Status and Requirements of Operational Earthquake Forecasting: An ICEF Perspective

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CSEP Workshop on Testing External Forecasts and Predictions

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Operational Earthquake Forecasting

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

- **No reliable method yet exists for predicting large earthquakes with high short-term probabilities**
  - **The search for diagnostic precursors has not yet produced a reliable scheme for the short-term prediction of large earthquakes**
- **But seismic hazards do 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**
- **Short-term statistical models can be used to estimate changes in the probabilities of future earthquakes**
  - **Provide the highest validated information gain per earthquake of any known technique**

International Commission on Earthquake Forecasting for Civil Protection (ICEF)

- **Charged on 11 May 2009 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 released by DPC (Oct 2009) and endorsed by IASPEI (July 2011)**
  - **Final report published in *Annals of Geophysics* (Aug 2011)**

http://www.annalsofgeophysics.eu/index.php/annals/article/view/5350

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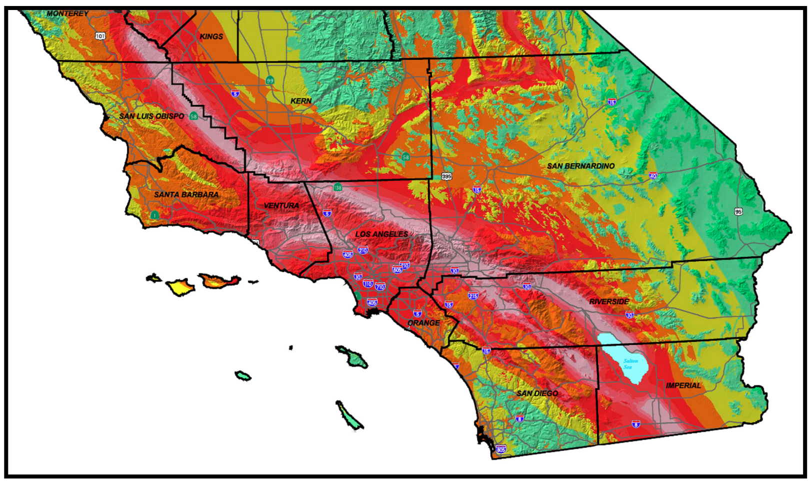
Deterministic Prediction vs. Probabilistic Forecasting

- **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**



Probabilistic Hazard Map for Southern California (NHSMP, 2002)

RTP Alarm for California M ≥ 6.4, 29 Oct 2003 – 5 Sep 2004 (Keilis-Borok et al., 2004)

Deterministic Earthquake Prediction
(a.k.a. "Silver Bullet Approach")

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

Proposed methods include:

- **foreshocks & seismicity patterns**
- **strain-rate acceleration**
- **material property changes**
- **electromagnetic signals**
- **thermal anomalies**
- **hydrologic changes**
- **geochemical signals**
- **animal behavior**

ICEF Finding:

- ***The search for diagnostic precursors has not yet produced a reliable scheme for the short-term prediction of large earthquakes.***

Probabilistic Earthquake Forecasting
(a.k.a. "Brick-by-Brick Approach")

- **Time-independent statistical models**
  - Stationary Poisson process
- **Long-term statistical models**
  - Reid renewal process
- **Short-term statistical models**
  - Omori-Utsu clustering process
- **Physics-based models**
  - Tectonic fault loading, earthquake nucleation, slip-mediated stress transfer, rupture radiation damping

Forecasting Time Scales

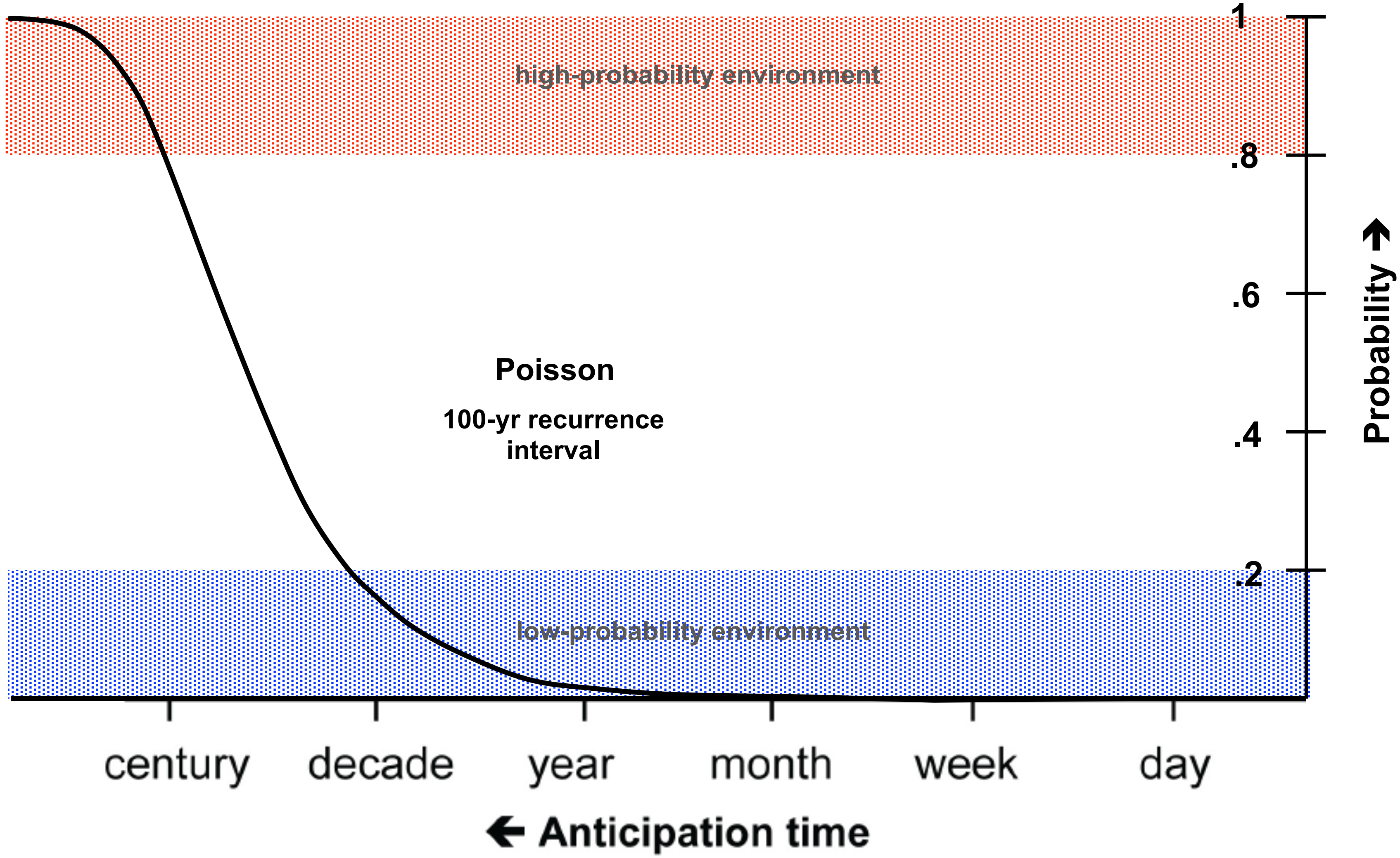
Long-term (centuries to decades)	Medium-term (years to months)	Short-term (weeks to minutes)

Probabilistic Seismic Hazard Analysis (PSHA) ⟷ ***Operational Earthquake Forecasting (OEF)***

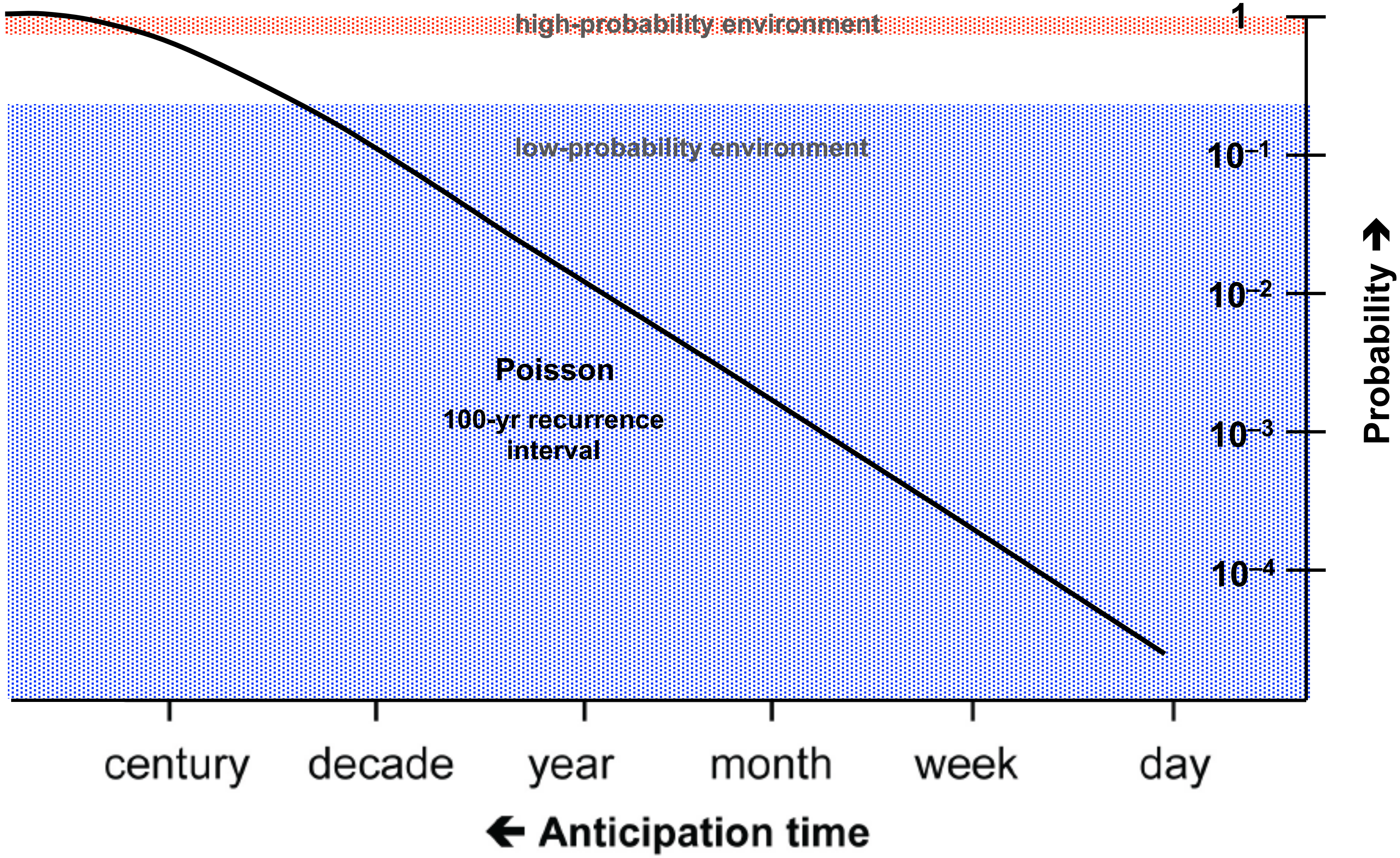
"Seismic Climate Forecasting"

"Seismic Weather Forecasting"

Scales of Seismic Hazard Change



Scales of Seismic Hazard Change



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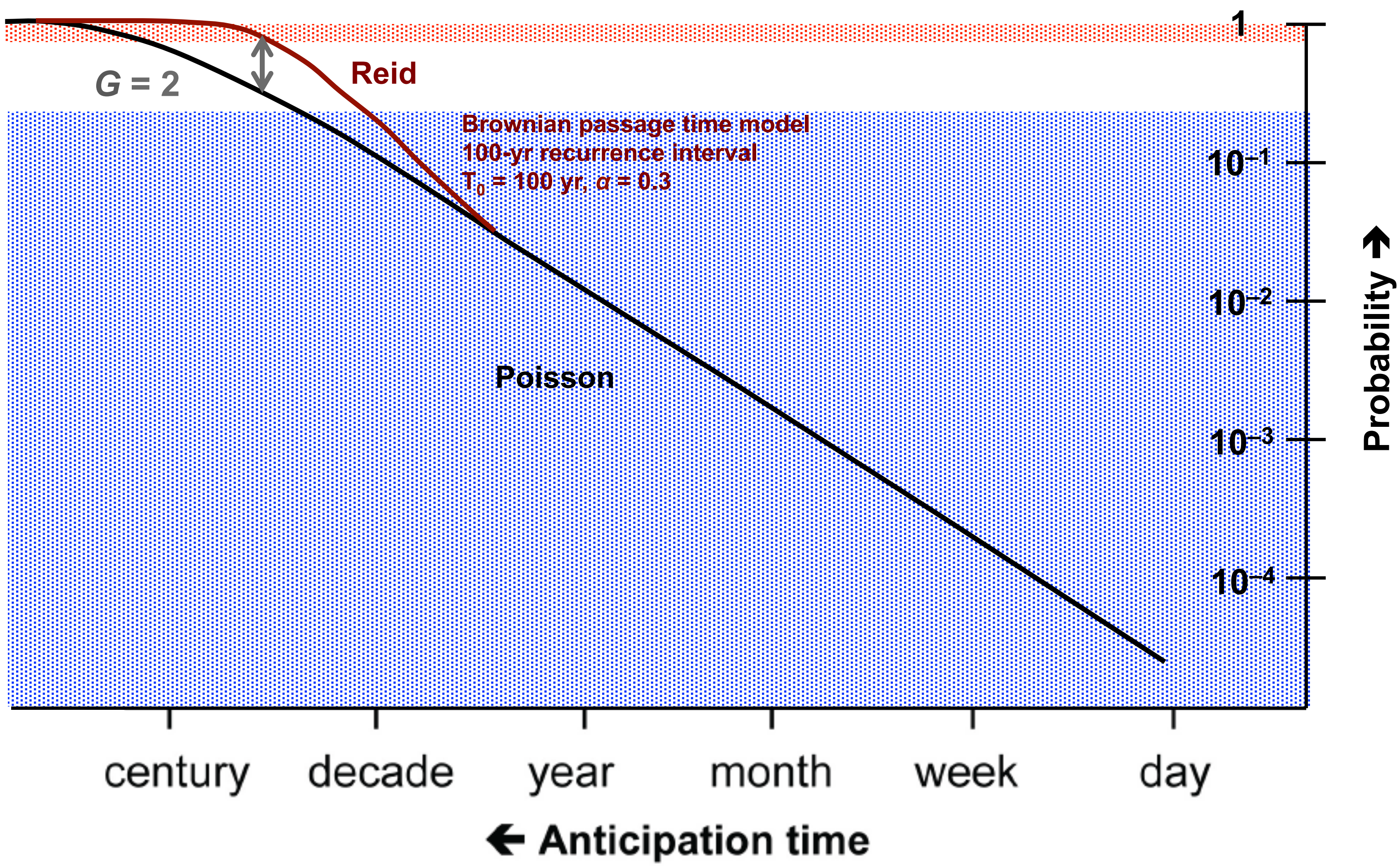
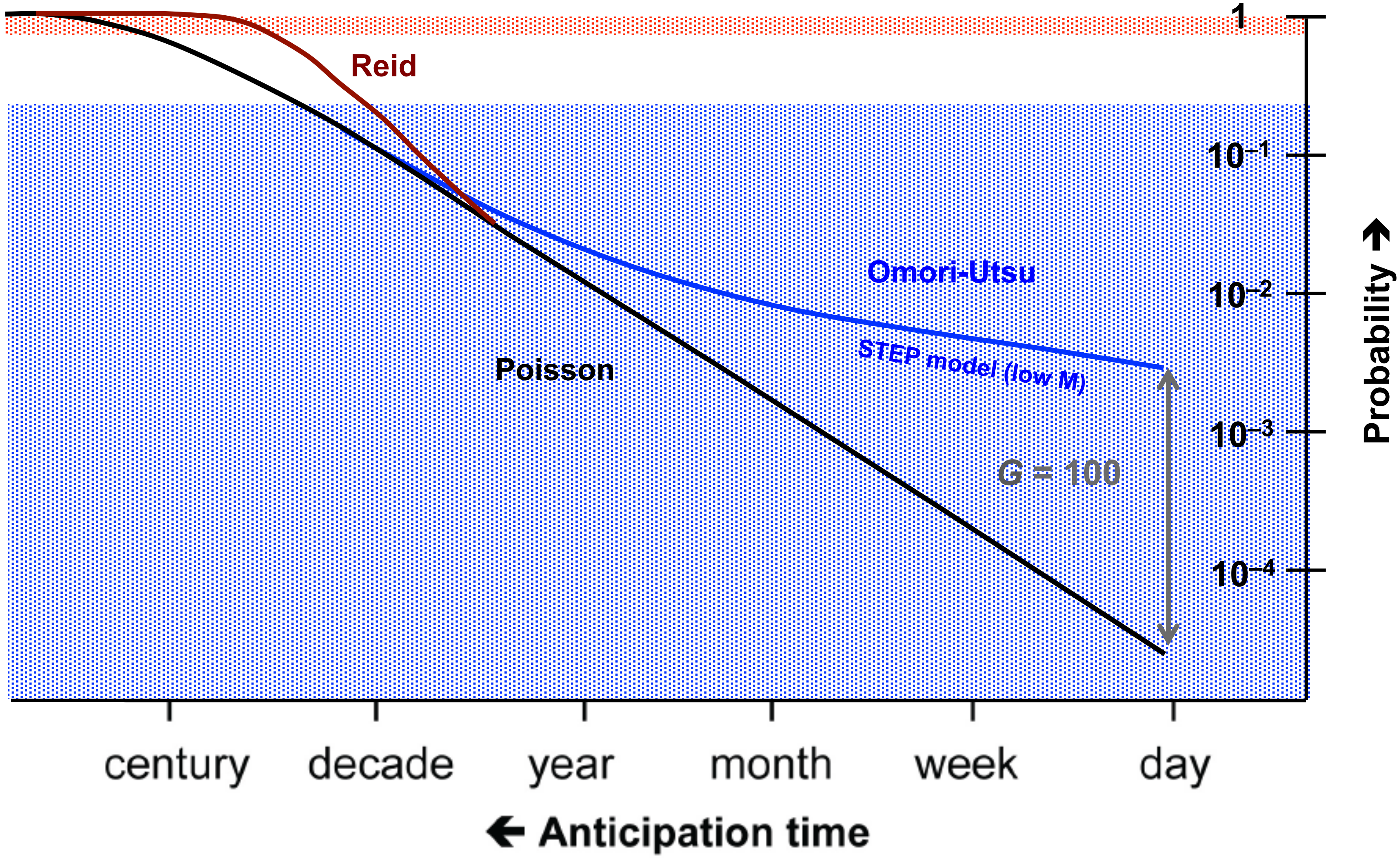
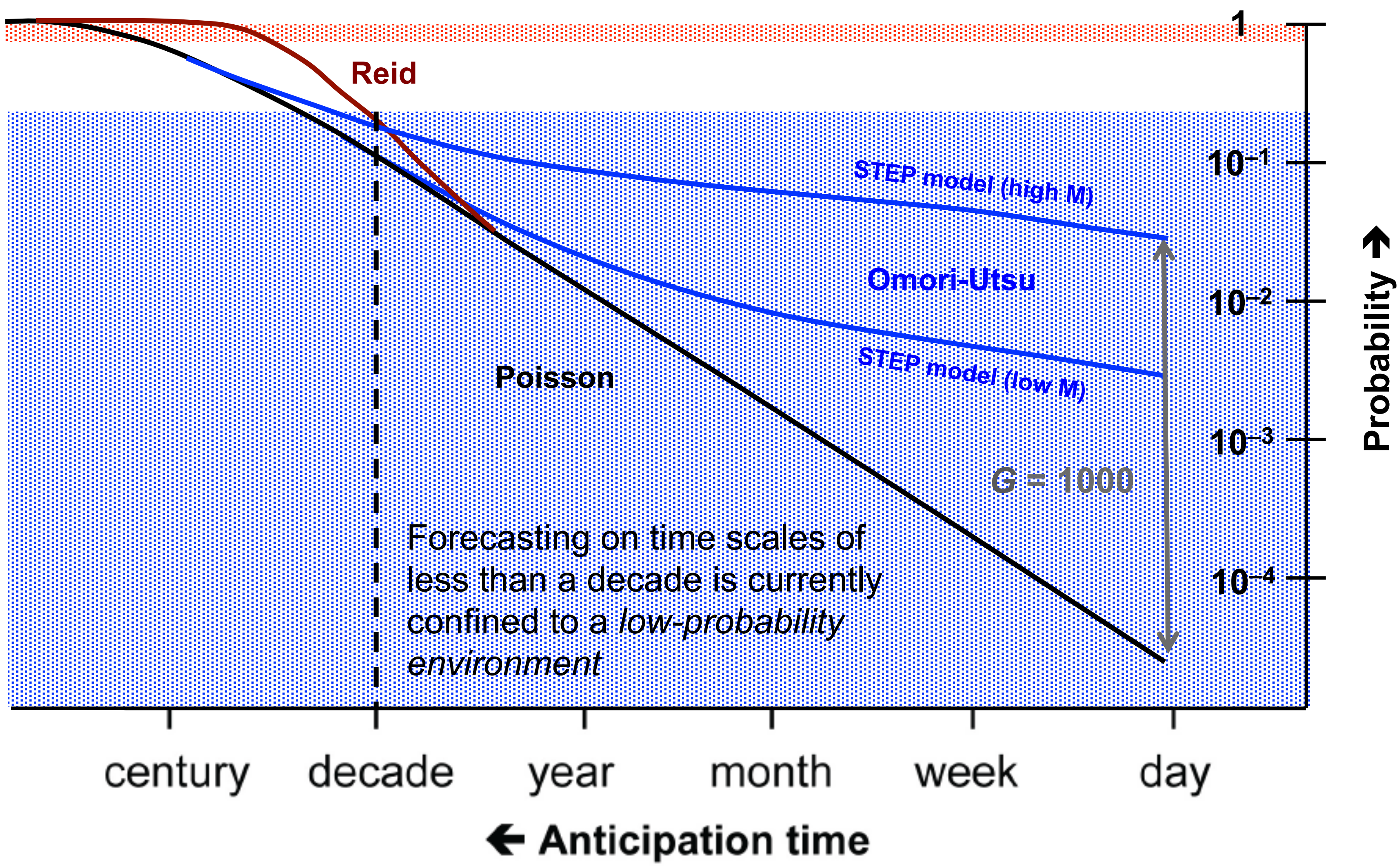


Scales of Seismic Hazard Change



Scales of Seismic Hazard Change



Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties

IPCC Cross-Working Group Meeting on Consistent Treatment of Uncertainties (July, 2010)

Table 1. Likelihood Scale

Term	Likelihood of the Outcome
Virtually certain	99-100% probability
Very likely	90-100% probability
Likely	66-100% probability
About as likely as not	33 to 66% probability
Unlikely	0-33% probability
Very unlikely	0-10% probability
Exceptionally unlikely	0-1% probability

Earthquake forecasting involves very unlikely events!

The OEF Deployment Problem

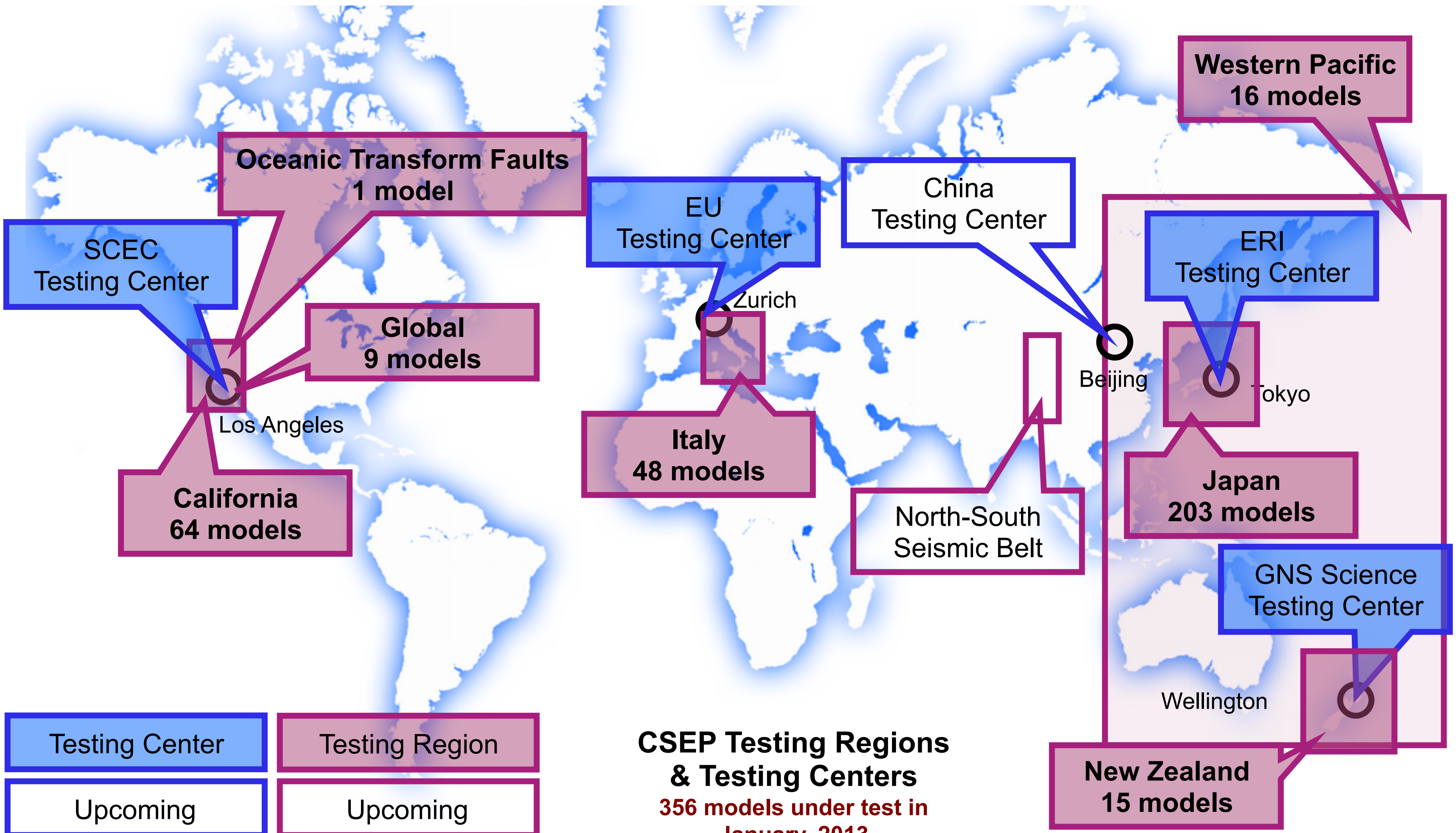
- While the probability gains of short-term, seismicity-based forecasts can be high (> 1000 relative to long-term forecasts), the probabilities of large earthquakes typically remain low (< 1% per day)
  - Preparedness actions appropriate in such high-gain, low-probability situations have not been systematically investigated
- Standardization of OEF methods and protocols is in a nascent stage of development
  - Incremental benefits of OEF for civil protection (e.g., relative to long-term seismic hazard analysis) have not been convincingly demonstrated
- Under these circumstances, the responsible governmental agencies have been cautious in deploying OEF capabilities
  - The ICEF survey of China, Greece, Italy, Japan, Russia, and United States showed that public dissemination of forecasting information is sporadic
  - None of these high-risk countries have fully deployed OEF systems

The OEF Validation Problem

- **Scientists should take caution from the many episodes when prediction methods thought to be reliable from limited data were later shown to be completely unreliable**
  - They should clearly distinguish forecasting methods suggested by exploratory research from those validated by prospective testing
  - They should refrain from announcing unreliable predictions in public forums
- **Forecasting methods considered for operational use should demonstrate reliability and skill, both retrospectively and prospectively, with respect to established reference forecasts**
  - in particular, with respect to long-term, time-independent models
- **Blind, prospective testing is the gold standard for forecast validation**
  - All operational models should be under continuous prospective testing
  - The Collaboratory for the Study of Earthquake Predictability (CSEP) provides an appropriate infrastructure for blind, prospective testing

Collaboratory for the Study of Earthquake Predictability

Infrastructure for automated, blind, prospective testing of forecasting models in a variety of tectonic environments and on a global scale



CSEP Testing Regions & Testing Centers

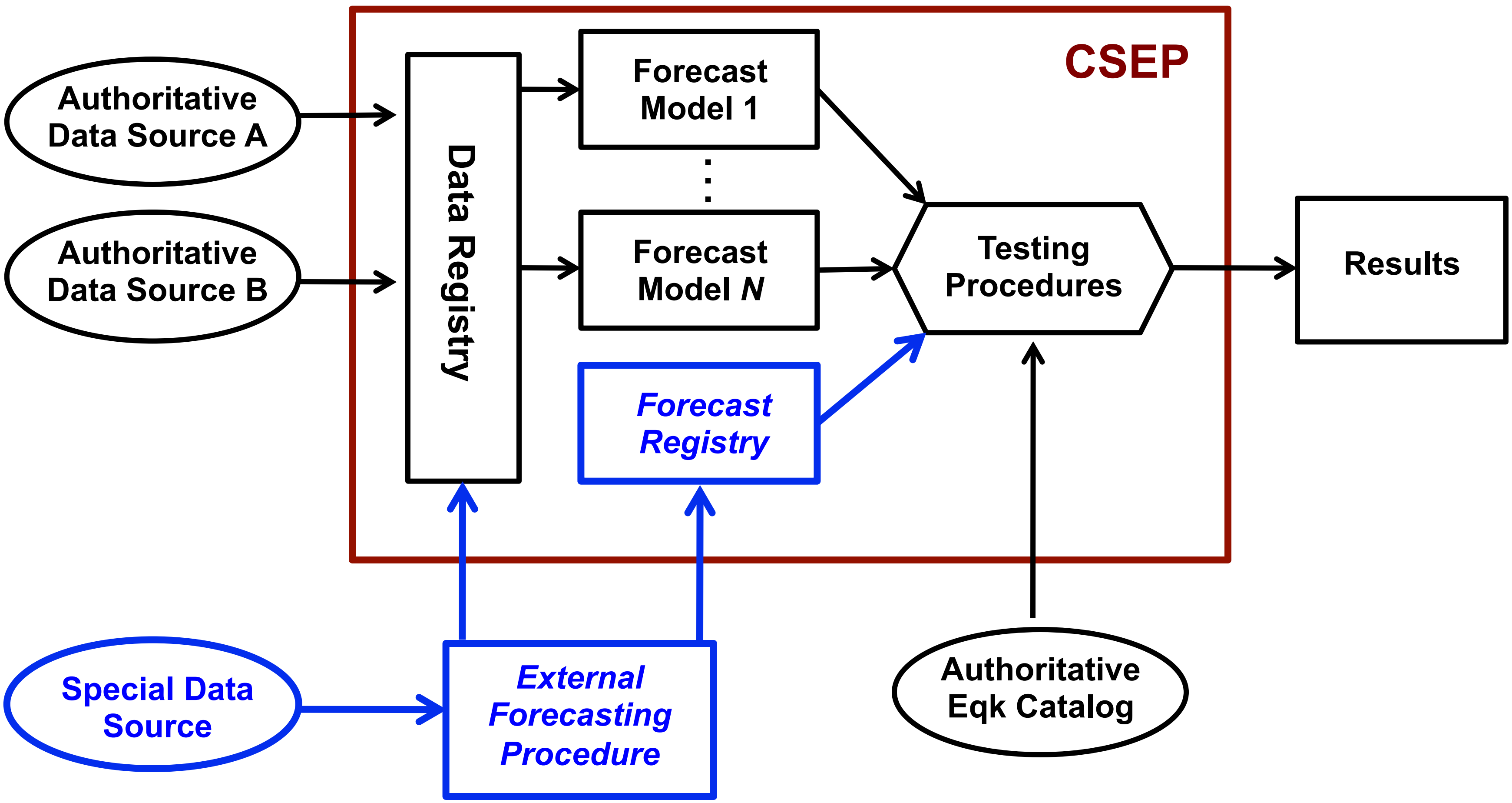
356 models under test in January, 2013

Five Phases of Forecast Development

1. Exploratory research on earthquake precursors and the physical and statistical aspects of earthquake predictability
2. Casting of testable precursory hypotheses and forecasting models
3. Retrospective testing to calibrate forecasting methods
4. Prospective testing of forecasting methods to assess reliability, skill, and information gain
5. Incorporation of significant information gain into OEF through ensemble forecasting

CSEP Structure

Accommodation of External Forecasting



ICEF Recommendations for OEF Development

- <u>Deployment of OEF is a requirement, not an option</u>
- Information vacuums spawn informal predictions and misinformation
  - Relying solely on informal communications between scientists and the public invites confusion
- The public expects scientists to forecast natural disasters based on the best evidence and most accurate methods.
  - Any valid information about enhanced seismic risk should be made available and utilized effectively
  - "We can't predict earthquakes" is not an excuse
- Electronic media and social networking have sped up the information cycle and public expectations of transparency
  - OEF systems must integrated into seismic network operations
- Without OEF, individual earthquake scientists are often called upon to advise the public in roles that exceed their civic authority, expertise in risk communication, and situational knowledge

ICEF Recommendations for OEF Development

- **The advisory role of scientists should not be conflated with the responsibilities of decision-makers for public protection**
- **Scientists should not be trapped by a seismic crisis into answering deterministic questions**
  - **For example, will a large earthquake occur or not?**
- **Probabilistic forecasting appropriately separates hazard estimation by scientists from the public protection role of civil authorities**
  - **For most decision-making purposes, probabilistic forecasting provides a more complete description of prospective earthquake information than deterministic prediction**

ICEF Recommendations for OEF Development

- **Public sources of information on short-term probabilities should be authoritative, scientific, open, and timely**
- **Advisories should be based on operationally qualified, regularly updated seismicity forecasting systems**
  - **Information should be made available at regular intervals, during periods of normal seismicity as well as during seismic crises, in order to educate the public and increase awareness of long-term risk**
- **Advisories should be rigorously reviewed and updated by experts in the creation, delivery, and utility of earthquake information**
  - **Quality of all operational models should be evaluated by continuous prospective testing against established long-term forecasts and alternative time-dependent models**
- **Scientists must be prepared to engage the public in the complex issues posed by seismic crises**
  - **Educate them into the conversation and convey the large epistemic uncertainties in OEF**

ICEF Recommendations for OEF Development

- <u>Alert procedures should be standardized to facilitate decisions at different levels of government and among the public</u>
- **Utilization of earthquake forecasts for risk mitigation and earthquake preparedness should comprise two basic components**
  - Scientific advisories expressed in terms of probabilities of threatening events
  - Protocols negotiated with stakeholders that establish how probabilities can be translated into mitigation actions and preparedness
- **Earthquake probability thresholds should be established to guide alert levels based on objective analysis of costs and benefits, as well as the less tangible aspects of value-of-information, such as gains in psychological preparedness and resilience**
- **The principles of effective risk communication established by social science research should be applied to the delivery of seismic hazard information**
  - Consistency from multiple sources is paramount
  - Mutual trust must be established among scientists, civil authorities, and the public through transparent processes

Previous Workshops

- *Remote Sensing Techniques for Improved Earthquake Warning, Monitoring, and Response*
  - held at the Naval Postgraduate School, Monterey CA, on January 25-27, 2011.
- SCEC-NASA Workshop: *Evaluating Ground-Based and Space-Based Methods of Earthquake Forecasting*
  - held at the University of Southern California, Los Angeles CA, on July 26-27, 2011.
- SCEC-CSEP Workshop: Final Evaluation of the Regional Earthquake Likelihood Models (RELM) Experiment and the Future of Earthquake Forecasting
  - held at Rancho Mirage, June 6-7, 2012

End

The OEF Valuation Problem

- **Earthquake forecasts acquire value through their ability to influence decisions made by users seeking to mitigate seismic risk and improve community resilience to earthquake disasters**
  - Societal value of seismic safety measures based on long-term forecasts has been repeatedly demonstrated
  - Potential value of protective actions that might be prompted by short-term forecasts is far less clear
- **Benefits and costs of preparedness actions in high-gain, low-probability situations have not been systematically investigated**
  - Previous work on the public utility of short-term forecasts has anticipated that they would deliver high probabilities of large earthquakes (deterministic prediction)
  - Actions should be formulated by decision-makers in collaboration with seismologists before seismic crises occur

The OEF Valuation Problem

- **Economic valuation is one basis for prioritizing how to allocate the limited resources available for short-term preparedness**
  - **In a low-probability environment, only low-cost actions are justified**

Cost-Benefit Analysis for Binary Decision-Making (e.g., van Stiphout et al., 2010)

Suppose cost of protection against loss L is $C < L$. If the short-term earthquake probability is P, the policy that minimizes the expected expense E:

- Protect if $P > C/L$
- Do not protect if $P < C/L$

Then, $E = \min\{C, PL\}$.

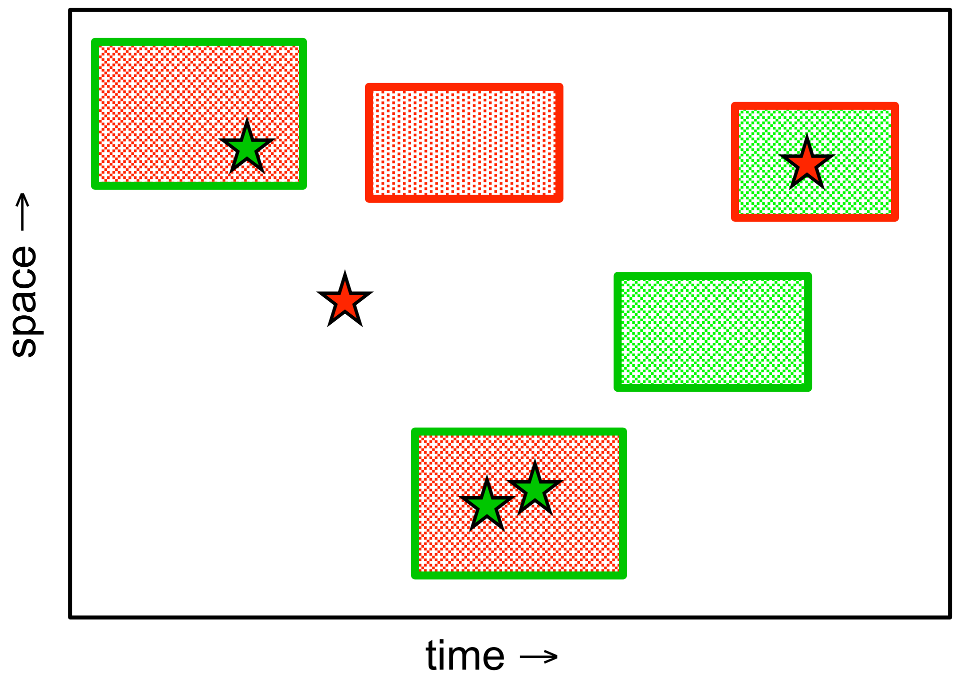
- **However, many factors complicate this rational approach**
  - **Monetary valuation of life, historical structures, etc. is difficult**
  - **Valuation must account for information available in the absence of forecast**
  - **Official actions can incur intangible costs (e.g., loss of credibility) and benefits (e.g., gains in psychological preparedness and resilience)**

The OEF Consistency Problem

- **Spatiotemporal consistency is an important issue for dynamic risk management, which often involves trade-offs among multiple targets and time frames**
  - Spatiotemporal inconsistencies can lead to inconsistencies in public messaging
- **In lieu of physics-based forecasting, consistency must be statistically enforced, which is a challenge because:**
  - Long-term renewal models are less clustered than Poisson
  - Short-term triggering models are more clustered than Poisson
- **Consistency can be lacking if long-term forecasts specify background seismicity rates for the short-term models (e.g., STEP)**
  - Seismicity fluctuations introduced by earthquake triggering can occur on time scales comparable to the recurrence intervals of the largest events
- **Model development needs to be integrated across all time scales of forecast applicability**
  - Approach adopted by WGCEP for development of UCERF3

Three Types of Binary Error in Deterministic (Alarm-Based) Earthquake Prediction

Spacetime Diagram



Contingency Table

		Outcome	
		Event	No Event
Prediction	Alarm	correct alarm	false alarm
	No alarm	failure to predict	correct no-alarm
	Anti-alarm	false anti-alarm	correct anti-alarm

Target Earthquake

Three Interrelated Questions Regarding Earthquake Forecasting

- **What is the societal value of low-probability earthquake forecasting?**
- **What protocols should be used to communicate forecasting information to decision-makers, including the general public?**
- **What are the professional responsibilities of earthquake scientists to inform the public about uncertain knowledge of future earthquakes?**

CSEP Workshop on Testing External Forecasts and Predictions

The goals of this workshop are to:

- ***Assess the needs of the user communities for CSEP-based testing of external forecasting and prediction (EFP) procedures,***
- ***Establish standards for EFP registration and testing within CSEP,***
- ***Identify EFP models that can be deployed as prototypes for CSEP testing***

Operational Forecasting in California

- **In California, OEF is practiced by the California Earthquake Prediction Evaluation Council (CEPEC)**

1991 Notification Protocols

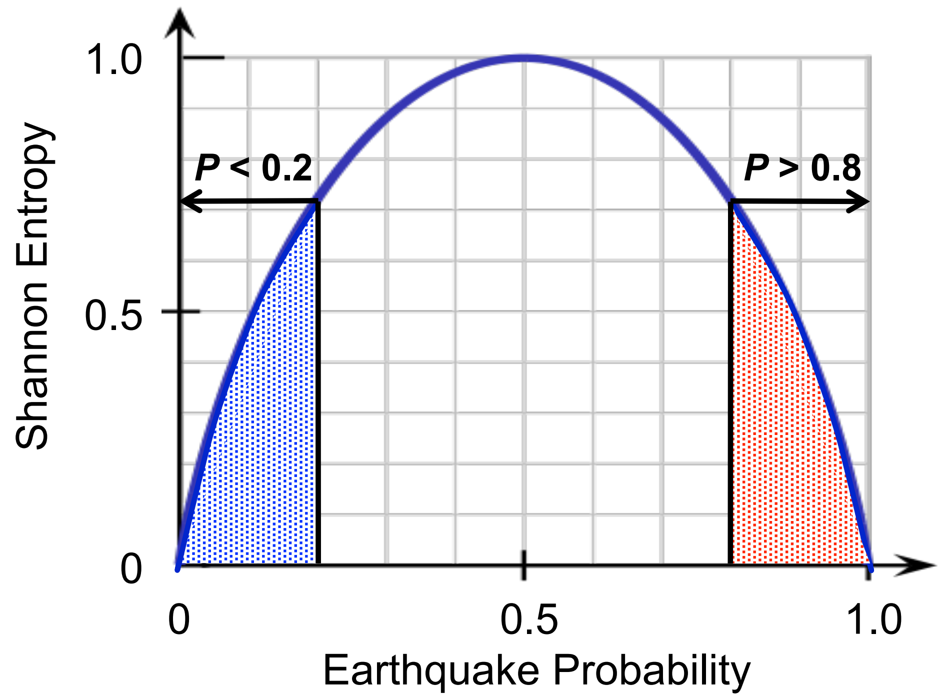
Level	*P* (M ≥ 7.5) in next 3 days	Notification action	Expected frequency	Instances 1992 - 2011*
D	0.1 – 1%	Local USGS & CalEMA offices	6 months	Many
C	1 – 5%	Also USGS OEVE & CalEMA Director	5 years	~10
B	5 – 25%	Also USGS Director & State Geologist; start intensive monitoring	27 years	2
A	> 25%	"Go to war"	Very rare**	0

- **However, procedures are deficient in several respects:**
  - 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

Deterministic Prediction vs. Probabilistic Forecasting

As tools for helping communities prepare for potential earthquake disasters,

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

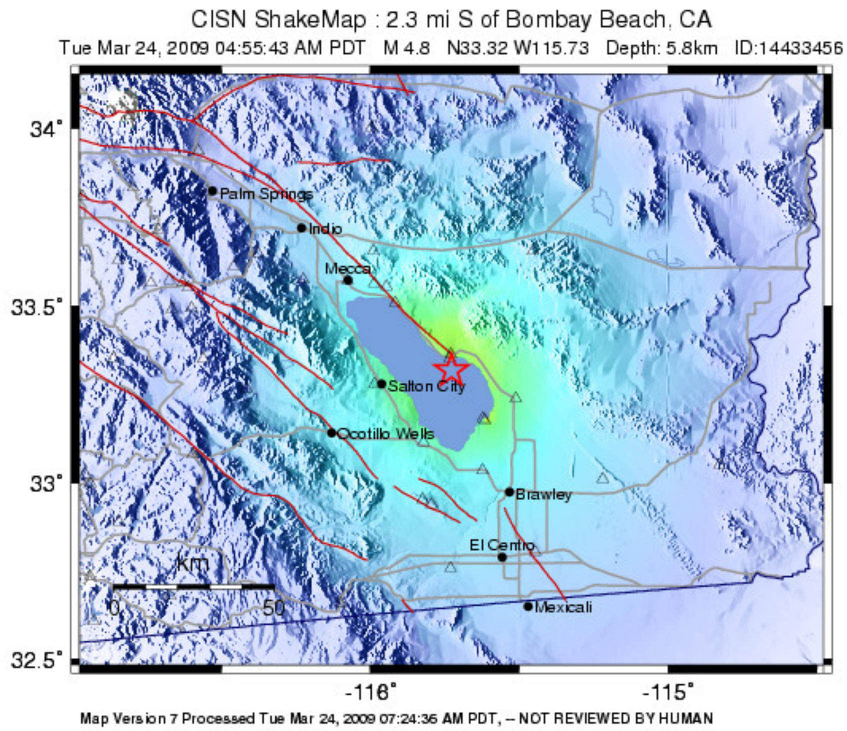


ICEF Findings:

- ***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.***

CEPEC Statement on 2009 Bombay Beach Sequence

March 24, 2009



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

"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…

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 potential will rapidly diminish over this time period."

Owing to a lack of understand of CEPEC procedures and protocols, CalEMA officials (who were recently appointed to their jobs) did not transmit this advisory to local authorities for over 24 hours.