Forecasting and Nowcasting Major Earthquakes

An Automated Cloud-Based Approach

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Chairman, Open Hazards Group

Topics:

Science

Applications

Tohoku, Japan

Earthquake and Tsunami
March 11, 2011

How do we estimate risk from these events?

What does this mean for the insurance industry?

Nowcasting

Forecasting is a probability of future activity in the hazard (earthquake) cycle

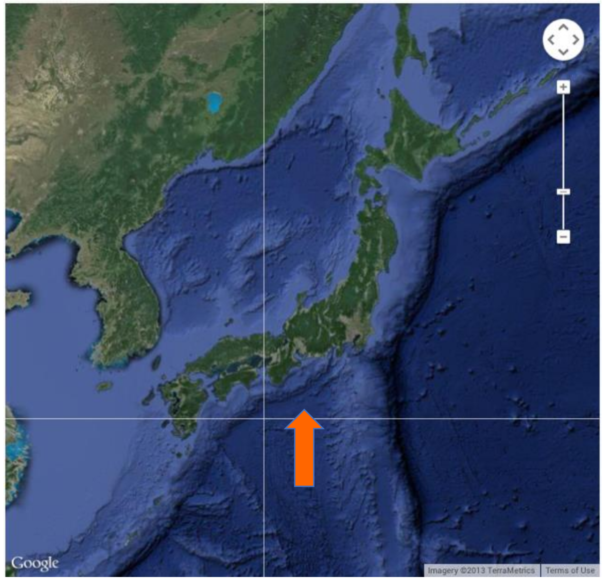
Nowcasting describes the current state of the hazard cycle

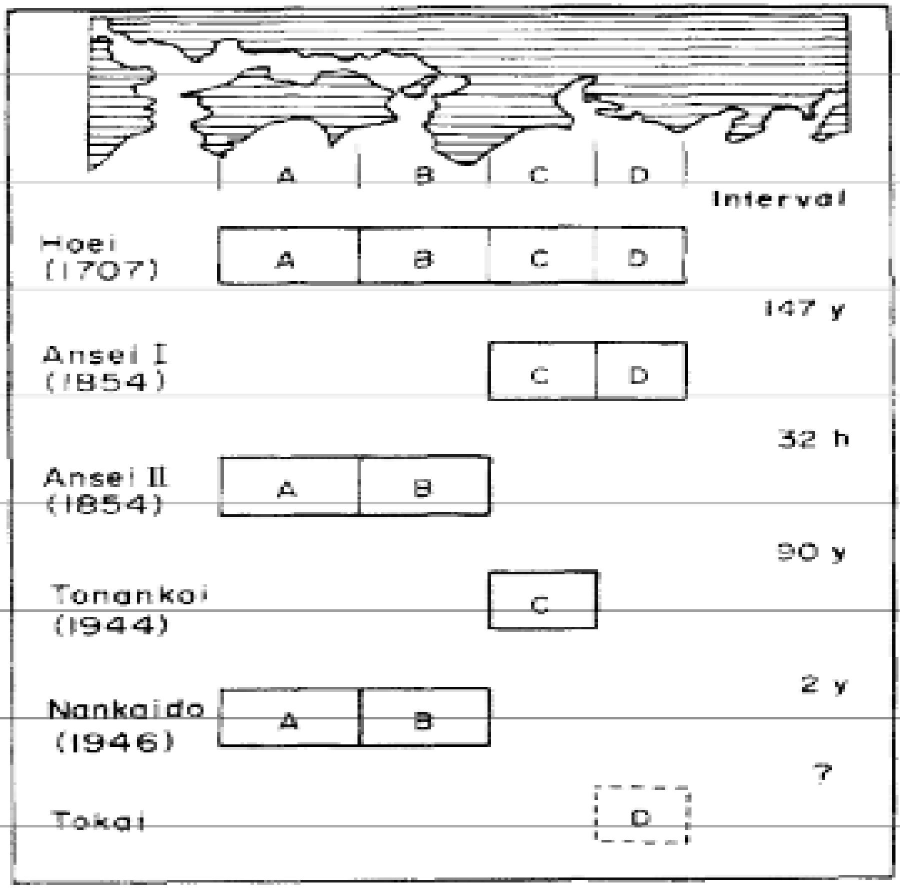
The term “Nowcasting” was first used to describe the current state of the economic/business cycle

Earthquake Cycle Example: Nankai Trench, Japan

M Ando, Tectonophysics, v27, p112 (1975)

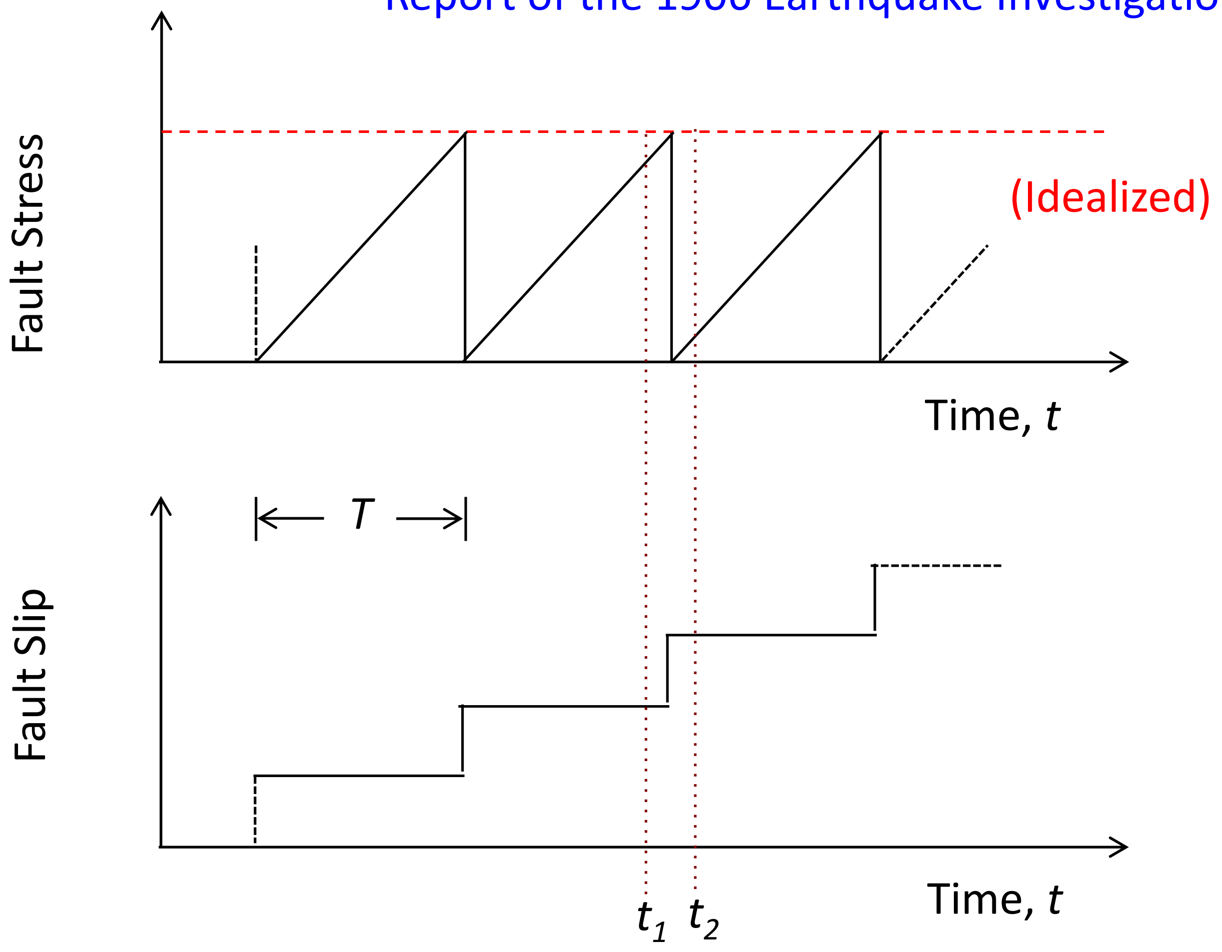
- Data from historic writings in Japan
- The basic idea of the earthquake "cycle" started in Japan using historical data





The Earthquake Cycle Arises from Elastic Rebound

Report of the 1906 Earthquake Investigation (1910)

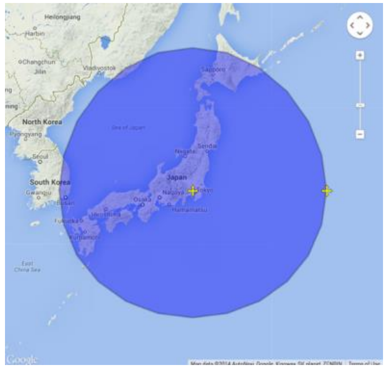


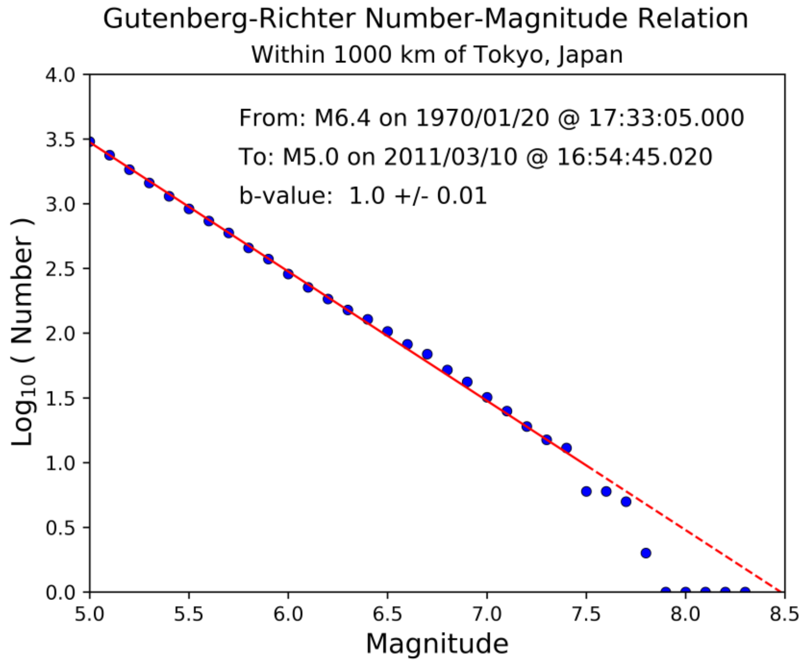
Harry Fielding Reid (1859-1944)

But: How do we measure the time-dependent state of stress?

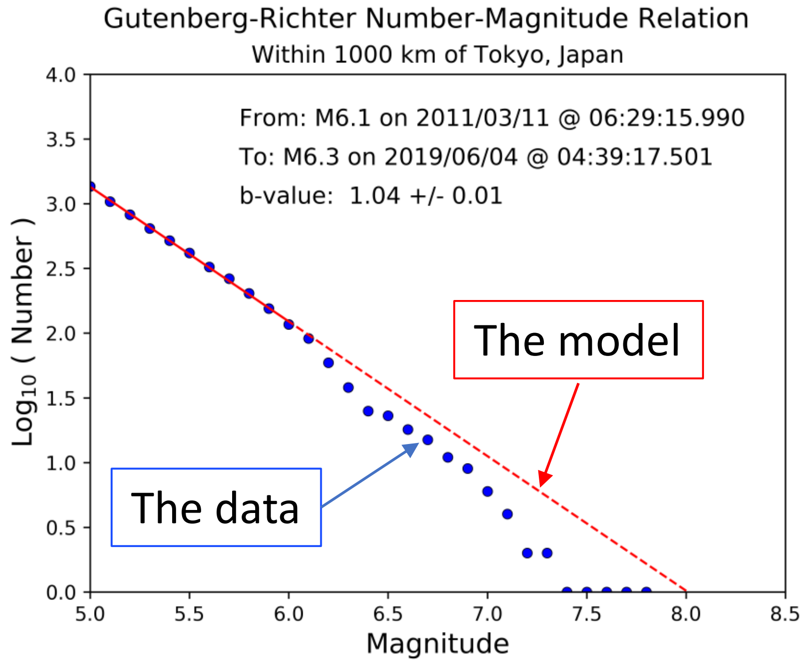
Example: Magnitude-Frequency Data is Modeled by the Gutenberg-Richter Law

1000 km Around Tokyo (Accessed April 24, 2018)





Before the 3/11 M9.1 Mainshock



After the M7.7 Aftershock

Basic ideas of Nowcasting:

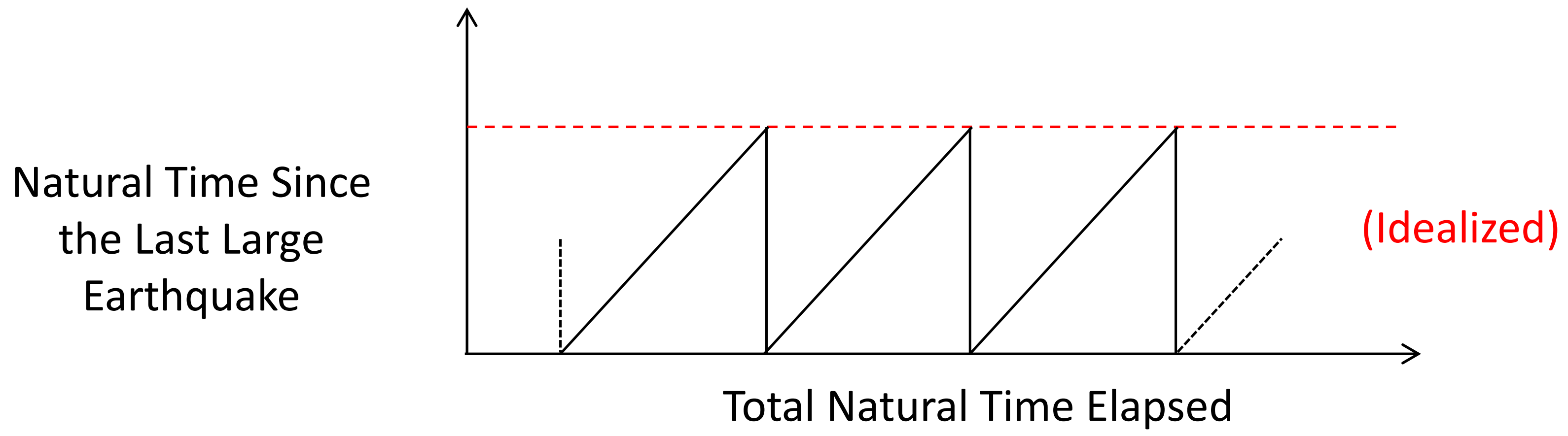
Deficiency of large earthquakes must be filled in eventually

Example: For every M>6 earthquake, there are on average 1000 M>3 earthquakes

Basic Nowcasting Includes Elastic Rebound via Small Earthquake Proxy Data

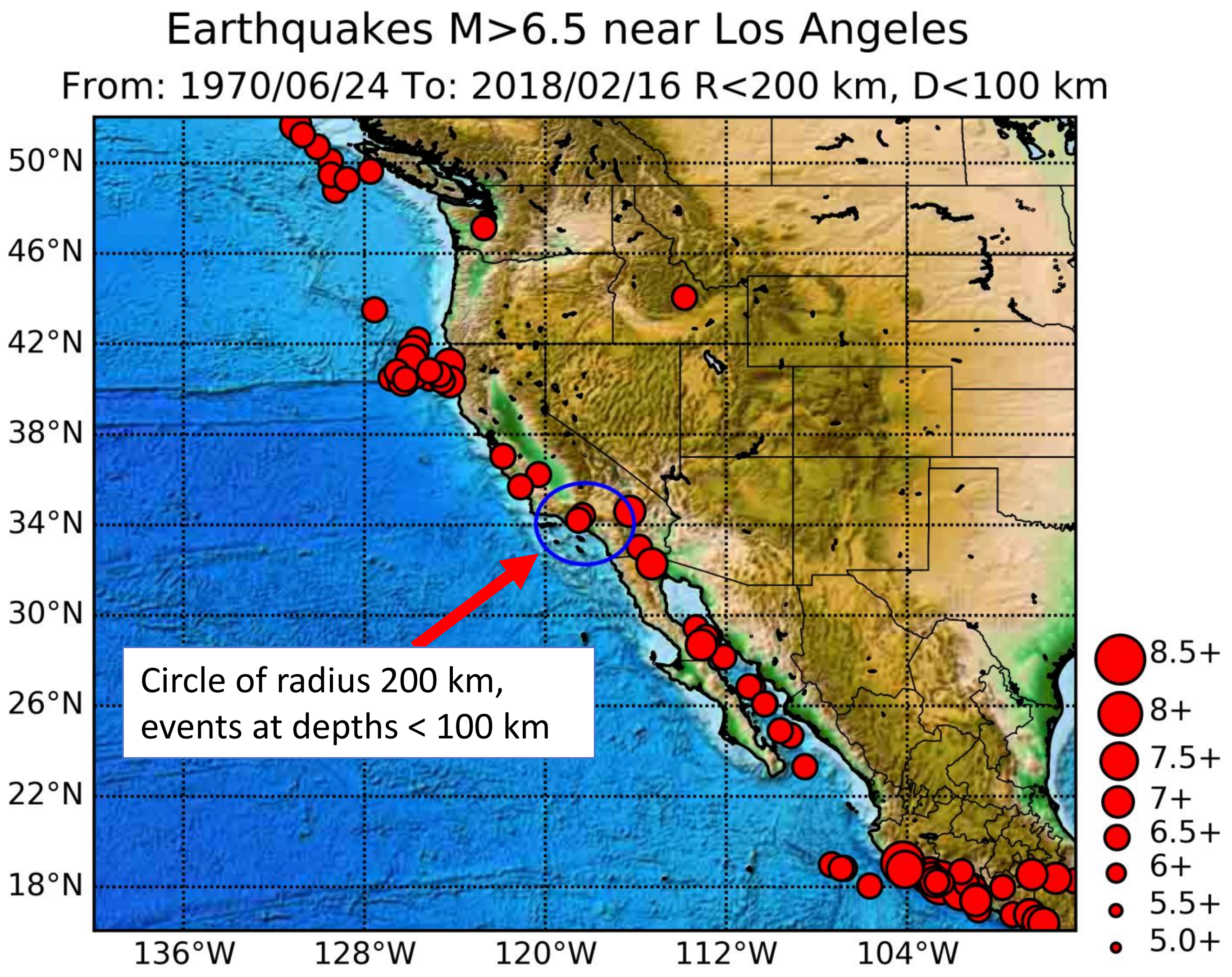
Example:
"Large" EQ: $M_L > 6$
"Small" EQ: $6 > M_S > 4$

Natural Time = Count of Small Earthquakes



Accumulating small earthquakes are readily observable proxy data, unlike stress

Seismicity around Los Angeles



Los Angeles

M7.1 Searles Valley, California Earthquake 2019/7/5 is 195 km from Los Angeles

Global Natural Hazard Viewer

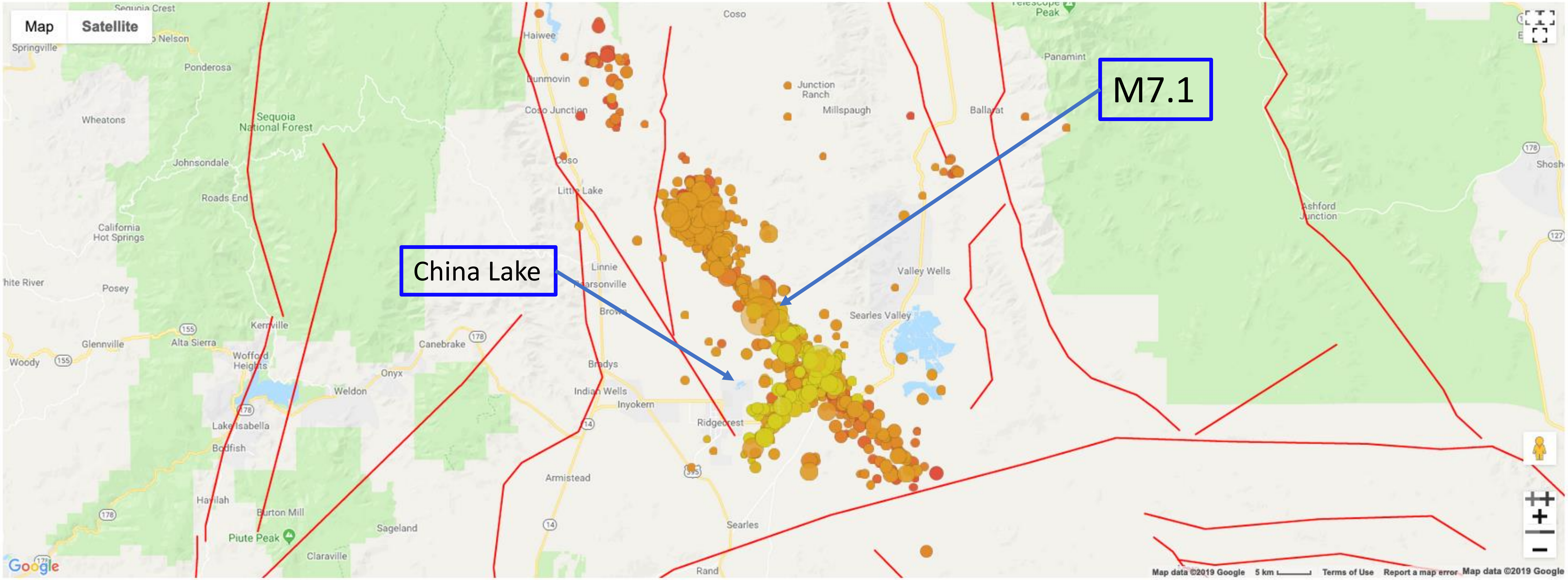
Global Forecast Heat Map: M>6.5, 1 Year, within 50 km. **California Forecast Heat Map: M>5, 1 Year, within 50 km.** **(Open Hazards Group)**

Earthquake magnitude shown by circle size. **Hotter colors are more recent events.** **Click on earthquake markers for event data.** **(USGS)**

Show Forecasts: ☐ Global ☐ California **Load Earthquakes:** ☐ M ≥ 1.0, Last Day ☑ M ≥ 2.5, Last Week ☐ M ≥ 4.5, Last Month

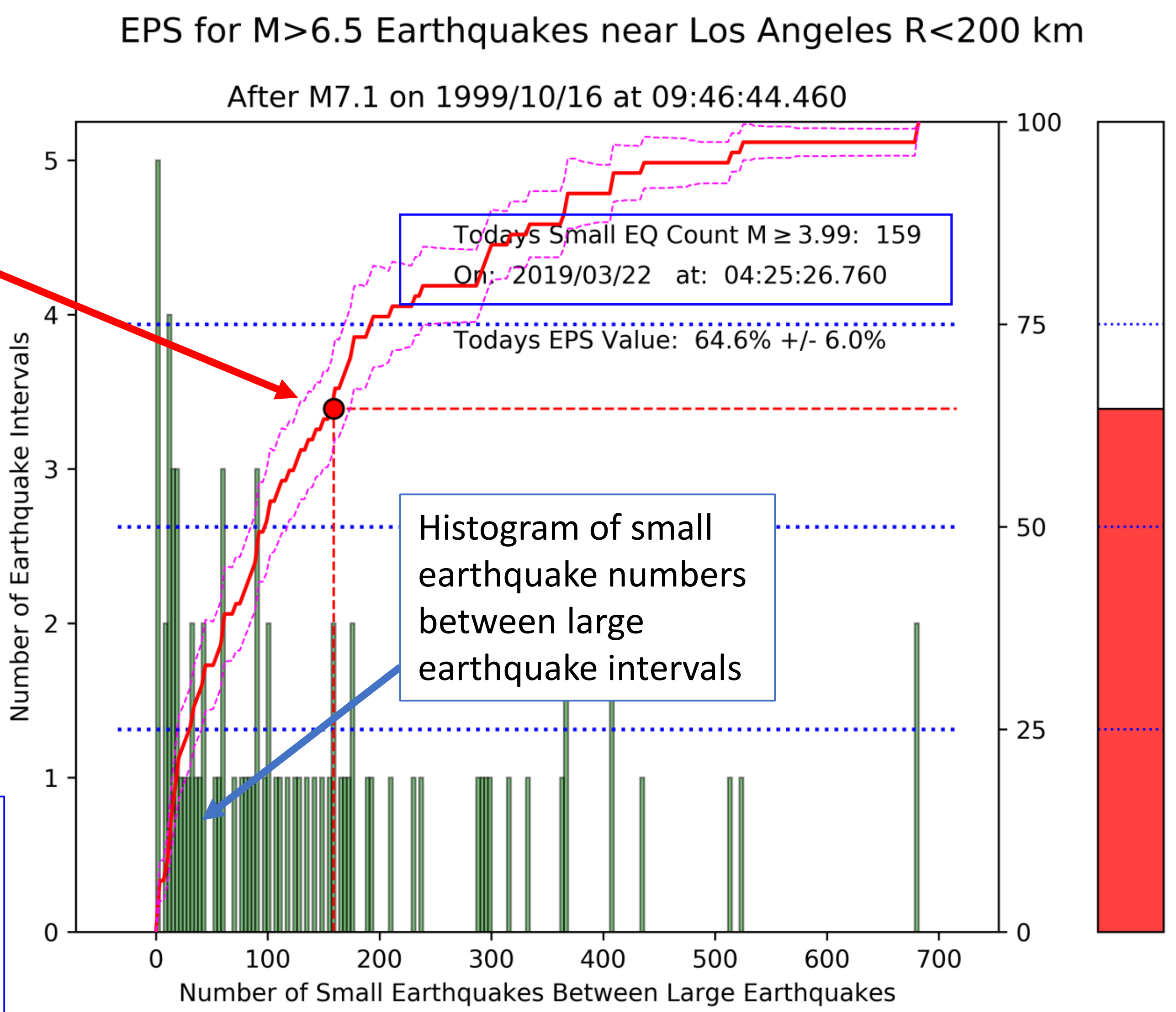
Filter Earthquakes: ☐ M ≥ 5 ☐ M ≥ 6.5 ☐ Depth ≤ 30 km **Show or Hide Loaded Earthquakes:** ☑ **Show California Faults:** ☑

Other Hazards: **Show GDACS Data:** ☐ **Get a Space-Time Earthquake Forecast from the Open Hazards Site**



Earthquake Potential Score

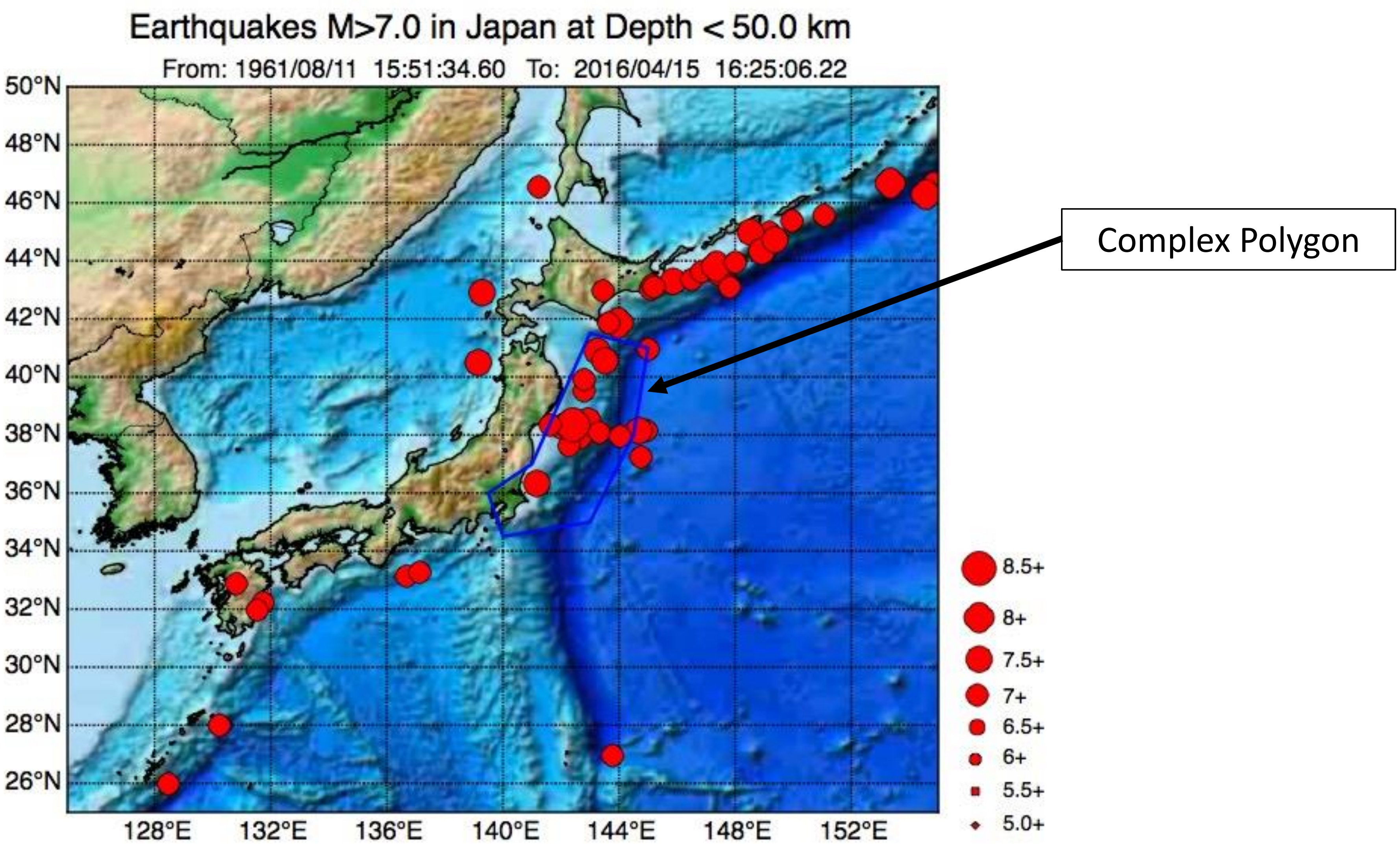
Cumulative Distribution Function of small earthquake intervals with 68% confidence error estimate



2019/7/5 M7.1 Searles Valley earthquake is 195 km from Los Angeles, within the 200 km circle

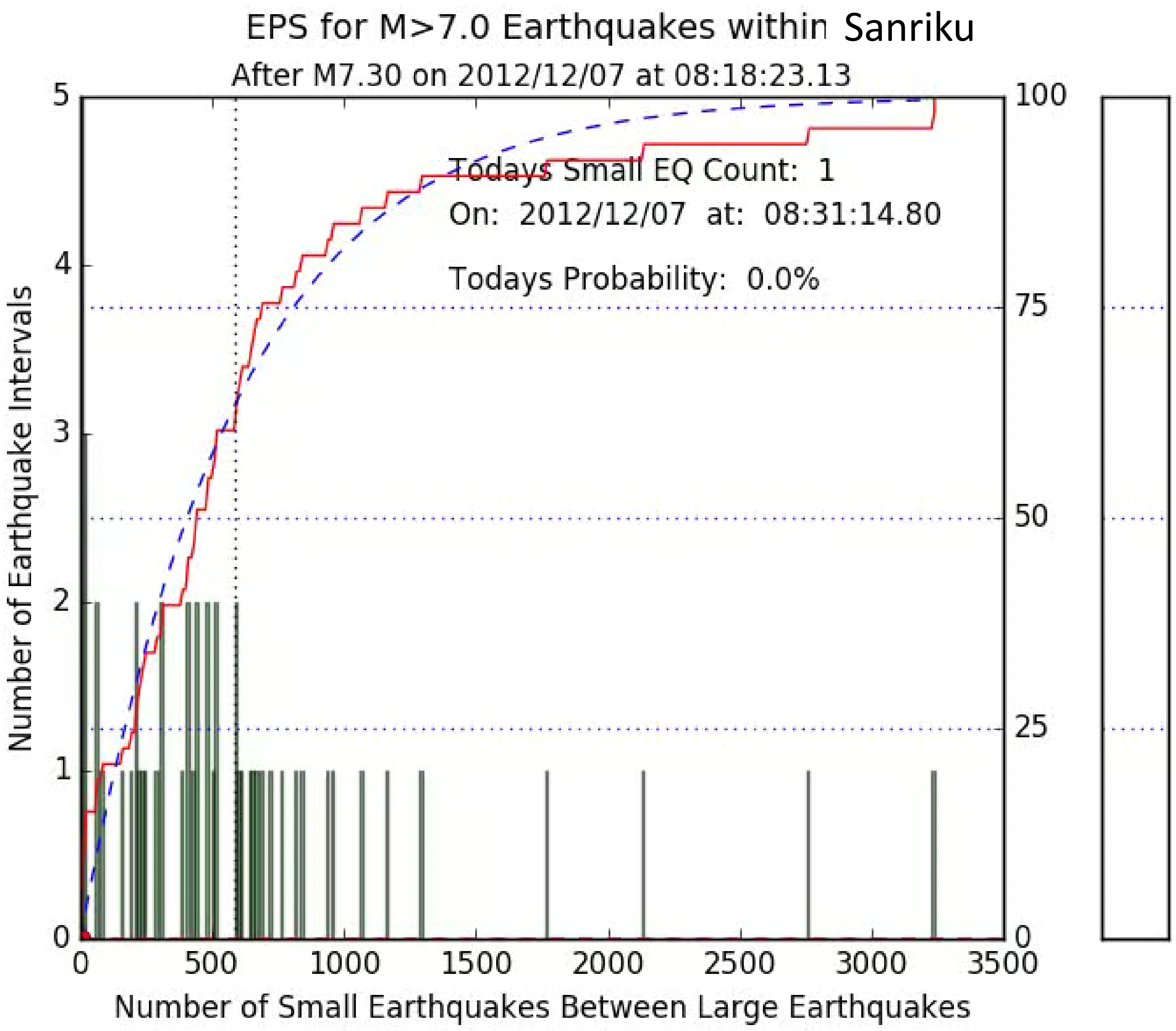
Los Angeles

Example: Nowcasting the Sanriku-Japan Trench



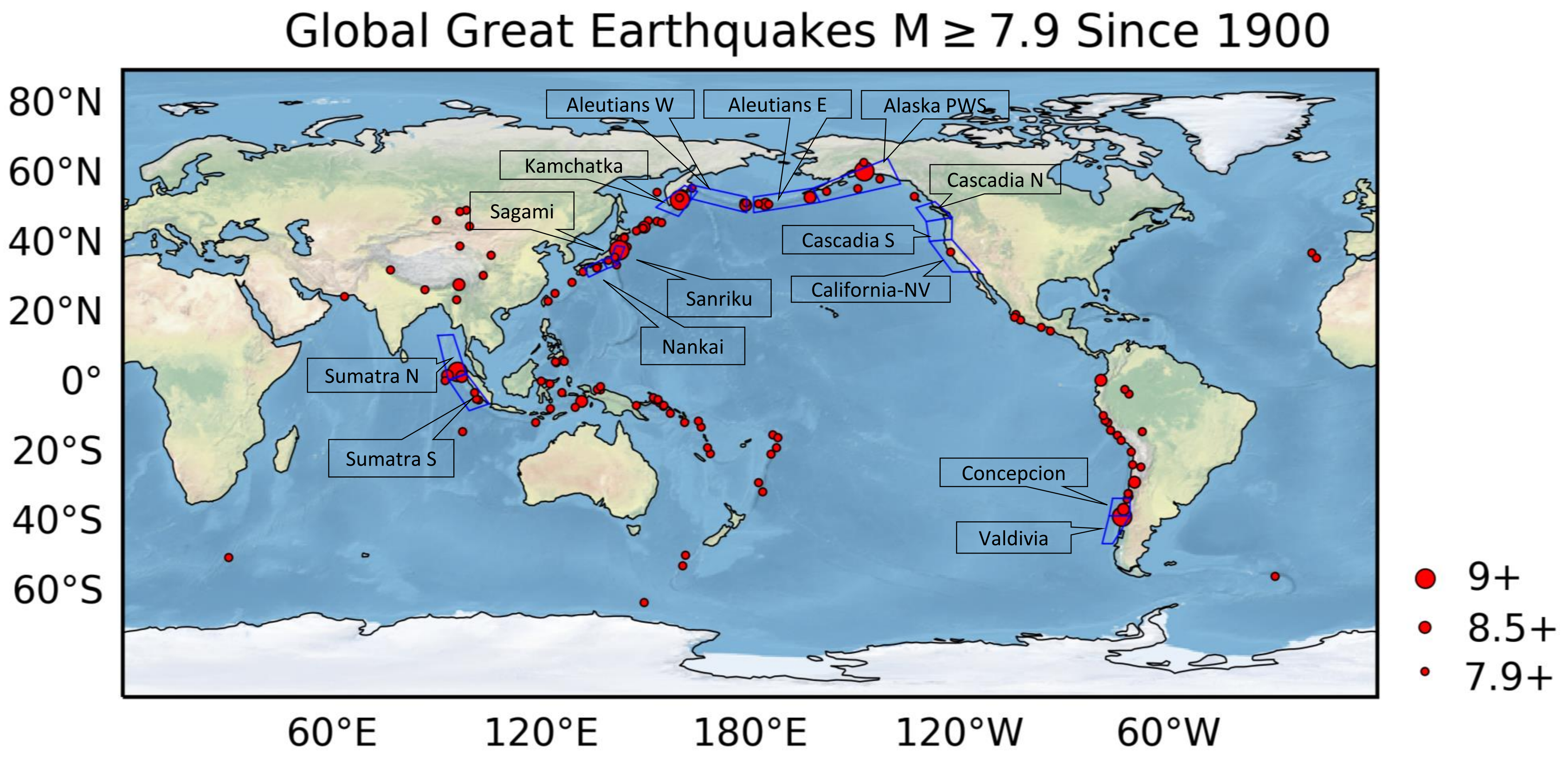
Earthquake Potential Score, Sanriku Trench

Computed 3/31/2017. Depths < 50 km

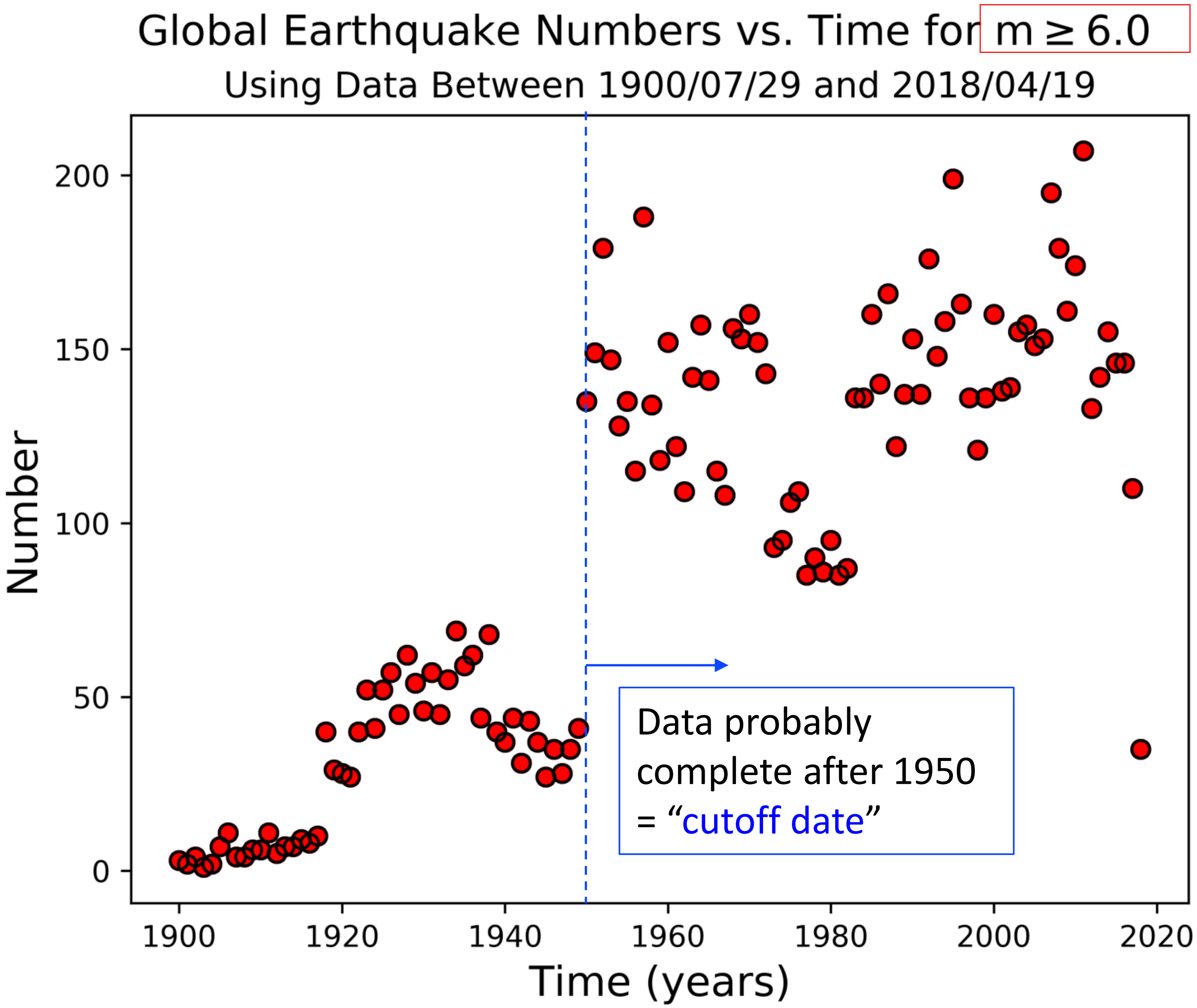


Nowcasting Great Earthquake and Tsunamis

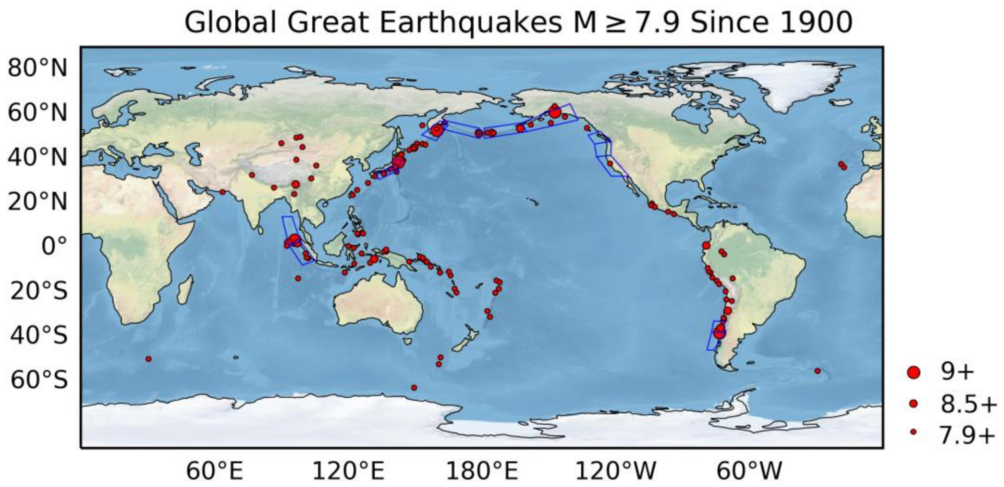
Source Regions



Global Seismicity, 1900 - 2018

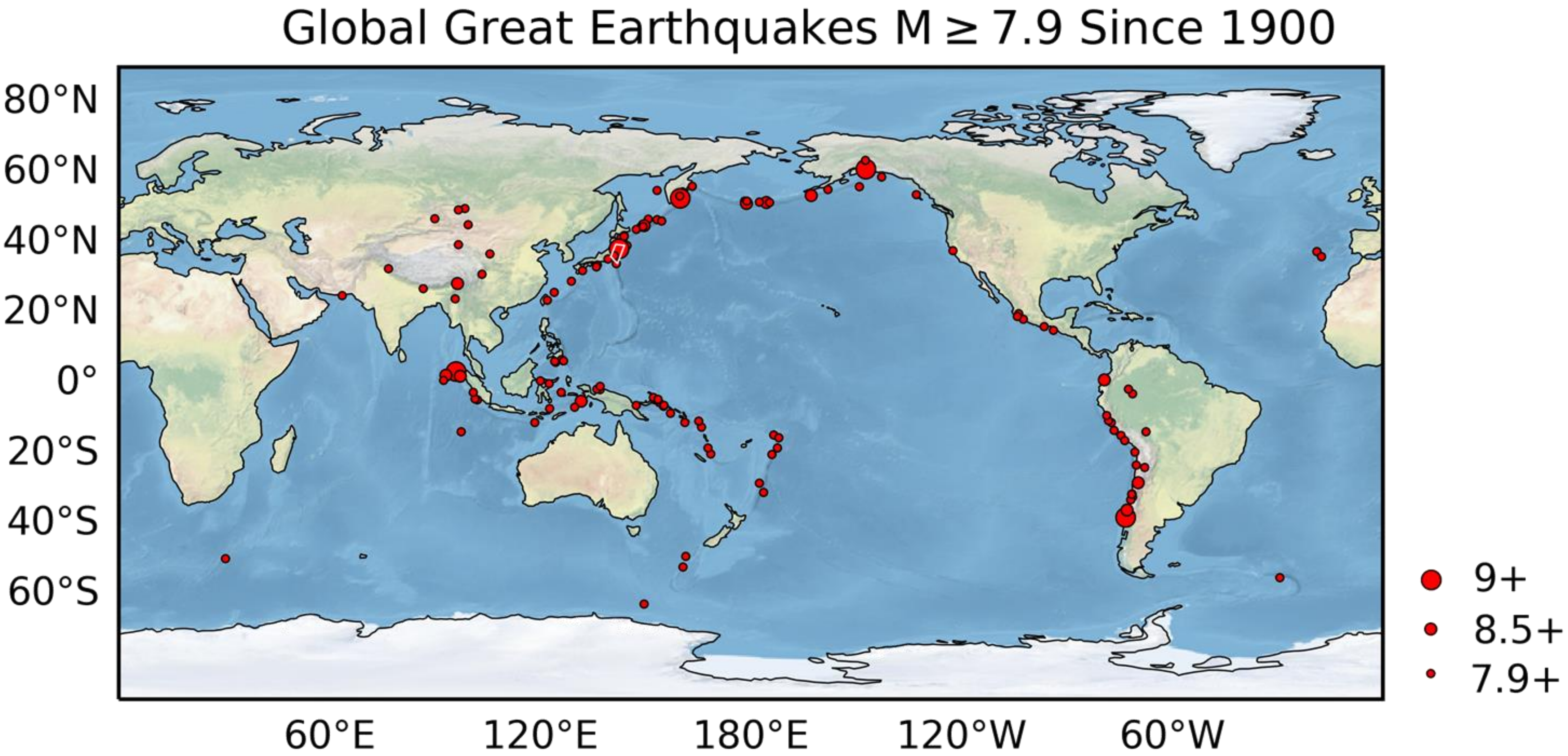


Summary Data

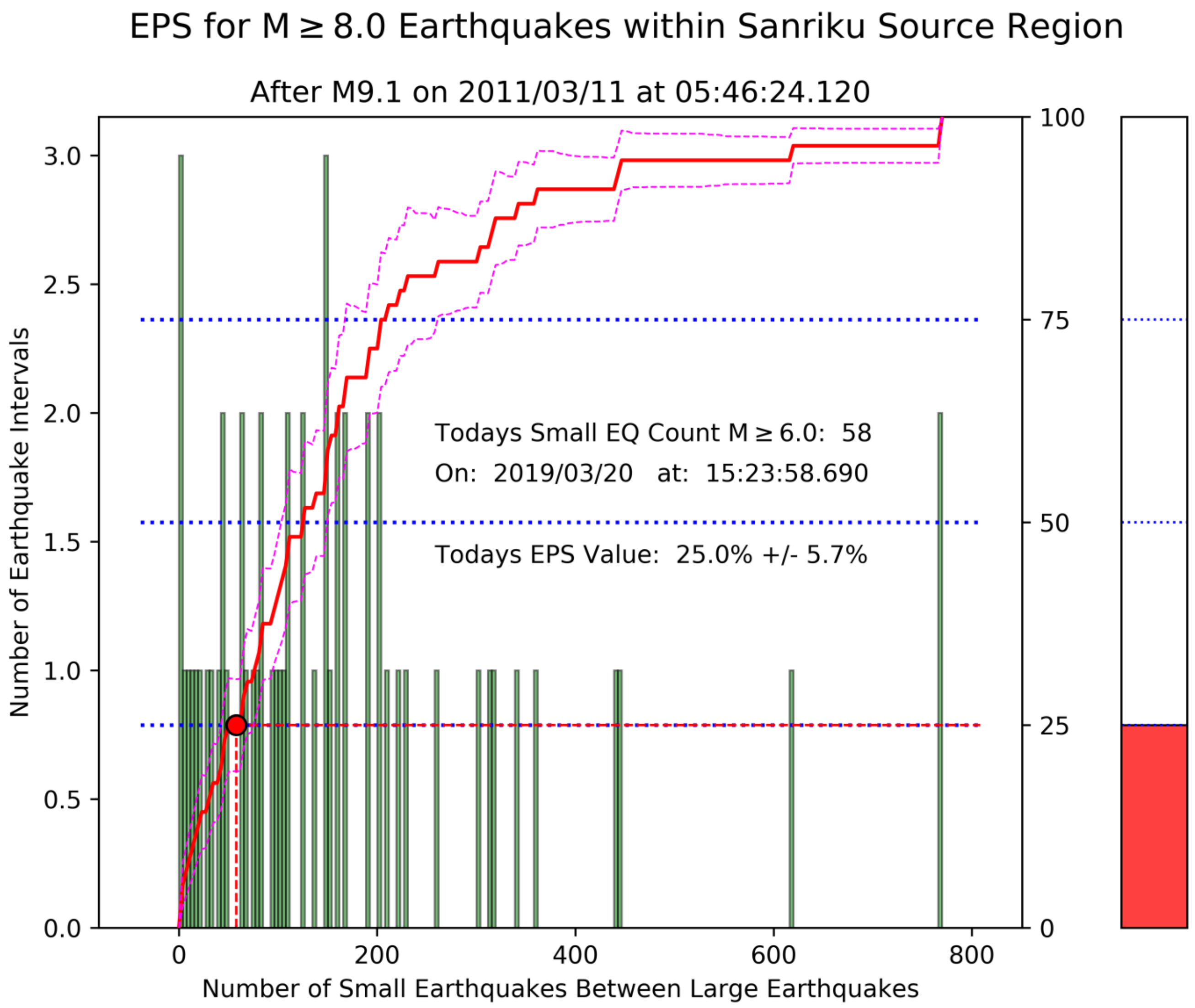


Location (Source Polygon)	EPS(%) Score on 2019/06/17 at 13:18:50 PT	Date Most Recent Large EQ in Polygon	Mag Most Recent Large EQ in Polygon	Nat. Time Count on 2019/06/17 at 13:18:50 PT	Current Potential Magnitude	Mean Count Worldwide	Std Dev Worldwide	Number Large EQs Worldwide in Catalog
AleutionsE	80.4	1946/04/01	8.6	254	8.3	168.73	171.40	95
Kamchatka	71.4	1952/11/04	9	204	8.2	168.73	171.40	95
CascadiaS	69.8	1922/01/31	7.3	26	7.3	21.09	20.43	678
CascadiaN	59.4	1946/06/23	7.5	31	7.4	32.65	30.82	460
California-Nevada	43.9	1906/04/18	7.9	69	7.7	115.23	124.59	133
AleutionsW	42.9	1965/02/04	8.7	104	7.9	168.73	171.40	95
AlaskaPWS	37.5	1964/03/28	9.2	86	7.8	168.73	171.40	95
Sagami	25.0	1923/09/01	8.1	64	7.7	168.73	171.40	95
SumatraN	25.0	2004/12/26	9.1	62	7.7	168.73	171.40	95
Sanriku	25.0	2011/03/11	9.1	58	7.7	168.73	171.40	95
SumatraS	25.0	2005/03/28	8.6	58	7.7	168.73	171.40	95
Valdivia	19.6	1960/05/22	9.5	46	7.6	168.73	171.40	95
Concepcion	17.9	2010/02/27	8.8	40	7.5	168.73	171.40	95
Nankai	12.5	1946/12/20	8.3	22	7.3	168.73	171.40	95

Sanriku Coast Polygon Source Region



Enhanced Nowcast for Sanriku Source Region



From Nowcasts to Forecasts

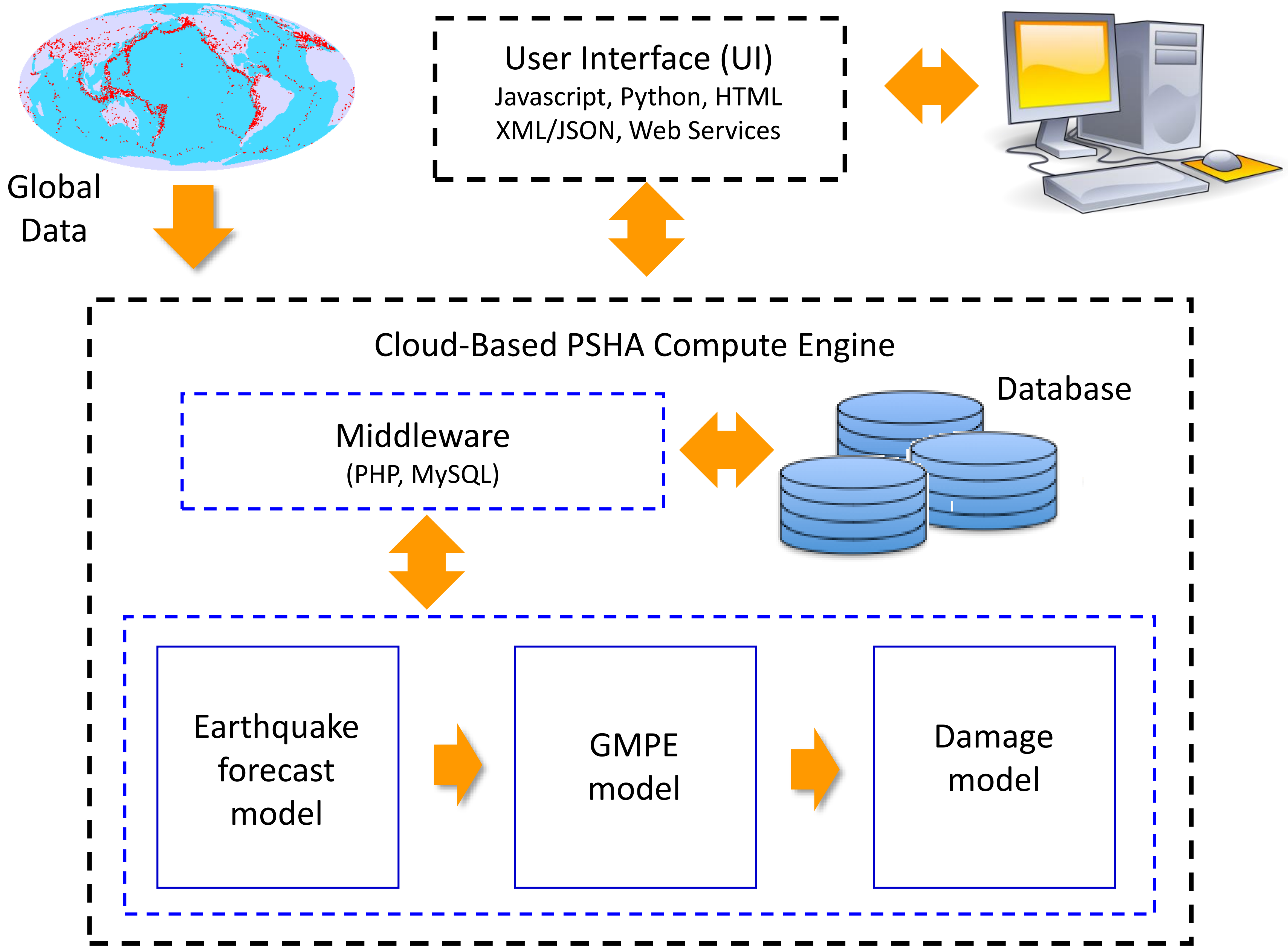
Forecasting with the Natural Time Weibull Method

JR Holliday et al. (2014)

- We begin by counting small earthquakes since the last large earthquake (Nowcasting)
- We build on the Nowcast by projecting the count forward in time using the current rate of small earthquake activity
- We combine these ideas with Weibull (1952) statistics, which are commonly used for engineering failure analysis
- The result is a fully automated computation of probability of future large earthquake occurrence
- Automation allows backtesting and optimization
- We have built this technology into a series of automated cloud-based web sites:

www.openhazards.com

Open Hazards PSHA Cloud Computational Framework



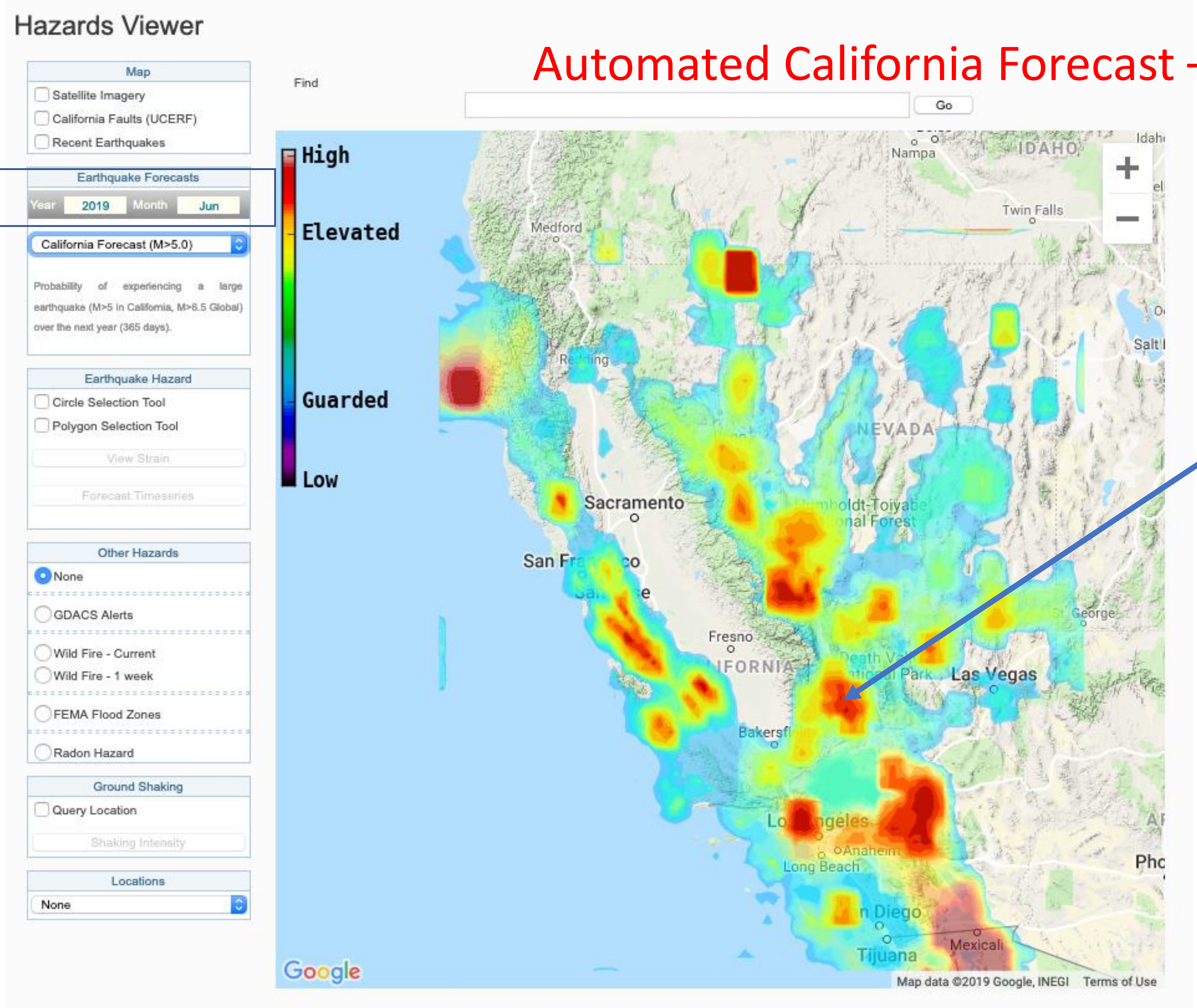
Automated forecasting and risk analysis allows rigorous backtesting.

Expert elicitation generally does not allow rigorous backtesting

Automated Forecasting in the Cloud

www.openhazards.com

Automated California Forecast – Updated Nightly



July 5, 2019, M7.1 Searles Valley Earthquake Epicenter

Forecasting in a Circular Region

Region Selection Tool

200 km circle around Los Angeles

Hazards Viewer

Map
- Satellite Imagery
- California Faults (UCERF)
- Recent Earthquakes

Earthquake Forecasts

Year 2019 Month Jun

Select Forecast

Probability of experiencing a large earthquake (M>5 in California, M>6.5 Global) over the next year (365 days).

Earthquake Hazard
- Circle Selection Tool
- Polygon Selection Tool

View Strain

Forecast Timeseries

Other Hazards
- None
- GDACS Alerts
- Wild Fire - Current
- Wild Fire - 1 week
- FEMA Flood Zones
- Radon Hazard

Ground Shaking
- Query Location

Shaking Intensity

Locations

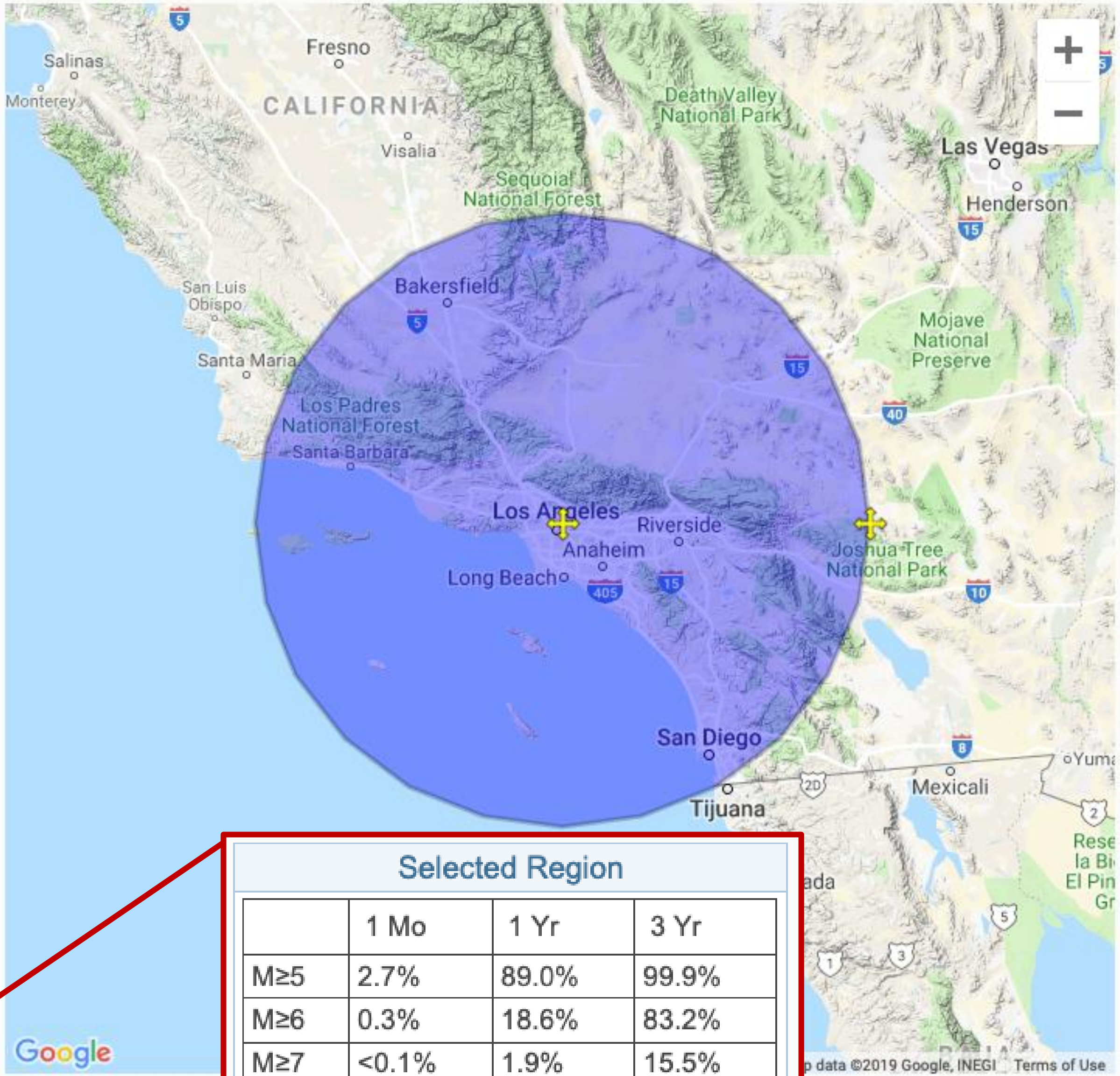
None

Selected Region

	1 Mo	1 Yr	3 Yr
M≥5	2.7%	89.0%	99.9%
M≥6	0.3%	18.6%	83.2%
M≥7	<0.1%	1.9%	15.5%
M≥8	<0.1%	0.2%	1.9%

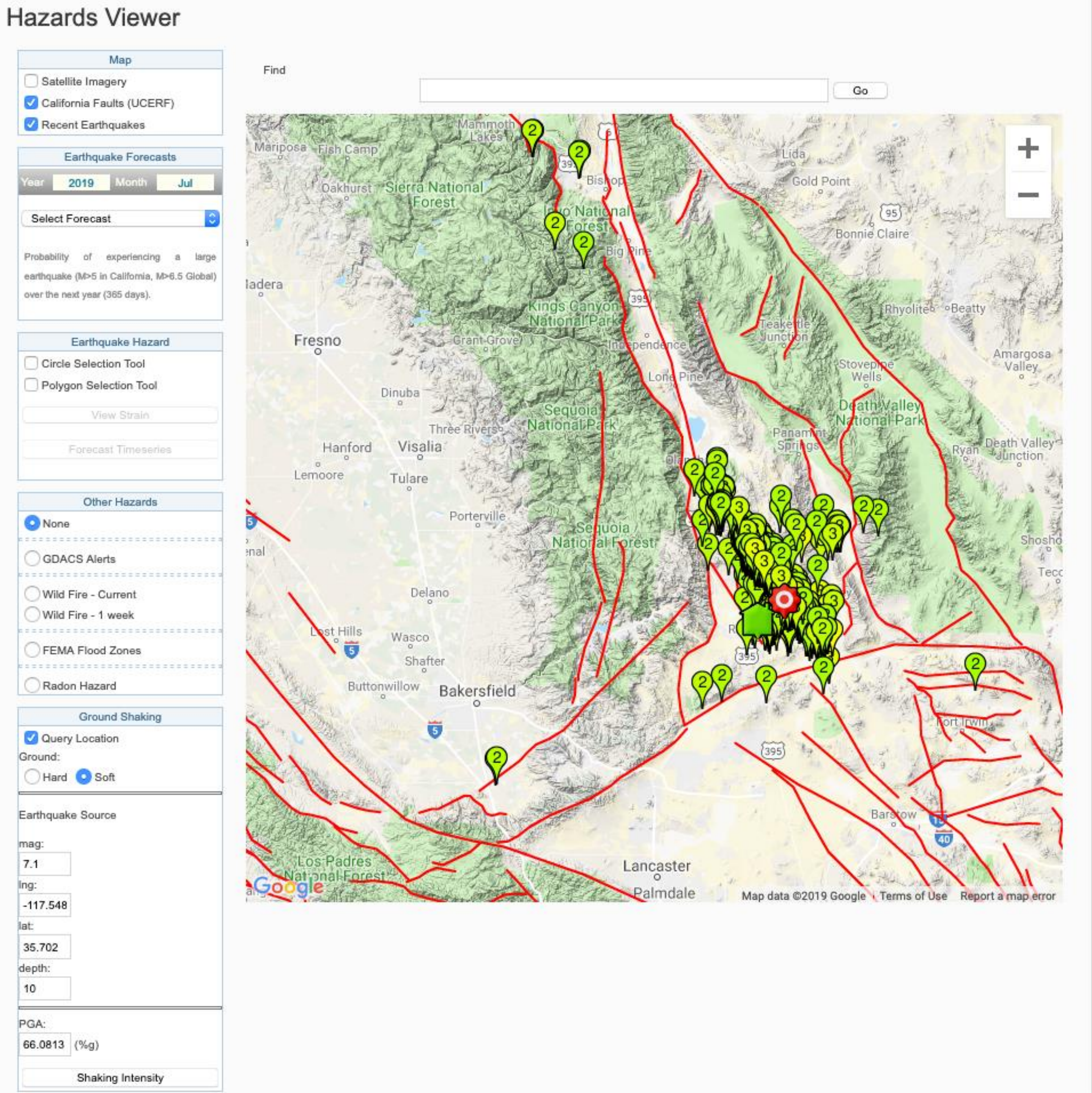
Find

Go



Selected Region

	1 Mo	1 Yr	3 Yr
M≥5	2.7%	89.0%	99.9%
M≥6	0.3%	18.6%	83.2%
M≥7	<0.1%	1.9%	15.5%
M≥8	<0.1%	0.2%	1.9%



66% g acceleration computed for Ridgecrest City during the M7.1 earthquake.

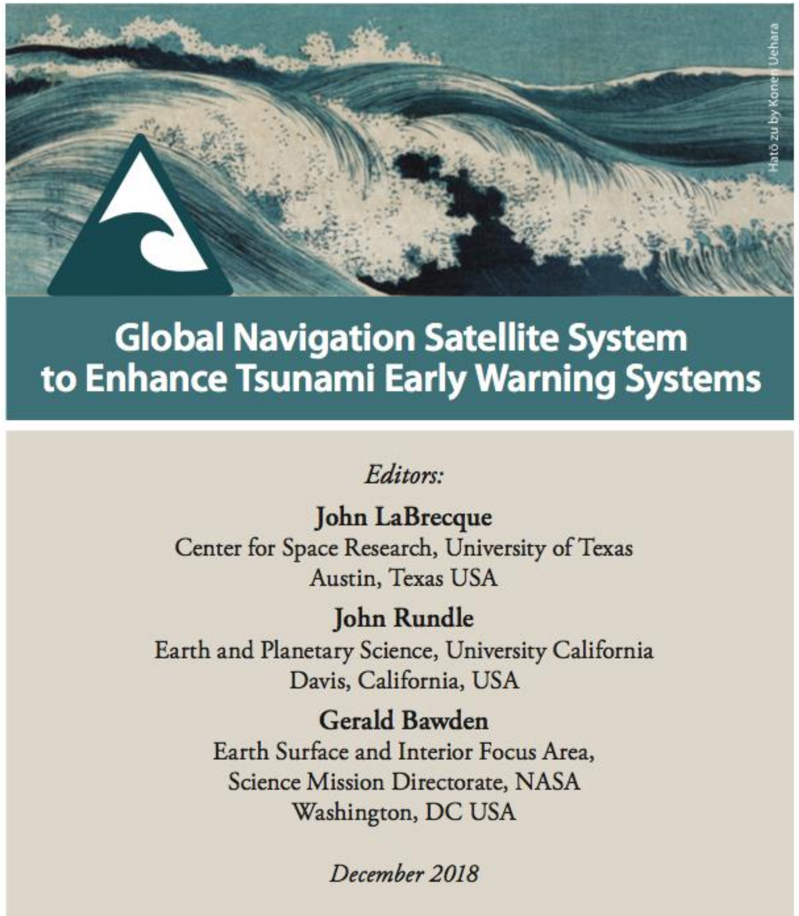
Mercalli Intensity IX (violent)

Shaking Intensity Tool

From Earthquakes to Tsunami Early Warning

Content:

- Recorded Proceedings and Presentations of the GTEWS 2017 Workshop
  https://www.dropbox.com/s/e53sksa7q9z8dkl/2017 GTEWS Program.pdf?dl=0
- GSTEWS: GEONET Captures Tohoku-oki earthquake
  https://www.dropbox.com/s/7v3rmz2b1stjpnw/GTEWS_Tohoku.mp4?dl=0
- *Motivation and Support*
- *GTEWS Development History*
- *Tsunami Detection and Monitoring*
- *GTEWS Requirements*
- *Prototype GTEWS Networks*
- *Workshop Findings and Recommendations*
- *Bibliography*



Global Navigation Satellite System (GTEWS) Tsunami Early Warning (TEW)

- The GNSS Tsunami Early Warning Systems workshop (**GTEWS 2017**) was held in Sendai, Japan on July 25-27, 2017
- It was supported by NASA in collaboration with:
  - The Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG)
  - The Association of Pacific Rim Universities (APRU) Multi-Hazards Hub at Tohoku University in Sendai, and
  - The International Research Institute of Disaster Science (IRIDeS) at Tohoku University.

Sendai Framework

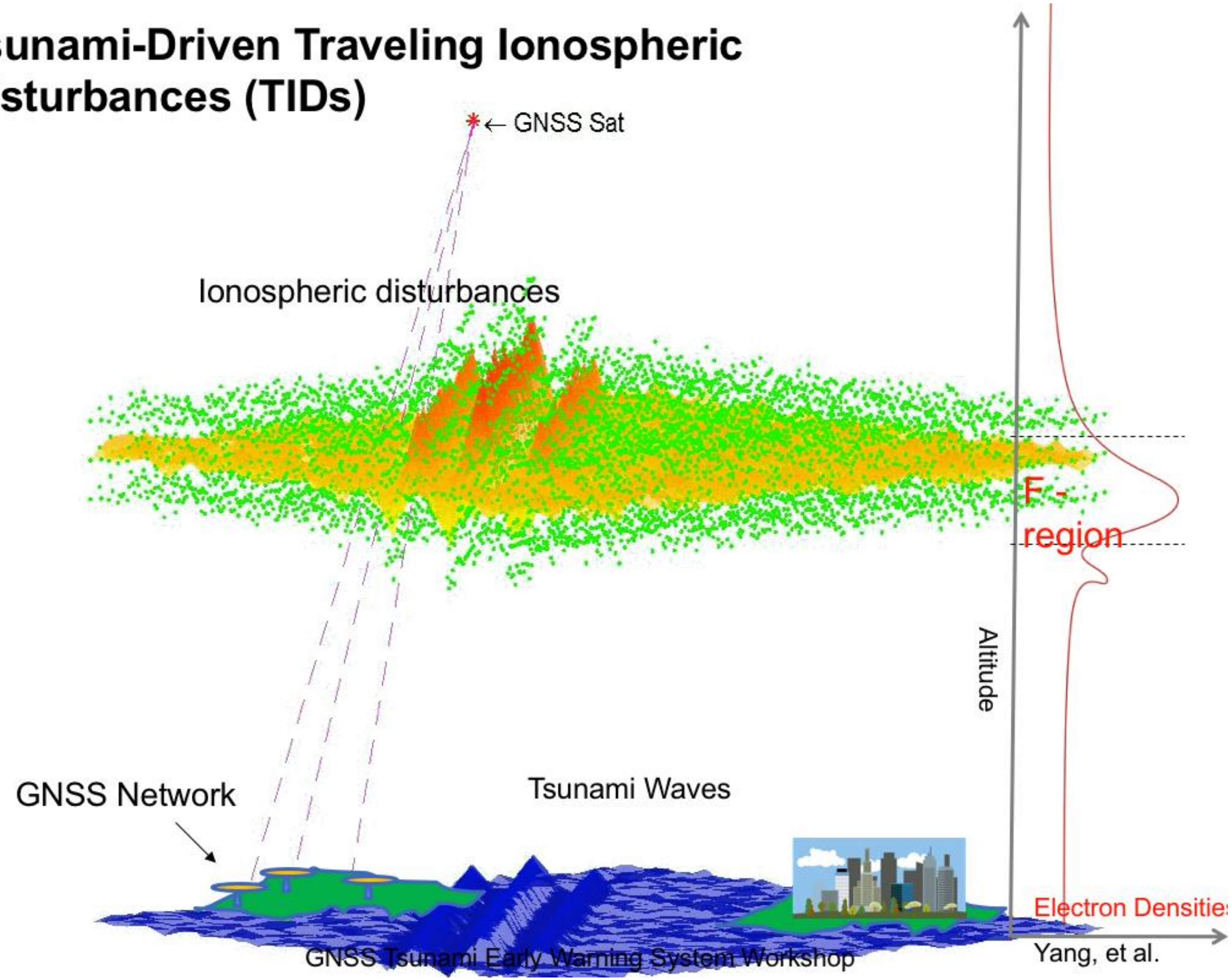
- The GTEWS 2017 workshop sought to implement the vision articulated by IUGG 2015 Resolution #4 to encourage broader cooperation within the Indo-Pacific community of APEC economies for the adoption of GTEWS.
- The GTEWS 2017 workshop was aligned with the goals and priorities the UNDRR Sendai Framework for Disaster Risk Reduction 2015-2030 (*https://www. unisdr.org/we/coordinate/sendai-framework*).
- The recommendations of GTEWS 2017 workshop support the Sendai Framework goal to substantially reduce disaster mortality through the application of multi-national investments

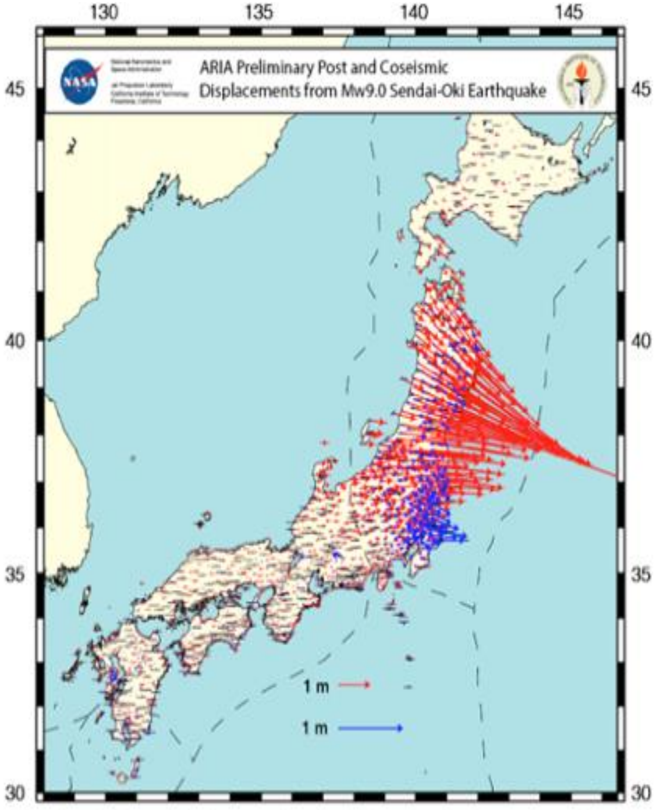
Action Priorities of the Sendai Framework

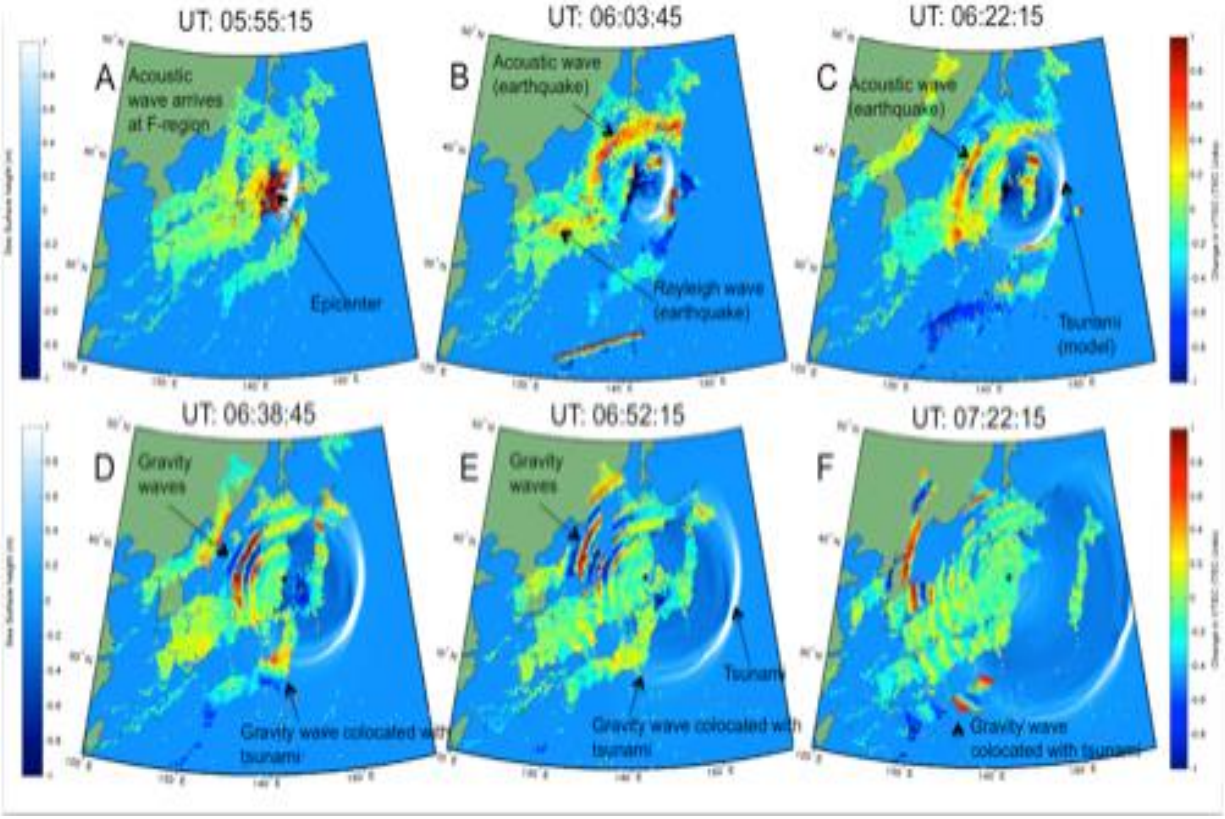
Understand disaster risk:

- Short term disaster risk will be improved by rapid and accurate tsunami disaster warnings for a clearer understanding of impending disaster risk.
- More rapid accurate information will also improve the community response to warnings and will save lives in the medium term.
- The GTEWS network improvements will provide better long term estimates of disaster risk through better scientific understanding of the evolving geologic forces.

Tsunami-Driven Traveling Ionospheric Disturbances (TIDs)



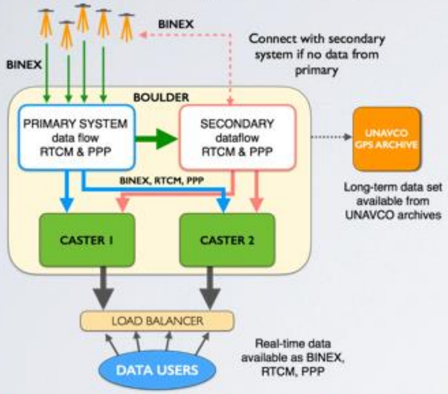

130
135
140
145
45
40
35
30
ARIA Preliminary Post and Coseismic
Displacements from Mw9.0 Sendai-Oki Earthquake
1 m
1 m


UT: 05:55:15
A
Acoustic wave arrives at F-region
Epicenter
UT: 06:03:45
B
Acoustic wave (earthquake)
Rayleigh wave (earthquake)
UT: 06:22:15
C
Acoustic wave (earthquake)
Tsunami (model)
UT: 06:38:45
D
Gravity waves
Gravity wave colocated with tsunami
UT: 06:52:15
E
Gravity waves
Tsunami
Gravity wave colocated with tsunami
UT: 07:22:15
F
Gravity wave colocated with tsunami

STEPS INVOLVED IN GNSS DERIVED TSUNAMI EARLY WARNING

UNAVCO

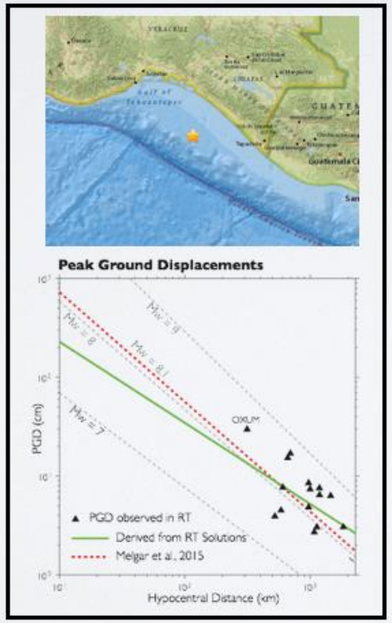
Step 1: Collect and process the high-rate GNSS data (< 10 secs)



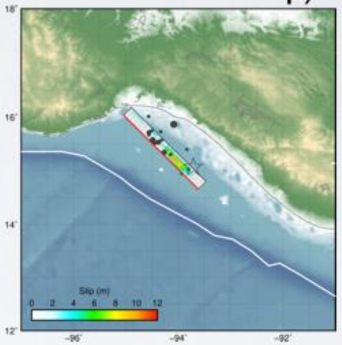
Tsunami model from Diego Melgar, U. Oregon

- Model based on source fault slip inversion with data from tide gauges, static coseismic offsets from GPS, and real-time kinematic GPS solutions from NSF-funded stations.
- Given appropriate and reliable RT data streams and computational resources, tsunami amplitude and inundation models can be generated within **~300 s** after origin time of the earthquake

Step 2: Estimate the earthquake magnitude and location (~60 secs)

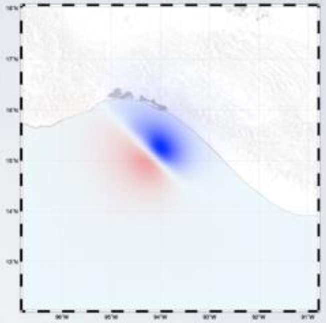


Step 3: Inversion for finite fault model, ~ 90 secs (length and distribution of slip)

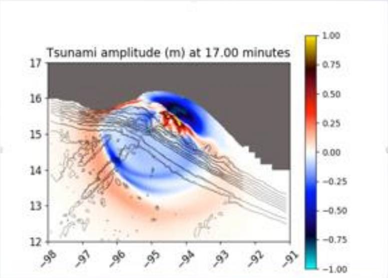


* currently methods using seismic data only

Step 4: Predict ground displacement using the FFM (~120 secs)



Step 5: Run tsunami simulation, using submarine displacements from step 4 (~300 secs)



Summary

- Forecasting: Computing the probability of future activity
- Nowcasting: Determining the current state of progress through the hazard cycle
- Uses: Ranking the current seismic risk of cities and tsunami source regions world wide
- Tsunami Early Warning using Global Navigation Satellite Systems
    - A cooperative project of NASA, NOAA, APRU-MH, APEC, GGOS, and others
    - Consistent with the Sendai Framework for DRR

Thank you for your attention

Much more information at:

www.openhazards.com

Sensitivity Analysis

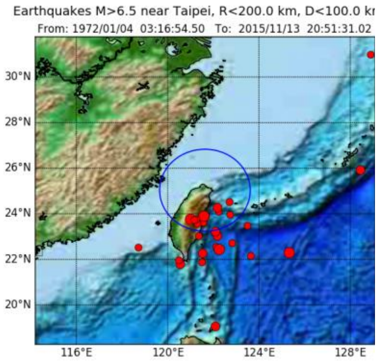
Varying region sizes and completeness magnitudes

Fixed Conditions:

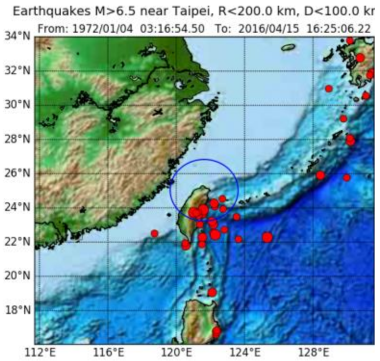
1) Computed for M>6.5 2) 200 km radius around cities 3) Depth < 100 km

1) Change the large region diameter: 1500 km, 2000 km, 3000 km, 4000 km

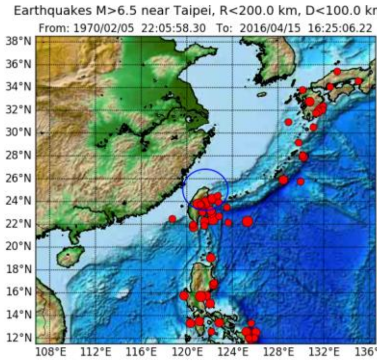
Larger



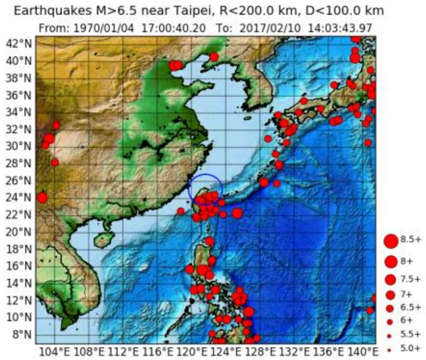
1500 x 1500 km



2000 x 2000 km



3000 x 3000 km



4000 x 4000 km

2) Change the completeness threshold for San Francisco and Los Angeles calculations from M3.0 to M4.0

Result: Under reasonable conditions, EPS changes by only about +/- 10%

Enhanced Nowcasting adds Two Simple Model Ideas

- **Definition: Cutoff Date.** Date after which catalog is assumed to be complete at the defined completeness level
  - For M>6, cutoff date is apparently 1950 (next slide)
  - Sensitivity tests show cutoff date of 1960 gives similar results
- **Idea 1.** Small earthquakes that occur after the cutoff date are counted. Small earthquake numbers prior to the cutoff date are estimated using the average rate from after the cutoff date
- **Idea 2.** Current estimated magnitude m is computed as:

$$m = m_C + (1/b) \, \mathrm{Log}_{10}(N)$$

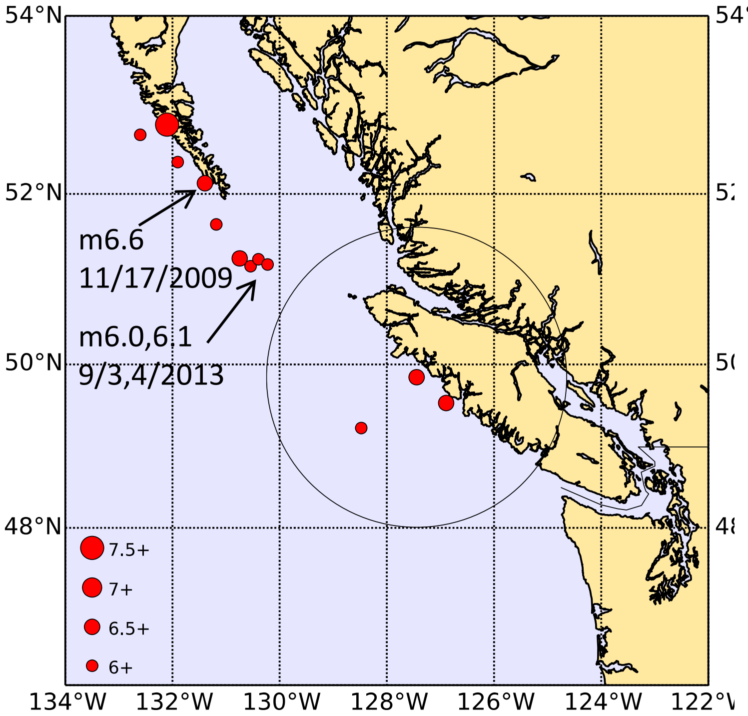
Where:

N = Natural time count of small earthquakes since last large earthquake

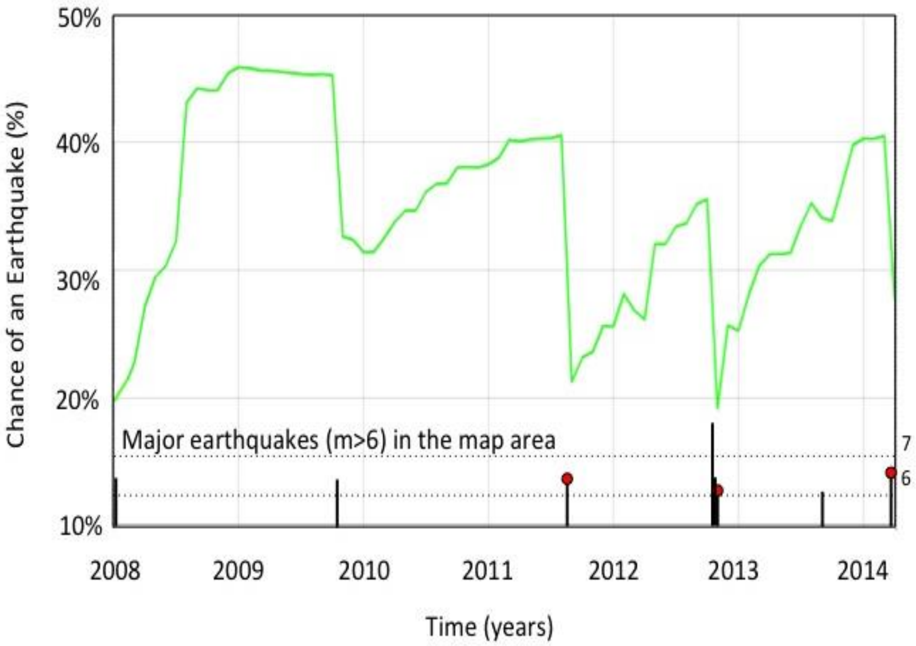
m_C = Catalog completeness magnitude

Example: Vancouver Island Earthquakes, NTW Forecast

Latest Significant Event was M6.6 on 4/24 /2014
JR Holliday et al. (2014)

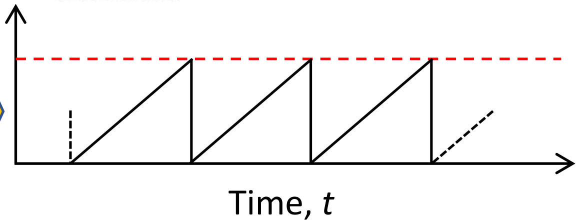


Chance of M>6 earthquake in circular region of radius 200 km for next 1 year.
Data accessed 4/26/2014



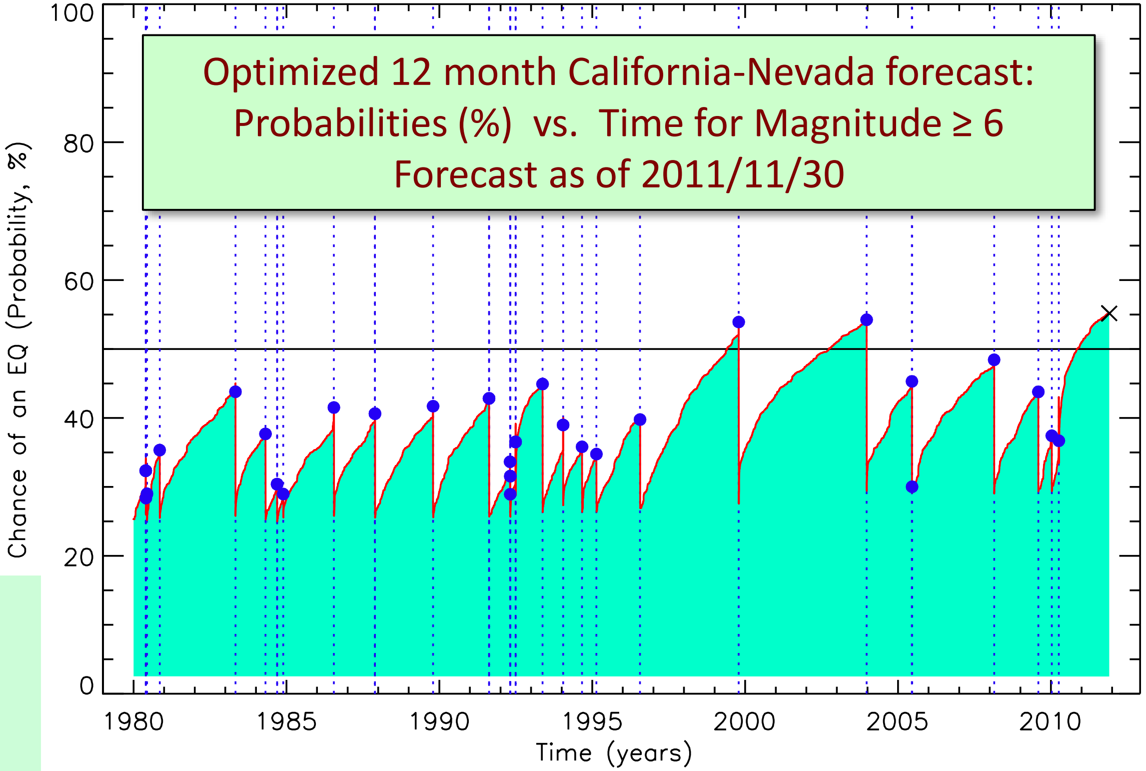
Observed Behavior

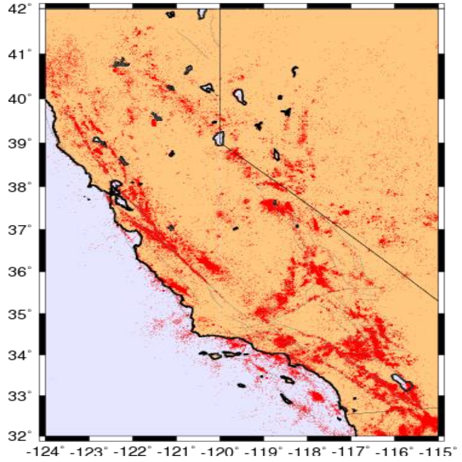
Idealized Expected Behavior



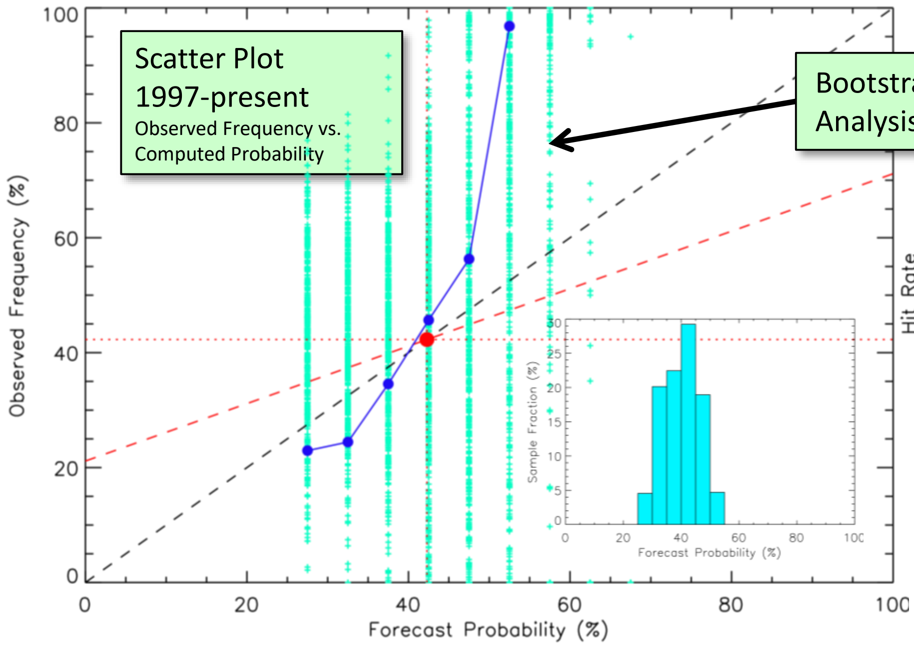
Optimal California-NV Forecast

Optimal forecasts via backtesting, using common validation and verification testing procedures.

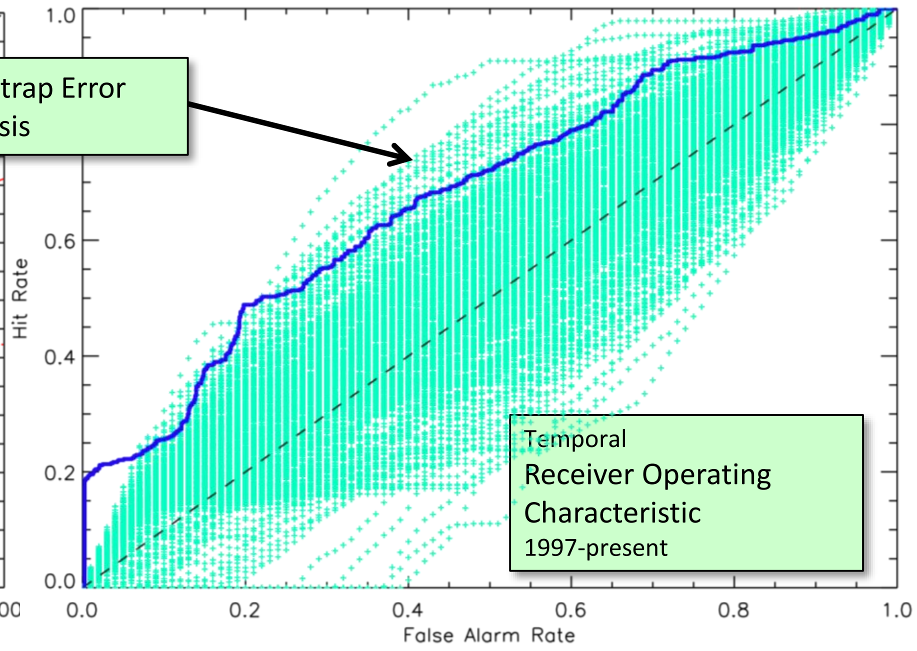




Automating Forecasts Allows Backtesting and Optimizing!



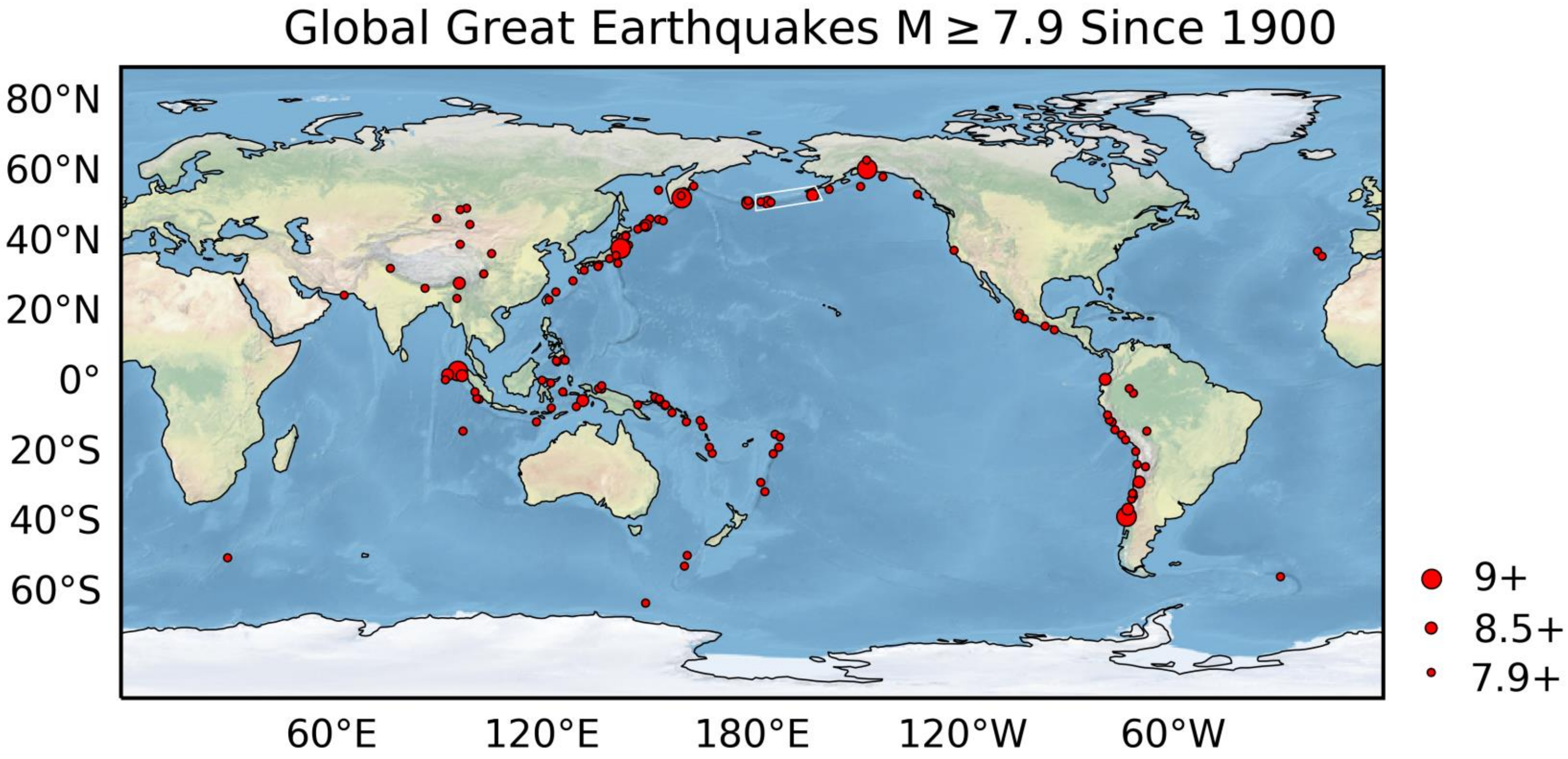
Bootstrap Error Analysis

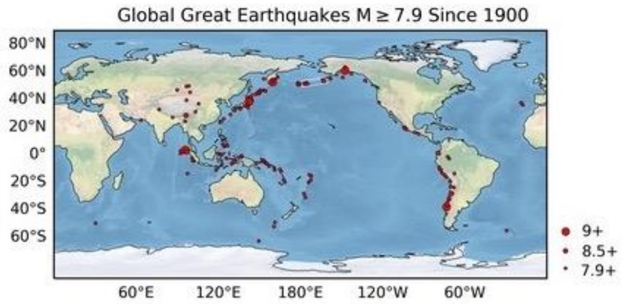


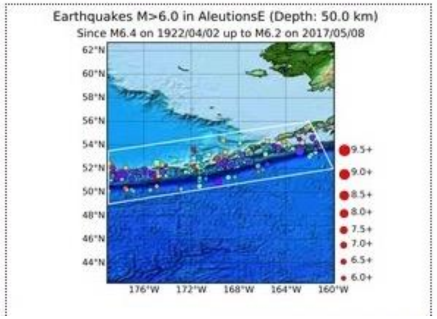
Earthquake Forecasting
Current Practice

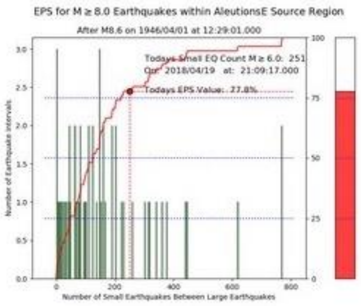
- Expert elicitation is frequently used in forecasting, meaning that backtesting is not possible
- Most/many current forecasts use time-independent Poisson statistics in forecasting
- Poisson forecasts have the property that they have no memory of past events
- An example is the current UCERF3 forecast for California, which has not been backtested

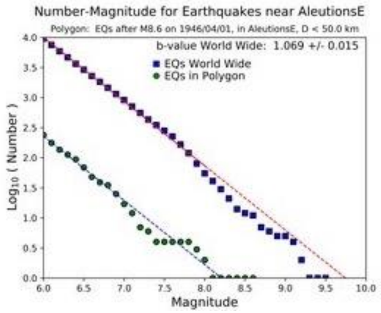
Aleutians E Polygon Source Region



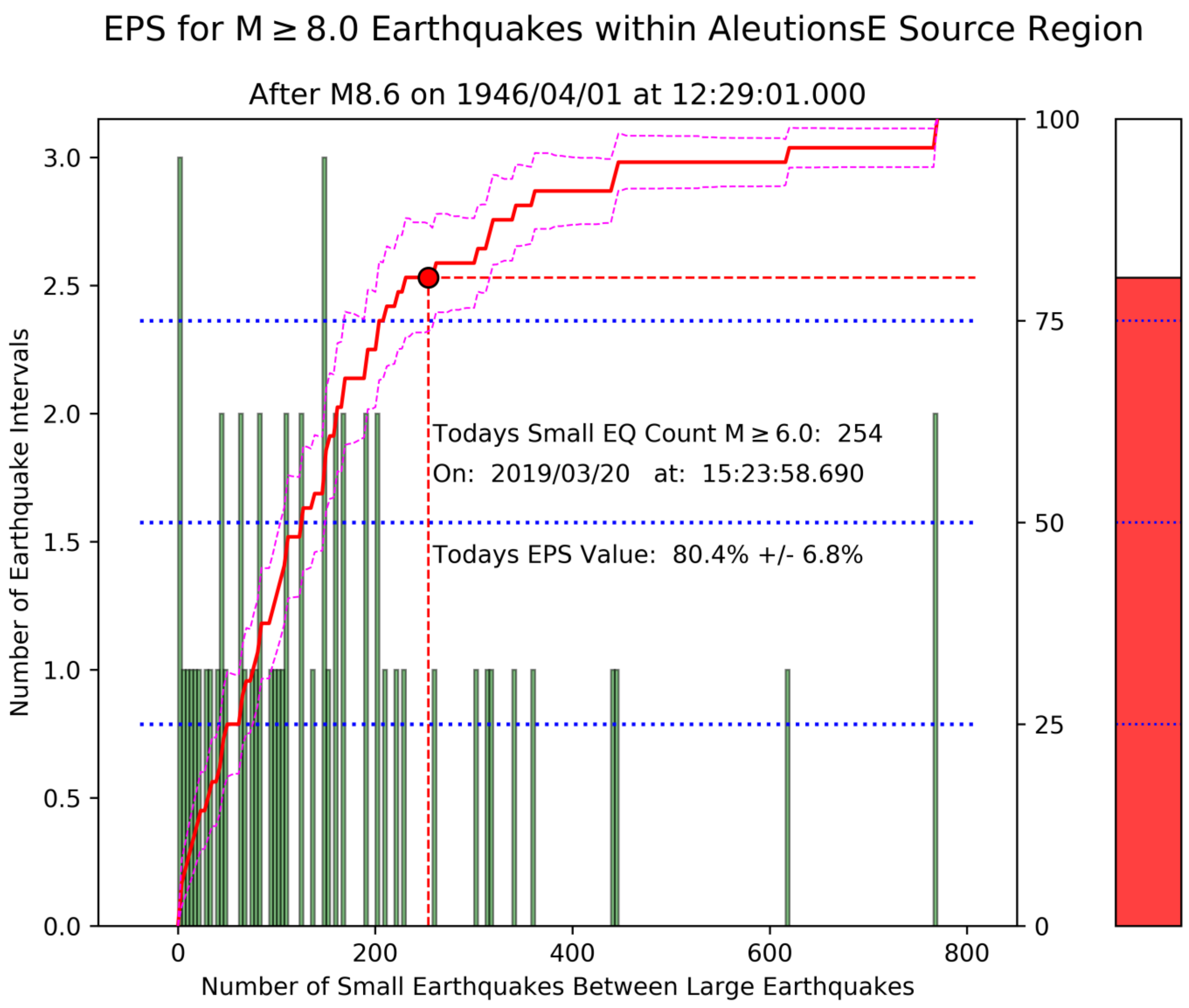








Enhanced Nowcast for Aleutians E



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Nowcasting and Forecasting

Pricing Earthquake Risk: Current Practice

Science

Earthquake forecast model

Poisson
Log Normal
BPT
Fault models
Pattern Analysis
AMR
ETAS
NTW
Nowcast
Etc.

Engineering

Ground shaking model

Attenuation
PGA/PGV
Lquifaction
Surface geology
Basin structure
Etc.

Economics

Economic loss model

EP curves
Building damage
Socioeconomic data
Supply chain disruption
Lost income
Lifelines
Etc.

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Pricing of insurance & financial securities

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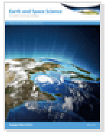

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Abstract

Nowcasting is a term originating from economics and finance. It refers to the process of determining the uncertain state of the economy or markets at the current time by indirect means. We apply this idea to seismically active regions, where the goal is to determine the current state of the fault system, and its current level of progress through the earthquake cycle. In our implementation of this idea, we use the global catalog of earthquakes, using "small" earthquakes to determine the level of hazard from "large" earthquakes in the region. Our method does not involve any model other than the idea of an earthquake cycle. Rather, we define a specific region and a specific large earthquake magnitude of interest, ensuring that we have enough data to span at least ~20 or more large earthquake cycles in the region. We then compute the earthquake potential score (EPS) which is defined as the cumulative probability distribution $P(n < n(t))$ for the current count n(t) for the small earthquakes in the region. From the count of small earthquakes since the last large earthquake, we determine the value of EPS = $P(n < n(t))$. EPS is therefore the current level of hazard, and assigns a number between 0% and 100% to every region so defined, thus providing a unique measure. Physically, the EPS corresponds to an estimate of the level of progress through the earthquake cycle in the defined region at the current time.

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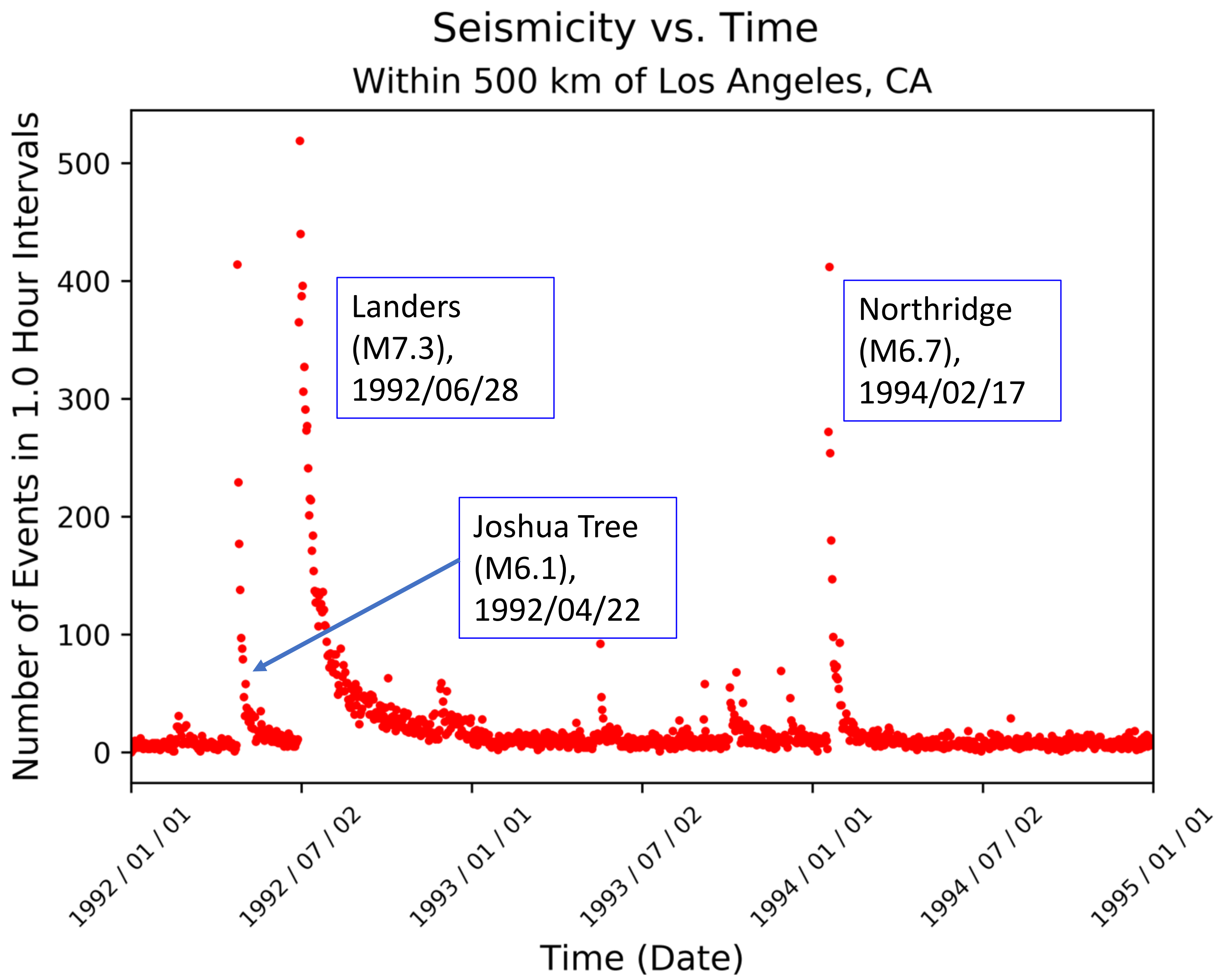
Seismicity vs. Time
Within 500 km of Los Angeles, CA
Number of Events in 1.0 Hour Intervals
0
100
200
300
400
500
Landers
(M7.3),
1992/06/28
Northridge
(M6.7),
1994/02/17
Joshua Tree
(M6.1),
1992/04/22
1992 / 01 / 01
1992 / 07 / 02
1993 / 01 / 01
1993 / 07 / 02
1994 / 01 / 01
1994 / 07 / 02
1995 / 01 / 01
Time (Date)