Faster-Than-Real-Time Computing of Tsunami Early Warning Systems

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EDANYA Research Group

(Differential Equations, Numerical Analysis and Applications)

Universidad de Málaga

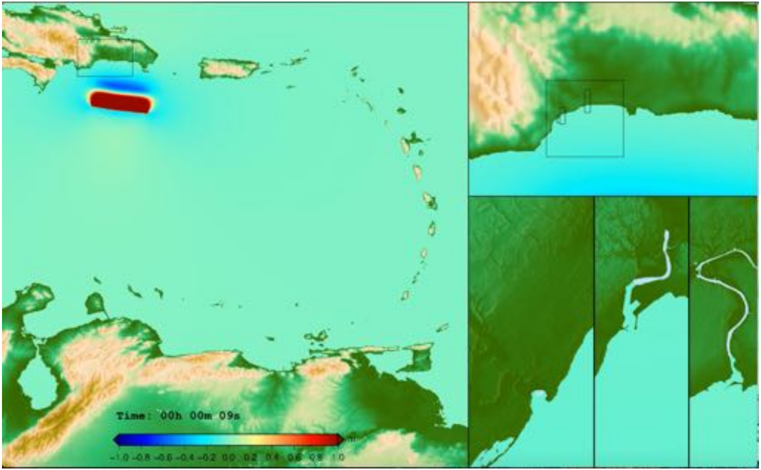
UNIVERSIDAD DE MÁLAGA

GPU Technology Conference, San Jose, CA, 26-29 March, 2018

"Life-Saving Actions"

In 2016 UNESCO project

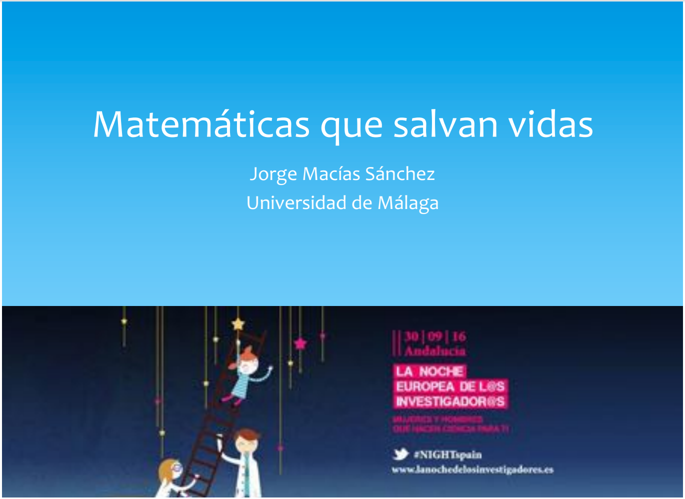
"**Life-Saving Actions:** Disaster preparedness and seismic and tsunami risk reduction in the south coast of the Dominican Republic"



“Life-Saving Mathematics”

2016 European Researchers’ Night: “Life-Saving Mathematics”

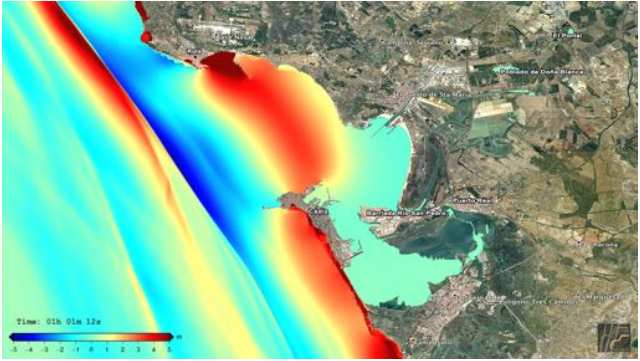
Outreach activities for students and the general public



“Life-Saving GPUs”

2018 NVIDIA Global Impact Award: “Life-Saving GPUs”

GPU fast computing aiming saving lives



Global Impact Award Finalist Using GPUs with Aim to Spare Lives Ahead of Tsunamis

March 12, 2018 by TONIE HANSEN

The University of Málaga team advances capabilities of tsunami early warning systems.

Why we do

What we do / Why we do it

Why we do

What we do / Why we do it

Tsunami Science - Aim: Saving Lives

- 0 casualties in the farfield
- Minimize casualties in the nearfield

Why we do

What we do / Why we do it

Tsunami Science - Aim: Saving Lives

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As modelers / Numerical specialists

- Developing numerical tools to simulate tsunamis
- Get our numerical models used in TEWS
- Need to compute extremely fast (if aim is saving lives)
- This was UNTHINKABLE some years ago

What we do: solution to a specific problem

Focus

Achieving much FTRT predictions in the context of TEWS

How we do it

Two Ingredients

1. Numerical model: Tsunami-HySEA

- Robust
- Efficient
- Precise
- Validated

2. GPU and multi-GPU

- Extremely fast computing (and inexpensive)

The result

A novel approach

How TEWS do work

- **Decision Matrices**
- **Precomputed Databases**

The rules of the game have changed

Tsunami-HySEA. Model features

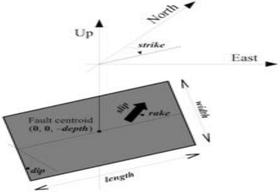
Seabed deformation model: Okada Model

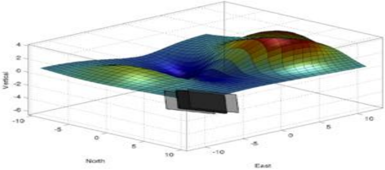
- Okada model for seabed deformation
- Hypothesis: Intantaneous transmition to the water free surface
- Then a shallow water model propagates the initial tsunami wave

Okada Model (1985)

To define the initial seabed deformation is necesary to provide:

- Longitude, Latitude, and source depth
- Fault plane length and width
- Dislocation
- Strike angle, slip angle and dip angle





Tsunami-HySEA model

Tsunami-HySEA. Model features

Seabed deformation model: Multi-Okada Model

- Multiple Okada segments can be defined
- Rupture can be synchronous or asynchronous

Seabed deformation model

- Other rupture models can be implemented
- Filtering (as Kajiura) - Nosov-Kolesov
- Support for rectangular or triangular faults

Tsunami-HySEA model

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Others capabilities

- Nested meshes (two-way)
- 2D domain decomposition and load balancing
- Direct output of time series
- NetCDF input/output files
- Resuming a stored simulation (new grids and new points for the time series)
- Overlapping writing and computing

Tsunami-HySEA. Model equations

Shallow Water Models

- frequently used in ocean and coastal simulations
- seldom used to explicitely reproduce coastal inundation or run-up height.

Non Linear Shallow Water Equations

$$\begin{cases} \dfrac{\partial h}{\partial t} + \dfrac{\partial q_x}{\partial x} + \dfrac{\partial q_y}{\partial y} = 0, \\[2ex] \dfrac{\partial q_x}{\partial t} + \dfrac{\partial}{\partial x}\left(\dfrac{q_x^2}{h} + \dfrac{g}{2}h^2\right) + \dfrac{\partial}{\partial y}\left(\dfrac{q_x q_y}{h}\right) = gh\dfrac{\partial H}{\partial x} - S_x, \\[2ex] \dfrac{\partial q_y}{\partial t} + \dfrac{\partial}{\partial x}\left(\dfrac{q_x q_y}{h}\right) + \dfrac{\partial}{\partial y}\left(\dfrac{q_y^2}{h} + \dfrac{g}{2}h^2\right) = gh\dfrac{\partial H}{\partial y} - S_y. \end{cases}$$

- ρ density; g gravity;
- $H(\mathbf{x})$ bathymetry; $h(\mathbf{x}, t)$, water layer thickness;
- $(u_x(\mathbf{x}, t), u_y(\mathbf{x}, t))$ flow velocity;
- $q_x(\mathbf{x}, t) = u_x(\mathbf{x}, t)h(\mathbf{x}, t), \qquad q_y(\mathbf{x}, t) = u_y(\mathbf{x}, t)h(\mathbf{x}, t)$ fluxes;
- $S_f = (S_x, S_y)$ bottom friction effects.

Tsunami-HySEA

Tsunami-HySEA. Numerics

Numerics: A family of Finite Volume numerical schemes

- **Scenarios**: WAF method (LW+HLL)[1] and higher order
- **TEWS**: hybrid 2s+WAF[2]
- **Laboratory experiments**: higher order methods
- Wet/Dry front treatment[3,4,5]
- Nested meshes and/or AMR (GPU)

[1] **de la Asunción et al. (2012).** Efficient GPU implementation of a two waves TVD-WAF method for the two-dimensional one layer shallow water system on structured meshes, *Computers & Fluids.*

[2] Article in progress

[3] **Castro, González-Vida, Parés (2005).** Numerical treatment of wet/dry fronts in shallow water flows with a modified Roe scheme. *Math. Mod. and Meth. in Applied Sci.*

[4] **Gallardo, Parés, Castro (2007)**. On a well-balanced high-order finite volume scheme for shallow water equations with topography and dry areas. *J. Comput. Phys.*

[5] **Castro, Fernández, Ferreiro, García, Parés (2009)**. High order extensions of Roe schemes for two dimensional nonconservative hyperbolic systems. *J. Sci. Comput.*

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Nice properties

- Well-balanced (avoid spurious oscillations)
- Transitions from sub to super critical situations (arrival to coast)
- Positivity (no negative layer thickness)
- Inundation area and runup heights are model outputs
- Discontinuities in data or solutions (no need to smooth bathymetry)

Implementation

- CUDA/MPI - GPU/Multi-GPU (very short computing times)

Tsunami-HySEA. Validation

A long and exhaustive benchmarking process - NTHMP standards

- **1. Propagation and Inundation**
- **2. Tsunami currents**
- **3. Landslide generated tsunamis**

Benchmarks composed of

- **1. Analytical solutions**
- **2. Laboratory experiments**
- **3. Field data**

Validation. MMS Approved

NTHMP certification - August 2017

National Tsunami Hazard Mitigation Program Benchmarked Tsunami Models

Reference: http://nthmp.tsunami.gov/documents/nthmpWorkshopProcMerged.pdf

Updated: 17 August 2017

Model Name	Model affiliation & contact Download website (if available)	States or Territories that use	Digital Elevation Model Developer	Resolution	Model specifics Physics	Uses (sources)	NTHMP Benchmarks Inundation	Currents	Landslide	Documentation or peer-review	Pros	Cons	Comments
Alaska GI'-T	Alaska Geophysical Institute Dmitry Nicolsky djnicolsky@alaska.edu	Alaska: Inundation	NCEI	?	SW	Seismic; Landslide	Y	Pending	Pending				User interface
ATFM	National Tsunami Warning Center Paul Huang paul.Huang@noaa.gov	US TWCs: Forecasting	NCEI	?	SW	Seismic	Y	Pending					
FUNWAVE-TVD, v.1.0	University of Delaware Jim Kirby kirby@udel.edu	East Coast: Inundation	NCEI, ?	?	B	Seismic	Y	Pending					
GeoClaw	University of Washington Randy LeVeque http://www.clawpack.org/installing.html	Washington: Inundation	NCEI	?	B	Seismic	Y	Pending		http://www.clawpack.org	Adaptive mesh refinement		
MOST	NOAA PMEL Diego Arcas diego.arcas@noaa.gov	US TWCs: Forecasting Washington: Inundation	NCEI, PMEL	1/3 - 3 arcSec	SW	Seismic	Y	Pending			Computationally Fast	Can become unstable	User interface: ComMIT
NEOWAVE	University of Hawaii Kwok Fai Cheung cheung@hawaii.edu	Hawaii, Am. Samoa, Puerto Rico, Gulf of Mexico, BC	Hawaii	1/3 - 3 arcSec	NH	Seismic	Y	Y?			Two-way nested grids	-	
SELFE	Oregon Health & Science University Joseph Zhang http://www.stccmop.org/CORIE/modeling/selfe/	Oregon: Inundation	Oregon, NCEI?	?	CFD	Sceismic	Y	Pending			Resolves current vortices		
THETIS	Univ. of Rhode Island Stephan Grilli http://thetis.enscbp.fr	N/A	NCEI, ?	?	CFD	Seismic; Landslide	Y	Pending	Pending		Resolves current vortices		
TSUNAMI3D	Texas A&M University at Galveston Juan Horrillo horrillj@tamug.edu	Gulf of Mexico: Inundation	NCEI	?	CFD	Seismic; Landslide	Y	Pending	Pending		Resolves current vortices		
BOSZ	Tohoku Univ. & Univ of Hawaii Voelker Roeber roeber@irides.tohoku.ac.jp	Hawaii: Inundation	Hawaii, NCEI?	1/9 - 3 arcSec	B	Seismic	Y	Pending			Resolves current vortices, works also for swell waves	no grid nesting	
Cliffs	NW Research Associates Elena Tolkova, e.tolkova@gmail.com https//:github.com/Delta-function/cliffs-src	Alaska (testing):Tsunami Modeling	NCEI	Any	SW	Seismic	Y	Pending		E.Tolkova, PAAG, 171(9), 2289-2314 (2014); User Manual at: http://arxiv.org/abs/1410.0753	Computationally Fast; easy set-up	-	NetCDF I/O
HySEA	University de Malaga Jorge Macías (jmacias@uma.es) NOAA/PMEL Diego Arcas (diego.arcas@noaa.gov) https://edanya.uma.es/hysea/	PMEL (testing)- US TWCs: forecasting	NCEI	1/3 - 3 arcSec	SW/B	Seismic; Landslide	Y	Pending	Pending	https://edanya.uma.es/hysea/index.php/references	Computationally Fast; Robust; Stable	-	Nested meshes; run on GPUs and mulit-GPU architectures
NHWAVE	University of Delaware	East Coast: landslide tsunami generation	NCEI	?		Seismic	Y	Pending	Pending				

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Alaska GI'-T	Alaska Geophysical Institute Dmitry Nicolsky	Alaska: Inundation	NCEI	?	SW	Seismic;	Y	Pending	Pending				User interface
NEOWAVE	University of Hawaii Kwok Fai Cheung	Hawaii, Am. Samoa, Puerto Rico,	Hawaii	1/3 - 3	NH	Seismic	Y	Y?			Two-way nested	-	
	Elena Tolkova, e.tolkova@gmail.com https//:github.com/Delta-function/cliffs-src	Alaska (testing):Tsunami Modeling								Manual at: http://arxiv.org/abs/1410.0753	Fast, easy set-up		
HySEA	University de Malaga Jorge Macías (jmacias@uma.es) NOAA/PMEL Diego Arcas (diego.arcas@noaa.gov) https://edanya.uma.es/hysea/	PMEL (testing)- US TWCs: forecasting	NCEI	1/3 - 3 arcSec	SW/B	Seismic; Landslide	Y	Pending	Pending	https://edanya.uma.es/hysea/index.php/references	Computationally Fast; Robust; Stable	-	Nested meshes; run on GPUs and mulit-GPU architectures
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HySEA
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PMEL (testing)- US TWCs: forecasting

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Computationally Fast; Robust; Stable
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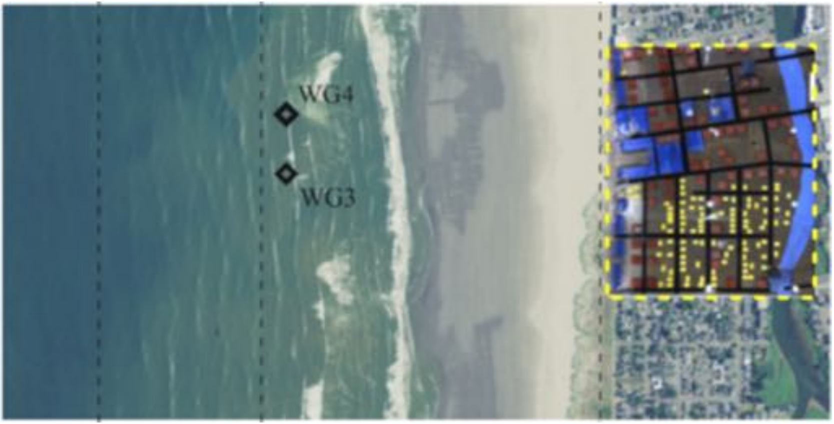
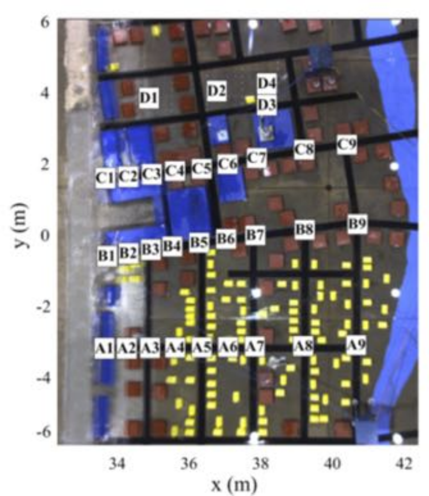
Example for Tsunami currents. BP4 Seaside (Oregon)



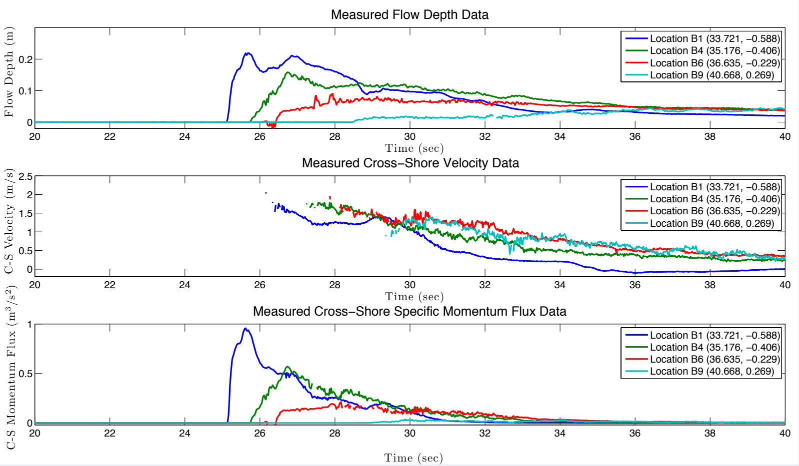
Benchmark Problem 4 - Seaside (Oregon)

Measurement locations



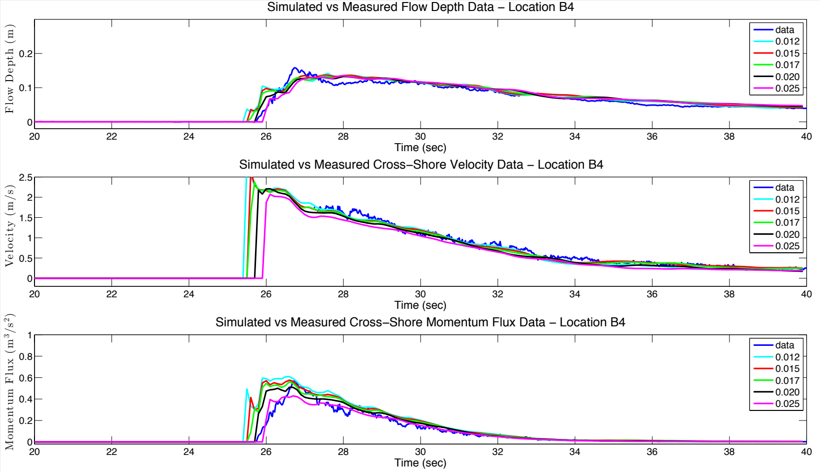
Benchmark Problem 4 - Seaside (Oregon)

Measured Data at B1, B4, B6, B9 (Flow Depth - Velocity - Specific Momentum Flux)



Benchmark Problem 4 - Seaside (Oregon)

Simulated vs Measured Data comparison at B4



The Mediterranean challenge (by INGV)

INGV. A TEWS for all the Mediterranean

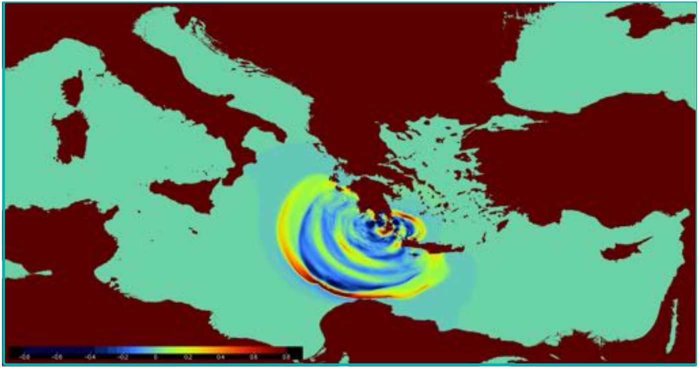
- Computational domain: the whole Mediterranean
- Spatial resolution: 30 arc-sec.
- Size of the problem: $5.221 \times 1.921 = 10.029.541$ cells
- Simulation time: 8 hours

The Mediterranean challenge (by INGV)

Output

- Times series at 17,000 predefined locations
- Maximum height in all the domain

In the Italian NTWC



The Challenge:

Do it in less than 6 min!!!

Times for the Mediterranean case

2014 Computing times and speed-up

# GPUs	Computing times	Speed-up
1	2141.1 (35 min 41 s)	1.00
2	1139.5 (18 min 59 s)	1.88
4	601.3 (10 min 1 s)	3.56
8	378.1 (6 min 18 s)	5.66
10	352.0 (5 min 52s)	6.08

Requirement: computing time $<$ 6 min

* Times for nVIDIA Titan Black GPUs (Kepler, 2012). 1 Gb ethernet network

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Continuous improvements

- Static load balancing
- CFL adjustment
- Writing while computing
- Overlapping of processes

Times for the Mediterranean case

2017 Computing times and speed-up

# GPUs	Computing times	Speed-up
1	1764.0 (29 min 24 s)	1.00
2	908.6 (15 min 9 s)	1.94
4	507.8 (8 min 28 s)	3.47
8	312.1 (5 min 12 s)	5.65
12	259.0 (4 min 19 s)	6.81

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But also new architectures...

2 NVIDIA Tesla P100 ... (already “obsolete”)

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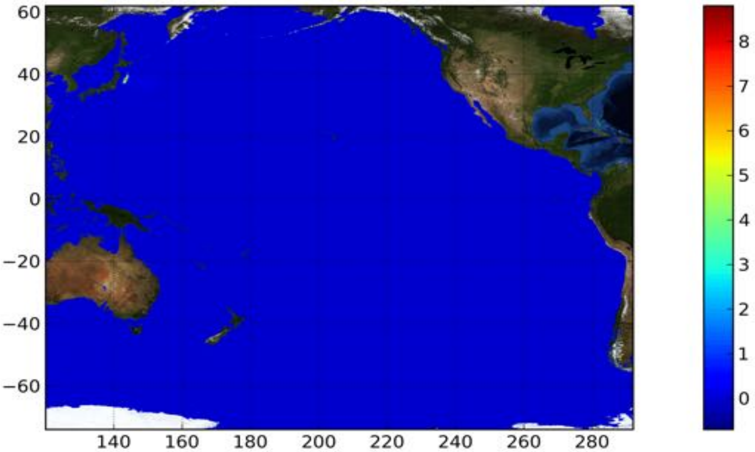
The emblematic example of Tohoku 2011

Problem settings: Topo-bathy grids

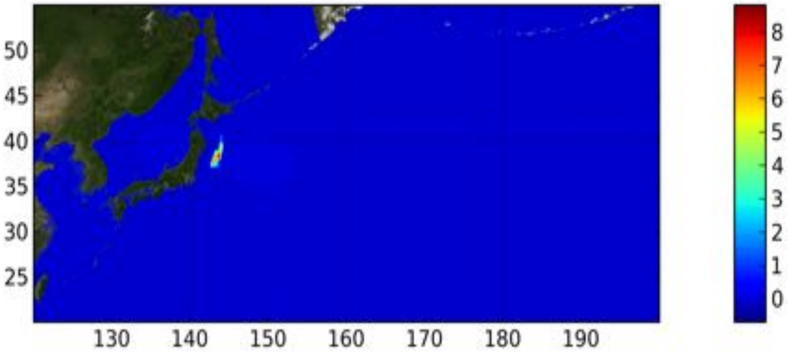
- One global Pacific Ocean grid (2 arc-min) -provided by NCTR-NOAA-
- Grid size: 7,430,699 cells
- Bathymetry data: JODC 500-m and GSI 50-m DEM



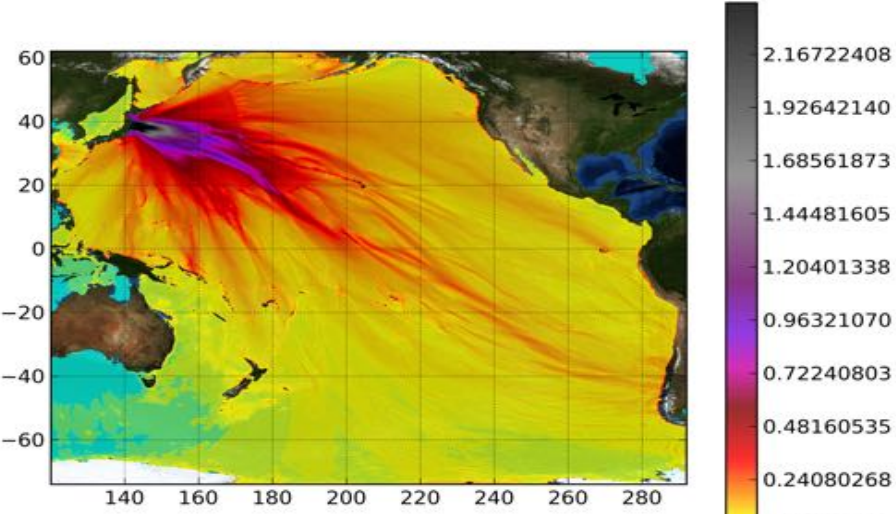
The emblematic example of Tohoku 2011

Problem settings: initial conditions

Initial bottom deformation provided by NCTR-NOAA.



Tohoku 2011. Maximum amplitudes. Res. 2 arc-min



Tohoku 2011. Computation time

Propagation in global domain

6 hours (21,600 s) were simulated using three resolution levels:

- Original resolution (2 arc-min): 7,430,699 cells $(2,581 \times 2,879)$
- Resolution x2 (1 arc-min): 29,722,796 cells $(5,162 \times 5,758)$
- Resolution x4 (30 arc-sec): 118,891,184 cells $(10,324 \times 11,516)$

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time	2 arc-min	# FTRT	1 arc-min	# FTRT	30 arc-sec	# FTRT
1 GPU	7m 28.4s	48.16	35m 36s	10.11		
2 GPUs	4m 19.5s	43.22	21m 41s	17.37	2h 35m 21s	2.32
4 GPUs	2m 27s	146.94	11m 38.8s	30.91	1h 21m 49s	4.4
8 GPUs	77.74s	277.85	6m 22.3s	56.5	43m 55s	8.20

Tohoku 2011. Computation time

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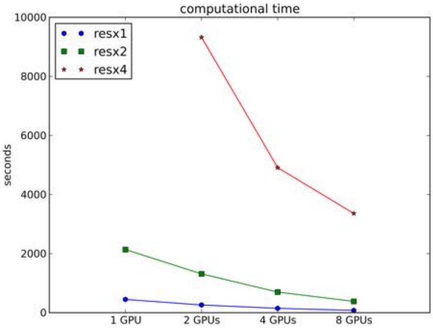
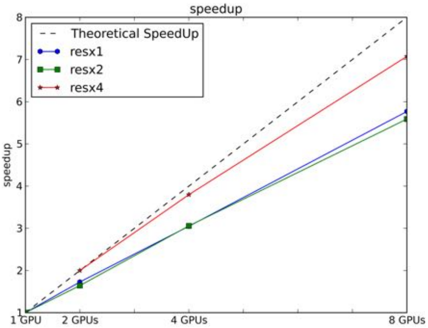
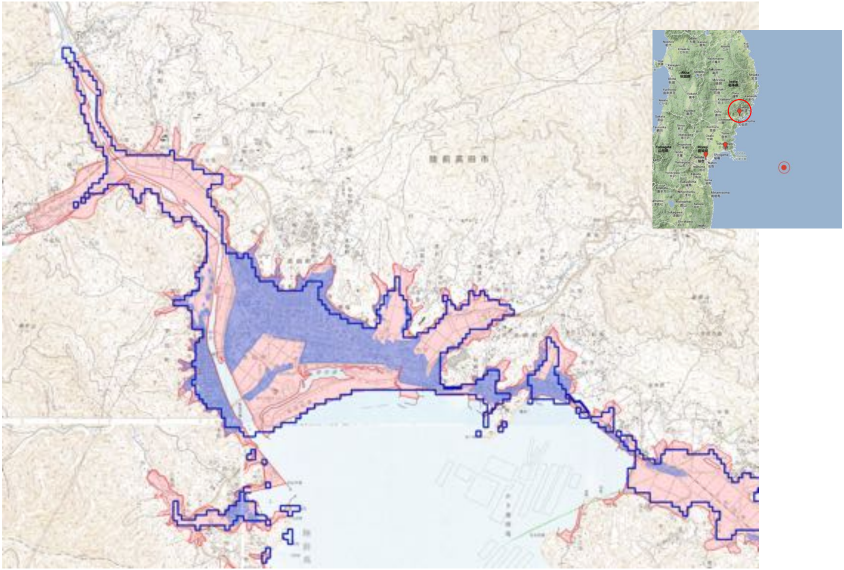
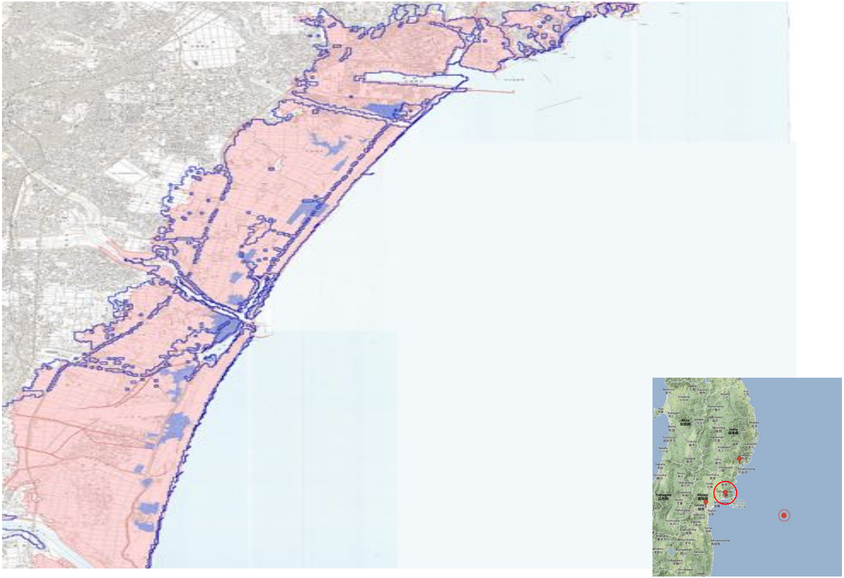




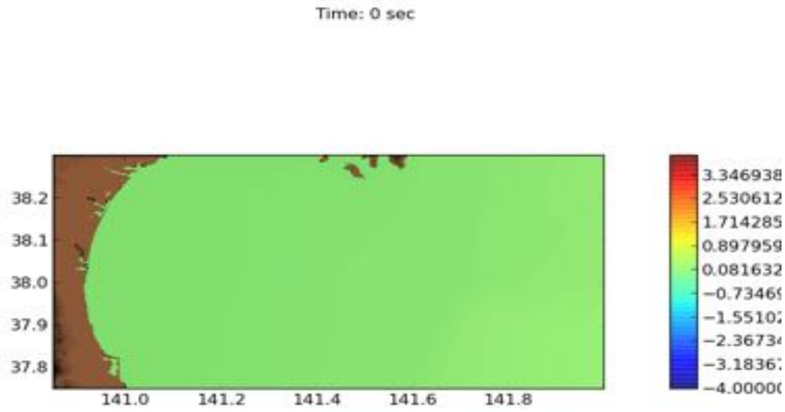
Tohoku 2011. Inundation map for Rikuzentakata



Tohoku 2011. Inundation map for Sendai



Tohoku 2011. Inundation at Sendai coastline



Leverage

We already mention:

- **Innovation**
- **Specific problem**
- **The Impact**

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- **Specific problem**
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Conclude

- **How Tsunami-HySEA can benefits other researchers**
- **helping to achieve further progress in Tsunami Science**

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Stefano Lorito (CAT-INGV)

"Tsunami-HySEA is making easier and boosting the basic tsunami research we perform in our group"

Leverage

Stefano Lorito (CAT-INGV)

“Tsunami-HySEA is making easier and boosting the basic tsunami research we perform in our group”

A tool for the whole process

1. **TEWS**
2. **Precomputed databases**
3. **Inundation Maps**
4. **PTHA**

Leverage

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A tool for the whole process

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4. **PTHA**

In particular, for PTHA

TSUMAPS project: First Probabilistic Tsunami Hazard Assessment study for the NEAM region

Leverage

EDANYA Team: A collaborative group

Sharing tools and knowledge

1. Open source code
2. Collaboration agreements
3. Contracts for customized solutions
4. Training courses
5. Technical assistance
6. Computational support

Acknowledgements

Nominator

- **Diego Arcas**, Director of PMEL (NOAA)

Endorsers

- **Stefano Lorito**, ICG/NEAMTWS Vice-Chair, CAT-INGV Steering Committee
- **Patricio Carrasco**, Rear Admiral SHOA (Chile)
- **Alessandro Anunziato**, Scientific Officer JRC (EC)

Also to

- **The IGN Team**, NTWC (Spain) leaded by Emilio Carreño

Gracias por su atención

Thanks for your attention

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