Forecasting and Nowcasting Earthquakes and Tsunamis:
Anticipating Great Natural Disasters Using Machine Learning

John Rundle

Distinguished Professor, University of California

Chairman, Open Hazards Group

Topics:

Science

Applications

Motivation: Tohoku, Japan

Earthquake and Tsunami
March 11, 2011

How do we estimate risk from these events?

What does this mean for the insurance industry?

Forecasting and Nowcasting

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

- We wish to calculate the probability of a future large earthquake
- We need to estimate the time, location, and magnitude of the event

Nowcasting describes the current state of the hazard cycle

- First used to describe the current state of the economic/business cycle
- Also used in weather and climate applications

Machine Learning

- Machine learning is an application of artificial intelligence (AI)
- Provides systems the ability to automatically learn and improve from experience
- Machine Learning (“ML”) focuses on the development of computer programs that can access data and build models of the process
- Aims to learn patterns in past data and predict future data
- Now commonly used in data science applications including advertising in Google, Amazon, Facebook, etc.
- Several sophisticated ML libraries are now readily available on the web as open source

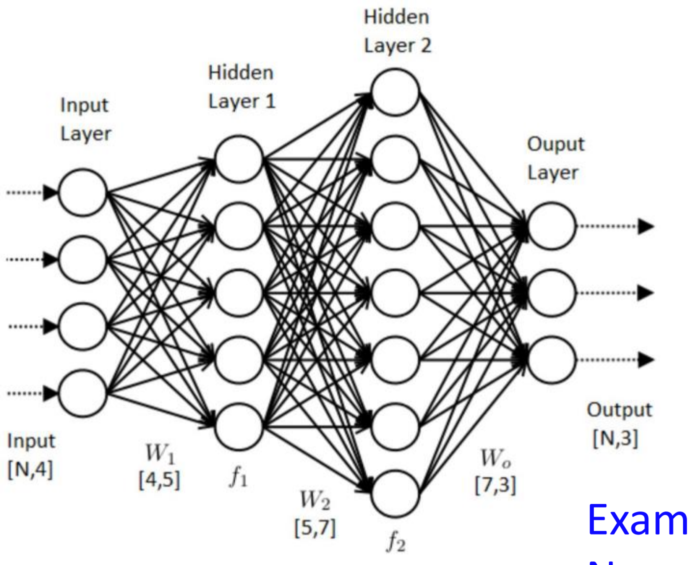
Machine Learning

	Supervised Learning	Unsupervised Learning
Goal	A program that performs as well as humans	To find structure in the data
Task	Well defined (e.g., a target function to constrain results)	Not well defined or could be undefined
Past Experience	Training data set provided by a human	None supplied
Performance	Error/accuracy with respect to the task	Unable to evaluate
Subcategories	Classification and Regression	Clustering/Dimensional Reduction (including feature extraction/selection)

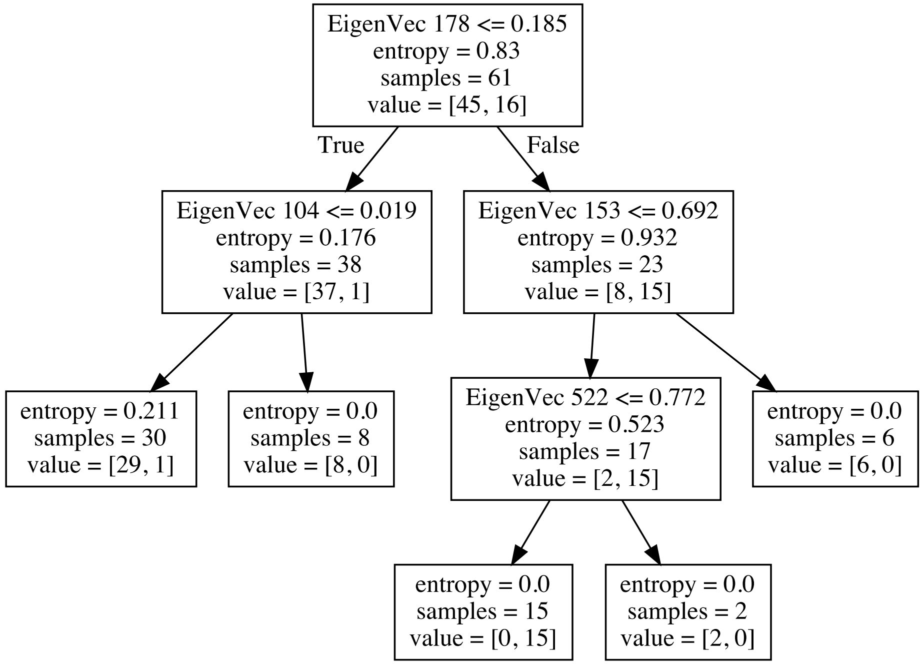
- ML methods are based on defining labeled "feature vectors".
- Labels are target variables for each feature vector.
- Typical feature vectors are statistical quantities characterizing the system
- Labels could be "1" for presence of a desired characteristic, "0" for its absence
- As an example, label "1" could be a major earthquake in the next year, "0" otherwise

Machine Learning Open Source Libraries

- Scikit-Learn (Classification and Regression)
- Tensorflow (Neural Networks including Deep Learning)
- PyTorch (Deep Learning)
- Keras (Deep Learning)



Example of an Artificial Neural Network

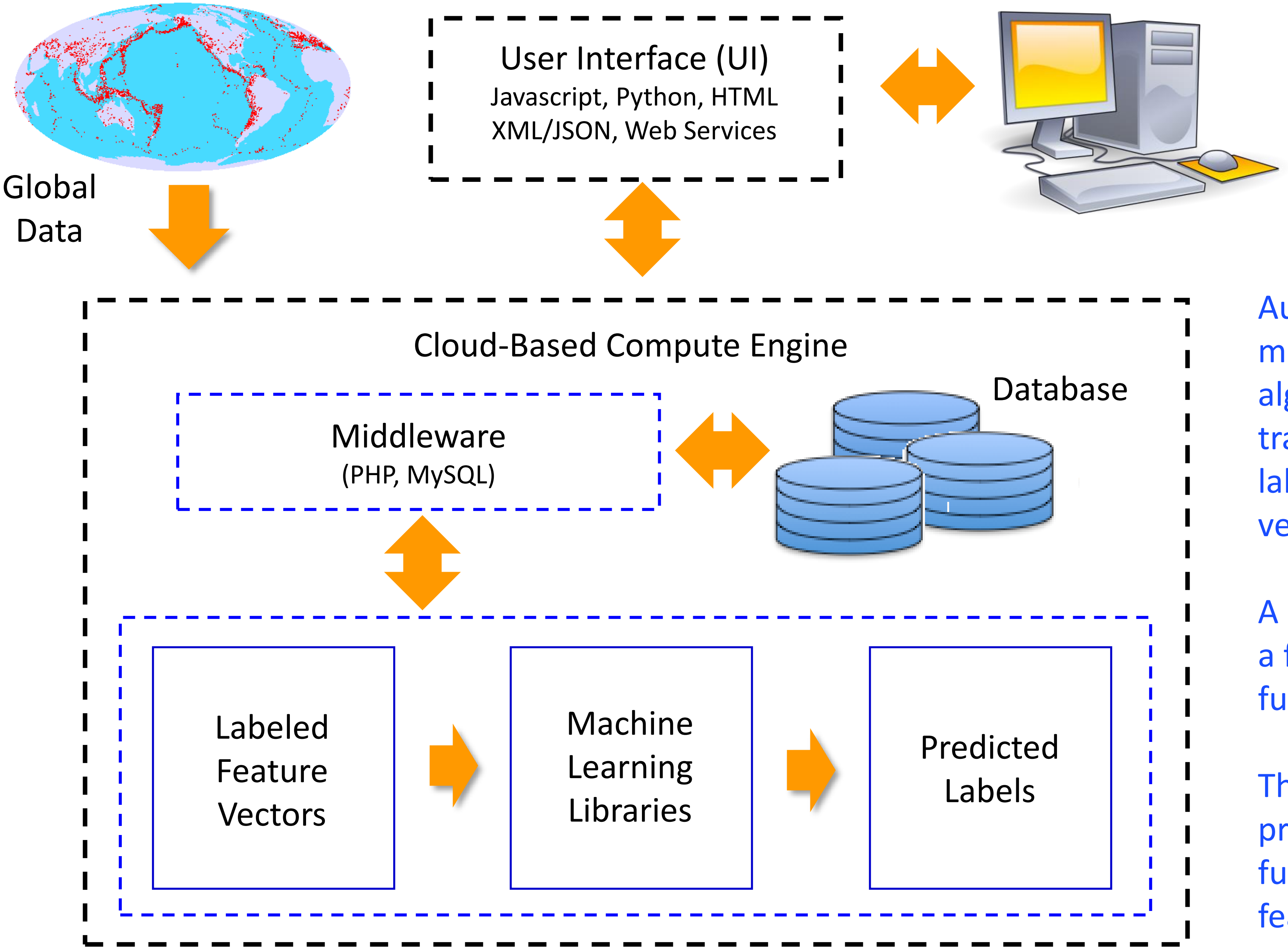


Example of a decision tree in Scikit-Learn application (Rundle et al., 2020)

Workflow for Forecasting/Nowcasting with Machine Learning

Machine Learning Libraries include:

- Scikit-Learn
- Tensorflow
- PyTorch
- Keras



Automated machine learning algorithms involve training and testing labeled feature vectors

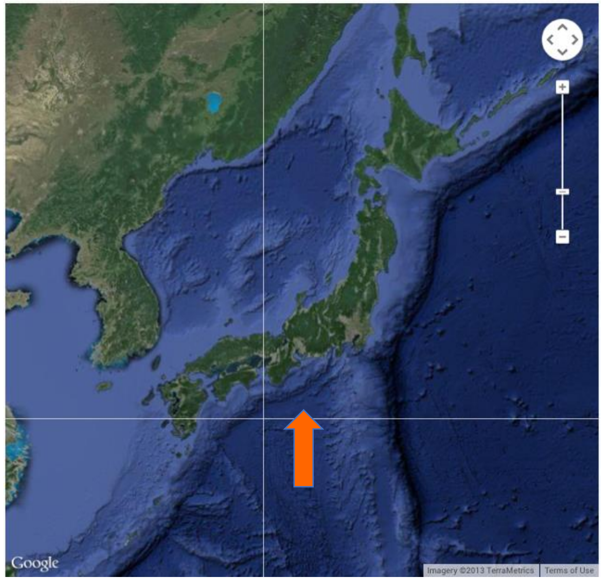
A new label implies a forecast for future data

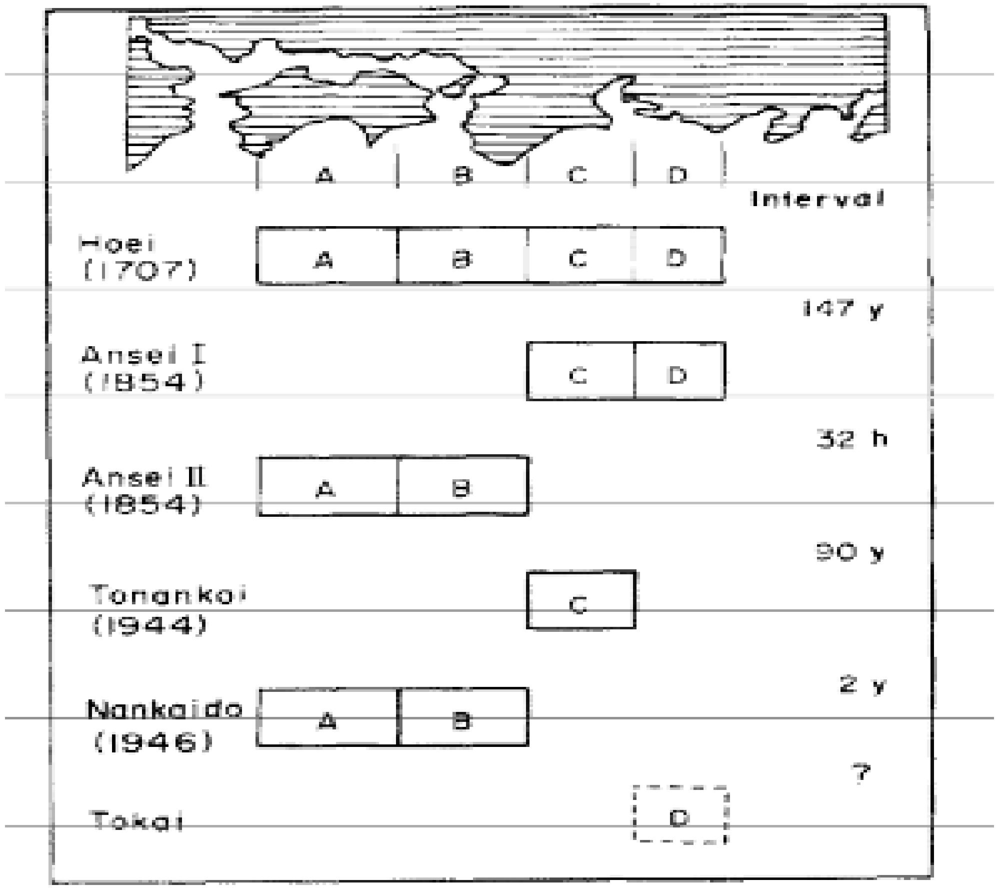
The result is predicted labels for future unlabel feature vectors

Example: The Earthquake Cycle in the Nankai Trench, Japan

M Ando, Tectonophysics, v27, p112 (1975)

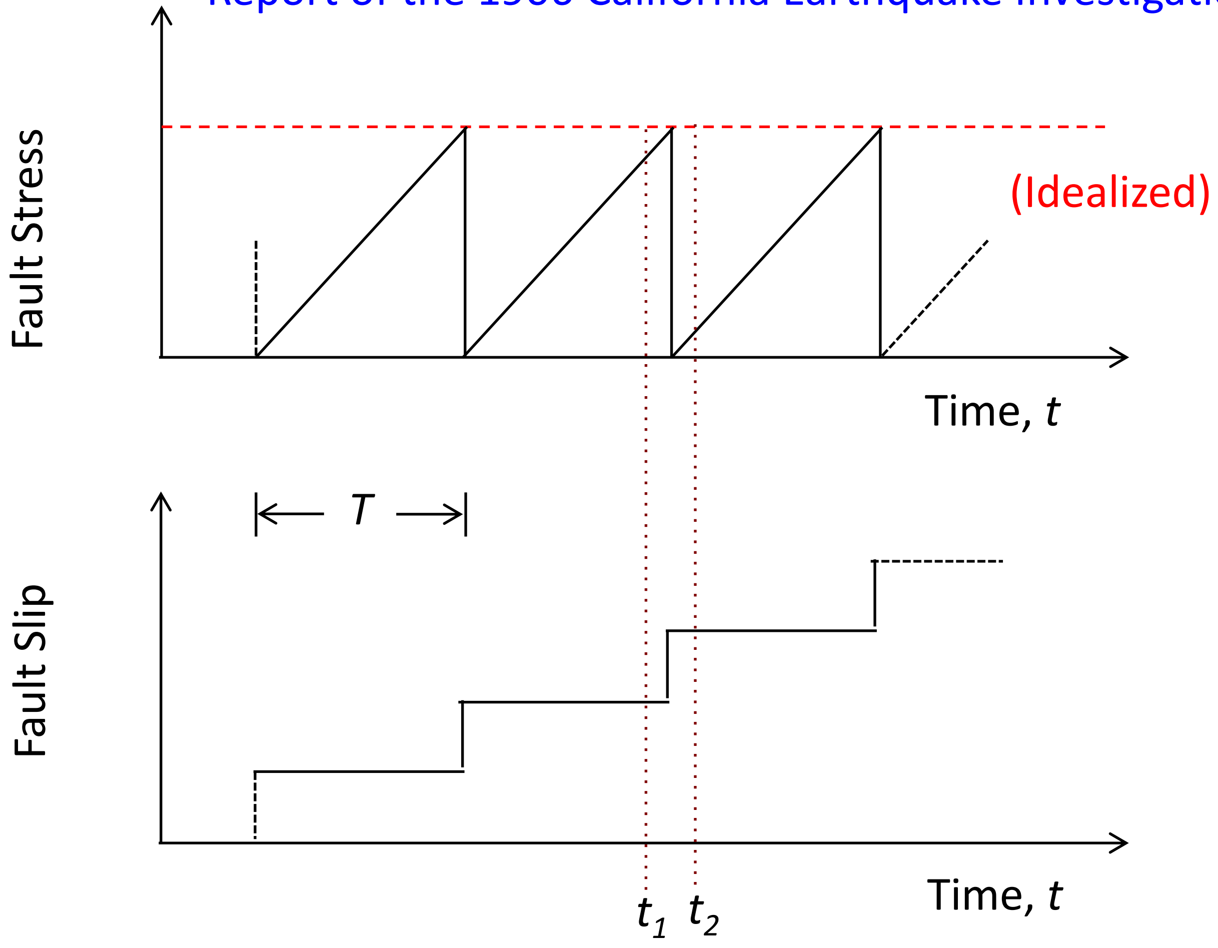
- Data from historic writings in Japan
- The basic idea of the earthquake "cycle" started in Japan using historical data





The Earthquake Cycle

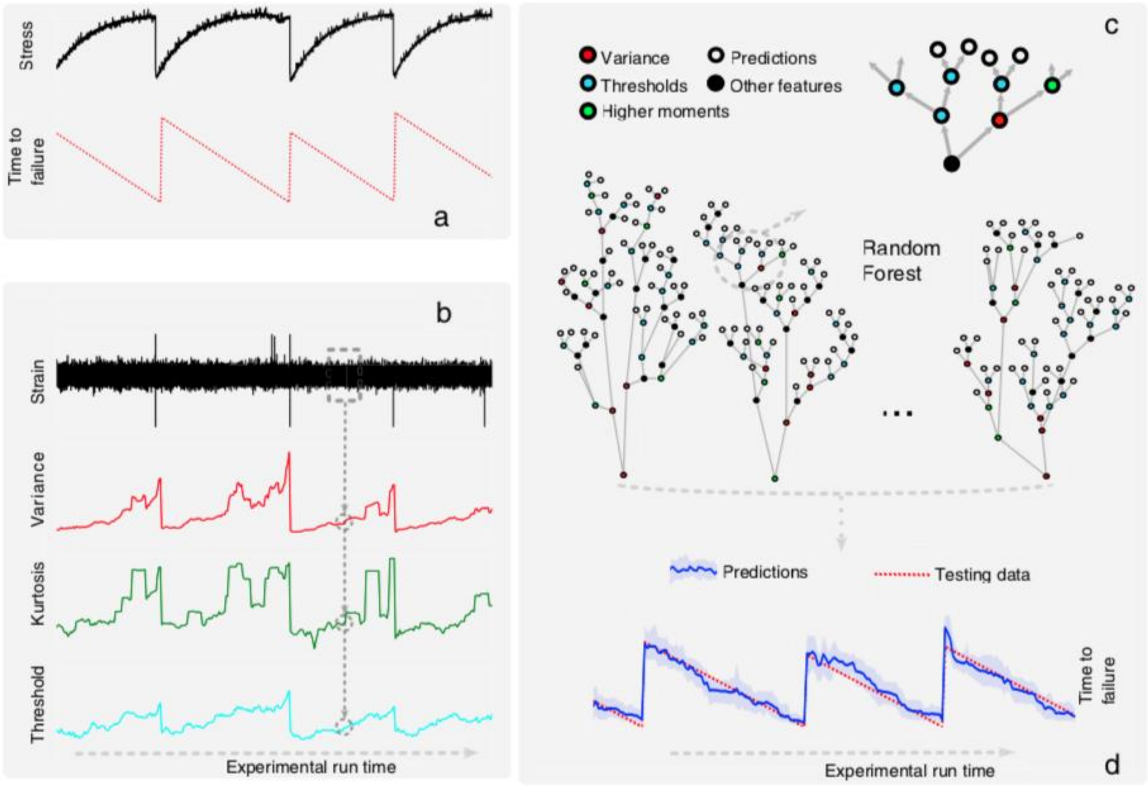
Report of the 1906 California Earthquake Investigation (1910)



Harry Fielding Reid (1859-1944)

Applications of ML to Earthquake Forecasting
(Rouet-Luduc et al., 2017,2019)

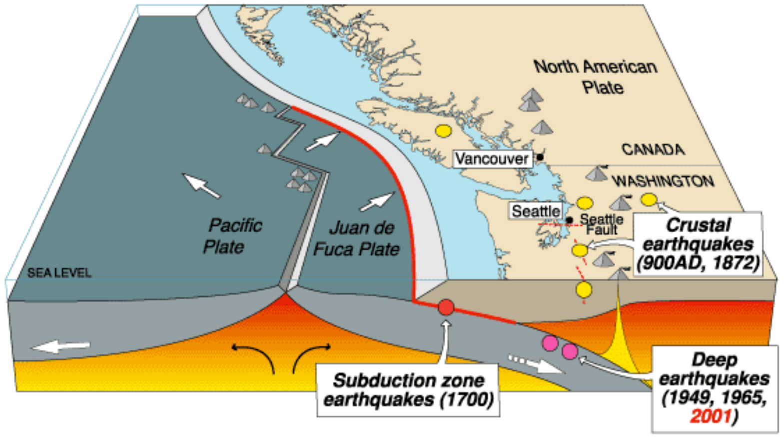
- Earthquake forecasting in the laboratory
- Laboratory experiments on model earthquakes faults showed sudden slip accompanied by bursts of acoustic emissions (AE: small laboratory ”earthquakes”)
- R-L used a machine learning technique called ”Random Forest” to predict the onset of sliding from the AE
- The Random Forest method is an example of “supervised learning”



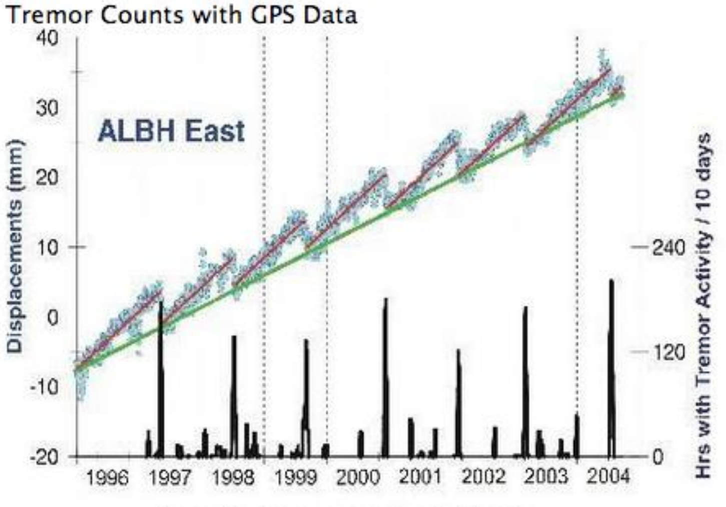
Applications to Cascadia
(Rouet-Luduc et al., 2017,2019)

- Episodic Tremor and Slip (ETS) is a process of sudden small slip on faults accompanied by a burst of small earthquakes
- Similar to the laboratory friction experiments
- Rouet-Leduc applied the method to the Pacific Northwest subduction zone and found similar quality results to predict the ETS events

Cascadia earthquake sources



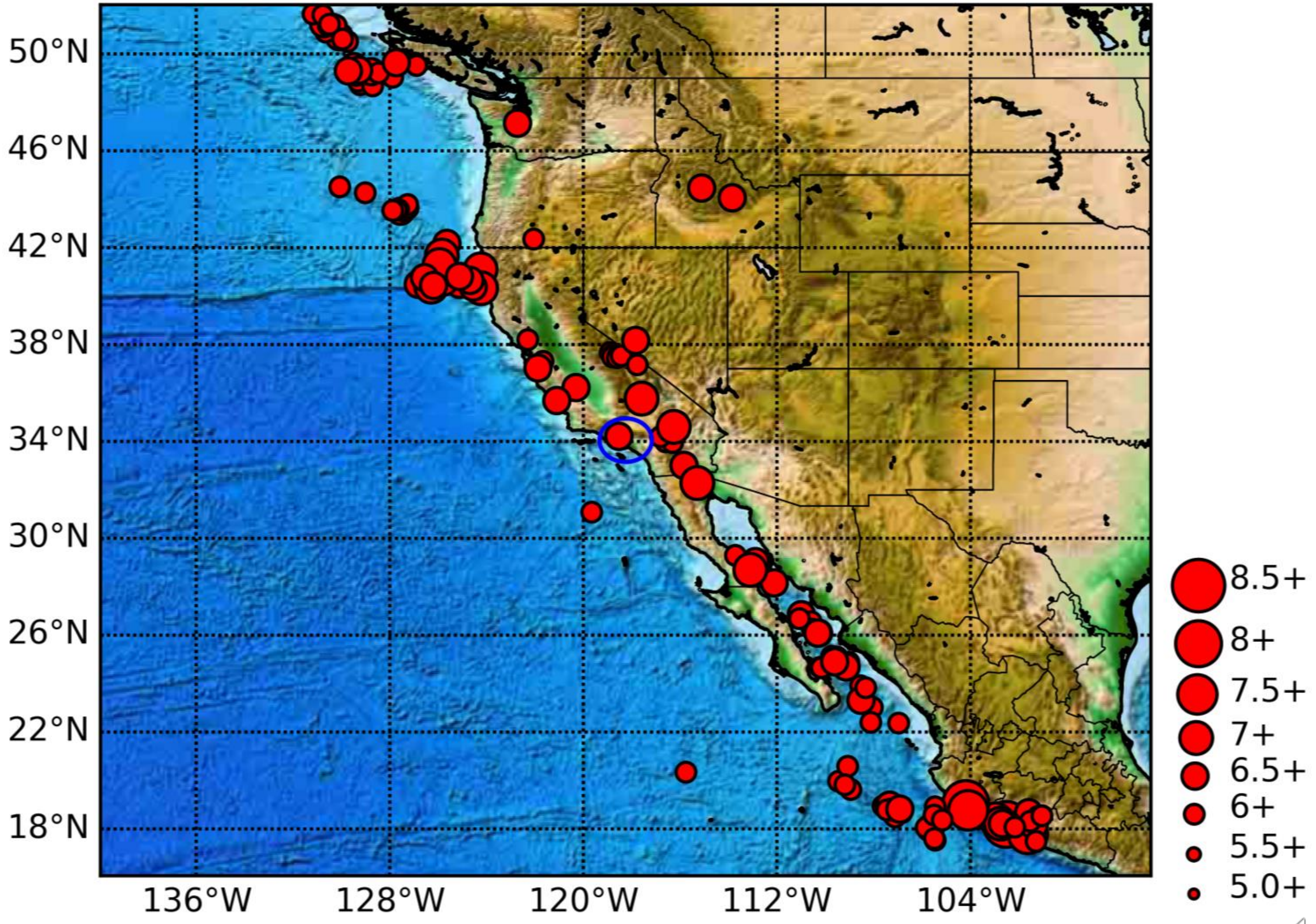
	Source	Affected area	Max. Size	Recurrence
(red)	Subduction Zone	W.WA, OR, CA	M 9	500-600 yr
(pink)	Deep Juan de Fuca plate	W.WA, OR,	M 7+	30-50 yr
(yellow)	Crustal faults	WA, OR, CA	M 7+	Hundreds of yr?



*source: http://gsc.nrcan.gc.ca/geodyn/ets_e.php

Applications:

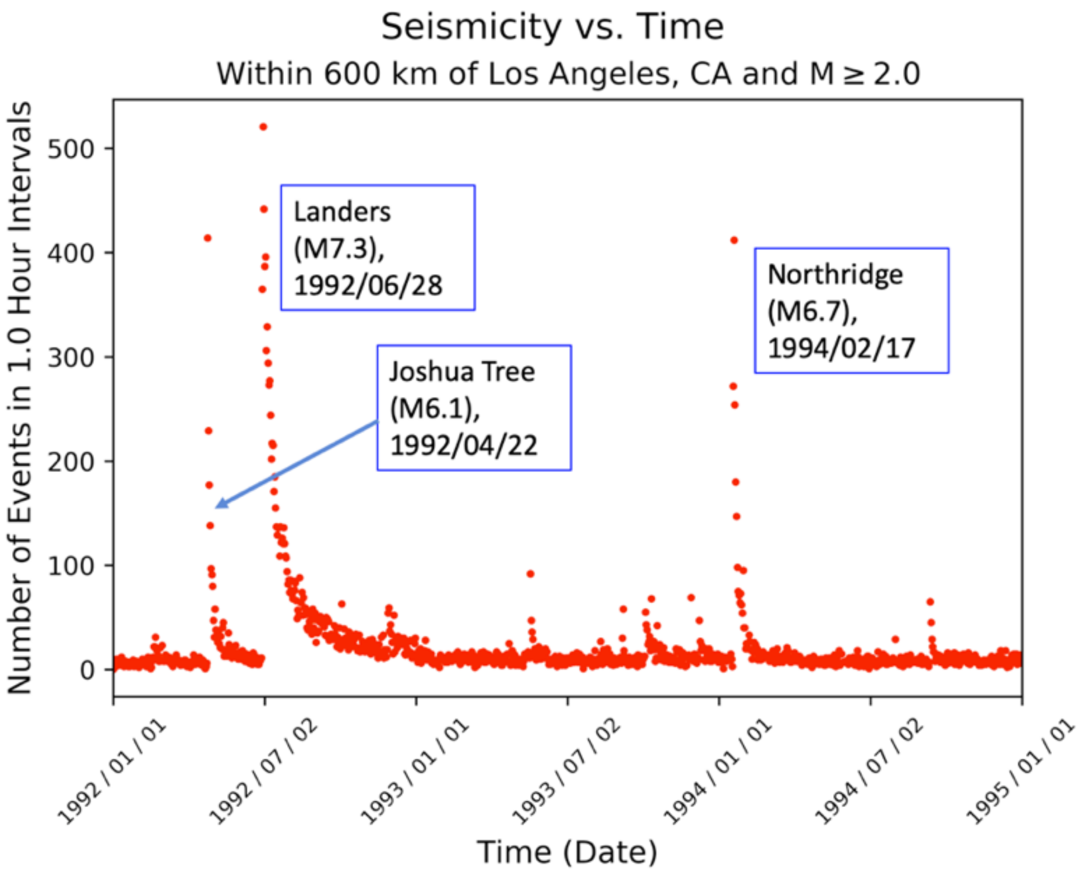
Earthquakes along the west coast of the US , Mexico and Canada since 1980



These earthquakes occur irregularly in time and do not show the rather periodic patterns shown in the laboratory or in Cascadia

Earthquake “Bursts”

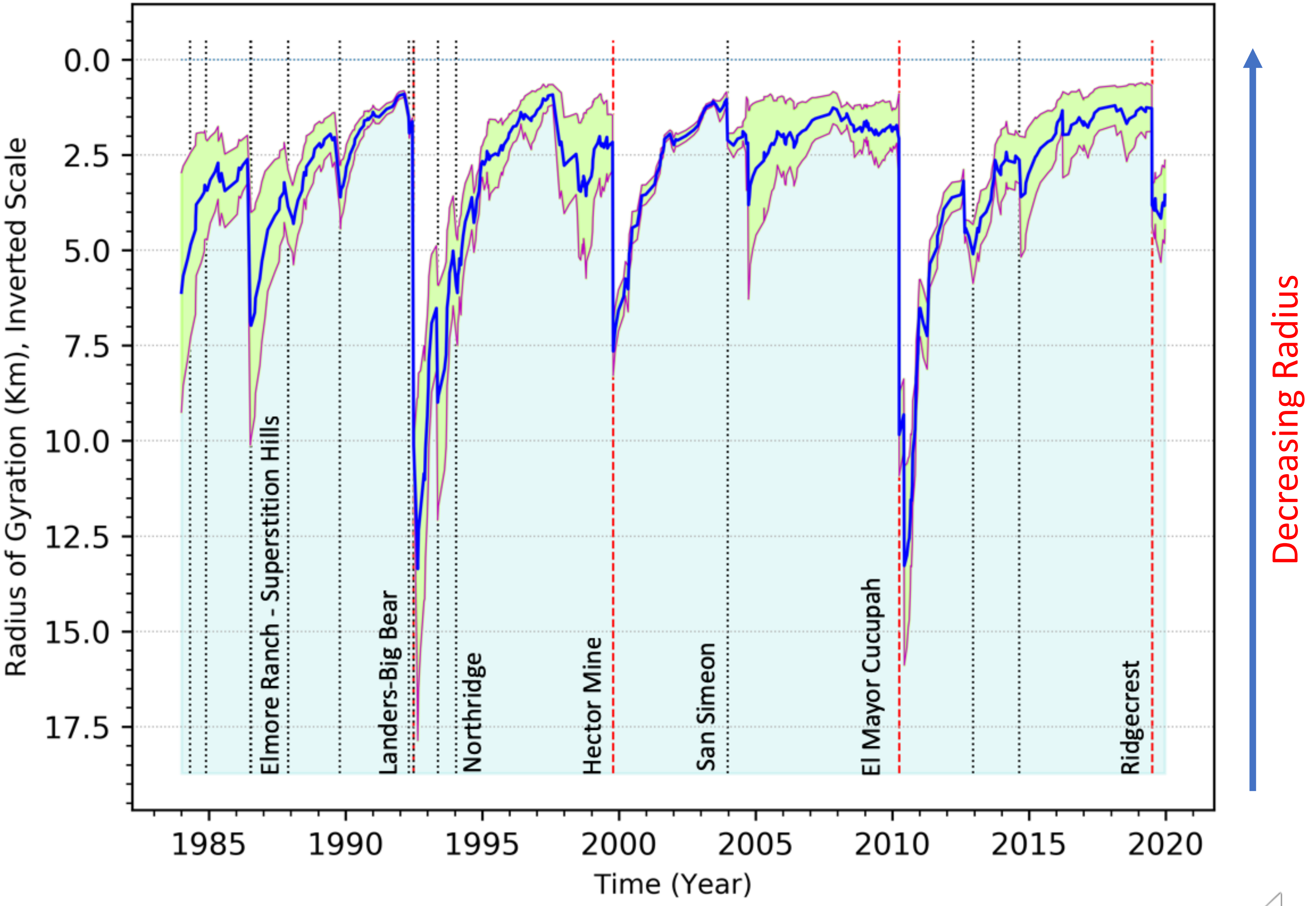
- Major earthquakes are accompanied by many small small magnitude earthquake burst events
- One type of burst is represented by earthquake aftershocks
- Other types of burst events are called “swarms”, where there is no large main event
- We have used ML classification techniques to show that the size of these bursts varies systematically in time prior to large earthquakes in California (Rundle and Donnellan, 2020)



Earthquake "Bursts"

Rundle and Donnellan (2020)

- Horizontal radius of small earthquake bursts as a function of time
- Region is a 600 km radius circle around Los Angeles, CA
- Data show that burst radius decreases with time prior to M>7 earthquakes
- Most recent earthquake is a M7.3 earthquake in east-central California on July 5, 2019, the Searles Lake Ridgecrest, California earthquake



Vertical red dashed lines: $M \geq 7$ earthquakes

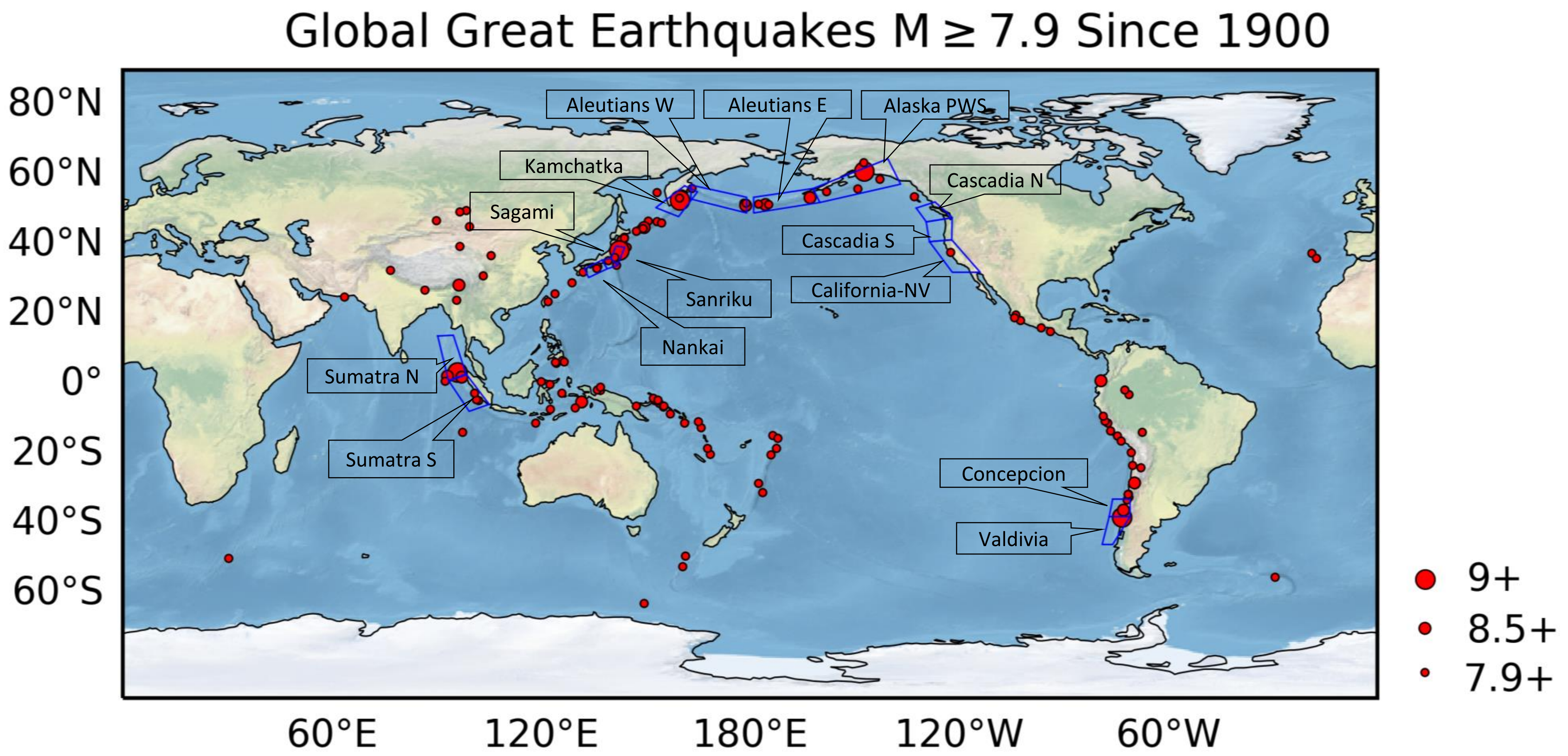
Vertical black dashed lines: $6 \leq M \leq 7$ earthquakes

Application: Nowcasting Tsunamis and Runup for Tsunami Early Warning

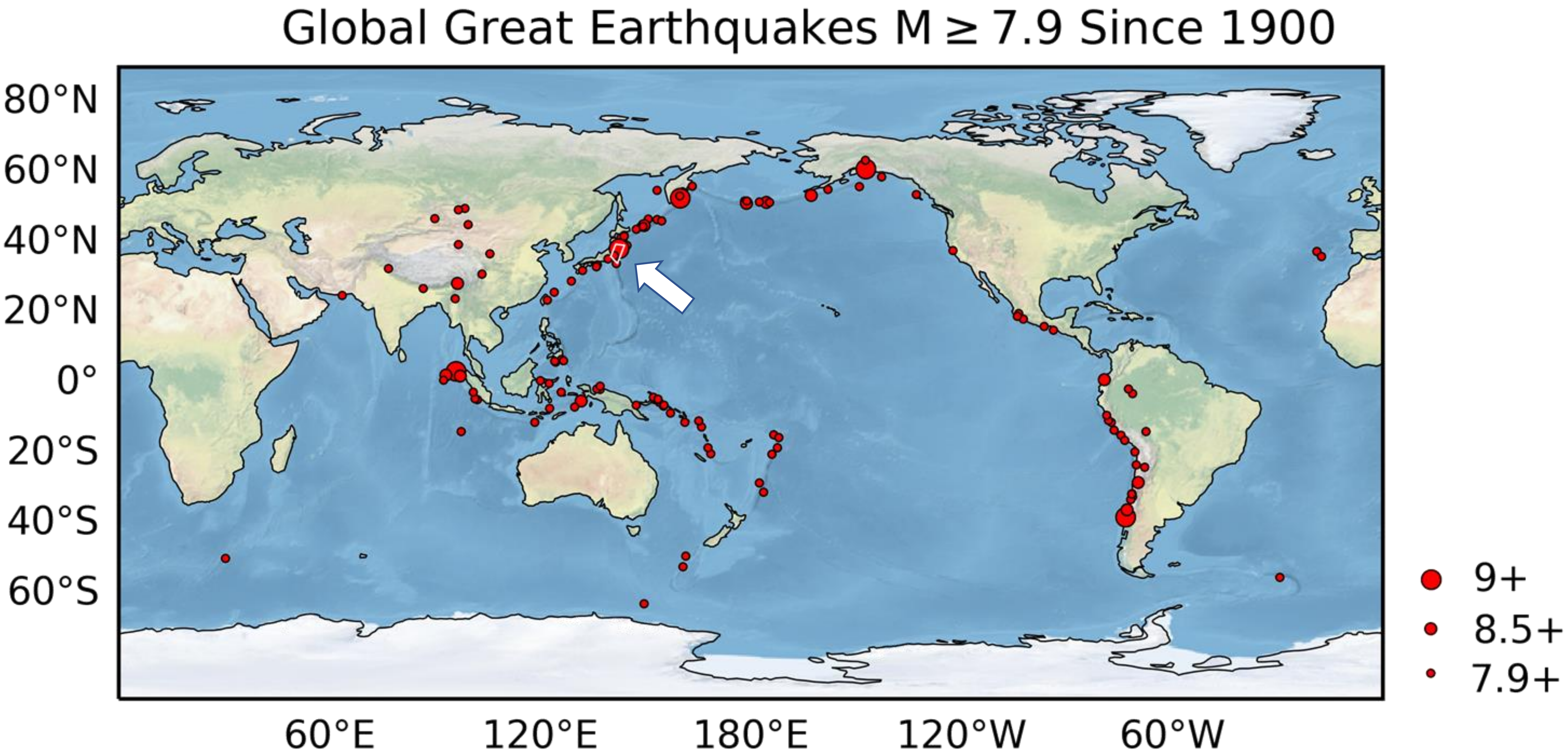
- We would like to provide an estimate of risk from a major earthquake and tsunami
- Both long term (months to years) risk as well as early warning (minutes)
- For this we need not only an earthquake model, but a tsunami inundation model

Nowcasting Great Earthquake and Tsunamis

Source Regions

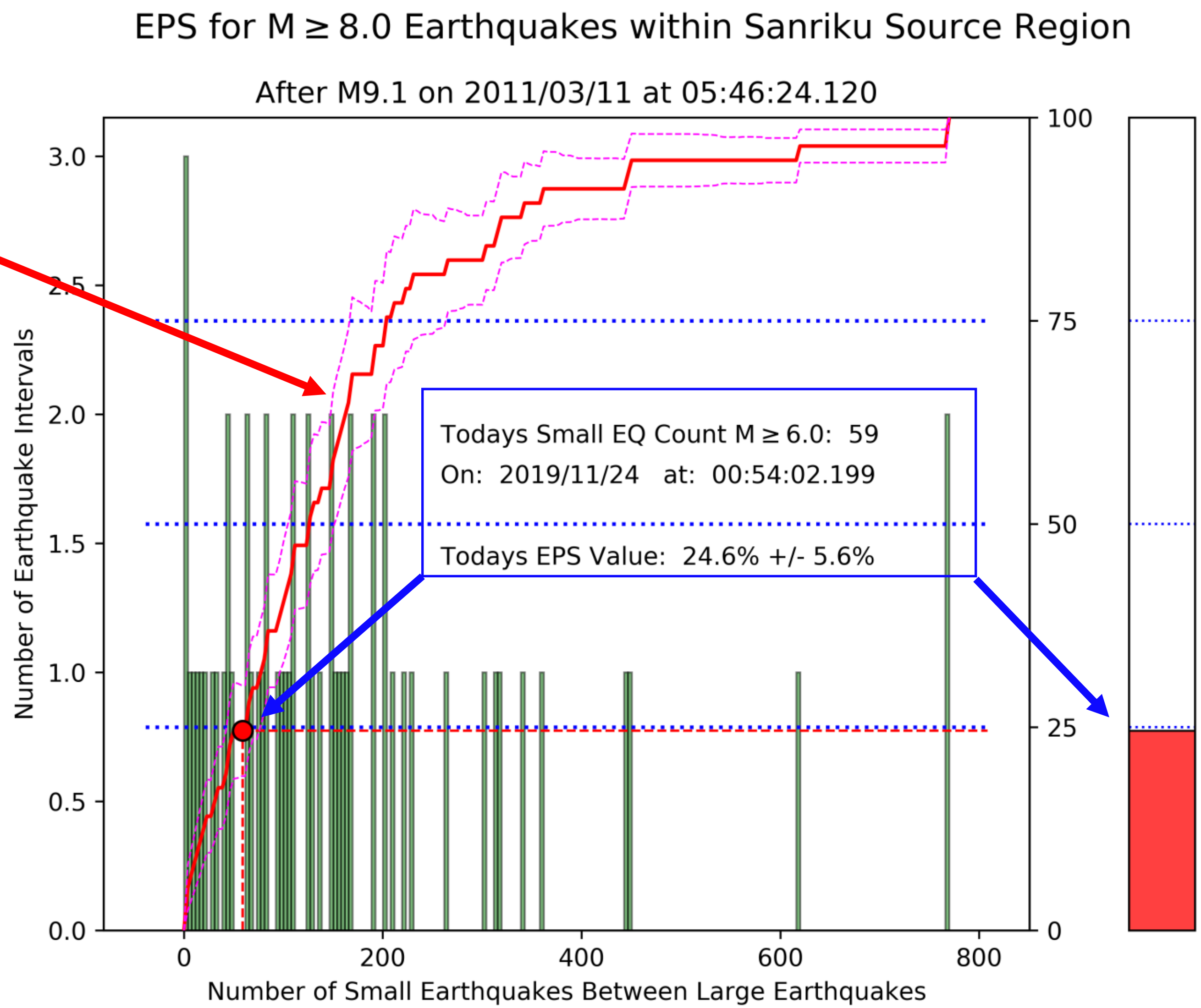


Sanriku Coast Source Region



Earthquake Potential Score

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

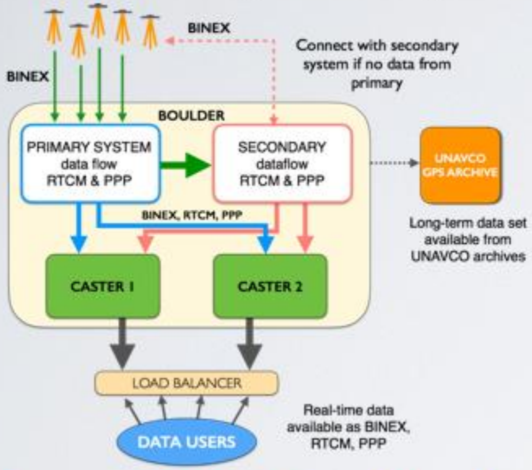


Histogram of small earthquake numbers between large earthquake intervals

UNAVCO

STEPS INVOLVED IN GNSS DERIVED TSUNAMI EARLY WARNING

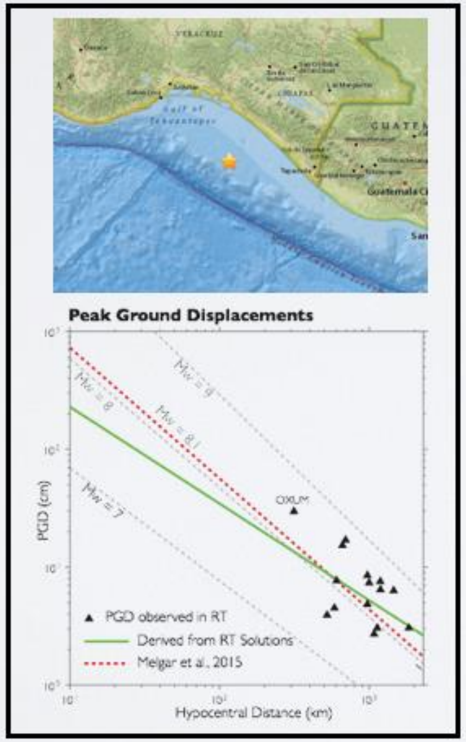
Step 1: Collect and process the high-rate GNSS data (< 10 secs)



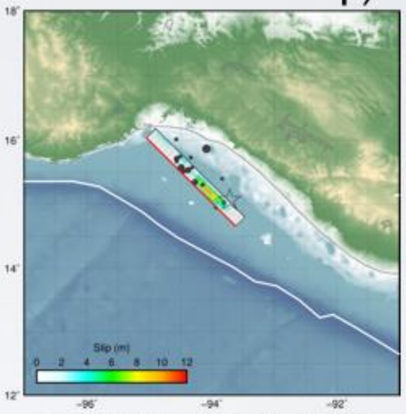
Tsunami model from Diego Melgar, U. Oregon

- 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)

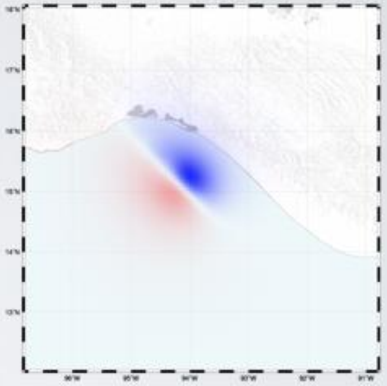


Step 3: Inversion for finite fault model, ~ 90 secs (length and distribution of slip)

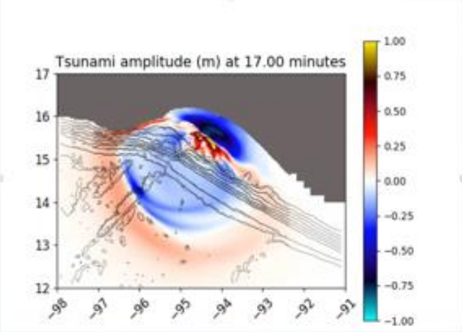


* currently methods using seismic data only

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

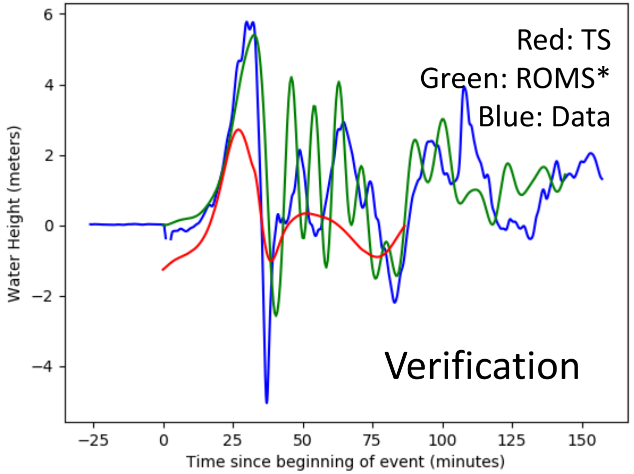


Step 5: Run tsunami simulation, using submarine displacements from step 4 (~300 secs)



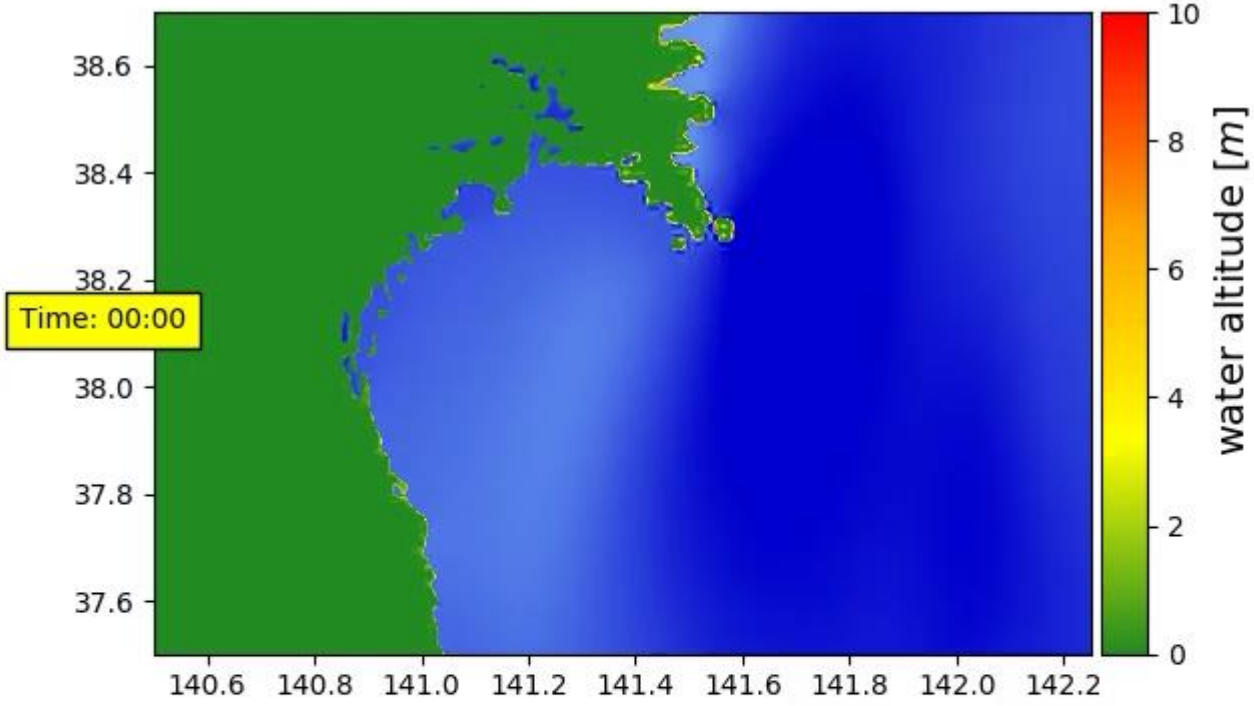
Simulating Great Tsunamis: Tohoku Earthquake and Tsunami March 11, 2011

Simulations by David Grzan and John Wilson with help from Steve Ward



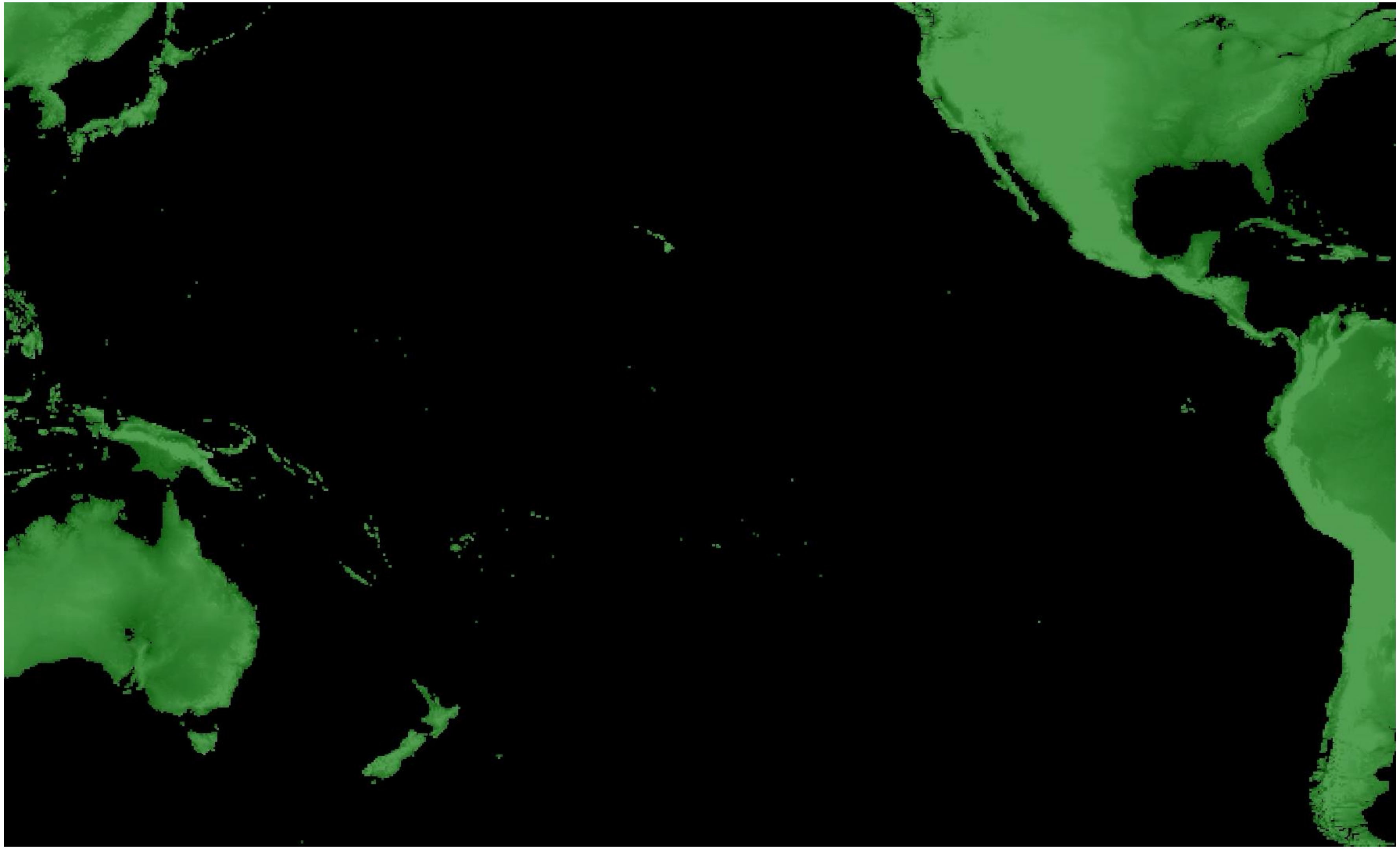
*ROMS: Regional Ocean Modeling System (Finite Difference)

Coastal Inundation



Tsunami Squares is a simulation method that can compute coastal runup and inundation, as well as basin-wide tsunamis. We verify results of the simulations with buoy data and runup data. As part of the simulation, we conserve mass, momentum and energy.

Pacific Basin – Wide Simulation by Tsunami Squares Method



Summary

- Great earthquakes and tsunamis present major risks to populated regions
- Anticipating these events by means of forecasting and nowcasting remains an important problem
- Modern methods of Machine Learning are promising tools for advancing the science
- Early warning depends on advances in models and technology

Thank you for your attention!