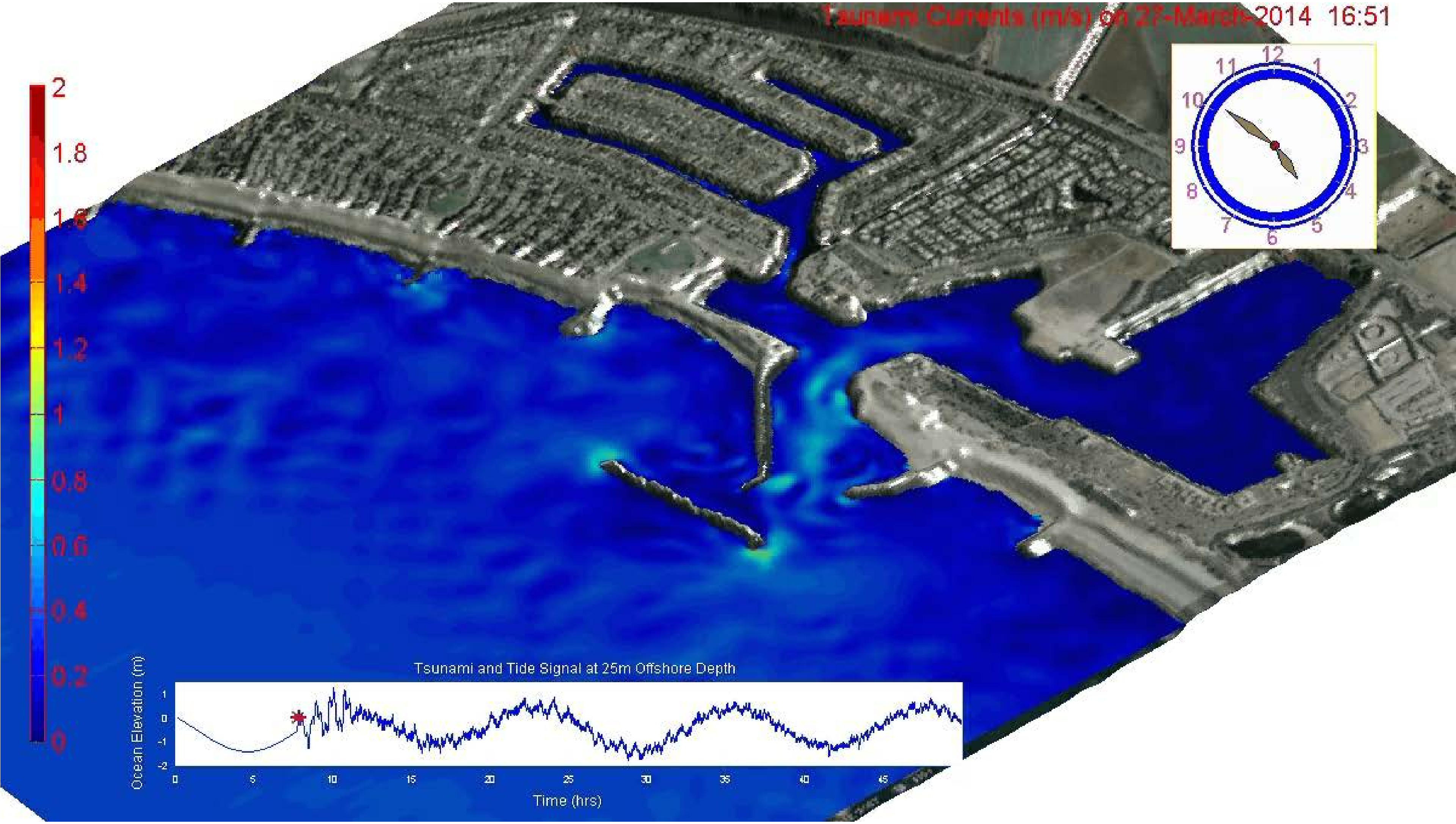
Large-Scale Coastal Modeling: Tsunami Applications



Patrick Lynett

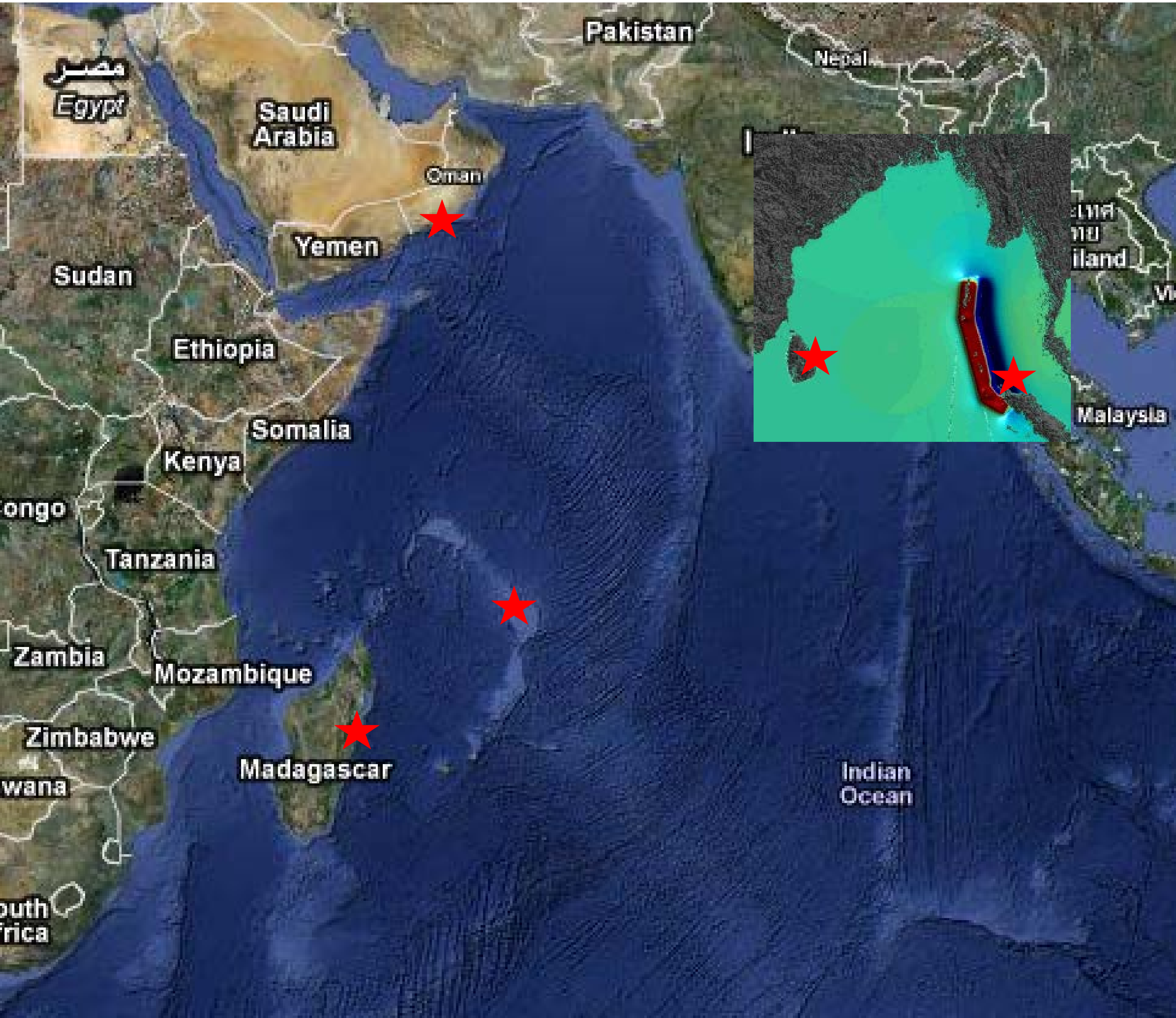
Sonny Astani Department of Civil Engineering

University of Southern California

Tsunami Interaction with Nearshore Infrastructure:
Outline

- *Review tsunami generation and propagation modeling, focus on nearshore complexities*
- *Present recent observations of nearshore effects, and the motivation to develop simulation tools to predict some of the effects*
- *Apply the developed tool to look at the dynamic currents near coastal structures*

Recent Events & Observations

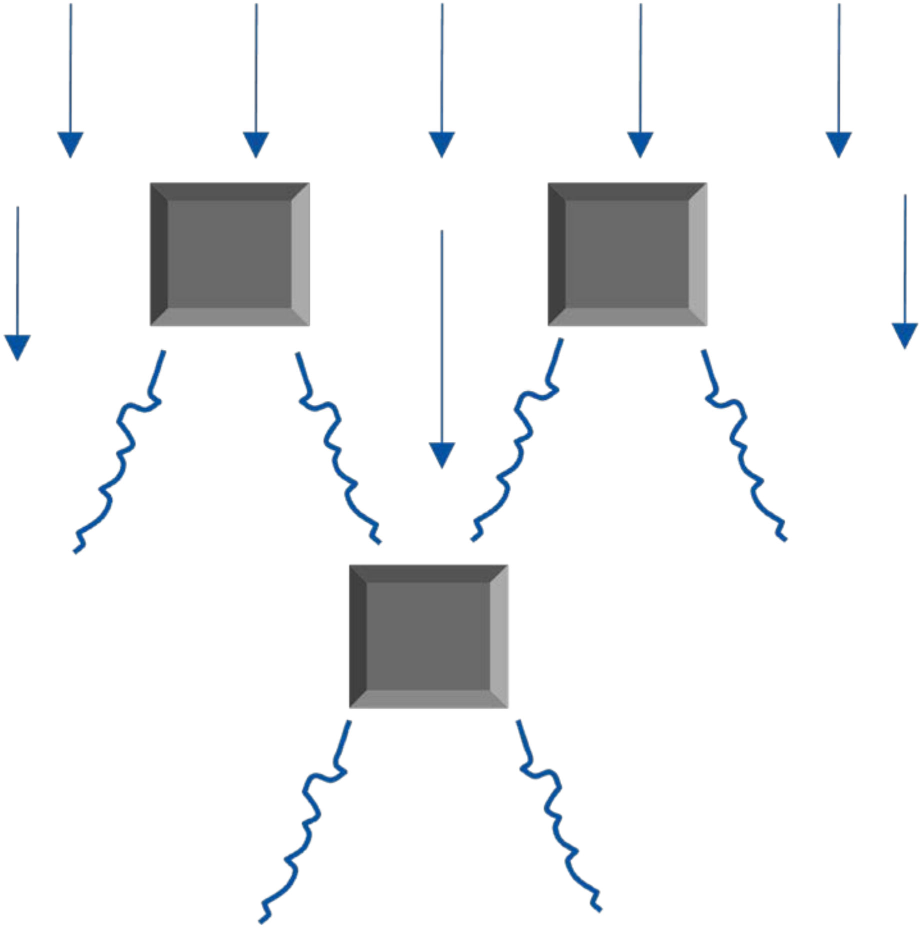


2004 Indian Ocean Tsunami

- *9.3 Mag EQ*
- *~10 minute rupture*
- *30m+ runup near source*
- *5m+ runup Sri Lanka, India, Thailand*
- *3m+ runup Eastern Africa, Oman, Yemen*
- *230,000 dead*
- *1.7 million displaced*

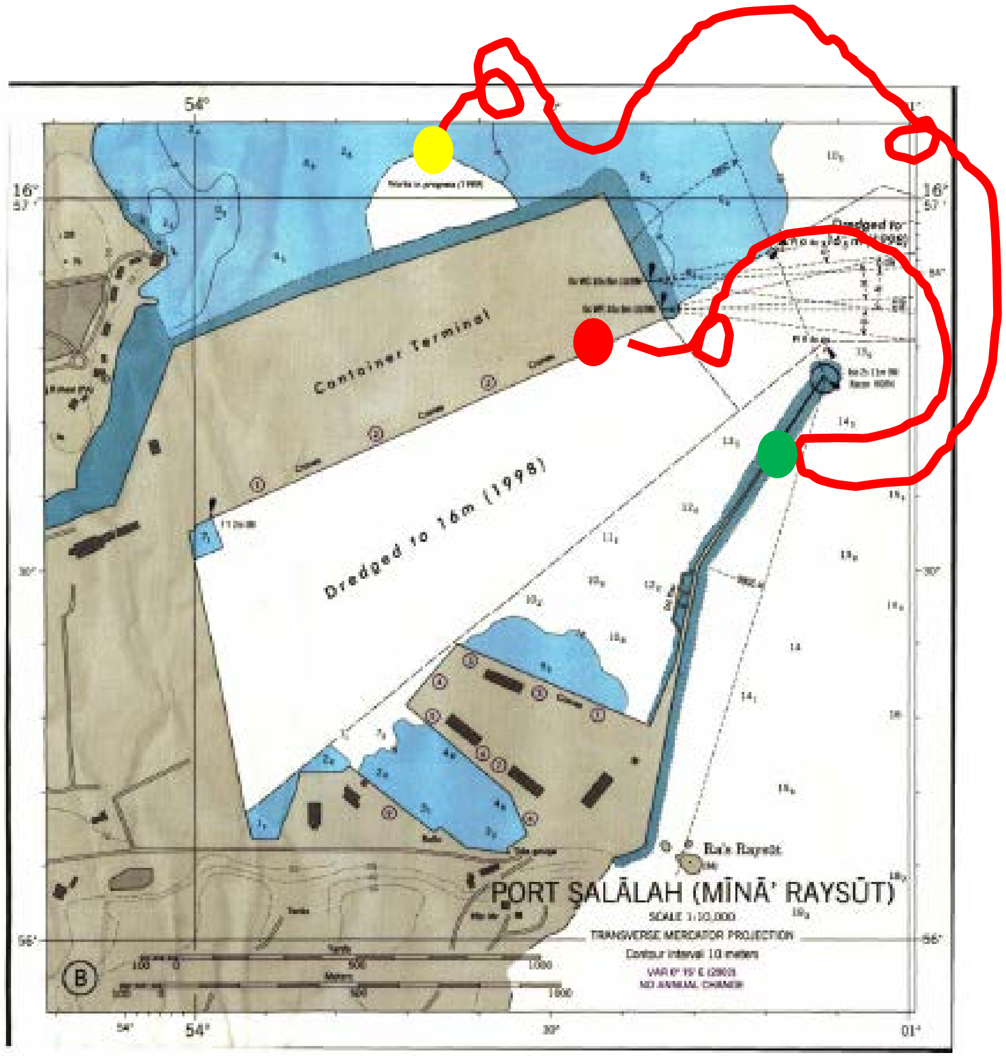
Recent Events & Observations

Recent Events & Observations



Recent Events & Observations

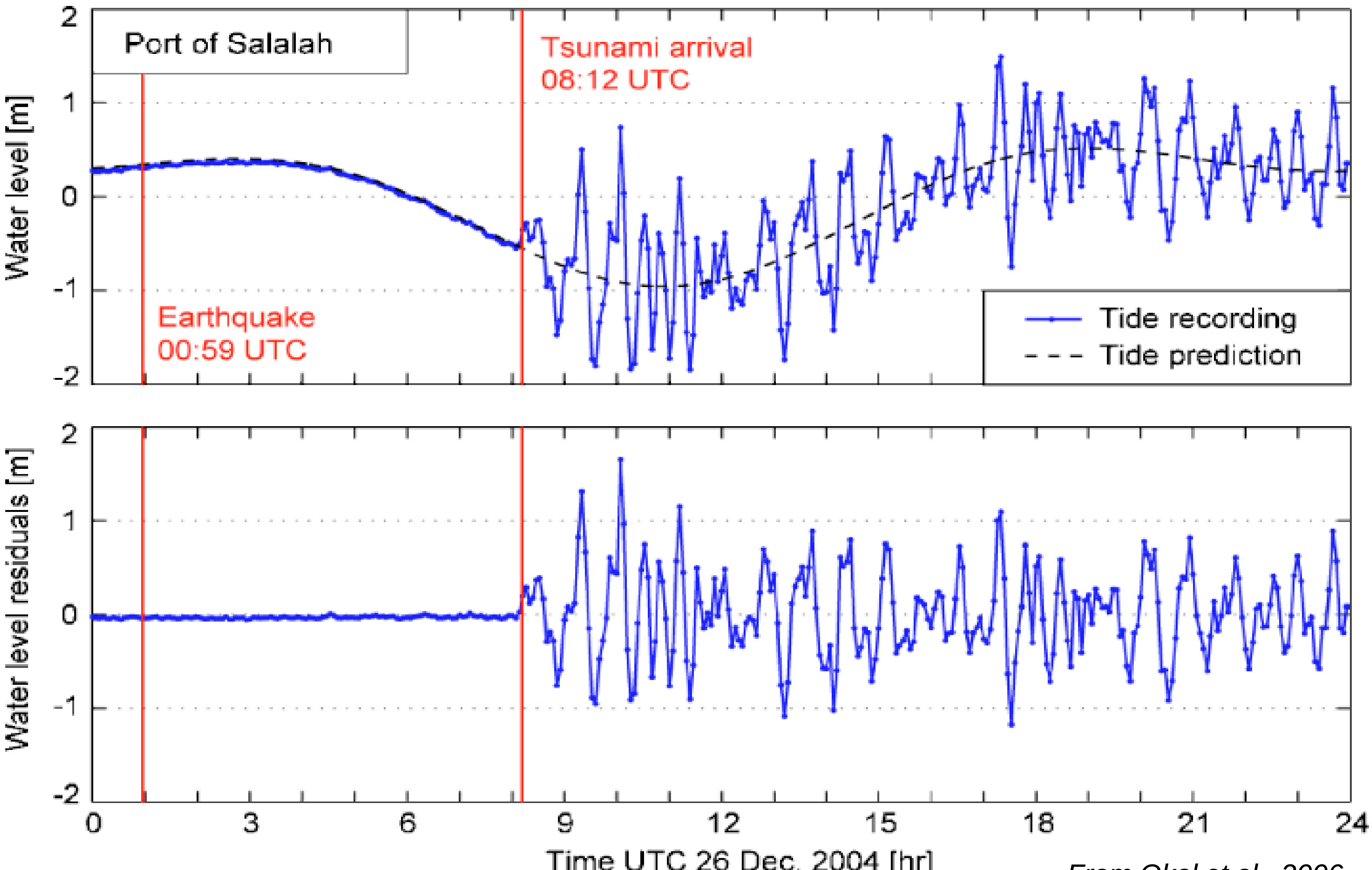
Port Salalah, Oman



285-m container ship Maersk Mandraki

- *Broke moorings, was pulled out of the Port by a large eddy* (red)
- *Drifted around the breakwater, nearly impacted the breakwater on the ocean side* (green)
- *Drifted back across entrance, to the other side of the terminal, beached on a sand bar* (yellow)

Motivation:
Recent Events & Observations



From Okal et al., 2006

Recent Events & Observations

Le Port, Réunion

196-m container ship MSC Uruguay

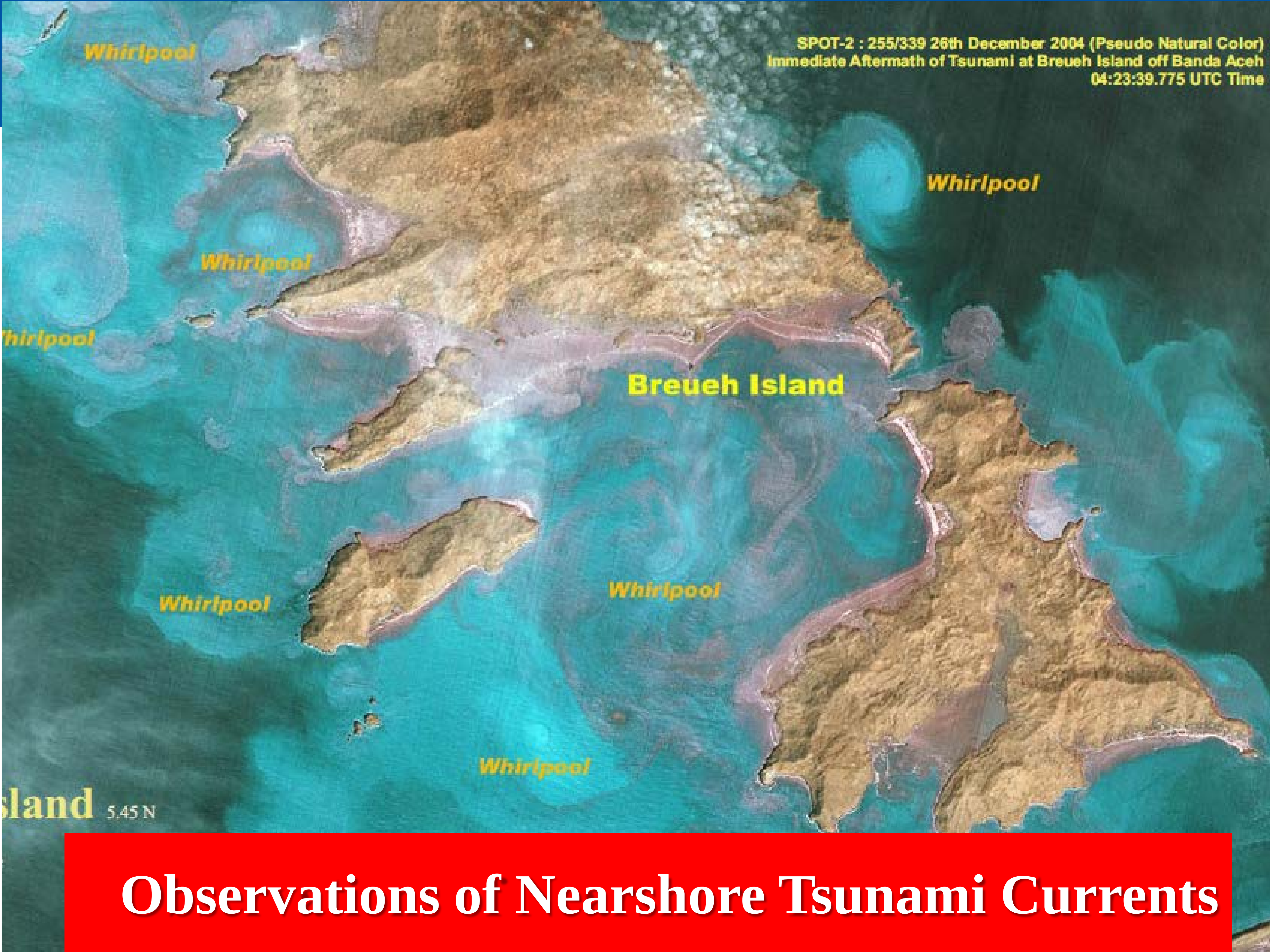
- *Broke all 12 of its hawsers, began drifting*
- *Drifted for 2 hours, striking & damaging gantry cranes*
- *Port crews re-secured moorings lines ~ 3 hours later, only to have them break again*

Recent Events & Observations

50-m freighter Soavina III

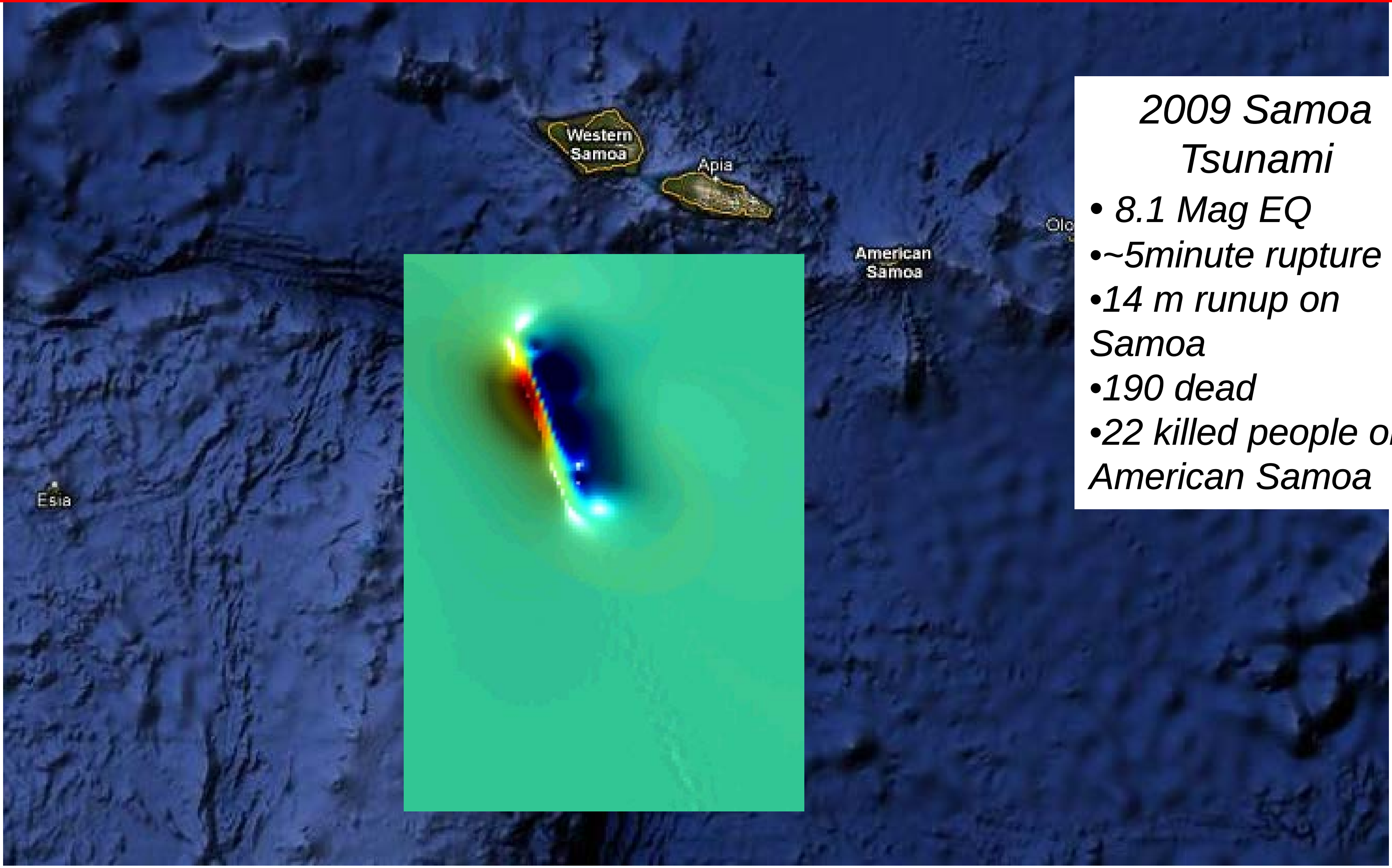
From Okal et al., 2006

- *Broke its moorings, began drifting into interior harbor*
- *Impacted dock*
- *After ~ 3 hours of drifting, finally beached on nearby shore*



Observations of Nearshore Tsunami Currents

Recent Events & Observations



2009 Samoa Tsunami

- *8.1 Mag EQ*
- *~5minute rupture*
- *14 m runup on Samoa*
- *190 dead*
- *22 killed people on American Samoa*

Recent Events & Observations

Recent Events & Observations

Recent Events & Observations

Recent Events & Observations

Recent Events & Observations


ON U.I.C. RAILWAY
24000 KG

Recent Events & Observations

Recent Events & Observations


MANU'ATELE III
MANU'ATELE III

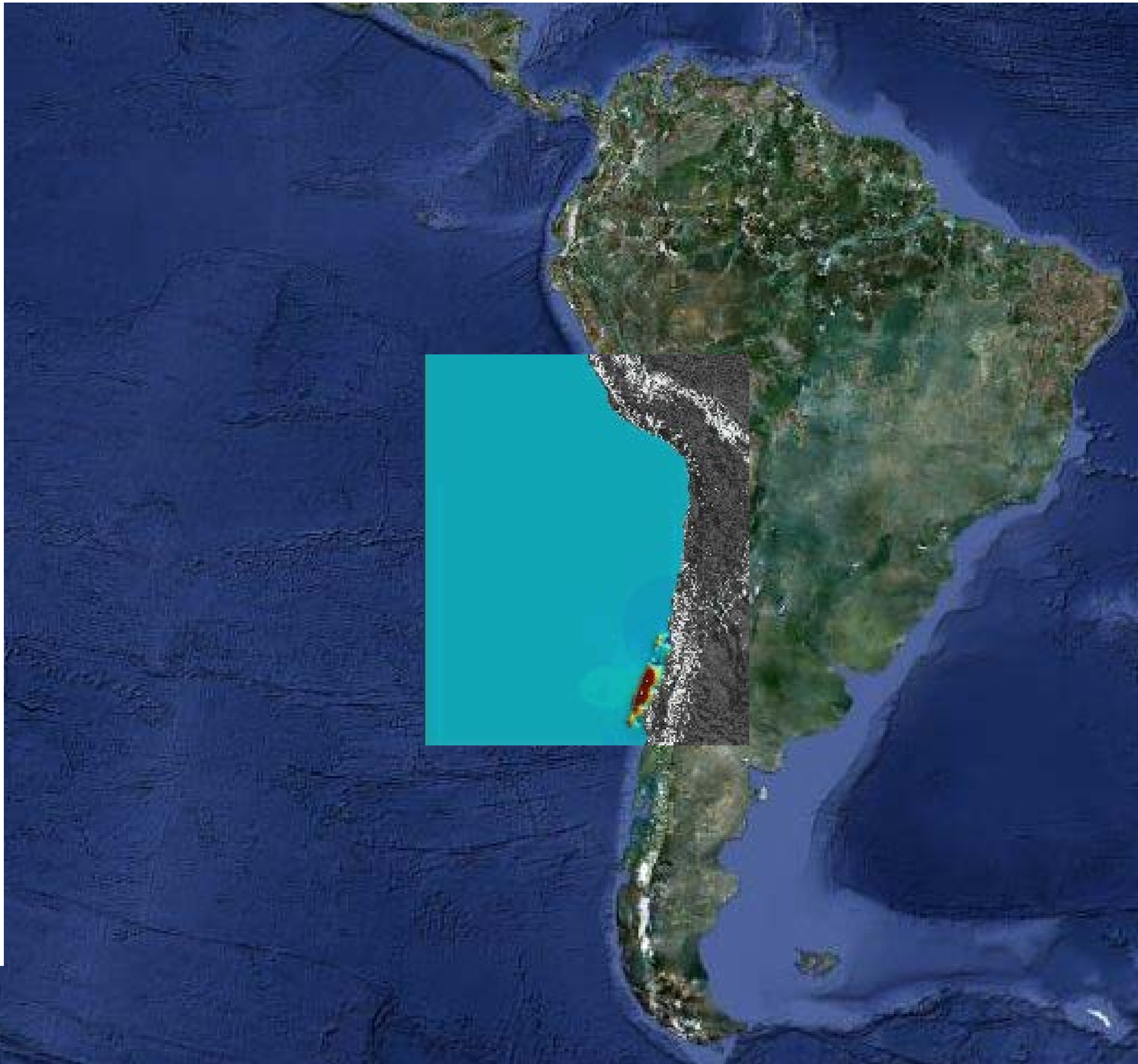

KOORALE


TACOMA

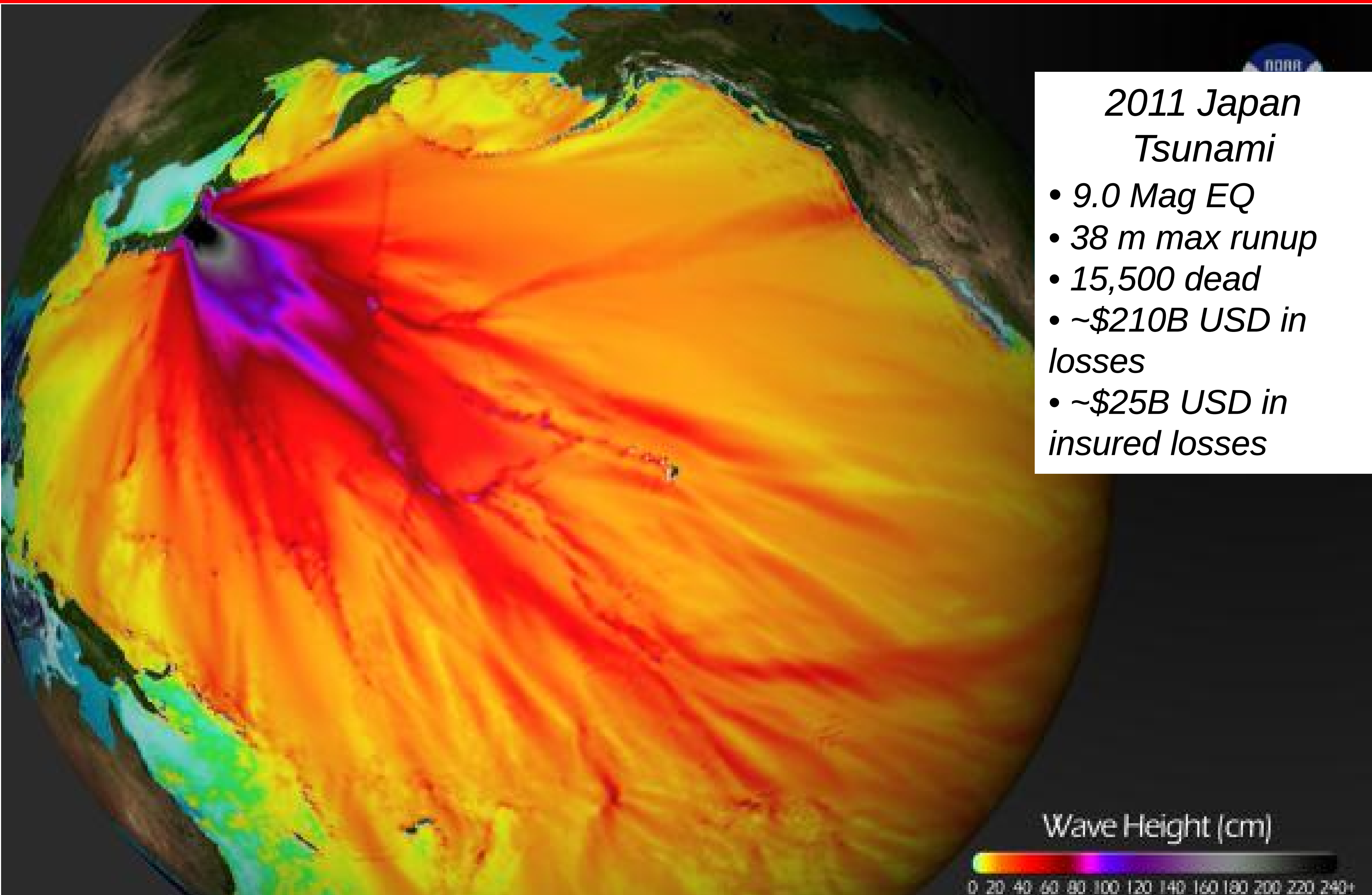
Motivation: Recent Events & Observations

2010 Chile

- *8.8 Mag EQ*
- *Tsunami Warnings issued in 53 countries*
- *30 m runup along cliffside in Chile*
- *Widespread 5-10 m runup in Chile near epicenter*
- *4,200 boats were damaged or destroyed by the earthquake and tsunami in the Valparaiso-Concepción-Temuco area*
- *1+m in many locations, including Hawaii, Japan, south Pacific islands*



Recent Events & Observations



2011 Japan Tsunami

- *9.0 Mag EQ*
- *38 m max runup*
- *15,500 dead*
- *~$210B USD in losses*
- *~$25B USD in insured losses*

Recent Events & Observations

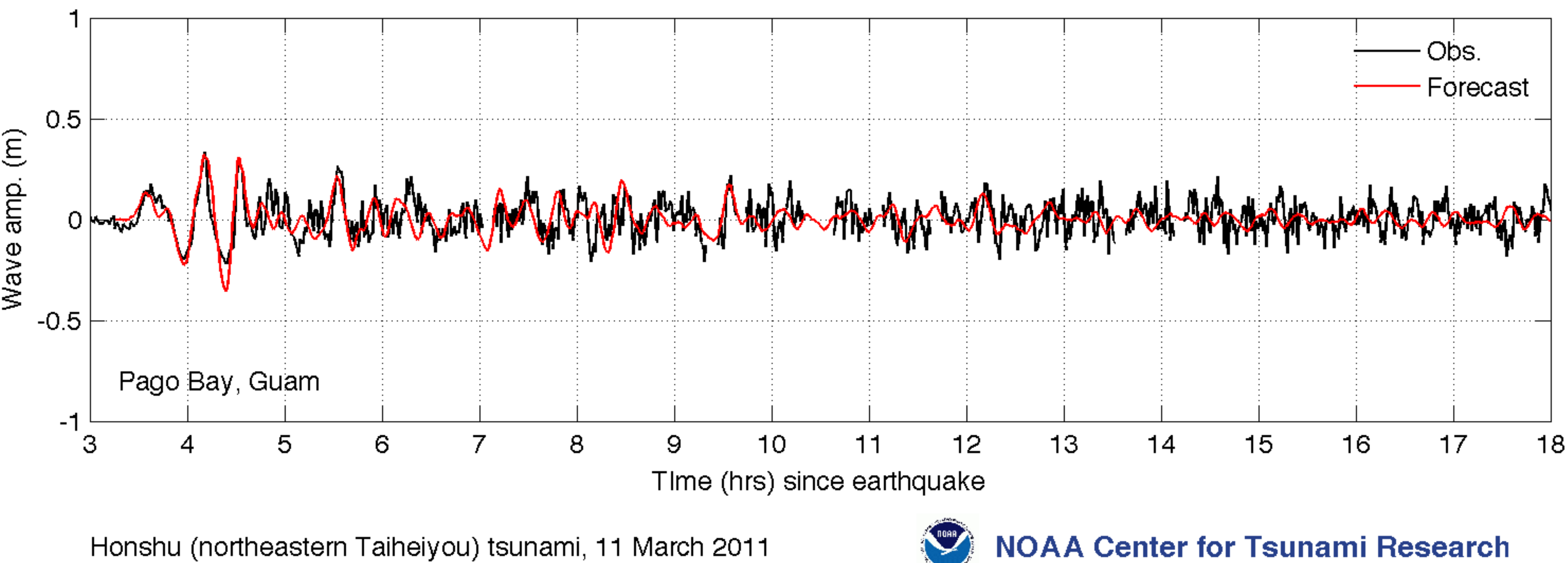
2011 Japan Tsunami

- *350 ports suffered some damage*
- *18,000+ fishing boats out of operation*

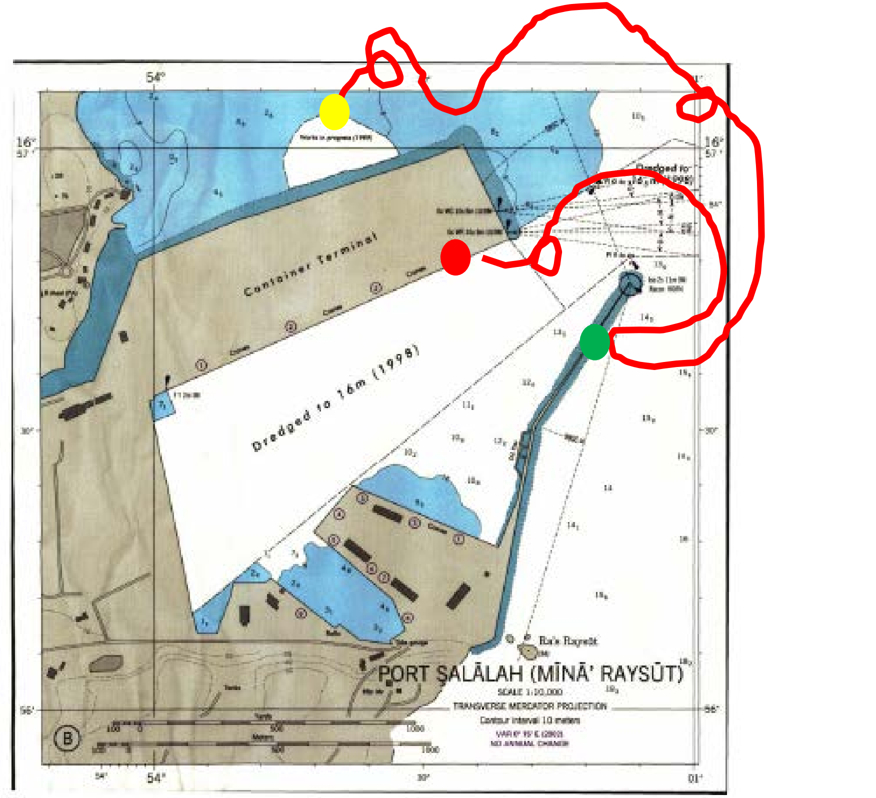
Recent Events & Observations

2011 Japan Tsunami
*In Guam, two nuclear submarines (*USS Houston and USS City of Corpus Christi) broke free of moorings

Recent Events & Observations



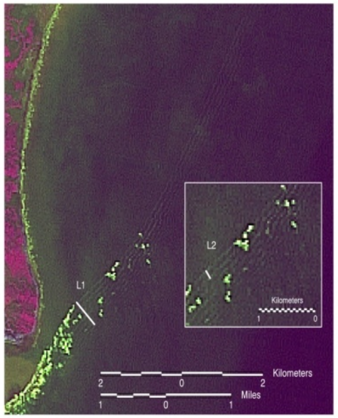
2011 Japan Tsunami
*In Guam, two nuclear submarines (*USS Houston and USS City of Corpus Christi) broke free of moorings


Container Terminal
Dredged to 16m (1998)
Ra's Raysūt
PORT SALĀLAH (MĪNĀ' RAYSŪT)
TRANSVERSE MERCATOR PROJECTION
Contour interval 10 meters


bean' Ny Tanana Mikambana

Nearshore Dynamics of Tsunamis

- **Overarching theme of this work:**
  - **Increase our understanding of nearshore tsunami evolution, such that we are better able to mitigate their effects and estimate the risk**
- How well do we understand the physics?
  - Traditional, accepted knowledge describes a tsunami as a long wave (nondispersive, ~ steady flow)
  - Observations of tsunami in the past decade indicate that is not necessarily, or even likely, the case in the nearshore



- **IF we want to be able to predict the dynamics of the flow…**
  - **Forces on structures**
  - **Sediment transport**
  - **Local current & energy amplifications**

  → **We need a different approach, with "better" physics**

Inclusion of Rotational & Turbulent Effects in Depth-Integrated Models

- *Theory: Kim et al. (2009, Ocean Modelling); Kim & Lynett (2011, Physics of Fluids)*

$O(\mu^2)$ Dispersive Corrections

$O(\beta\mu)$ Turbulent-Rotational Corrections

O(1) Shallow Water terms

$$\frac{\partial HU_i}{\partial t} + \frac{\partial HU_iU_j}{\partial x_j} + gH\frac{\partial \zeta}{\partial x_i} + H\left(D_i + \overline{\xi_i} + D_i^\nu + \overline{\xi_i^\nu}\right) + U_i\left(\mathcal{M} + \mathcal{M}^\nu\right)$$

$$- H\frac{\partial}{\partial x_j}\left(2\nu_t^h S_{ij}\right) + 2H\frac{\partial}{\partial x_i}\left(\nu_t^v \frac{\partial U_j}{\partial x_j}\right) + \frac{\tau_i^b}{\rho} - HF_i = 0$$

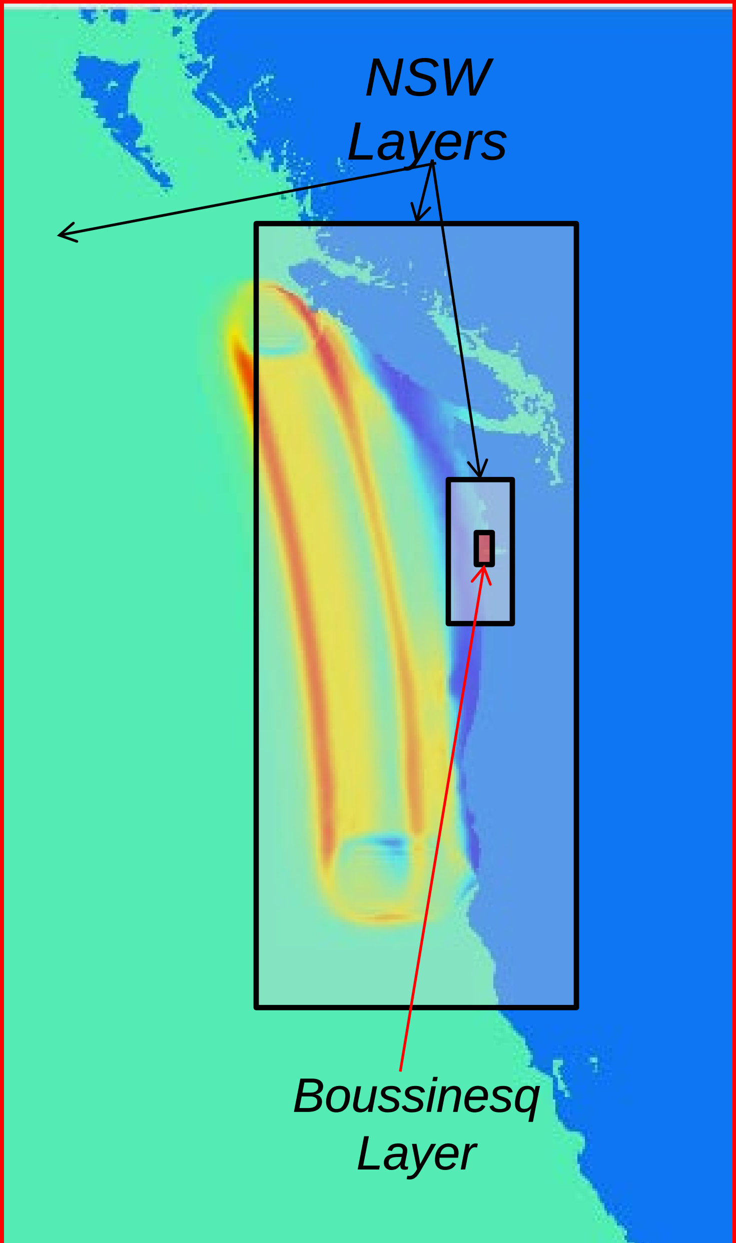
$O(\alpha\mu)$ Turbulent Mixing in Horizontal Plane. Eddy viscosity closed with Smagorinsky model

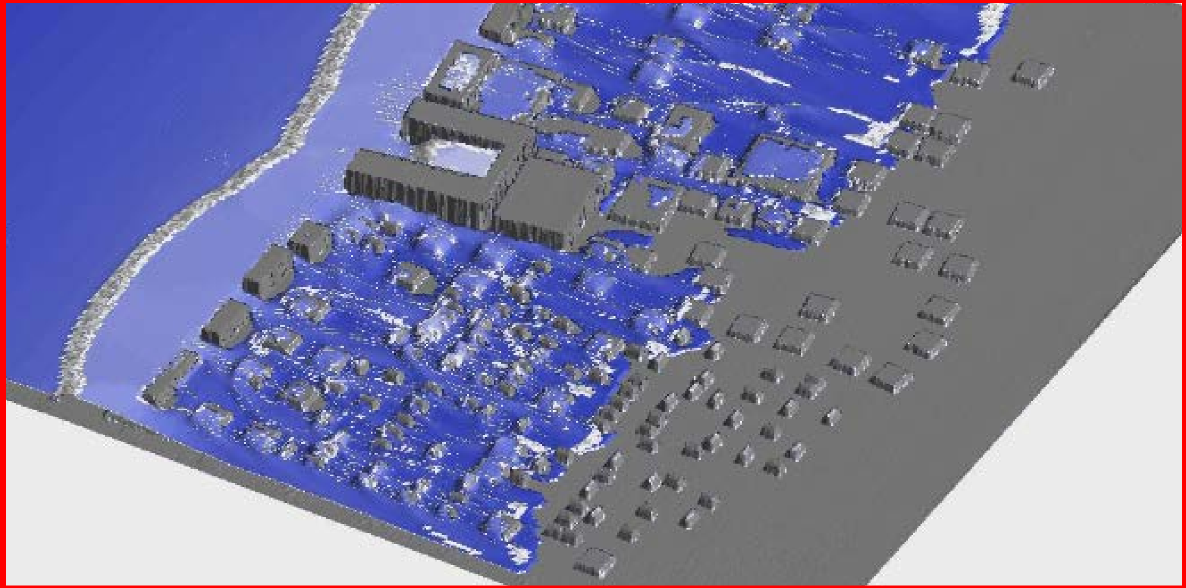
$O(\beta\mu)$ Turbulent Mixing in Vertical Plane. Eddy viscosity closed with Elder's model

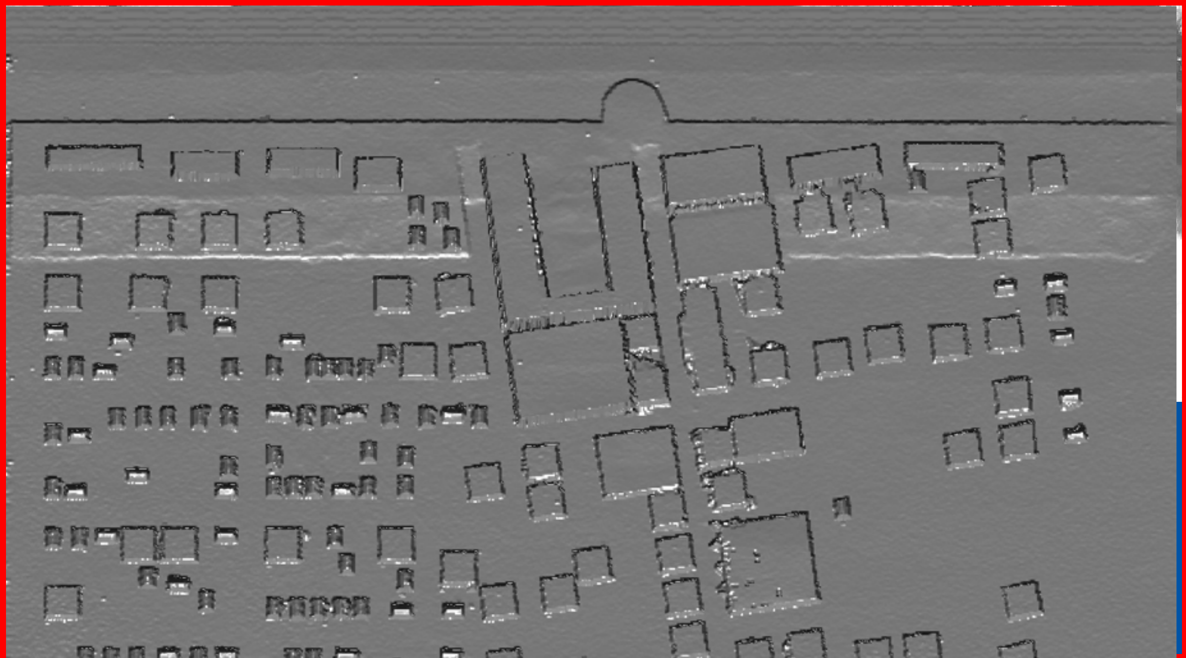
$O(\beta\mu)$ Bottom Stress, closed with Mannings, Moody, etc.

$O(\gamma)$ Depth-averaging stress terms, closed with BSM

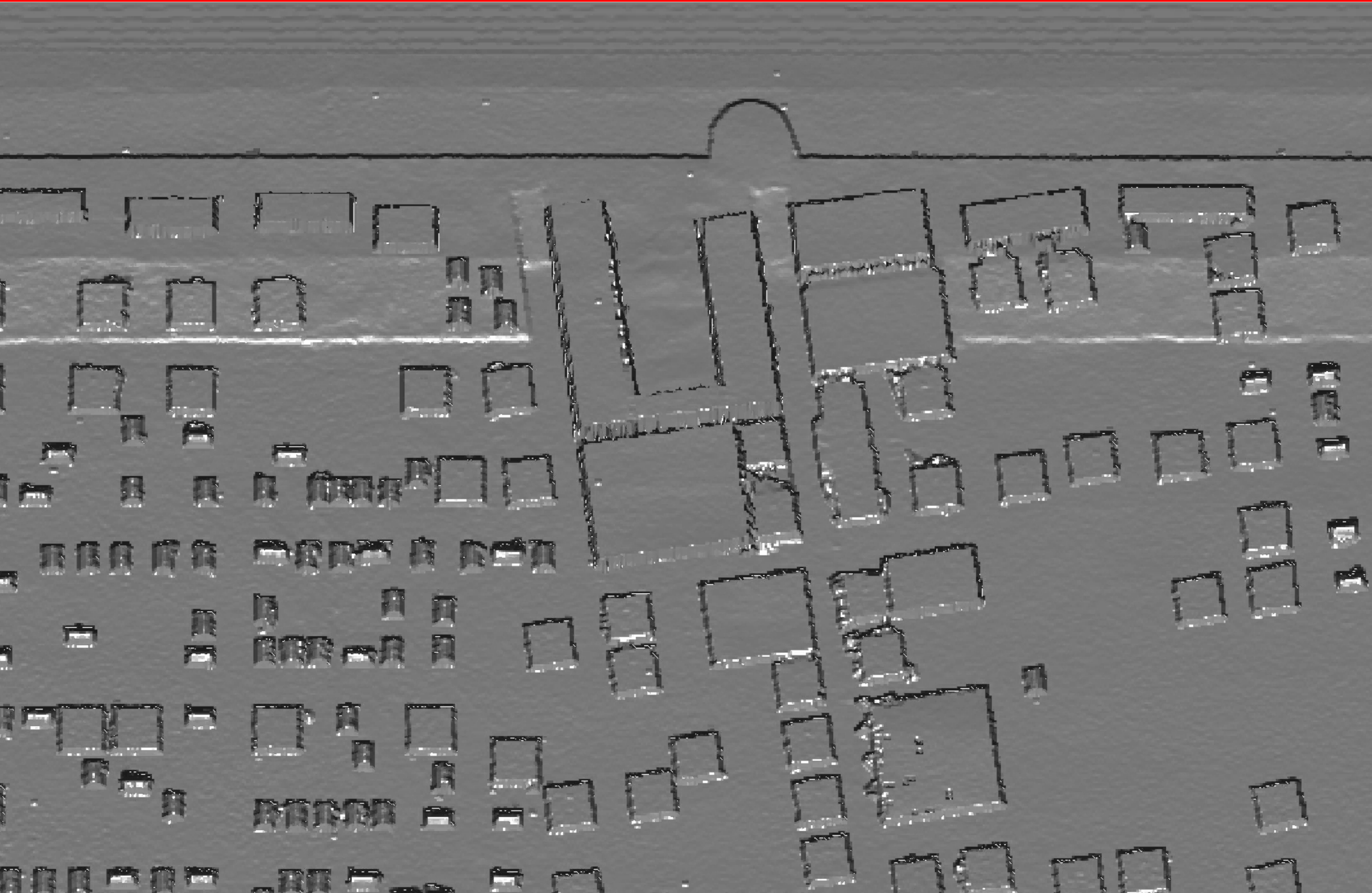
Applications: Tsunami Inundation of Coastal Infrastructure







Applications: Tsunami Inundation of Coastal Infrastructure



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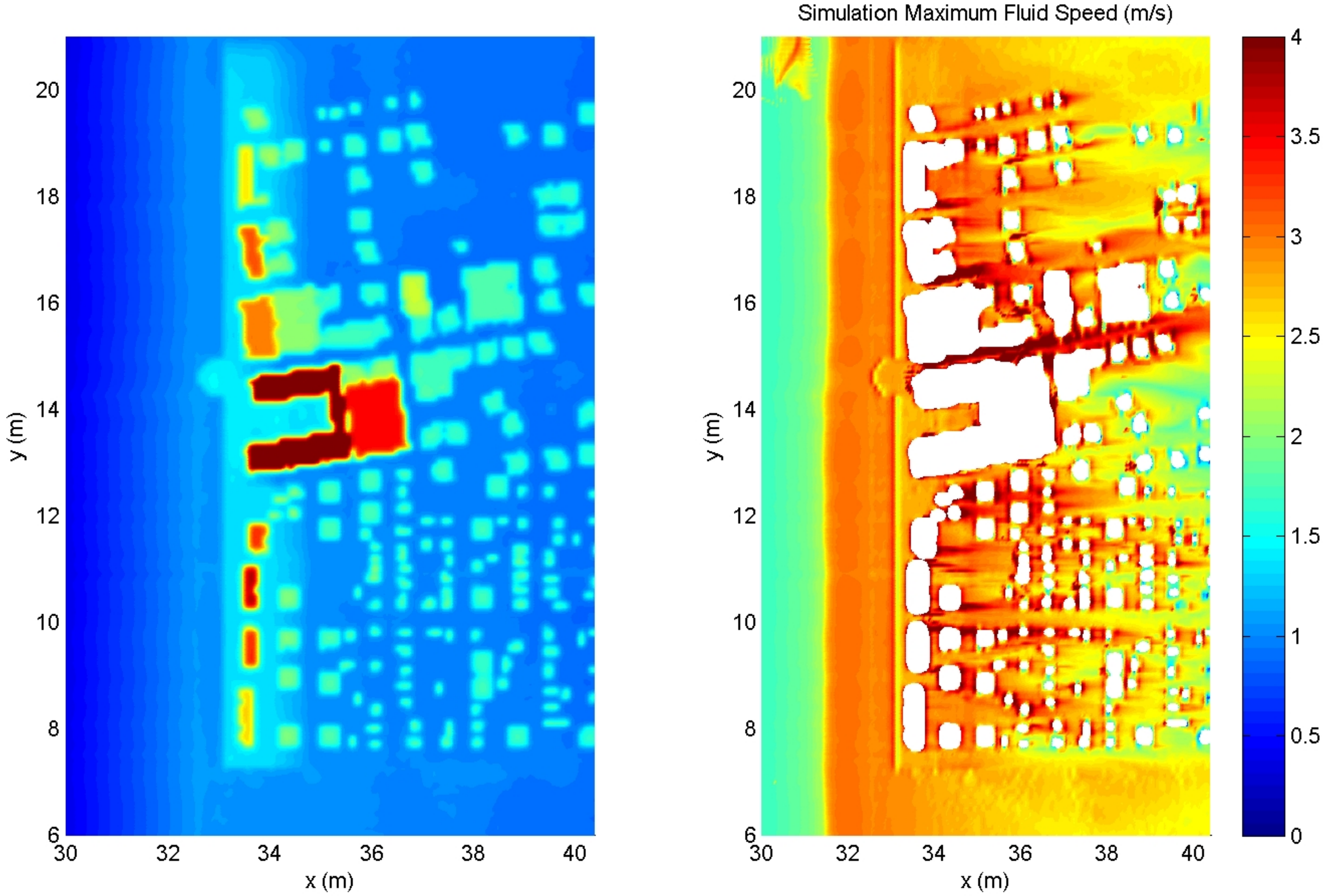

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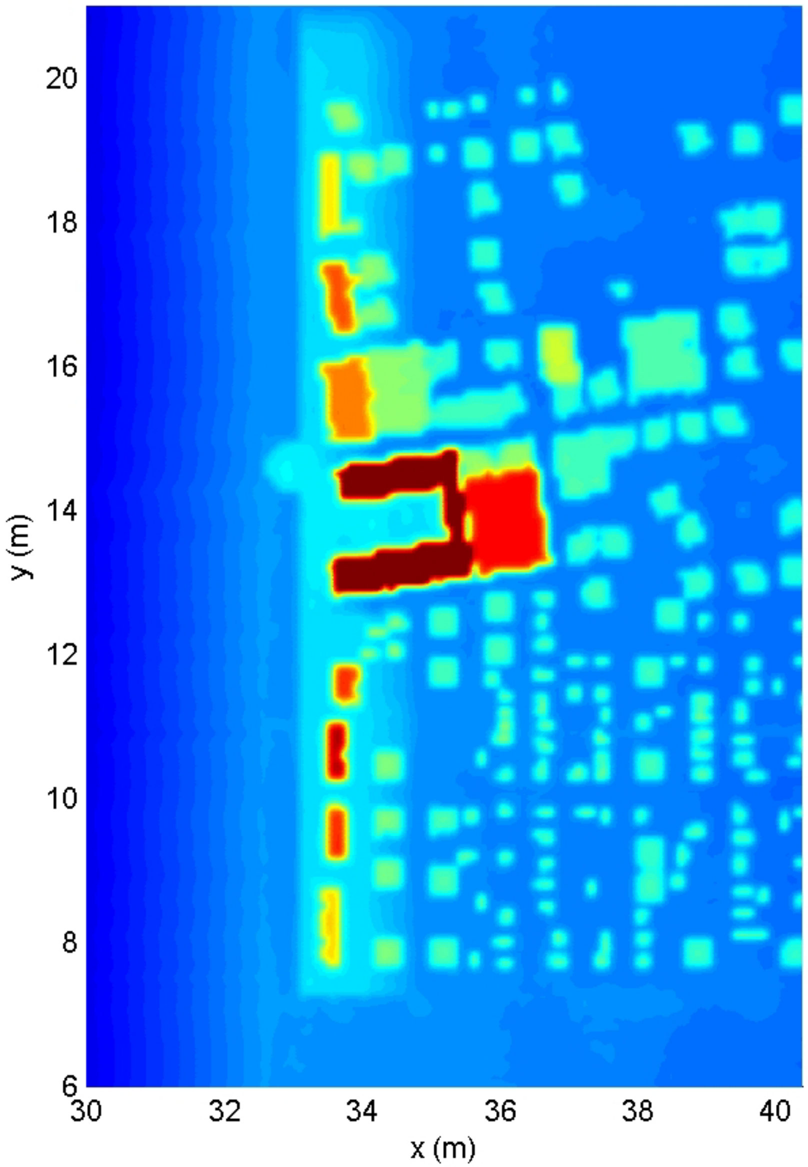

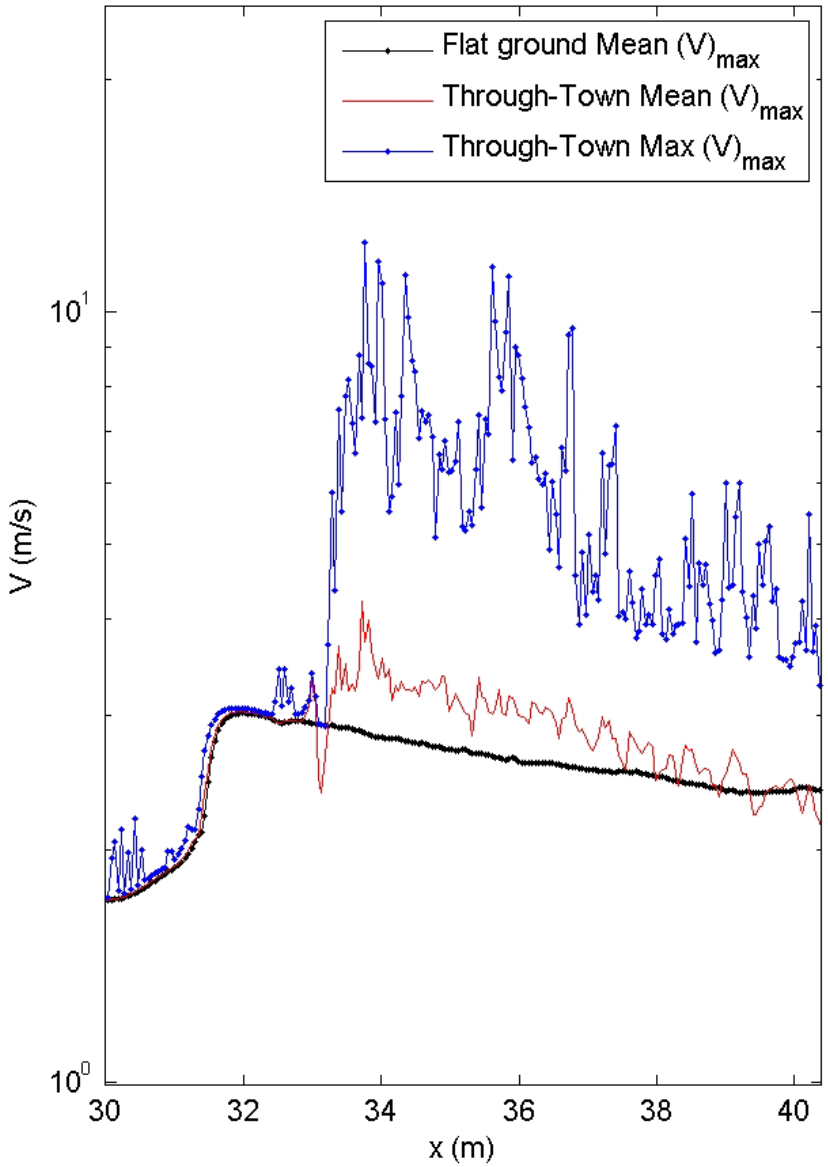

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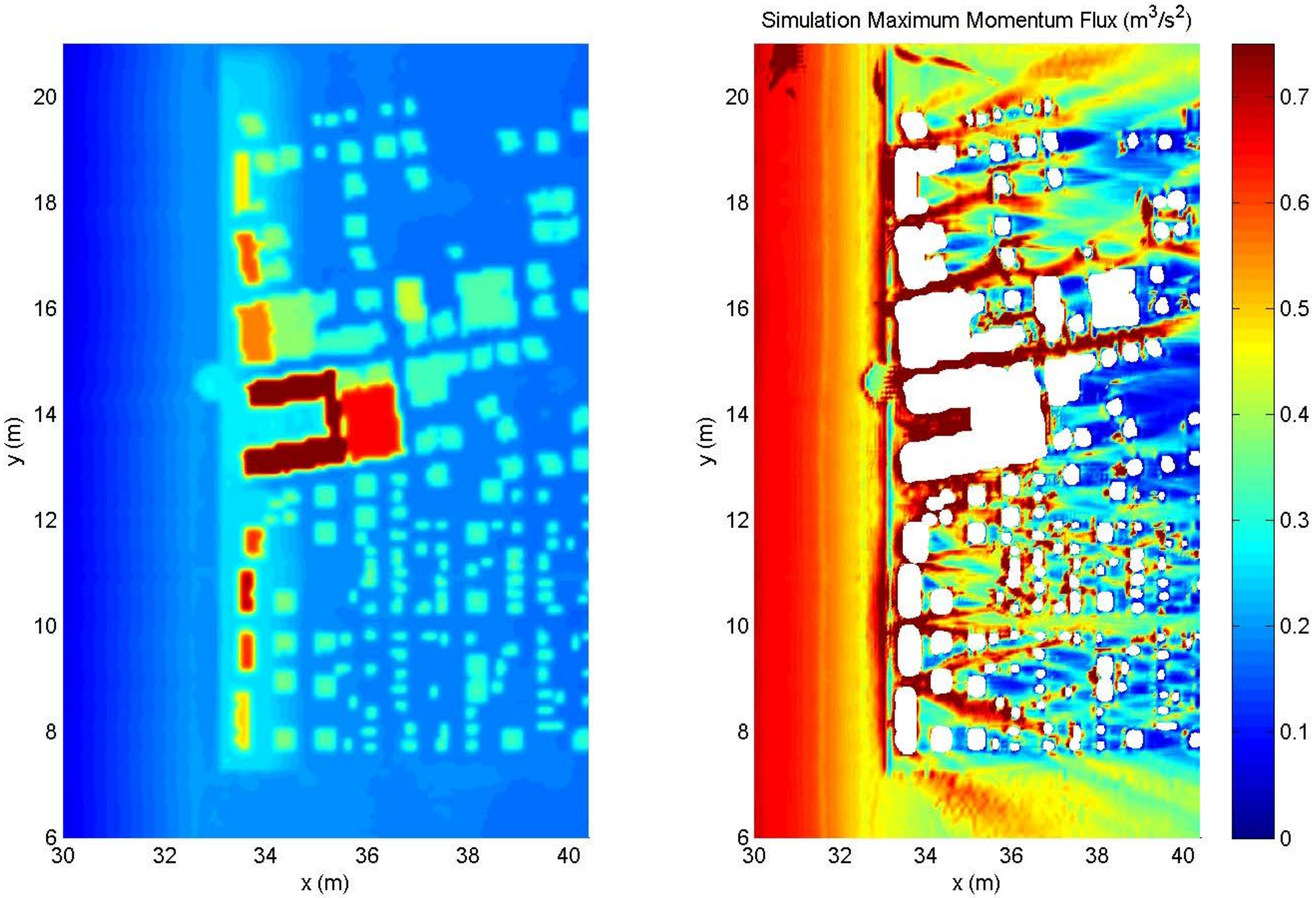

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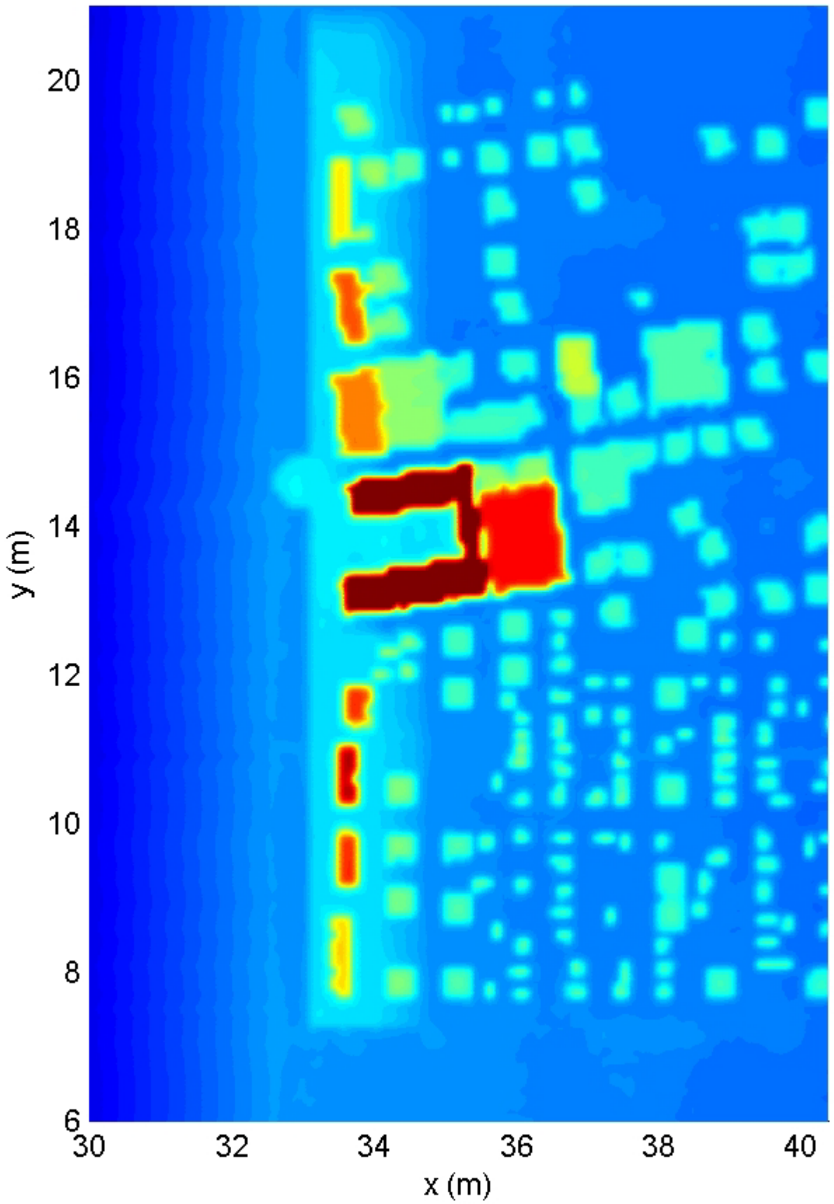

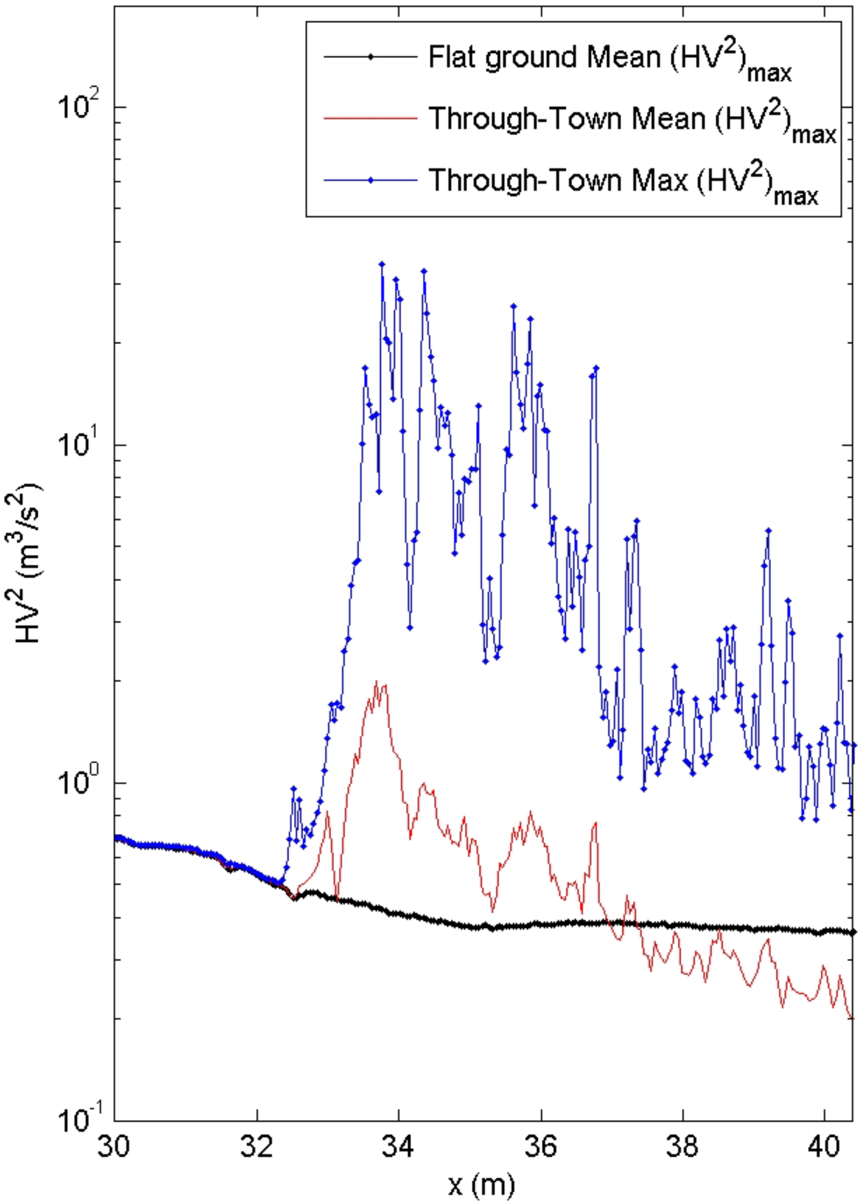

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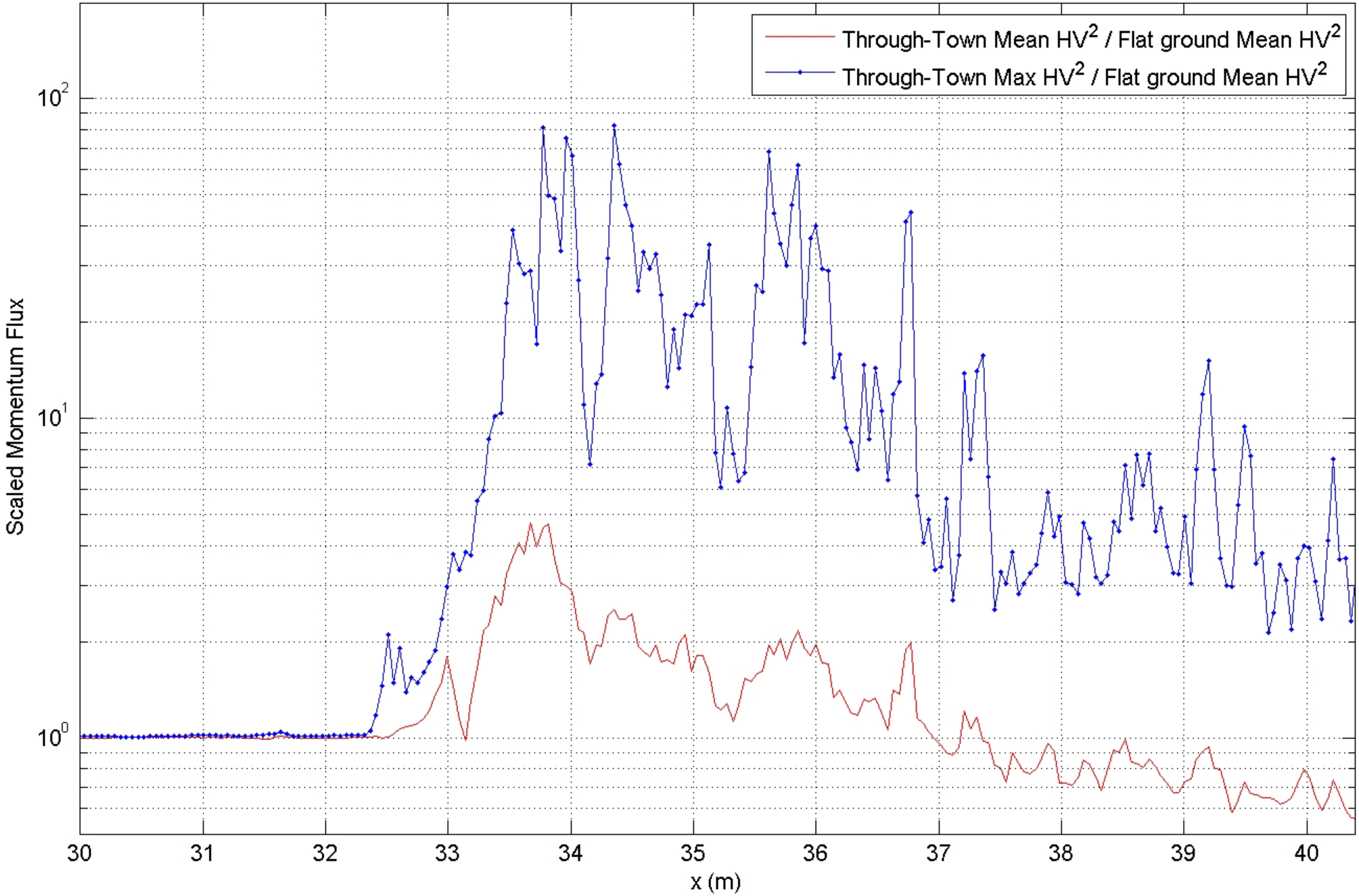

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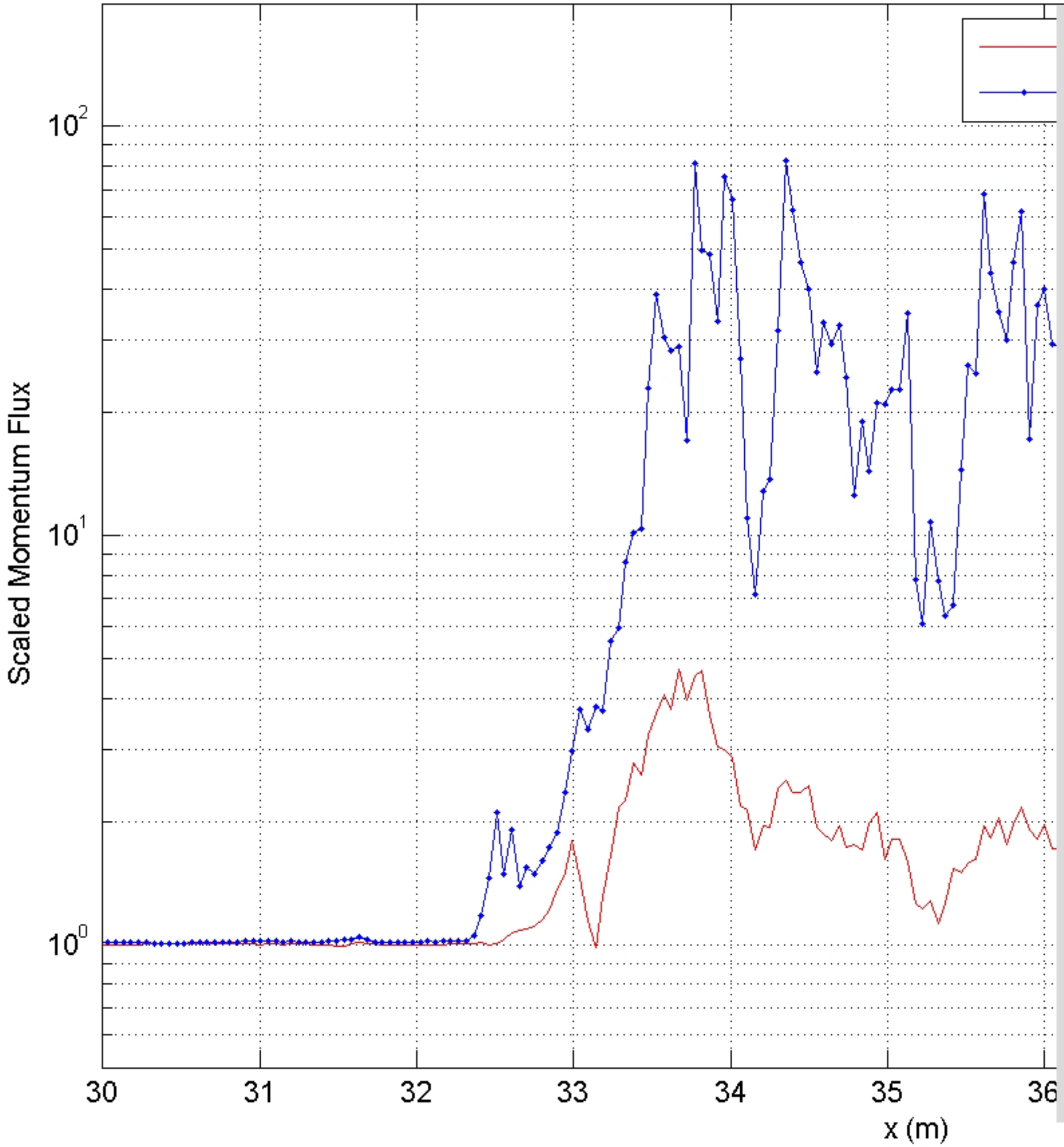
Applications: Tsunami Inundation of Coastal Infrastructure

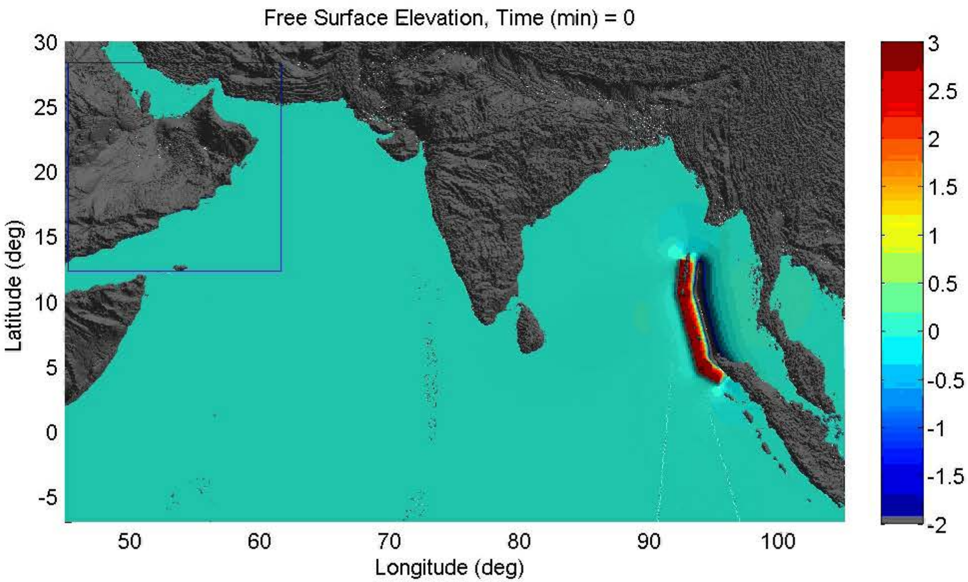


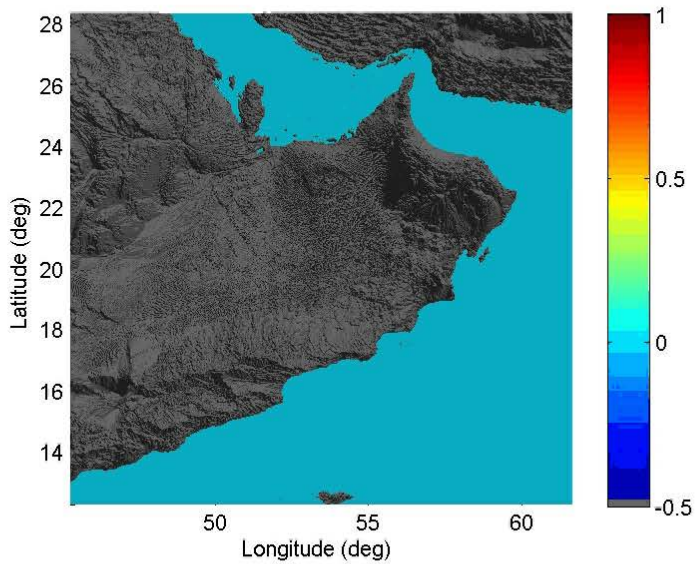
- *Dataset created at OSU for nonlinear, transient long wave inundation through built environment*
  - *Unique for presenting velocities and momentum flux*
  - *Excellent test for models*
- *Validated model shows significant variation in maximum fluid force potential with town/building layout*
- *How to include this variation in planning & design efforts?*

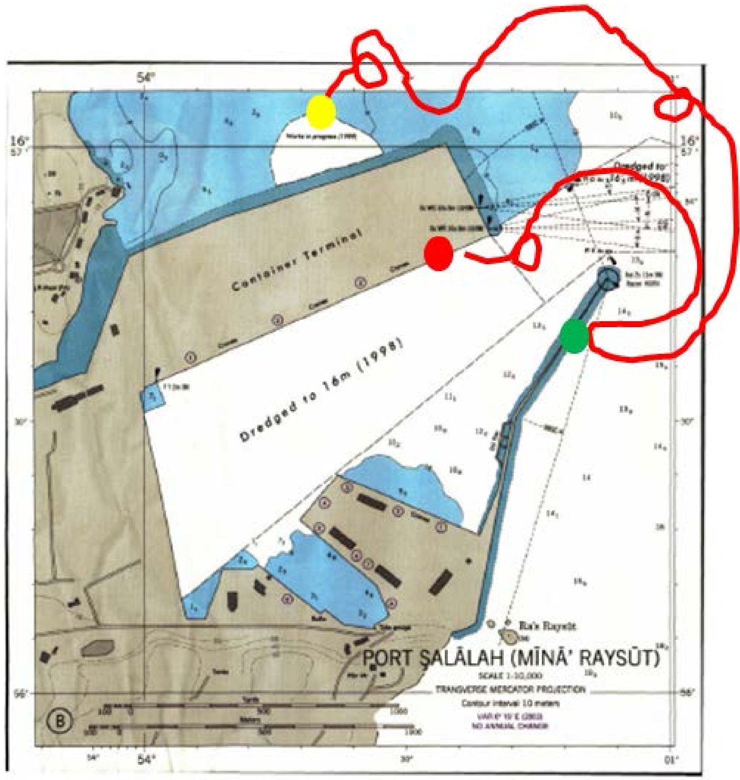
Harbor Studies

2004 Indian Ocean Tsunami

Port Salalah, Oman







Harbor Studies

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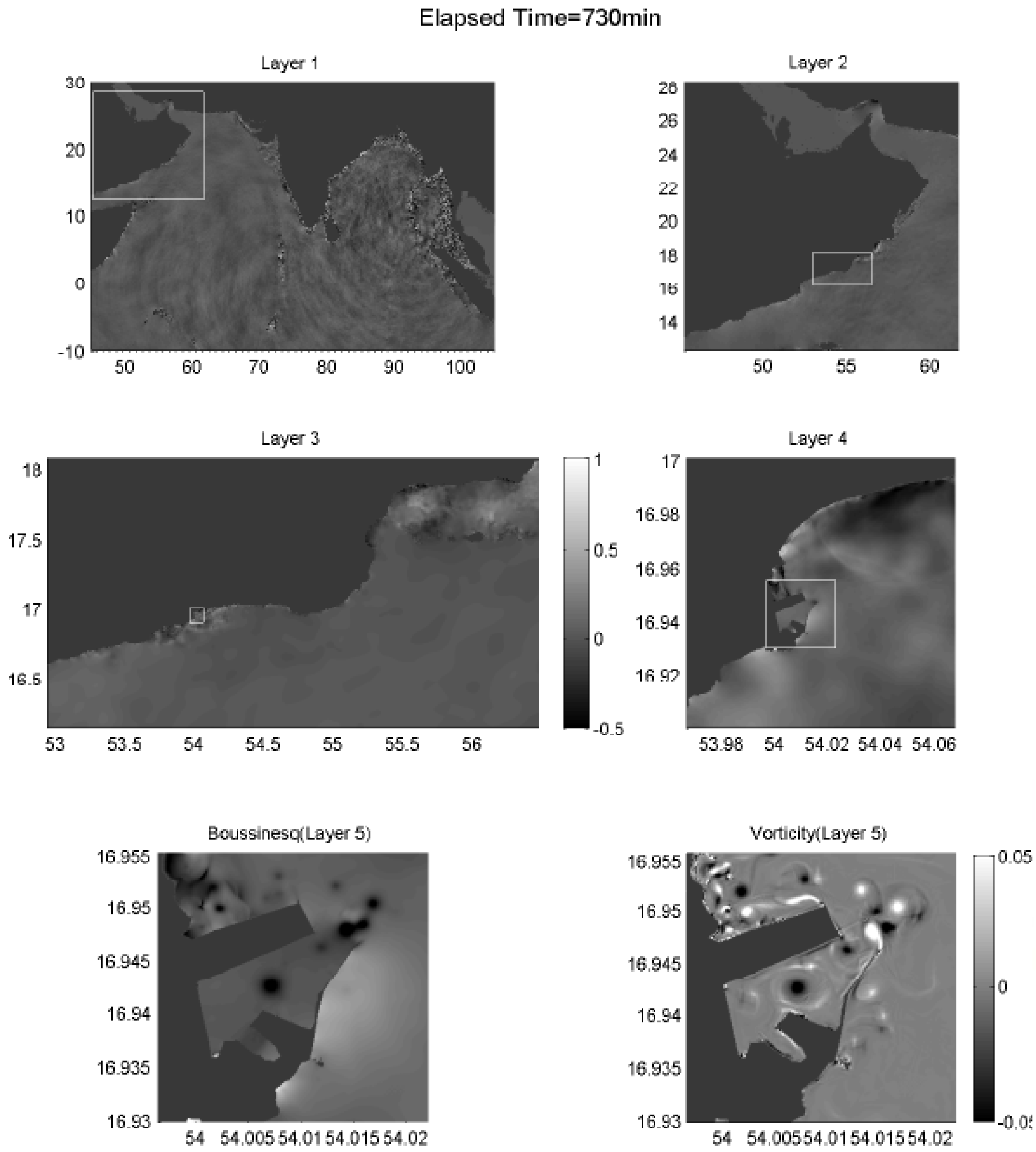
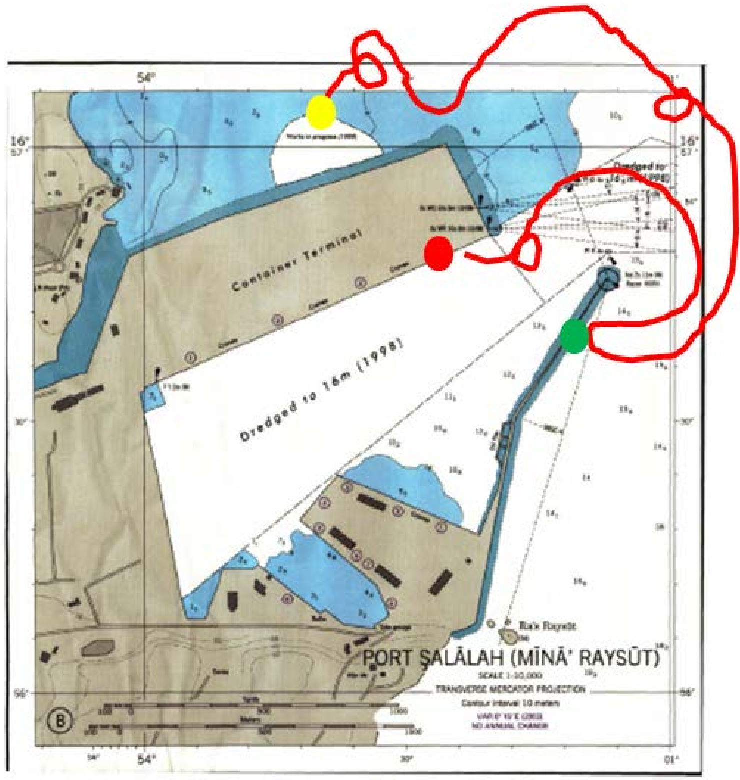




Son et al. (2011, Ocean Modelling)

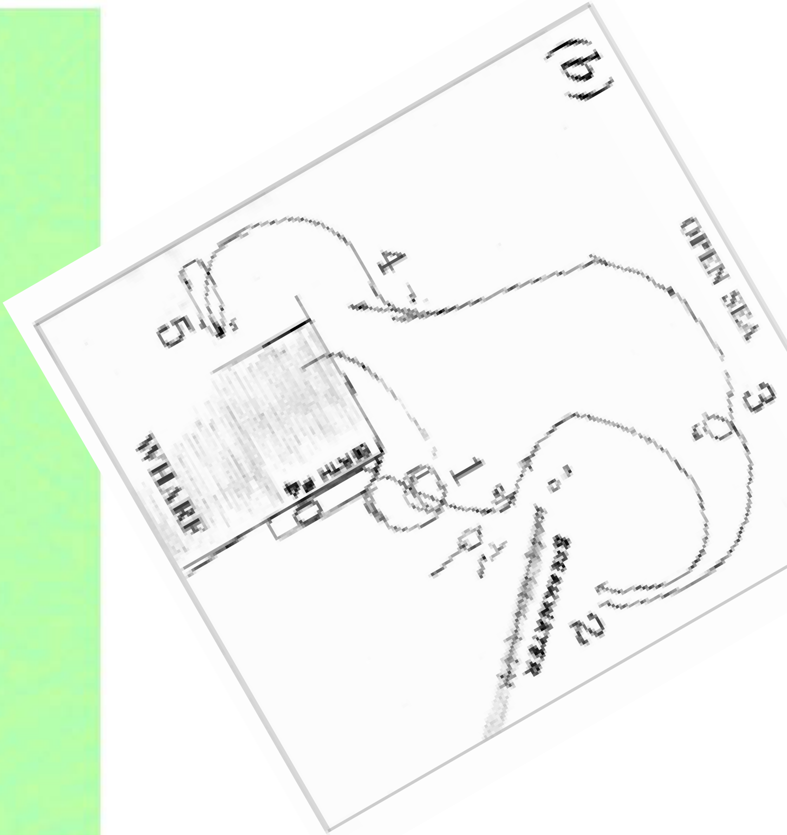
Elapsed Time=401min

Oman Salalah Harbor Grid - 5th Layer Boussinesq: FSE

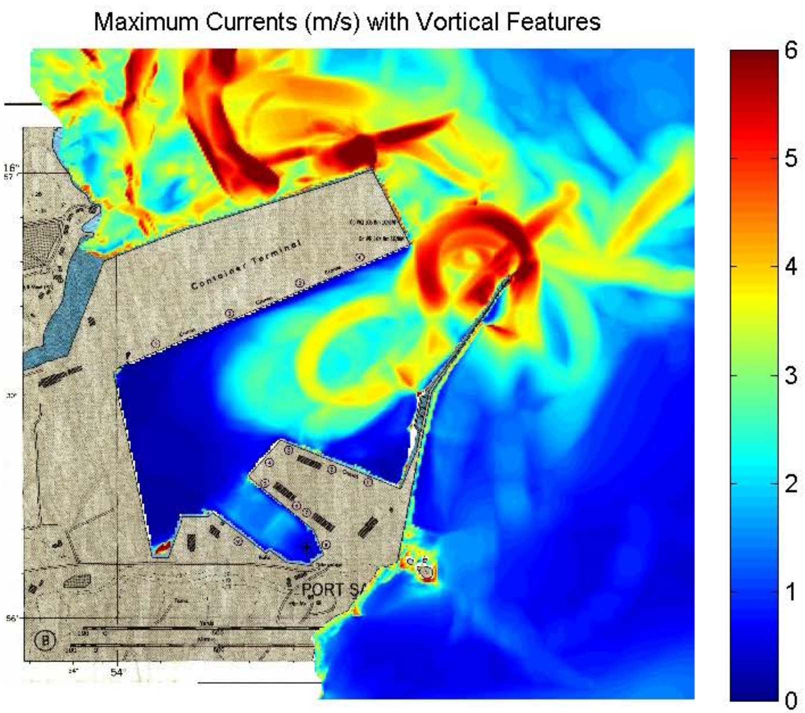
Harbor Studies

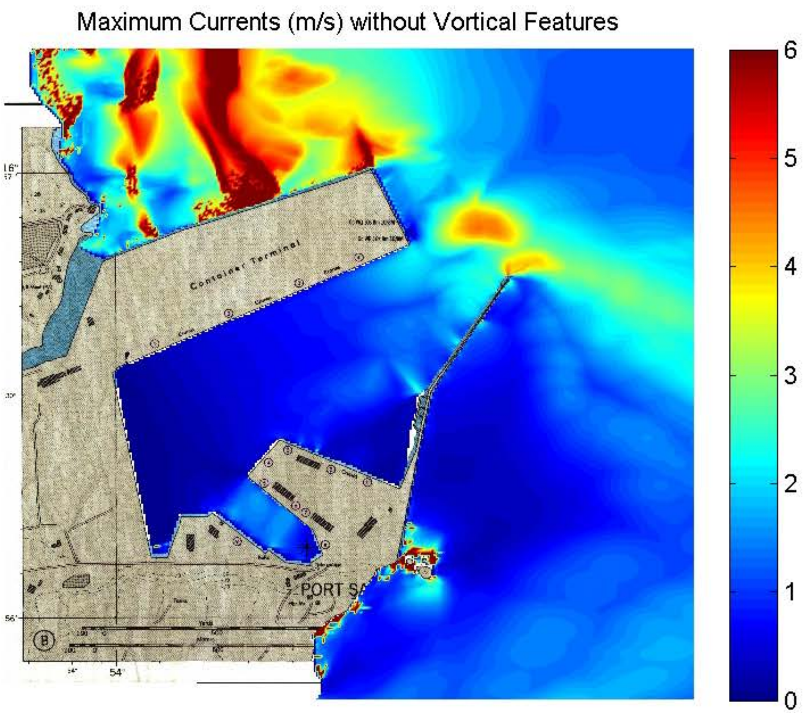
Elapsed Time=399min

Oman Salalah Harbor Grid - 5th Layer Boussinesq: Vorticity



Harbor Studies



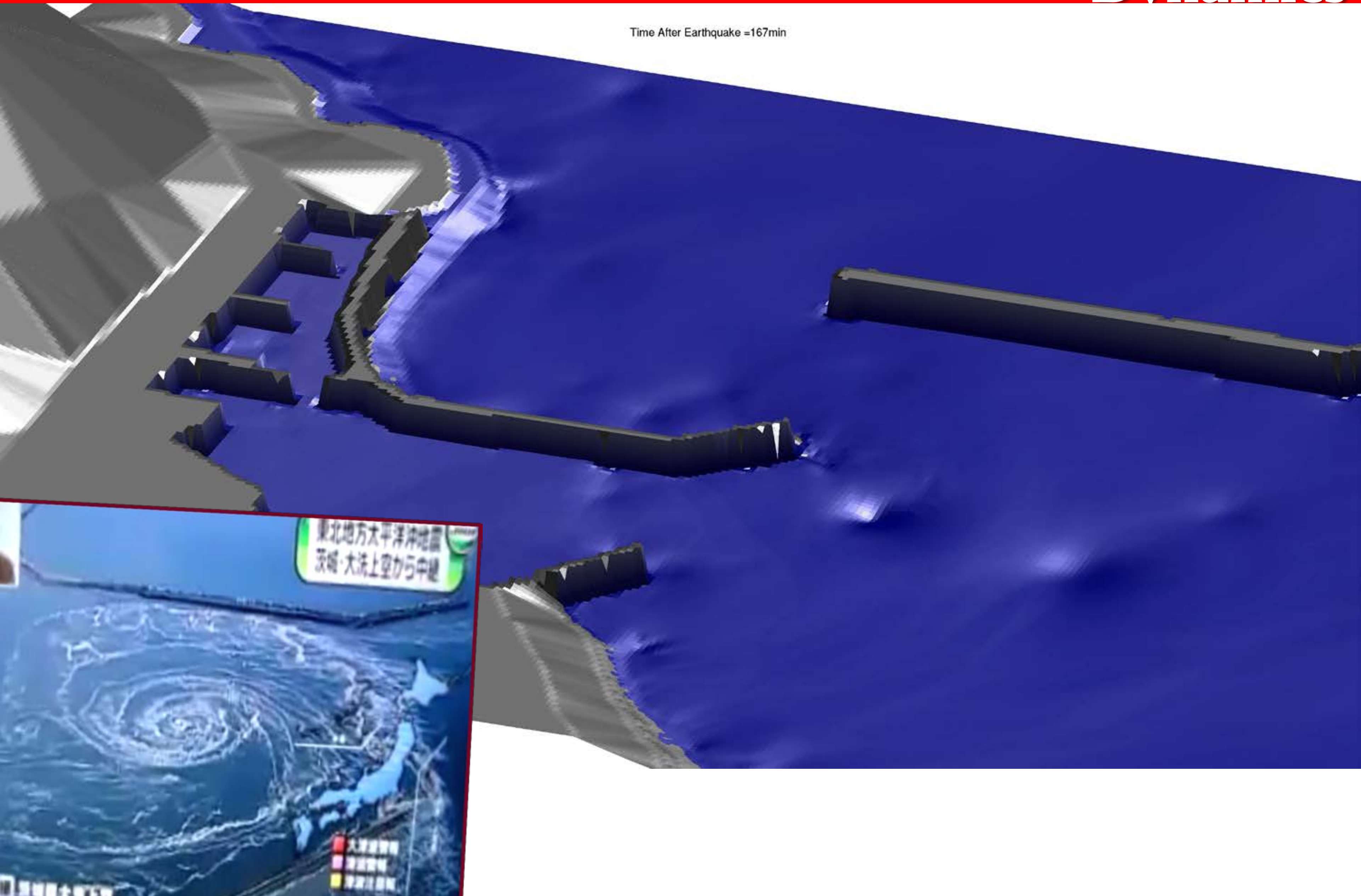


Upwind differencing in low-order NLSW model leads to numerical diffusion=

$$(1-Cr)\frac{u\Delta x}{2}\frac{\partial^2 u}{\partial x^2} = \nu_{num}\frac{\partial^2 u}{\partial x^2} \qquad \text{with Cr} \sim 0.5,\ \text{u} \sim 1\text{-}5\text{m/s},\ \Delta\text{x} \sim 10\text{m},\ \nu_{num} \sim 10\, {}^{m^2}\!/_{s}$$

- ✓*Shear layers are numerically damped (eddies can't generate)*
- ✓*Any generated eddies are quickly diffused*

Applications: Turbulent, Tsunami-Induced Harbor Dynamics



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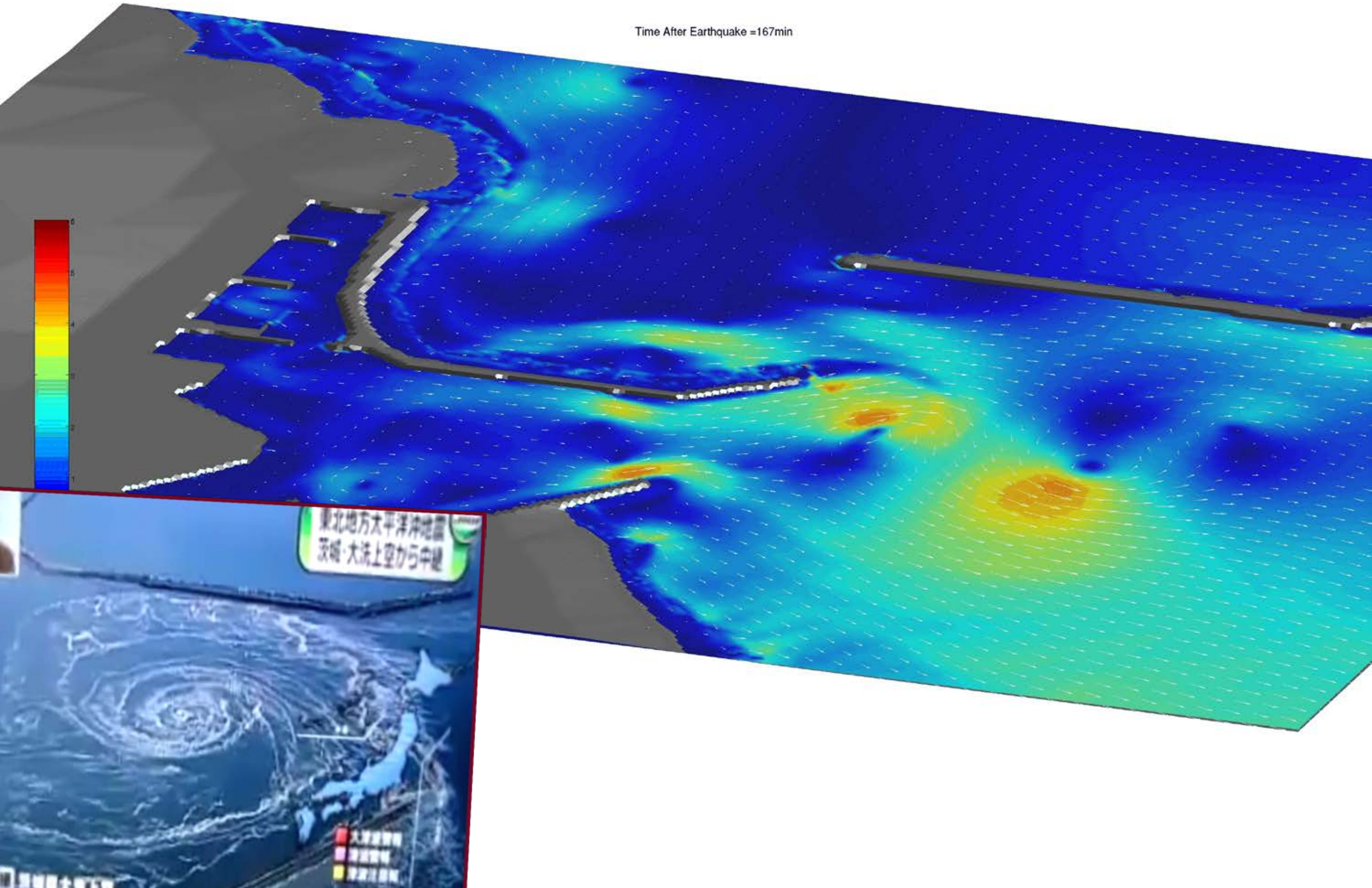
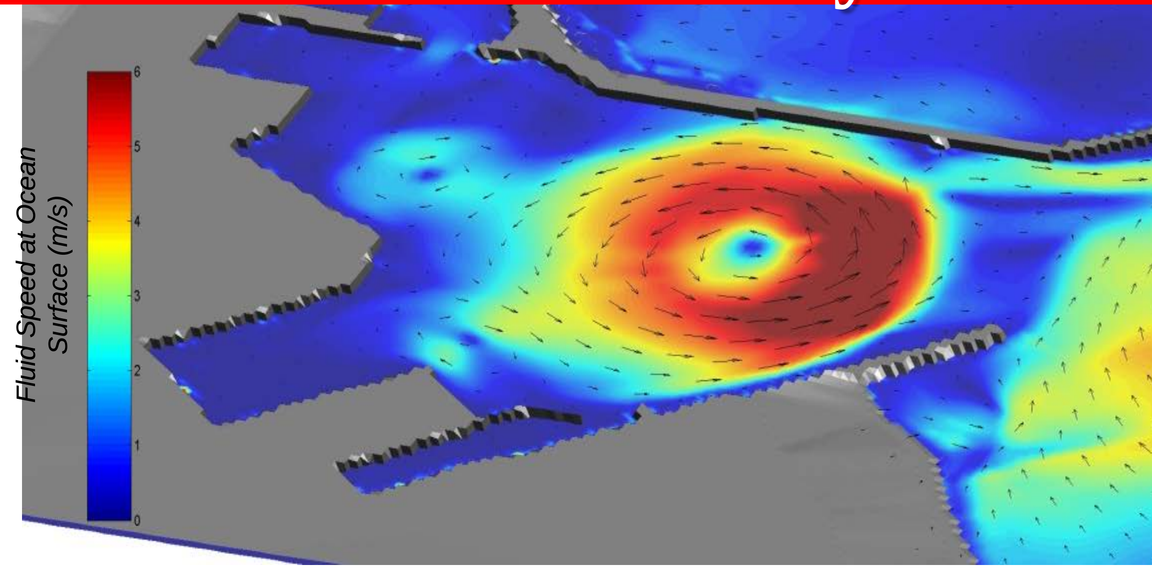
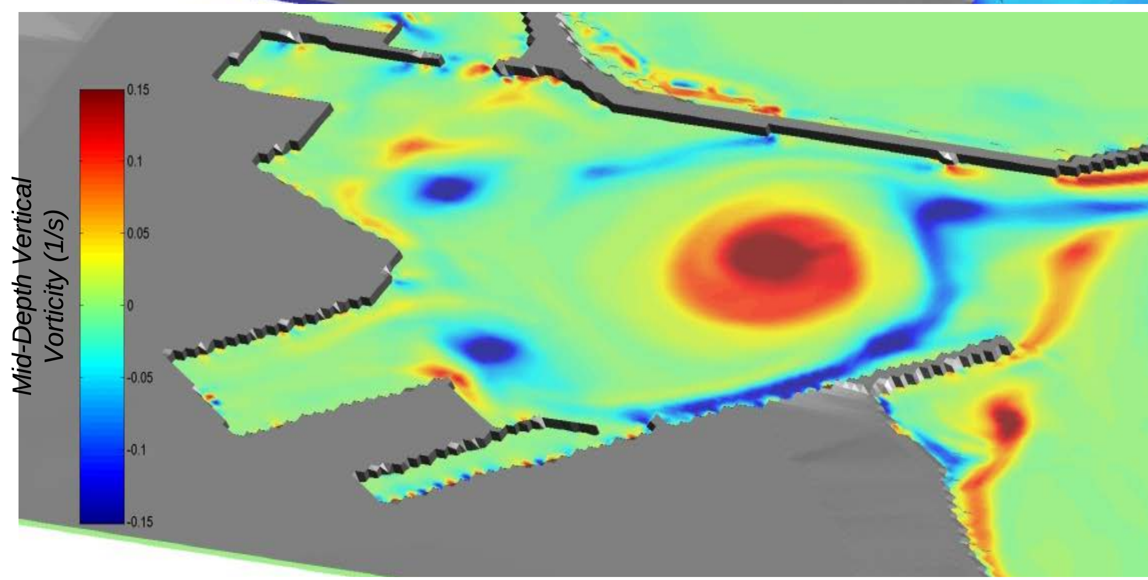


Applications: Turbulent, Tsunami-Induced Harbor Dynamics

- *Numerical simulation results of the 2011 Japan tsunami, with a focus on the predictions in the Port of Oarai.*
- *Snapshots are from 188 minutes after the earthquake.*





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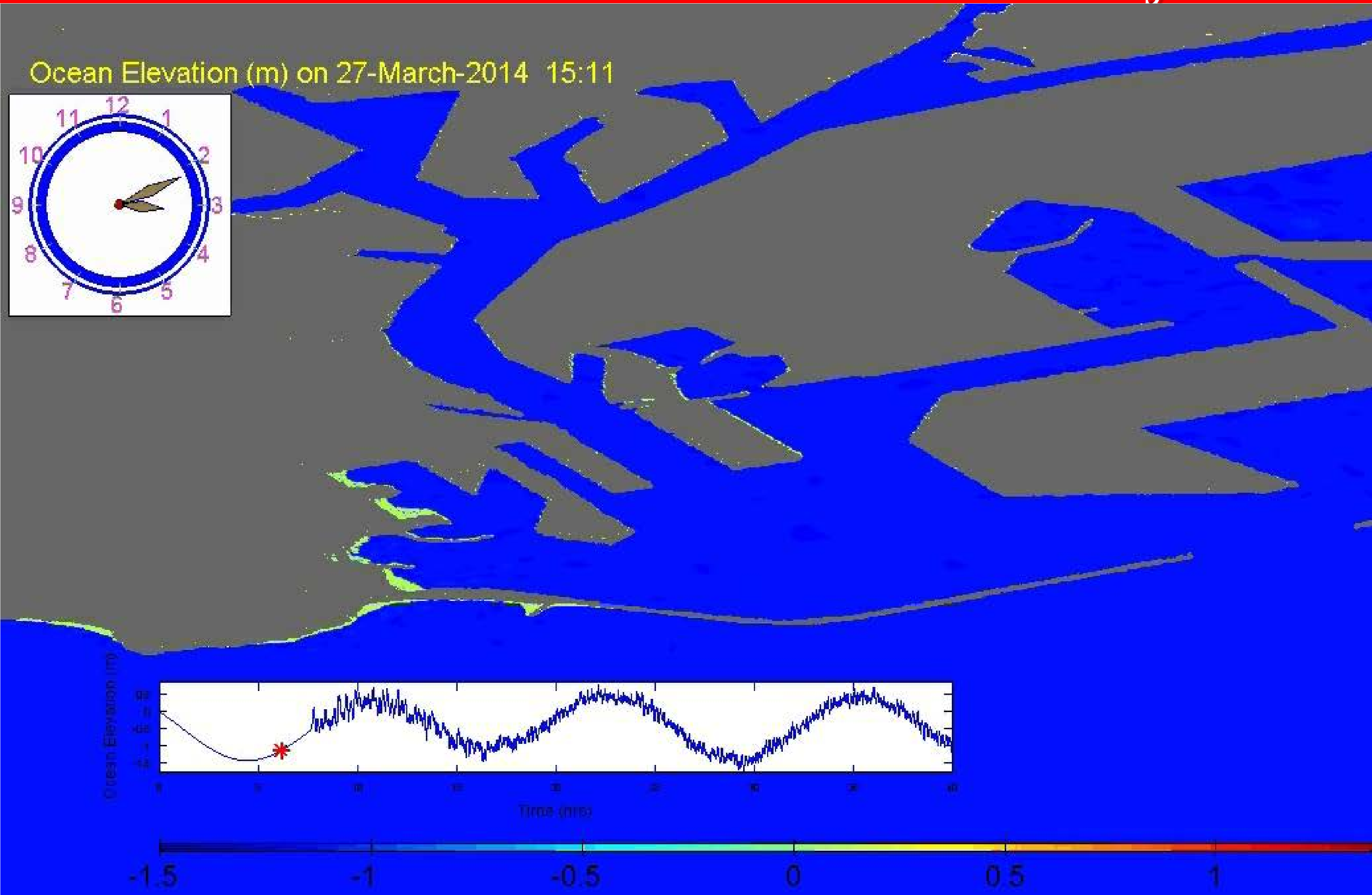

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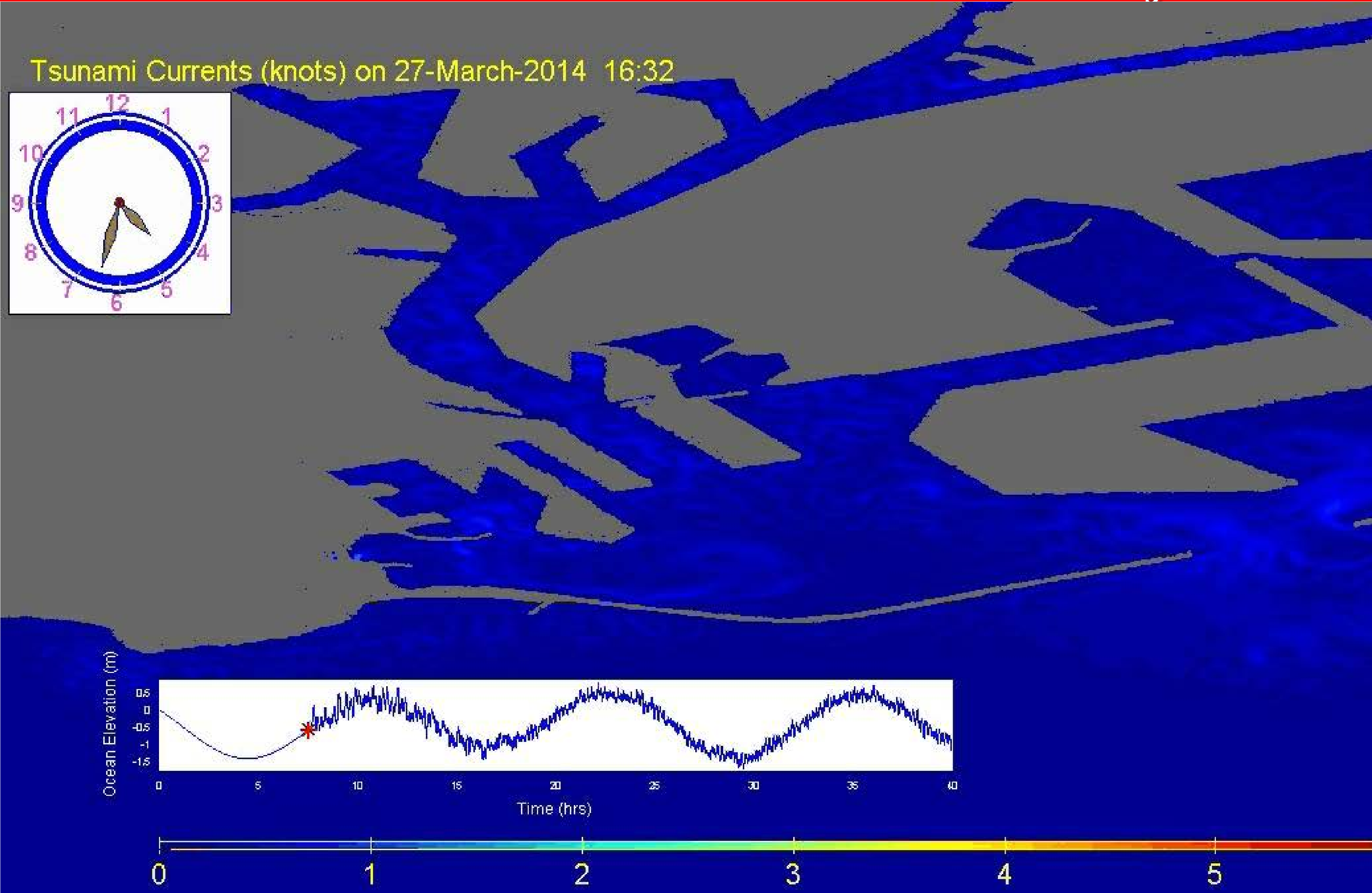

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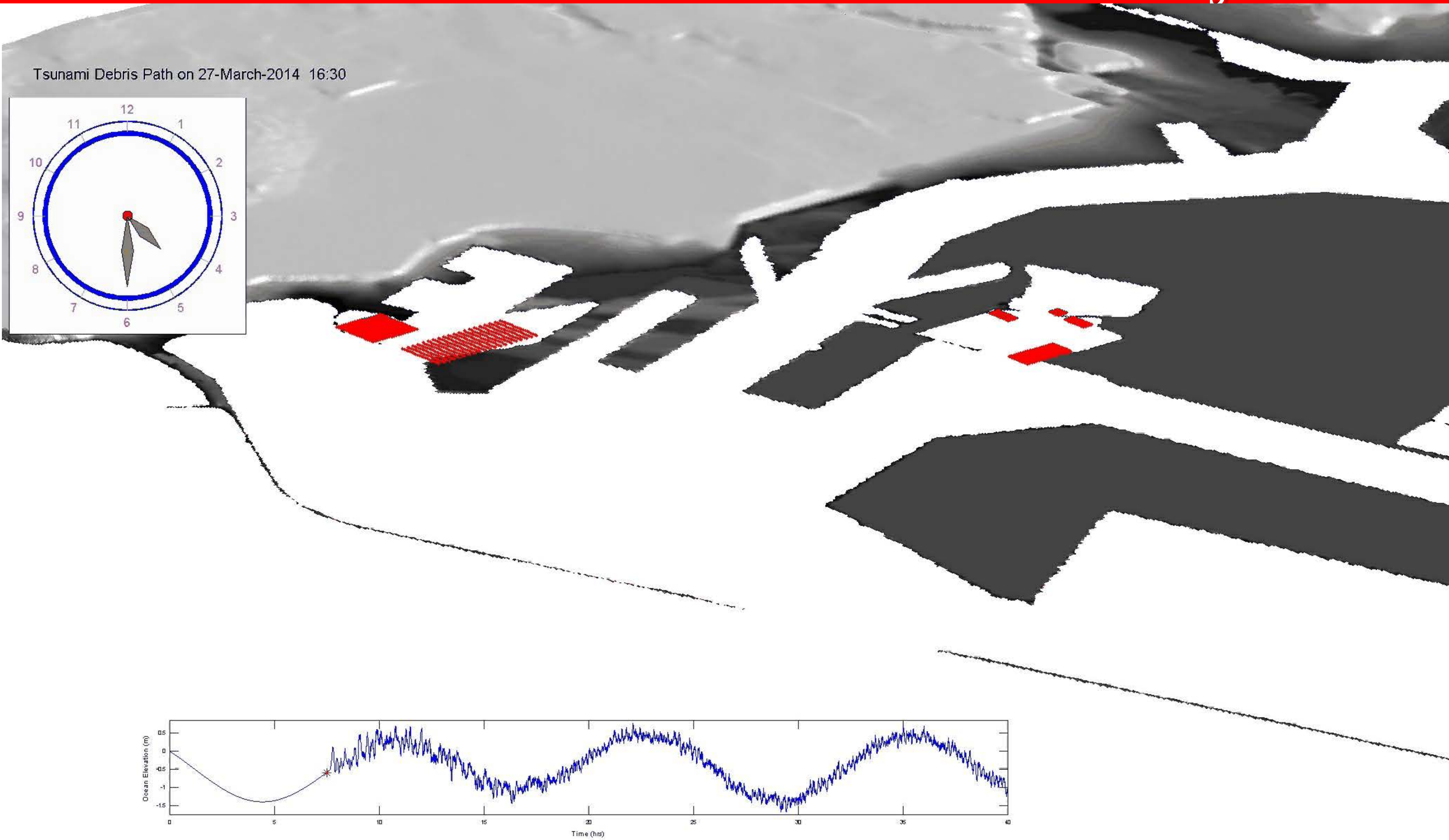
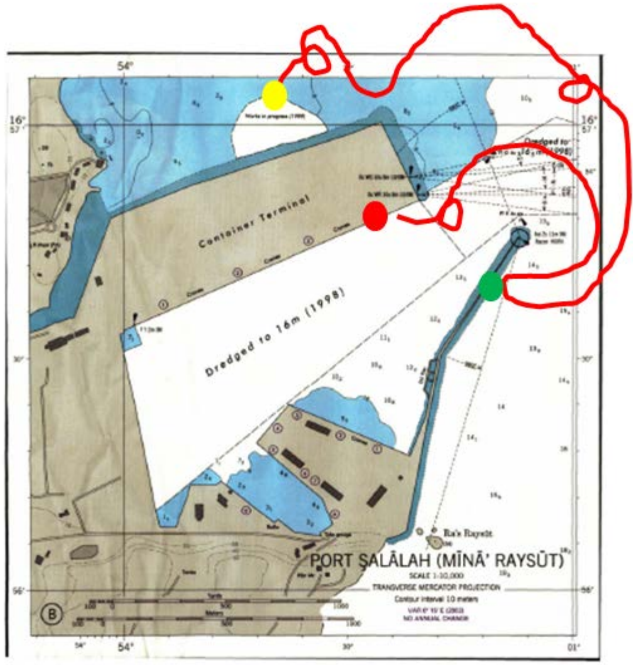
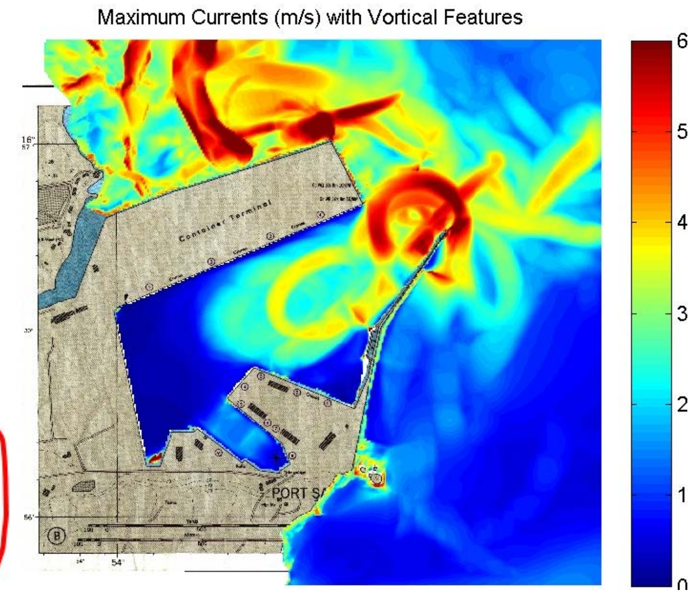


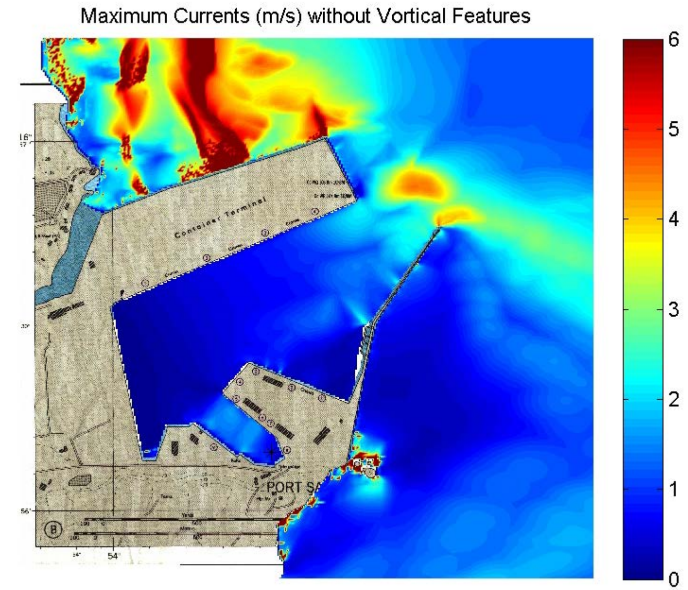
Applications: Turbulent, Tsunami-Induced Harbor Dynamics

*Tsunami harbor effects include geometric amplification, resonance, **large eddy creation***

- *Even when tsunami is “small” (~1 m), generated currents can be strong enough to break lines*
- *Turbulent structures, sensitive to precision of incident wave form, bathy/topo, etc.*
- *Deterministic approach?*

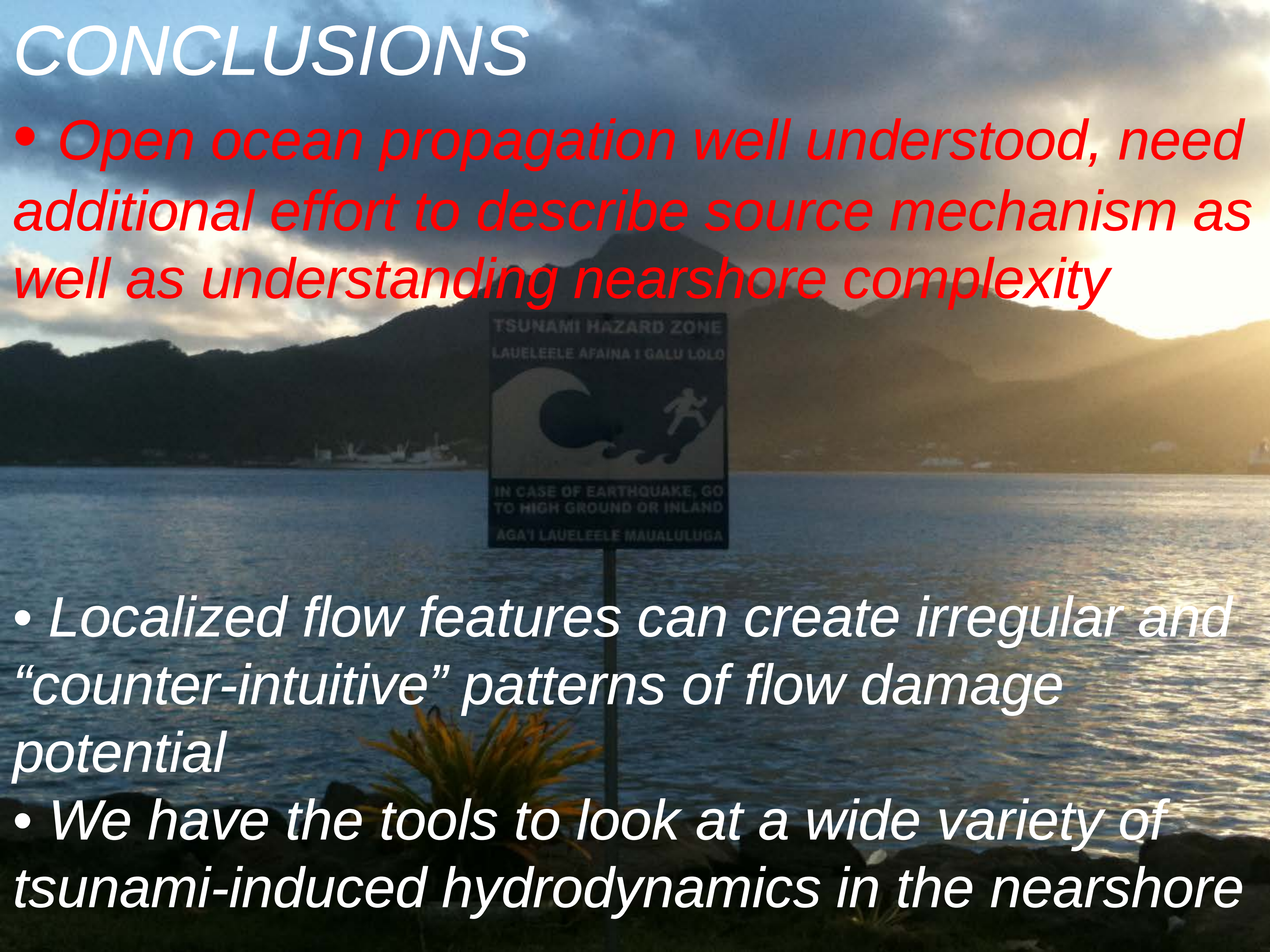






CONCLUSIONS

- *Open ocean propagation well understood, need additional effort to describe source mechanism as well as understanding nearshore complexity*



- *Localized flow features can create irregular and "counter-intuitive" patterns of flow damage potential*
- *We have the tools to look at a wide variety of tsunami-induced hydrodynamics in the nearshore*