Prospects for Operational Earthquake Forecasting

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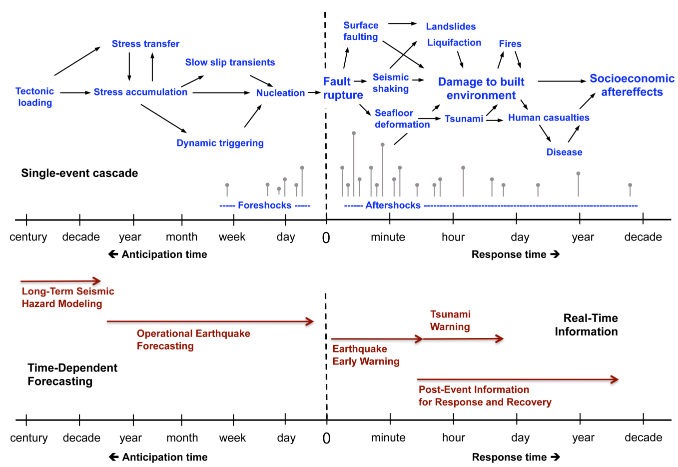
NEPEC Meeting

4 Nov 2010

Time-Dependent Probabilistic Seismic Hazard Analysis

- **Research goal: understand how seismic hazards change across time scales of scientific and societal interest, from millennia to seconds**



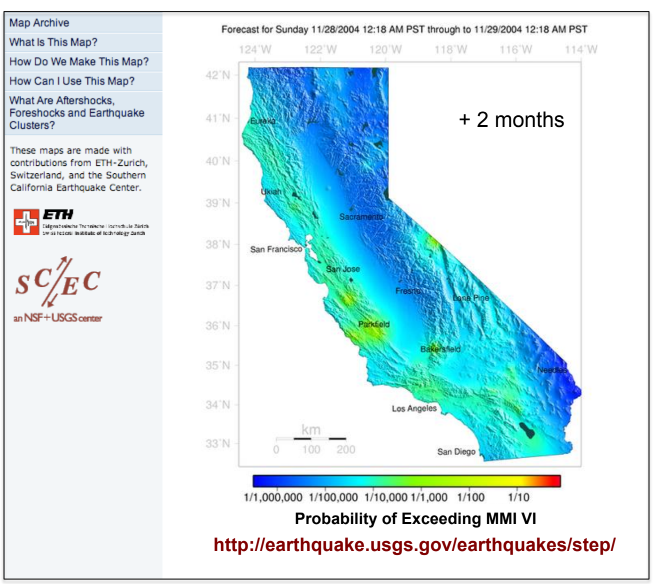
- **Practical goal: enable new geotechnologies for reducing earthquake risk and improving community resilience**

Operational Earthquake Forecasting

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

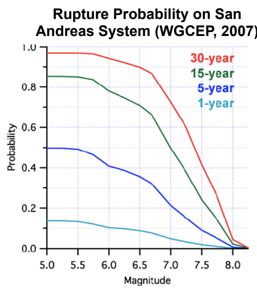
- **Seismic hazard changes with time**
  - **Earthquakes release energy and suddenly alter the tectonic forces that will eventually cause future earthquakes**
- **Statistical models of earthquake interactions can capture many of the temporal and spatial features of natural seismicity**
  - **Excitation of aftershocks and other seismic sequences**
- **Such models can use regional earthquake history to estimate short-term changes in the probabilities of future earthquakes**
  - **Authoritative short-term forecasts should be provided to the public in a transparent way**

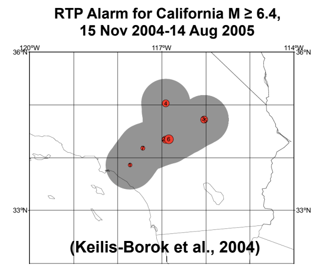
Short-Term Earthquake Probability (STEP) Model



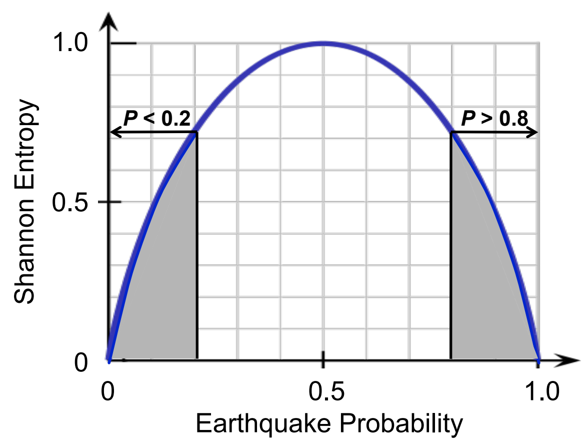
Prediction vs. Forecasting

- **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**





Prediction vs. Forecasting



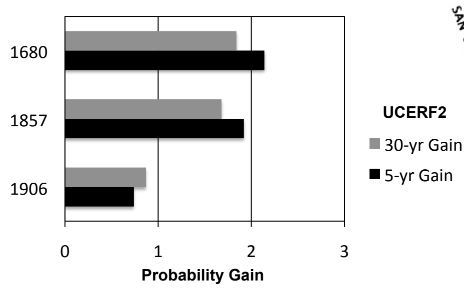
- ***Deterministic prediction* requires a high-probability environment**
- ***Probabilistic forecasting* can be useful in a low-probability environment**

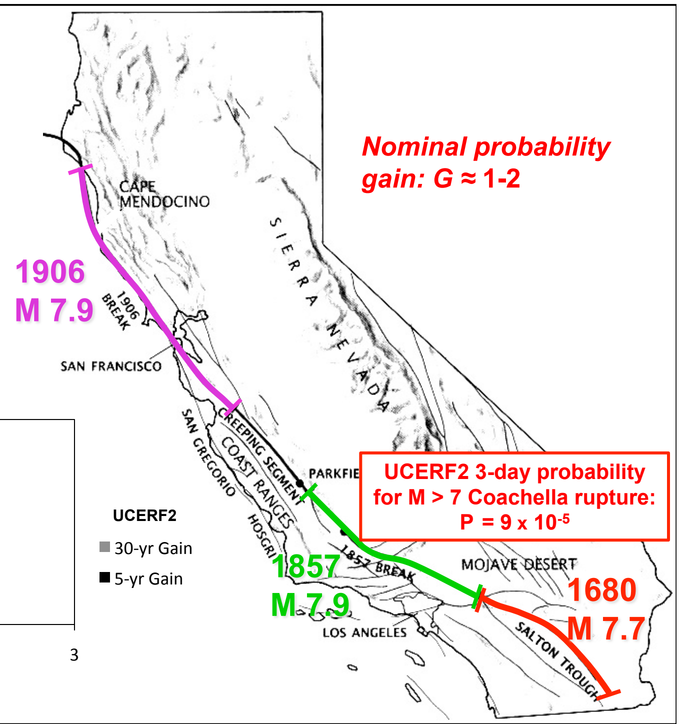
Issues for Operational Earthquake Forecasting

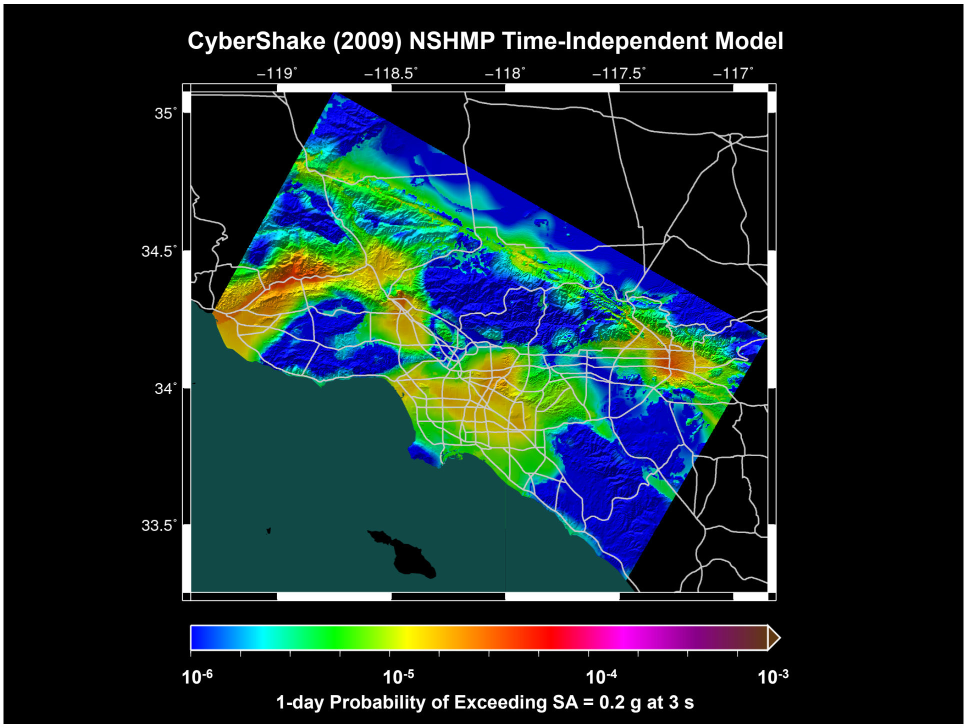
- **What are the performance characteristics of current short-term forecasting methodologies?**
- **How should short-term forecasts be integrated with long-term forecasts?**
- **How should operational methods be developed, validated, and deployed?**
- **How should low-probability, short-term forecasts be used in decision-making related to civil protection?**

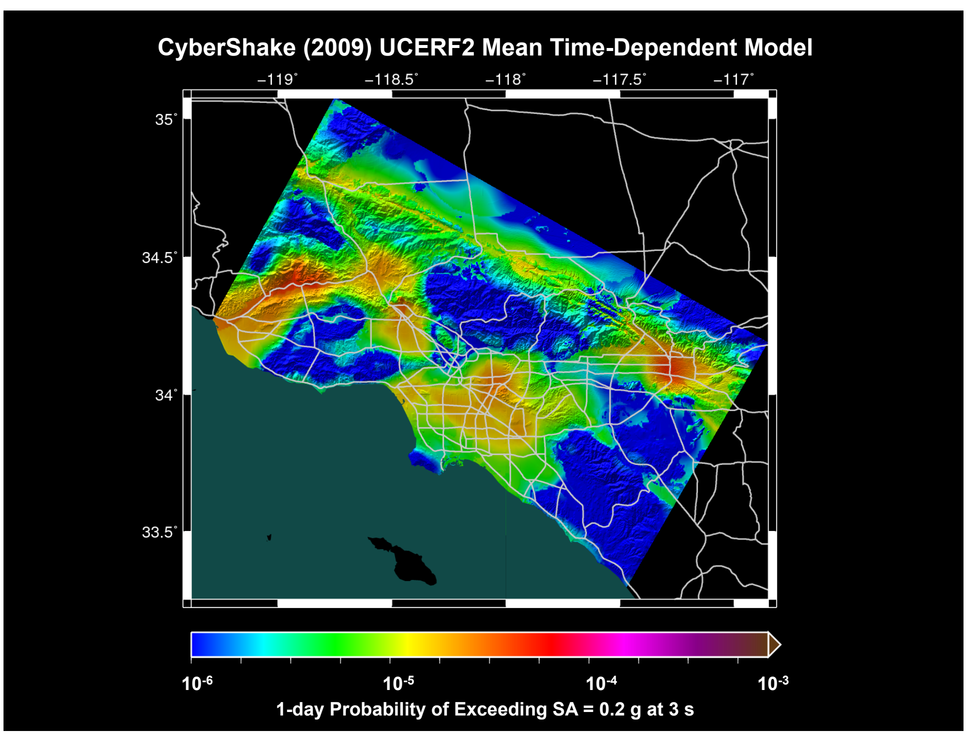
Long-Term Renewal Models

Working Group on California Earthquake Probabilities (1988, 1989, 1996, 2003, 2007)



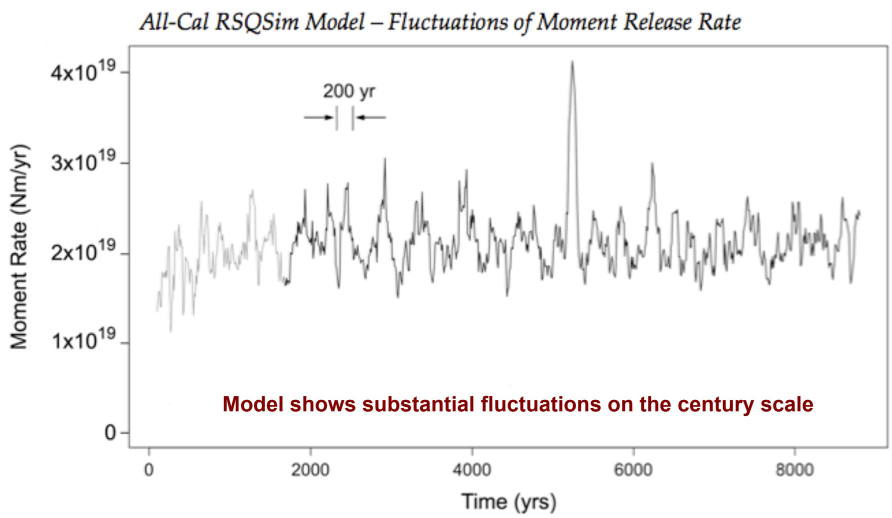



CyberShake (2009) NSHMP Time-Independent Model
–119˚
–118.5˚
–118˚
–117.5˚
–117˚
35˚
34.5˚
34˚
33.5˚
10^{-6}
10^{-5}
10^{-4}
10^{-3}
1-day Probability of Exceeding SA = 0.2 g at 3 s


CyberShake (2009) UCERF2 Mean Time-Dependent Model
–119˚
–118.5˚
–118˚
–117.5˚
–117˚
35˚
34.5˚
34˚
33.5˚
10^{-6}
10^{-5}
10^{-4}
10^{-3}
1-day Probability of Exceeding SA = 0.2 g at 3 s

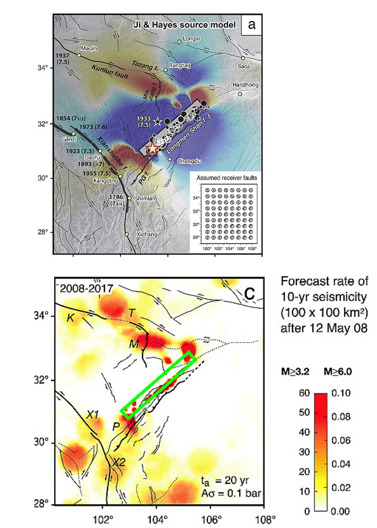
Long-Term Fluctuations from RSQSim Earthquake Simulator

(Dieterich & Richards-Dinger, 2010)



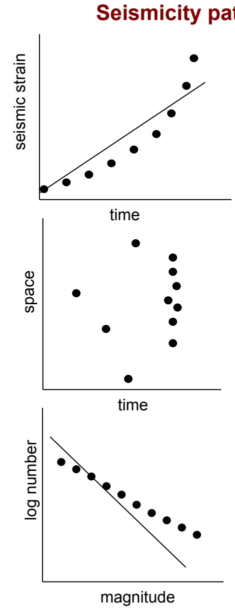
Medium-Term Forecasting Models

Coulomb stress change



Wenchuan Earthquake Region (Toda et al., 2008)

Seismicity patterns



Accelerating Moment Release

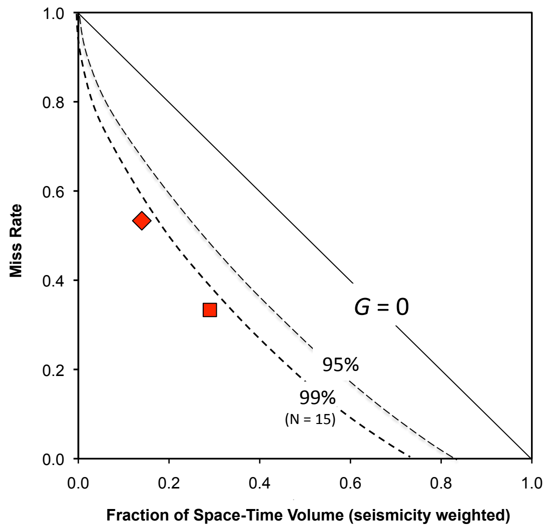
Long-Range Correlation

Change in *b*-value

(Keilis-Borok et al.)

Medium-Term Prediction Models

(seismicity pattern recognition)



Data on Prospective Predictions
(V. Kossobokov, pers.com., 2009)

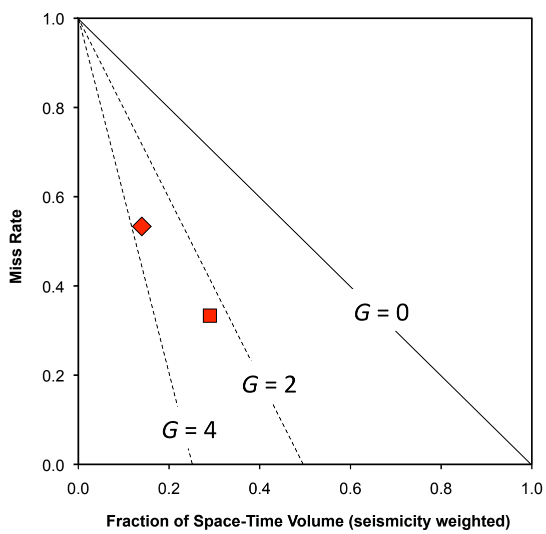
M8 Global (M ≥ 8.0) 1992-2009 (N = 15)

MSc Global (M ≥ 8.0) 1992-2009 (N = 15)

Probability gain is statistically significant…

Medium-Term Prediction Models

(seismicity pattern recognition)



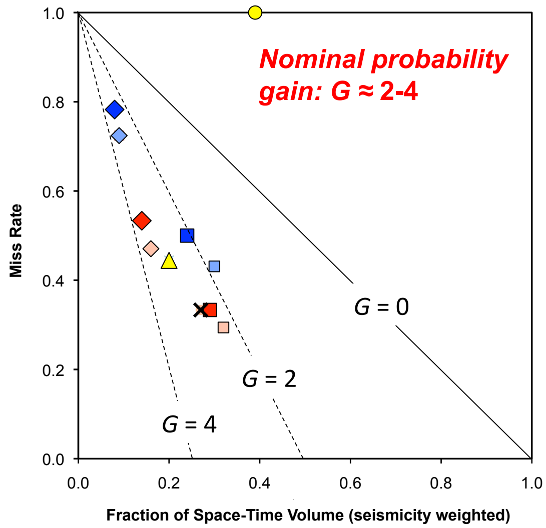
Data on Prospective Predictions
(V. Kossobokov, pers.com., 2009)

M8 Global (M ≥ 8.0) 1992-2009 (N = 15)

MSc Global (M ≥ 8.0) 1992-2009 (N = 15)

… but the gain factors are modest

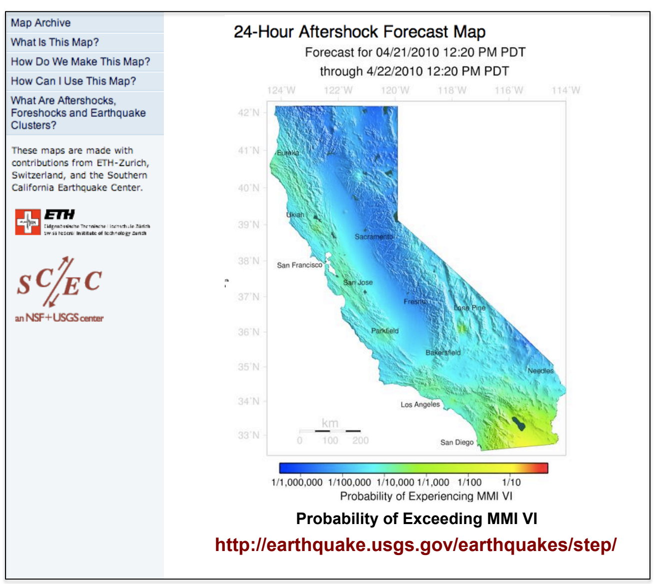
Medium-Term Prediction Models
(seismicity pattern recognition)



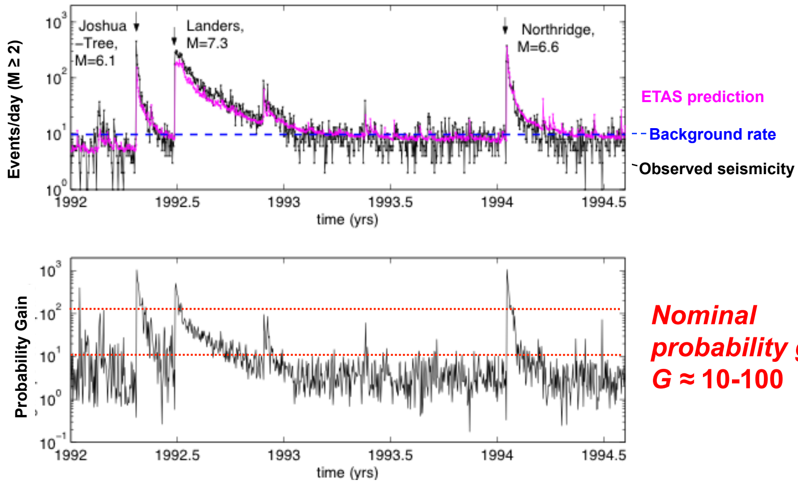
Data on Prospective Predictions
(V. Kossobokov, pers.com., 2009)

- M8 Global (M ≥ 8.0) 1985-2009 (N =17)
- M8 Global (M ≥ 8.0) 1992-2009 (N = 15)
- M8 Global (M ≥ 7.5) 1985-2009 (N = 58)
- M8 Global (M ≥ 7.5) 1992-2009 (N = 46)
- MSc Global (M ≥ 8.0) 1985-2009 (N =17)
- MSc Global (M ≥ 8.0) 1992-2009 (N = 15)
- MSc Global (M ≥ 7.5) 1985-2009 (N = 58)
- MSc Global (M ≥ 8.0) 1992-2009 (N = 46)
- M8S Italy (M ≥ 6.0) 2002-2009 (N = 1)
- M8S Italy (M ≥ 5.5) 2002-2009 (N = 9)
- CN Italy (M ≥ 5.4-5.6) 2002-2009 (N = 6)

Short-Term Earthquake Probability (STEP) Model



Short-Term ETAS Model



Nominal probability gain:
G ≈ 10-100

Retrospective daily ETAS predictions of Southern California seismicity (Helmstetter et al., 2006)

Short-Term Foreshock Models

Model of Agnew & Jones (1991):

P(F) = probability that event is a foreshock of a mainshock in a class C

P(C) = *a priori* probability of a mainshock in class C

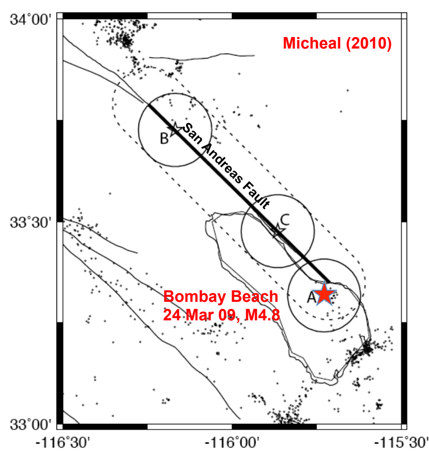
P(B) = probability that event is background

P(F) = *G* P(C), where the gain factor is

G = P(F|C) ÷ [P(F|C) P(C) + P(B)]

Application to Bombay Beach event 24 Mar 09, M4.8 by Micheal (2010)

Foreshock window: 3 days, 10 km
Seismicity analysis:



***G* = 1300 - 5400** (relative to Poisson seismicity model)
= 100 - 700 (relative to UCERF2 model)

P(F) = 0.3% - 19%

Summary of Probability Gains

Method	Gain Factor	P_{max}(3 day) Coachella	Prospectively verified?
Long-term renewal	1-2	1×10^{-4}	
Medium-term seismicity patterns	2-4	2×10^{-4}	✔
Short-term ETAS	10-100	3×10^{-3}	✔
Short-term foreshock	100-1000	3×10^{-2}	

Operational Forecasting in California

- **Organizations:**
  - USGS - National Earthquake Prediction Evaluation Council (NEPEC)
  - CalEMA - California Earthquake Prediction Evaluation Council (CEPEC)
- **Operational forecasting tools**
  - Long-term models (UCERF2)
  - Short-term models (Reasenberg-Jones, STEP, ETAS, Agnew-Jones)
- **Notification protocols**
  - Southern San Andreas Working Group (1991)
  - California Integrated Seismic Network notifications
    - For M ≥ 5 events, probability of M ≥ 5 aftershocks and expected number of M ≥ 3 aftershocks

Alert Levels Used by CEPEC

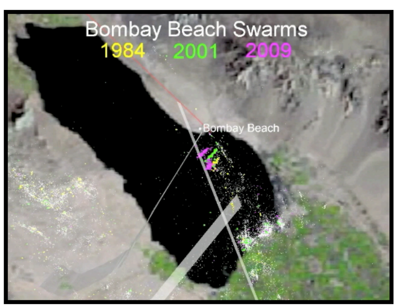
- W. H. Bakun et al., *Parkfield, California, Earthquake Prediction Scenarios and Response Plans.* USGS OFR 87-192, 1987.
- Southern San Andreas Working Group, *Short-Term Earthquake Hazard Assessment for the San Andreas Fault in Southern California*, USGS OFR 91-32, 1991.

Level *	Probability of M>7.5 earthquake in next 72 hours	# instances	USGS action
D	0.1% to 1%	many	Notify scientists involved in data collection and OES Ontario office
C	1% to 5%	~ 10	As for level D, and also notify Comm. Officer of OES in Sacranmento, and OEVE chief.
B	5% to 25%	2	As for levels C and D, and also notify USGS Director, and CDMG State Geologist, and start intensive monitoring.

* SSAWG estimated that the highest probabilities attainable for the southern SAF are ~10-20%, and A-level alerts (P > 25%) are therefore not possible with current knowledge.

CEPEC Statement on 2009 Bombay Beach Sequence

March 24, 2009



At the request of the California Emergency Management Agency, the California Earthquake Prediction Evaluation Council (CEPEC) met by teleconference at 8:30 A. M. (PDT) today, March 24, 2009, to discuss and evaluate this sequence. The close proximity of the earthquakes to the San Andreas increases the concern that these earthquakes could trigger a large earthquake (M7.0 +) on the San Andreas itself. A major earthquake on this southern portion of the San Andreas Fault has not occurred in over 300 years, so the probability of a large earthquake is thought by seismologists to be higher than on portions of the fault that have ruptured more recently (e.g. in 1857 and 1906).

CEPEC believes that that stresses associated with this earthquake swarm may increase the probability of a major earthquake on the San Andreas Fault to values between 1 to 5 percent over the next several days. This is based on methodology developed for assessing foreshocks on the San Andreas Fault. This potential will rapidly diminish over this time period.

Operational Forecasting in California

- **Earthquake forecasting in a "low-probability environment" is already operational in California, and the dissemination of forecasting products is becoming more automated**
  - Level-A probability threshold of 25% has never been reached
  - Level-B threshold of 5-25% has been exceeded only twice (Joshua Tree and Parkfield)
- **However, several deficiencies deserve immediate attention:**
  - CEPEC has generally relied on generic short-term earthquake probabilities or *ad hoc* estimates calculated informally, rather than probabilities based on operationally qualified, regularly updated seismicity forecasting systems
  - Procedures are unwieldy, requiring the scheduling of meetings or telecons, which lead to delayed and inconsistent alert actions
  - How the alerts are used is quite variable, depending on decisions at different levels of government and among the public

ICEF Findings & Recommendations

- Criteria for operational fitness
  - Quality of the forecast
    - Reliability and skill
    - Retrospective and prospective testing (CSEP)
  - Consistency among forecasts
    - Short-term vs. long-term models; California vs. national
    - Integrated development (e.g., UCERF3)
  - Value of the forecast to users
    - Economic cost/benefit analysis; psychological value
    - Pre-set action thresholds
    - Transparent messaging system; public education

ICEF Findings & Recommendations

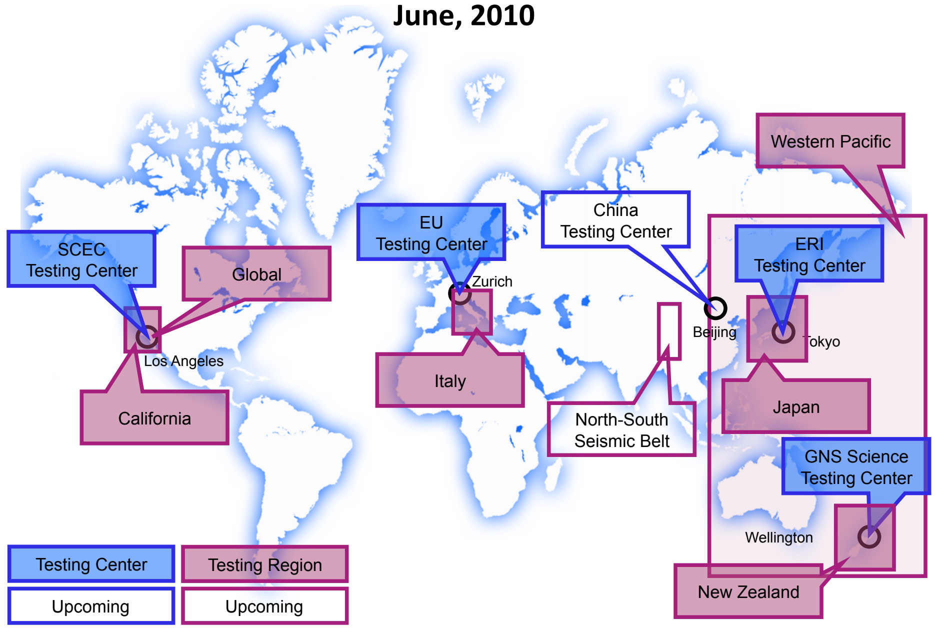
- **Validation of Earthquake Forecasting Methods**
  - **Forecasting methods considered for operational purposes should demonstrate reliability and skill with respect to established reference forecasts, such as long-term, time-independent models.**

  Recommendations:

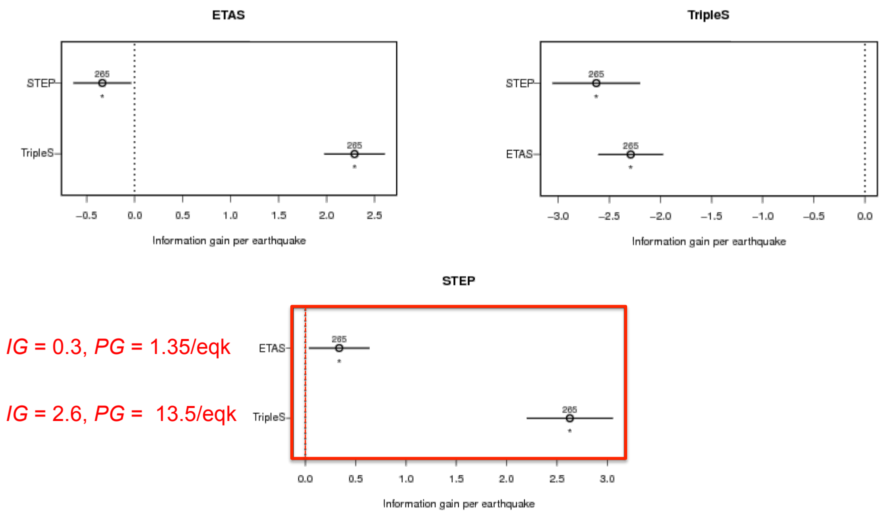
  - ***Forecasting methods intended for operational use should be scientifically tested against the available data for reliability and skill, both retrospectively and prospectively.***
  - ***All operational models should be under continuous prospective testing.***
  - ***CSEP should be used as the infrastructure for verifying the forecasting models for Italy.***

CSEP Testing Regions & Testing Centers

June, 2010



CSEP Testing of Short-Term Models in CA Natural Lab
(Rhoades T-test & W-test)



ICEF Findings & Recommendations

- **Utilization of Earthquake Forecasts**
  - **An outstanding challenge is short-term decision-making in a "low-probability environment."**

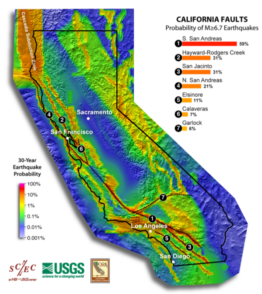
    Recommendation:* *Quantitative and transparent protocols should be established for decision-making that include mitigation actions with different impacts that would be implemented if certain thresholds in earthquake probability are exceeded.

  - **Providing probabilistic forecasts to the public is an important operational capability.**

    Recommendation:* *DPC should continuously inform the public about the seismic situation in Italy based on probabilistic forecasting, in accordance with social-science principles for effective public communication and in concert with partner organizations.

Working Group on California Earthquake Probabilities (2012)

Uniform California Earthquake Rupture Forecast (UCERF3)



- **UCERF3 will be a candidate for operational forecasting**
  - **Will incorporate short-term triggering and clustering**
  - **Delivery date: 30 June 2012**
- ***How should it be tested?***
- ***How should time dependence be portrayed to the public?***

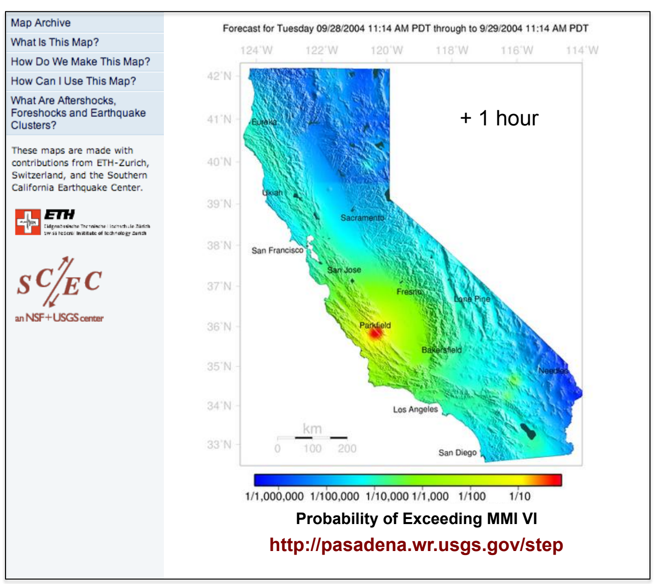
Here… | **… here…** | **… or here?**

Earthquake Rupture Forecast → Attenuation Relationship → Shaking Intensity → Loss

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

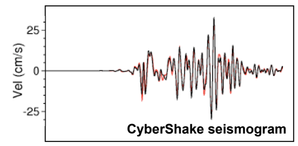
Hazard | **Risk**

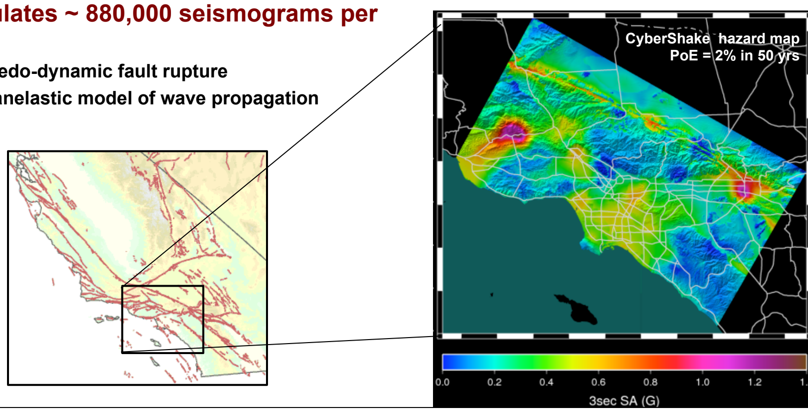
STEP Map for 2004 Parkfield Earthquake



CyberShake 1.0 Hazard Model
(225 sites in Los Angeles region, f < 0.5 Hz)

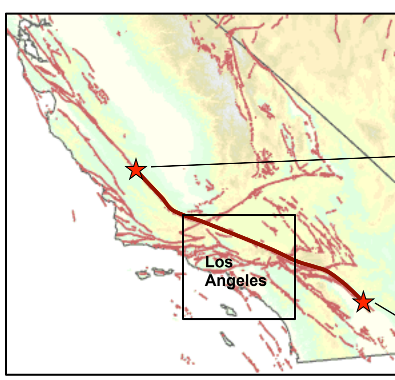
- **Uses an extended earthquake rupture forecast**
  - Source area probabilities
  - Hypocenter distributions (conditional)
  - Slip variations (conditional)
- **Calculates ~ 880,000 seismograms per site**
  - Psuedo-dynamic fault rupture
  - 3D anelastic model of wave propagation

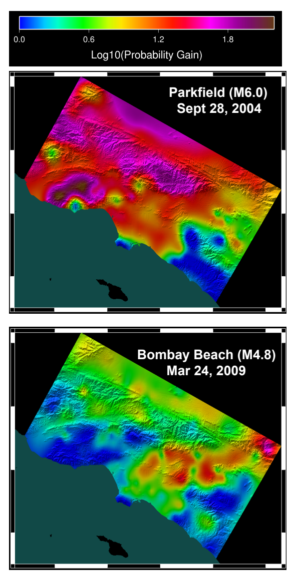




SOUTHERN CALIFORNIA EARTHQUAKE CENTER
SCEC

CyberShake as a Platform for Short-Term Earthquake Forecasting





- Compute probability gain from Agnew & Jones (1991) model. Example: $G = 1000$ for $R \leq 10$ km
- Apply probability gain to CyberShake ruptures and re-compute ground motion probabilities for short interval following events. Example: 1 day

Conclusions

- **Current short-term forecasting methodologies can provide nominal (unvalidated) probability gains up to 100-1000**
  - Issue: unification of methodologies across temporal and spatial scales
- **Governments should develop and maintain an open source of authoritative, scientific information about the short-term probabilities of future earthquakes**
    - keep the population aware of the current state of hazard
    - decrease the impact of ungrounded information
    - improve preparedness
  - Issue: decision-making in a low-probability environment
- **Operational forecasting procedures should be qualified for usage according to standards for "operational fitness"**
  - Quality: correspondence between the forecasts and actual earthquake behavior
  - Consistency: compatibility of methods at different spatial or temporal scales
  - Value: realizable benefits relative to costs incurred
- **All operational forecasting models should be under continuous prospective testing in CSEP**
  - Issue: evaluation of operational forecasts in terms of ground motions

FY11 Budget proposal

- USGS proposes to expand the partnership with the Southern California Earthquake Center (SCEC), a university and government consortium with core funding jointly from USGS and the National Science Foundation, to prototype "operational earthquake forecasting", using California as the testbed. This project will seek knowledge about what information can be derived from observations before an earthquake and how this knowledge can be used to reduce seismic risk to communities, prepare them for earthquake disasters, and enhance their resiliency to seismic damage. This will include testing and validation of models and a focus on the San Andreas fault. Products will be forecasts of earthquake risk in California on timescales from hours to centuries. Primary partners are the California Emergency Management Agency and SCEC. USGS will work with the State of California to determine the best approach for distribution of these forecasts.

Operational Earthquake Forecasting FY11 Budget Proposal

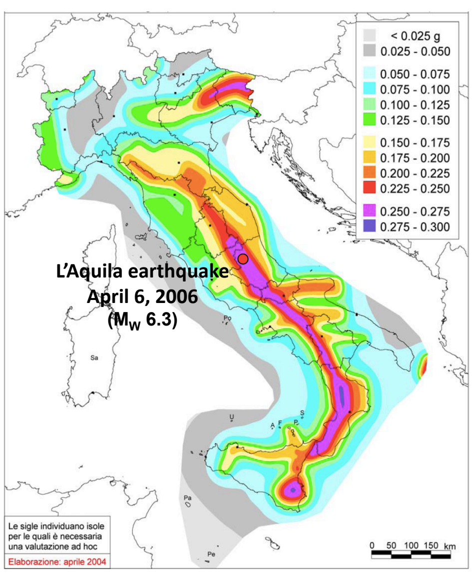
- **Products will be forecasts of earthquake risk in California on timescales from hours to centuries**
- **This will include testing and validation of models and a focus on the San Andreas fault**
- **Primary partners are the California Emergency Management Agency and SCEC.**
- **USGS will work with the State of California to determine the best approach for distribution of these forecasts**

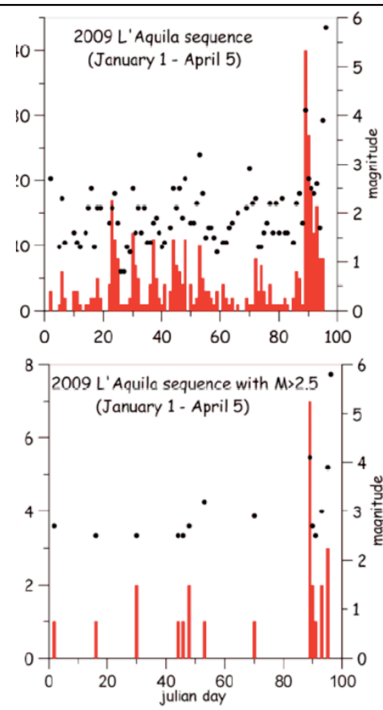
Broad outline

- **Partner with SCEC, but USGS issues warnings**
- **Implement existing technologies**
- **Develop user friendly products with our partners**
- **Develop new approaches**
- **Test, test, and test**

End

2009 L'Aquila Earthquake Sequence





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

Members:

T. H. Jordan, Chair, USA

Y.-T. Chen, China

P. Gasparini, Secretary, Italy

R. Madariaga, France

I. Main, United Kingdom

W. Marzocchi, Rome, Italy

G. Papadopoulos, Greece

G. Sobolev, Russia

K. Yamaoka, Japan

J. Zschau, Germany

ICEF Findings & Recommendations

- Deterministic Earthquake Prediction
  - No method for short-term prediction of large earthquakes has been demonstrated to be both reliable and skillful.
  - Search for diagnostic precursors has not yet produced a successful short-term prediction scheme, but there are promising areas of research (e.g., subseismic & infraseismic phenomena).

    Recommendation: ***A basic research program focused on the scientific understanding of earthquakes and earthquake predictability should be part of a balanced national program to develop operational forecasting.***
- Probabilistic Earthquake Forecasting
  - Appropriate models can convey information about future earthquake occurrence on time scales ranging from long term (years to decades) to short term (months or less)

    Recommendation: ***DPC should deploy the infrastructure and expertise needed to utilize probabilistic information for operational purposes.***

ICEF Findings & Recommendations

- **Long-Term Forecasting Models**
  - **Currently the most important forecasting tools for civil protection against earthquake damage.**

    ***Recommendation:* DPC should continue its directed research program on development of time-independent and time-dependent forecasting models with the objective of improving long-term seismic hazard maps.**
- **Short-Term Forecasting Models**
  - **Properly applied, short-term aftershock forecasting models have operational utility.**

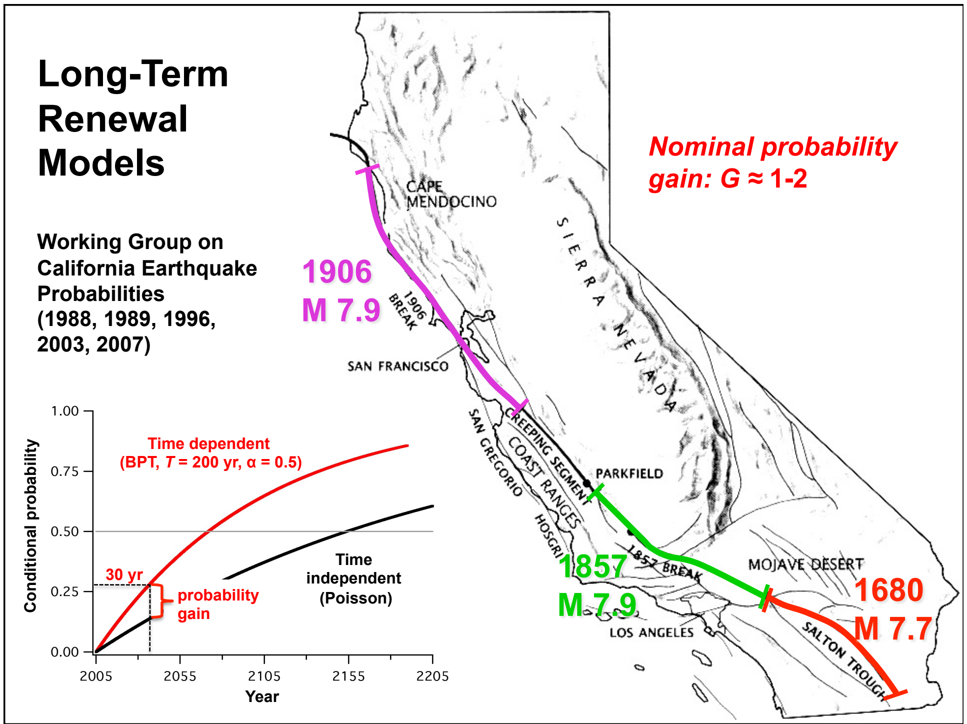
    ***Recommendation:* DPC should emphasize the deployment of an operational capability for forecasting aftershocks.**
  - **Models of earthquake triggering and clustering used in aftershock forecasting can be more generally applied to short-term earthquake forecasting.**

    ***Recommendation:* DPC should support development of earthquake forecasting methods based on seismicity changes to quantify short-term probability variations.**

Long-Term Renewal Models

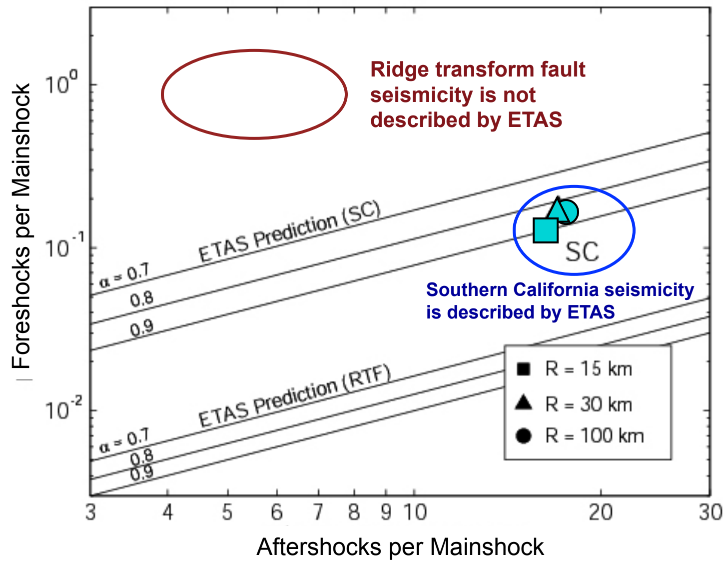
Working Group on California Earthquake Probabilities (1988, 1989, 1996, 2003, 2007)

Nominal probability gain: G ≈ 1-2

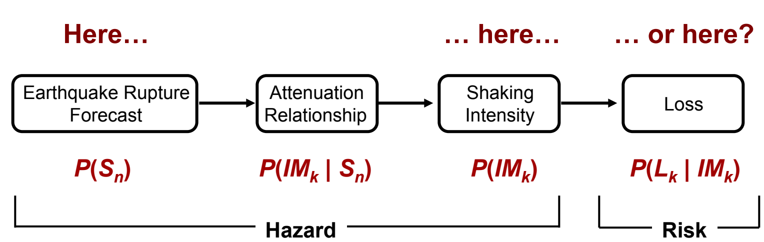


Non-ETAS Behavior of Mid-Ocean Ridge Transform Faults

(McGuire, Boettcher & Jordan, 2005)



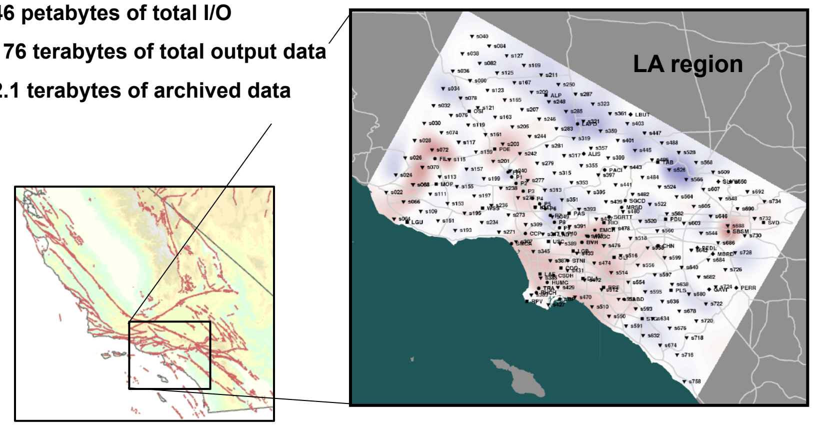
How Should the Time-Dependence of Risk be Portrayed to the Public?



Probabilistic Seismic Hazard and Risk Analysis

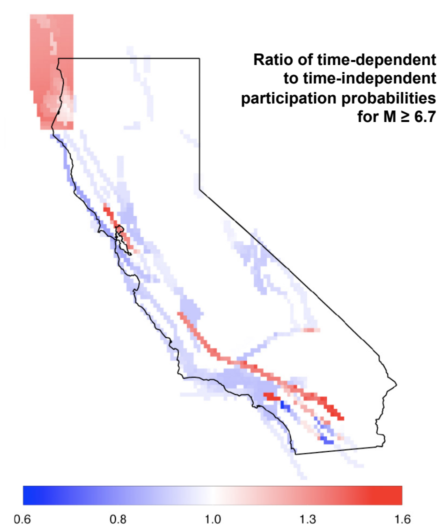
Physics-Based PSHA: CyberShake Platform

- **CyberShake 1.0 computation (225 sites in LA region, f < 0.5 Hz)**
  - **440,000 simulations per site**
  - **50-day run on *Range*r (5.3 million hrs, 4,400 cores)**
  - **189 million jobs**
  - **46 petabytes of total I/O**
  - **176 terabytes of total output data**
  - **2.1 terabytes of archived data**



Working Group on California Earthquake Probabilities (2007)

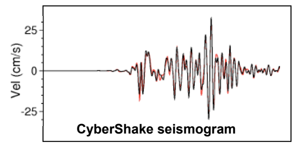
Uniform California Earthquake Rupture Forecast (UCERF2)

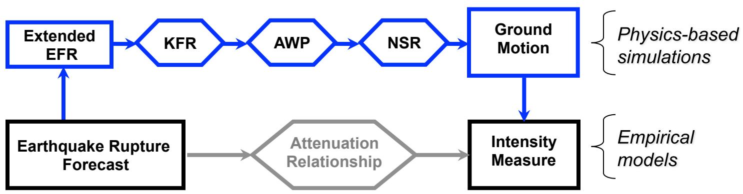


How different is the time-dependent UCERF2 model from the time-independent NSHMP model?

Physics-Based PSHA: CyberShake Platform

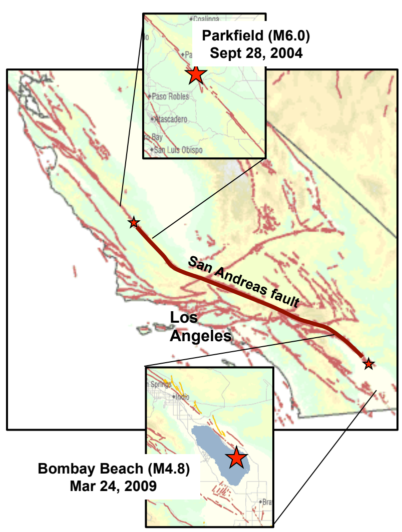
- **CyberShake uses an *extended* earthquake rupture forecast**
  - Source area probabilities
  - Hypocenter distributions
  - Slip variations
- **Pre-calculates *seismograms* for ~440,000 events**
  - Psuedo-dynamic fault rupture
  - 3D anelastic model of wave propagation
  - Nonlinear site response (not yet implemented)





KFR = kinematic fault rupture model
AWP = anelastic wave propagation model
NSR = nonlinear site response

CyberShake as a Platform for Operational Earthquake Forecasting

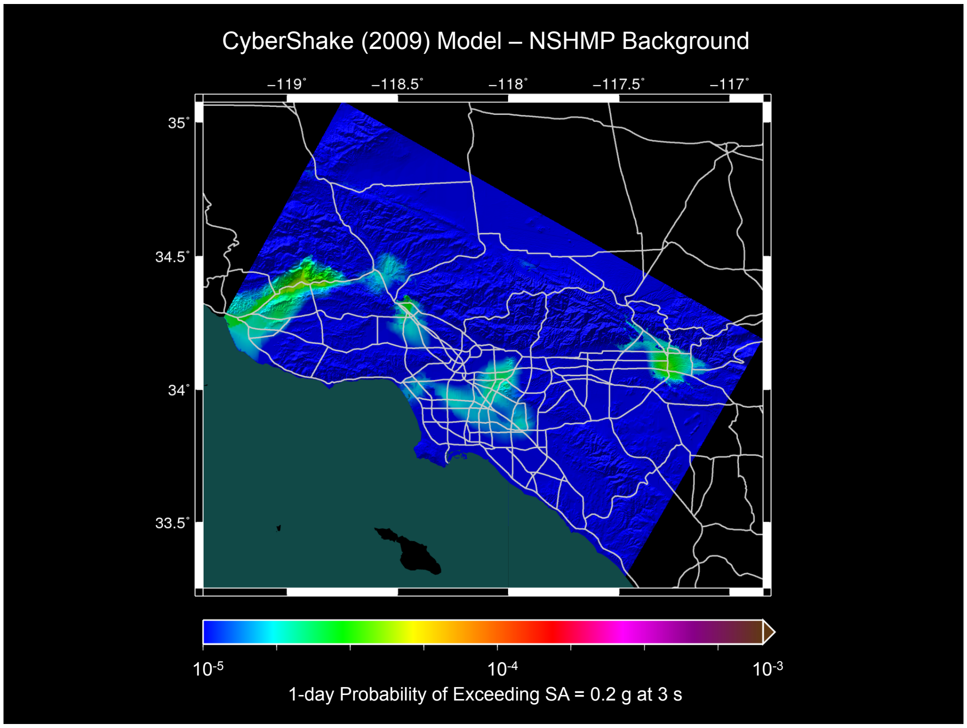


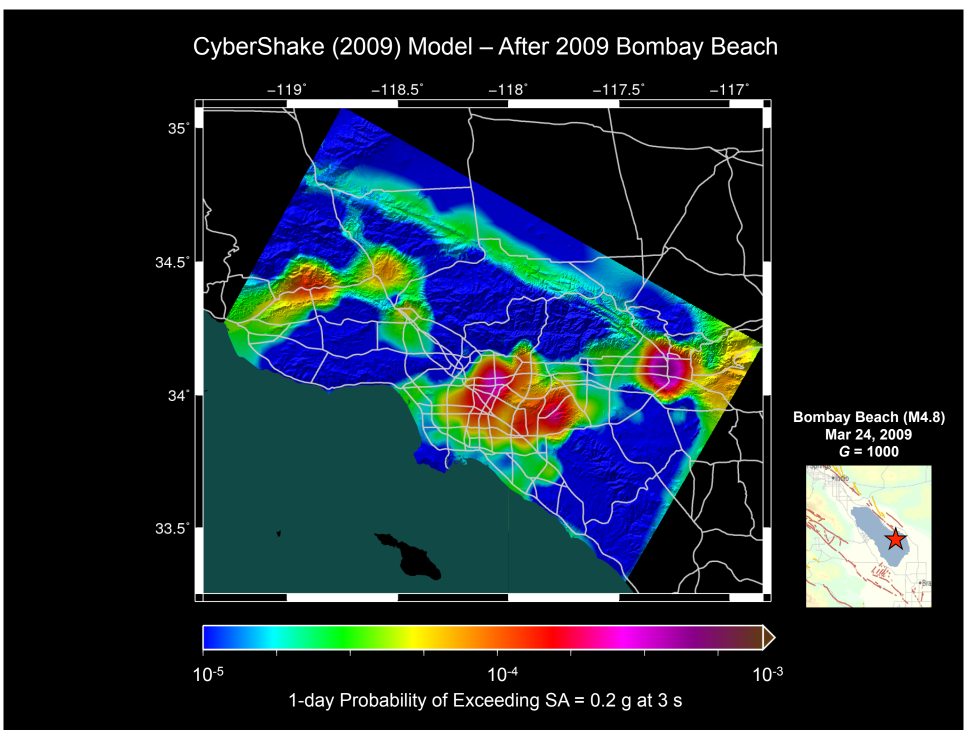
- **Compute probability gain associated with recent seismic activity**

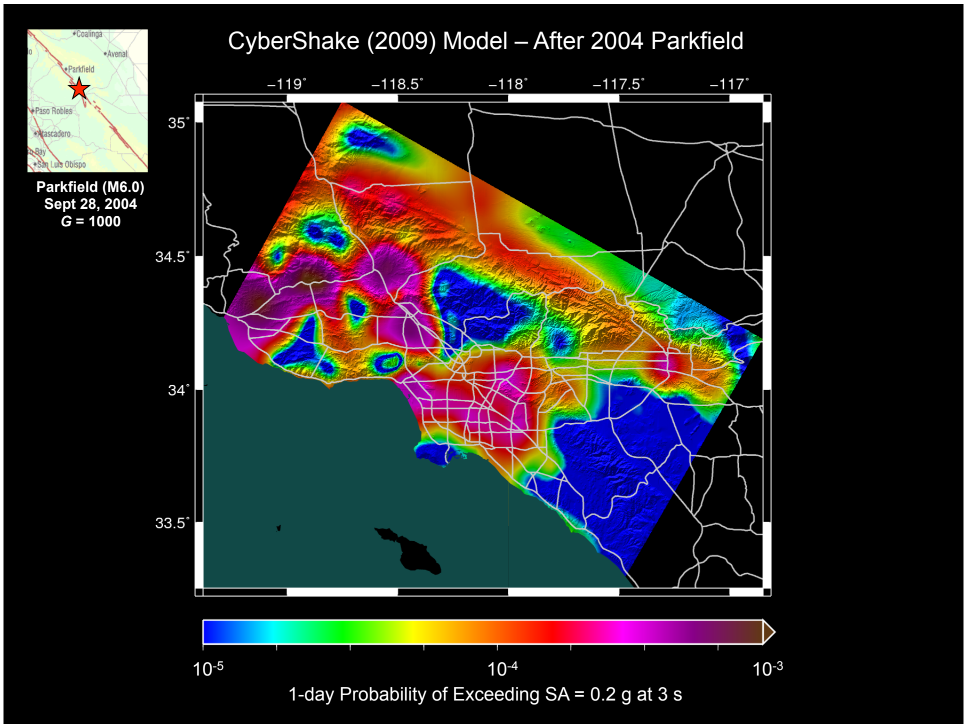
  Example: Agnew-Jones model
- **Apply probability gains to CyberShake ruptures with hypocenters near recent events**

  Example: *G* = 1000 for *R* ≤ 10 km
- **Re-compute CyberShake ground motion probabilities for short interval following events**

  Example: 1-day probabilities


CyberShake (2009) Model – NSHMP Background
–119˚
–118.5˚
–118˚
–117.5˚
–117˚
35˚
34.5˚
34˚
33.5˚
10-5
10-4
10-3
1-day Probability of Exceeding SA = 0.2 g at 3 s


CyberShake (2009) Model – After 2009 Bombay Beach
–119˚
–118.5˚
–118˚
–117.5˚
–117˚
35˚
34.5˚
34˚
33.5˚
Bombay Beach (M4.8)
Mar 24, 2009
G = 1000
10-5
10-4
10-3
1-day Probability of Exceeding SA = 0.2 g at 3 s


CyberShake (2009) Model – After 2004 Parkfield
Coalinga
Avenal
Parkfield
Paso Robles
Atascadero
San Luis Obispo
Parkfield (M6.0)
Sept 28, 2004
G = 1000
−119˚
−118.5˚
−118˚
−117.5˚
−117˚
35˚
34.5˚
34˚
33.5˚
10-5
10-4
10-3
1-day Probability of Exceeding SA = 0.2 g at 3 s