



*On the Job Training on*

*Tsunami Inundation Modelling and Mapping and Development of Tsunami Hazards Maps for  
Implementation of UNESCO-IOC Tsunami Ready Pilot Sites in Madagascar, Maldives, Seychelles and Sri Lanka  
Hyderabad – India, 16–21 March 2026*

# *Introduction to inundation modelling concepts*

**Patanjali Kumar Chodavarapu, M.S (DM), Ph.D**

*Scientist -F*

*Indian National Center for Information Services (INCOIS), MoEs, Hyderabad*

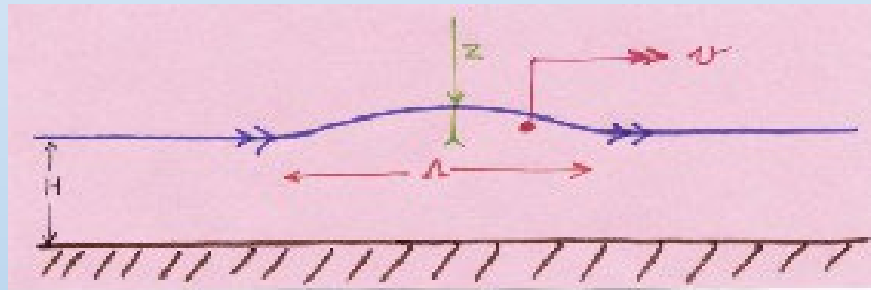
*patanjali@incois.gov.in*

# Physical Characteristics of a Tsunami in Deep Water

- Propagation Speed: Speed depends on ocean depth,  $H$ .

- In practice:  $H=5$  Km,  $v=220$  m/s ( $\sim=800$  Km/h)
- (approximate cruise velocity of a commercial airliner)

$$v = \sqrt{gH}$$

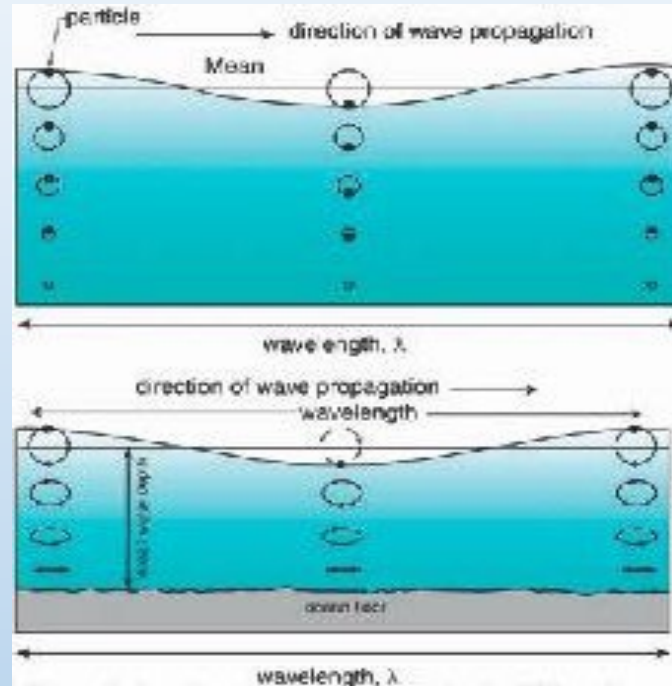


- Maximum Amplitude,  $z$ : from a few centimeters to a half meter.

- Typical Wavelength:  $\Lambda = 300$  km (period  $\sim 600$  s-3000s)
- A tsunami is always composed of several waves.

# Physical Characteristics of a Tsunami in Deep Water

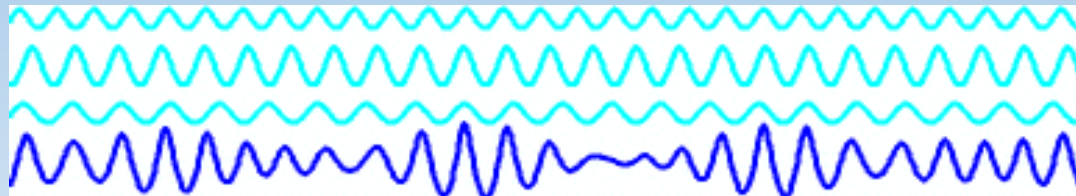
- A tsunami is always a long wave (alt. A wave in shallow water).



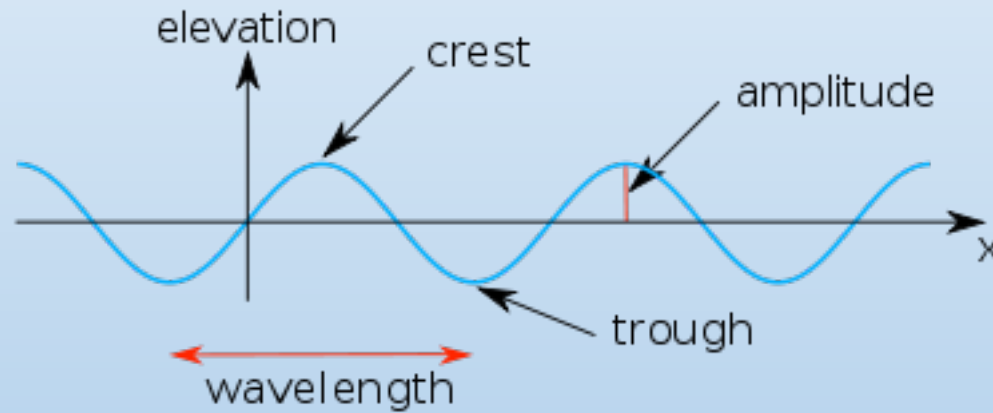
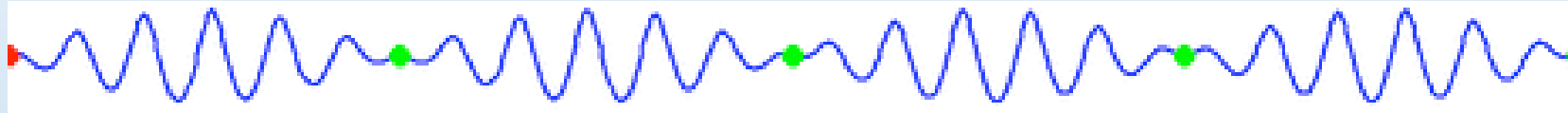
- A tsunami is a non-dispersive wave.

$$c = \frac{\omega}{k} = \sqrt{\frac{g \times \text{Tanh}(kH)}{k}}$$

Example of dispersive wave behavior



# Wave Dispersion



In general, Wave length or wave frequency varies with wave speed (by definition)

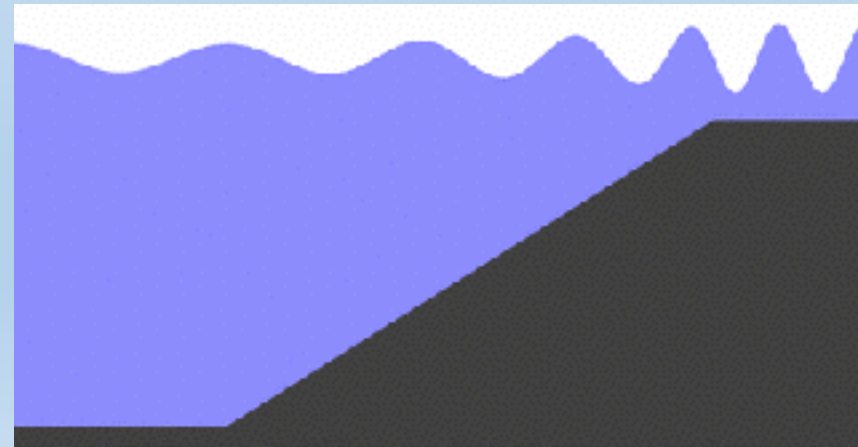
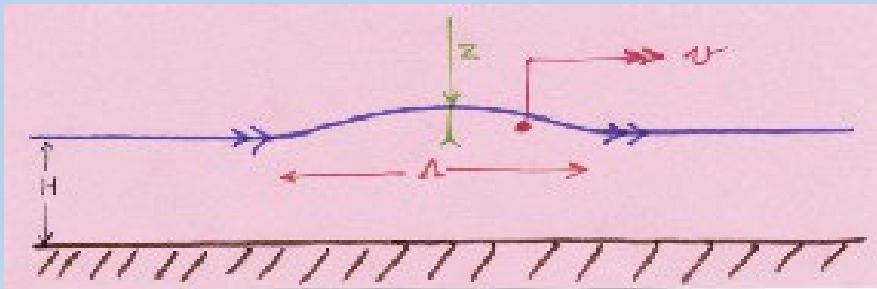
(long wavelength --> low frequency ; Short wavelength --> high frequency)

# Physical Characteristics of a Tsunami in Shallow Water

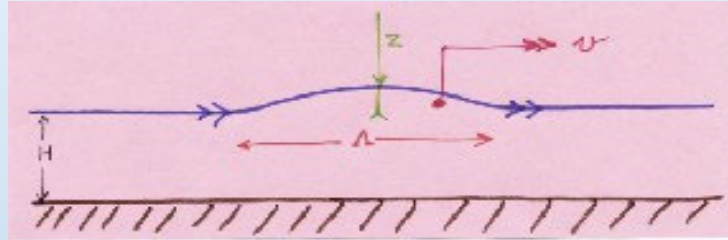
- Propagation Speed: Speed depends on ocean depth,  $H$ .

$$v = \sqrt{gH}$$

- The leading part of the wave slows down as it enters shallow waters, the trailing part of the wave is still in deep water and moving faster than the leading part. This causes the wave height to increase and the wavelength to shorten.



## Physical Characteristics of a Tsunami in Shallow Water.



- Tsunami wave heights in shallow water can reach tens of meters.
  - Typical wavelengths will range between 10-20 Km.
- The size of the tsunami wavelength makes it much more destructive than storm waves.

# Methods to solve the Shallow water Equations

1 **Analytical solutions**  
Closed-form solution. This is not possible in all cases.

2 **Finite Difference Method (FDM)**  
Differential Equations are discretized using Taylor series and time-integrated  
Ex: **comMIT**, TUNAMI, COMCOT, **MOST**, FUNWAVE

3 **Finite Element Method (FEM)**  
Subdivides domain into smaller parts called finite elements and are then assembled into the main domain  
Ex: ADCIRC, CAST3M, (ABAQUS, ANSYS, COMSOL)

4 **Finite Volume Method (FVM)**  
Volume integrals with divergence term are converted to surface integrals, using the divergence theorem and fluxes are evaluated at the surfaces  
Ex: ANUGA, CLAWPACK, FVCOM, OPEN-FOAM, (FLUENT)

5 **Finite Particle Method (FPM)**  
The differentials are converted into a summation formula using kernel functions that operates on nearby data points  
Ex: Smoothed Particle Hydrodynamics (SPH)

# SIMPLIFICATIONS IN THE SHALLOW WATER EQUATIONS

- Long wavelength compared with the local depth
- Uniform vertical profiles of horizontal velocities
- Hydrostatic pressure conditions.
- Inviscid fluid.

$$\omega = \sqrt{gk \tanh(kH)} \xrightarrow{kH \gg 1} v = \frac{\omega}{k} = \sqrt{gH}$$

Angular frequency -----> tsunami wave speed  
(dispersion wave)

# Dispersive vs. Non-dispersive Models

## Non-dispersive Model Characteristics

### 1 Range of Validity:

- in deep water
- for long waves.
- for long and intermediate wavelengths
- for wave of any amplitude

### 2 Capable of computing inundation

### 3 Capable of including numerical and amplitude dispersion

### 4 Intermediate computational speed

### 5 Example: MOST (ComMIT), GeoClaw,..

## Dispersive Model Characteristics

### 11-Range of Validity:

- in water of intermediate depth(Standard Boussinesq,  $O(\varepsilon)=O(\mu^2)\ll 1$ ).
- $\varepsilon=a/h$ ,  $\mu=kh$ , Valid of weakly non-linear waves.

- for long and intermediate wavelengths.

- for waves of any amplitude.

### 2 Capable of computing inundation

### 3 Capable of computing numerical, amplitude and frequency dispersion.

### 4 Intense and slow computational speed

### 5 Example: COULWAVE, FunWAVE,..

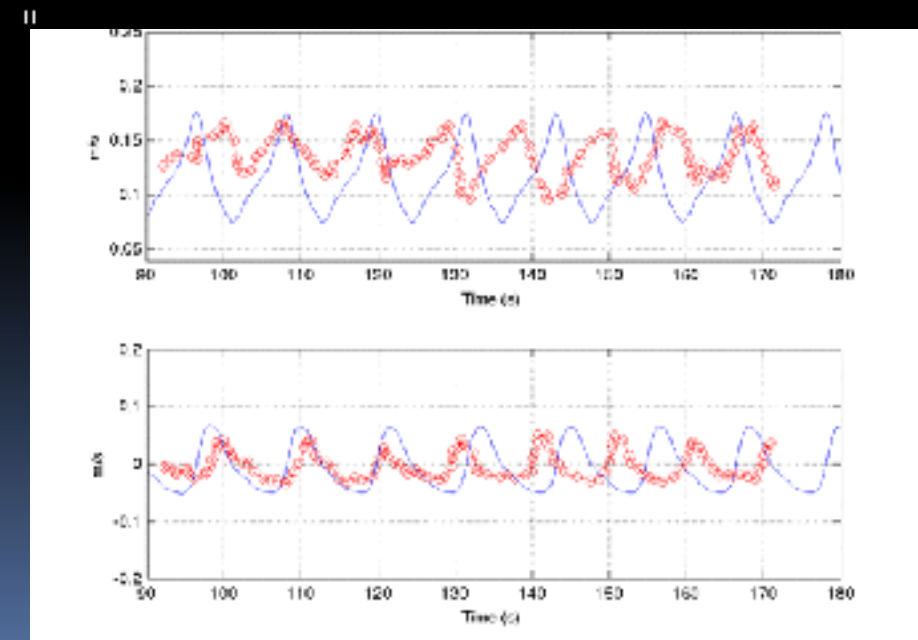
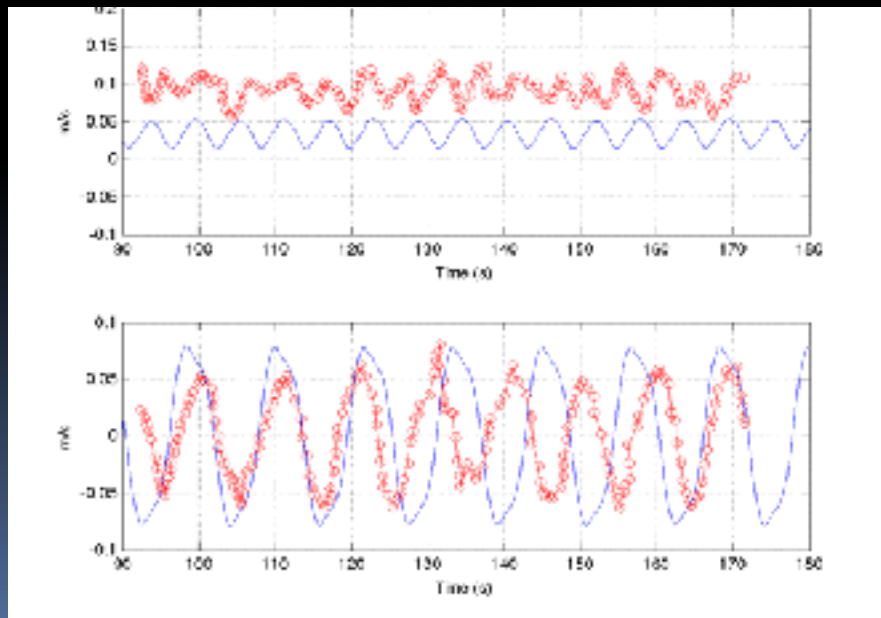
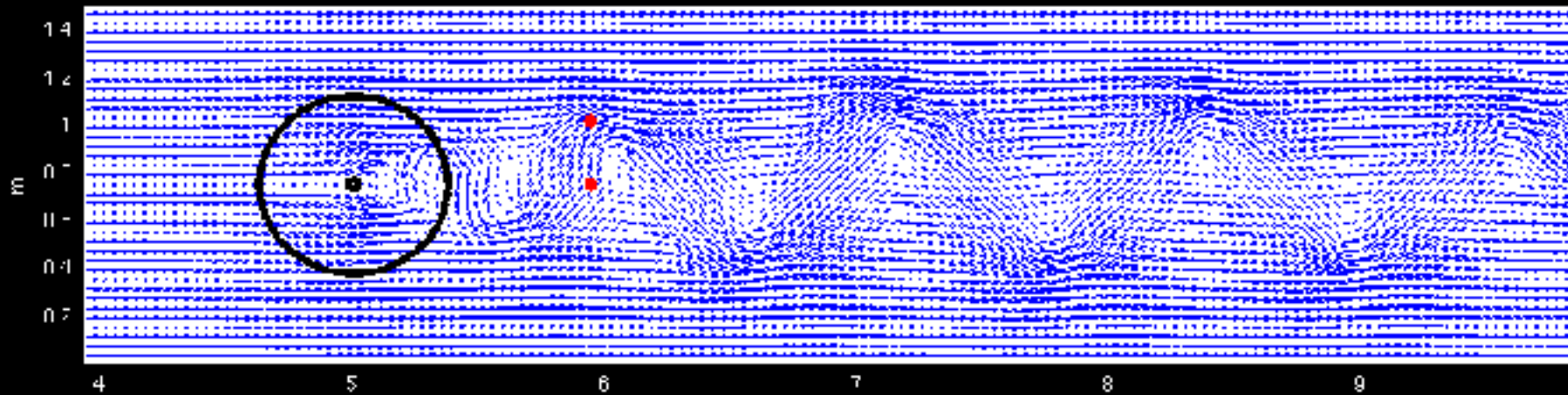
**Table 1.1.** List of Numerical Tsunami Models approved by NTHMP/MMS.

#	Model Name	Usable Sources		NTHMP		Available for download			Relative run-time ⌚ hrs-days ⌚⌚ days ⌚⌚⌚ month	Model Physics <sup>1</sup>
		Seismic	Landslide (including volcanic, mass failures, underwater, over water)	Propagation	Inundation	Documentation	Available thru website	User interface		
1	ALASKA GI'T	√	√	√	√	Limited	√	√	⌚	SW
2	BOSZ	√		√	√	Limited			⌚⌚	B
3	COMCOT	√		√	√	Good	√		⌚⌚	SW
4	FUNWAVE-TVD, v.10	√		√	√	Good	√		⌚⌚	B
5	GeoClaw	√		√	√	Good	√		⌚⌚	B
6	MOST (ComMIT)	√		√	√	Limited		√	⌚	SW
7	NEOWAVE	√		√	√	Good			⌚⌚	B
8	SELFE	√		√	√	Good	√		⌚⌚⌚	CFD
9	TSUNAMI3D	√	√	√	√	Limited			⌚⌚⌚	CFD
10	TUNAMI/TUNAMI-N2	√		√	√	Good			⌚⌚	SW

<sup>1</sup>Model Physics

SW = A 2D model which employs linear and non-linear **Shallow Water (SW)** equations for tsunami generation, propagation and wave runup/drawdown. Pressure field is hydrostatic and the formulation ignores viscous effects, so these models are not recommended for landslide generated tsunamis. No vertical velocity and the modeled horizontal velocities are depth-averaged. Physical tsunami dispersion is often mimicked through numerical model dispersion. A practical choice for tsunami propagation and inundation simulations, however, models using depth-averaged wave equations cannot adequately address all the wave-structure interaction issues near the coast.

# VALIDACION DE LAS CORRIENTES DE TSUNAMI

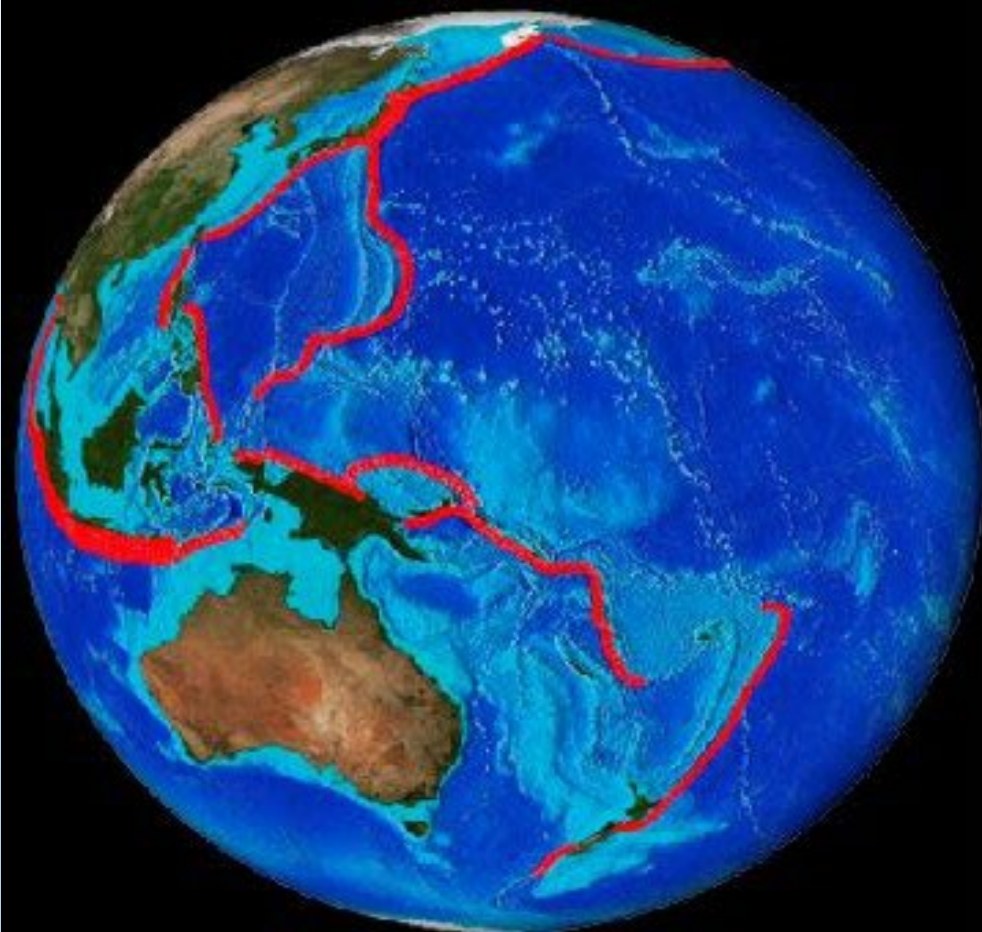


# What can we do about forecasting Tsunamis?

- Deploy Detection Hardware.
- Develop algorithms to interpret in-coming data.
- Develop numerical models to forecast/assess tsunami impact on the coast.

- What do we constrain with the deep-water DART measurement?

NOAA deep-water propagation  
model run database...

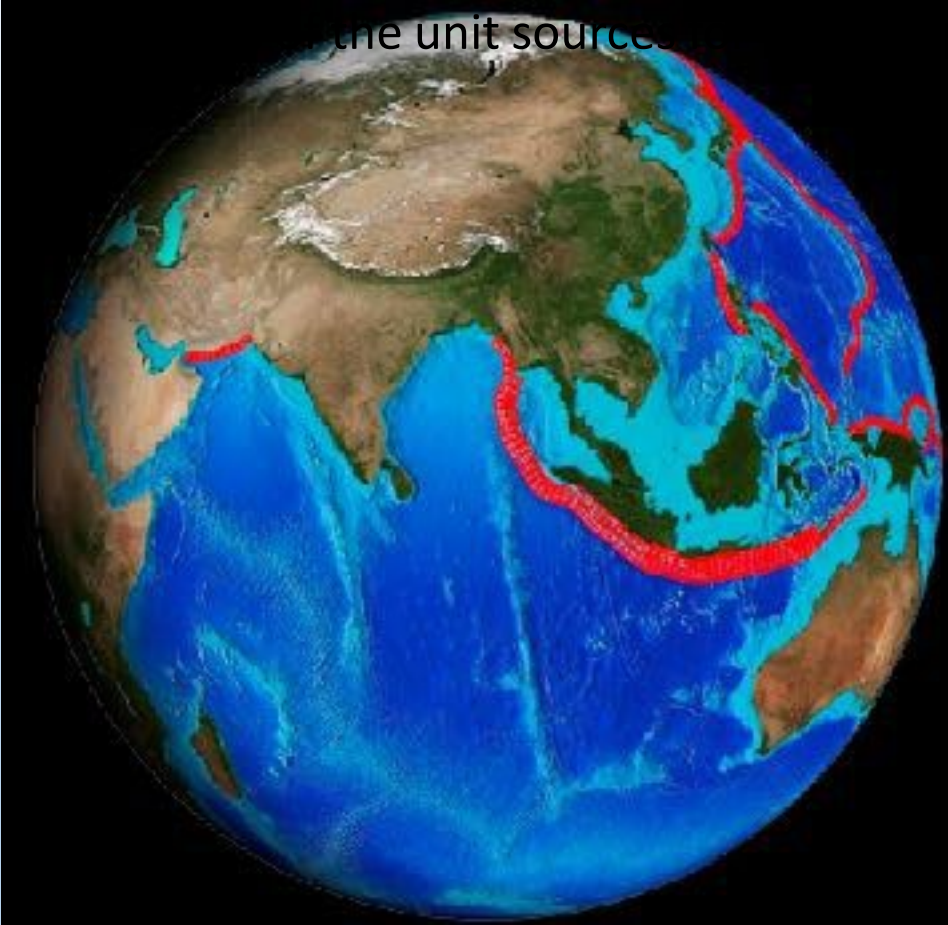


West Pacific



East Pacific

the unit sources of events.



Indian Ocean



Atlantic Ocean

- Why can we just add arbitrary pre-run models together during a

Any combination of solutions to the linear equations of motion is also a solution:

Linearity...

# SIMPLIFICATIONS IN THE SHALLOW WATER EQUATIONS

Continuity Equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

X-Momentum Equation:

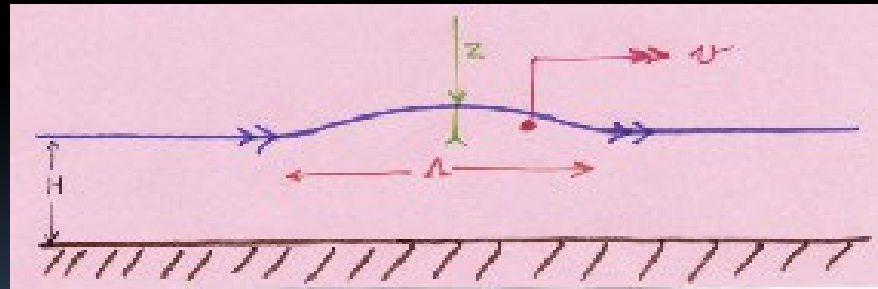
$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x}$$

Y-Momentum Equation:

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y}$$

Z-Momentum Equation:

$$\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + g$$

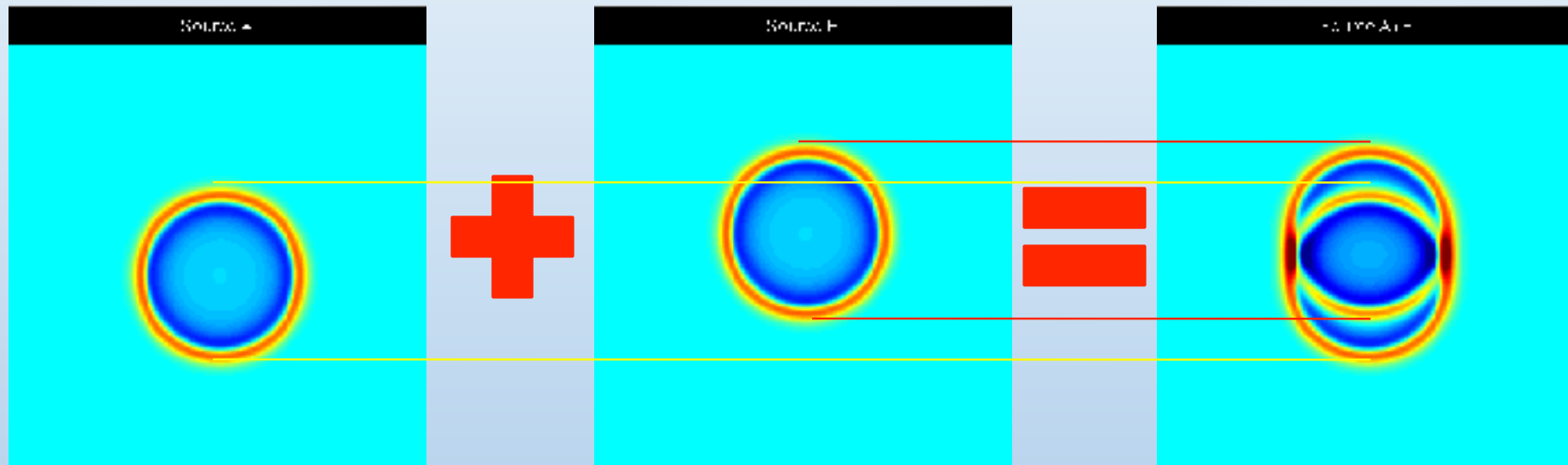


Hydrostatic Approximation:

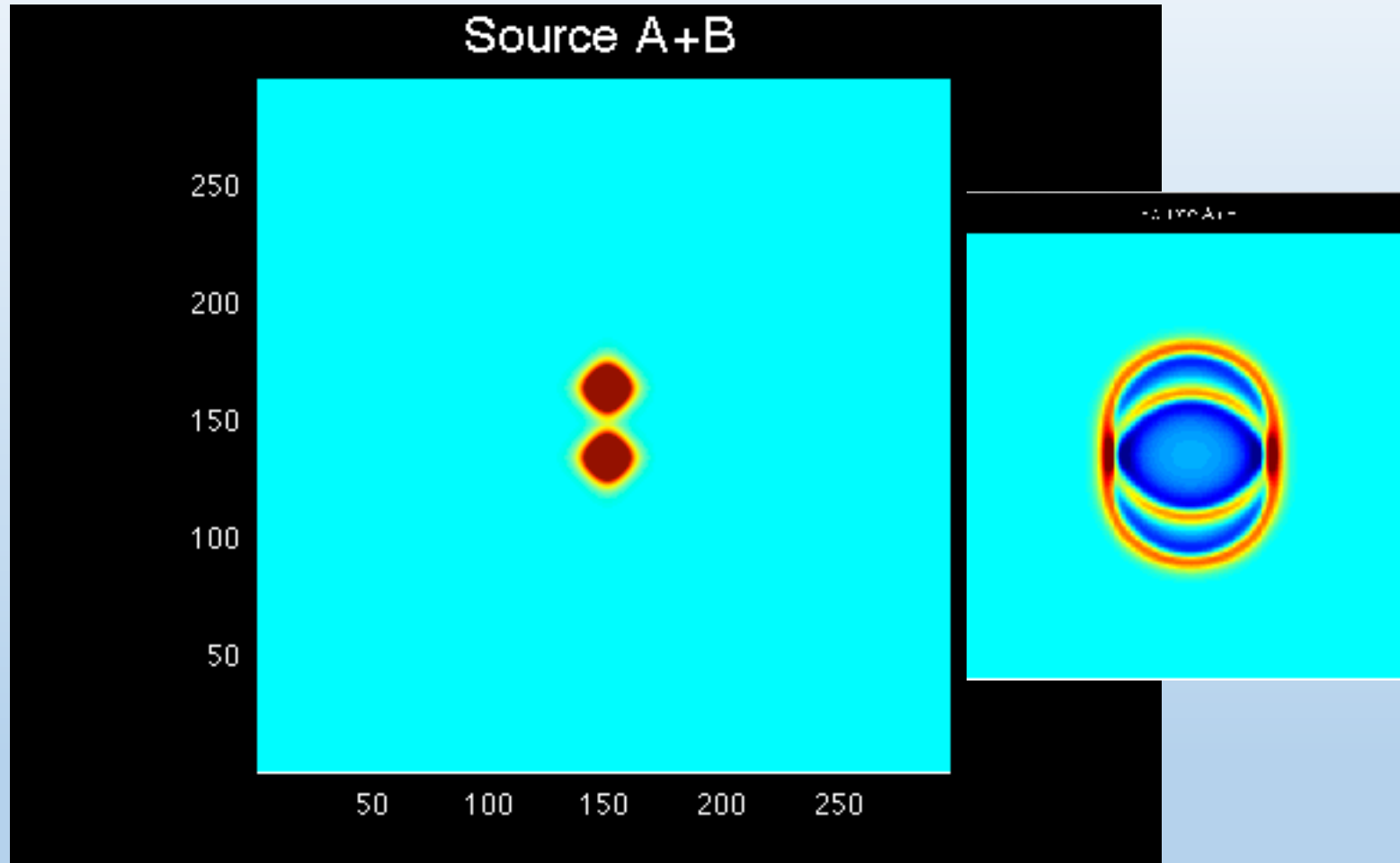
$$\frac{\partial p}{\partial z} = \rho g$$

$$p(x, y, z, t) = \int_z^{\eta} \rho g dz = \rho g [\eta(x, y, t) - z]$$

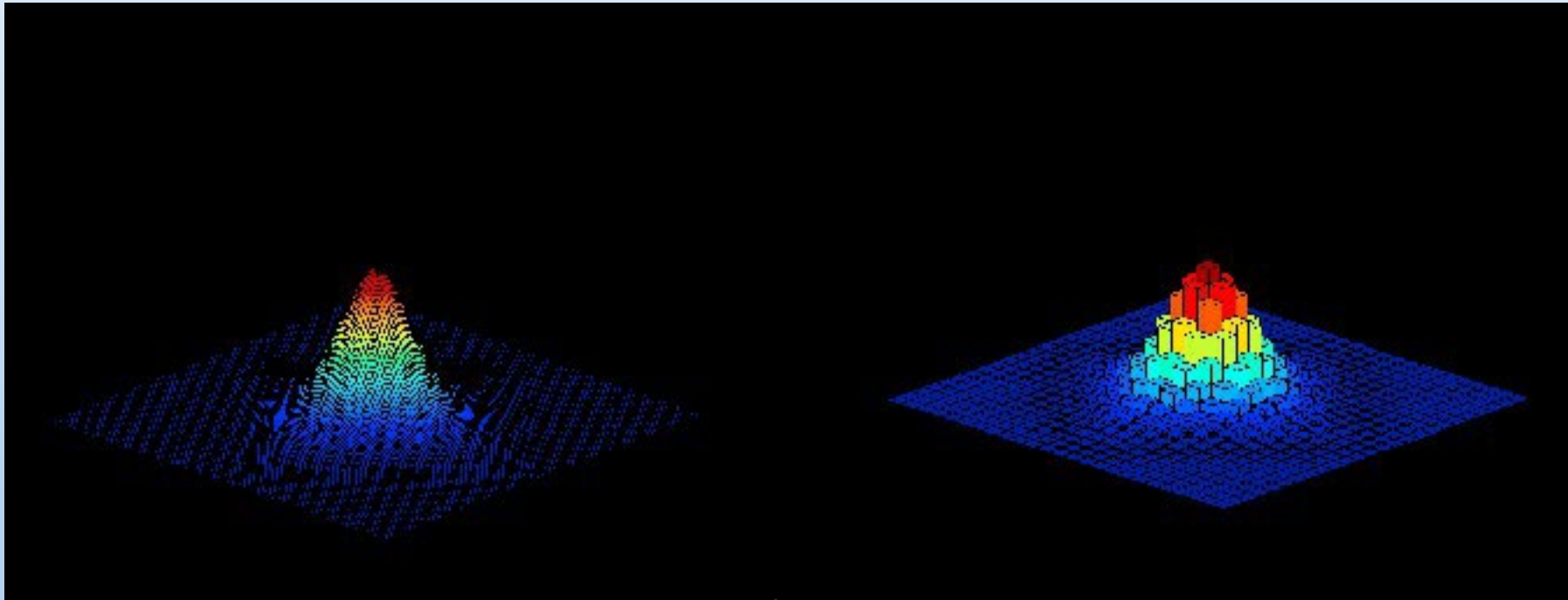
# Illustration of Deep Water Linearity



# Illustration of Deep Water Linearity

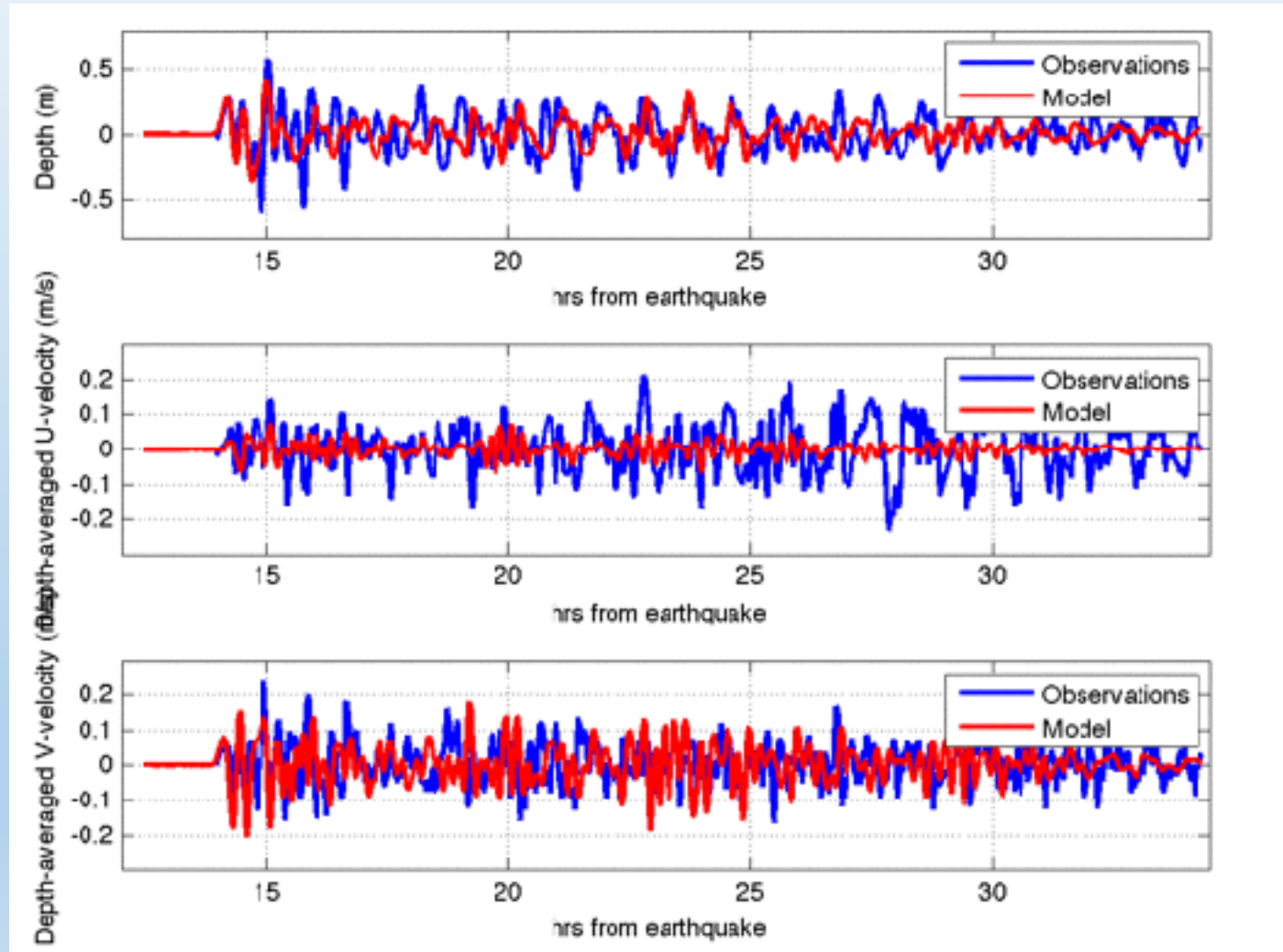


# Linearity allows for the reconstruction of an arbitrary tsunami sources using elementary building blocks



# For linearity $u \ll gh$

$$\sqrt{0.1^2 + 0.1^2} \ll \sqrt{9.8 \times 10}$$



- We know the deep-water tsunami obeys linear equations of motion
- We have many, many pre-run deep-water model runs in a “Propagation Database”

How do we produce the right combination during an event?

## Forecasting: Inversion

- WebSIFT demo
- <http://sift.pmel.noaa.gov/websift>

## Hazard Assessment: Historical Record

- TsuCAT demo
- <http://nctr.pmel.noaa.gov/TsuCAT>

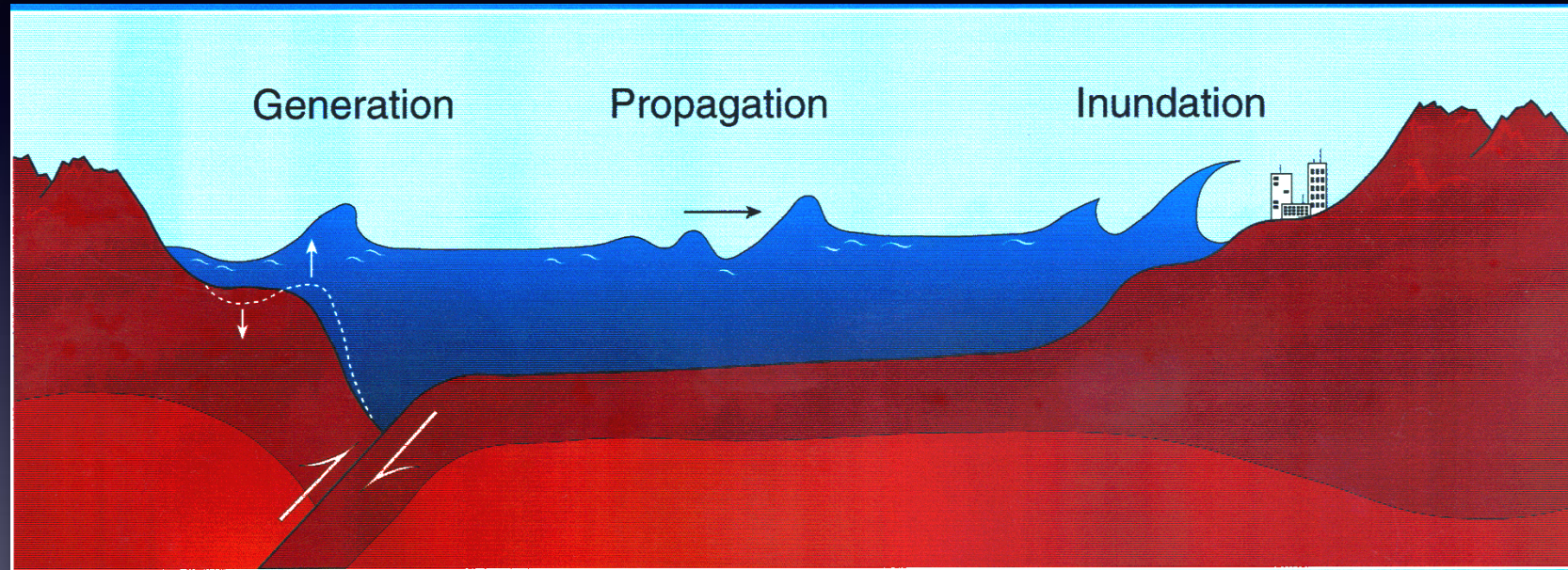
- Now we have the “best-fit” deep-water propagation run...
- How do we get the solution to the harbor?

## Inundation... with ComMIT

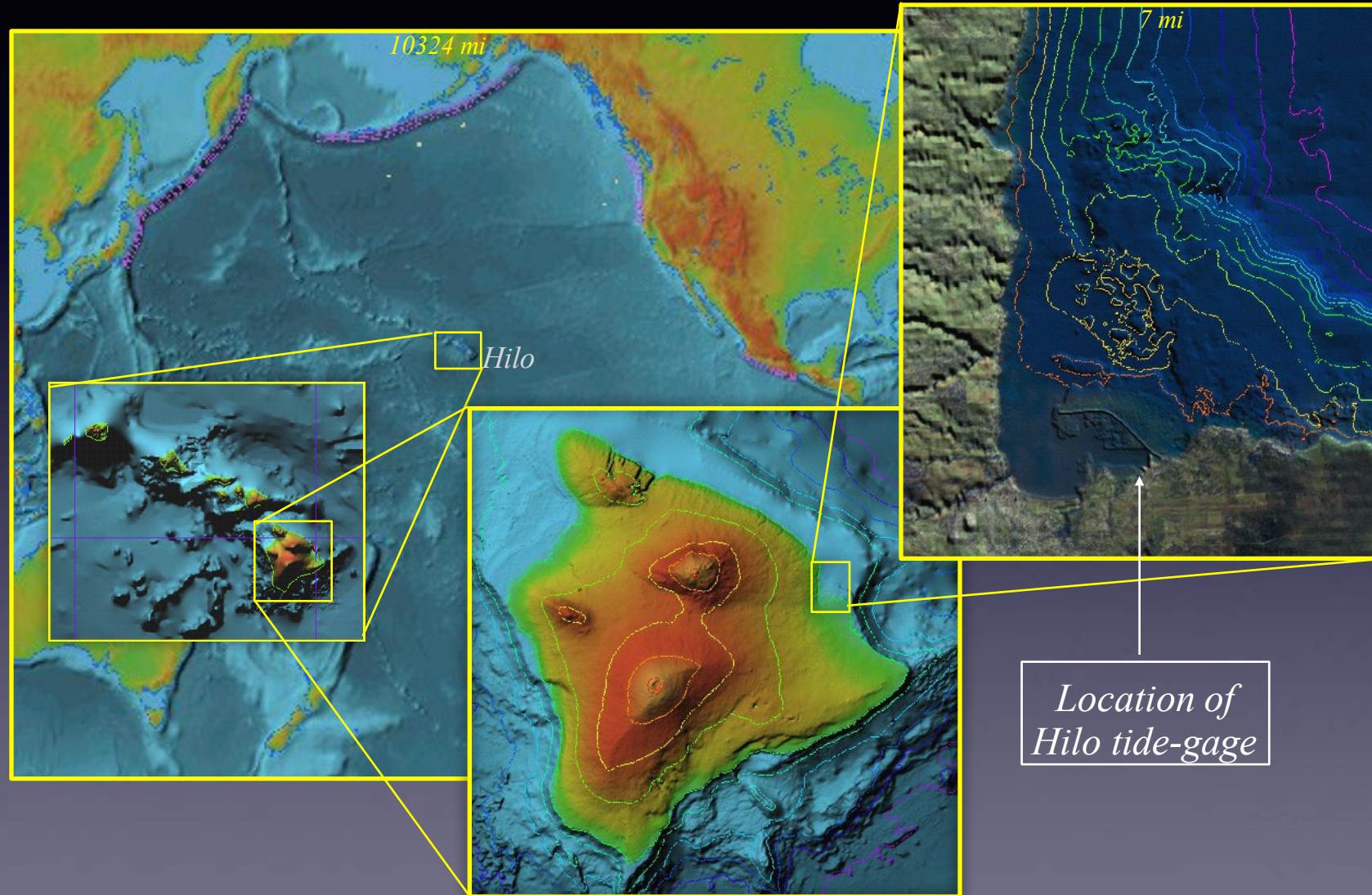
# Inundation: 3 telescoping grids

- 3 nested grids used to model the shoaling wave evolution from deep-water to shallow bay, harbor, or coastline
- optimized to run quickly
- takes forcing from linearly-combined, pre-run Propagation model output

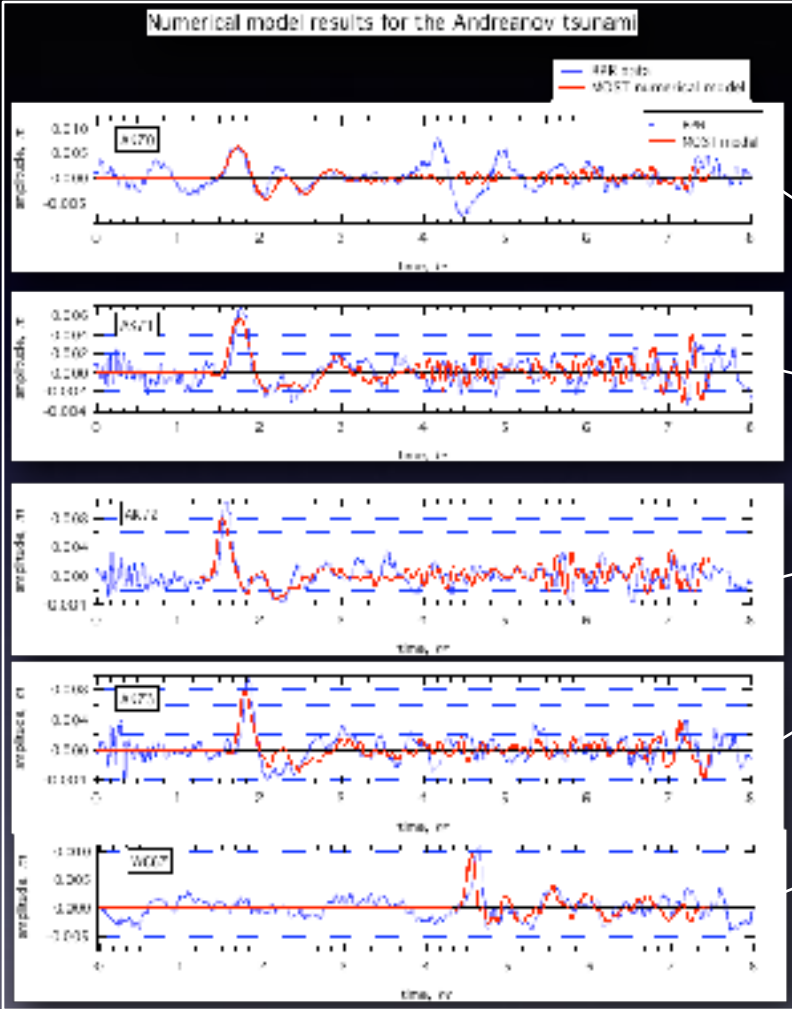
# Why model separately?



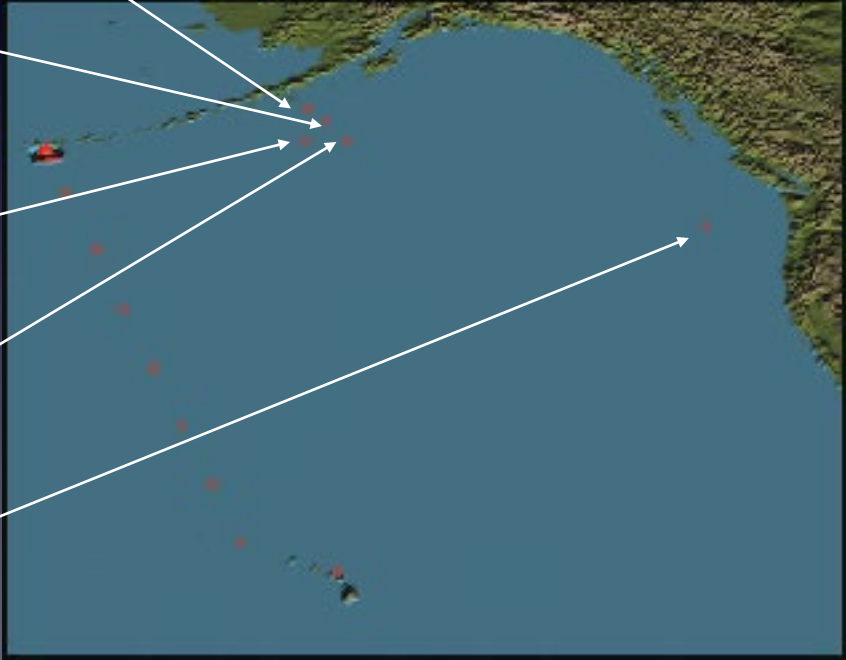
# Reason 1 : Different scales



# Propagation scale



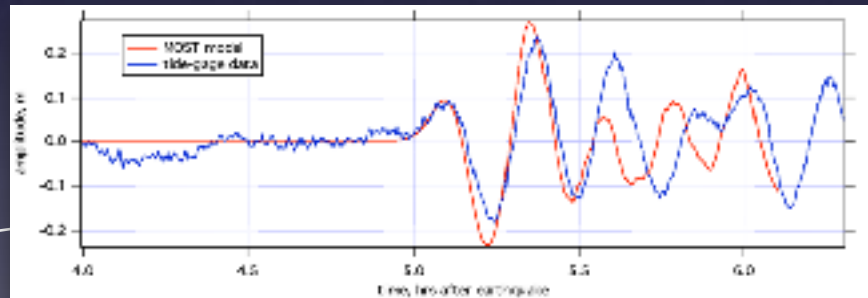
*June 10, 1996 Andreev tsunami  
(Titov & Gonzalez, 1997)*



# Inundation model scale



*Andeanov tsunami  
“inundation” model  
comparison with tide-gage  
data*

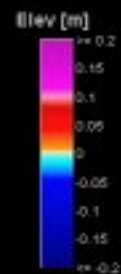


# Cen. Kuri Tsunami Mw = 8.1

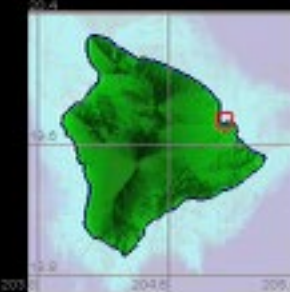
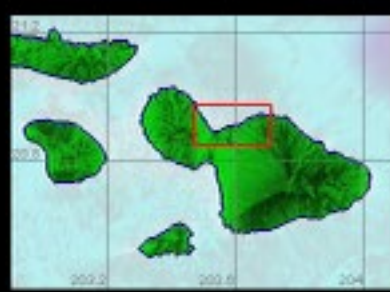
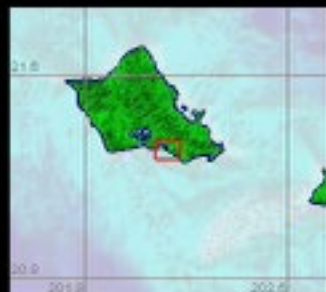
2006.11.15 11:14:16 UTC

05h50m01s

NOAA/PMEL/NCTR



— SIM  
— observation



Nawiliwili



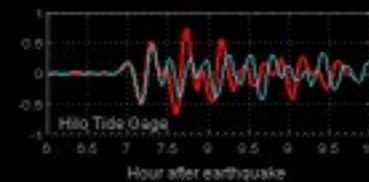
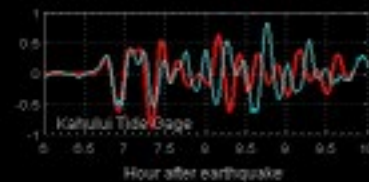
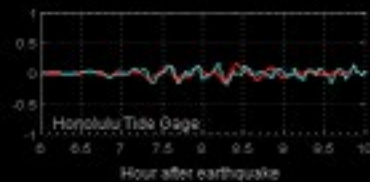
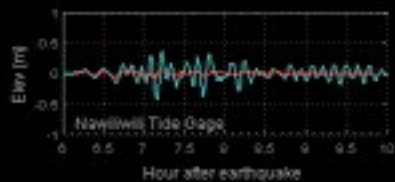
Honolulu



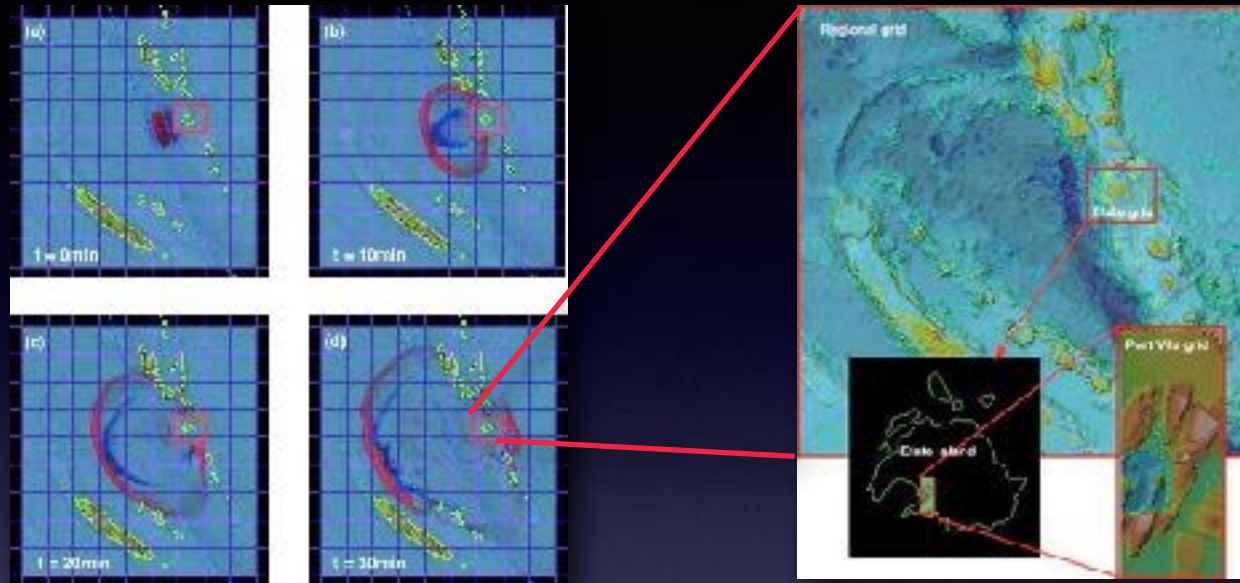
Kahului



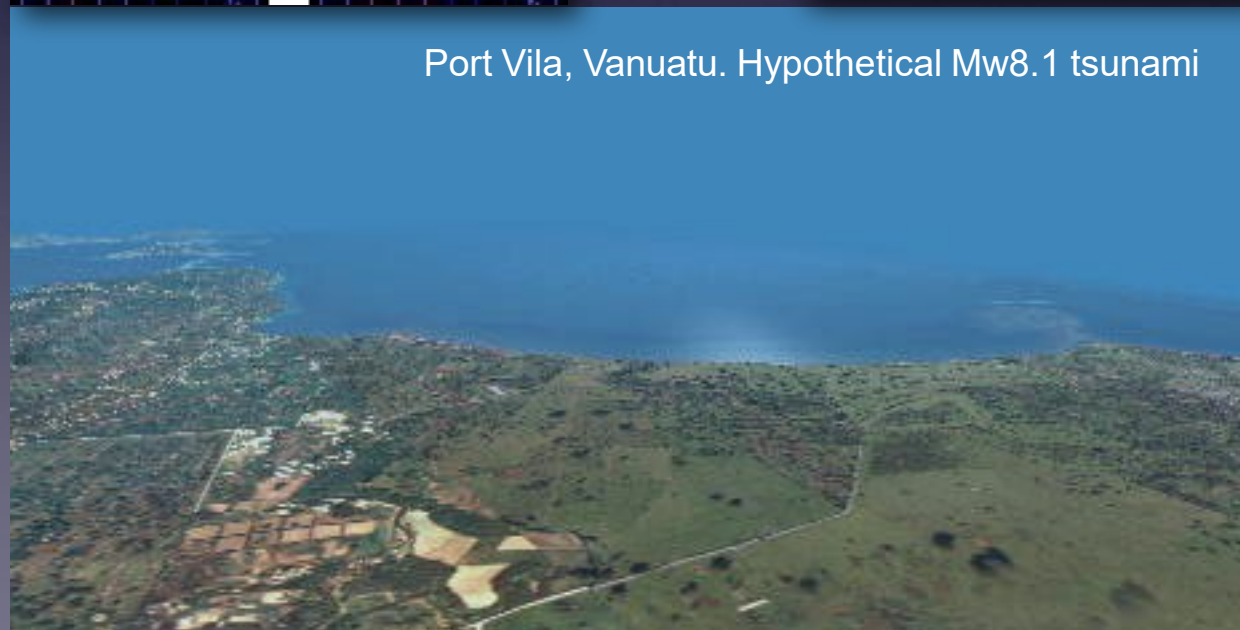
Hilo



# Small scale inundation effects



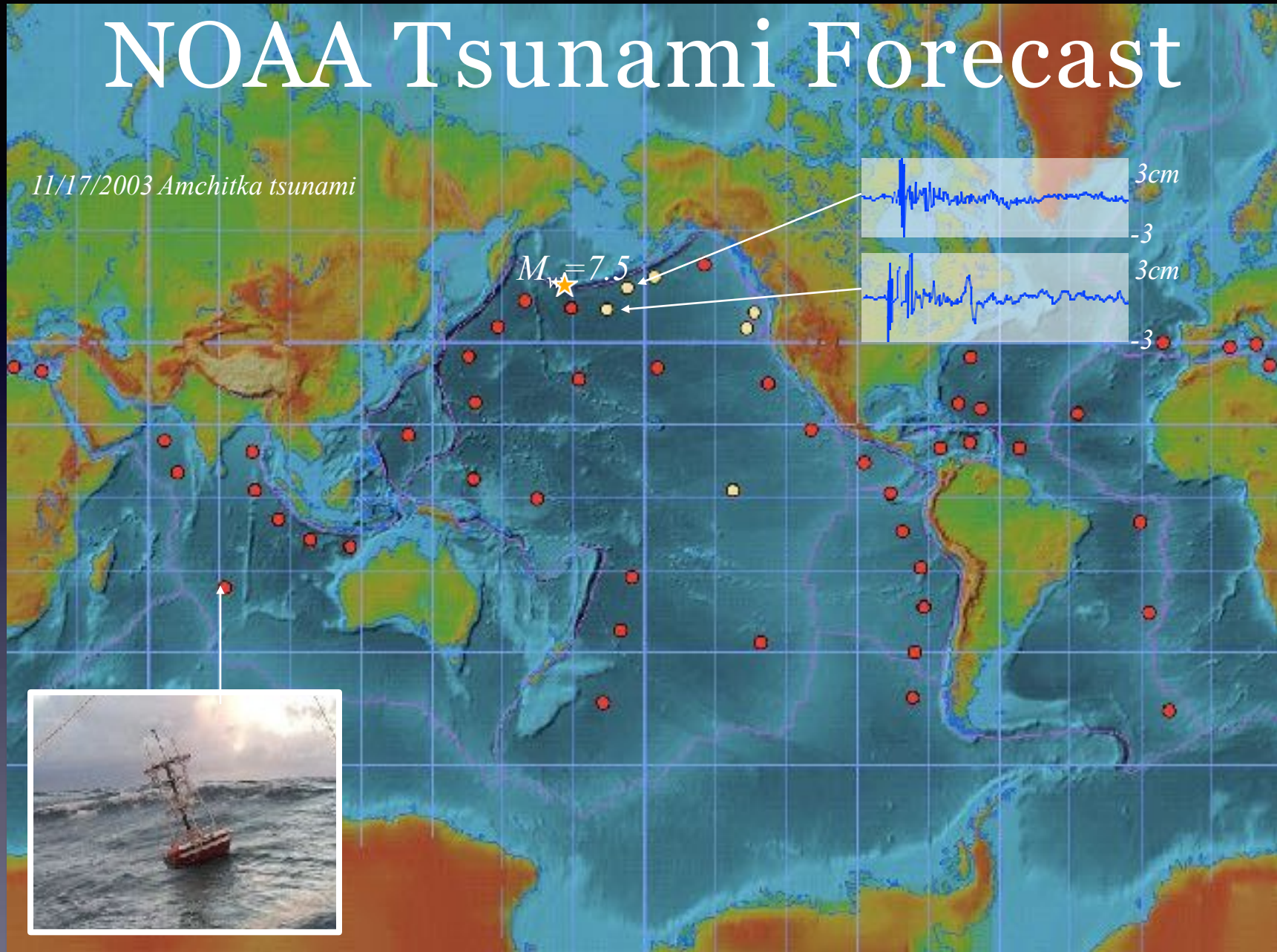
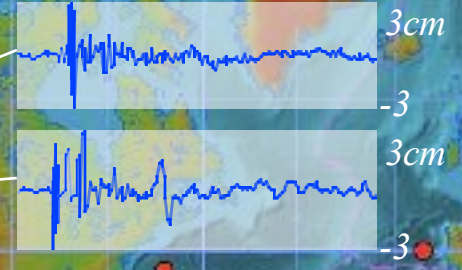
Port Vila, Vanuatu. Hypothetical Mw8.1 tsunami



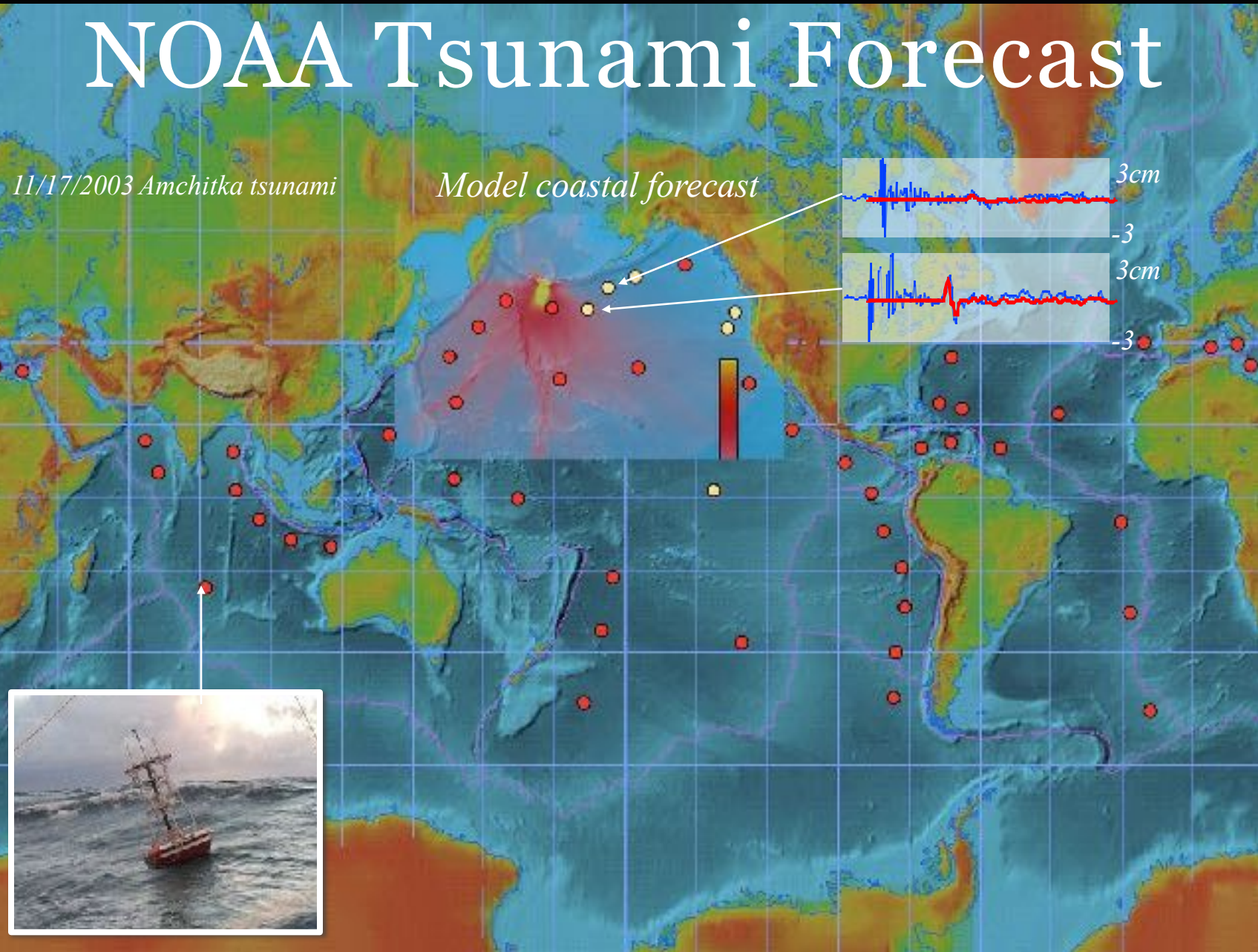
# NOAA Tsunami Forecast

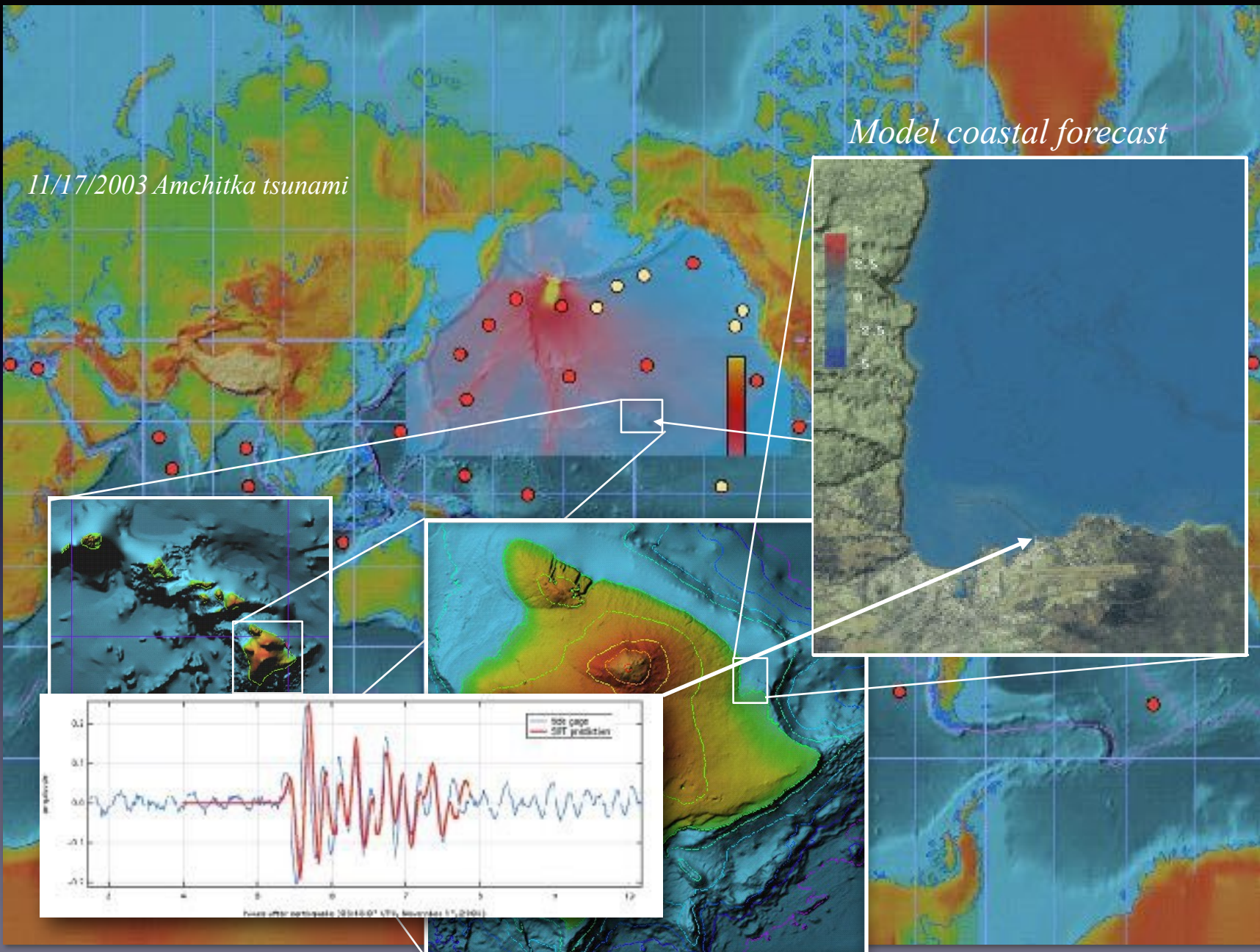
11/17/2003 Amchitka tsunami

$M_w = 7.5$



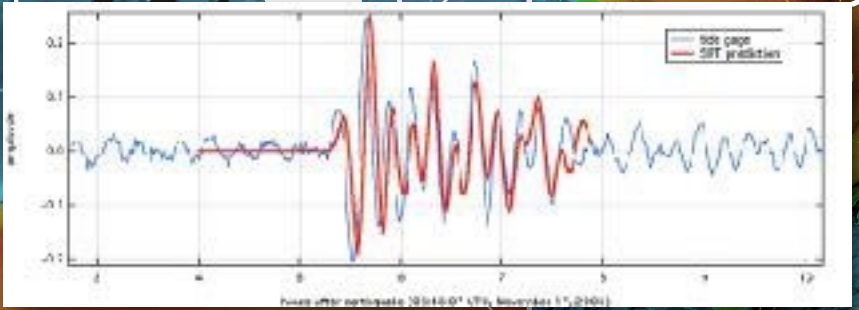
# NOAA Tsunami Forecast



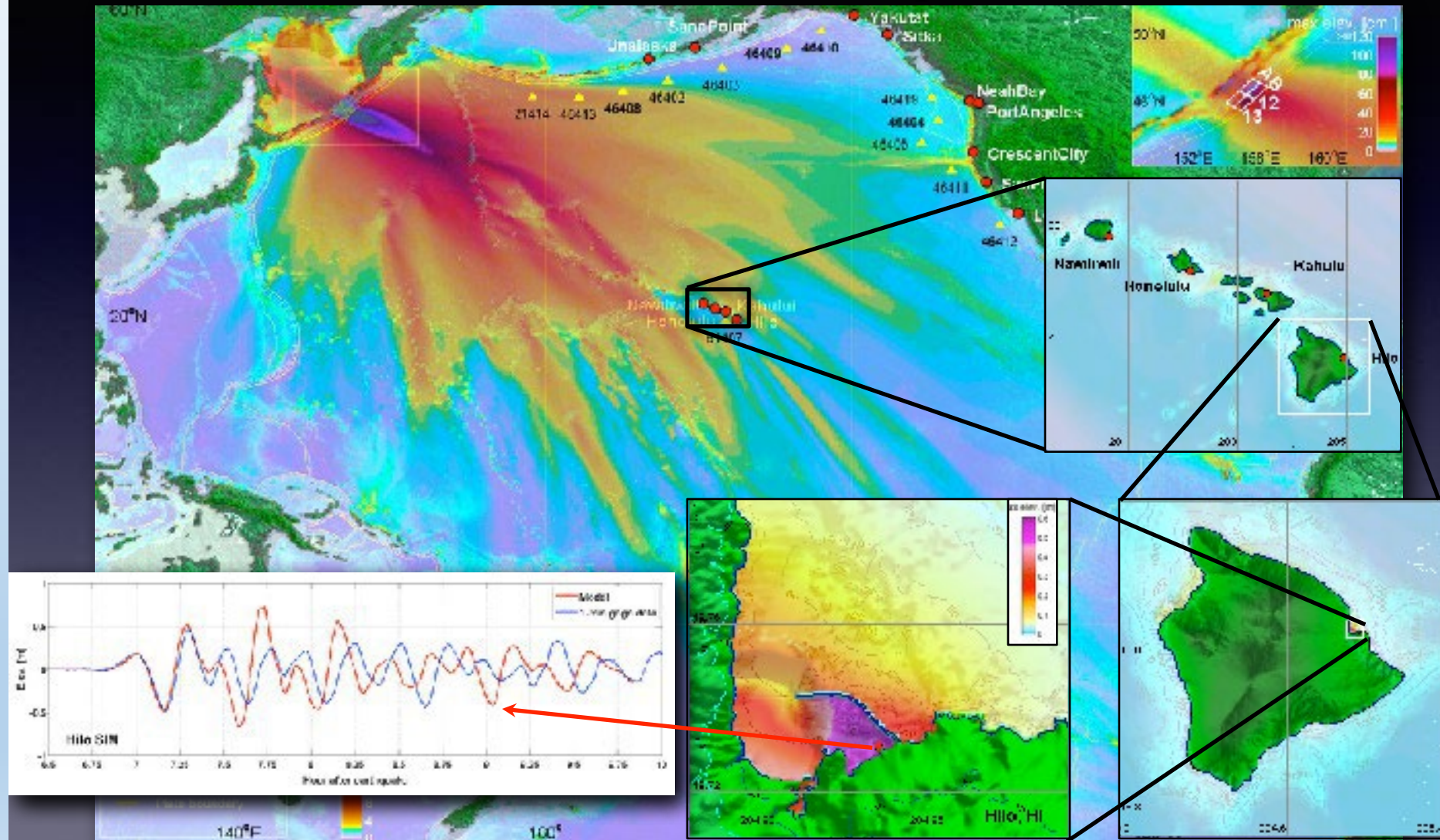


11/17/2003 Amchitka tsunami

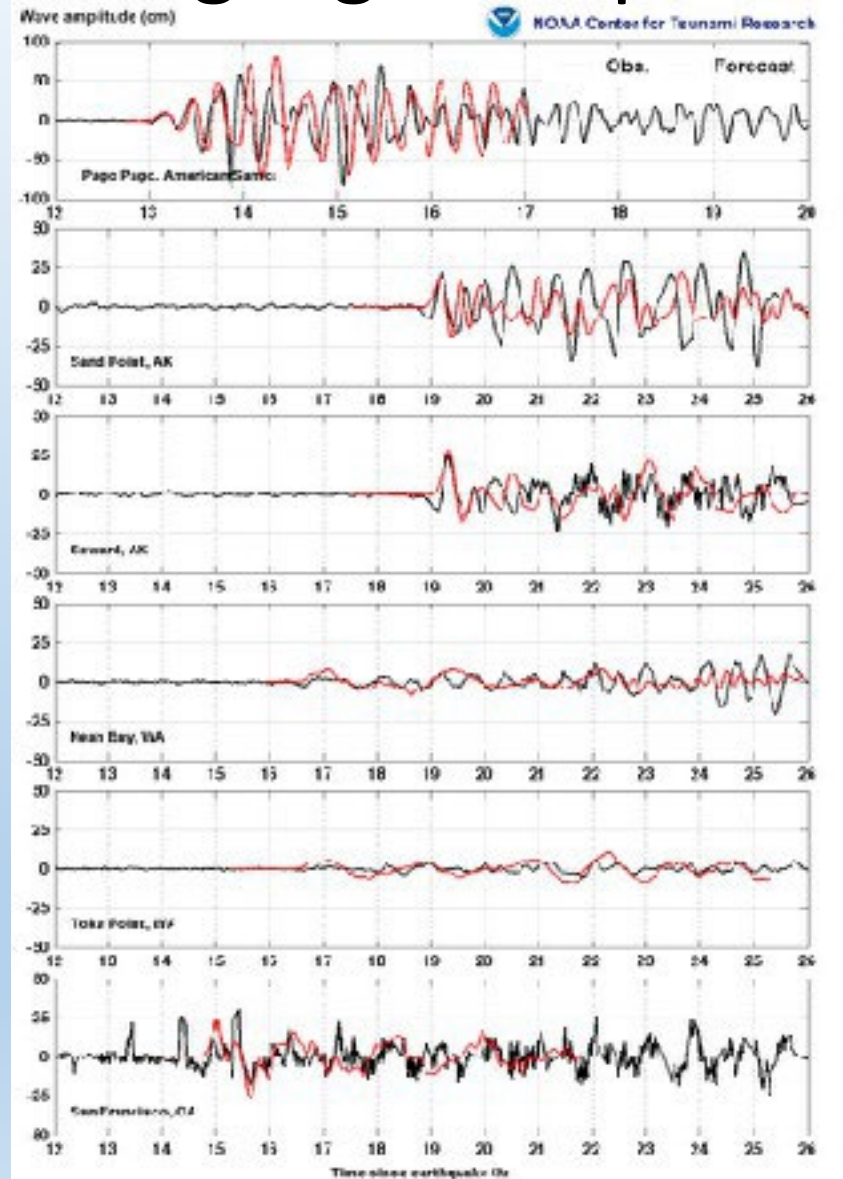
Model coastal forecast



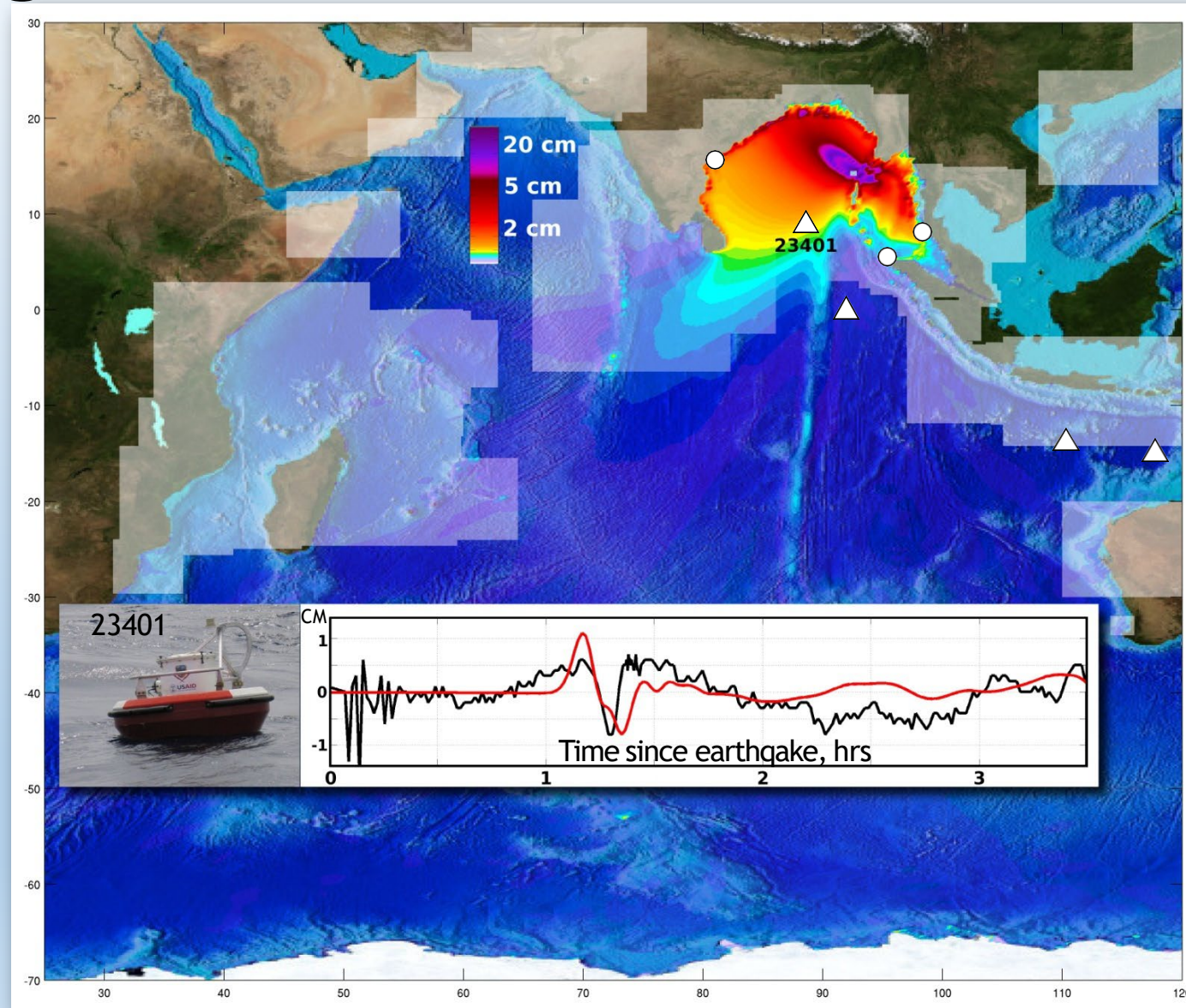
# The November 15, 2006 Central Kuril Tsunami



# Results: Tide gauge comparisons, Chile 2010



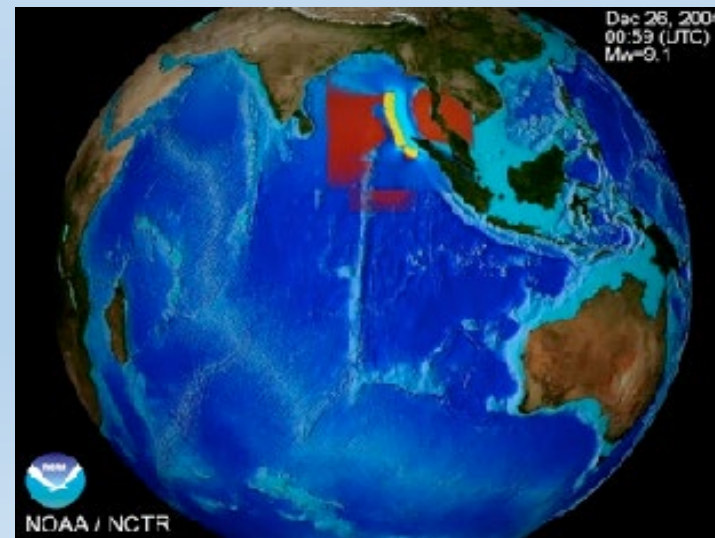
# August 10, 2009 Andaman





# Summary - NOAA's numerical forecasting techniques

- Earthquakes are the major generation mechanism, but tsunamis can have more than one.
- The source is complicated, so we measure the wave directly.
- DART buoy data helps us to constrain the model
- Inverted propagation model is used to force the inundation model.

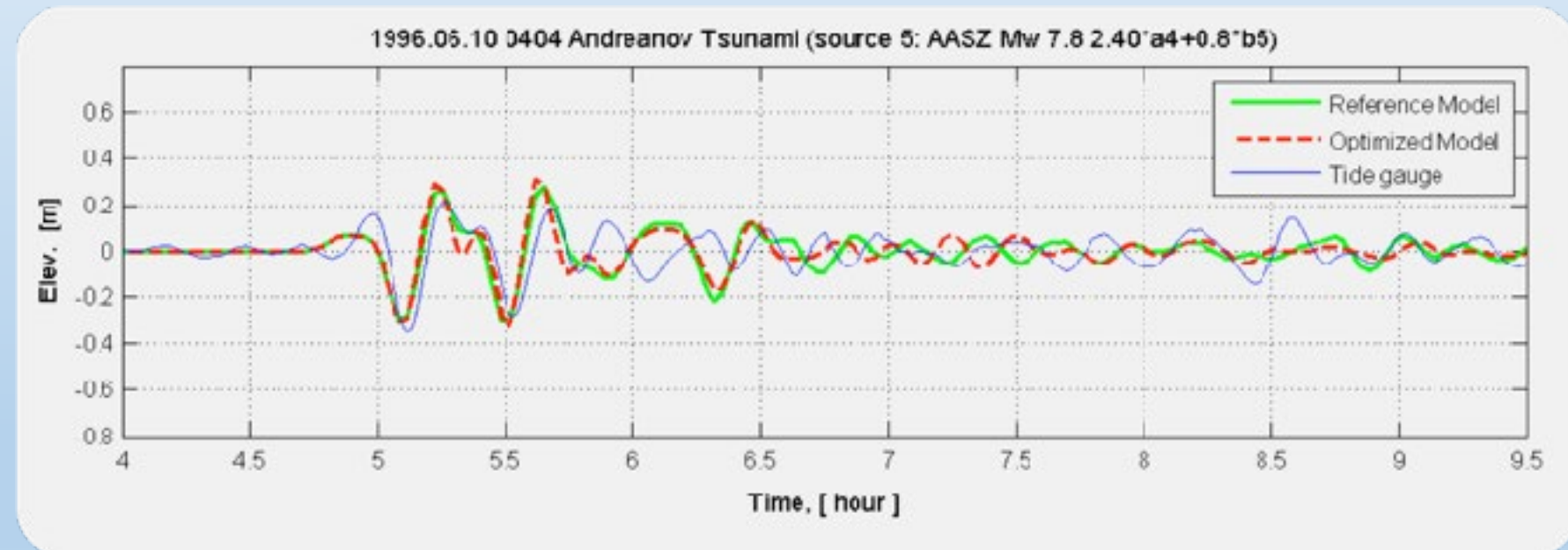


# Developing Inundation Grids

- Reference model uses the highest quality and resolution available for a community
- Model from different sources is combined to form 3 nested grids
- Tested against historical data, and for robustness
- Highly optimized grids are derived from the reference grids

# Creation of the SIM Set of Grids

Monitor time series degradation at Warning Point and/or Tide Gage by comparison with Reference Run. (No tide-gage data available for Seaside)



# Thank you