Intergovernmental Oceanographic Commission

Indian Ocean Tsunami Information Centre

Training/Workshop on

Tsunami Evacuation Maps, Plans, and Procedures and the UNESCO-IOC Tsunami Ready Recognition Programme for the Indian Ocean Member States

Hyderabad - India, 15-23 April 2025

Tsunami Inundation Modelling and MAP

TIMM #: Tsunami Science, Modelling and Forecasting - II Summary of different models

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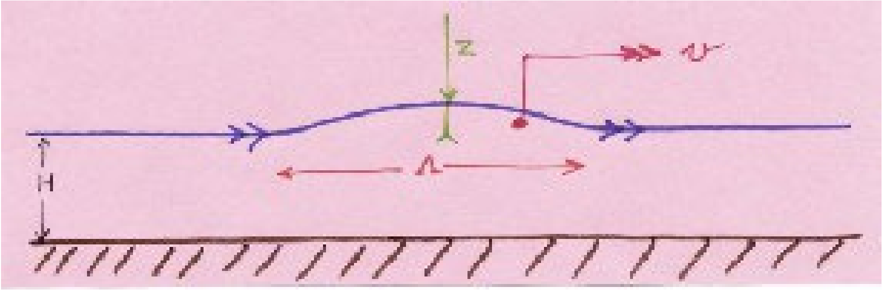
Physical Characteristics of a Tsunami in Deep Water

- Propagation Speed: Speed depends on ocean depth, H.
  - In practice: H=5 Km, v=220 m/s (~=800 Km/h)
  - (approximate cruise velocity of a commercial airliner)

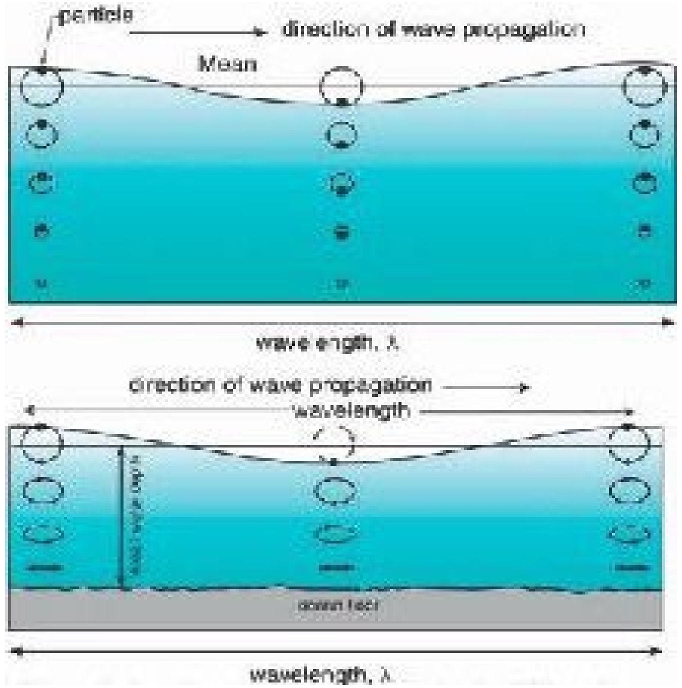
$$v = \sqrt{gH}$$



- Maximum Amplitude, z: from a few centimeters to a half meter.
  - Typical Wavelength: Λ = 300 km (period ~ 600 s-3000s)
  - A tsunami is always composed of several waves.

Physical Characteristics of a Tsunami in Deep Water

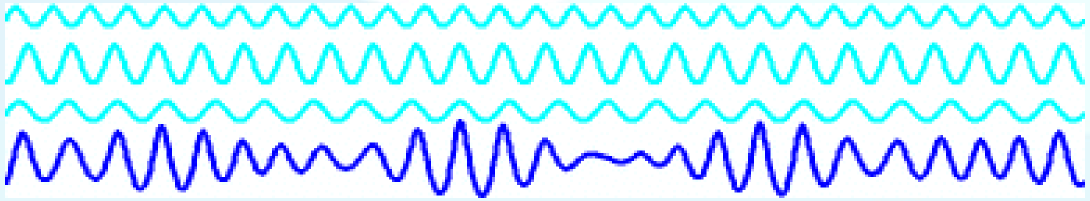
- A tsunami is always a long wave (alt. A wave in shallow water).



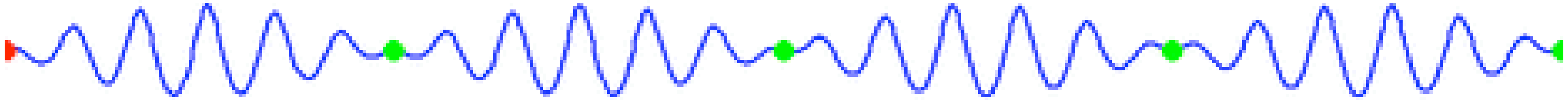
- A tsunami is a non-dispersive wave.

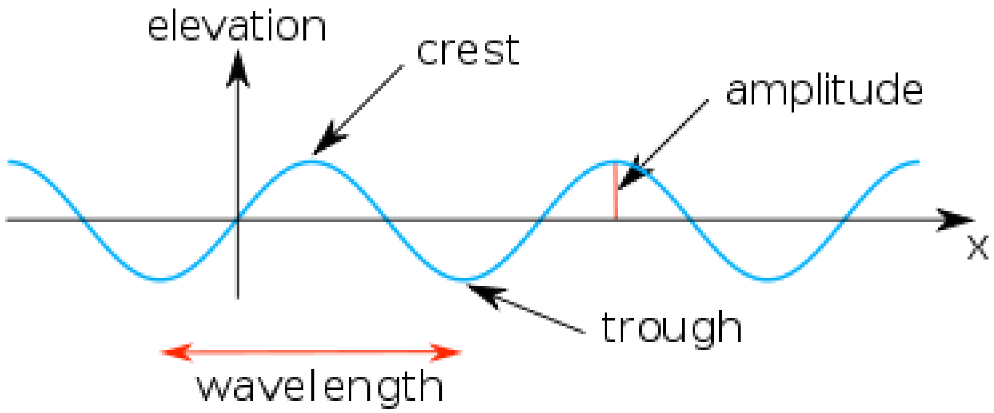
$$c = \frac{\omega}{k} = \sqrt{\frac{g \times Tanh(kH)}{k}}$$

Example of dispersive wave behavior



Wave Dispersion



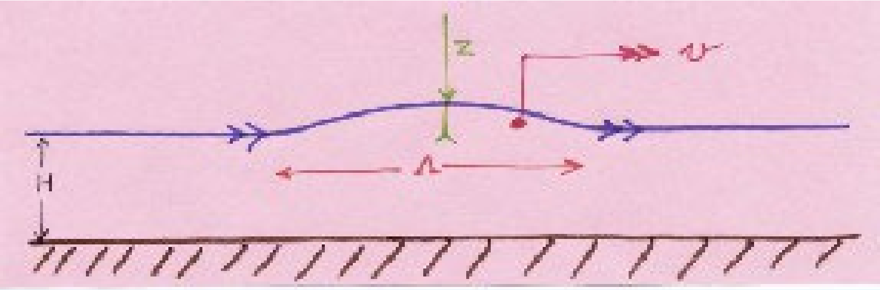


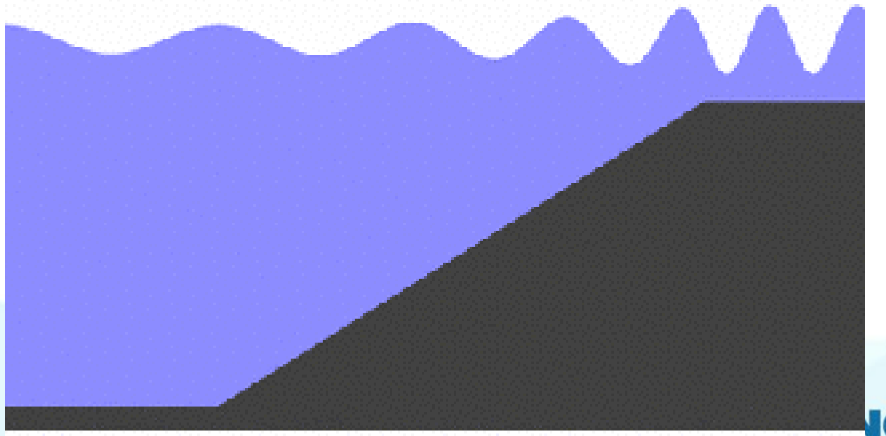
Physical Characteristics of a Tsunami in Shallow Water

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

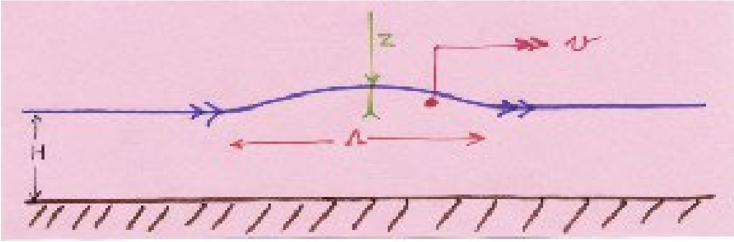
$$v = \sqrt{gH}$$

- 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.

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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.

$$\omega = \sqrt{gk\,Tanh(kH)} \xrightarrow{kH \to 0} v = \frac{\omega}{k} = \sqrt{gH}$$

Dispersive vs. Non-dispersive Models

Non-dispersive Model Characteristics	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,..	11-Range of Validity: -in water of intermediate depth(Standard Boussinesq, $O(\varepsilon)=O(\mu^2)<<1$). $\varepsilon=a/h$, $\mu=kh$, 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,..

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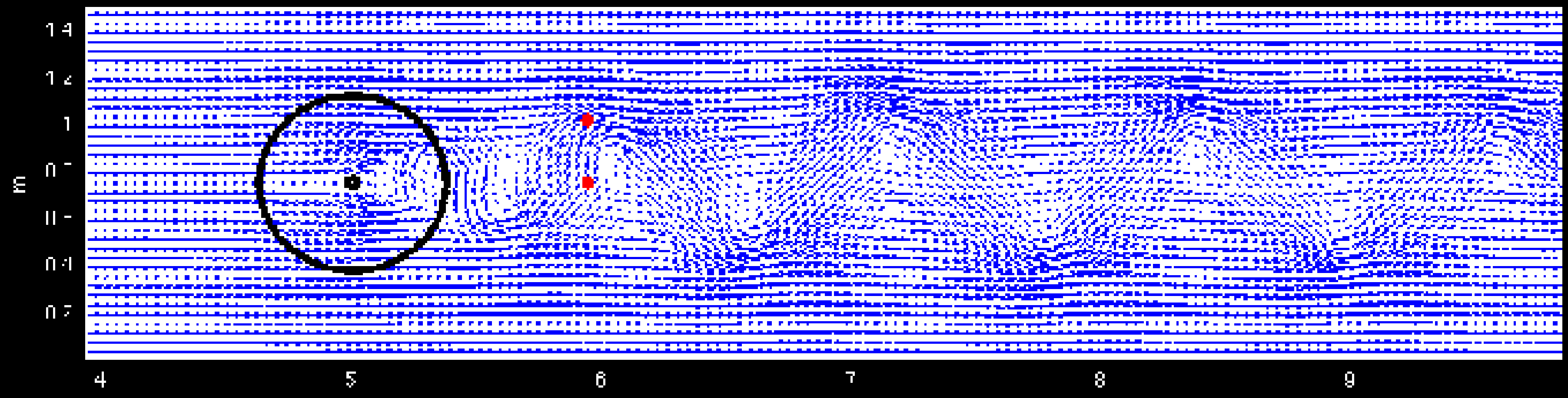
Table 1.1. List of Numerical Tsunami Models approved by NTHMP/MMS.

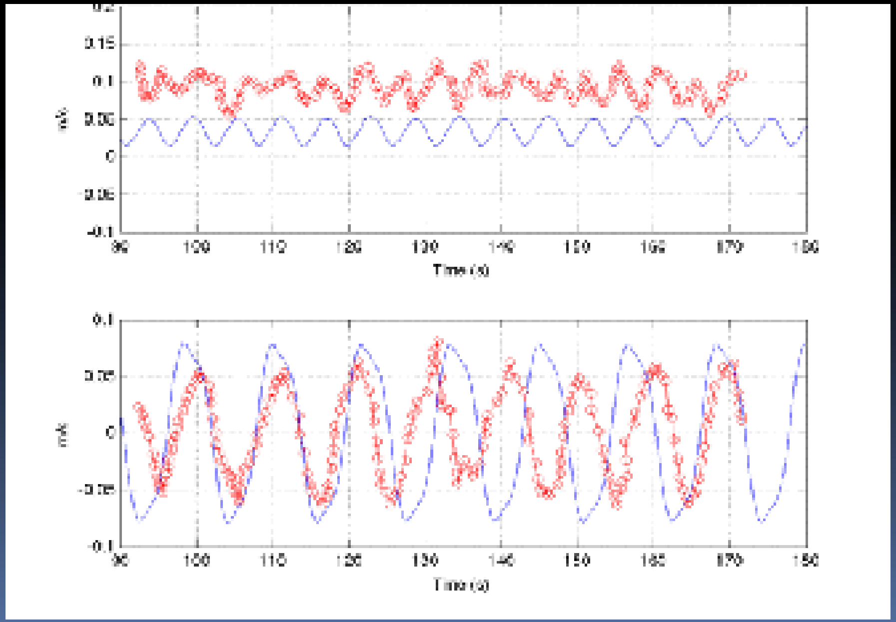
#	Model Name	Usable Sources		NTHMP Benchmarks		Available for download			Relative run-time	Model Physics[1]
		Seismic	Landslide (including volcanic, mass failures, underwater, over water)	Propagation	Inundation	Documentation	Available thru website	User interface	⌛ hrs-days ⌛⌛ days ⌛⌛⌛ month	
1	ALASKA 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

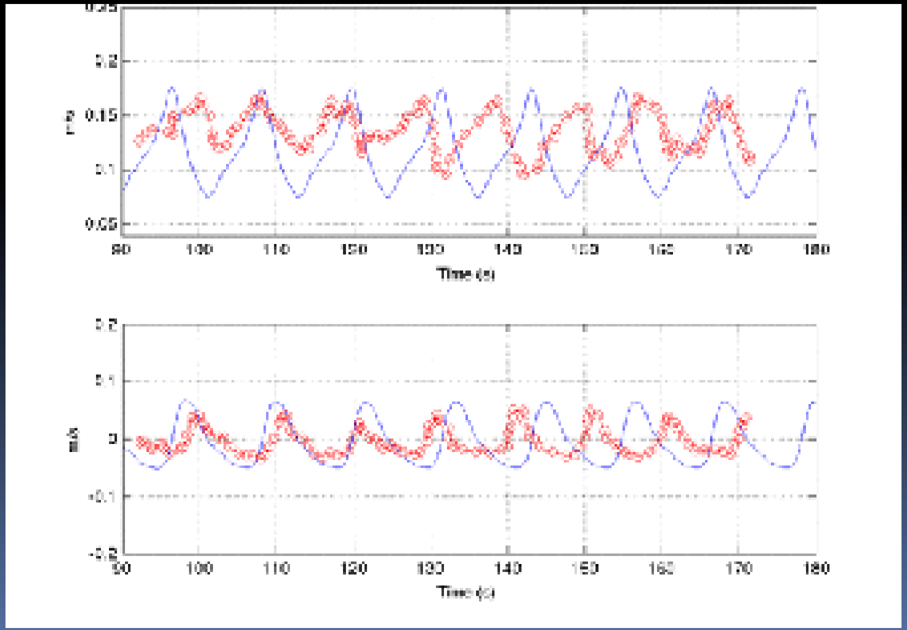
[1]**Model Physics**

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...

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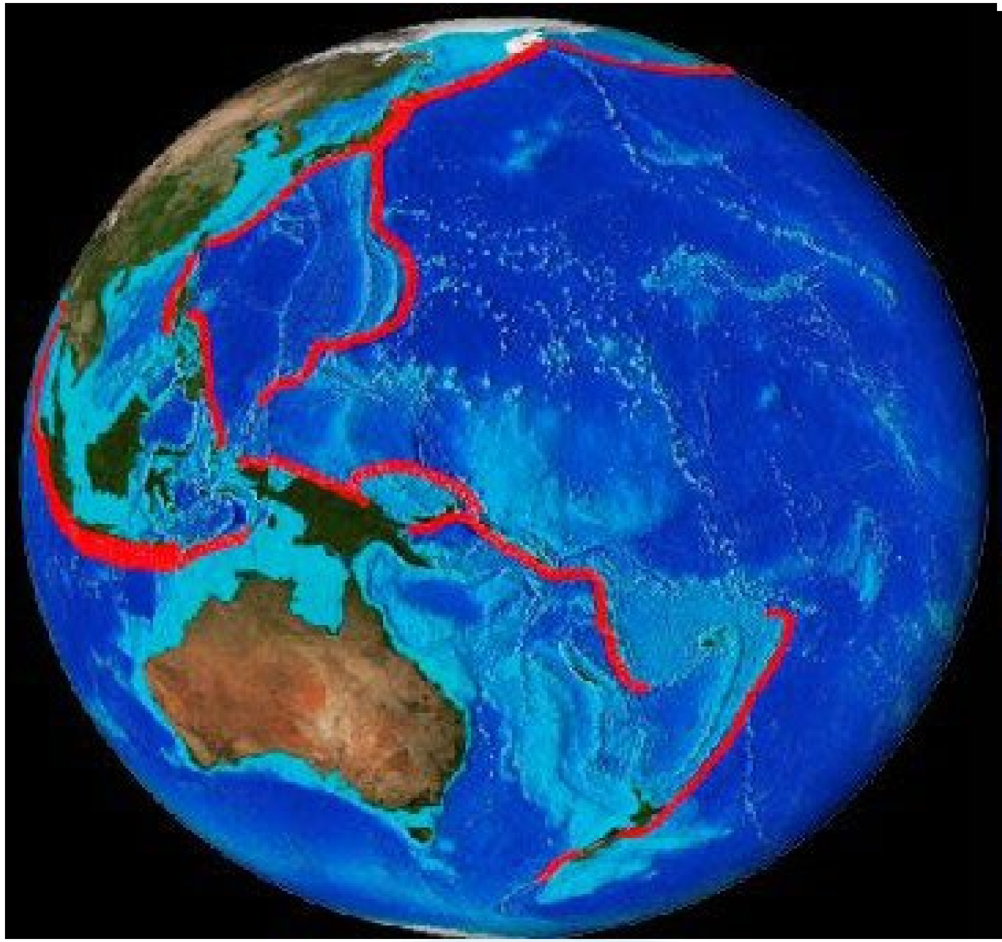
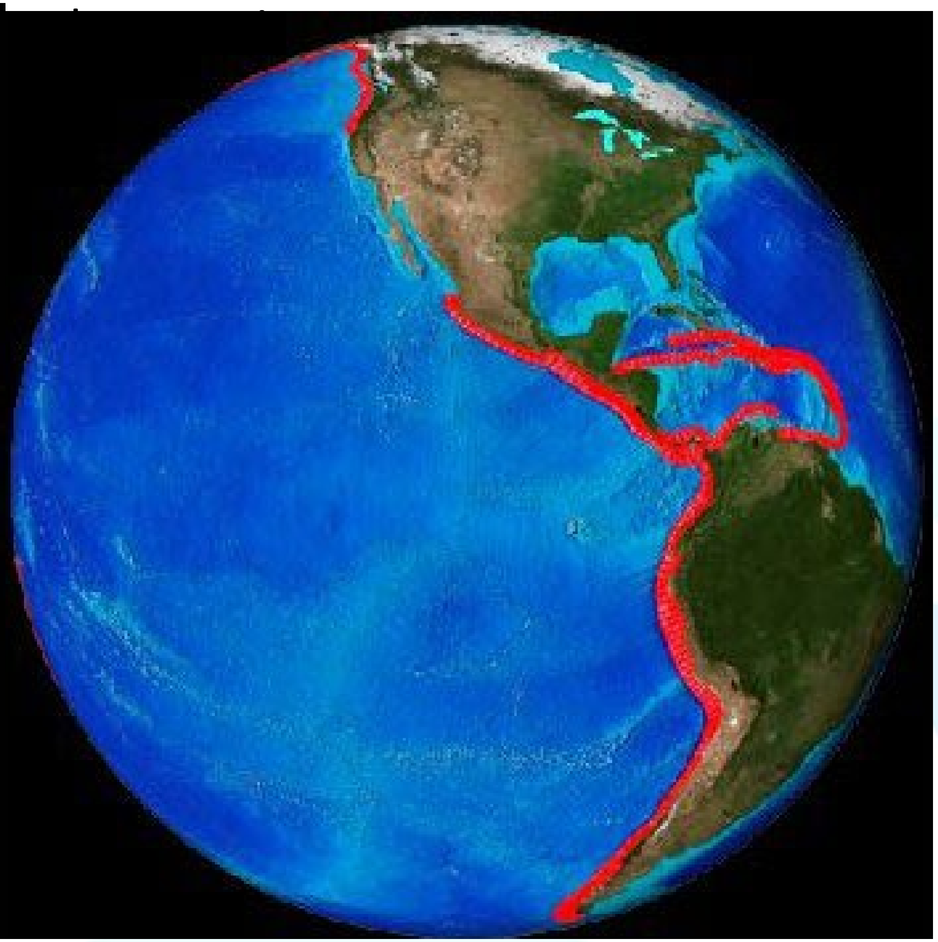
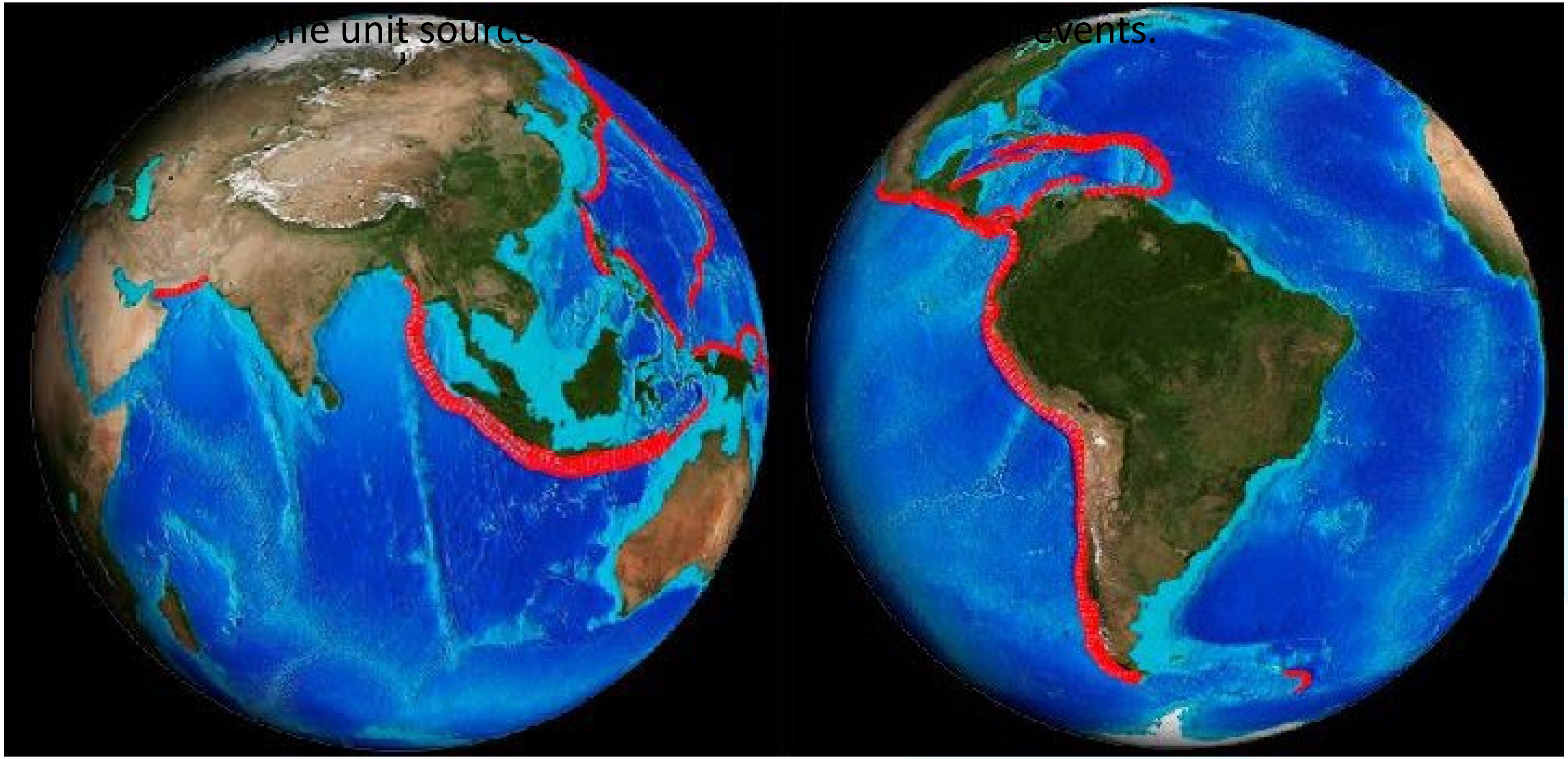




West Pacific East Pacific

the unit sources ... events.



Indian Ocean

Atlantic Ocean

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

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

Linearity...

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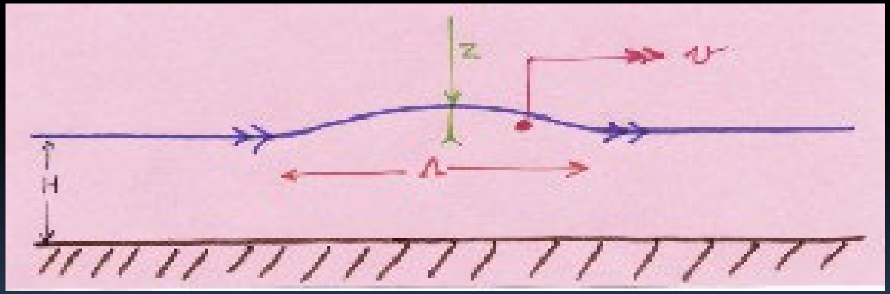
SIMPLIFICATIONS IN THE SHALLOW WATER EQUATIONS

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

Illustration of Deep Water Linearity

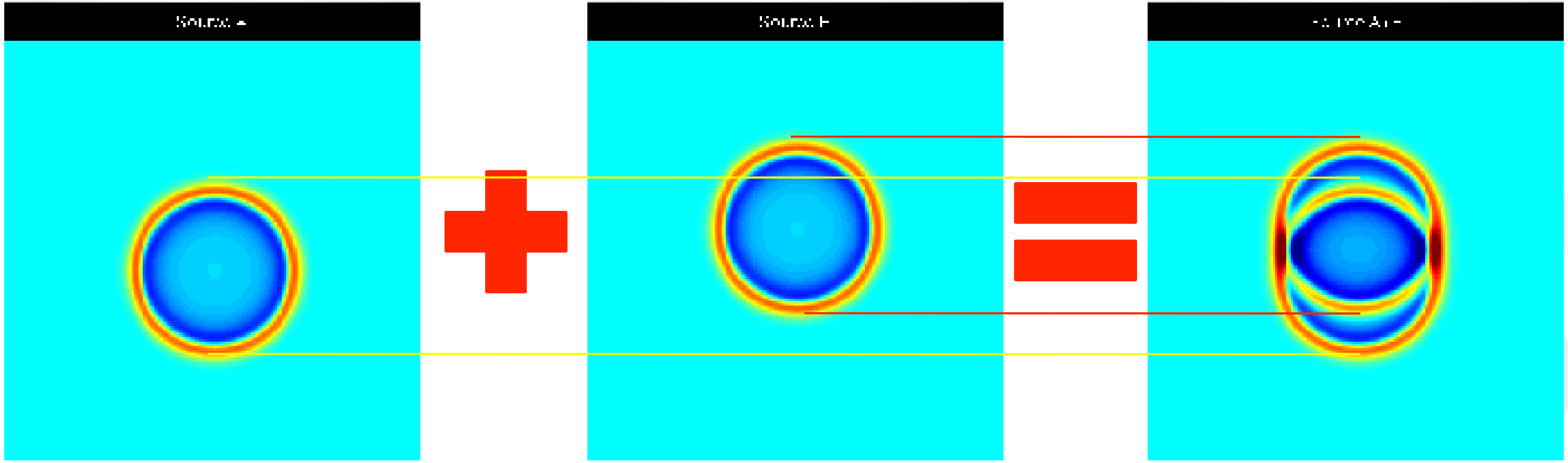
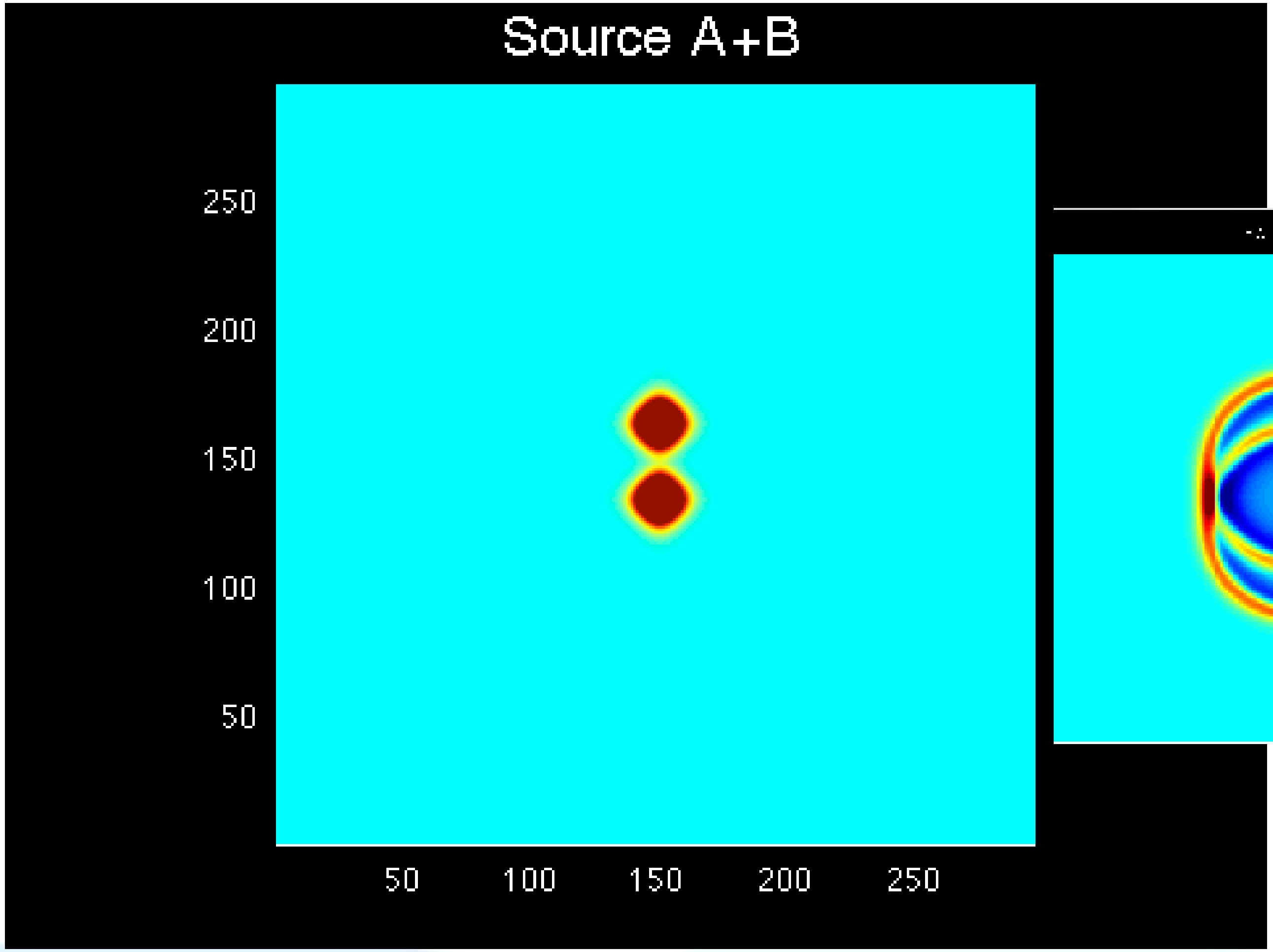
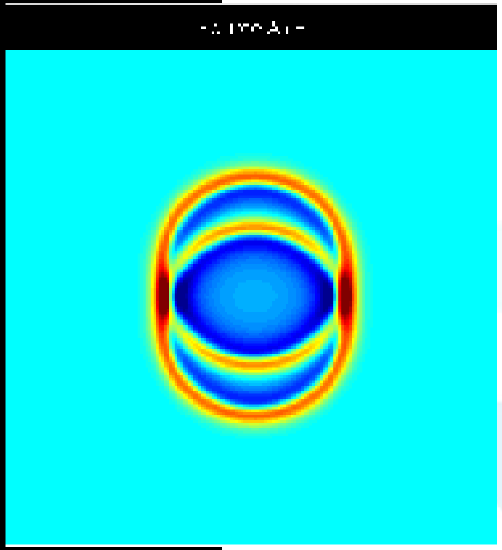


Illustration of Deep Water Linearity





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ESCAP
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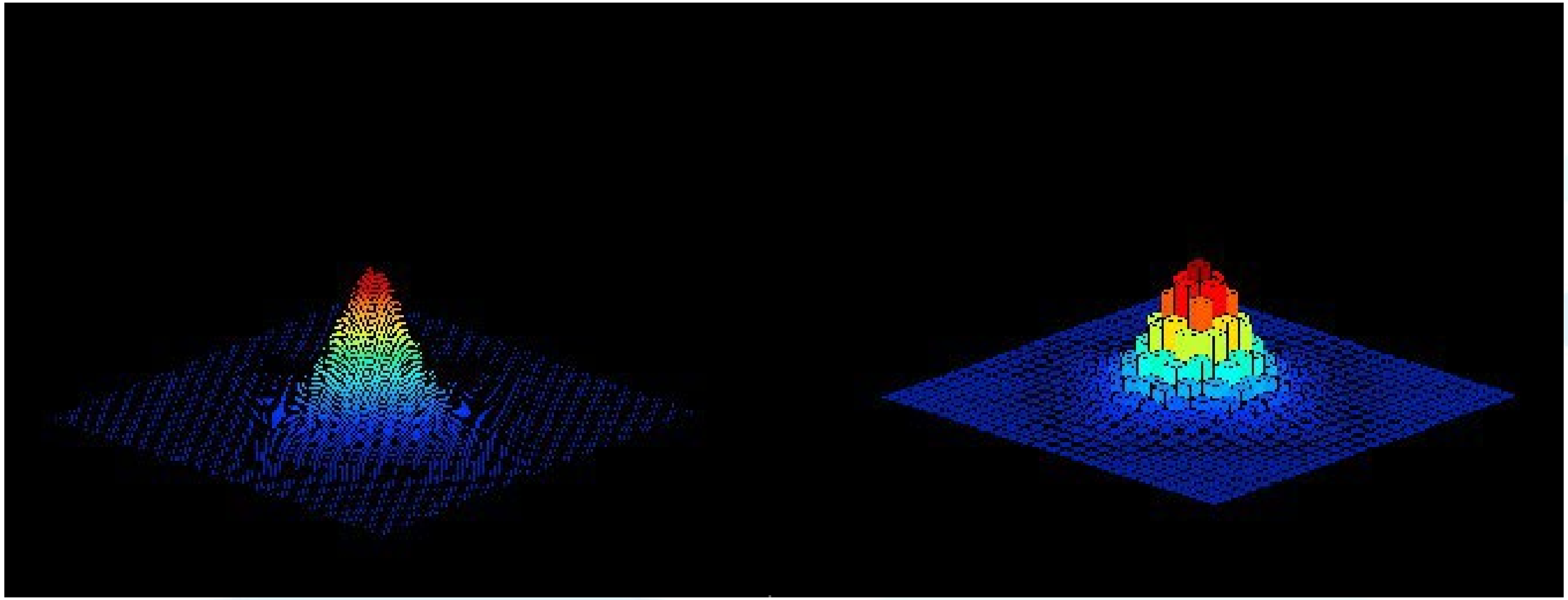
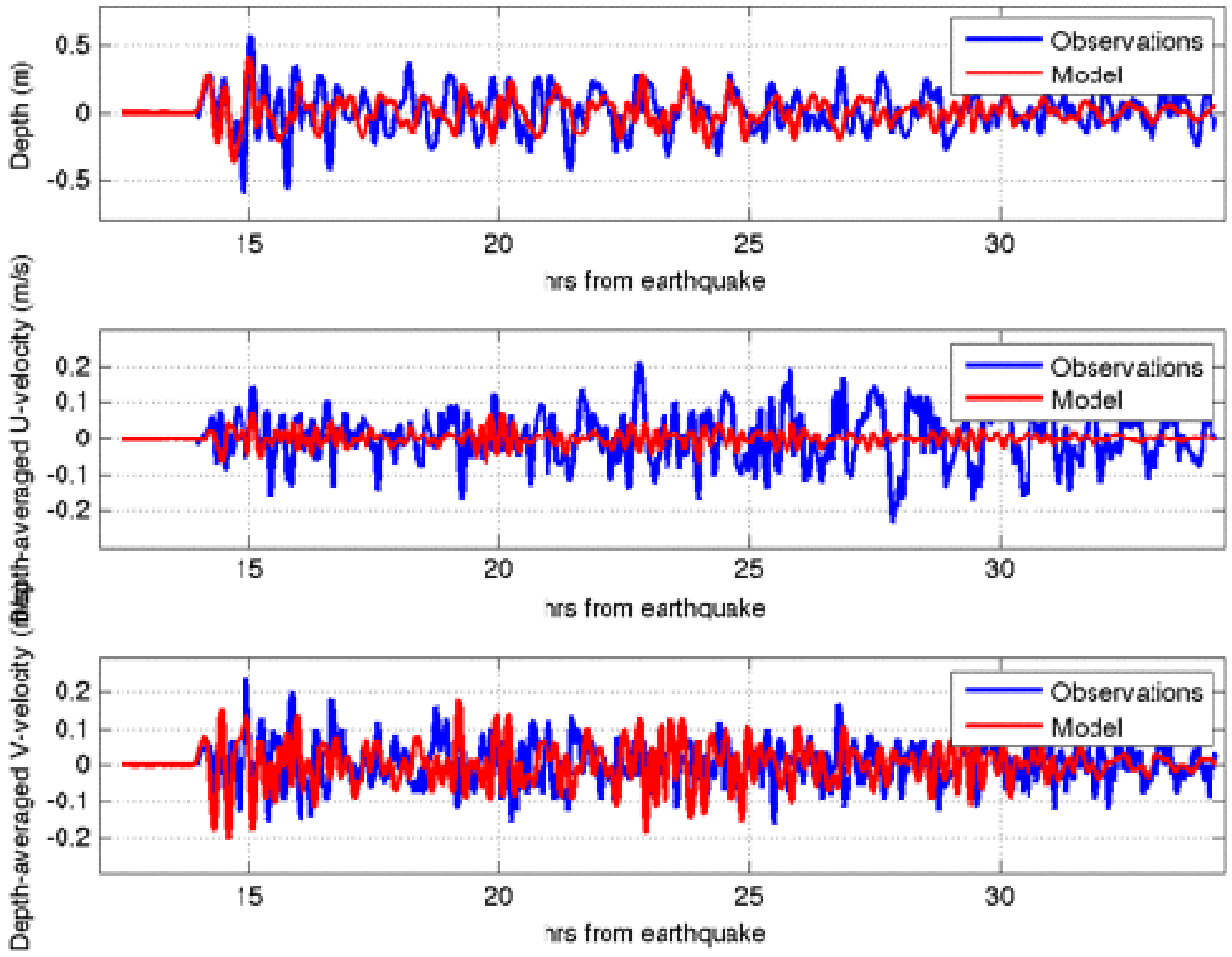
Tsunami Ready

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



For linearity u << gh

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



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- 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 duringan event?

Forecasting: Inversion

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

Hazard Assessment: Historical Record

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

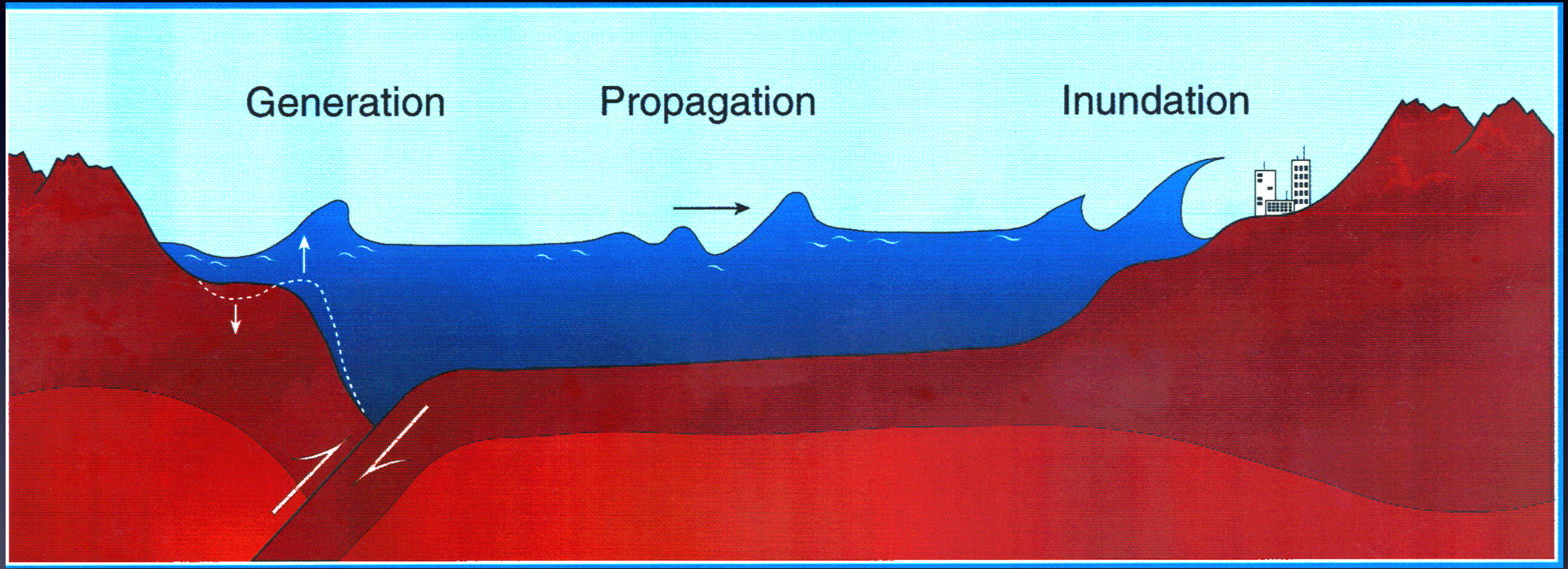
- Now we have the “best-fit” deep-water propagation run…
- How do we get the solution to the harbor?

Inundation… with ComMIT

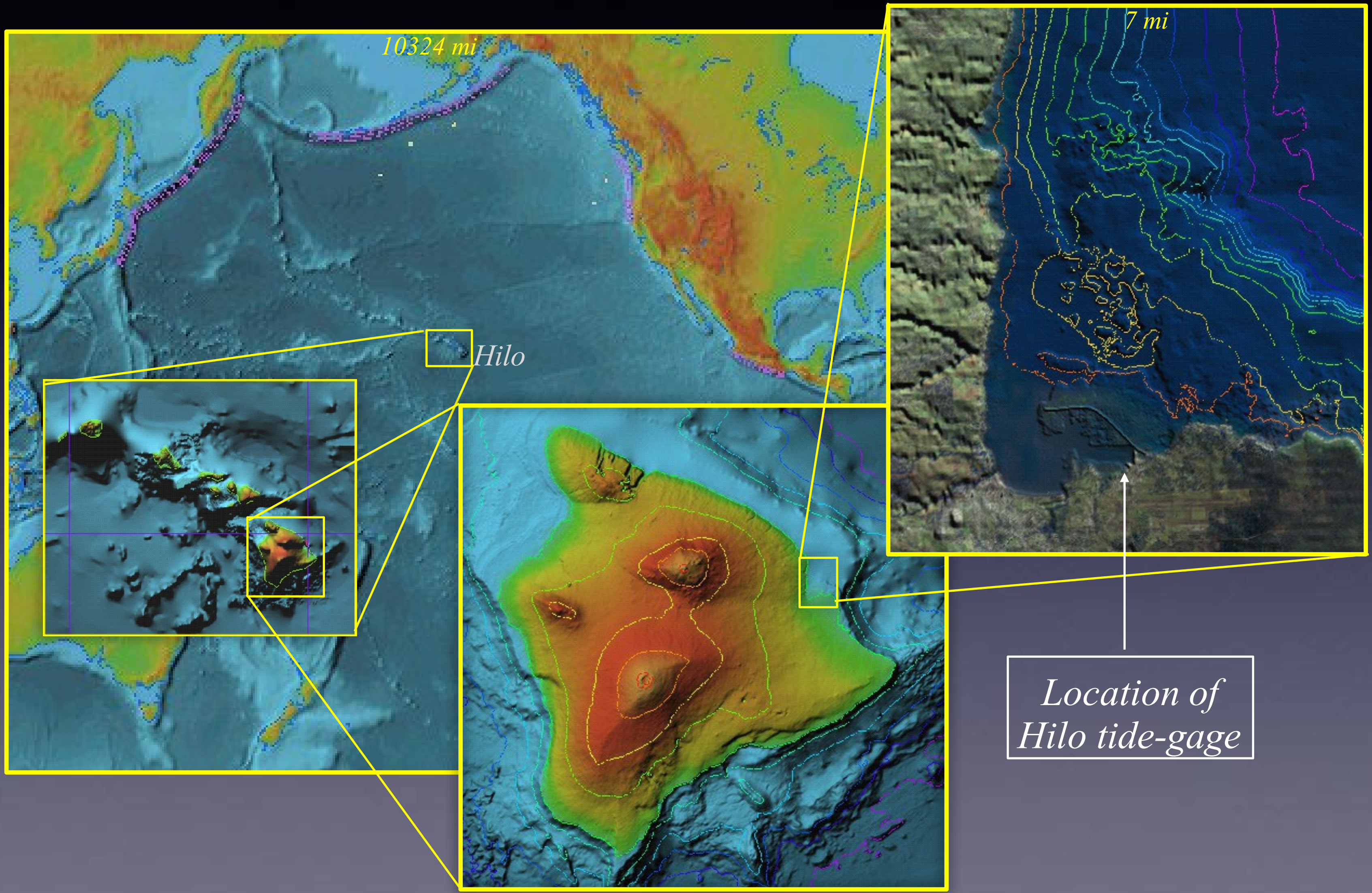
Inundation: 3 telescoping grids

- 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

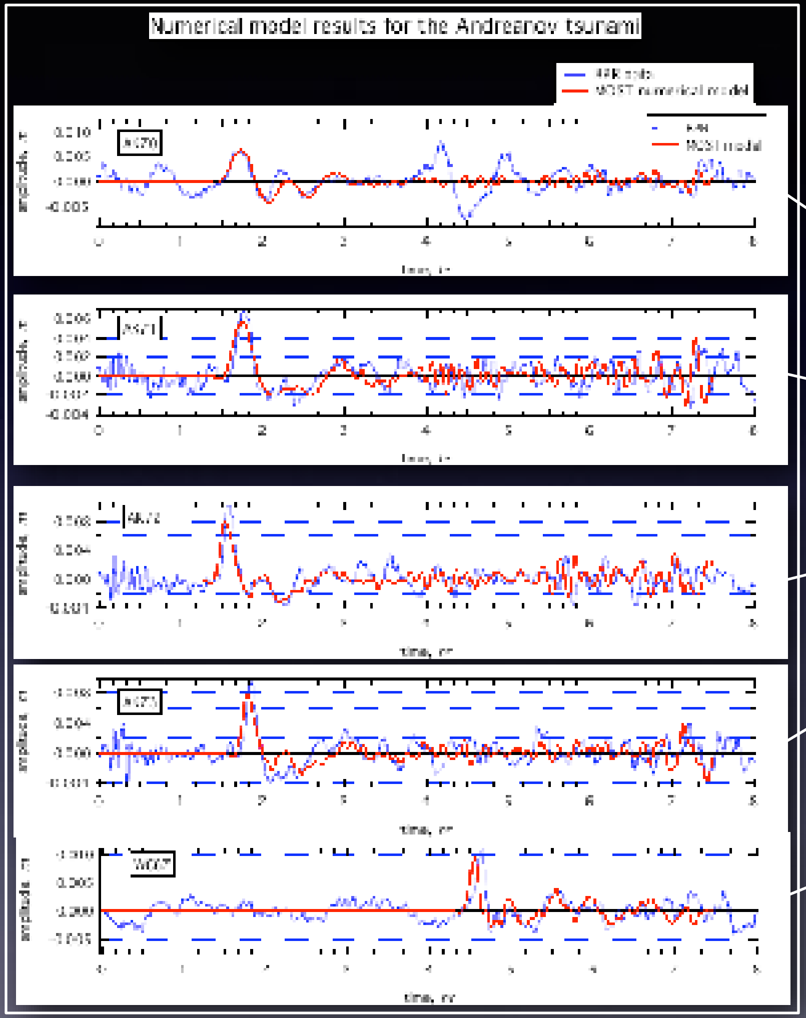
Why model separately?



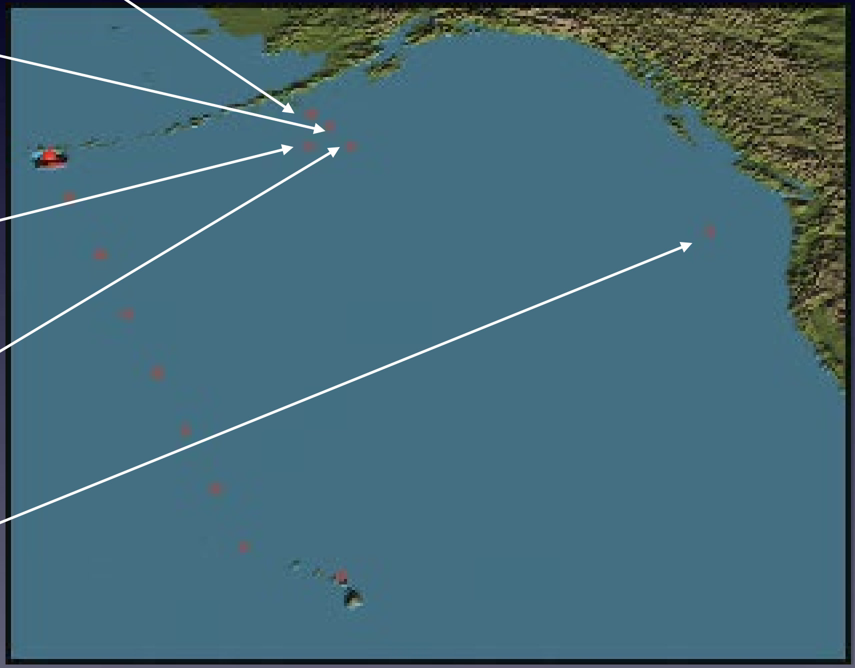
Reason 1 : Different scales



Propagation scale

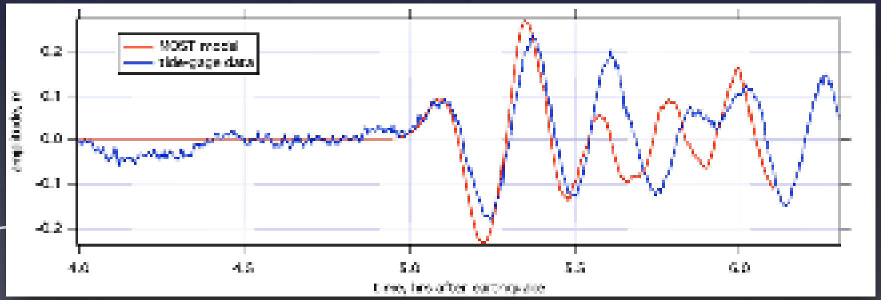


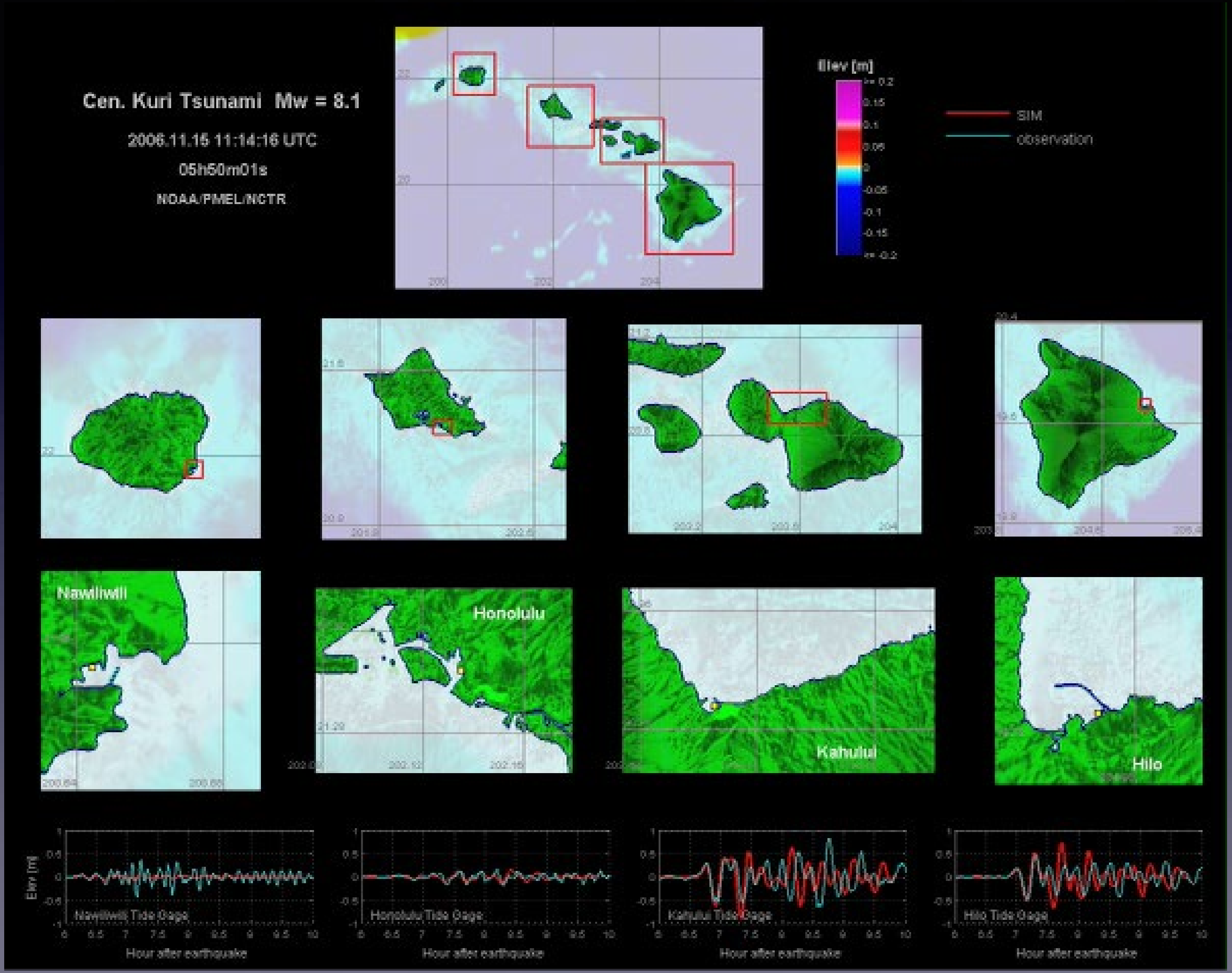
June 10, 1996 Andreanov tsunami
(Titov & Gonzalez, 1997)



Inundation model scale

Andreanov tsunami "inundation" model comparison with tide-gage data





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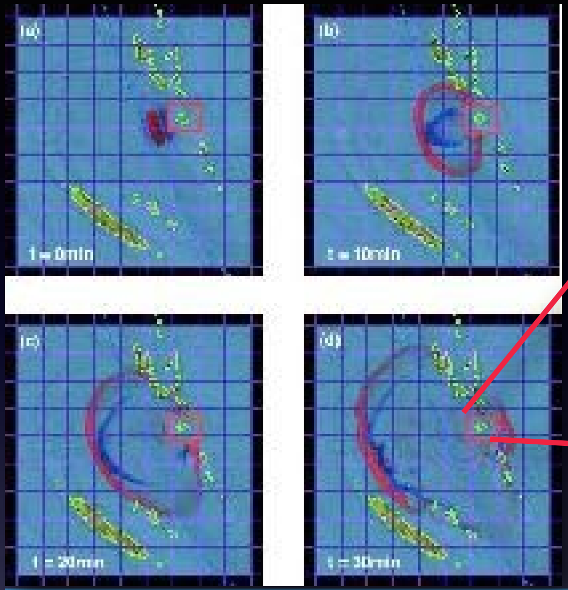
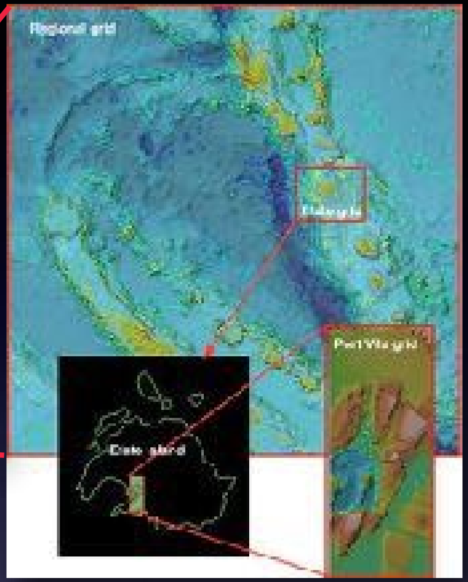
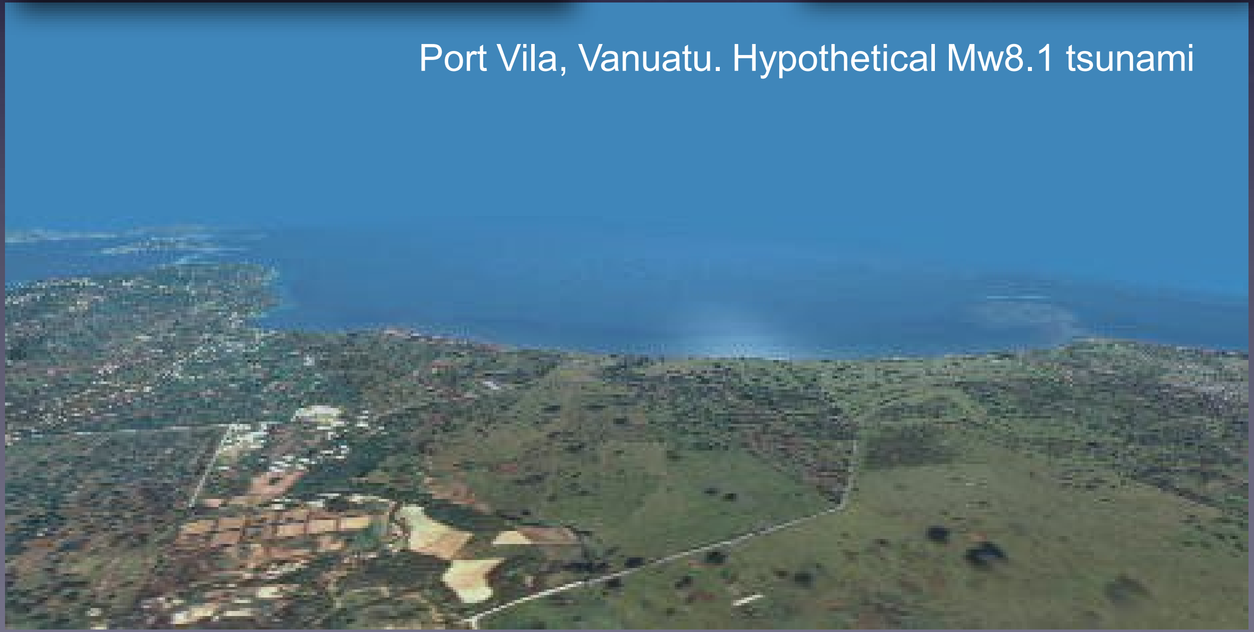
Tsunami Ready

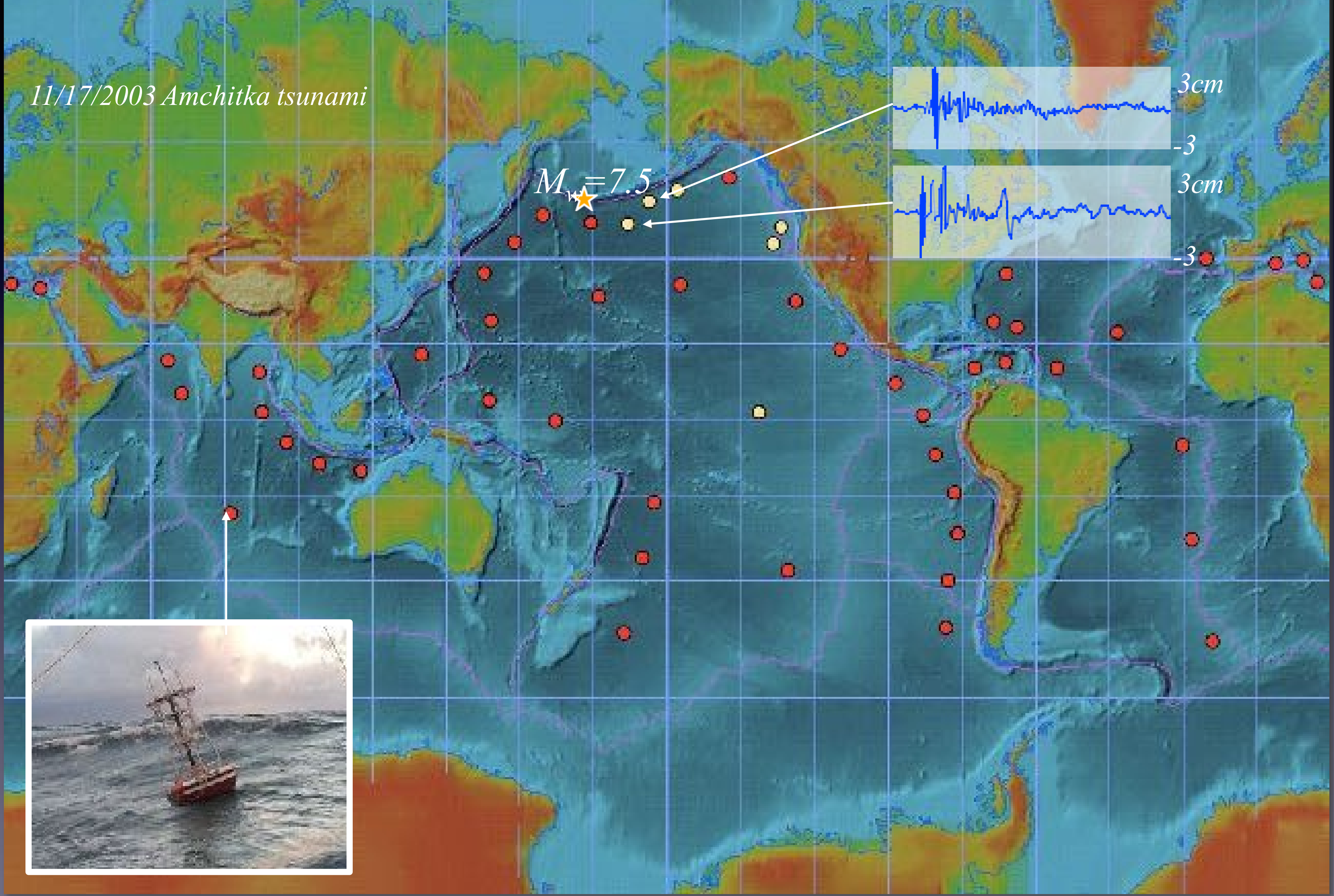
Small scale inundation effects



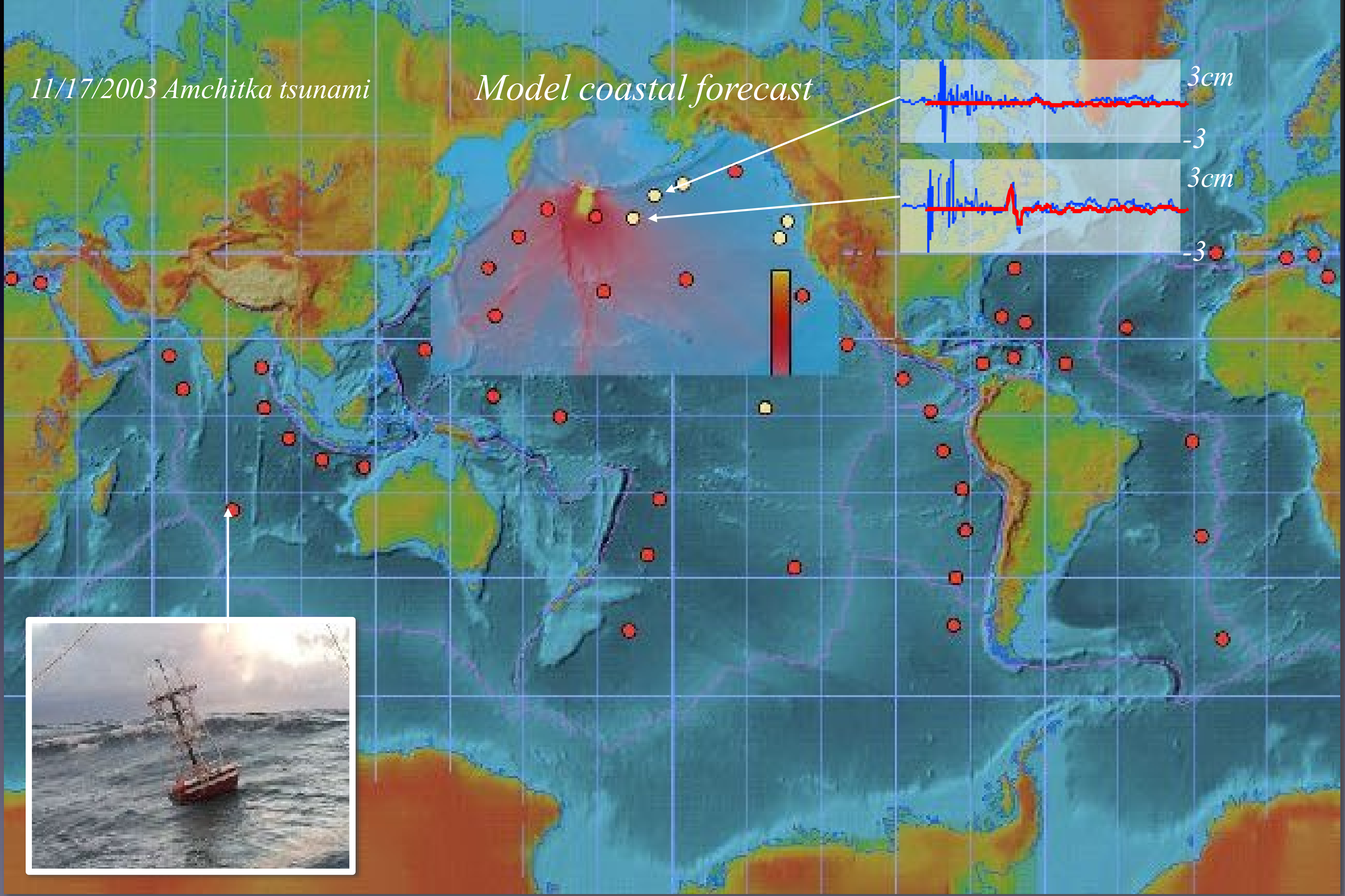


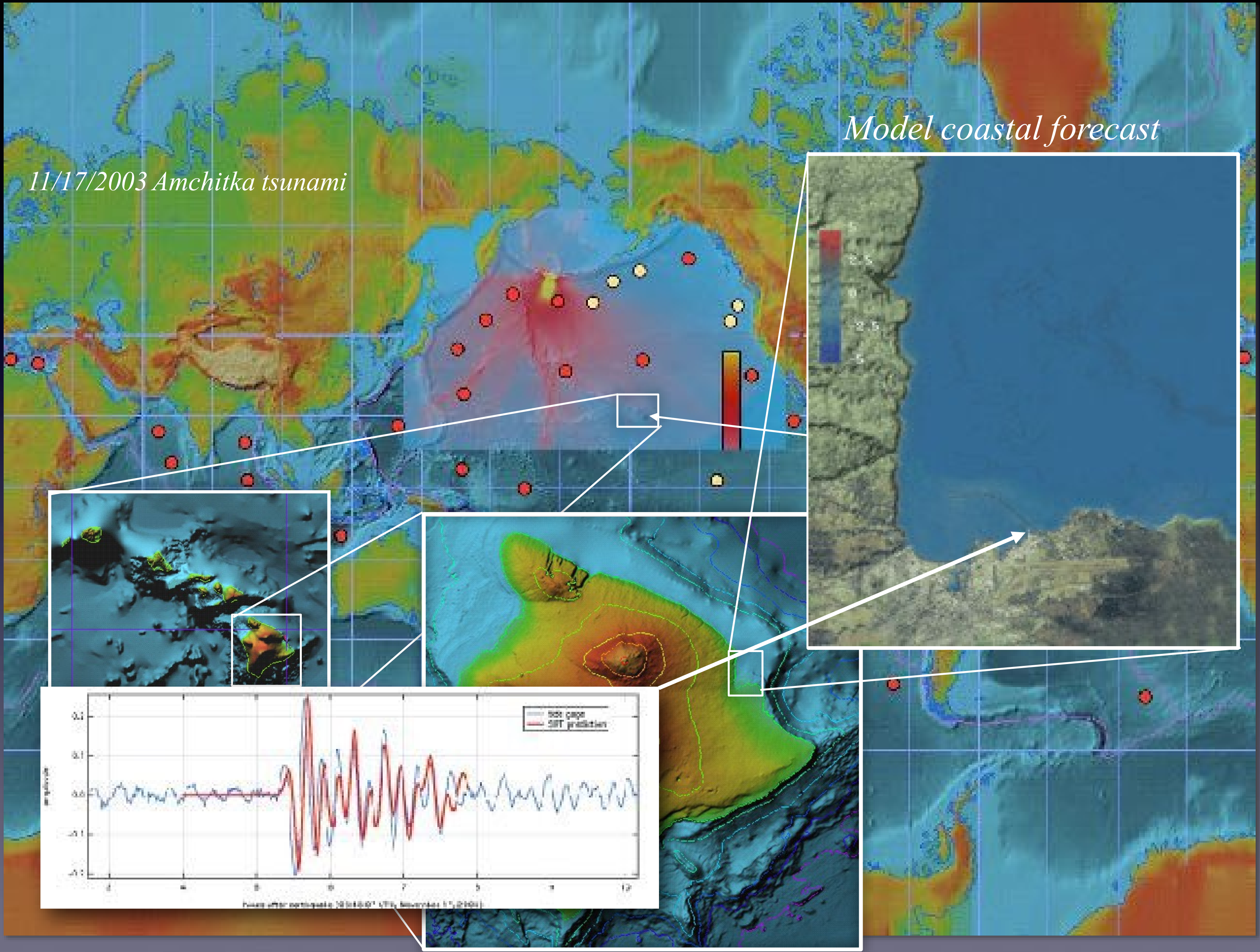


NOAA Tsunami Forecast



NOAA Tsunami Forecast





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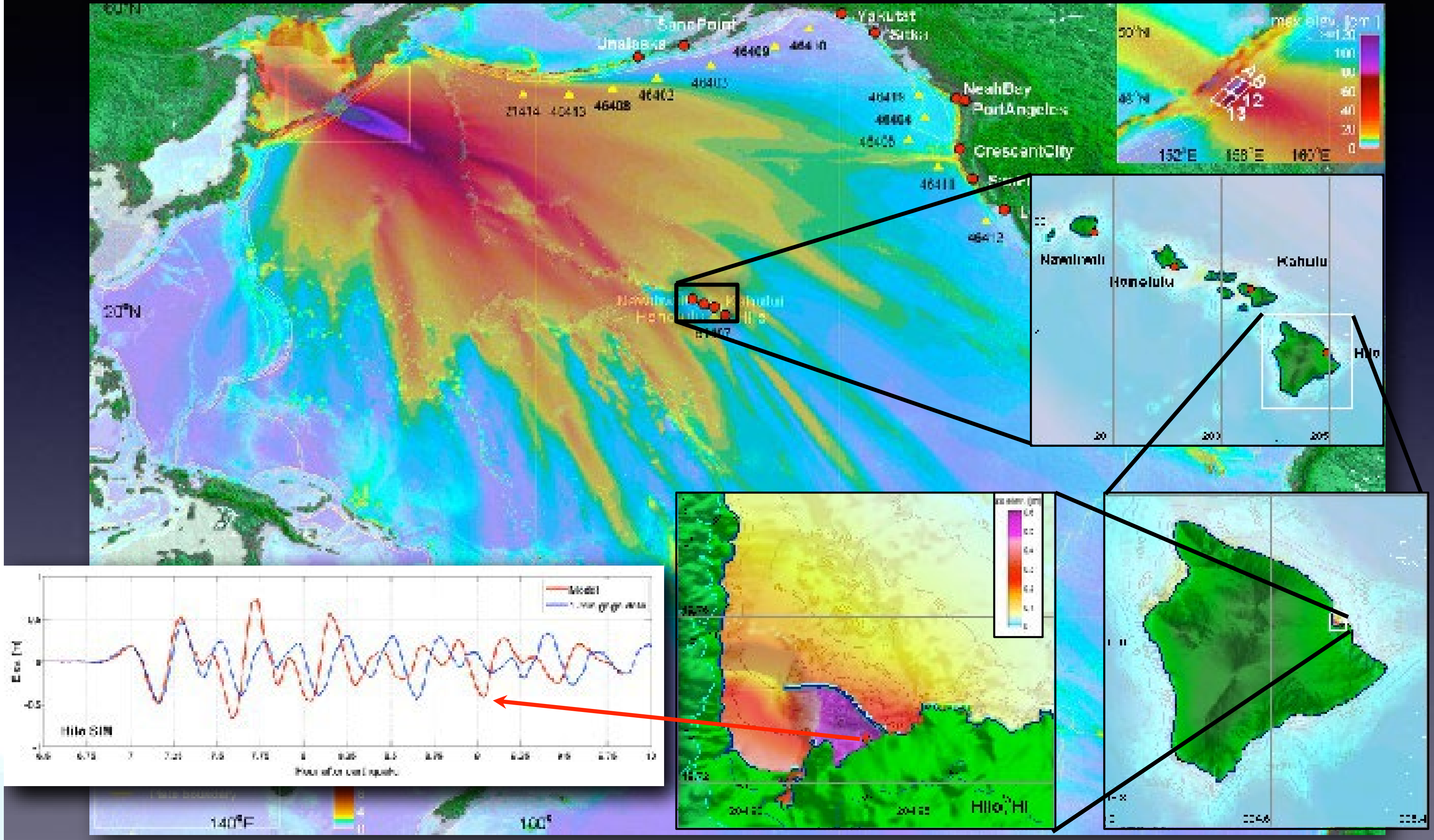
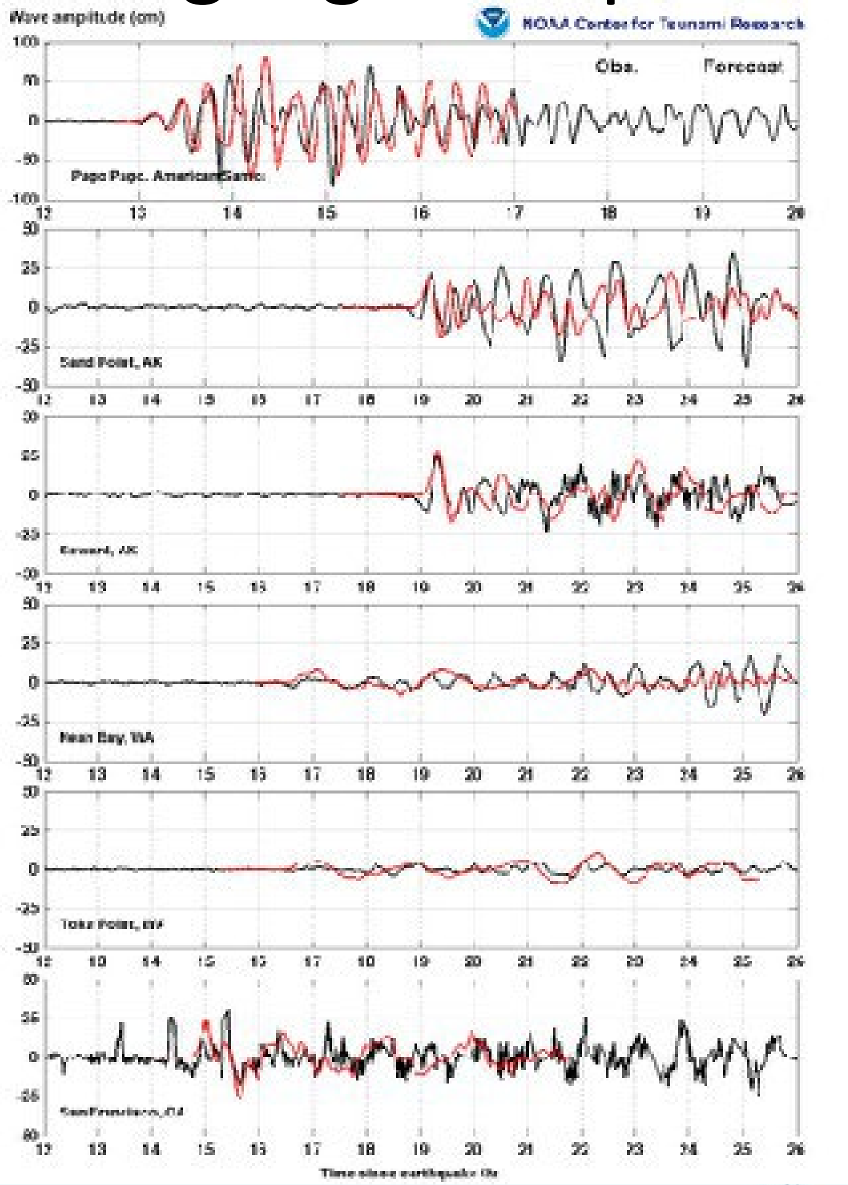
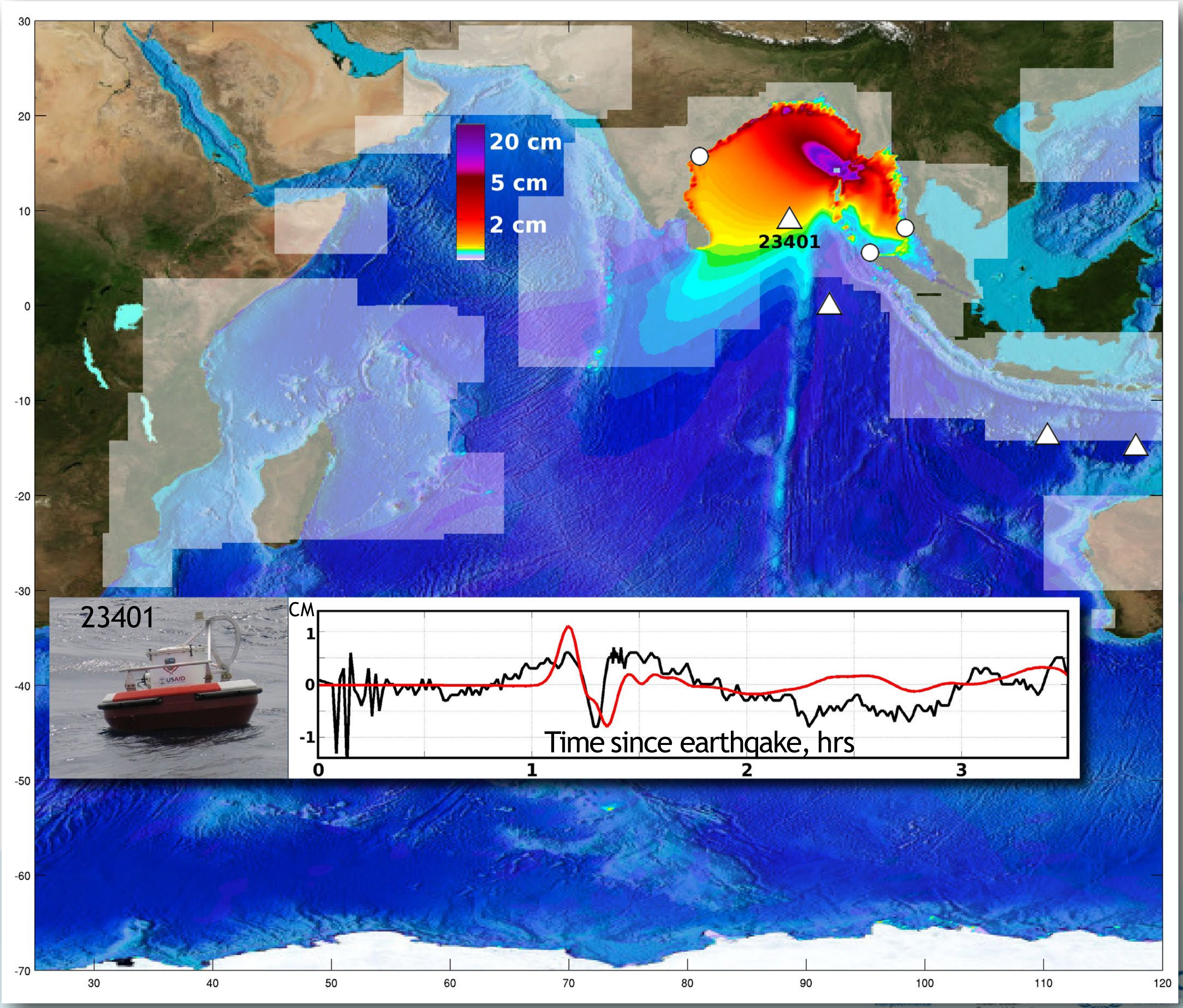
The November 15, 2006 Central Kuril Tsunami



Results: Tide gauge comparisons, Chile 2010



August 10, 2009 Andaman



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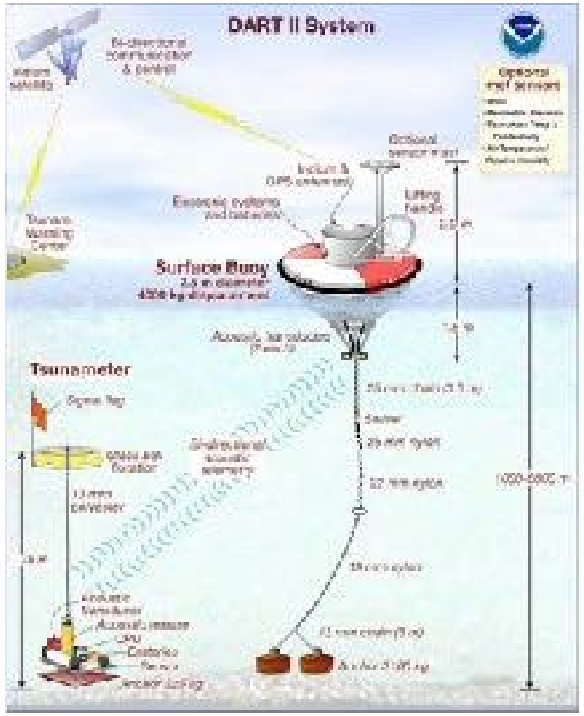
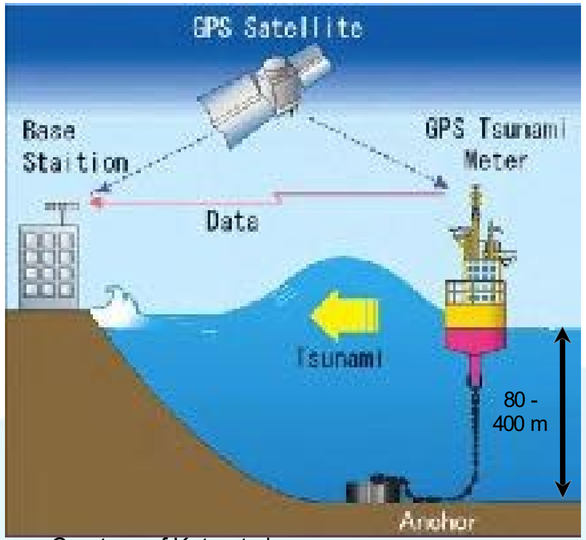
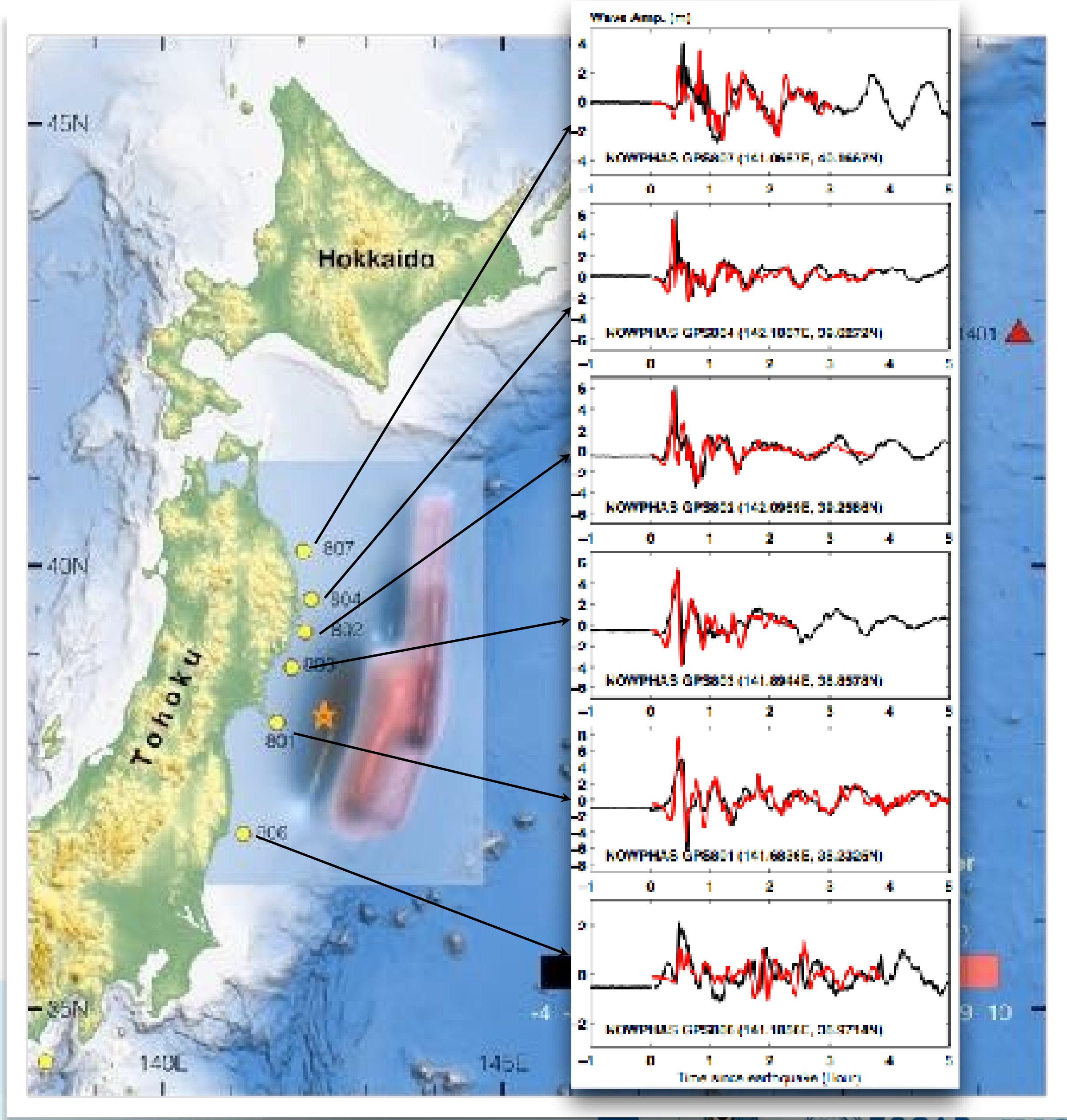


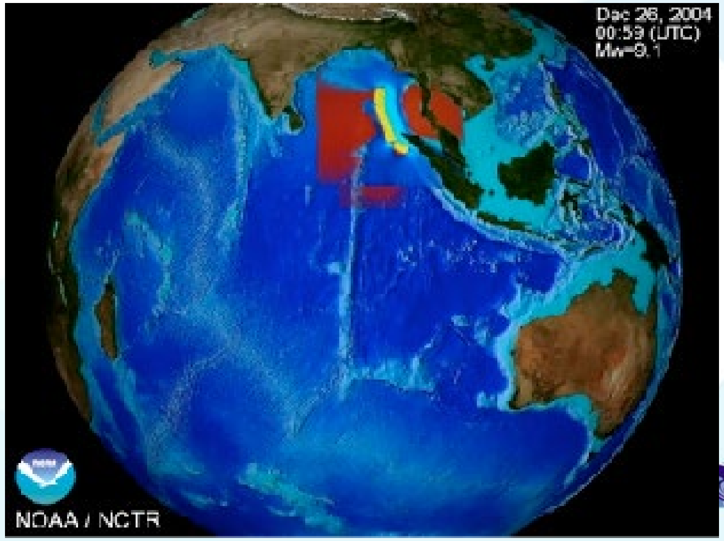


Courtesy of Kato et al.



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.

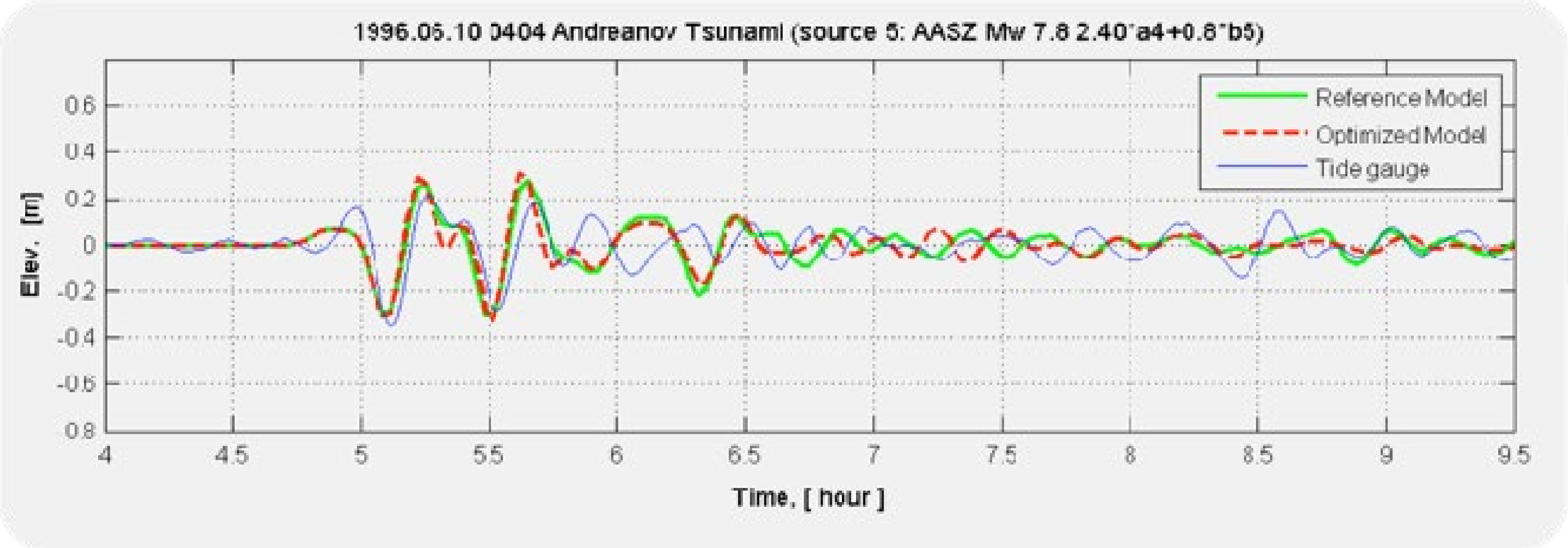


Developing Inundation Grids

- 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)



Graphics by Liujuan Tang UW/JISAO & NOAA/NCTR

Thank you