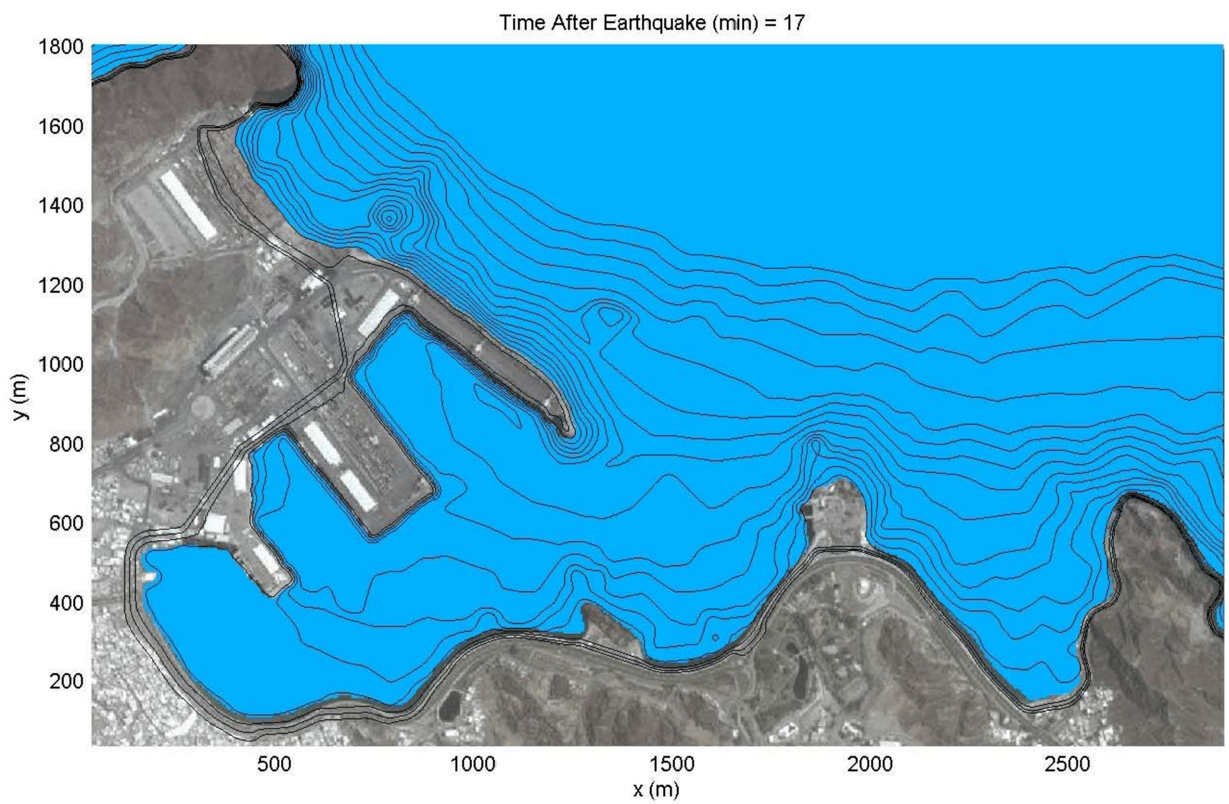
Inclusion of Viscous Effects in Long Wave Models: Tsunami-Induced Shallow Rotational Structures in Ports and Harbors



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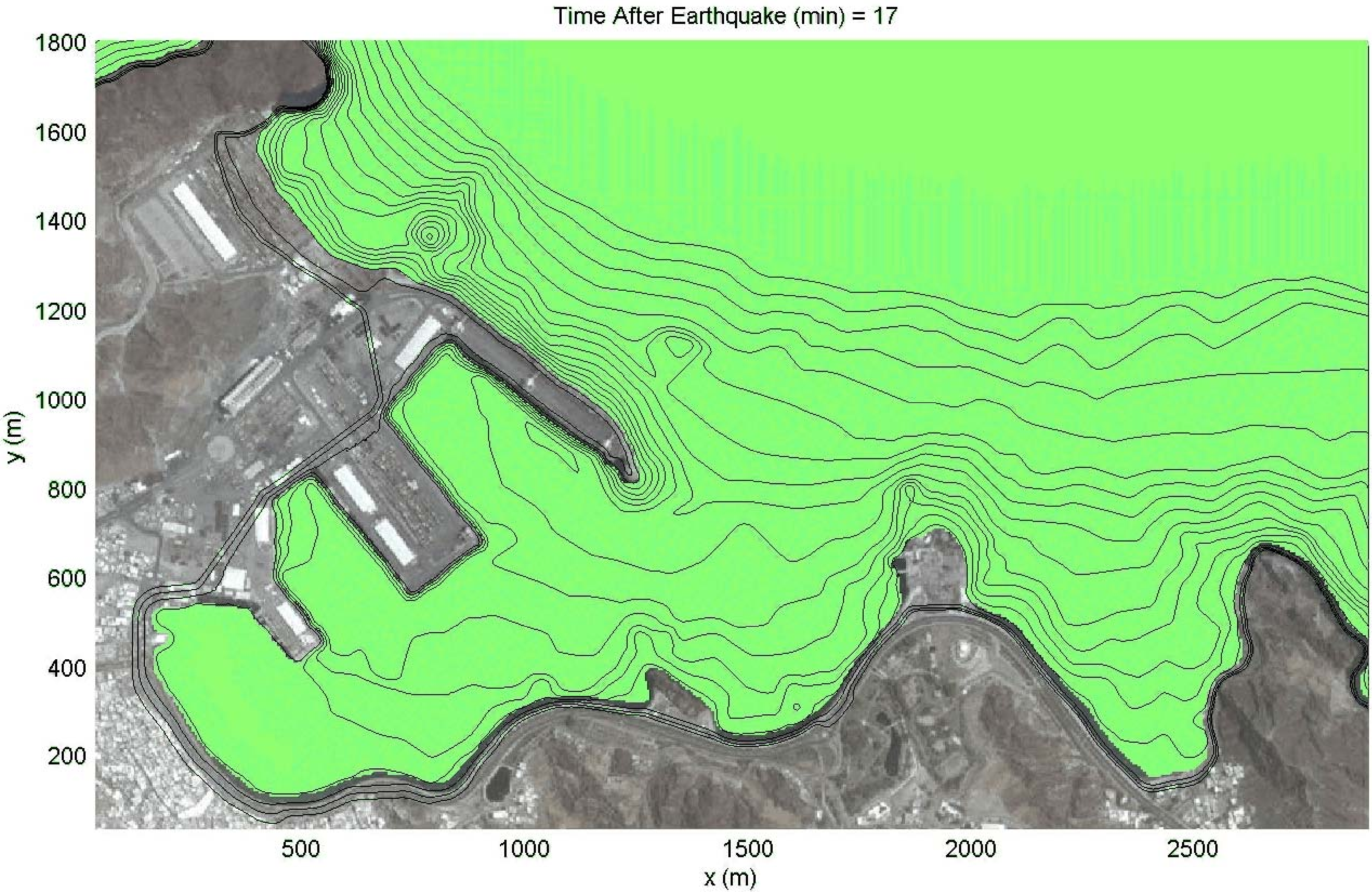

Time After Earthquake (min) = 17
1800
1600
1400
1200
1000
800
600
400
200
y (m)
500
1000
1500
2000
2500
x (m)

Outline & Approach

- *Review recent tsunami events, with a focus on damage in ports*
- *Turbulent "extensions" to the depth-integrated modeling theory*
- *Model development & application to tsunami simulation*

➢ *Even when tsunami is "small" (~1 m), and the port remains "dry", significant damage is possible*

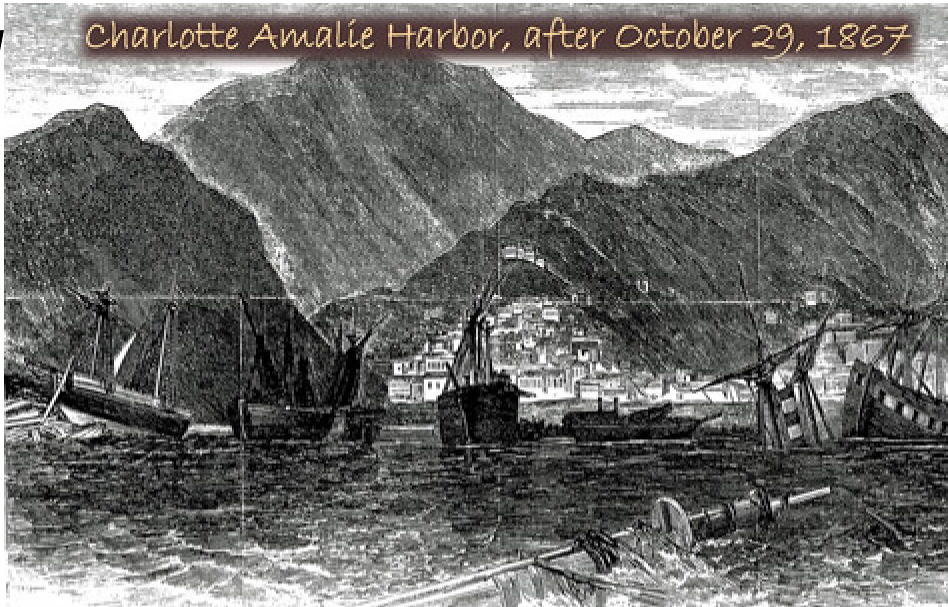
  - *Strong, erratic currents*
  - *"Large particle" transport*

➢ *Localized and extreme currents generated through eddies (gyres, whirlpools)*

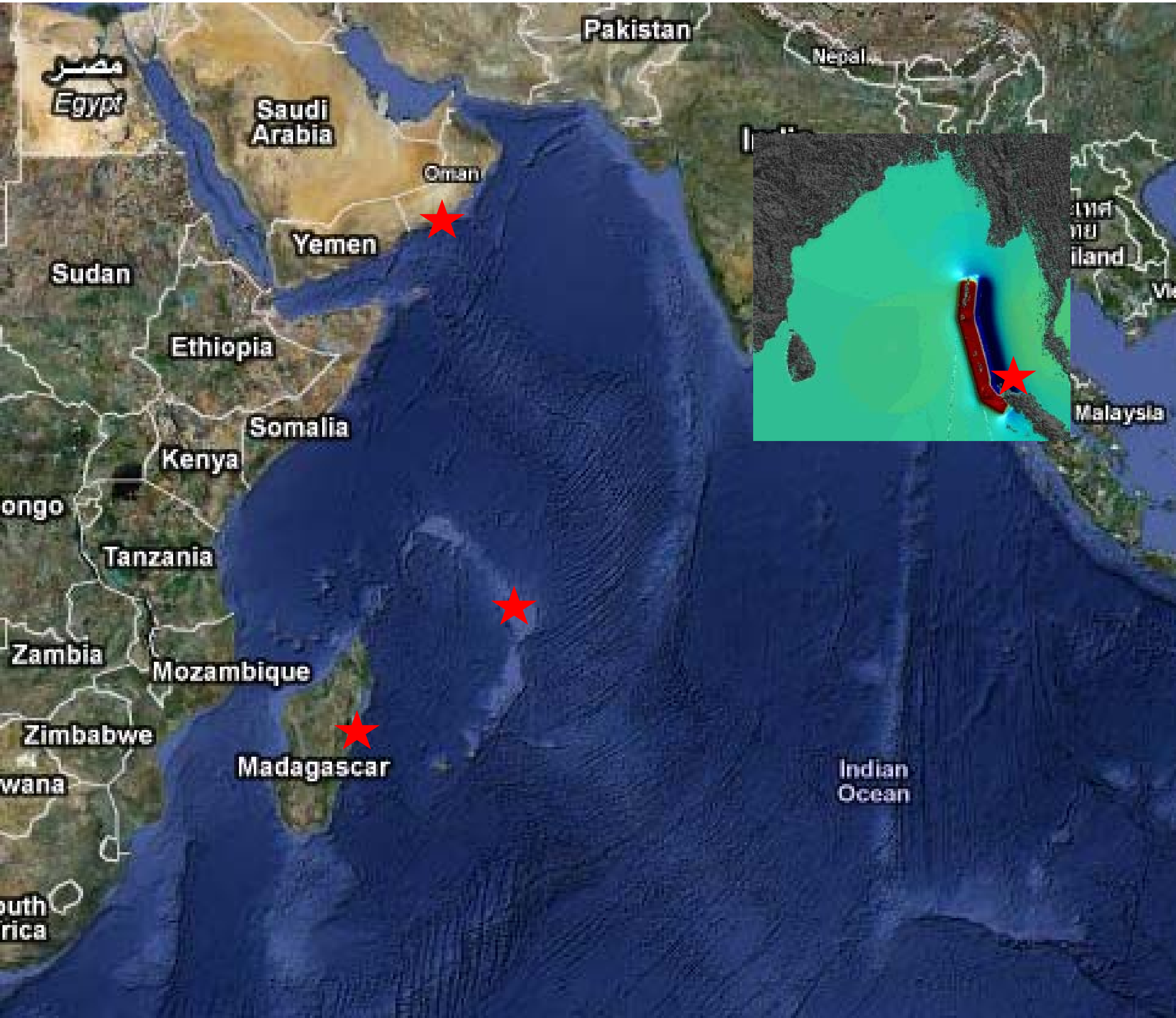
Historical Events

- *A 1867 earthquake in the Lesser Antilles caused extreme damage in many Caribbean ports (Reid and Taber, 1920)*
- *In the Port of Saint Thomas, Admiral J. S. Palmer, Commander of the U.S. Navy North Atlantic Squadron, was on board the U.S.S. Susquehanna noted the formation of a large whirlpool in the center of the bay, pulling floating debris towards it*
  - *Dropped a 2nd anchor; anchors held*

•*The U.S.S. DeSoto, captained by W. H. Boggs, was spun around 20 times in the receding waves, until finally settling in the large grye in the center of bay, spinning slowly for hours.*



Recent Events & Observations

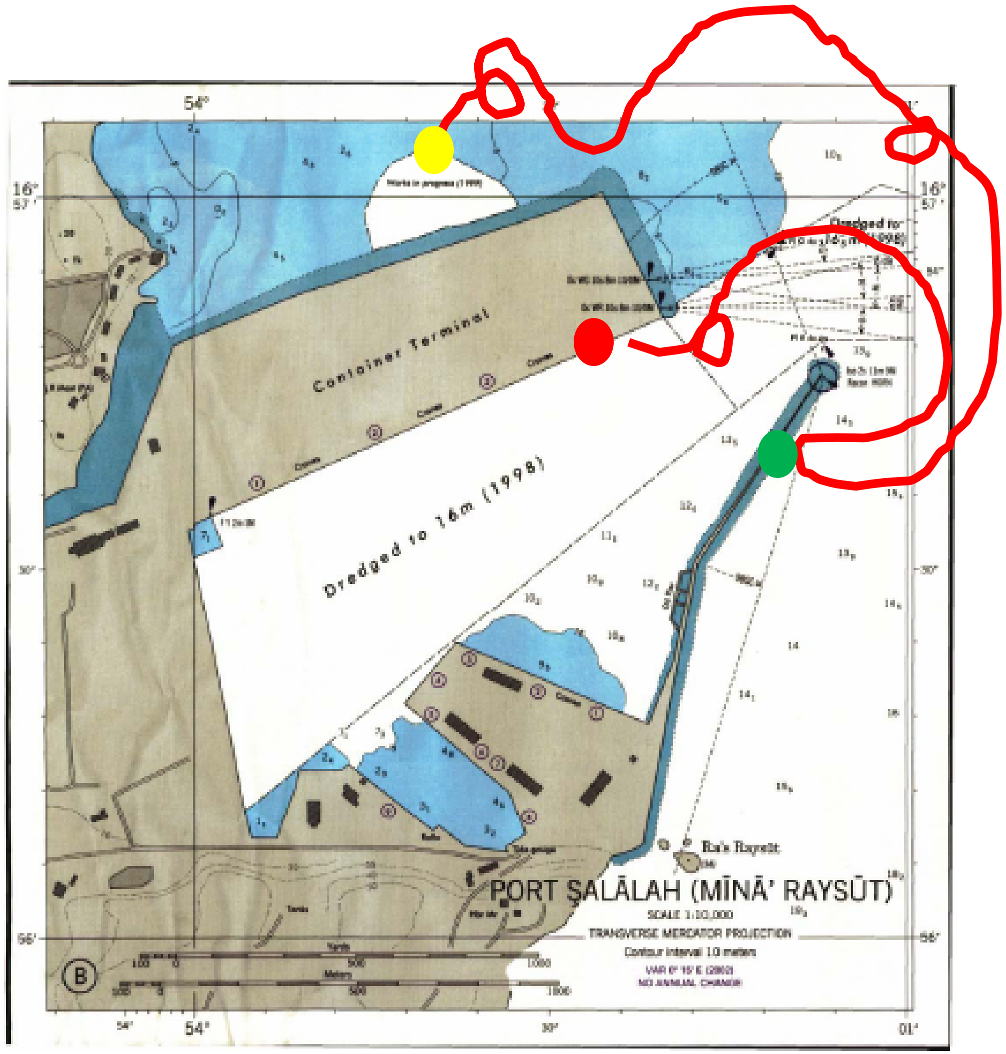


2004 Indian Ocean Tsunami

- *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

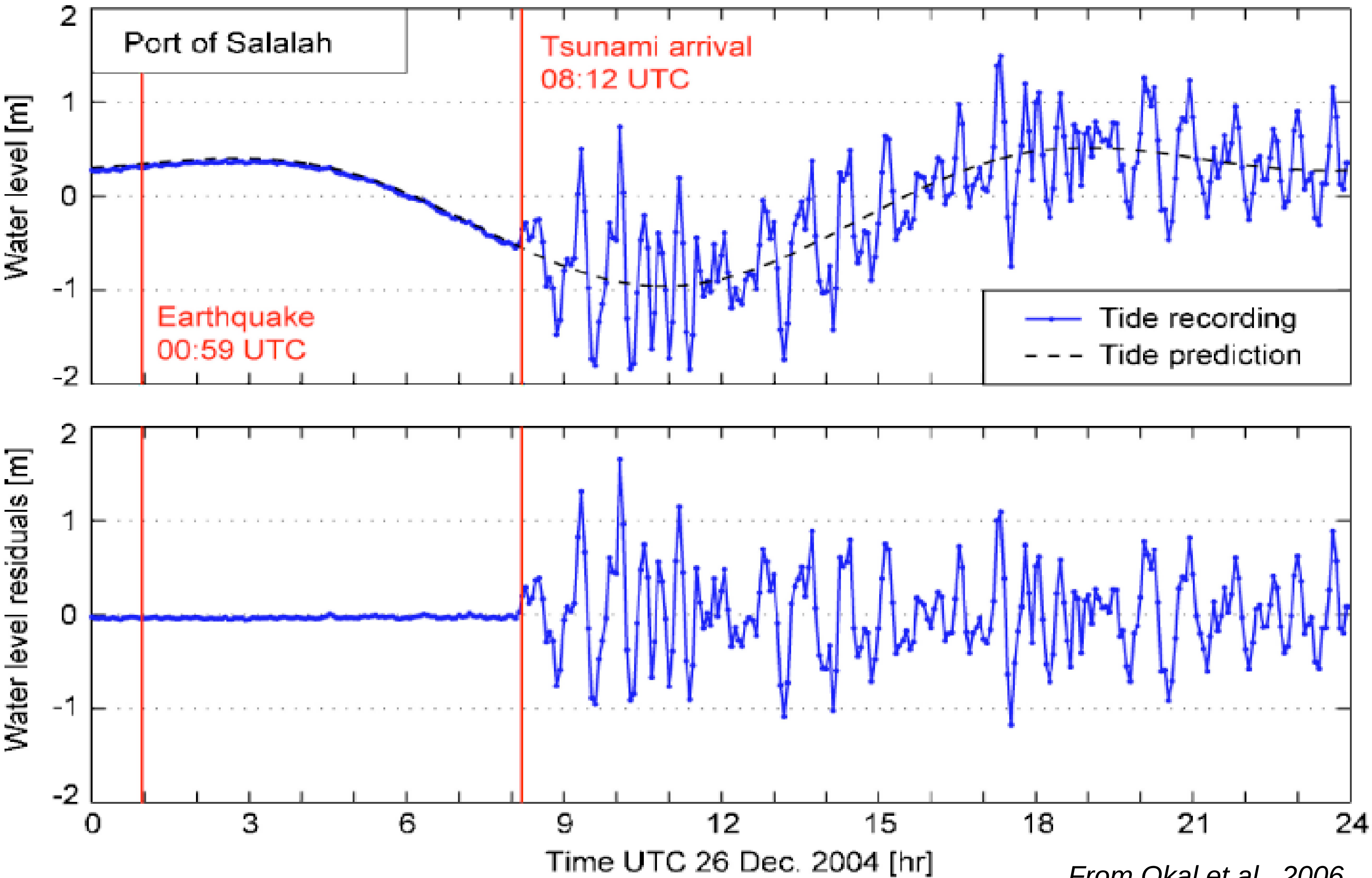
Port Salalah, Oman



285-m container ship Maersk Mandraki

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

Motivation:
Recent Events & Observations



From Okal et al., 2006

Recent Events & Observations

Le Port, Réunion

196-m container ship MSC Uruguay

From Okal et al., 2006

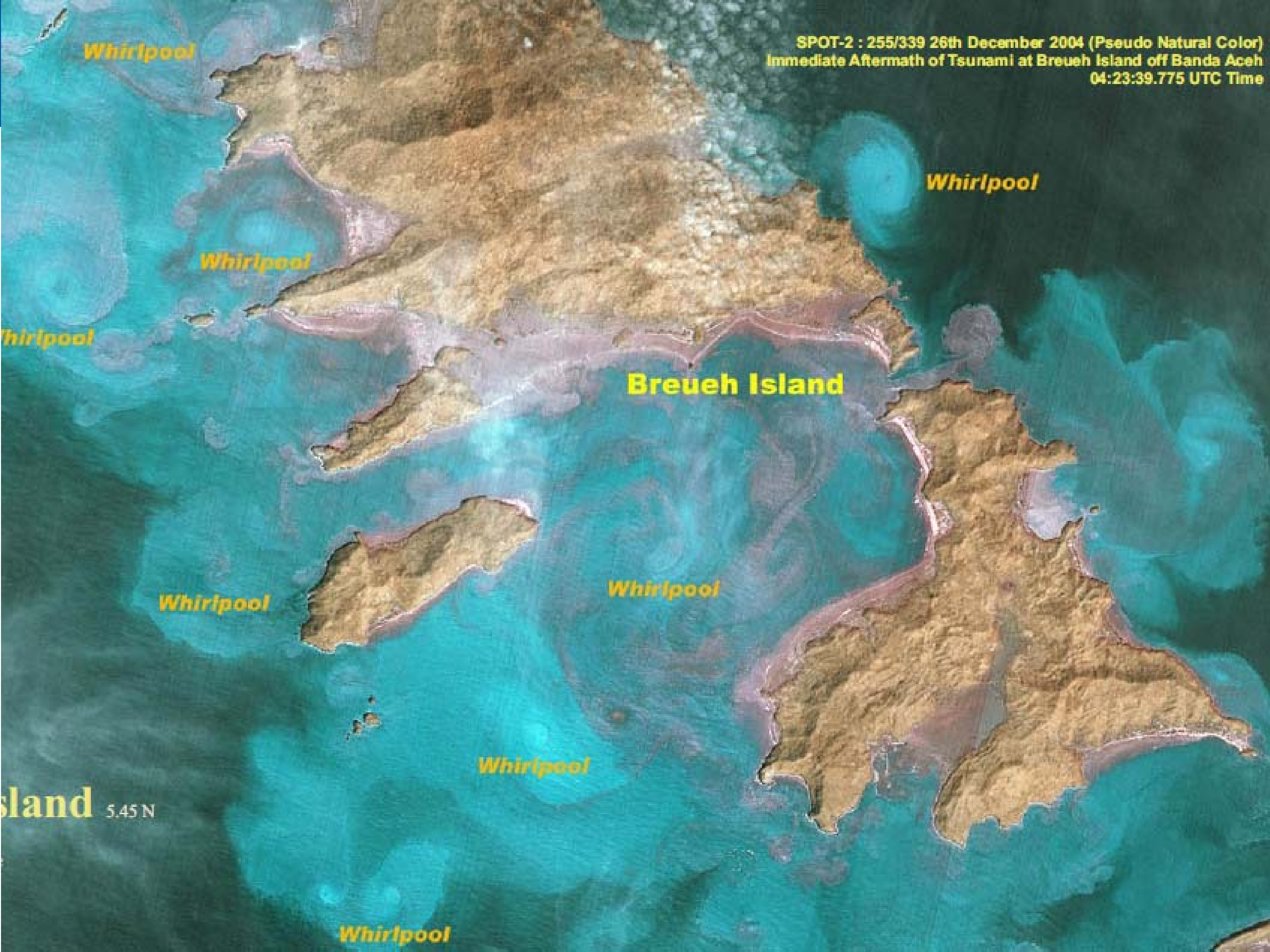
- *Broke all 12 of its hawsers, began drifting*
- *Drifted for 2 hours, striking & damaging gantry cranes*
- *Port crews re-secured moorings lines ~ 3 hours later, only to have them break again*

Recent Events & Observations

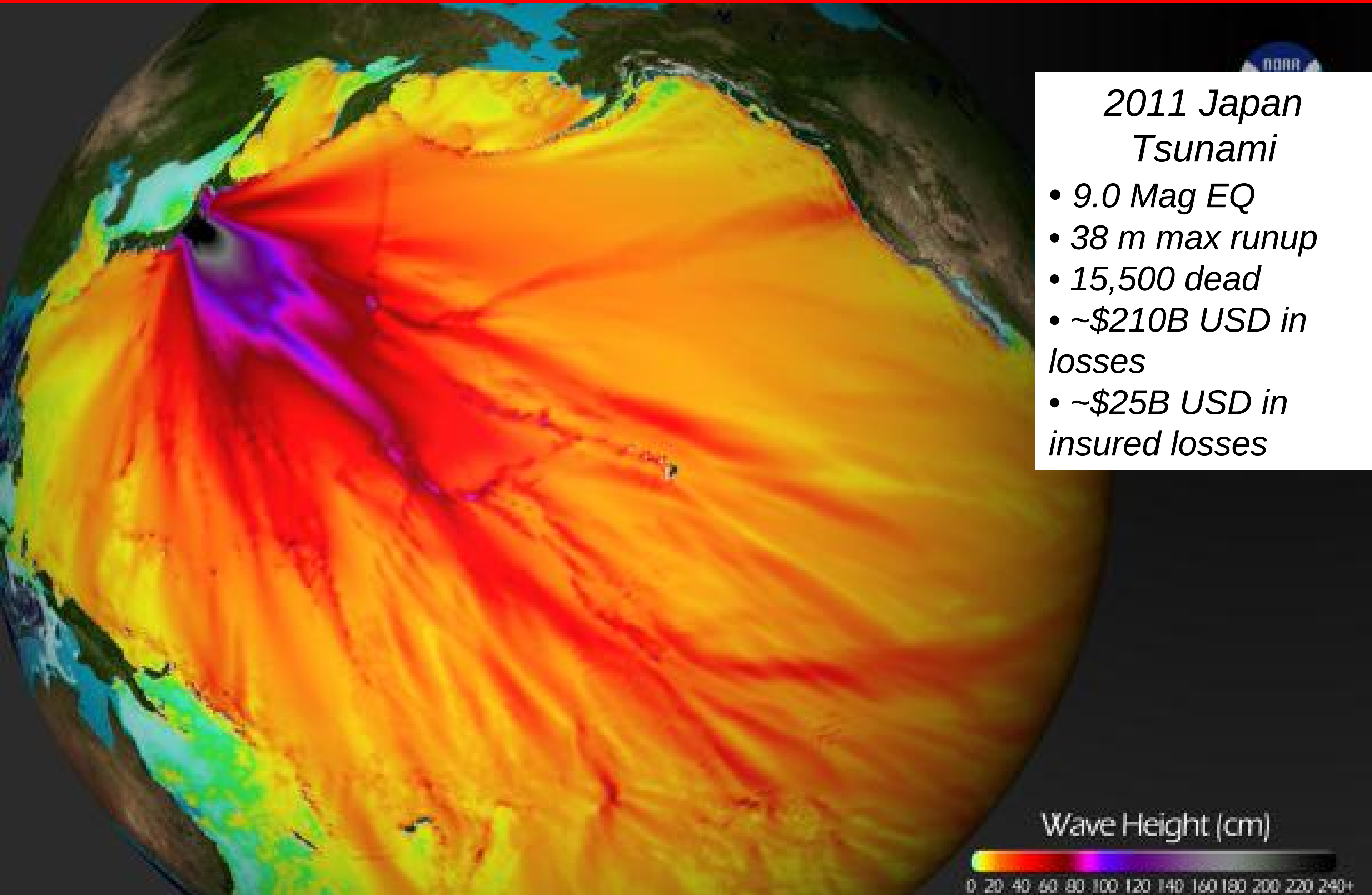
50-m freighter Soavina III

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*


SPOT-2 : 255/339 26th December 2004 (Pseudo Natural Color)
Immediate Aftermath of Tsunami at Breueh Island off Banda Aceh
04:23:39.775 UTC Time
Whirlpool
Whirlpool
Whirlpool
hirlpool
Breueh Island
Whirlpool
Whirlpool
Whirlpool
sland
5.45 N
Whirlpool

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

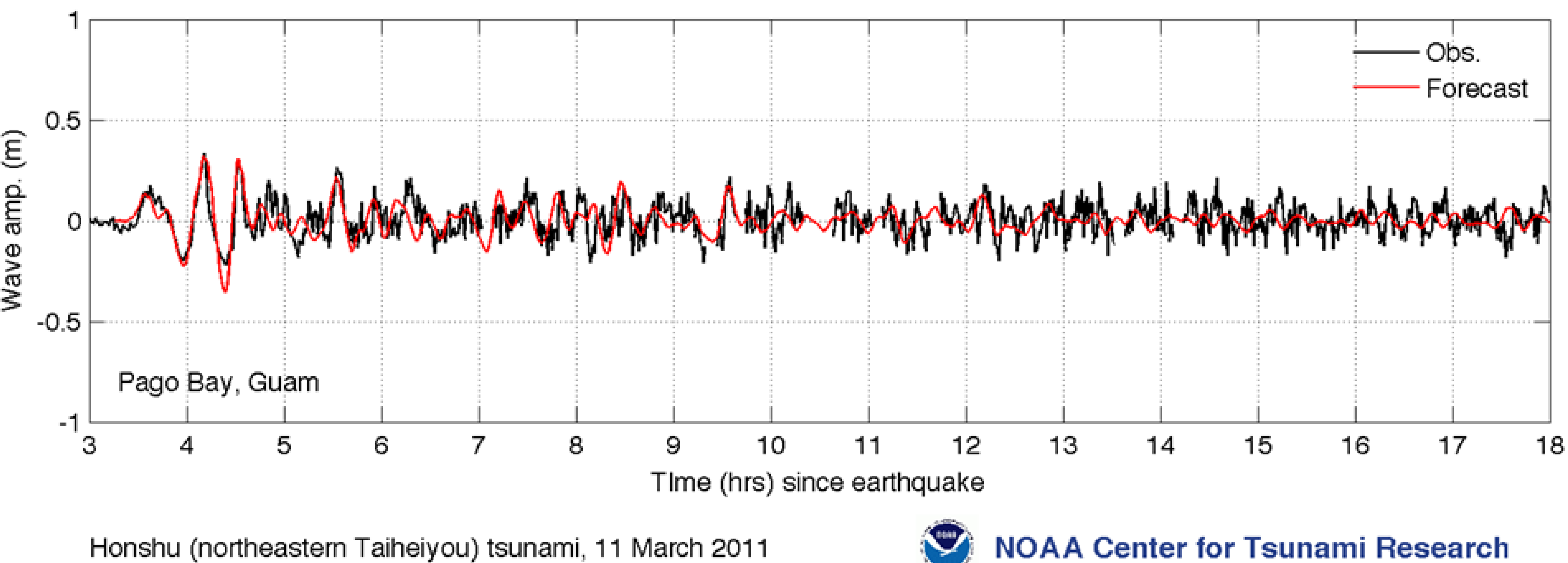
2011 Japan Tsunami

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

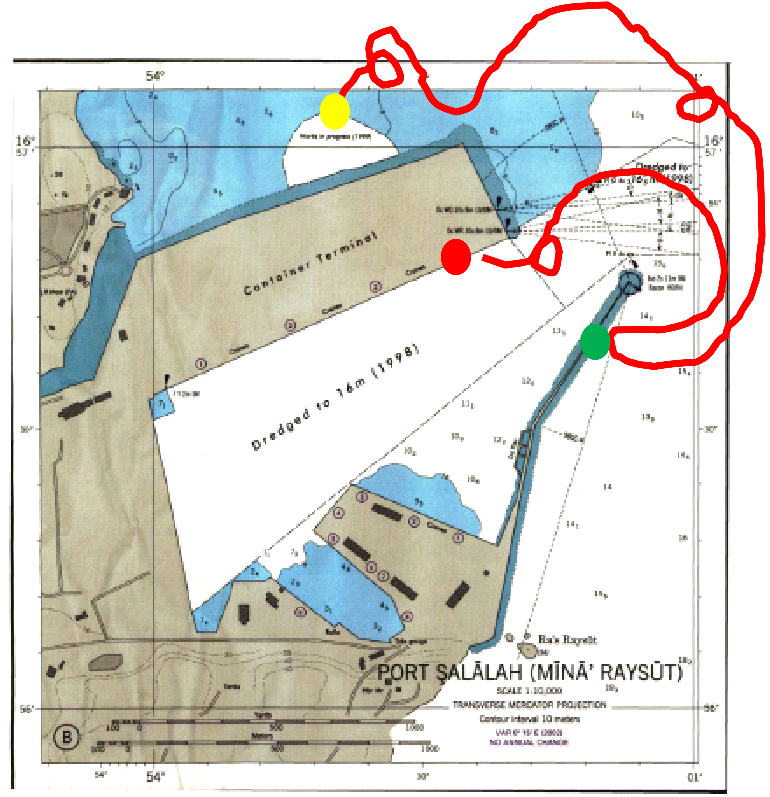
Recent Events & Observations

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

Recent Events & Observations

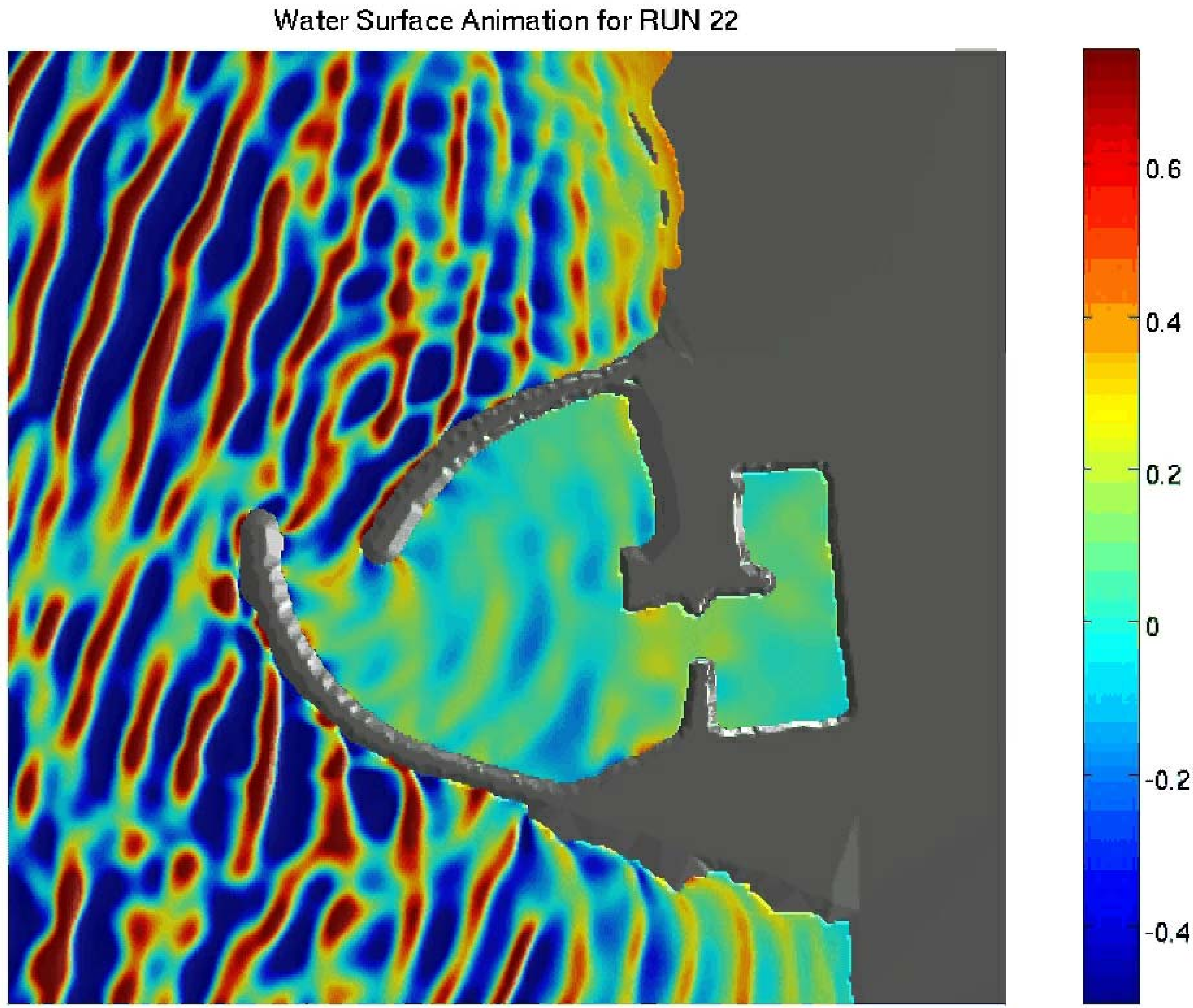


2011 Japan Tsunami
*In Guam, two nuclear submarines (*USS Houston and USS City of Corpus Christi) broke free of moorings


Container Terminal
Dredged to 16m (1998)
Ra's Raysūt
PORT SALALAH (MĪNĀ' RAYSŪT)
SCALE 1:10,000
TRANSVERSE MERCATOR PROJECTION
Contour interval 10 meters


bean' Ny Tanana Mikambana

Traditional Boussinesq Applications



Viscous-driven Vertical Structure in the Boussinesq-type Model

- $$\omega = \omega_o + \mu^2 \omega_1 + \mu^4 \omega_2 + \cdots$$

$$= \frac{\partial U_o}{\partial z} + \mu^2 \left(\frac{\partial U_1}{\partial z} - \frac{\partial W_o}{\partial x} \right) + \cdots$$

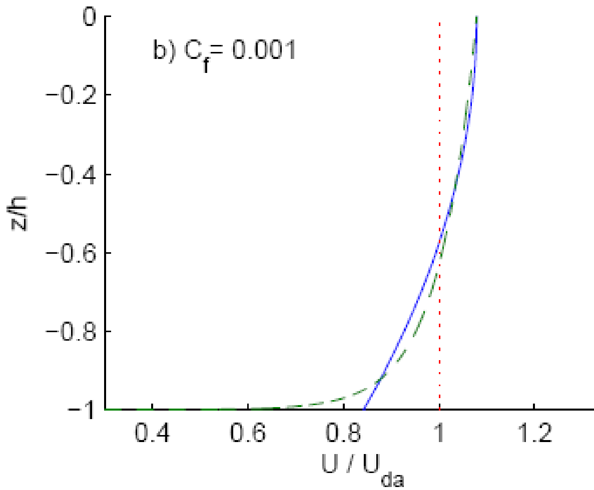
- $$\boldsymbol{U}_1 = -\frac{1}{2} z^2 \nabla S - z \nabla T + \frac{1}{2} h^2 \nabla S - h \nabla T \boxed{+ \int_{-h}^{z} \boldsymbol{\omega}_1 dz}$$

- $$\boldsymbol{\omega}_1 = \frac{\partial \boldsymbol{U}_1^r}{\partial z} = \frac{\boldsymbol{\tau}_b}{\nu_t^v} \frac{\zeta - z}{\zeta + h}$$

Linear shear distribution e.g. ***Rodi*** (1980)

$$\boldsymbol{U} = \boldsymbol{U}_\alpha + \mu^2 \boldsymbol{U}_1^\phi + \beta \mu \boldsymbol{U}_1^r + O\left(\mu^4, \beta^2 \mu^2\right)$$

$$\boldsymbol{U}_1^r = \int_{z_\alpha}^{z} \boldsymbol{\omega}_1 dz = \frac{\boldsymbol{\tau}_b}{\nu_t^v (\zeta + h)} \left\{ \frac{1}{2} \left(z_\alpha^2 - z^2 \right) + \zeta \left(z - z_\alpha \right) \right\}$$



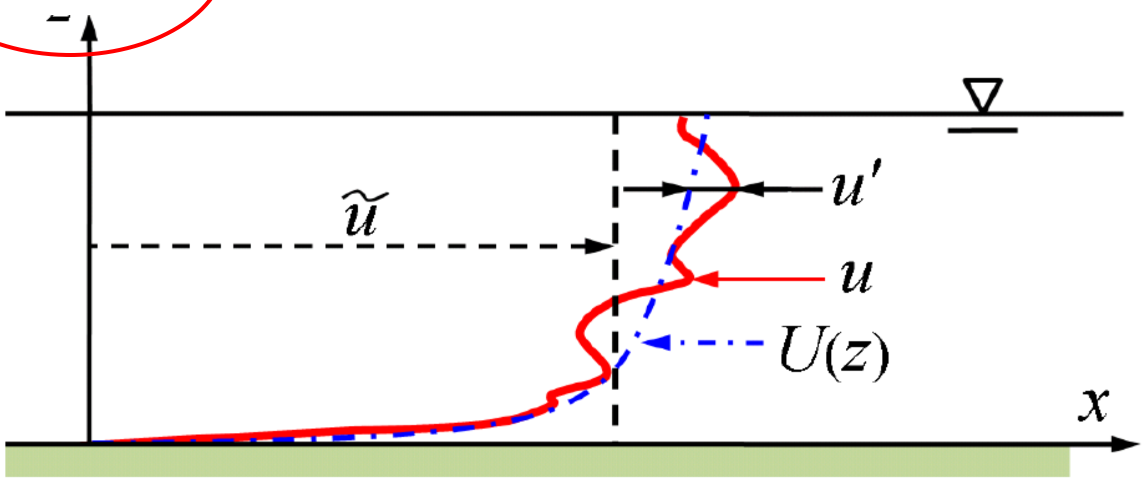
3D Turbulence Effects

- Spatially filtered N-S equations
- Depth-average

$$
\begin{aligned}
\frac{\partial H\widetilde{\overline{u}}_i}{\partial t} &+ \frac{\partial H\widetilde{\overline{u}}_i\widetilde{\overline{u}}_j}{\partial x_j} + H\widetilde{\frac{\partial \overline{p}}{\partial x_i}} \\
&= \alpha\mu\frac{\partial}{\partial x_j}\left(2H\nu_t^h\widetilde{\overline{S_{ij}}}\right) + \beta\mu^2 2\nu_t^v\frac{\partial}{\partial x_i}\left(\frac{\partial u_j}{\partial x_j}\right) + \beta\mu^2\tau_i^b \\
&+ \beta\mu^2\frac{\partial}{\partial x_j}\left(H\widetilde{\overline{u_i'u_j'}}\right)
\end{aligned}
$$

$$
F_i = C_B\frac{\sqrt{\widetilde{u}^2+\widetilde{v}^2}}{H}\sqrt{\frac{\nu\sqrt{c_f}}{\Delta t}}r_i
$$

Stochastic BSM by ***Hinterberger, Frohlich, Rodi*** (2007)



Inclusion of Rotational & Turbulent Effects in Depth-Integrated Models

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

$$\frac{\partial HU_i}{\partial t} + \frac{\partial HU_iU_j}{\partial x_j} + gH\frac{\partial \zeta}{\partial x_i} + H\left(D_i + \overline{\xi_i} + D_i^{\nu} + \overline{\xi_i^{\nu}}\right) + U_i\left(\mathcal{M} + \mathcal{M}^{\nu}\right)$$
$$- H\frac{\partial}{\partial x_j}\left(2\nu_t^h S_{ij}\right) + 2H\frac{\partial}{\partial x_i}\left(\nu_t^v \frac{\partial U_j}{\partial x_j}\right) + \frac{\tau_i^b}{\rho} - HF_i = 0$$

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

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

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

$O(\alpha\mu)$ 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

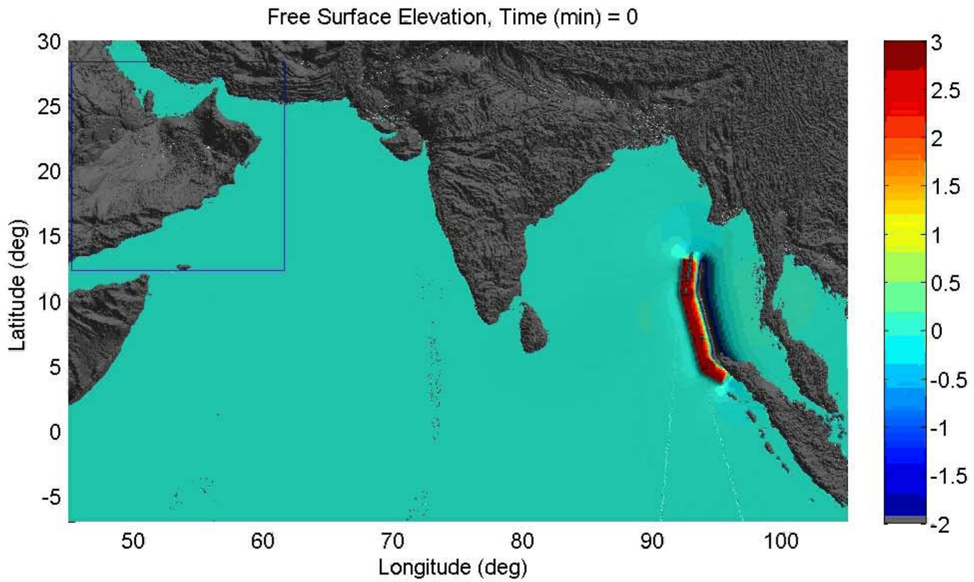
$O(\beta\mu)$ Bottom Stress, closed with Mannings, Moody, etc.

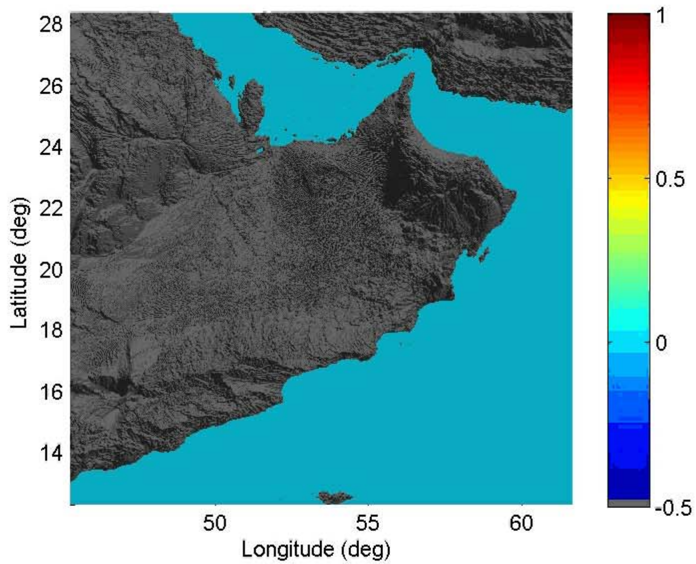
$O(\gamma)$ Depth-averaging stress terms, closed with BSM

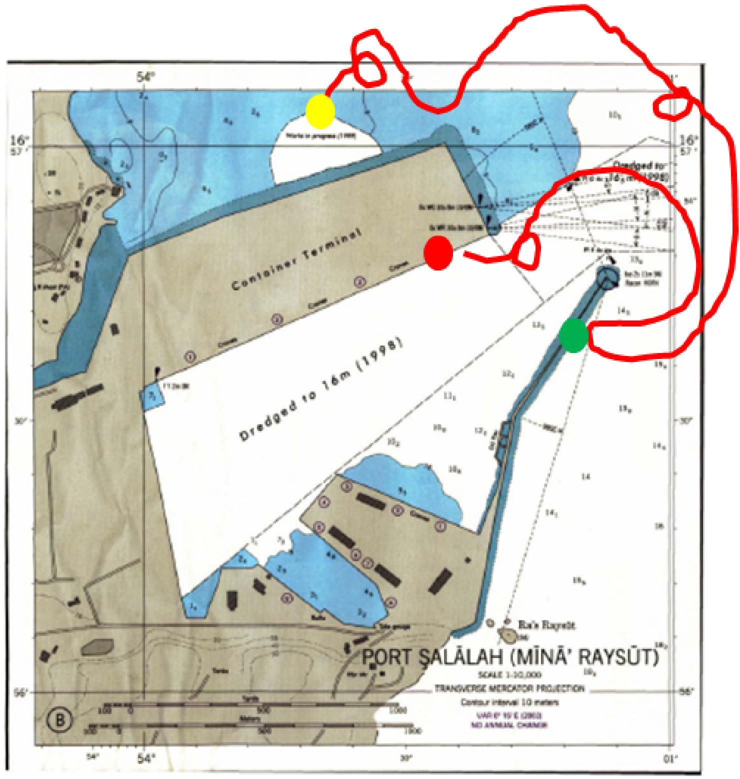
Harbor Studies

2004 Indian Ocean Tsunami

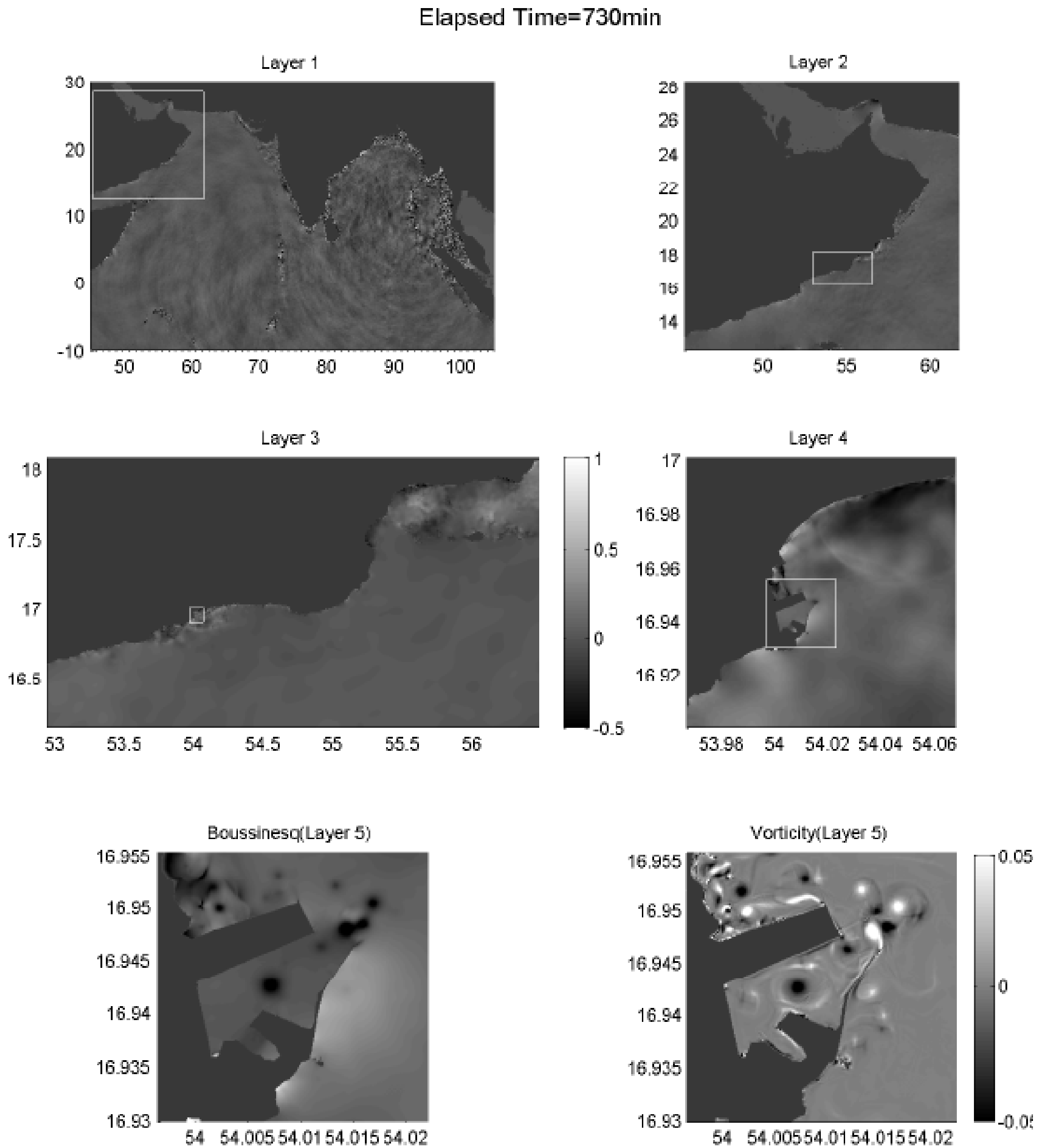
Port Salalah, Oman





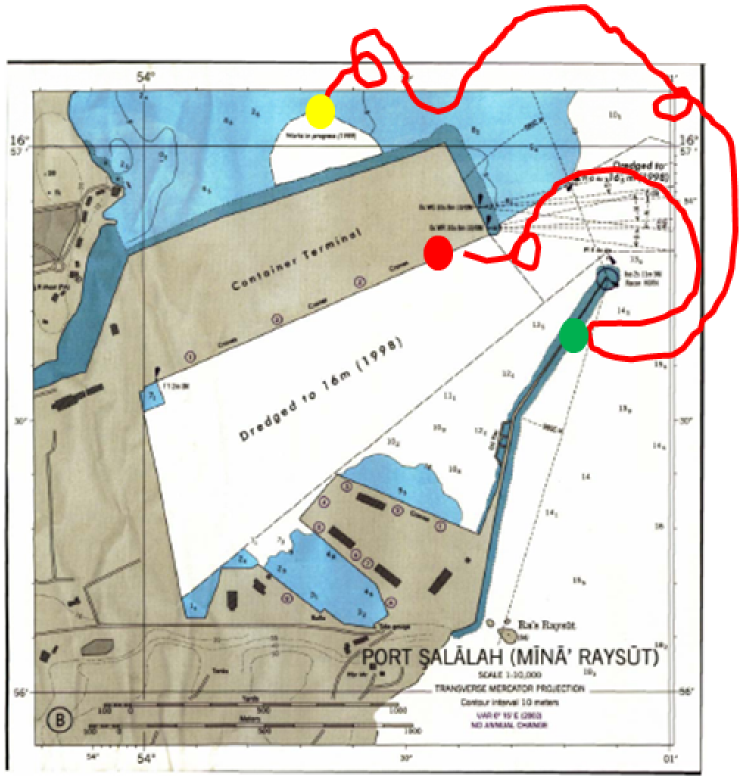


Harbor Studies



2004 Indian Ocean Tsunami

Port Salalah, Oman



Son et al. (2011, Ocean Modelling)

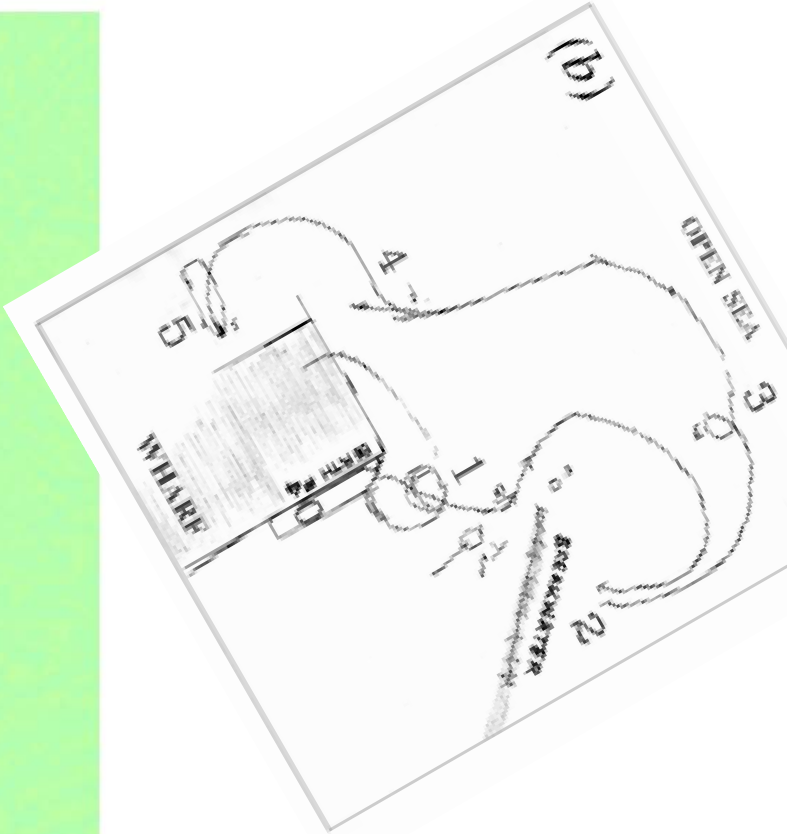
Elapsed Time=401min

Oman Salalah Harbor Grid - 5th Layer Boussinesq: FSE

Harbor Studies

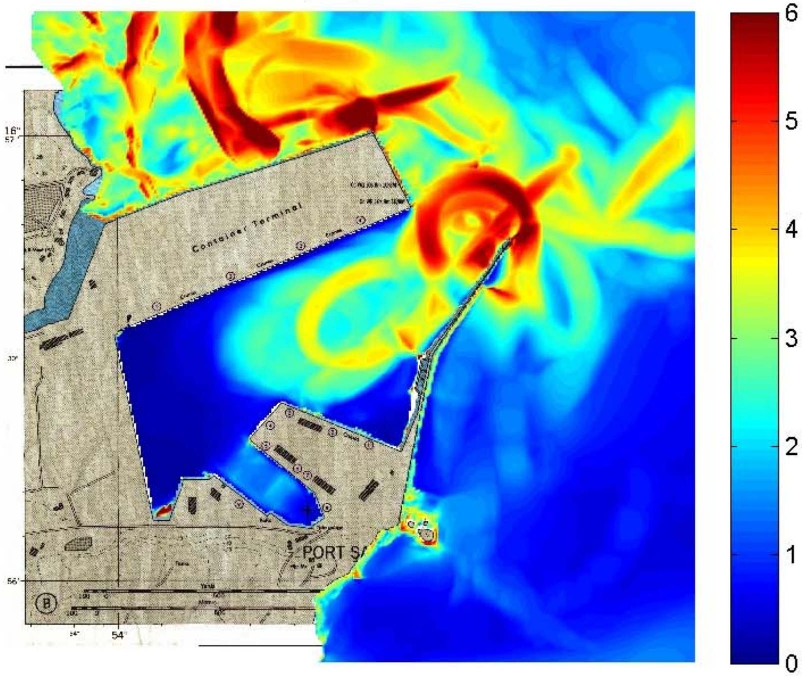
Elapsed Time=399min

Oman Salalah Harbor Grid - 5th Layer Boussinesq: Vorticity

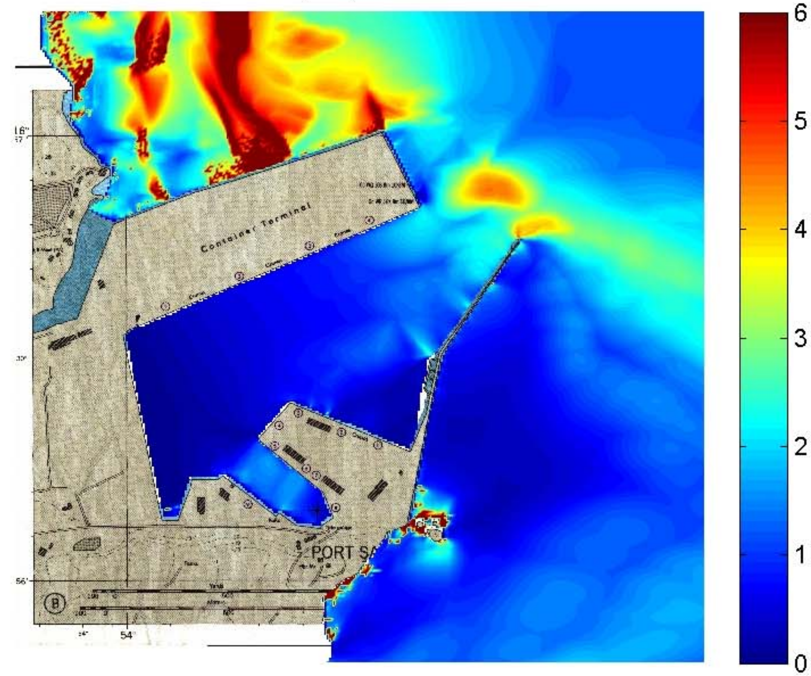


Harbor Studies

Maximum Currents (m/s) with Vortical Features



Maximum Currents (m/s) without Vortical Features



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

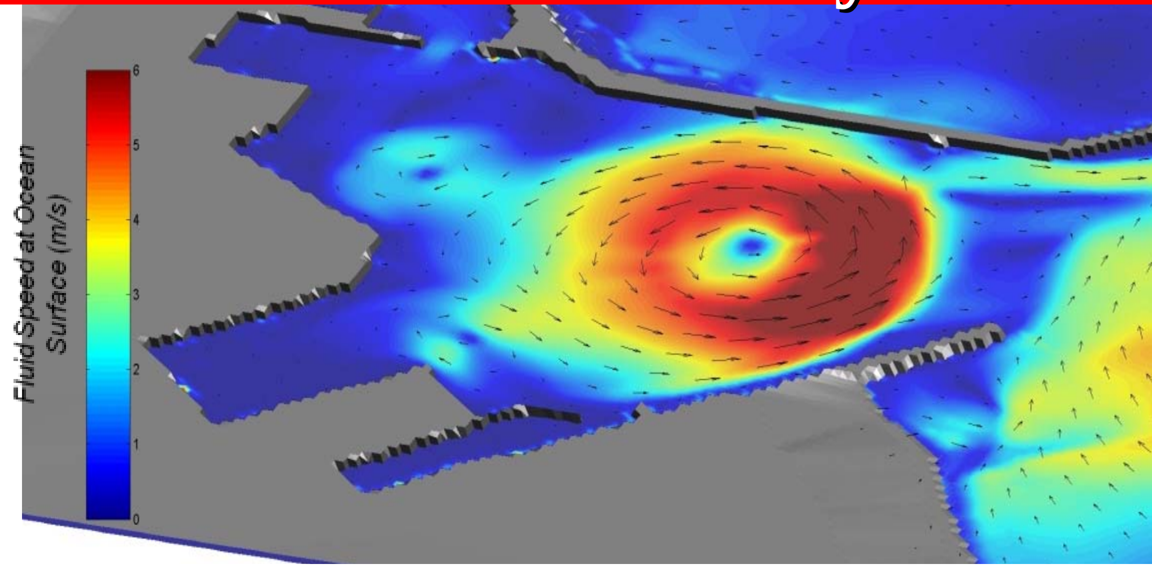
$$(1-Cr)\frac{u\Delta x}{2}\frac{\partial^2 u}{\partial x^2} = \nu_{num}\frac{\partial^2 u}{\partial x^2} \qquad \text{with Cr} \sim 0.5,\ \text{u} \sim 1\text{-}5\text{m/s},\ \Delta\text{x} \sim 10\text{m},\ \nu_{num} \sim 10\, {m^2}/{s}$$

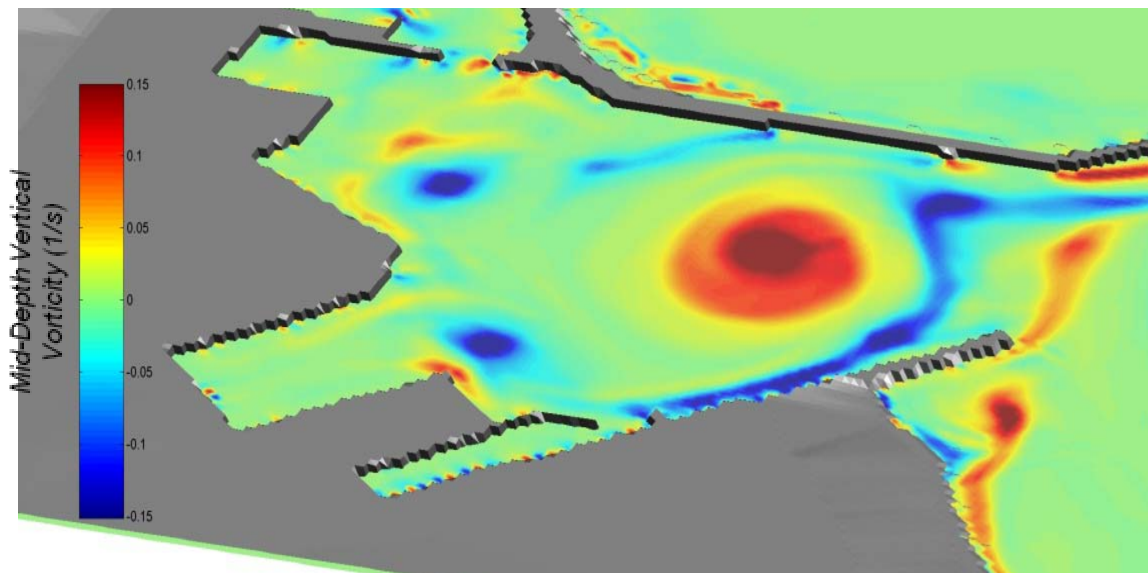
✓*Shear layers are numerically damped (eddies can't generate)*

✓*Any generated eddies are quickly diffused*

Applications: Turbulent, Tsunami-Induced Harbor Dynamics

- *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.*

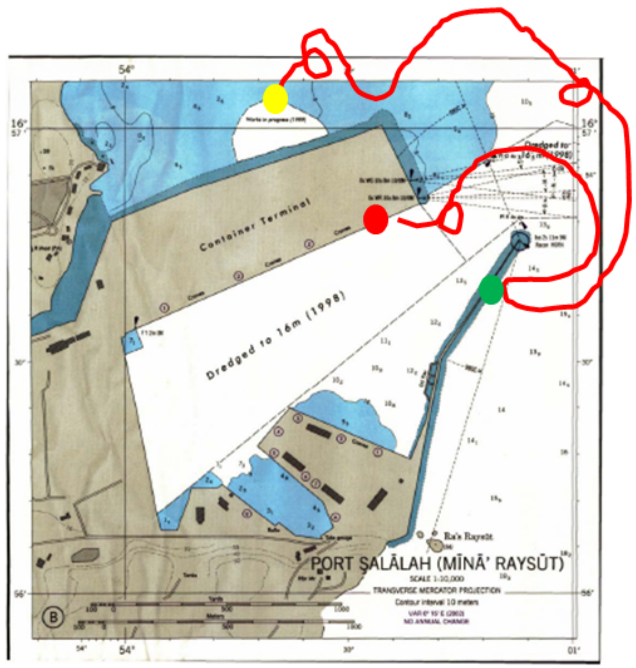


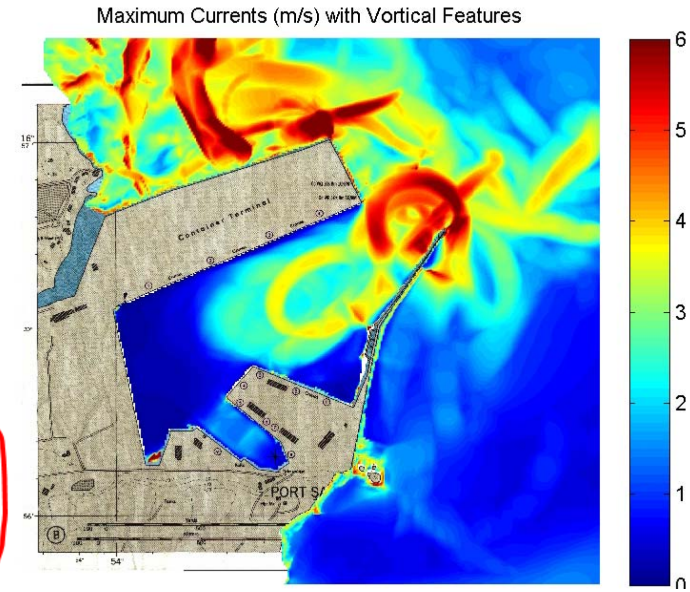


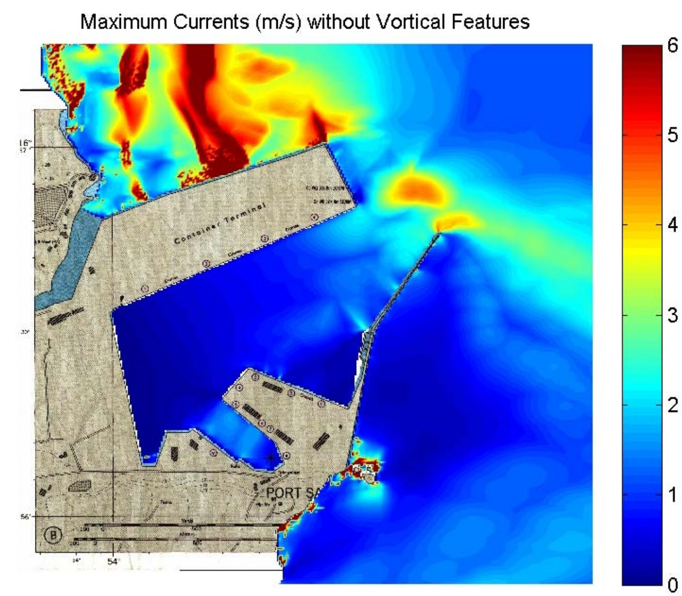
Applications: Turbulent, Tsunami-Induced Harbor Dynamics

*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?*

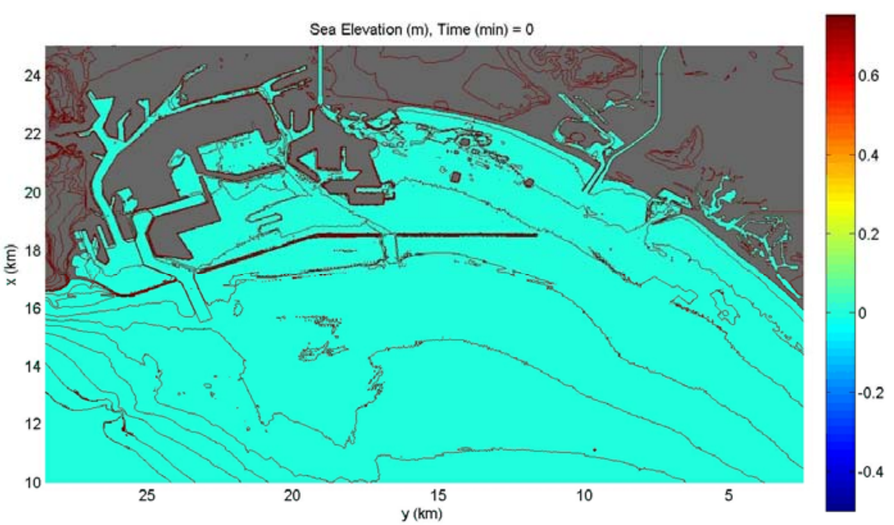


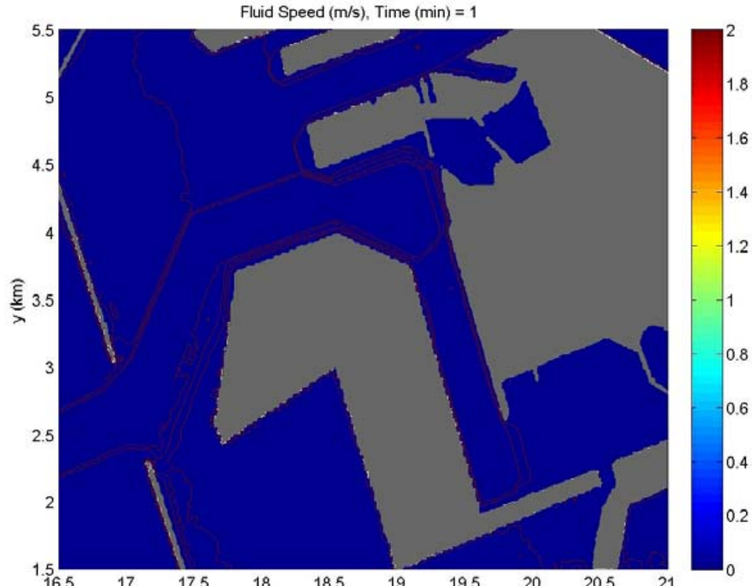


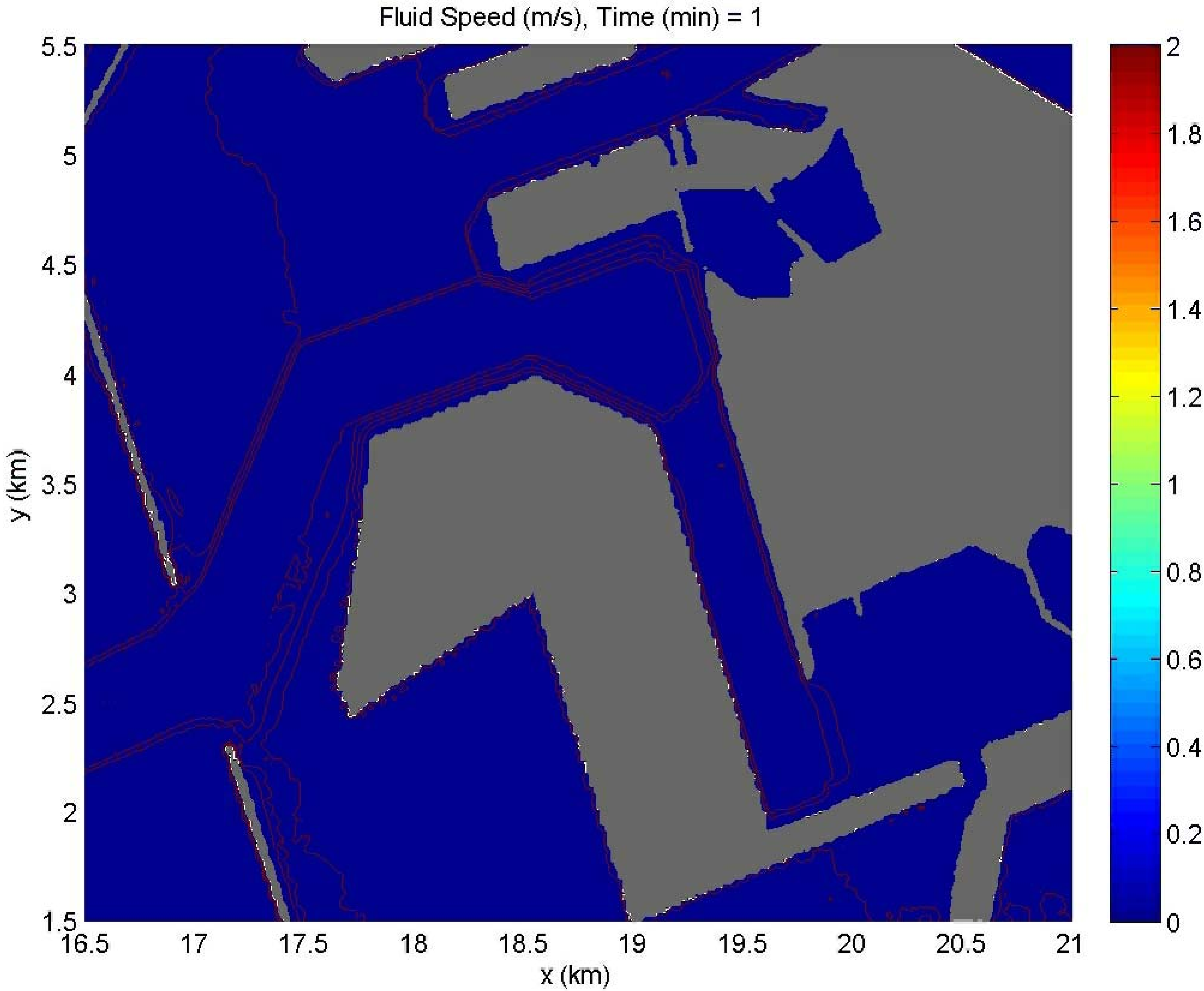


Inclusion of Viscous Effects in Long Wave Models

- Research Needs – Tsunami Currents in Ports & Harbors
  - Three-dimensionality: generation of turbulent structures is inherently fully 3D, vertical structure inside coherent structures is highly complex [model nesting & coupling]
  - DATA!: *very* limited velocity data available for tsunami events [rapid deployment capability]
  - Coupling with object and transport models: simulate the forces on and breaking of mooring lines, the paths of detached floating vessels or containers, forces exerted on objects during vessel impacts, scour and deposition locations [coupled "large" DEM and fluid models, sediment transport integration]







Fluid Speed (m/s), Time (min) = 1
y (km)
x (km)
5.5
5
4.5
4
3.5
3
2.5
2
1.5
16.5
17
17.5
18
18.5
19
19.5
20
20.5
21
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0