UNESCO/IOC – NOAA ITIC Training Program in Hawaii (ITP-TEWS Chile)
TSUNAMI EARLY WARNING SYSTEMS
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TSUNAMI EVACUATION PLANNING AND UNESCO IOC TSUNAMI READY PROGRAMME
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# TWC Operations: Travel Time and Amplitude Forecasting – Methods, Limitations, Uncertainty, Sensitivity Studies (Location, Depth, Magnitude)

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# Outline

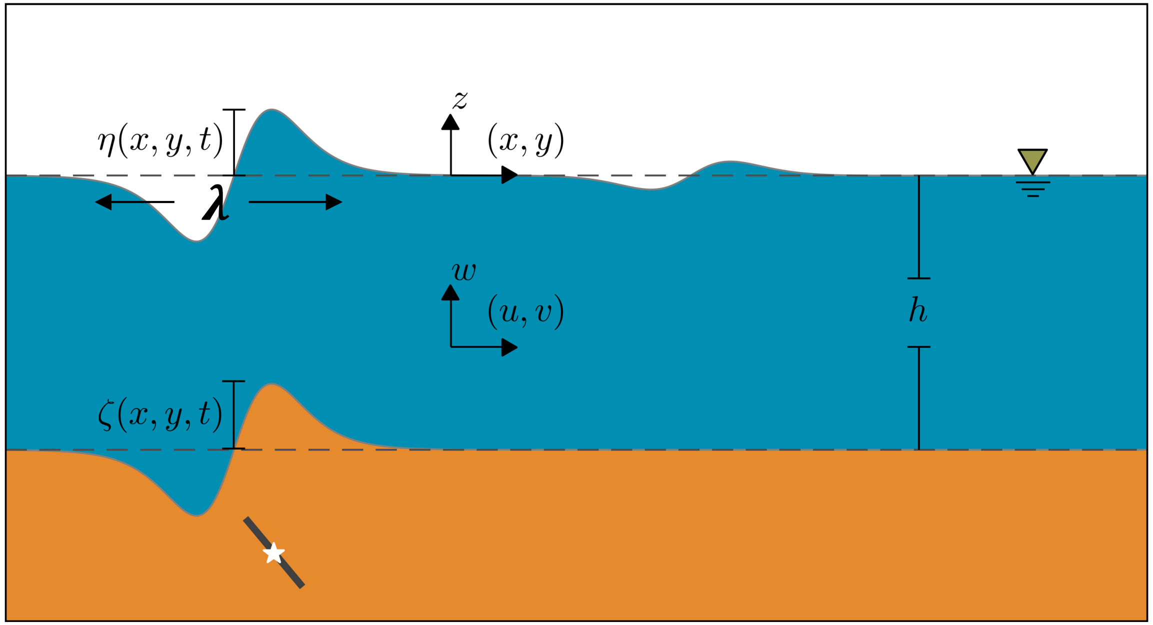
Quick Review of Essentials

The Travel Time Problem

Amplitude Forecasting

# Quick Review of Essentials

Tsunamis are primarily “long waves”. The term “long” refers to the fact that, in open waters, **tsunami waves** have lengths several times larger than water depth.



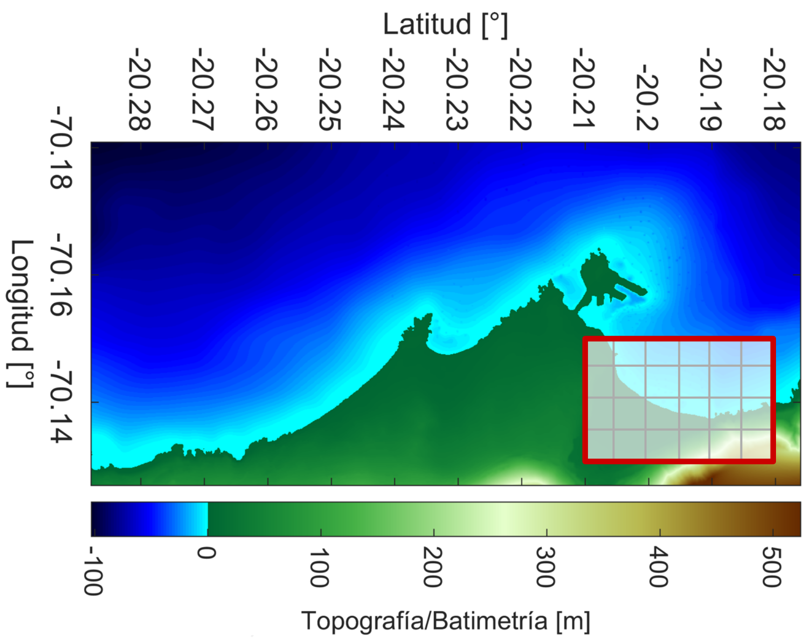



Long wave approximation

$$\lambda \gg h$$

# Quick Review of Essentials

These waves travel depending on the water depth. The surface that defines these depths is called **Bathymetry** and is one of the main inputs for tsunami modeling.




Each cell is linked to a geographical coordinate and a depth/height.

| | | | | | |
|---|---|---|---|---|---|
| 1,2 | -6 | -5,5 | -4 | -4,1 | -6 |
| 2,3 | -0,2 | -1,2 | -2,0 | -2,4 | -3,1 |
| 3,2 | 3,8 | 2,4 | 0,2 | 0,5 | 1,1 |
| 4,5 | 6,8 | 4,1 | 5,5 | 9,4 | 15 |

The sign change defines the shoreline

# Quick Review of Essentials

So, tsunami waves travel on a bathymetry… at what velocity?

It depends on the wave frequency.

As any wave, tsunamis can be decomposed in different frequencies (Fourier Transform)

$$\omega^2 = gk\tanh(kh)$$ → Wave Dispersion Equation

$$C_{ph}(\omega) = \frac{\omega}{k}$$ → Phase Velocity

$$C_g(\omega) = \frac{\partial \omega}{\partial k}$$ → Group Velocity

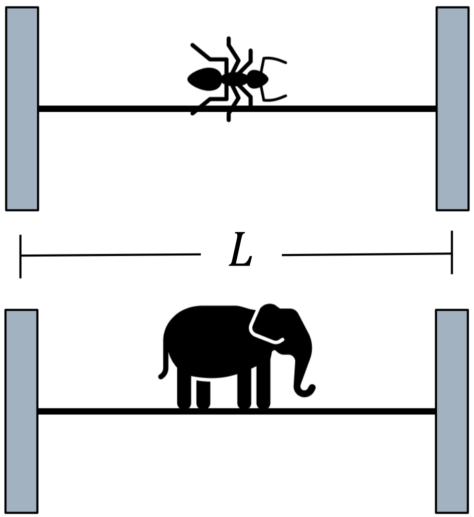
In the long wave predominance, $kh \ll 1, C_{ph} = C_g = \sqrt{gh}$

For $h = 4$ and $h = 5$ km, the speed is around **713 and 800 km/h**

# Quick Review of Essentials

In fact, the situation is somewhat more complicated.
Other effects may induce change in the wave travel. Let’s see one example

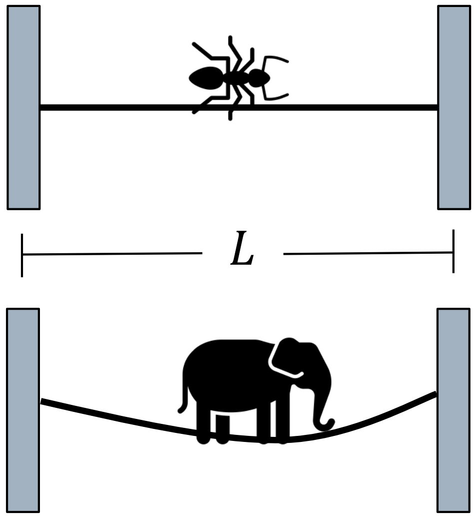
**Crossing a perfectly rigid bridge**




$$T_r = \frac{L}{v_a}$$

$$T_r = \frac{L}{v_e}$$

**Crossing an elastic bridge**




$$T_{nr} = T_r$$

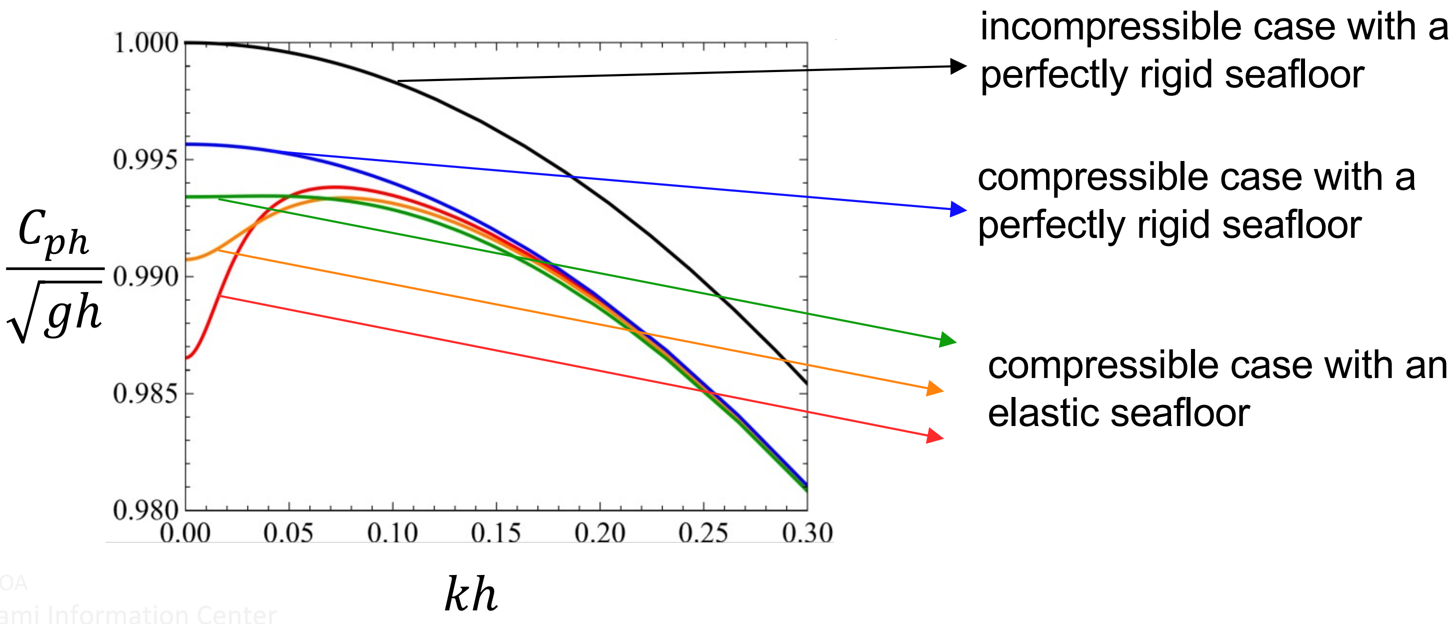
$$T_{nr} = \frac{L + \Delta L}{v_e} = T_r + \Delta \mathrm{T}$$

# Quick Review of Essentials

In fact, the situation is somewhat more complicated.

Other effects may induce change in the wave travel. Let's see one example

In a similar way, different wavelengths respond differently to the elastic properties of the seafloor.

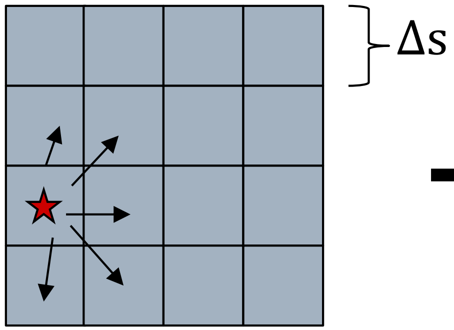


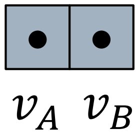
# The Travel Time Problem

# The Travel Time Problem

- Source – Observer Problem
- Common Methods
  - The TTT (*Tsunami Travel Time*): Huygen's Principle
  - Ray Tracing
  - Direct Tsunami Propagation Solvers

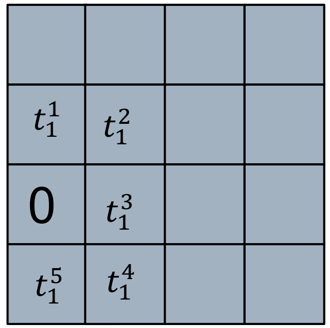
# TTT




$$\Delta T_{A,B} = \frac{\Delta s}{v_0}$$

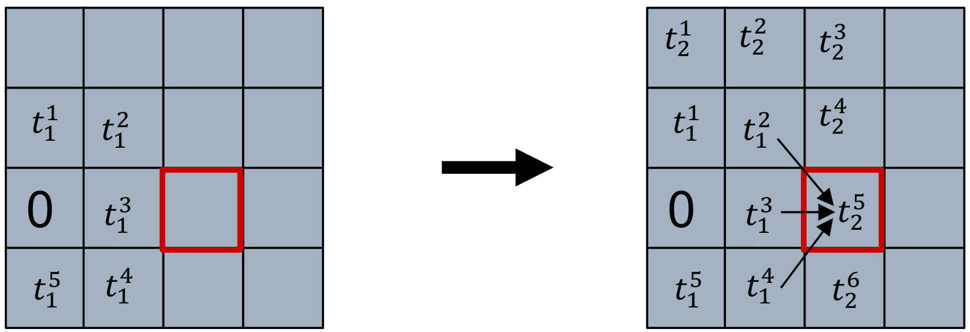
$$v_0 = \frac{v_A + v_B}{2}$$



# TTT

We compute the three posible time increments. We take the minimum!

$$\Delta T_{A,B} = \frac{\Delta s}{v_0}$$




Let's say that $t_1^3$ produces the minimum time increment, then

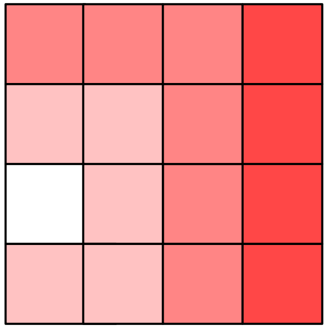
$$t_2^5 = t_1^3 + \Delta T_{A,B}$$

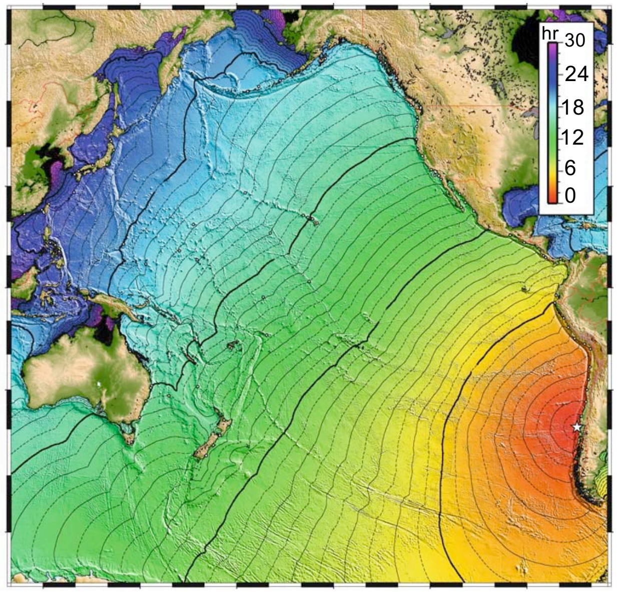
# TTT

Conect points with the same time (isochrones)

Apply it to real bathymetry

| | | | |
|---|---|---|---|
| $t_2^1$ | $t_2^2$ | $t_2^3$ | $t_3^1$ |
| $t_1^1$ | $t_1^2$ | $t_2^4$ | $t_3^2$ |
| 0 | $t_1^3$ | $t_2^5$ | $t_3^3$ |
| $t_1^5$ | $t_1^4$ | $t_2^6$ | $t_3^4$ |





# TTT

- Sensitive to bathymetry data
- Requires high computer power
- Needs high optimization to reduce computation times
- Do not consider wave frequencies nor second order effects
- Has relatively high uncertainty for far field arrival times

# Ray Tracing

**Eikonal Equations for Tsunami rays**

$$\frac{\mathrm{d}\theta}{\mathrm{d}s} = \frac{1}{R}\cos(\zeta)$$

$$\frac{\mathrm{d}\phi}{\mathrm{d}s} = \frac{1}{R}\frac{\sin(\zeta)}{\sin(\theta)}$$

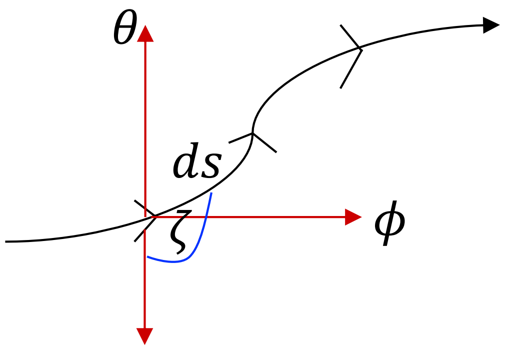
$$\frac{\mathrm{d}\zeta}{\mathrm{d}s} = \frac{\sin(\zeta)}{R}\frac{1}{C}\frac{\partial C}{\partial \theta} - \frac{\cos(\zeta)}{R\sin(\theta)}\frac{1}{C}\frac{\partial C}{\partial \phi} - \frac{\sin(\zeta)\cot(\theta)}{R}$$

$\theta$ : colatitude

$\phi$ : longitude

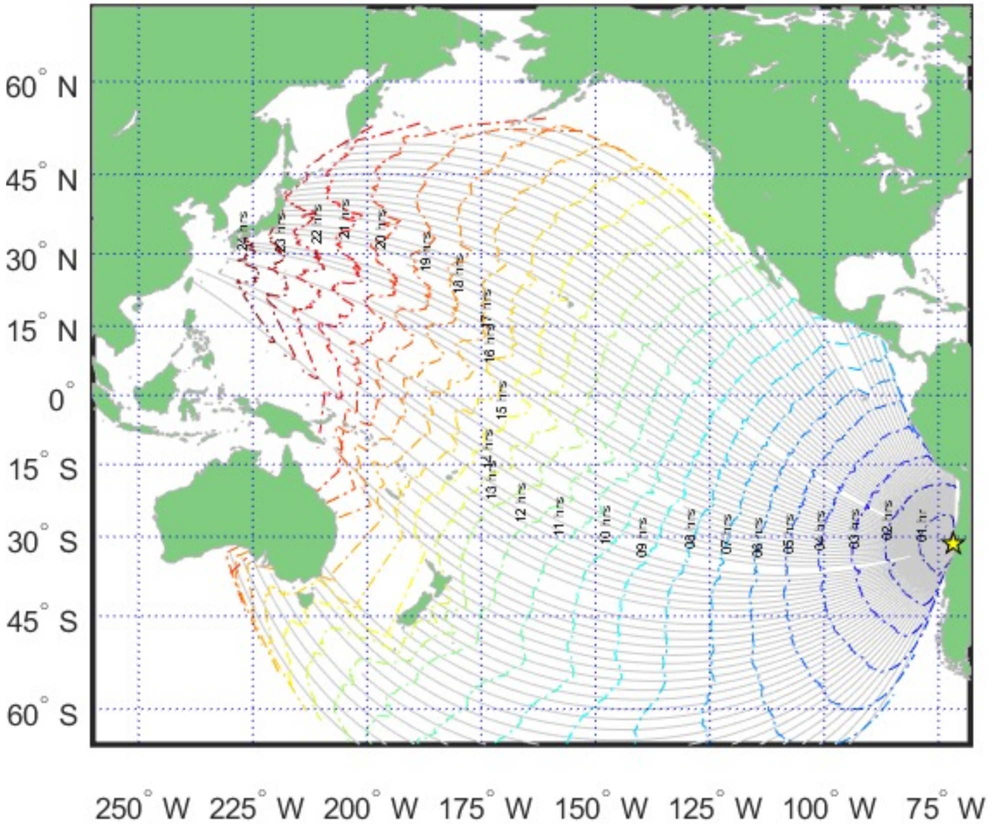
$R$ : Earth Radius (6371 km)

$C$ : Phase Velocity




$$ds = C \times dt$$

# Ray Tracing



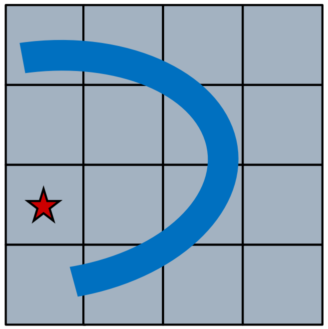

Again, connect ray points at equal times: this will produce Isochrones of the wavefront

# Ray Tracing

- Sensitive to bathymetry data
- Requires high computer power
- It could need an excessive number of rays to cover the whole bathymetry, making the process slow.
- Has relatively high uncertainty for far field arrival times

# Tsunami Propagation

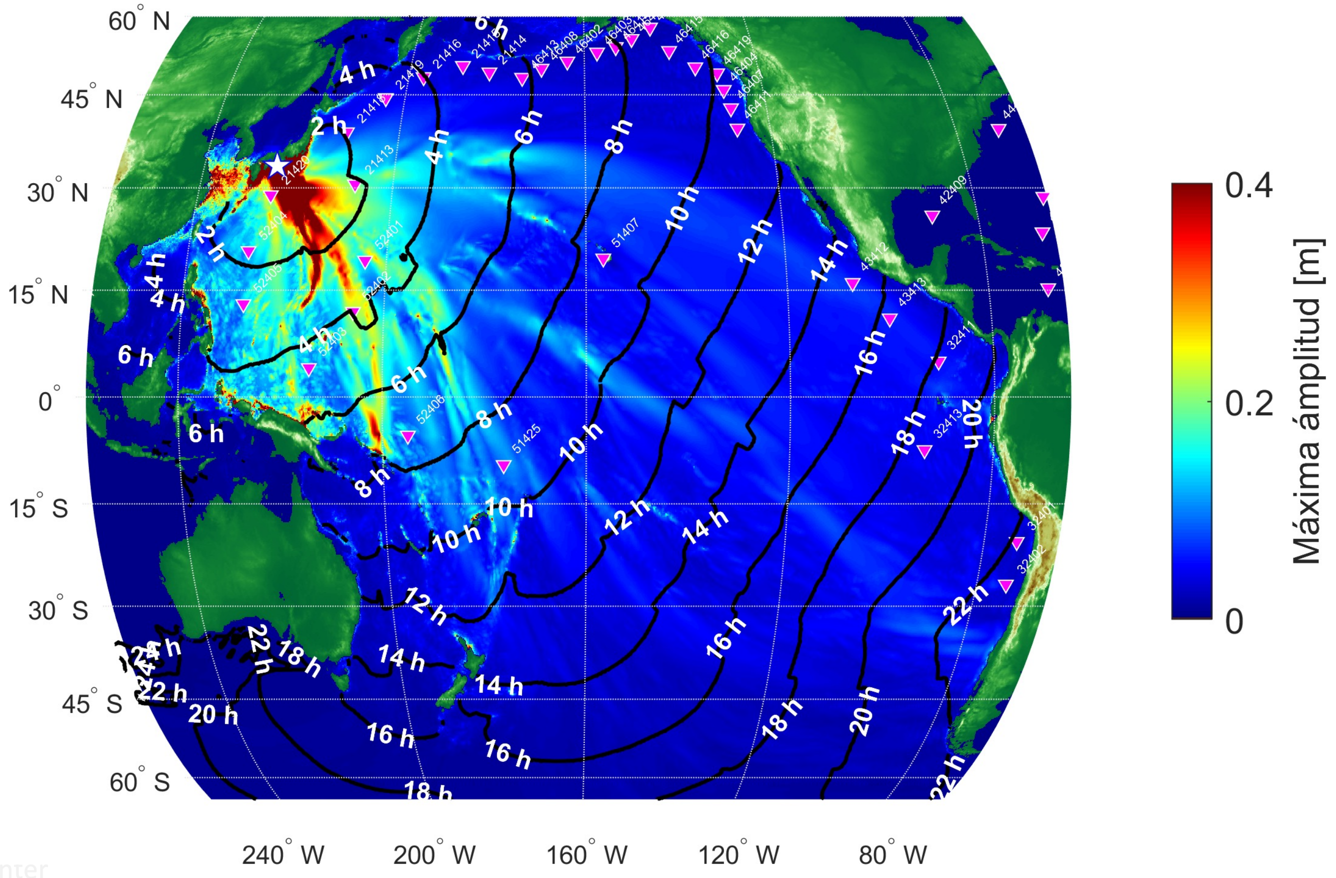
There are plenty of Tsunami Solvers out there, most of them are based on a version of the Non-Linear Shallow Water Equations (NLSWE), treated in finite difference schemes.



Arrival time is defined at every point amplitude exceeds a preset threshold (let's say 1 cm).

# Tsunami Propagation

Hypothetical source in the Nankai Trough



# Tsunami Propagation

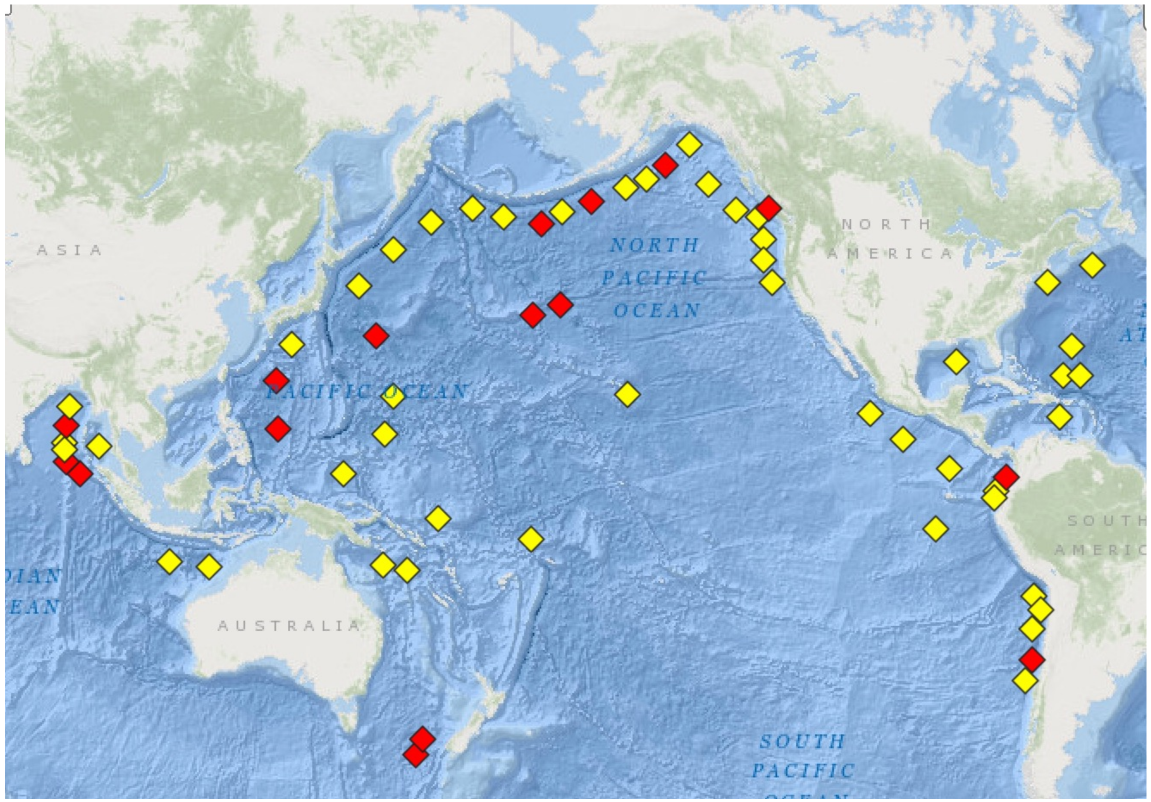
- Sensitive to bathymetry data
- Requires high computer power
- Sensitive to the source determination
- May vary from different numerical models

# Amplitude Forecasting

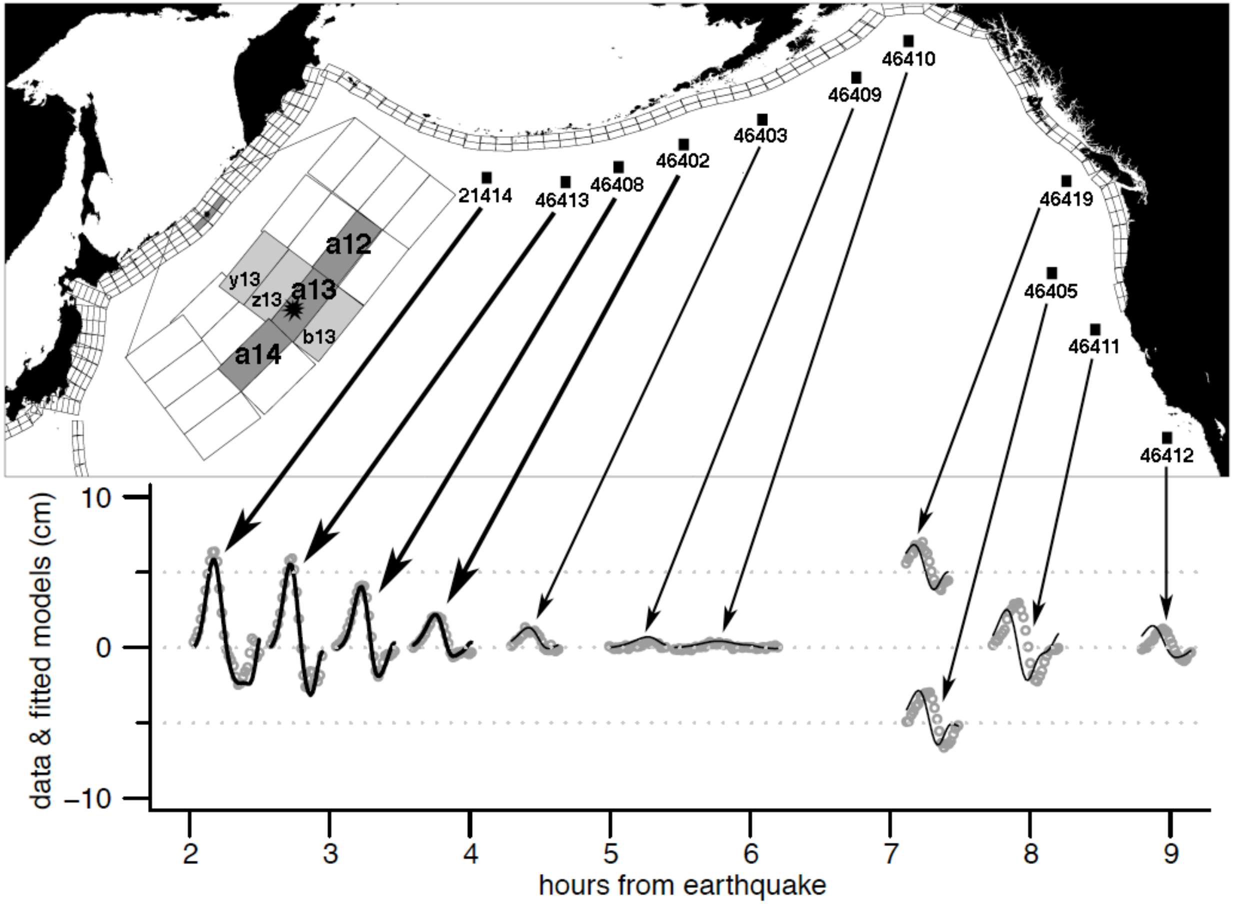
# Amplitude Forecasting

Tsunamis are recorded by **Tsunamimeters.**

In open waters, the waves have essentially linear behavior, and those records can be employed for an **inversion process**.



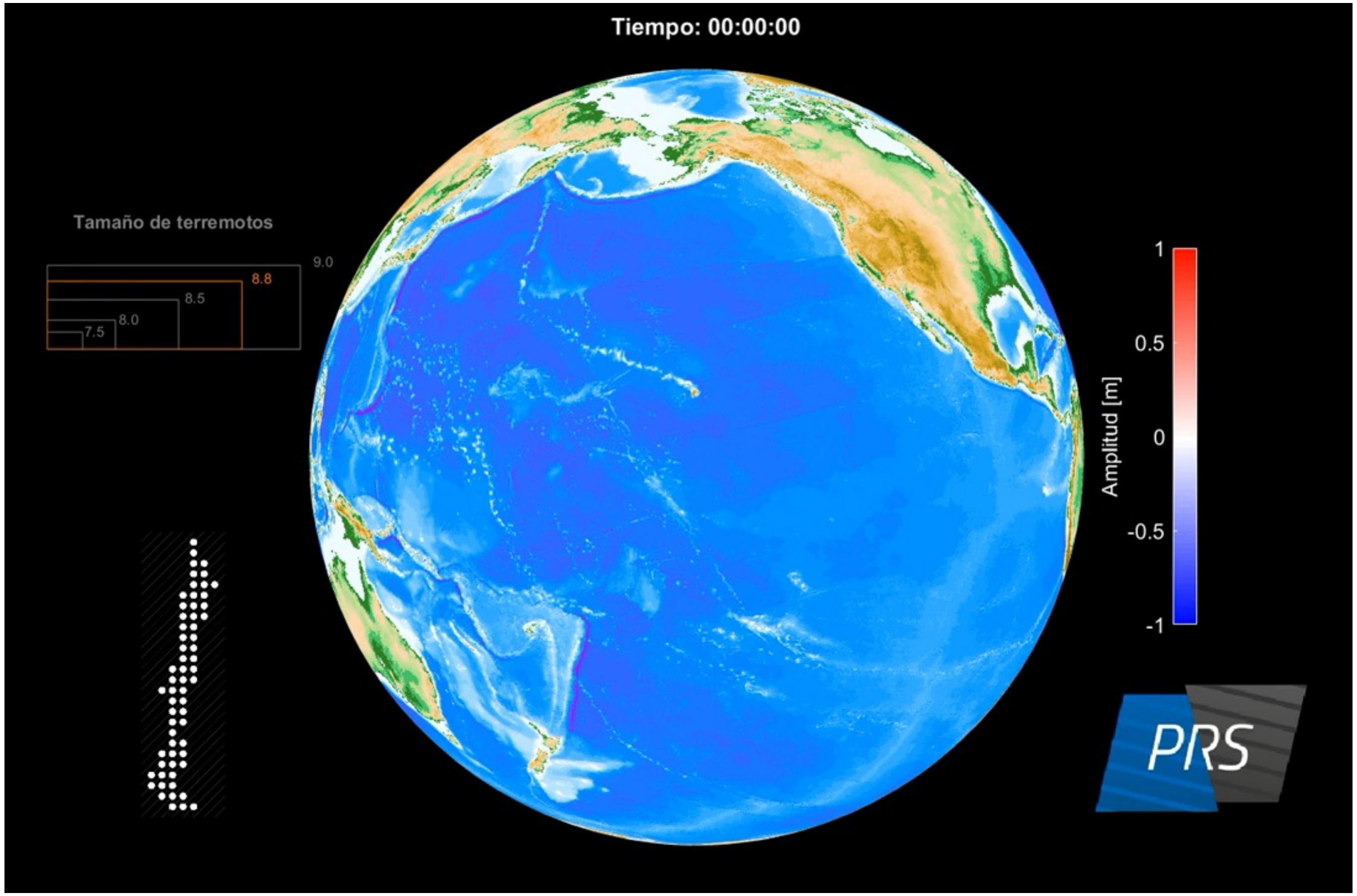
# Amplitude Forecasting




Predefined source candidates are set and then, selected and weighted according the data retrieved from the DART buoys.

Once the possible source is reconstructed, a forward model is run.

# Amplitude Forecasting




Evidently, this only has sense for communities where the waves have not yet arrived after the whole has finished.

**Far Field!**

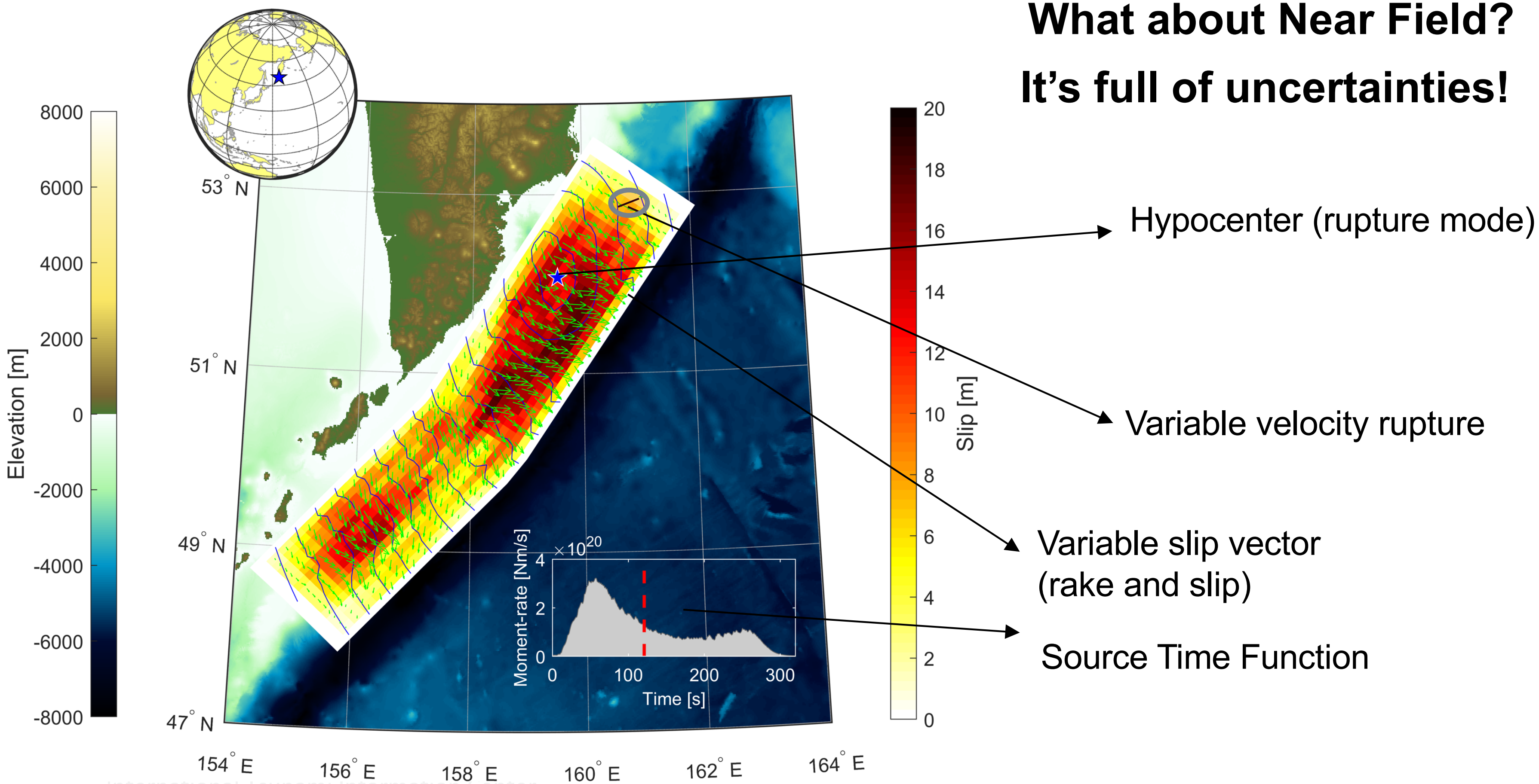
# Amplitude Forecasting

- Sensitive to bathymetry data
- Sensitive to data acquiring
- Not useful for tsunami early warning in the Near Field case
- Specific Tsunami Inundation Models depend on data that may not exist, and highly computational expensive.

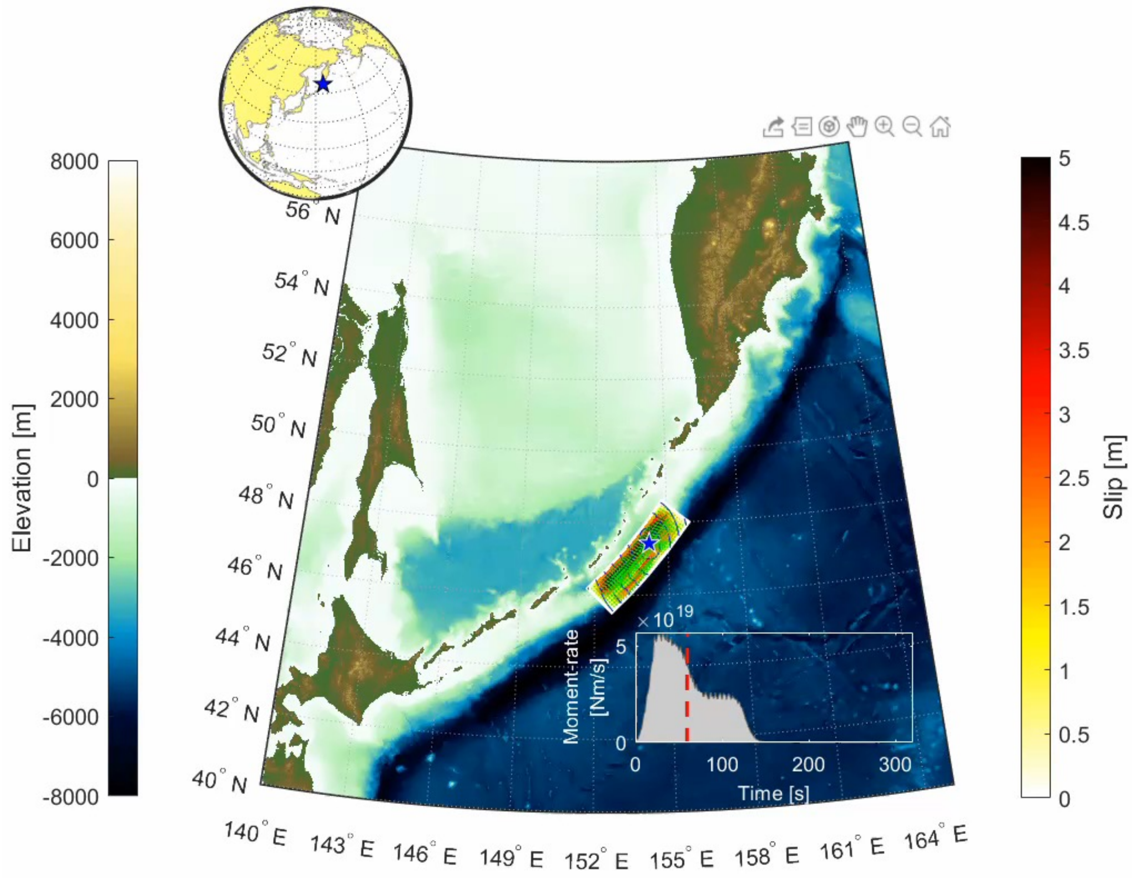
# Amplitude Forecasting

**What about Near Field?**

**It's full of uncertainties!**



# Amplitude Forecasting






There are infinitely many valid sources and it's not possible to perform (yet) to a reliable inversion and predict amplitudes before the tsunami impact.

Then, how we tackle the Early Warning Problem in the Near Field ?

Soon, in a talk, this Will be discussed ;)

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# Thank You


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