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NUMERICAL MODELING OF LOW FREQUENCY HYDRO-ACOUSTIC WAVES GENERATED BY SUBMARINE TSUNAMIGENIC EARTHQUAKE

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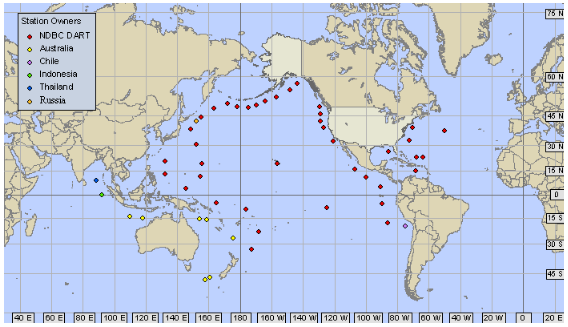
Motivations:
Improve Tsunami Early Warning System

- Systems based on seismic measurements
- Tsunami measurements are essential to increase the reliability of the system
- Can we use precursors of tsunami?



DART system

Hydro-acoustic waves (pressure waves in weakly compressible fluid)

- Travel at 1500 m/s
- Contain information on the tsunamigenic source
- Need of numerical modelling (3D models are computationally expensive)

This research aims at developing numerical models applicable on an oceanic scale

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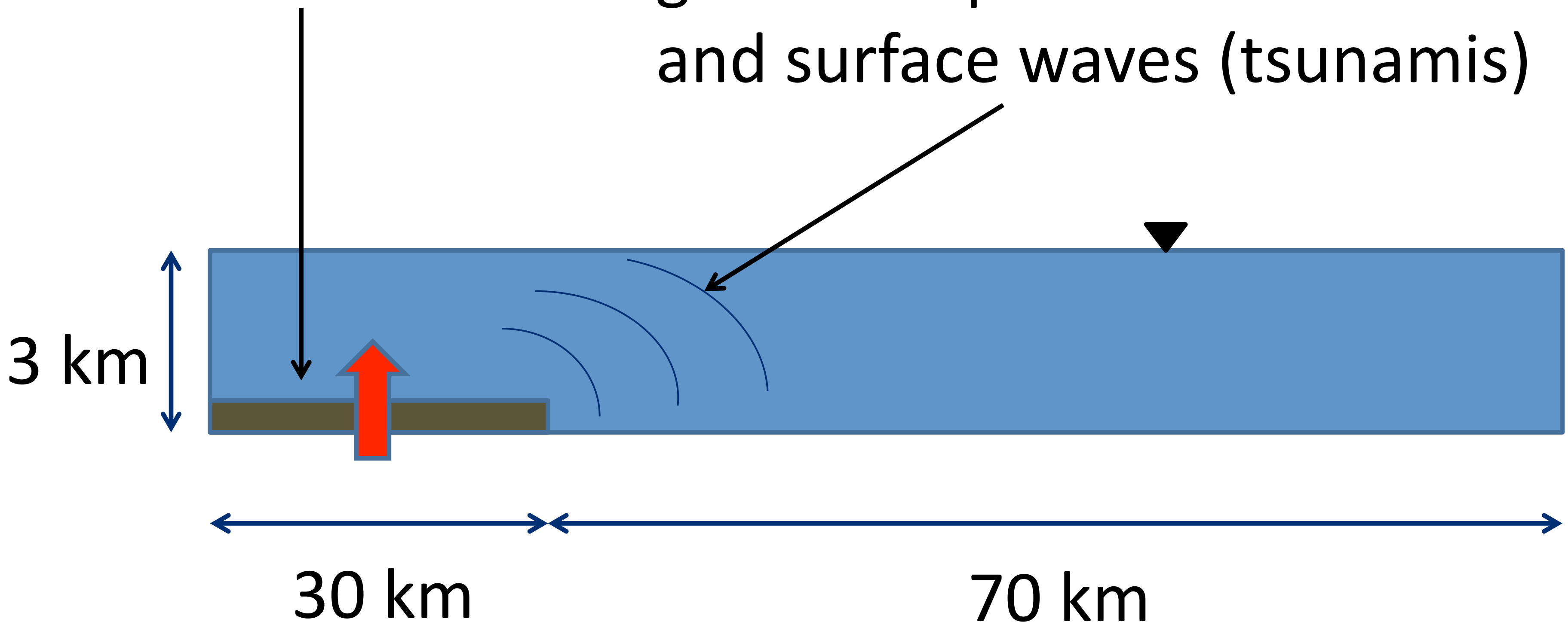
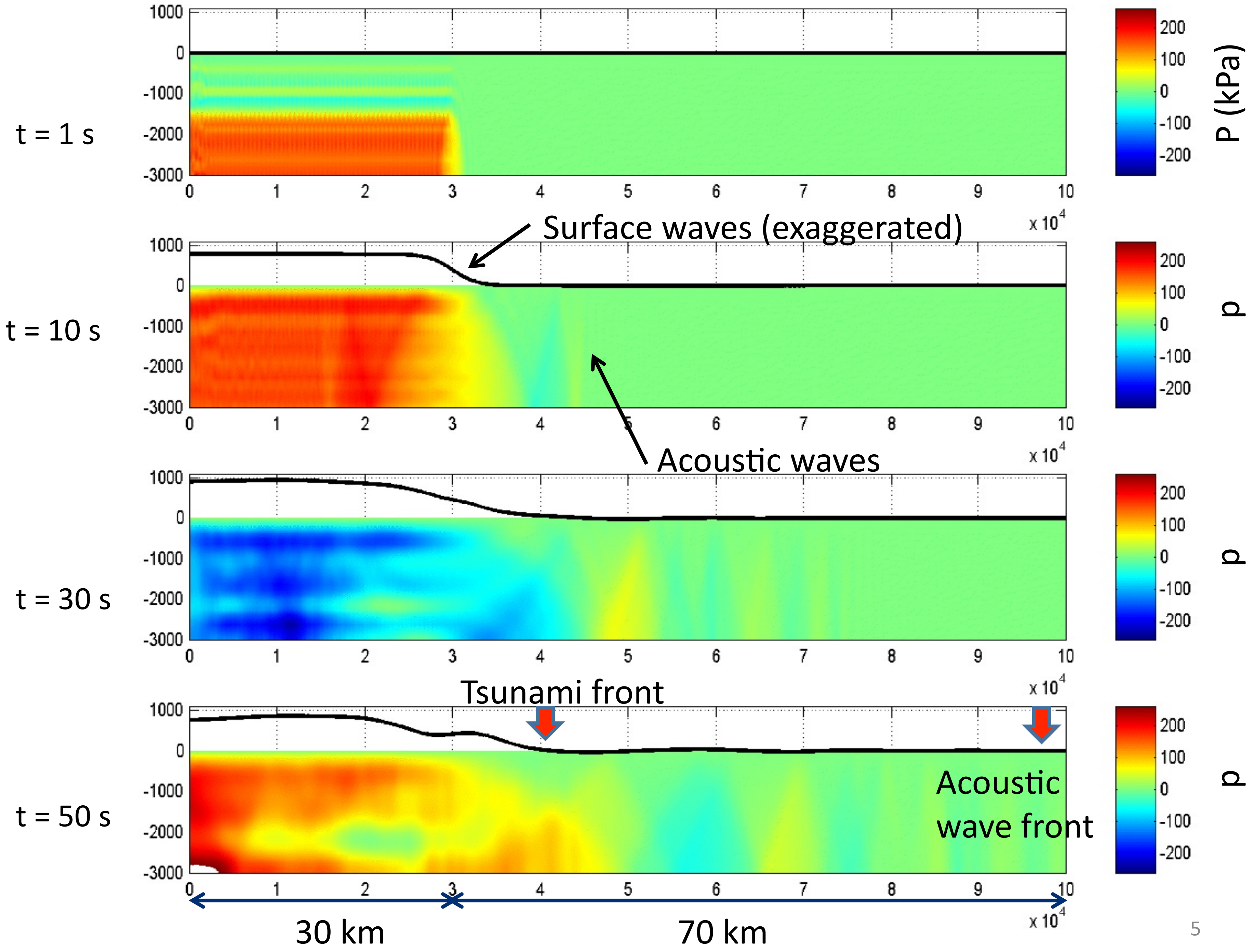
Hydro-acoustic wave



Simplified
earthquake

The movement of the bottom
generates pressure waves
and surface waves (tsunamis)

In the next slide results of computations related to this simple layout are shown



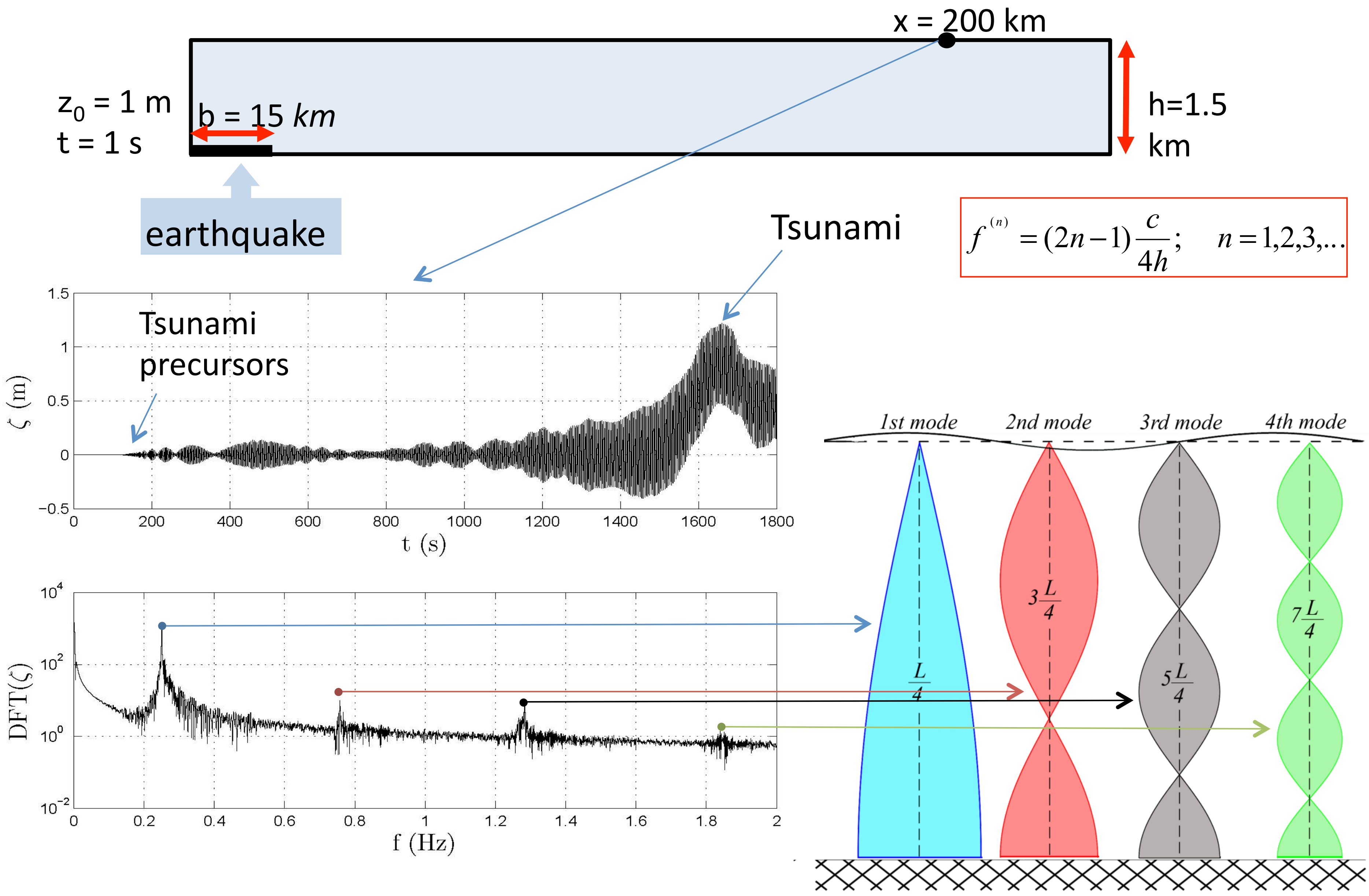
Surface waves (exaggerated)

Acoustic waves

Tsunami front

Acoustic wave front

Hydro-acoustic wave



x = 200 km

z_0 = 1 m

t = 1 s

b = 15 *km*

h=1.5 km

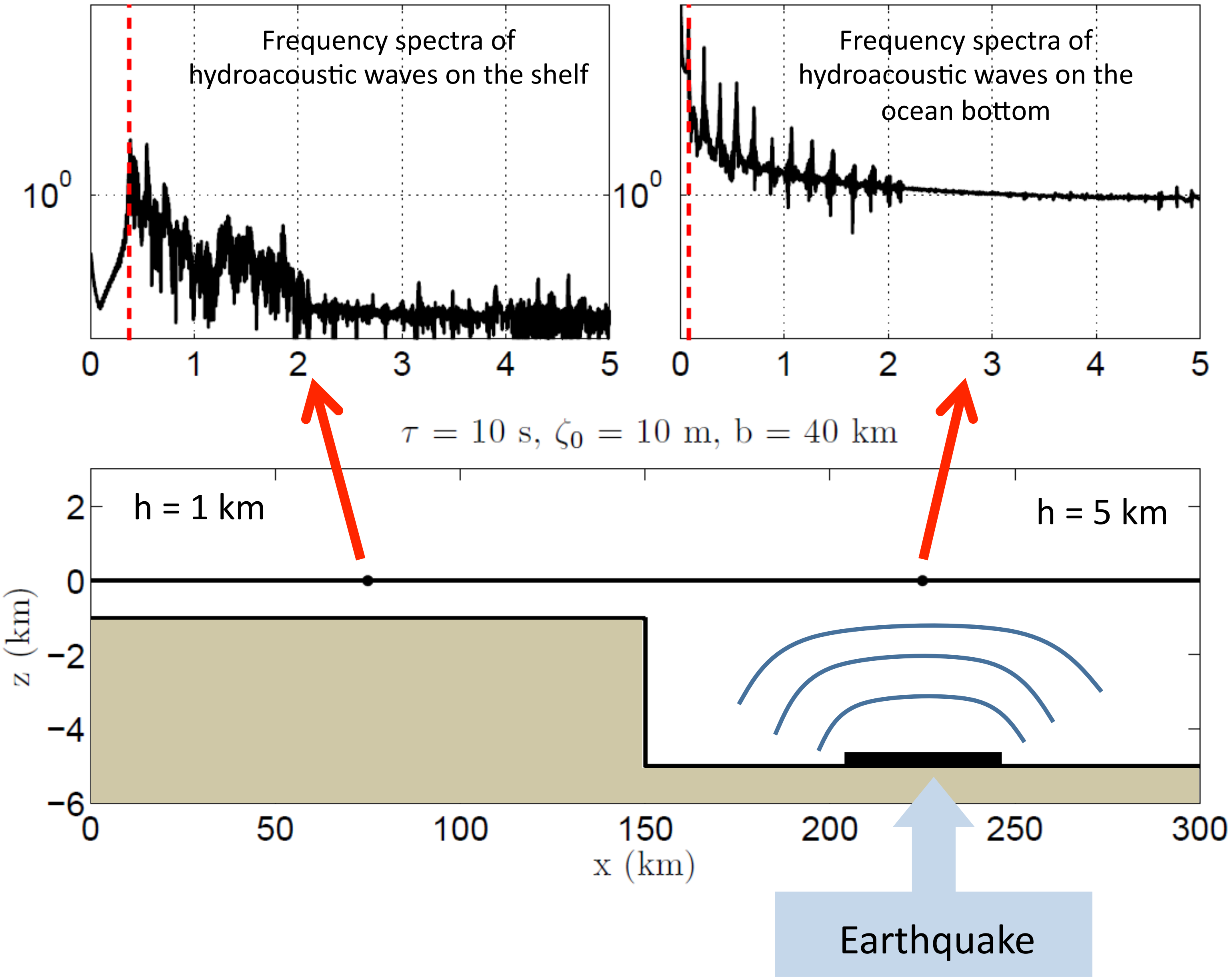
earthquake

Tsunami

$$f^{(n)} = (2n-1)\frac{c}{4h}; \quad n = 1,2,3,\ldots$$

Tsunami precursors

Depth Effect



Frequency spectra of hydroacoustic waves on the shelf

Frequency spectra of hydroacoustic waves on the ocean bottom

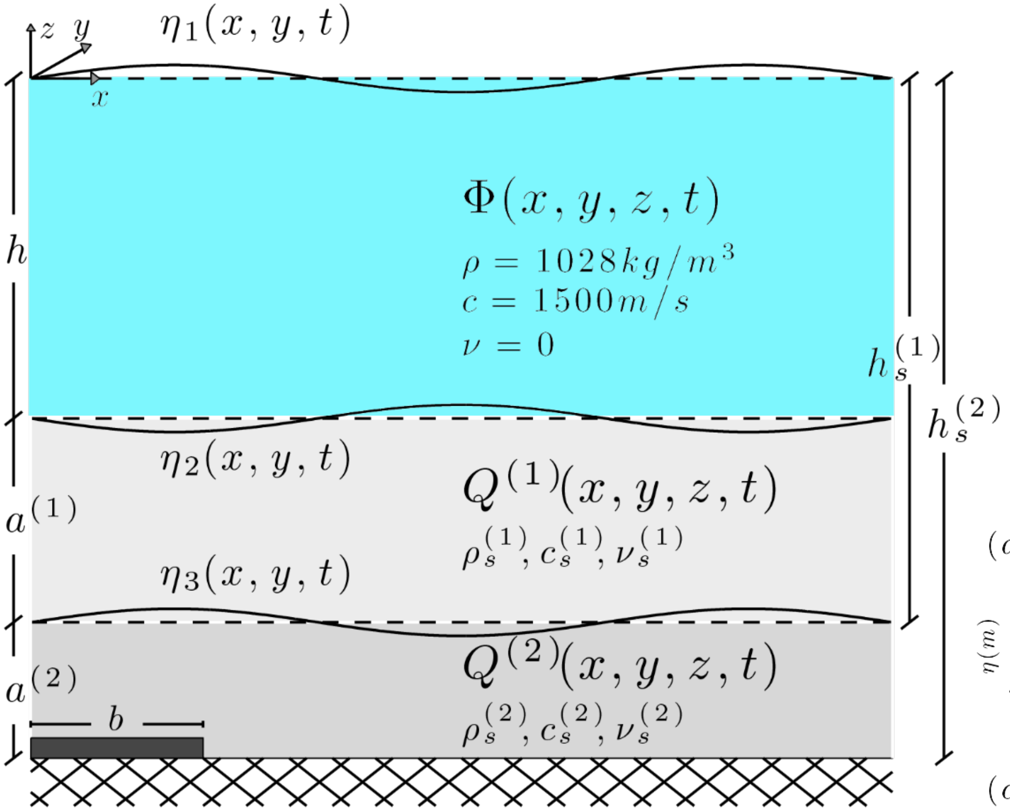
$\tau = 10$ s, $\zeta_0 = 10$ m, b = 40 km

h = 1 km

h = 5 km

Earthquake

Change in Normal Peak Frequencies



Layer	Density (kg/m^3)	Sound Celerity (m/s)	Layer Thickness (m)
Water	$\rho = 1028$	$c = 1500$	$h = 2200$
Sediment $(i = 1)$	$\rho_s^{(1)} = 1850$	$c_s^{(1)} = 2000$	$a^{(1)} = 1000$
Sediment $(i = 2)$	$\rho_s^{(2)} = 2200$	$c_s^{(2)} = 2500$	$a^{(2)} = 1000$

Fault Length (km)	Start Time (s)	Duration (s)	Residual Displacement (m)
$b = 112$	$t_0 = 5$	$\tau = 2$	$\zeta_0 = 1$

Sediment Layer(s)	1^{st} mode (Hz)	2^{nd} mode (Hz)	3^{rd} mode (Hz)
0 Layer	$f^{(1)} = 0.17$	$f^{(2)} = 0.51$	$f^{(3)} = 0.85$
1 Layers	$\gamma_1^{(1)} = 0.15$	$\gamma_1^{(2)} = 0.41$	$\gamma_1^{(3)} = 0.60$
2 Layers	$\gamma_2^{(1)} = 0.14$	$\gamma_2^{(2)} = 0.32$	$\gamma_2^{(3)} = 0.52$

Rigid bottom:

$$f^{(n)} = (2n-1)\frac{c}{4h}; \qquad n = 1,2,3,\ldots$$

1

Single Sedimentary Layer:

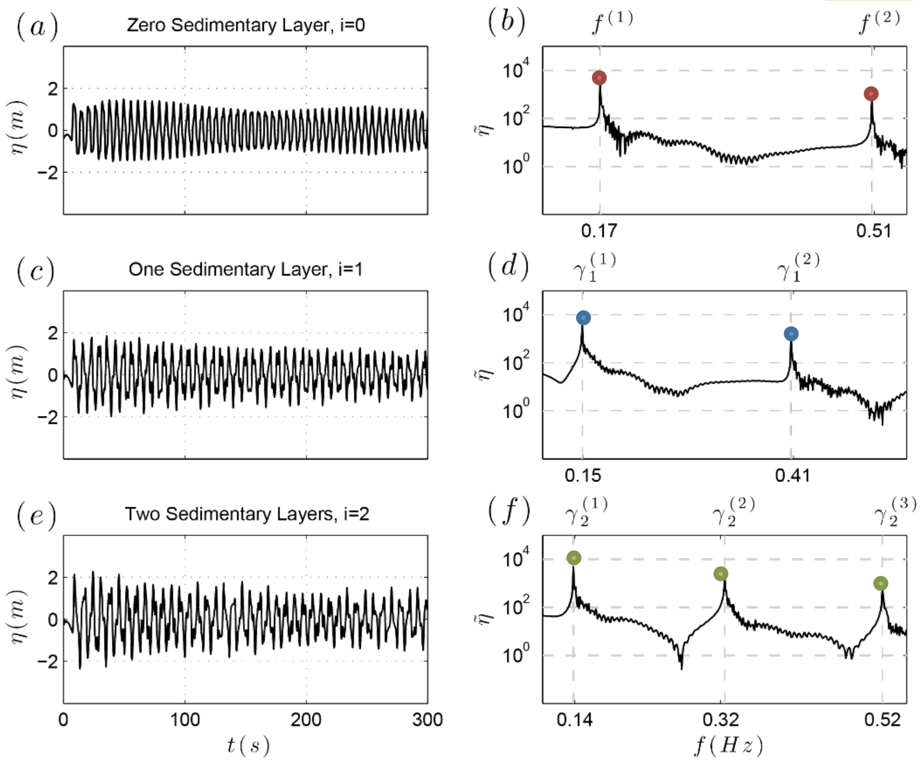
$$\tan\left[\frac{(2\pi\,\gamma_1^{(n)}h)}{c}\right]\tan\left[\frac{(2\pi\,\gamma_1^{(n)}a^{(1)})}{c_s^{(1)}}\right] = \frac{\rho_s^{(1)}\,c_s^{(1)}}{\rho\, c}$$

2

Two Sedimentary Layers:

$$\frac{\dfrac{\rho_s^{(2)}c_s^{(2)}}{\rho_s^{(1)}c_s^{(1)}} - \tan\left[\dfrac{2\pi\gamma_2^{(n)}a^{(1)}}{c_s^{(1)}}\right]\tan\left[\dfrac{2\pi\gamma_2^{(n)}a^{(2)}}{c_s^{(2)}}\right]}{\tan\left[\dfrac{2\pi\gamma_2^{(n)}a^{(2)}}{c_s^{(2)}}\right] + \dfrac{\rho_s^{(2)}c_s^{(2)}}{\rho_s^{(1)}c_s^{(1)}}\tan\left[\dfrac{2\pi\gamma_2^{(n)}a^{(1)}}{c_s^{(1)}}\right]} = \frac{\rho c}{\rho_s^{(1)}c_s^{(1)}}\tan\left[\frac{2\pi\gamma_2^{(n)}h}{c}\right]$$

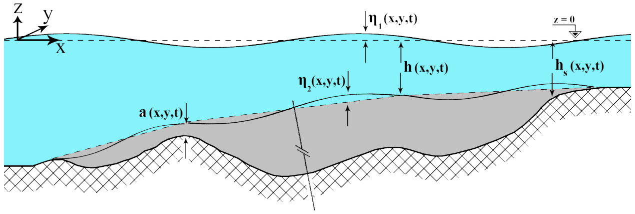
3



Depth integrated equation

Linearized 3d potential flow problem → Depth integration → MSE-like eq. In terms of velocity potential at z=0

$$\Phi_{tt} - c^2\nabla^2\Phi = 0 \;;$$



→

$$\boxed{\psi_{n,tt}\left(\frac{C_n}{c^2}+\frac{1}{g}\right)-\nabla.(C_n\nabla\psi_n)+\left(\frac{\omega^2}{g}-\beta_n^2C_n\right)\psi_n=\frac{h_{n,t}}{\cosh^2(\beta_n h)}}$$

Depth-integrated equation for large-scale modelling of low-frequency hydroacoustic waves, 2013, Journal of Fluid Mechanics, 722, R6.
DOI: http://dx.doi.org/10.1017/jfm.2013.153

Depth integrated equation for Rigid Bottom

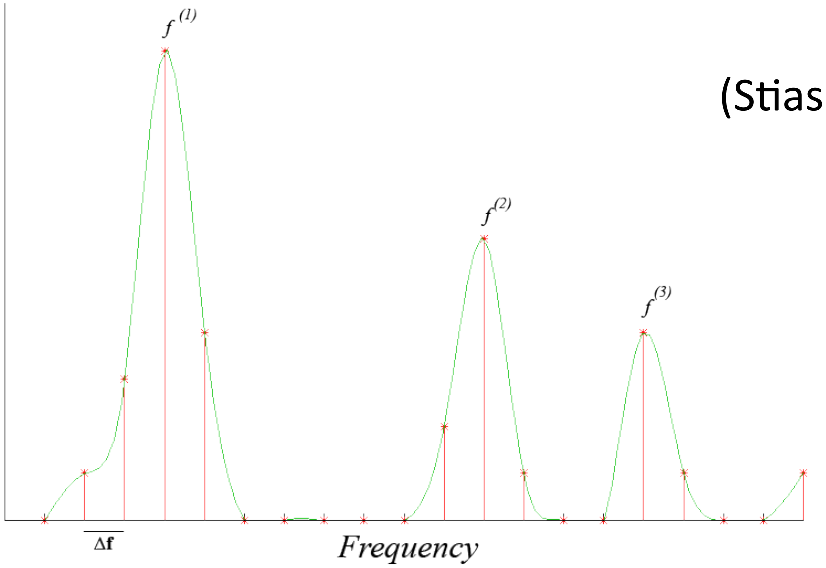
Rigid Bottom

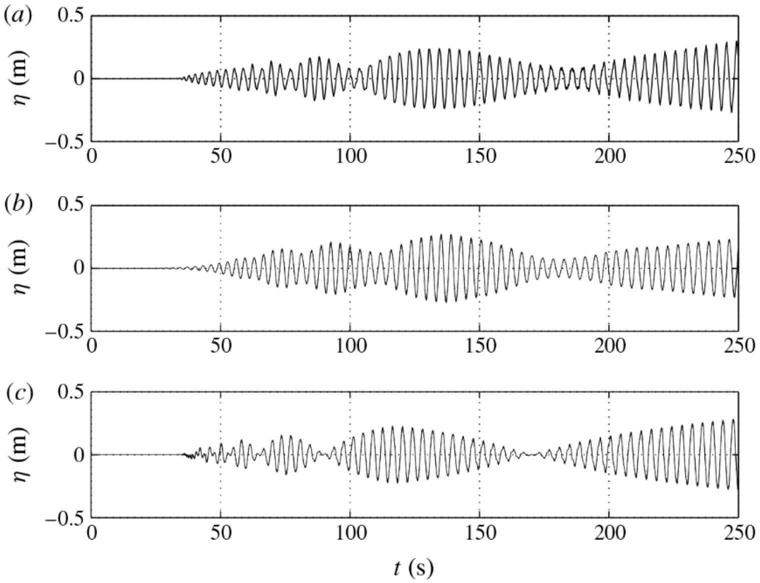
2013

$$\psi_{n,tt}\left(\frac{C_n}{c^2}+\frac{1}{g}\right)-\nabla.\left(C_n\nabla\psi_n\right)+\left(\frac{\omega^2}{g}-\beta_n^2 C_n\right)\psi_n=\frac{h_{n,t}}{\cosh^2(\beta_n h)}$$

Mild-slope equation weakly compressible fluid (MSEWC)

$$C_n=\frac{2\beta_n h+\sinh(2\beta_n h)}{4\beta_n\cosh^2(\beta_n h)}\qquad \omega^2=g\beta_n\tanh(\beta_n h)$$





3D

Theory

(Stiassnie 2010)

2D

Depth-integrated equation for large-scale modelling of low-frequency hydroacoustic waves, 2013, Journal of Fluid Mechanics, 722, R6.

DOI: http://dx.doi.org/10.1017/jfm.2013.153

Depth-integrated equation for porous bottom

$$\boxed{\left(I_2^m\,\psi_{m,t}\right)_t-\nabla_h\cdot\left(I_1^m\,\nabla_h\psi_m\right)+\left(\omega^2\,I_2^m-k_m^2\,I_1^m\right)\psi_m+2\,R\,\varepsilon\,\frac{\omega}{c_s^2}\,K_n\,\psi_{m,t}=D_1^m\,h_t+D_2^m\,h_{s,t}}$$

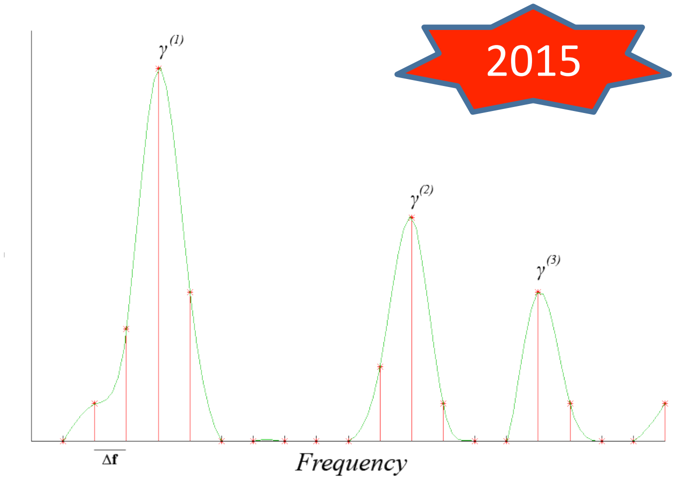
(MSEDWC)

$$I_1^m=I_{mm}+R\,K_{mm}$$

$$I_2^m=\frac{I_{mm}}{c^2}+R\,\frac{K_{mm}}{c_s^2}+\frac{1}{g}$$

$$D_1^m=-\left[M_m-R\,N_m\right]_{(-h)}$$

$$D_1^m=-\left[R\,N_m\right]_{(-h_s)}$$

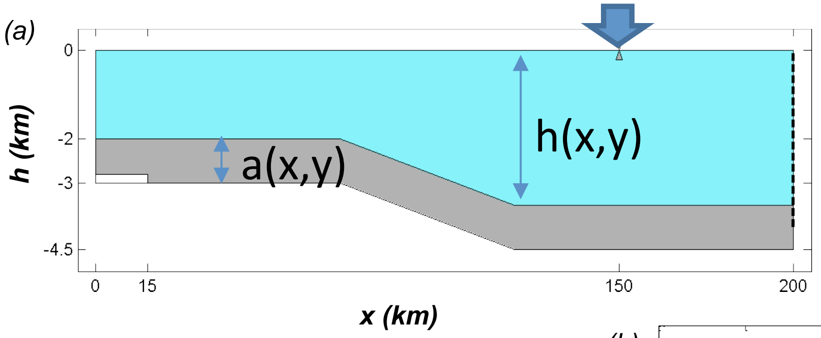


2015

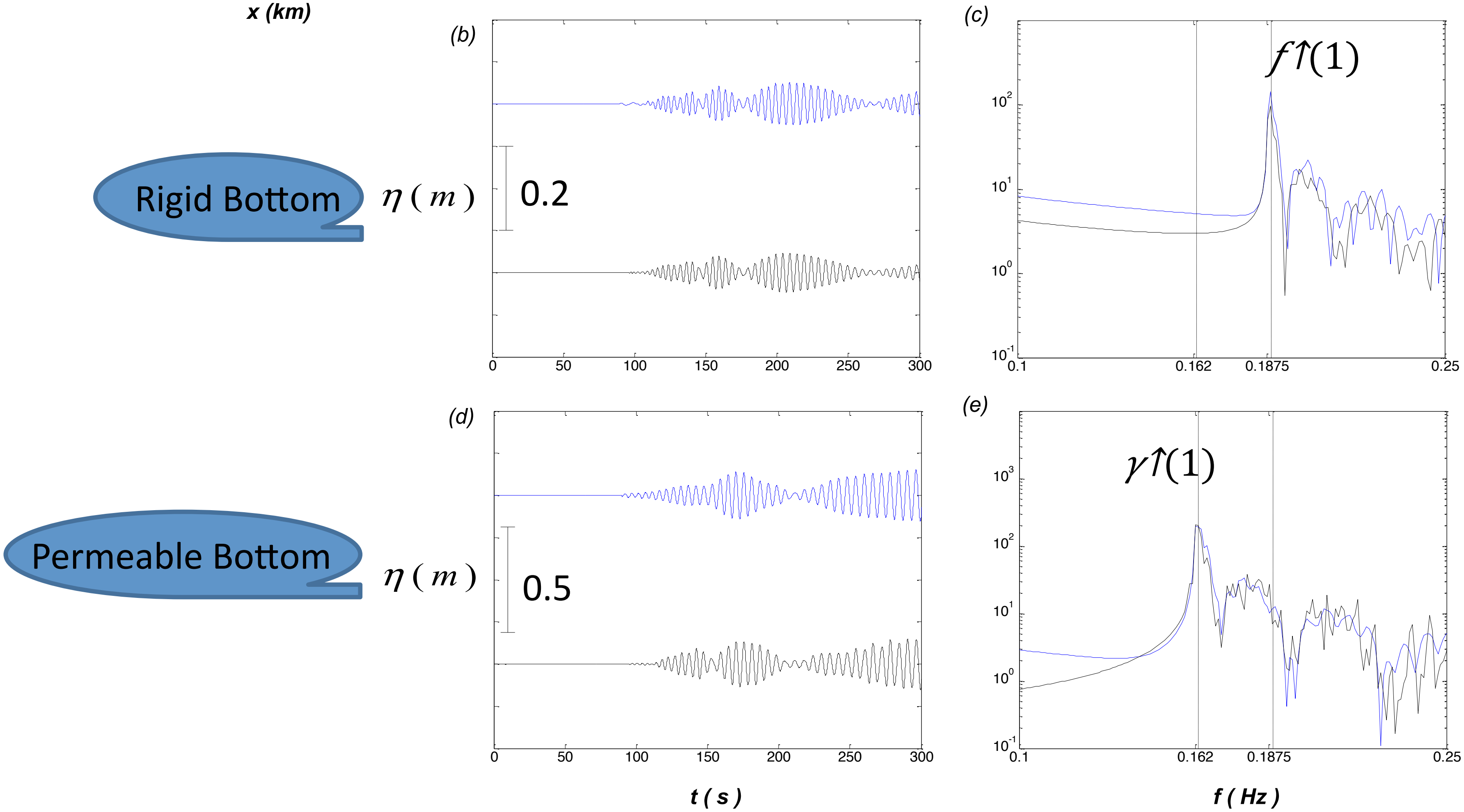
$$\begin{cases} M_n=\dfrac{\left(1-\lambda_n T_n\right)\cosh\left(\beta_{w,n}\left(h+z\right)\right)+\left(\lambda_n-T_n\right)\sinh\left(\beta_{w,n}\left(h+z\right)\right)}{\left(1-\lambda_n T_n\right)\cosh\left(\beta_{w,n}h\right)+\left(\lambda_n-T_n\right)\sinh\left(\beta_{w,n}h\right)} \\[2ex] N_n=\dfrac{\left(\lambda_n-T_n\right)\cosh\left(\beta_{s,n}\left(h_s+z\right)\right)}{\alpha_n\sinh\left(\beta_{s,n}a\right)\left[\left(1-\lambda_n T_n\right)\cosh\left(\beta_{w,n}h\right)+\left(\lambda_n-T_n\right)\sinh\left(\beta_{w,n}h\right)\right]} \end{cases}$$

Depth-Integrated Equation for Hydro-acoustic Waves with Bottom Damping, 2015.
Journal of Fluid Mechanics, 766, R1. DOI: http://dx.doi.org/10.1017/jfm.2015.37

Model validation for Varying Bottom

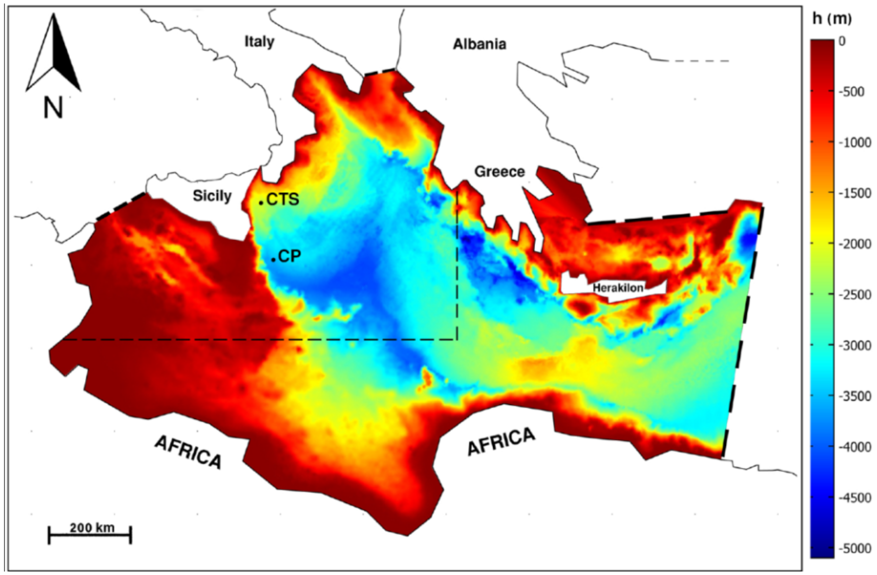


Results for FSE time series at *150 km* from tsunamigenic source from 3D (blue) and 2D models (black).
(b,c) Results for impermeable sea bottom and ***(d,e)*** for coupled model.

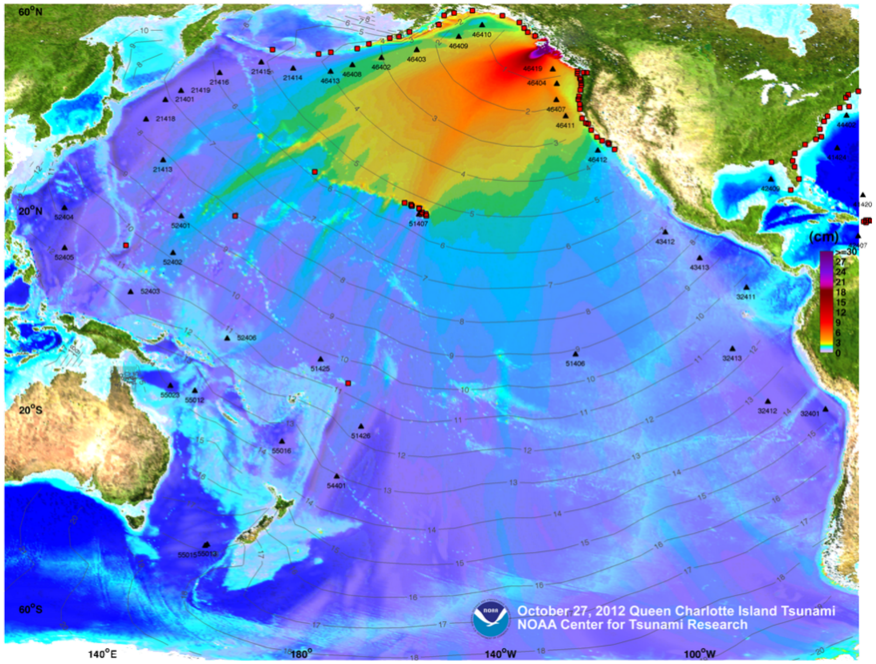


Large Scale Applications

365 AD Crete

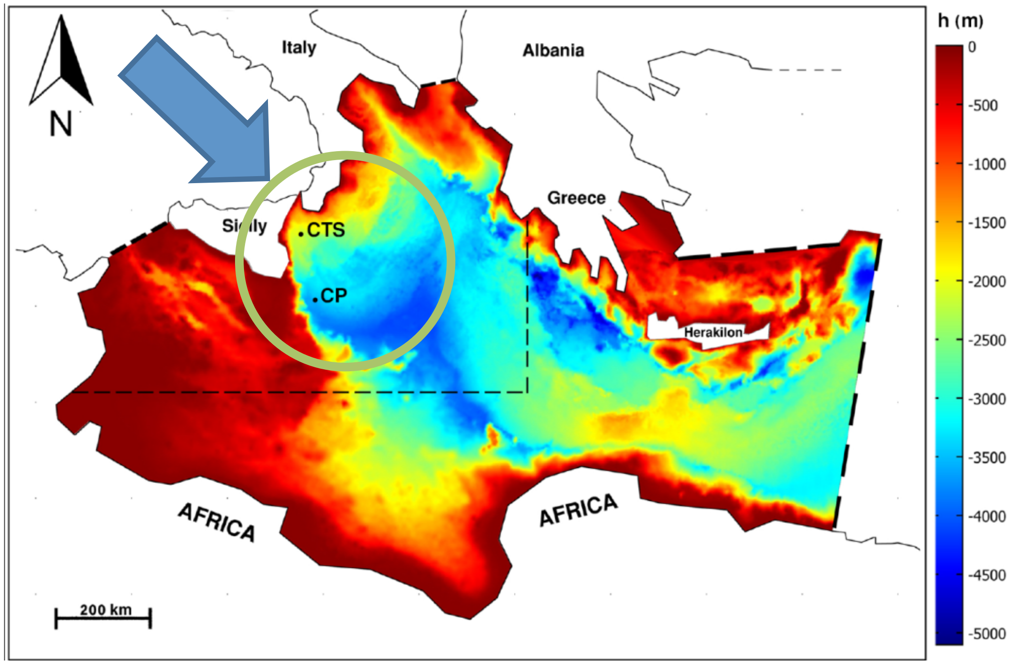


Haida Gwaii 2012



Multidisciplinary deep water observatories

- The Catania Test Site (CTS), 25 km offshore the East coast of Sicily, water depth 2 km → $f\uparrow(1) = 0.2\ Hz$
- The Capo Passero (CP) observatory, 100 km offshore the coast, water depth 3.5 km → $f\uparrow(1) = 0.1\ Hz$
- Both observatories are connected to shore through submarine electro-optical cables and equipped with hydrophones

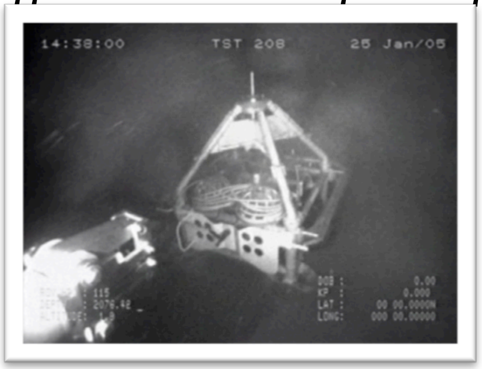


Submarine Multidisciplinary Observatory
SMO

INGV

european multidisciplinary seafloor & water column observatory
emso

http://web.infn.it/smo/



Large-scale numerical modeling of hydro-acoustic waves generated by tsunamigenic earthquakes (2014) Natural Hazards and Earth System Sciences-2014-153, DOI: 10.5194/nhessd-2-4629-2014

Long term observations in the open ocean – from seafloor to sea surface

EMSO (**European Multidisciplinary Seafloor and Water Column Observatory**) is a large-scale **European Research Infrastructure (RI)**. It is a European network of **fixed point, deep sea observatories** with the basic scientific objective of real-time, long-term monitoring of environmental processes related to the interaction between the geosphere, biosphere, and hydrosphere.

Submarine Multidisciplinary Observatory
SMO
INGV
european
multidisciplinary
seafloor & water column
observatory
emso

On the 22nd of April, 2014, the European Commission issued the response to the Step 1 application for the establishment of the EMSO-ERIC. The overall feedback is positive and the EMSO partners...

You are here: Home ▸ Infrastructure ▸ EMSO Sites description

EMSO Sites description

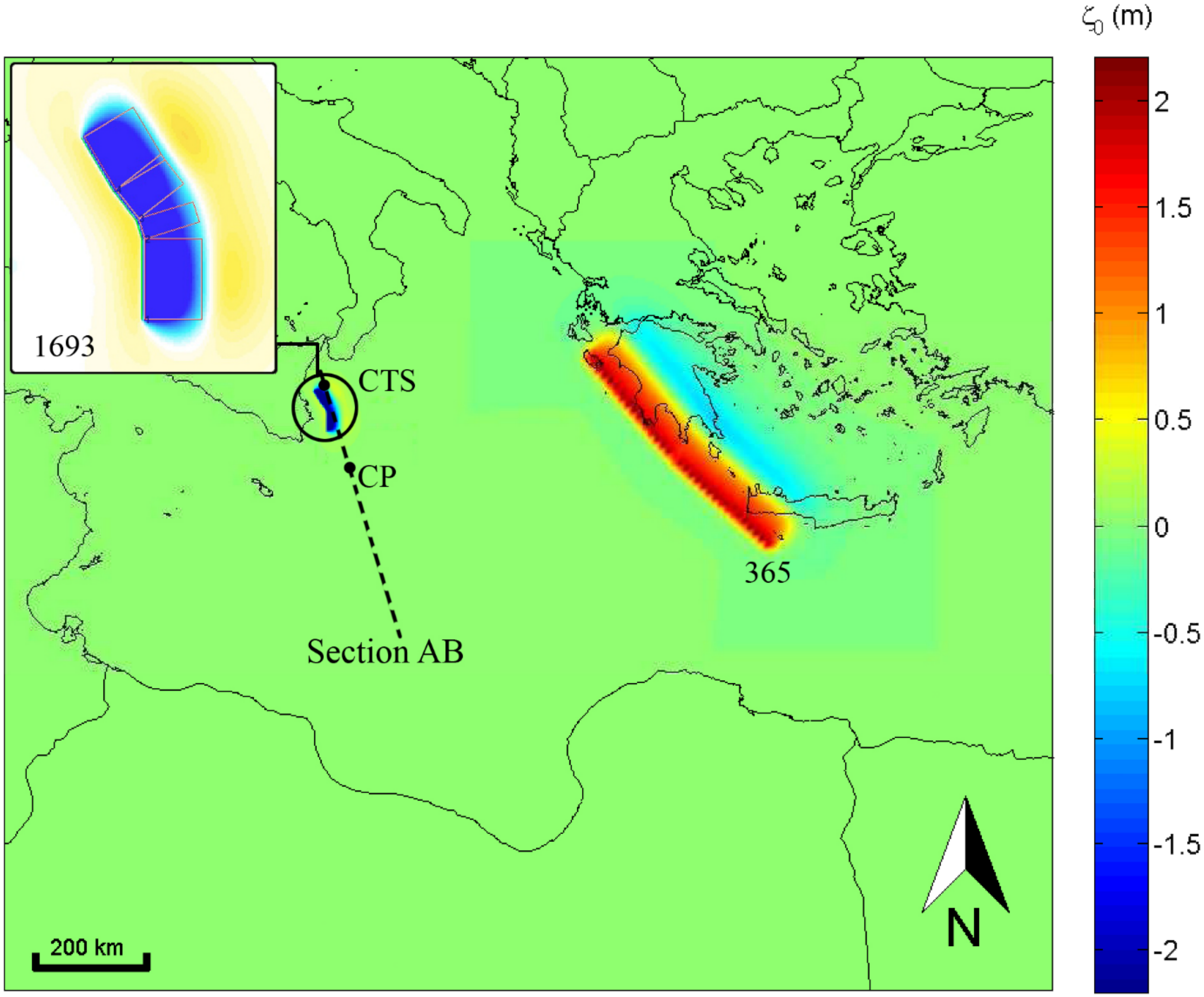
EMSO distributed research infrastructure is composed by an array of seafloor and water column observatories. For a detailed description of the characteristics of each EMSO site click on the corresponding link below.

- Arctic
- Celtic/Porcupine
- Azores Islands
- PLOCAN
- Norwegian Margin
- Iberian Margin
- Galway Bay, Irish West Coast
- Iroise Sea - Molene Island
- Ligurian Sea
- Western Ionian
- Hellenic Arc
- Marmara Sea
- Black Sea
- OBSEA
- Koljoe Fjord

http://www.emso-eu.org/

365 AD Scenario

Tonini et al. 2011,
NHESS vol. 11.



Sea Bottom Displacement

Bathymetry, Mediterranean Sea

Submarine Multidisciplinary Observatory
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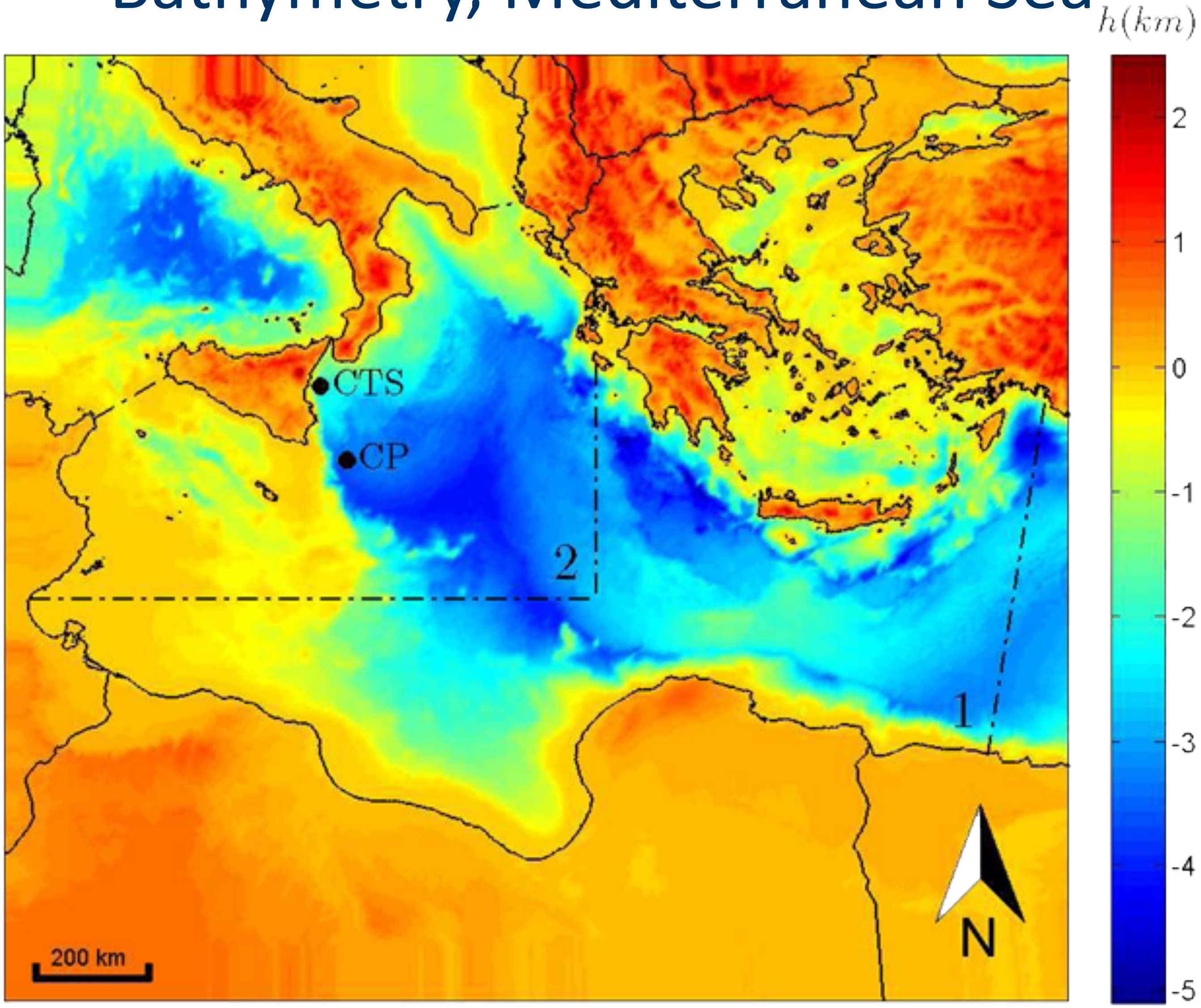
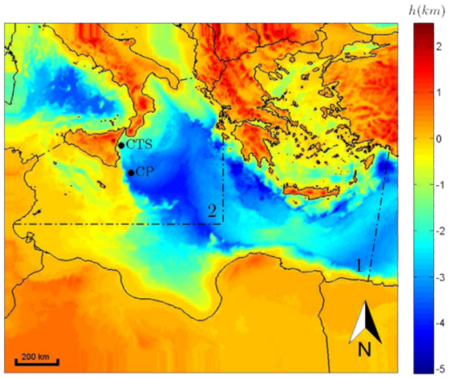
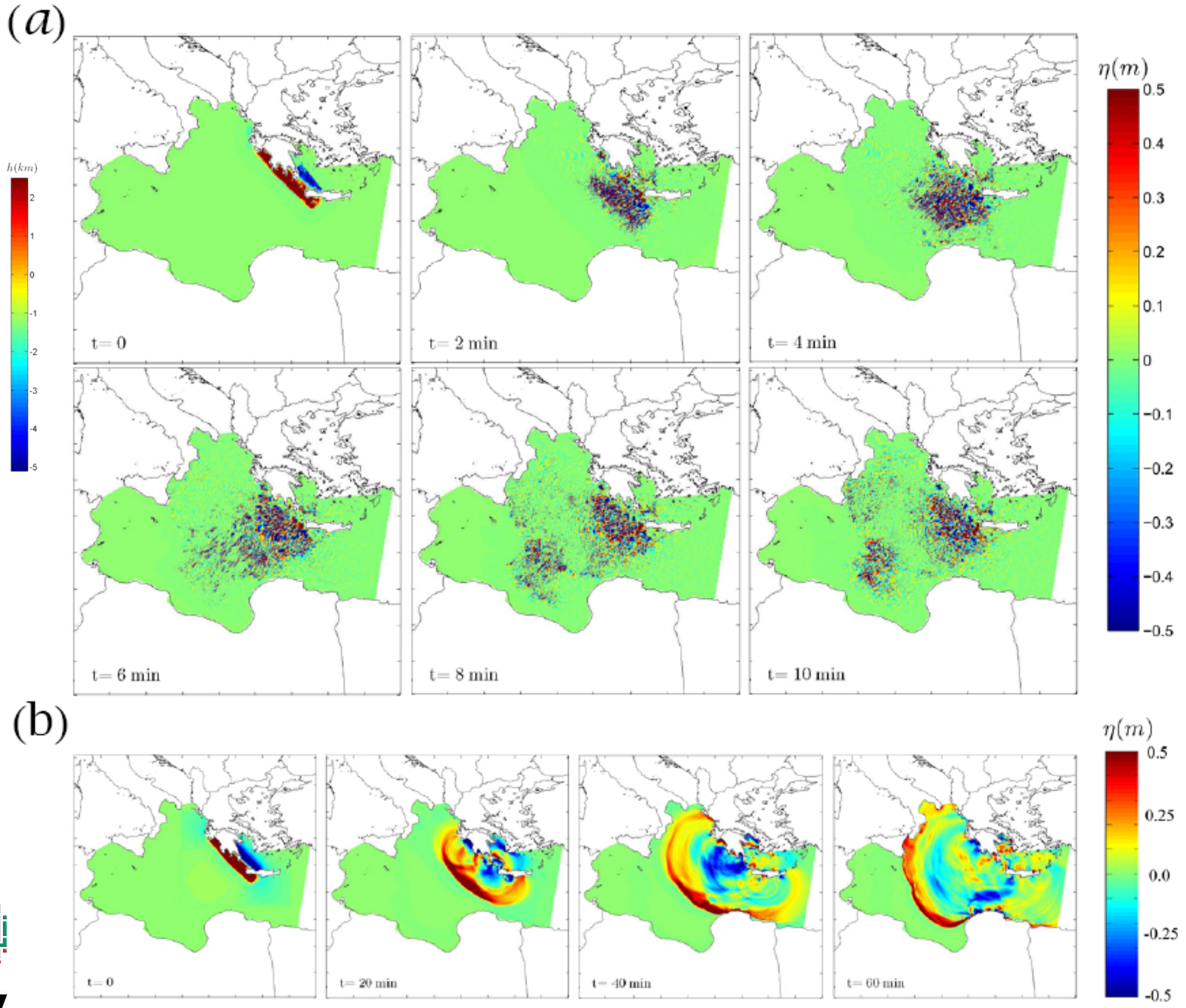
multidisciplinary
seafloor & water column
observatory
emso



A Depth-Integrated Equation For Large Scale Modeling Of Tsunami In Weakly Compressible Fluid, International Conference of Coastal Engineering ICCE, Seoul, June. 2014. DOI: http://dx.doi.org/10.9753/icce.v34.currents.9

365 AD Crete





Snapshots of the free surface (η) hydroacoustic perturbation (a) and gravity wave (b) given by the AD 365 earthquake. t = 0 refers to the time of occurance of the earthquake

Submarine Multidisciplinary Observatory

SMO

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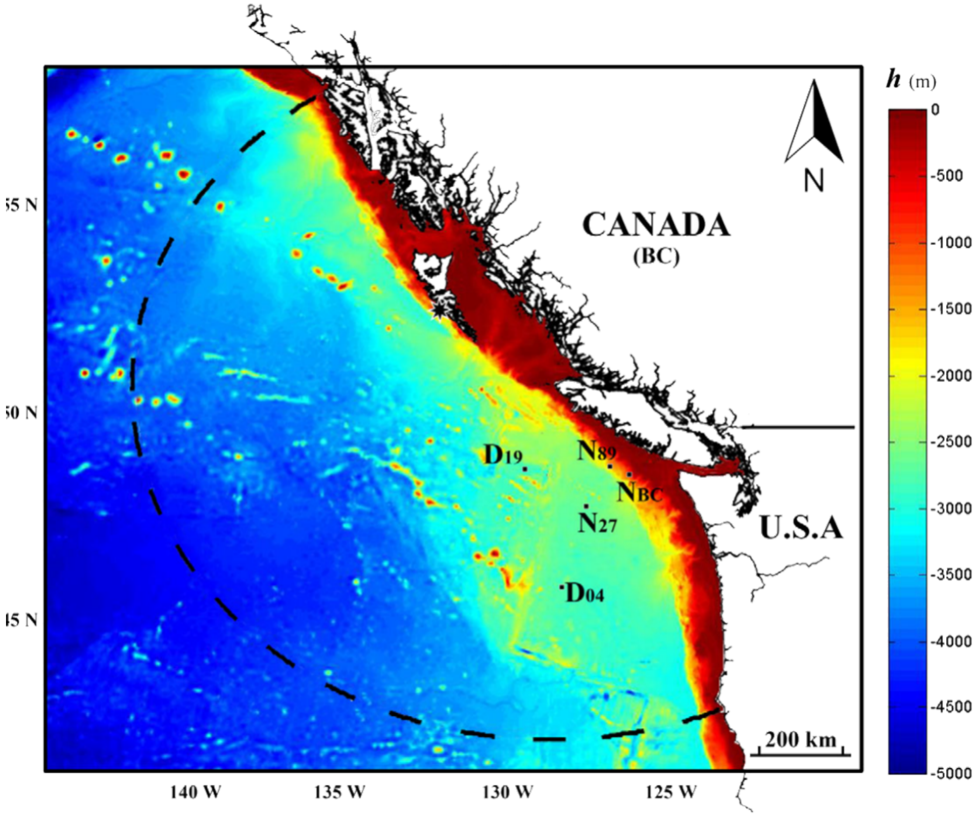
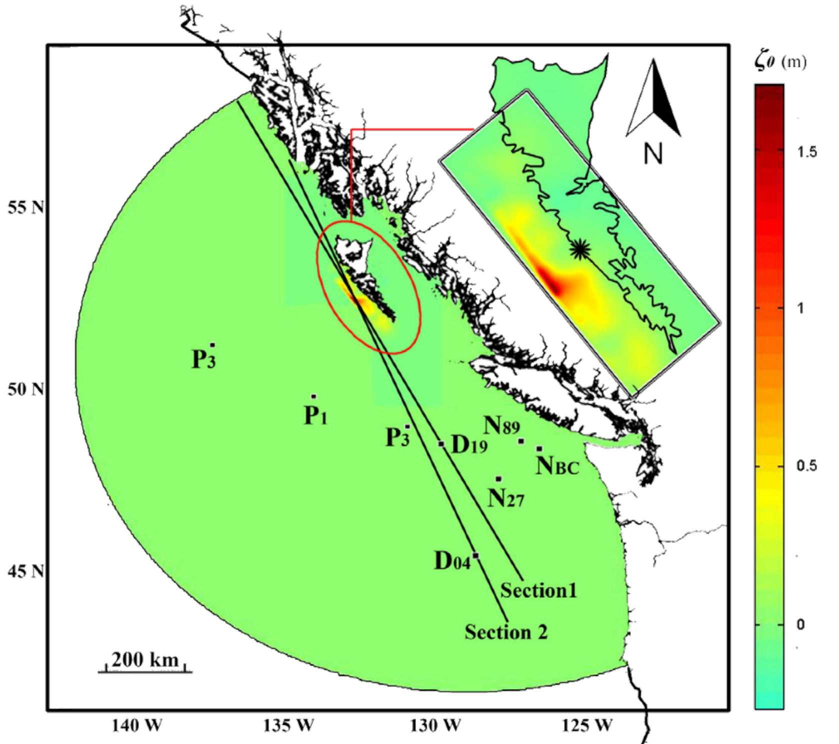
european
multidisciplinary
seafloor & water column
observatory

emso

Haida Gwaii 2012 Event
Bathymetry and vertical seabed displacement





Vertical residual seabed displacement on the numerical domain

- **Bathymetry data of the west Canadian and USA coast (ETOPO1 data).**
- **Lay et al. (2013)**
- **DART recordings at D04 and D19**
- **Ocean Networks Canada observatories including bottom pressure and seismometers**

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Tsunami Wave (Haida Gwaii, 2012)

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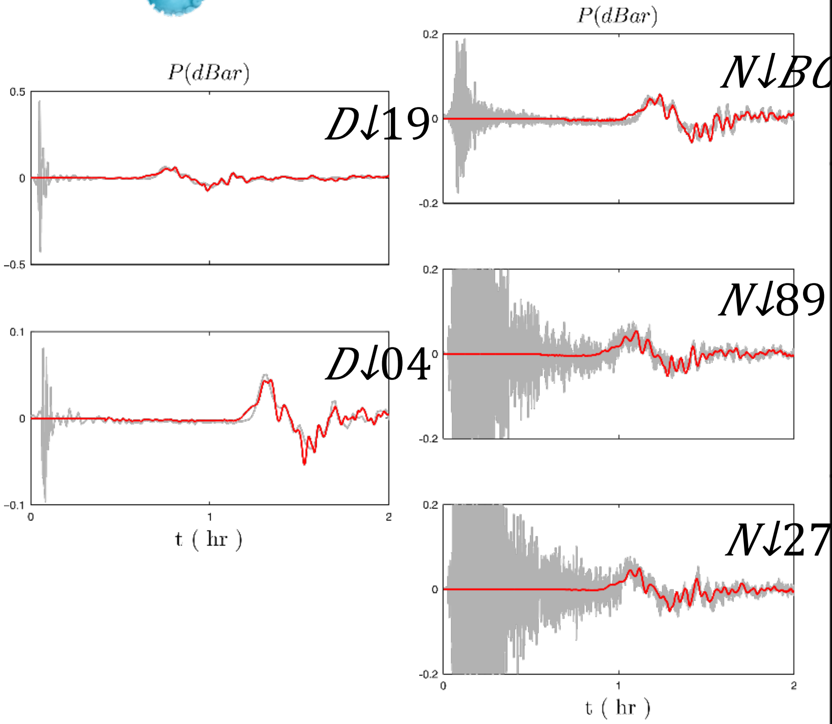
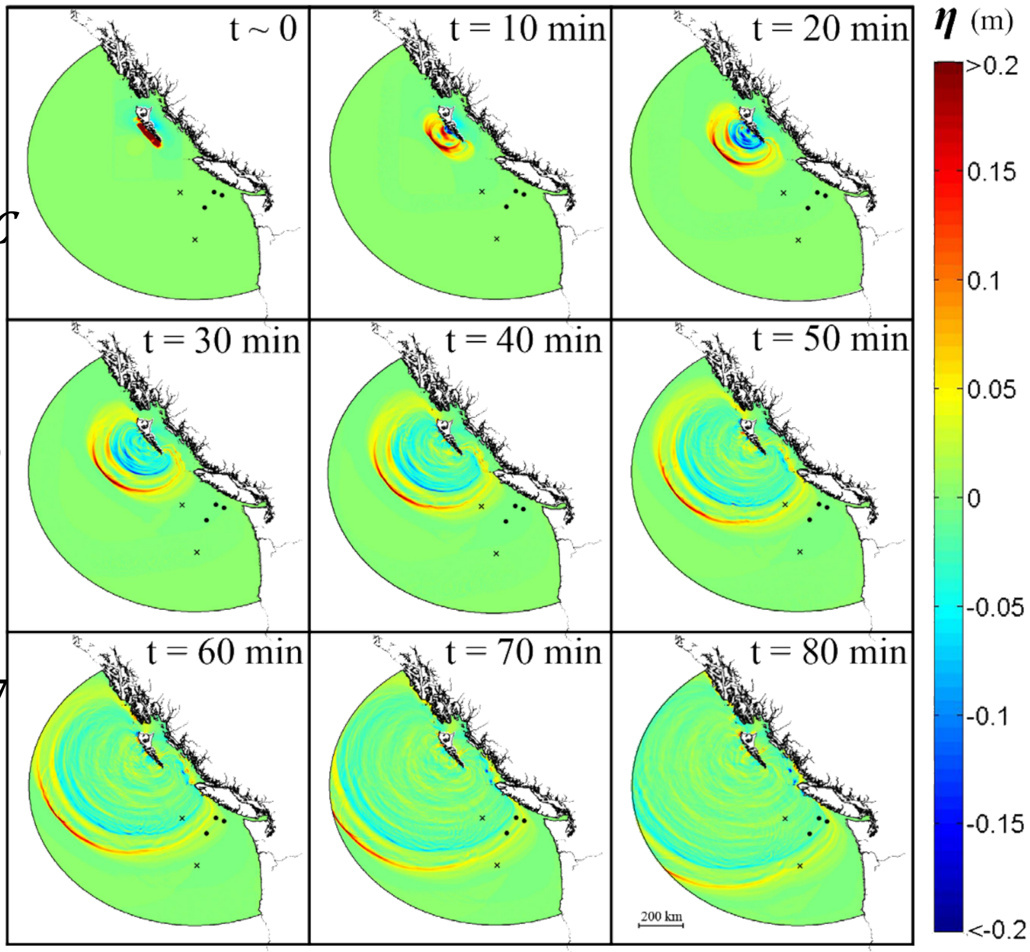


Pressure time series as measured by the NEPTUNE observatories and DARTs (Measurements in gray and model results in red)

Evolution of Long Gravitational Tsunami Waves



Hydro-acoustic Waves (Haida Gwaii, 2012)

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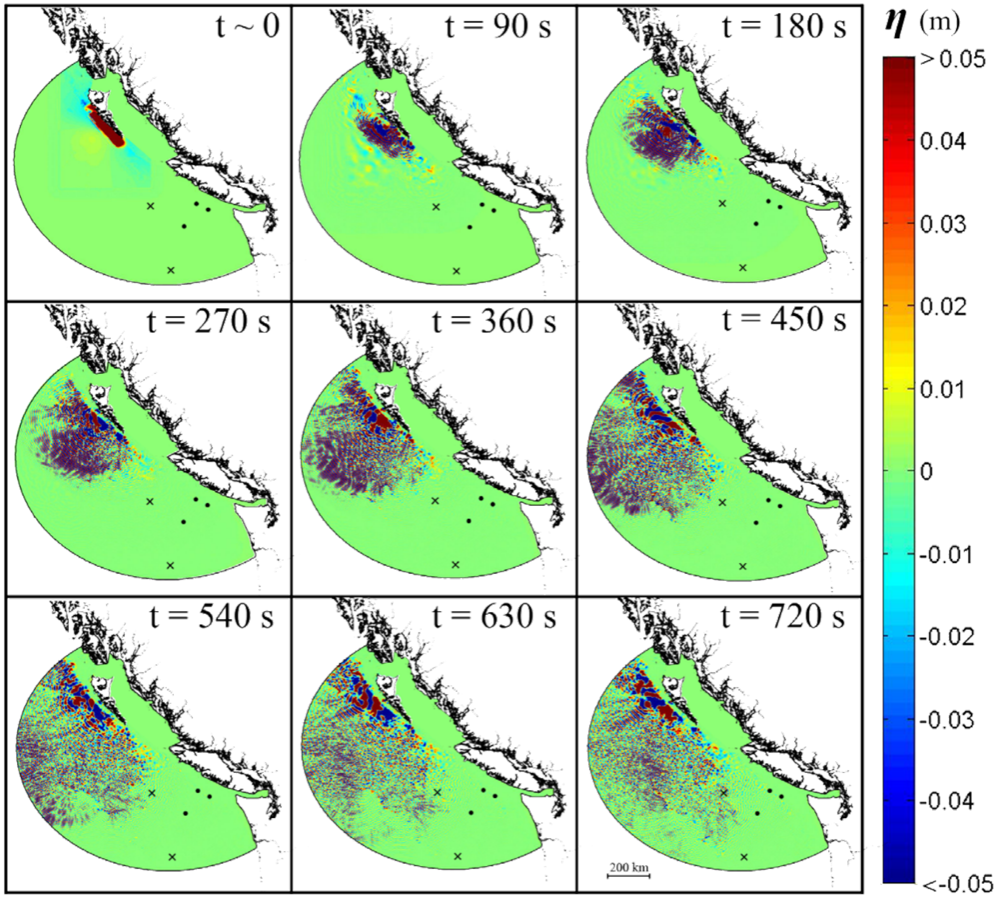
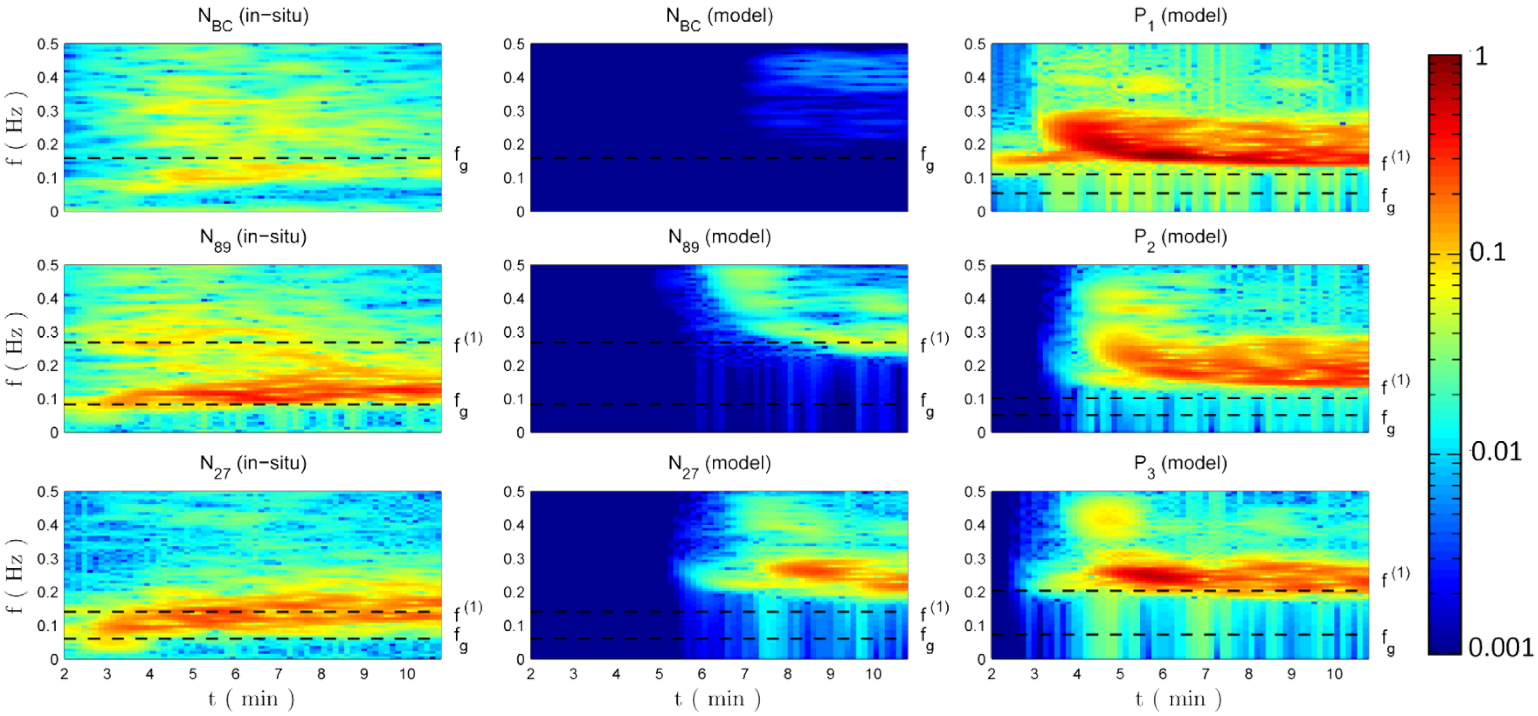
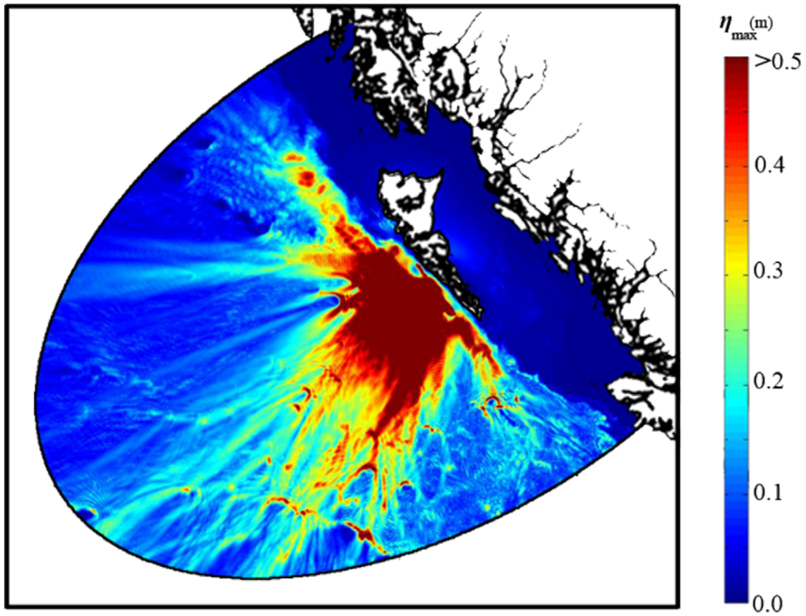
Hydro-acoustic and tsunami waves generated by the 2012 Haida Gwaii earthquake: modeling and in-situ measurements, 2015, Journal of Geophysical Research; Ocean, 120, 2014JC010385.
DOI: 10.1002/2014JC010385

Evolution of Hydroacoustic Waves





Spectrograms of the bottom pressure normalized by dividing by maximum value. The first column refer to the in situ bottom pressure recorded at NBC, N89, and N27; the second and third columns of plots refer to the simulated hydro-acoustic bottom pressure at the Neptune stations and at points P1, P2, and P3

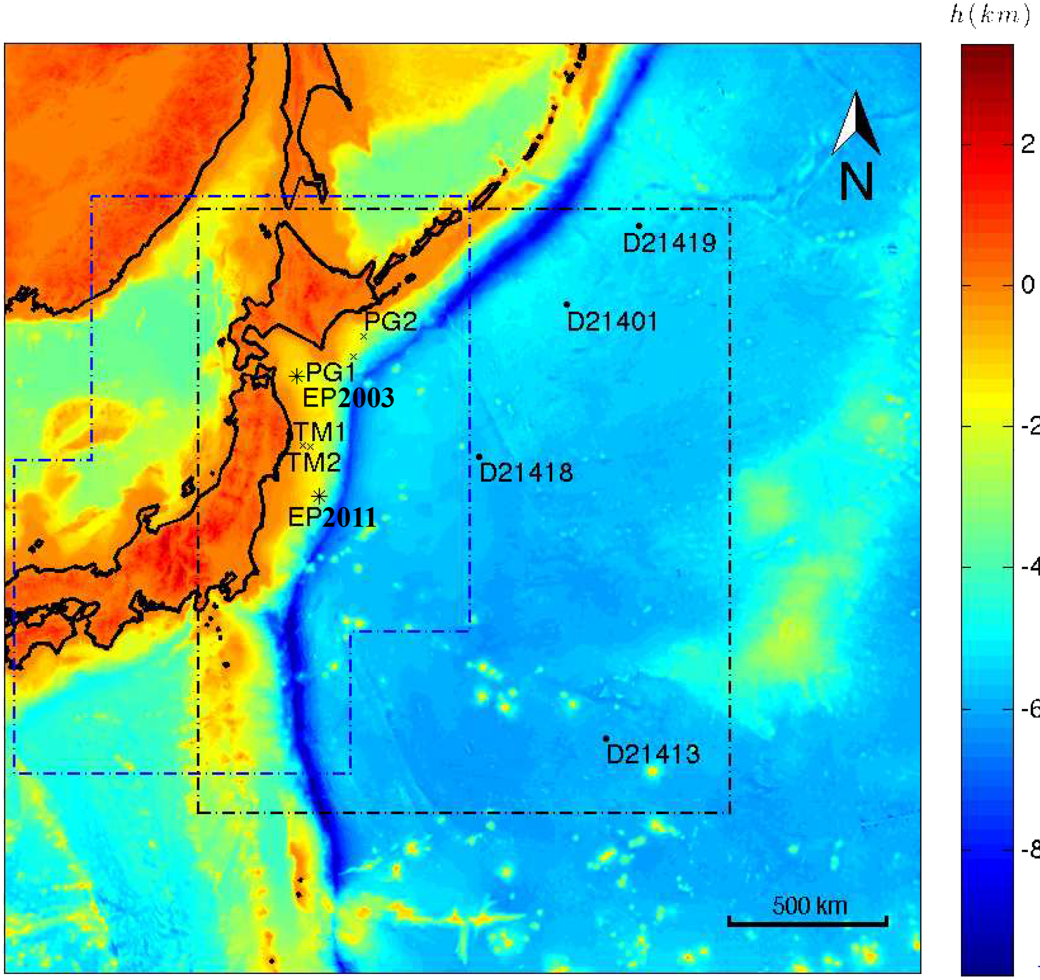


Maximum absolute values of the free surface (η) of the hydro-acoustic wave generated by the HaidaGwaii earthquake on 28 October 2012

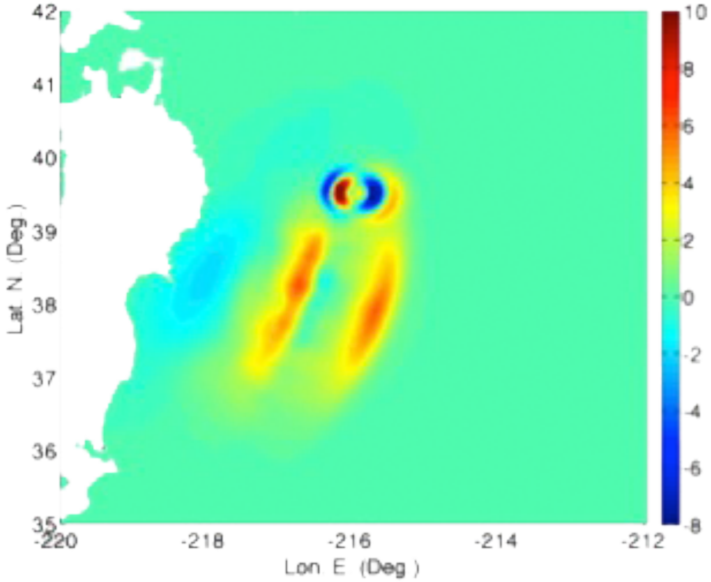
Conclusions

- We have derived a hyperbolic mild-slope equation for hydro-acoustic waves in weakly compressible fluids for rigid and porous bottoms (MSEWC & MSEDWC).
- The model equation has been validated by comparing with a three-dimensional solver of the governing equations
- First simulations on a real, large scale bathymetry
- Suggestion on where to locate the submarine observatories (hydrophones) for the early detection: not in shallow waters!

Next steps: Tohoku-Oki 2011 (Japan)



Bathymetry and numerical domain with placement of DART and JAMSTEC Observatories



Vertical residual seabed displacement (combination of SMF and Earthquake) (Tappin et al. 2014)

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Delaware Bay, USA, 2015

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