in the next 30 years. That turned out to be a success for the 1988 forecast. And the southern Santa Cruz Mountains segment, which last slipped in the 1906 San Francisco quake, was given a 30% chance of failing again within 30 years, which it did in 1989.

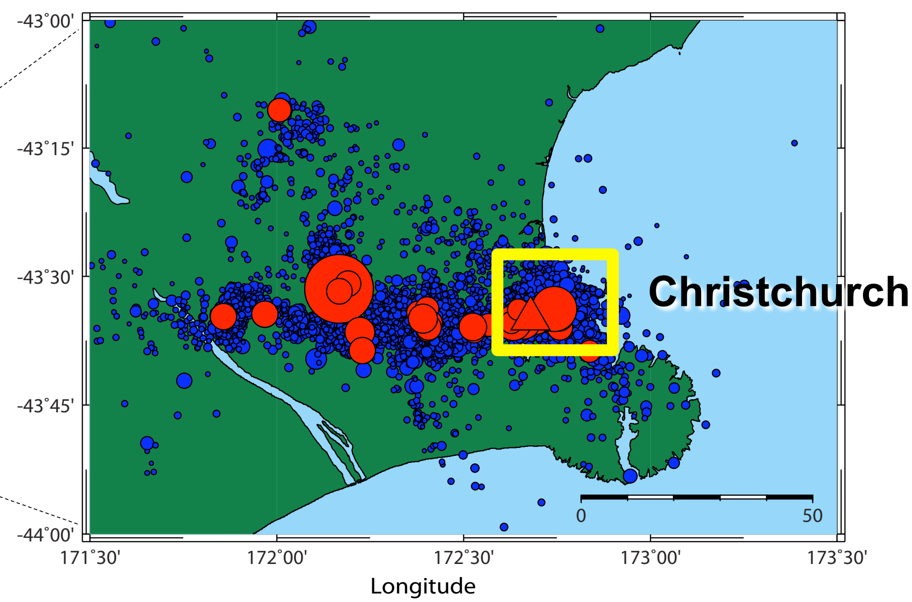
Since then, the 1988 San Andreas forecast

Darfield Earthquake Sequence

4 Sept 2010 – 1 July 2011



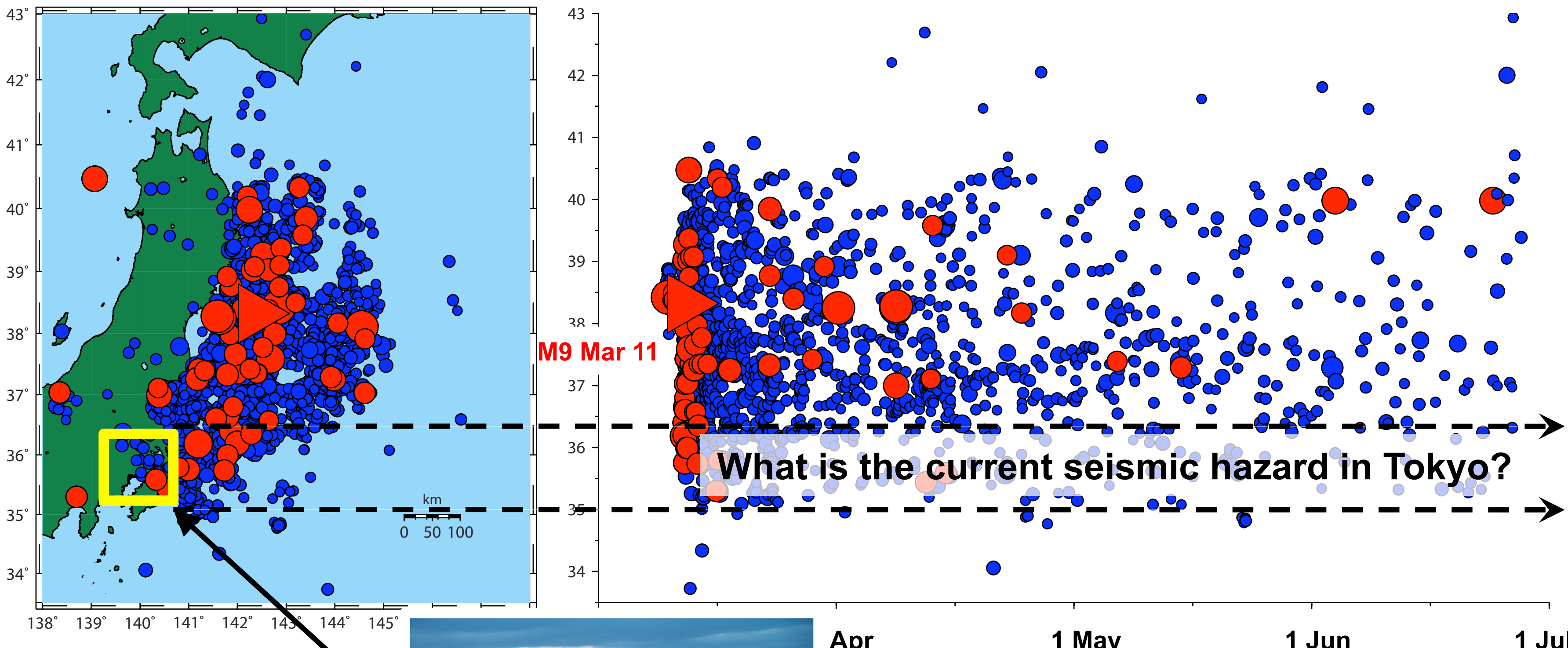
New
Zealand

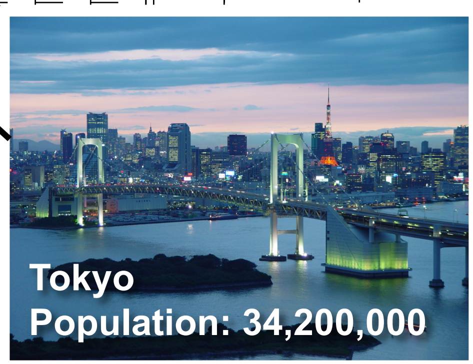


Epicentral dots scaled by magnitude;
M ≥ 5 in red

Tohoku Sequence

1 March – 1 July 2011

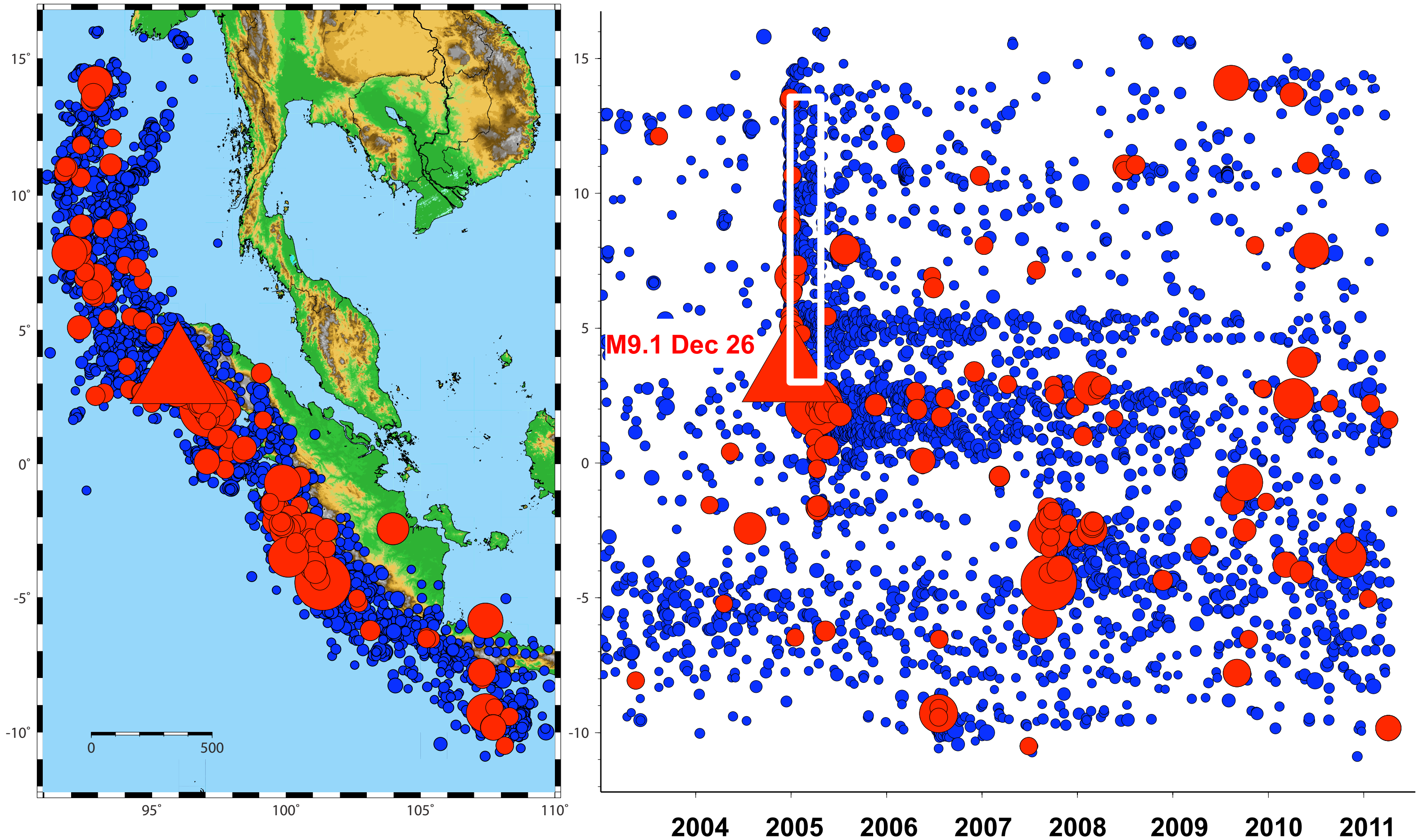




Epicentral dots scaled
by magnitude;
M ≥ 6 in red

Sumatra-Andaman Island Sequence

2003-2010



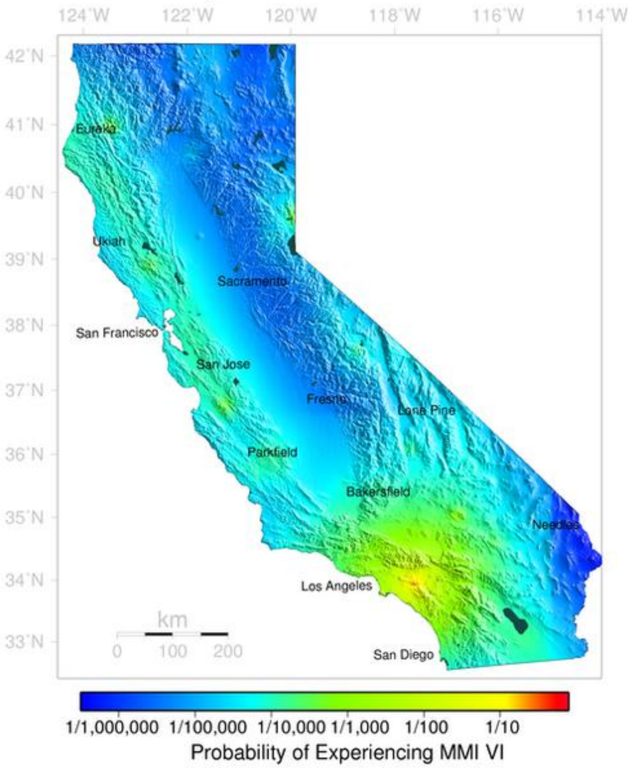
Epicentral dots scaled by magnitude;
M ≥ 6 in red

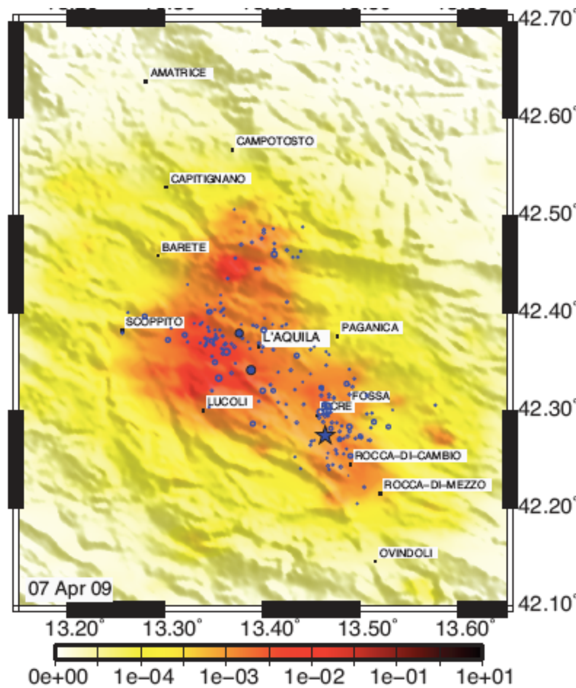
Operational Earthquake Forecasting

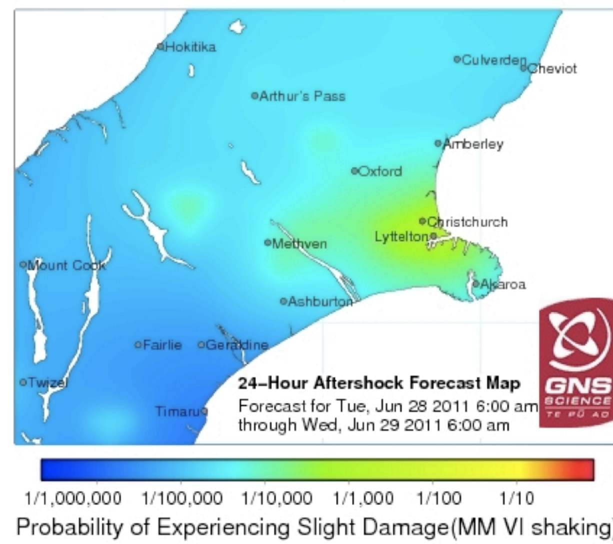
Authoritative information about the time dependence of seismic hazards to help communities prepare for potentially destructive earthquakes.

- **Seismic hazards change with time**
  - **Earthquakes release energy and suddenly alter the tectonic forces that will eventually cause future earthquakes**
- **Statistical models of earthquake interactions can capture many of the short-term temporal and spatial features of natural seismicity**
  - **Excitation of aftershocks and other seismic sequences**
- **Such models of regional seismicity can estimate short-term changes in the probabilities of future earthquakes**
  - **Provide the highest validated information gain per earthquake of any known technique**

24-hr Aftershock Forecast Maps







California	Italy	New Zealand
29 July 2008	**7 April 2009**	**28 June 2011**
(Gerstenberger et al., 2005)	**(Marzocchi & Lombardi, 2009)**	**(Gerstenberger, 2011)**

Issues of Operational Earthquake Forecasting

- What are the best available scientific methods for forecasting large earthquakes and their aftershocks?
- Can large earthquakes be forecast with short-term probabilities that are high enough and reliable enough to aid in civil protection?
- How should government authorities use low-probability scientific information to enhance civil protection?
- How should this information be communicated to the public?

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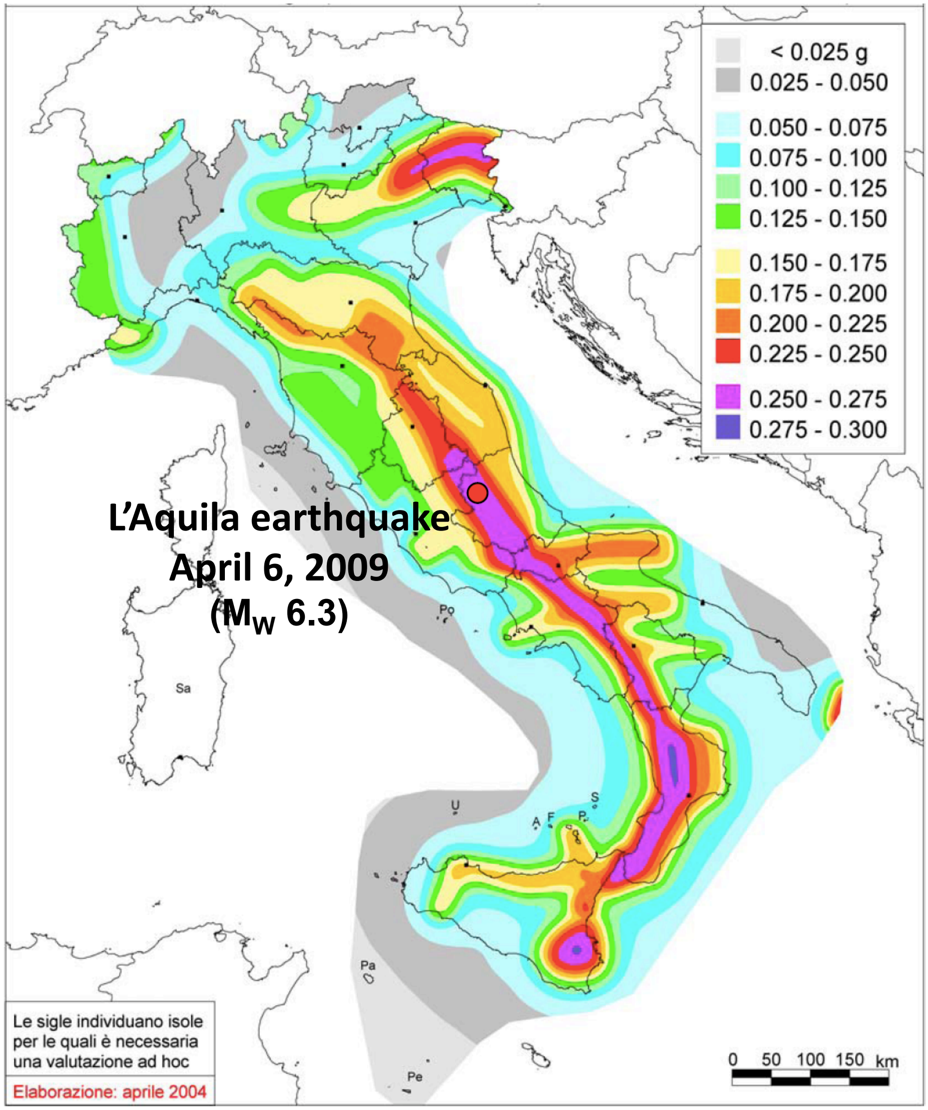
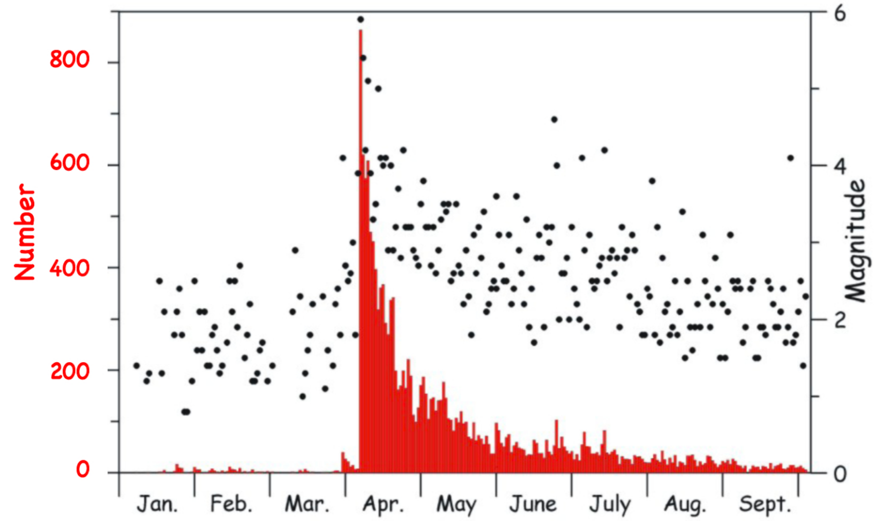
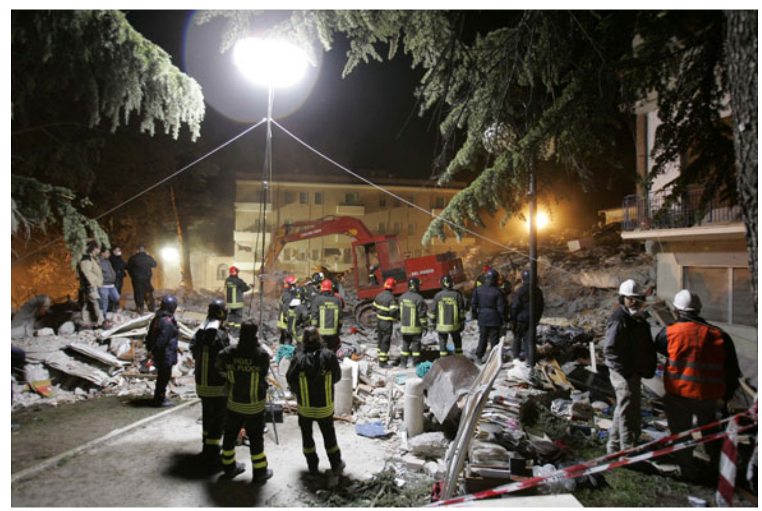
2009 L'Aquila Earthquake Sequence







Science June 3, 2011

ITALY

Quake Experts to Be Tried For Manslaughter

Seven scientists and technicians who analyzed seismic activity ahead of the devastating earthquake that struck the Italian town of L'Aquila on 6 April 2009 will indeed face trial for manslaughter, a judge announced

says Thomas Jordan, an earth scientist at the University of Southern California in Los Angeles, who chaired an international commission to review earthquake predictions in Italy in the light of the L'Aquila

tist at the University of Genoa; and Mauro Dolce, director of the office of seismic risk at the Civil Protection Department.

Central to the prosecutors' case is a meeting held 6 days before the quake in which the risks committee, as well as local politicians and representatives of the Civil Protection Department, discussed a series of recent tremors that had occurred in the province of L'Aquila, including a quake of magnitude 4.0 the previous day. According to the official minutes of the meeting, the seven accused committee members explained that

International Commission on Earthquake Forecasting (ICEF)

- **Charged by Dipartimento della Protezione Civile (DPC) to:**
  1. **Report on the current state of knowledge of short-term prediction and forecasting of tectonic earthquakes**
  2. **Indicate guidelines for utilization of possible forerunners of large earthquakes to drive civil protection actions**
- **ICEF report: *"Operational Earthquake Forecasting: State of Knowledge and Guidelines for Utilization"***
  - **Findings & recommendations issued on 2 Oct 2009; endorsed by IASPEI on July 4, 2011**
  - **Final report accepted by DPC in May 2011 and to be published by *Annals of Geophysics* in Aug 2011**

Members (9 countries):

T. H. Jordan, Chair, USA

Y.-T. Chen, China

P. Gasparini, Secretary, Italy

R. Madariaga, France

I. Main, United Kingdom

W. Marzocchi, Italy

G. Papadopoulos, Greece

G. Sobolev, Russia

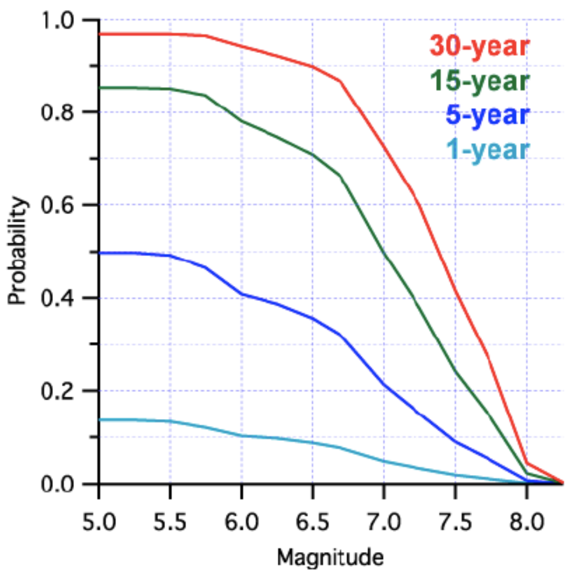
K. Yamaoka, Japan

J. Zschau, Germany

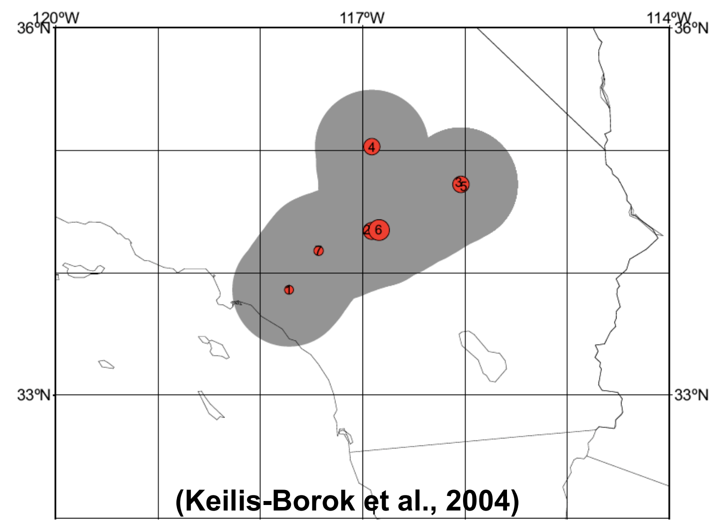
Definition of Prediction vs. Forecasting

- An ***earthquake forecast*** gives a <u>probability</u> that a target event will occur within a space-time domain
- An ***earthquake prediction*** is a <u>deterministic statement</u> that a target event will occur within a space-time domain

Rupture Probability for San Andreas Fault System (WGCEP, 2007)

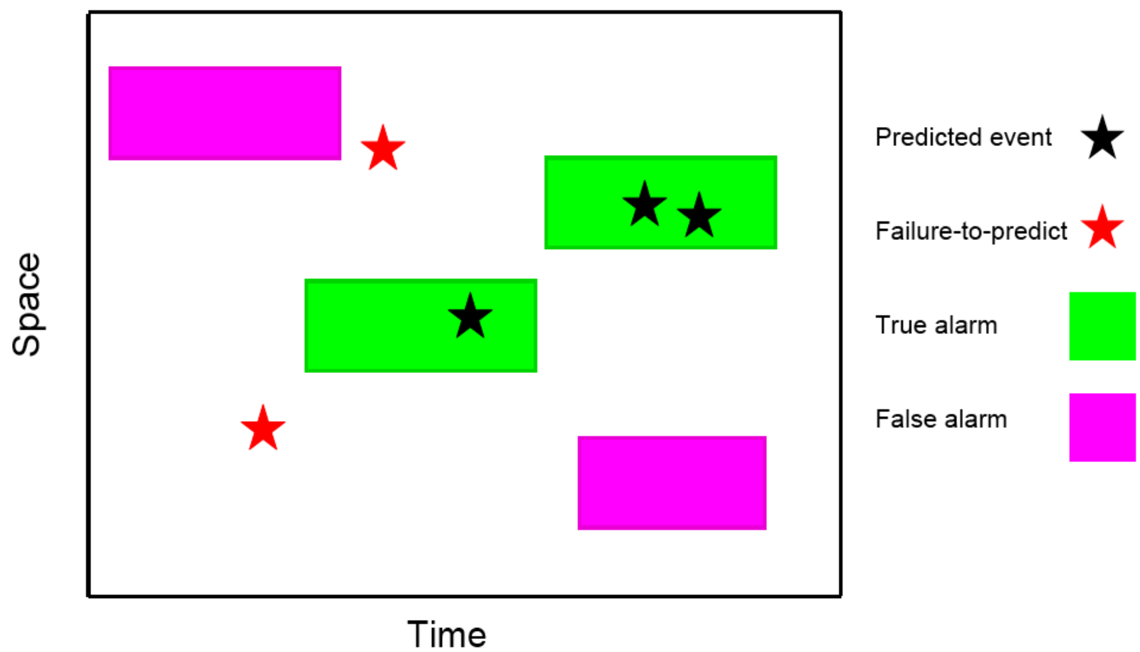


RTP Alarm for California M ≥ 6.4, 15 Nov 2004-14 Aug 2005



Earthquake Prediction

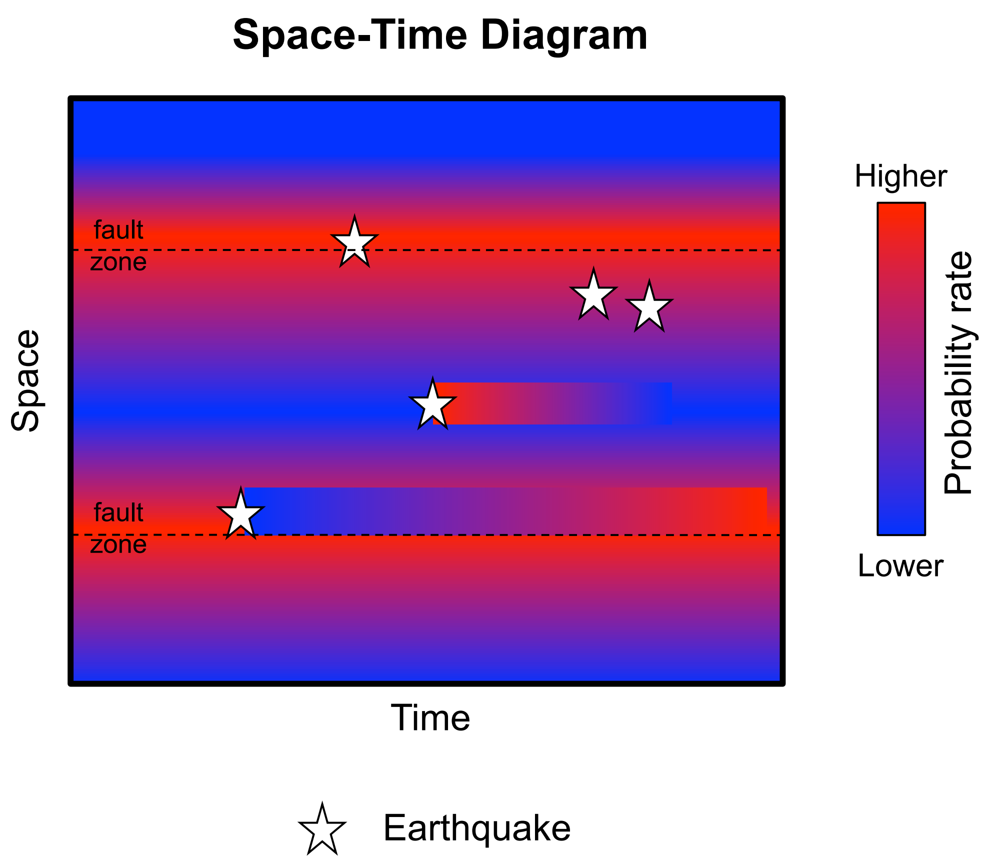
Space-Time Diagram



Prediction	Outcome: YES	Outcome: NO
YES	True alarm (*a*)	False alarm (*b*)
NO	Failure-to-predict (*c*)	True non-alarm (*d*)

- **A prediction specifies in advance a space-time set of increased probability (alarm) for target earthquakes**
  - **Example: epicenters of events with $M \geq M_0$**
- **Alarm-based predictions can be evaluated using contingency tables**
- **For predictions to be useful to society, they must**
  - **target large events**
  - **have low (and known) error rates**

Earthquake Forecasting

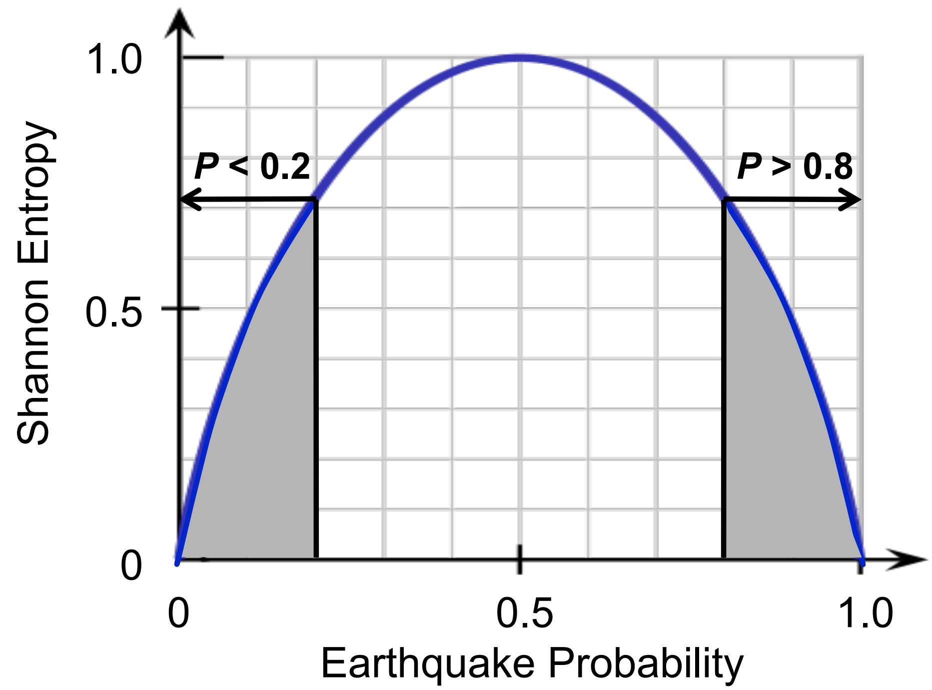


- **Time-independent models**
  - **Spatially varying models of long-term probability rates assuming stationary Poisson behavior**
- **Time-dependent models**
  - **Probability rates conditioned on earthquake history**
    - **Long-term stress-renewal models (less clustered than Poisson)**
    - **Short-term triggering models (more clustered than Poisson)**
- **Probabilistic forecasts can be evaluated using likelihood methods, Molchan, ROC, etc.**

Prediction vs. Forecasting

As tools for helping communities prepare for potential earthquake disasters,

- ***deterministic prediction*** **is useful primarily in a high-probability environment**
- ***probabilistic forecasting*** **can be useful in a low-probability environment**



ICEF Findings:

- ***For most decision-making purposes, probabilistic forecasting provides a more complete description of prospective earthquake information than deterministic prediction.***
- ***Probabilistic forecasting appropriately separates hazard estimation by scientists from the public protection role of civil authorities.***

Validation of Forecasting Methods

Criteria for operational fitness:

- **Quality validated by retrospective and prospective testing**
- **Consistency across temporal and spatial scales**
- **Value to users**

ICEF Recommendations:

- ***To be qualified for operational use, forecasting methods should be scientifically tested against the available data for reliability and skill, both retrospectively and prospectively.***
- ***All operational models should be under continuous prospective testing.***

Problems in Assessing the Quality of Earthquake Forecasts & Predictions

- Scientists are over-optimistic about their own results
- Scientific publications provide insufficient information for independent evaluation
- Active researchers are constantly tweaking their procedures, which become moving targets
- Standards are lacking for testing predictions against reference forecasts
- Data to evaluate prediction experiments are often improperly specified
- Infrastructure for conducting and evaluating long-term prediction experiments has not existed

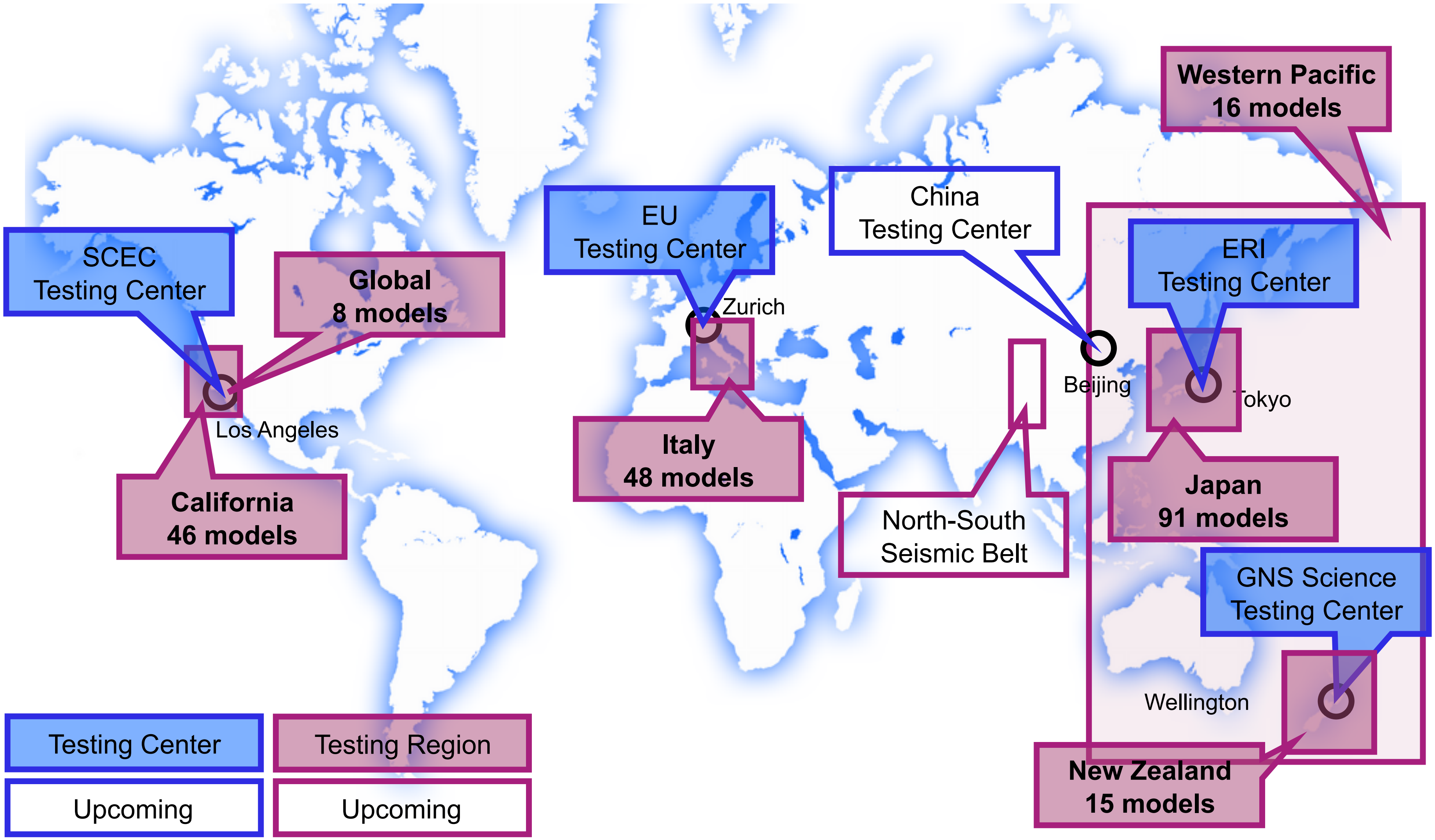
Collaboratory for the Study of Earthquake Predictability

- **CSEP goal is rigorous testing of predictability hypotheses and forecasting models**
  - Automate blind, prospective testing in a standardized, controlled environment
  - Establish experiments in a variety of tectonic environments and on a global scale

- **CSEP components:**
  - *Natural laboratories* comprising active fault systems with adequate, authorized data sources for conducting forecasting experiments
  - *Testing centers* with validated procedures for registering and evaluating prediction experiments
  - *Model classes* with common target events, forecasting regions, and forecast updating intervals

CSEP Testing Regions & Testing Centers

224 models under test in June, 2011



Prediction Using Diagnostic Precursors

A precursory change is *diagnostic* if it can predict an impending event's location, time, and magnitude with high probability and low error rates (false alarms and failures-to-predict)

- **Proposed methods include:**
  - **foreshocks & seismicity patterns**
  - **strain-rate acceleration**
  - **seismic velocity changes**
  - **electromagnetic signals**
  - **thermal anomalies**
  - **hydrologic changes**
  - **geochemical signals**
  - **animal behavior**

- **ICEF Finding**: ***Search for diagnostic precursors has not yet produced a successful short-term prediction scheme.***

Search for Diagnostic Precursors

- **Strategy predicated on two hypotheses:**
  - Large earthquakes are the culmination of progressive deformation sequences with *diagnostic* precursory changes in the regional stress and strain fields
  - *Diagnostic* information about an impending earthquake can be extracted from observations that are sensitive to these precursory stress and strain changes
- **Statistical analysis of retrospective correlations between proposed precursors and subsequent earthquakes has been problematic**
  - Data coverage rarely sufficient to characterize the background noise or evaluate the statistics of false alarms and failures-to-predict
  - Prediction success has often been over-estimated by cherry-picking and retrospective testing that is dependent on the data used in model-tuning
- **Few prediction schemes have been formulated in a manner that allows independent testing**
  - Prospective testing of formalized models has been infrequent
  - Where conducted (e.g., Parkfield), predictions have failed to demonstrate reliability and skill relative to baseline forecasts

Eleven Questions (abbreviated version)

1. What physical hypotheses about earthquake predictability have motivated your research?
2. What evidence can be used to support or reject these hypotheses?
3. What data are used?
4. How is noise treated in the data collection and analysis process?
5. Have earthquake-forecasting models that incorporate these hypotheses been formulated, and are they automated for independent evaluation?
6. Is there corroborating evidence (more than one indicator) within a forecast?
7. Under which circumstances have the forecasting models been tested?
8. What are the statistical results of formal testing?
9. Is significant information from this research ready for operational earthquake forecasting?
10. What are next steps for moving towards the use of this information in earthquake forecasting?
11. What are the next steps for improving our understanding of the physical hypotheses?

Pathway Towards Practical Utility

- Exploratory research on earthquake precursors
  - Physics-based concepts regarding physical principles and statistical properties of earthquake predictability
- Hypothesis formulation
  - Casting of testable precursory hypotheses
- Hypothesis testing
  - Retrospective and prospective testing of forecasting methods to assess reliability, skill, and information gain
- Implementation
  - Incorporation of significant precursory information into operational earthquake forecasting

Workshop Agenda

July 26, 2011

08:30 - 09:00	Workshop Goals and Objectives
09:00 - 12:00	Session I: Physical Processes That May Produce Precursor Signals
12:00 - 13:30	Lunch
13:30 - 15:30	Session II: Methods for Hypothesis Testing and Forecast Evaluation
15:30 - 15:45	Break
15:45 - 17:30	Session III: Status of Forecast Methods
17:30	Adjourn
18:30 - 21:00	Dinner at the University Club

July 27, 2011

08:30 - 10:00	Session IV: Status of Forecast Methods
10:15 - 12:00	Session V: Official Use of Forecasting Information
12:00 - 13:30	Lunch
13:30 - 15:30	Session VI: State of Knowledge and Next Steps
15:30	Adjourn

End