Large-Scale Coastal Modeling: Wind Wave Applications

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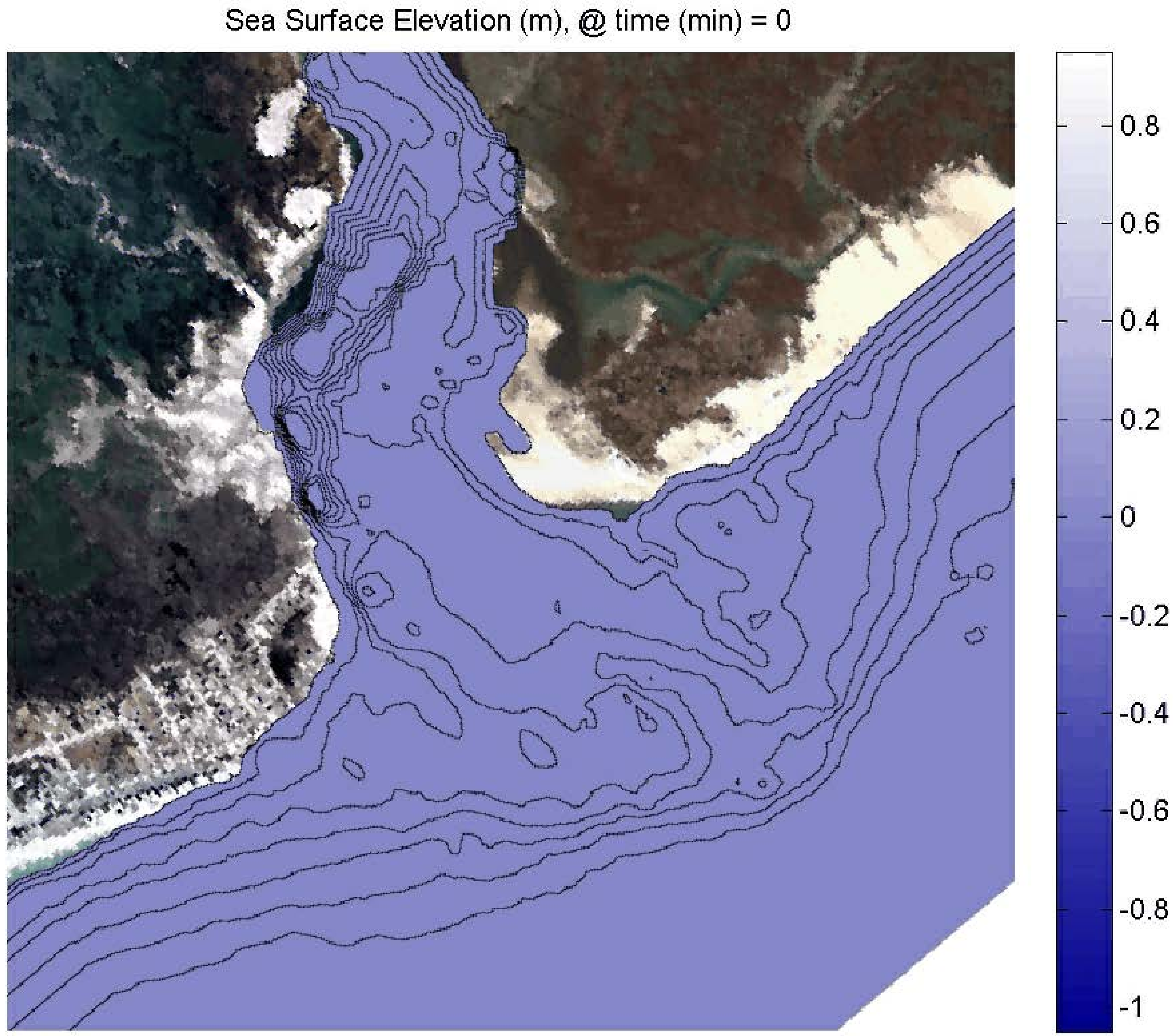
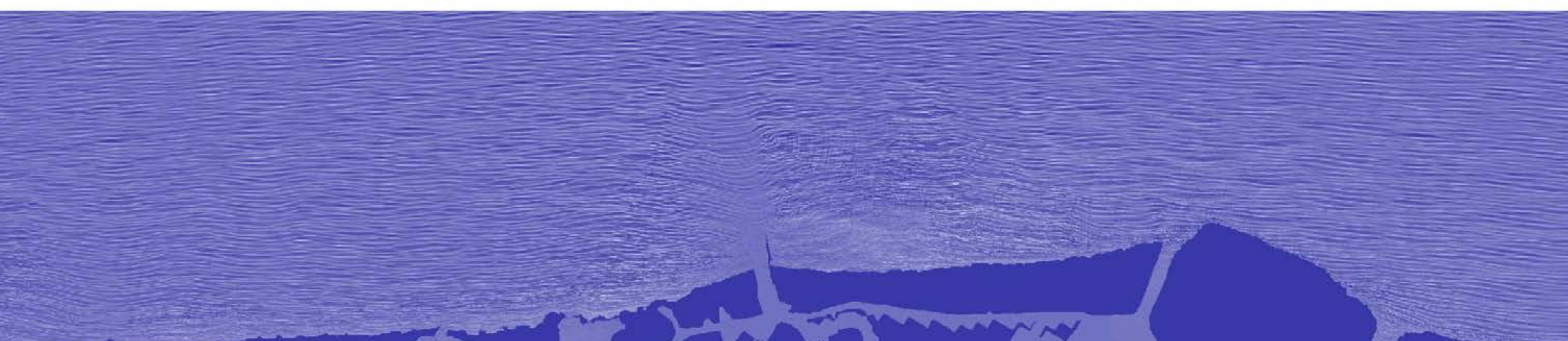


Presentation Outline

- Numerical setup for large-scale coastal wave problems
  - Bathy, wave generation, etc.
  - Which equations to use?
- Applications
  - Hurricane waves and levee overtopping
  - Nearshore waves and wave-induced circulation
  - Harbor resonance studies

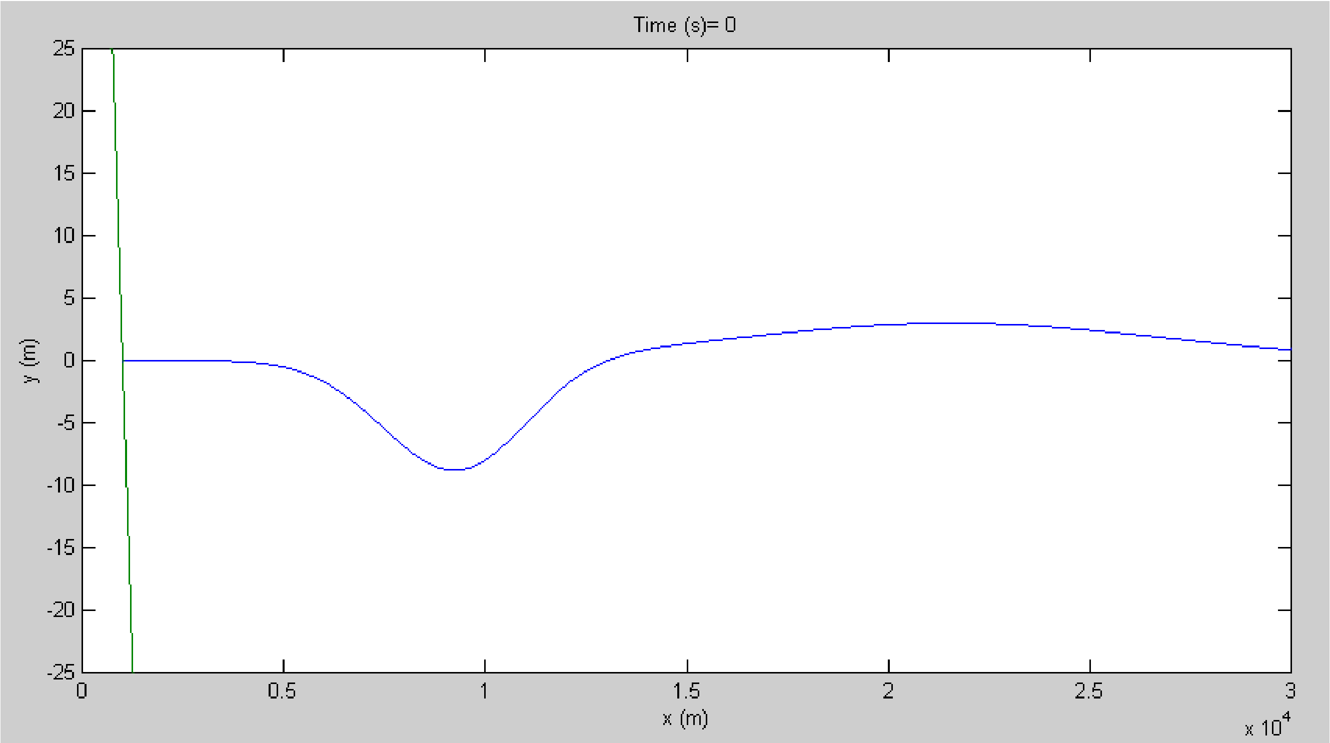


Creating bathy maps

- **Where do we get our bathy/topo?**
  - **GEBCO – 2 min data, expect inaccuracy in shallow water (<50 m depth). http://www.gebco.net/**
  - **NOAA Tsunami DEMs – gridded data down to 1/3 arcsec (~10 m). Great for coastal bathy, but only available in select locations. http://www.ngdc.noaa.gov/mgg/inundation/tsunami/inundation.html**
  - **NOAA Coastal Services Center's Digital Coast Data – some very high resolution coastal bathy/topo (lidar datasets ~1m resolution), lots of different datasets, US only. http://csc.noaa.gov/dataviewer/**
  - **Often need to rely on old navigation charts in areas with no coastal data. Buy the chart and digitize…**

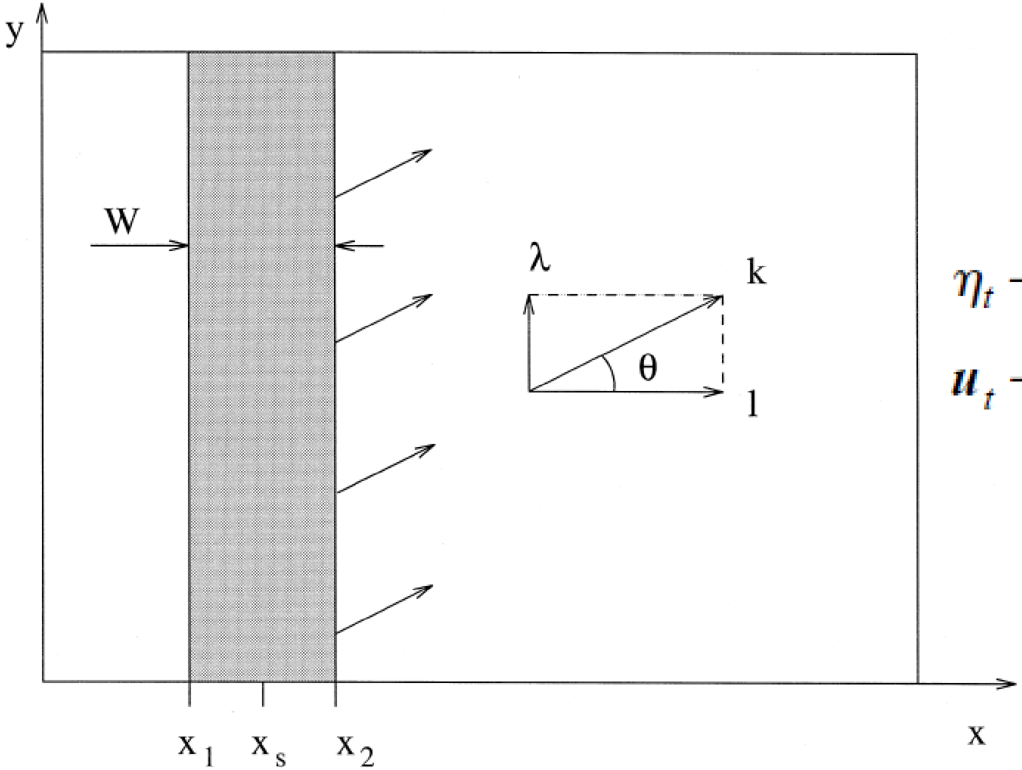
How to generate waves

- **Hot start**
  - **Earthquake sources – $\Delta h = \Delta \eta$**
  - **With velocity (e.g. Solitary Wave) our without (EQ)**



How to generate waves

- **Internal Source**
  - **Add a forcing term to the equations, adding either mass or momentum, along a strip inside the domain**



Linear Boussinesq-type equations over constant depth

$$\eta_t + h\nabla \cdot \boldsymbol{u} + \alpha_1 h^3 \nabla^2 (\nabla \cdot \boldsymbol{u}) = f(x, y, t)$$

$$\boldsymbol{u}_t + g\nabla\eta + \alpha h^2 \nabla^2 \boldsymbol{u}_t = 0$$

How to generate waves

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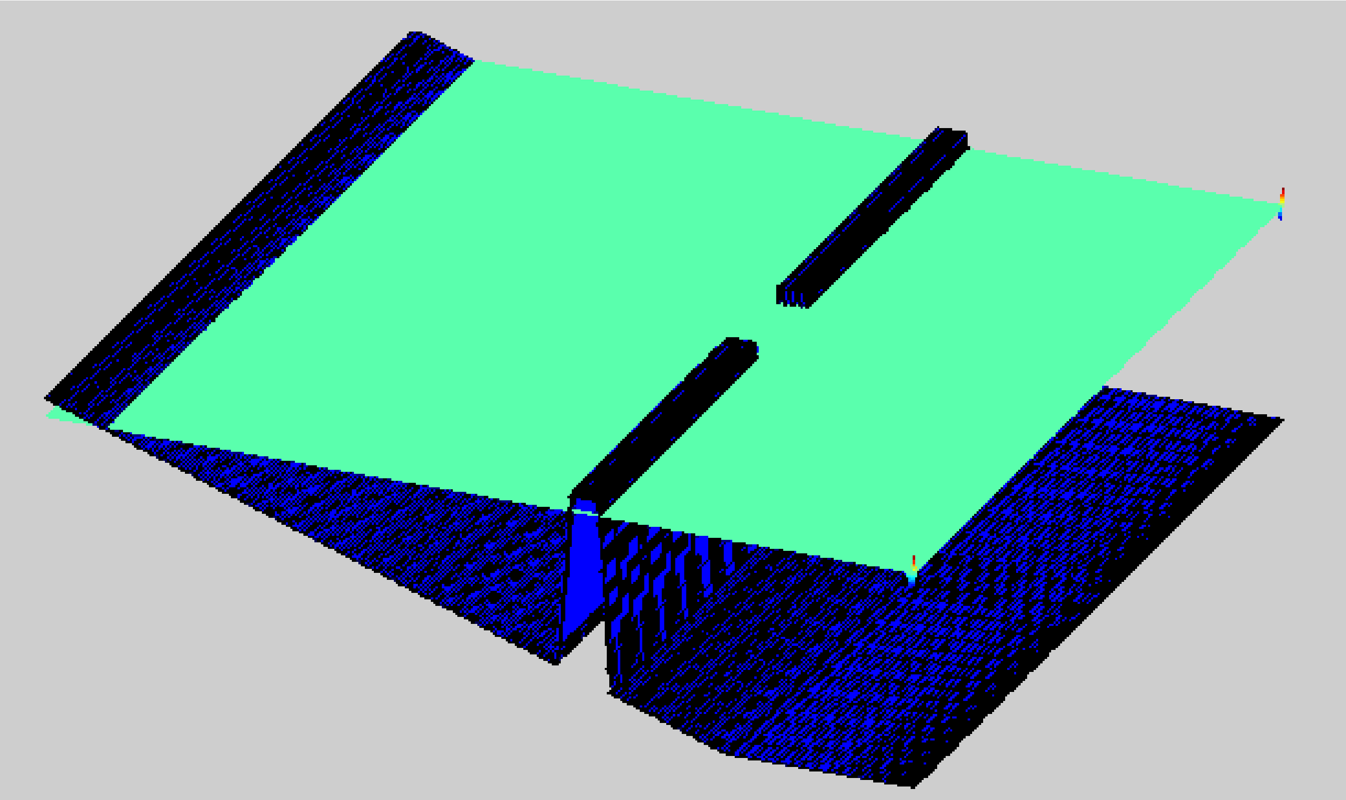

Boundary conditions

- **For lateral boundaries, little success with local radiation boundary conditions (nonlinear dispersive waves)**
- **Use sponge layers – another source term in both mass and momentum equations to remove mass & energy along the boundaries**

$$u_t + g\eta_x + \alpha h^2 u_{xxt} = c_1 \omega u + c_2 \frac{\omega}{k^2} u_{xx}$$

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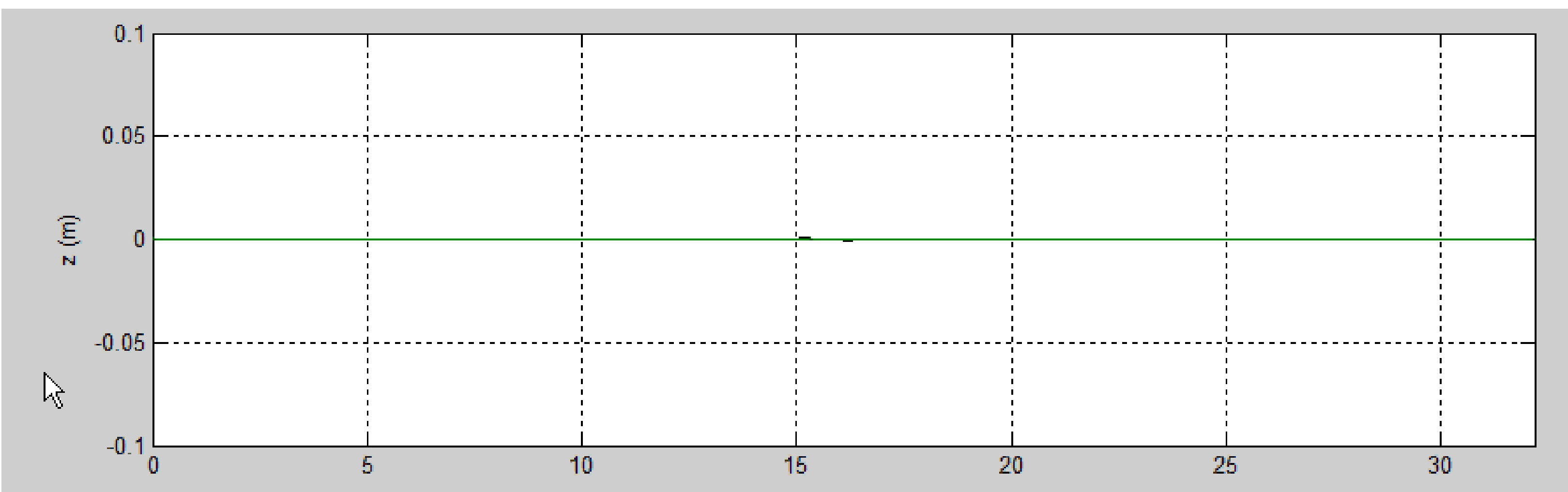


Dissipation Parameters

- **Bottom Friction**

$$\frac{\partial U_\alpha}{\partial t} + U_\alpha \cdot \nabla U_\alpha + \ \ldots + \frac{\tau_b}{\zeta + h} = 0$$

$$\tau_b^x = C_f u \sqrt{u^2 + v^2}, \quad \tau_b^y = C_f v \sqrt{u^2, +v^2}$$

```
if(bf_type.eq.0)then ! Moody approx
   Rh = max(100.0,sqrt(ua(i,j)**2)*Hs_i/dissipcoef)  ! Hydraulic Radius
   Cf_c = -1.8*log10(6.9/Rh+(ks/Hs_i/3.7)**1.11) ! ks=roughness height in meters
   Cf(i,j) = 0.25/Cf_c**2  ! dimensionless friction factor
   if (Rh.le.411.58) Cf(i,j) = 0.25*64./Rh
elseif(bf_type.eq.1)then    ! Mannings
   Cf(i,j)=n**2.*9.81/Hs_i**0.3333  ! n is Mannings "n", in SI units (standard units)
elseif(bf_type.eq.2)then   ! constant friction
   Cf(i,j)=f ! f is some constant dimensionless friction factor
endif
```

Dissipation Parameters

- **Breaking (ad-hoc "tack-on" to momentum equation)**

$$\frac{\partial \boldsymbol{U}_\alpha}{\partial t} + \boldsymbol{U}_\alpha \cdot \nabla \boldsymbol{U}_\alpha + \ \ldots + F_b = 0$$

$$F_{br} = \frac{1}{h+\eta}\left[(\nu((h+\eta)u_\alpha)_x)_x + \frac{1}{2}(\nu(((h+\eta)u_\alpha)_y + ((h+\eta)v_\alpha)_x))_y\right]$$

- **Tune parameters in eddy viscosity model based on comparisons with lab & field data**
  - **See: Kennedy, A. B., Chen, Q., Kirby, J. T., and Dalrymple, R. A. (2000).''Boussinesq modeling of wave transformation, breaking, and runup. I:1D.'' J. Wtrwy., Port, Coast., and Oc. Engrg., ASCE, 126(1), 39–47.**
- **…Or just use limiters**

Which Equations to use?

- **Weakly nonlinear, Depth-Averaged Boussinesq model** (Peregrine, D.H., 1967. Long waves on a beach. Journal of Fluid Mechanics 27, 815–827.)
  - **Continuity equation is exact, includes only 1st order derivatives**
  - **Momentum equation has truncation error = $O(\varepsilon\mu^2,\mu^4)$ w/ $\varepsilon=a/h$, $\mu=h/L$, includes 1st to third (u_{xxt}) derivatives.**
  - **Mixed derivative is group with local acceleration terms, and momentum is solved in a two step process, e.g**
  - $U_t + uu_x + g\eta_x = 0\ ,\ U = u + \frac{1}{3}h^2u_{xx}$
  - **Can use a relativity low-order numerical scheme**

Which Equations to use?

- **Weakly nonlinear, "extended" Boussinesq-type model** (Nwogu, O., 1993. Alternative form of Boussinesq equations for nearshore wave propagation. Journal of Waterway, port, Coastal, and Ocean Engineering 119 (6), 618–638.
  - Continuity equation has as truncation error = $O(\varepsilon\mu^2,\mu^4)$, includes 1st to third (u_{xxx}) derivatives.
  - Momentum equation has truncation error = $O(\varepsilon\mu^2,\mu^4)$ w/ $\varepsilon=a/h$, $\mu=h/L$, includes 1st to third (u_{xxt}) derivatives. (same as Peregrine's model)
  - Needed a differencing scheme with truncation error derivative order at least (u_{xxxx}) and time integration of at least (u_{tttt})
  - Considerably better dispersion properties that Peregrines model (usually important)

Which Equations to use?

- **Highly nonlinear, "extended" Boussinesq-type model** **(Wei, G., Kirby, J.T., Grill, S.T., Subramanya, R., 1995. A fully nonlinear Boussinesq model for surface waves. Part 1. Highly nonlinear unsteady waves. Journal of Fluid Mechanics 294, 71–92.)**
  - **Continuity equation has as truncation error = $O(\mu^4)$, includes 1st to third (u_{xxx}) derivatives. Nonlinear high-order derivatives as well, e.g $(vu_x)_{xy}$**
  - **Momentum equation has truncation error = $O(\mu^4)$ includes 1st to third (u_{xxt}) derivatives.**
  - **Need a differencing scheme with truncation error derivative order at least (u_{xxxx}) and time integration of at least (u_{tttt})**
  - **Better prediction of very nonlinear waves (e.g. near breaking) [sometimes important, but near the "noise" level of field data]**

Which Equations to use?

- **Weakly nonlinear, Peregine model**
  - **Memory cost per 100x100 grid points (using 2^{nd} order FV method, not memory optimized) ~ 2 MB**
  - **Intermediate variable "groups" size (nx,ny) ~20**
  - **Stencil is 3 points wide**
  - **CPU time / time step ~ 0.0025 s (single core, simple problem)**
- **Weakly nonlinear, "extended" model**
  - **Memory cost per 100x100 grid points (using 4^{th} order FV method, not memory optimized) ~ 5 MB**
  - **Intermediate variable "groups" size (nx,ny) ~25**
  - **Stencil is 5 points wide**
  - **CPU time / time step ~ 0.01 s (single core, simple problem)**
- **Highly nonlinear, "extended" model**
  - **Memory cost per 100x100 grid points (using 4^{th} order FV method, not memory optimized) ~ 15 MB**
  - **Intermediate variable "groups" size (nx,ny) ~80**
  - **Stencil is 9 points wide**
  - **CPU time / time step ~ 0.025 s (single core, simple problem)**

Which Equations to use?

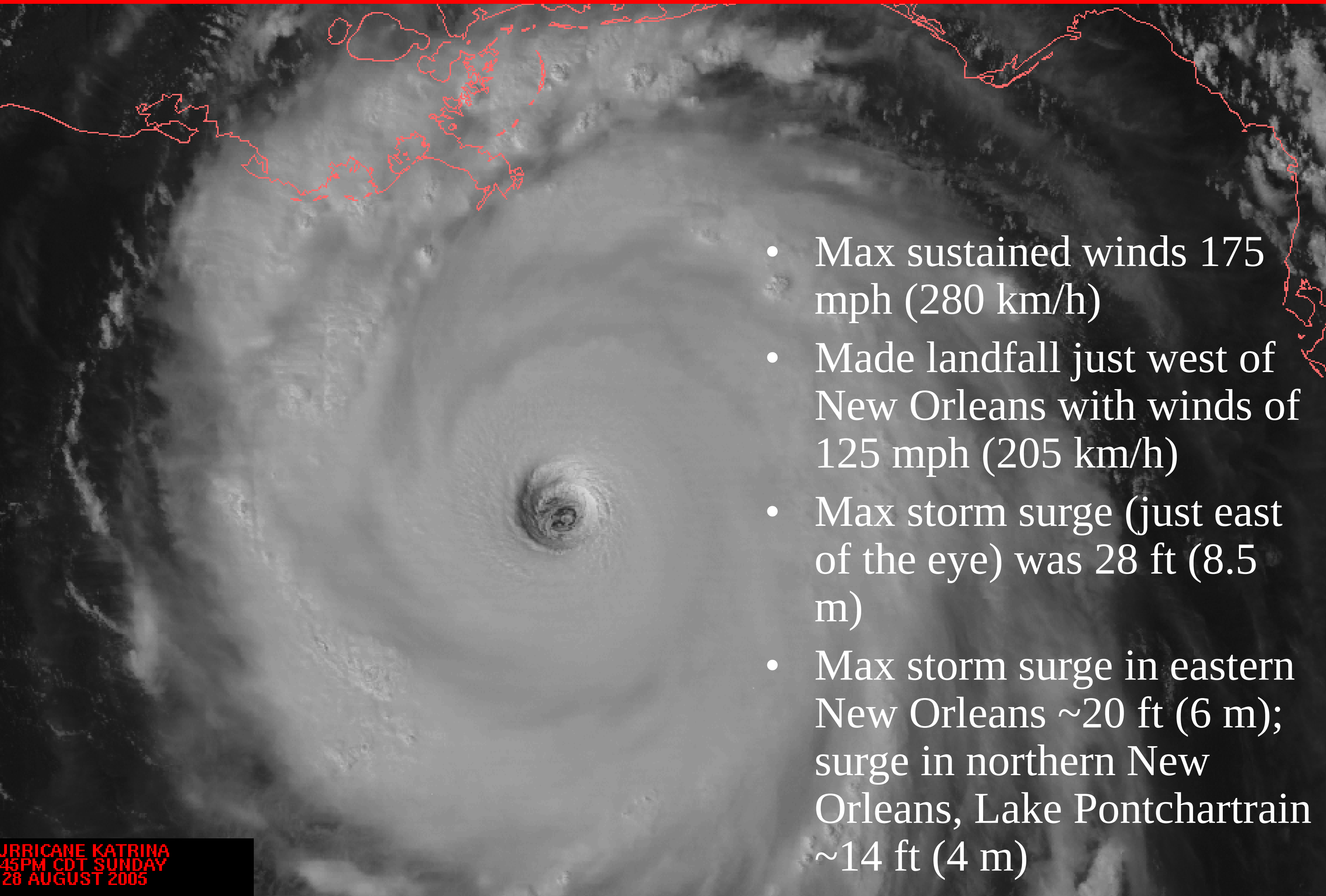
- **Weakly nonlinear, "extended" model**
  - **Memory cost per 100x100 grid points (using 4th order FV method, not memory optimized) ~ 5 MB**
  - **Intermediate variable "groups" size (nx,ny) ~25**
  - **Stencil is 5 points wide**
  - **CPU time / time step ~ 0.01 s (single core, simple problem)**

For the Boussinesq-type class of model to have a future it must be favorably competitive (in terms of computational time) with 3D models.

Can this equation set be accurately (and efficiently) solved on GPU? If not...

Hurricane Katrina

[movie]



- Max sustained winds 175 mph (280 km/h)
- Made landfall just west of New Orleans with winds of 125 mph (205 km/h)
- Max storm surge (just east of the eye) was 28 ft (8.5 m)
- Max storm surge in eastern New Orleans ~20 ft (6 m); surge in northern New Orleans, Lake Pontchartrain ~14 ft (4 m)

Hurricane Katrina -Damage in Mississippi

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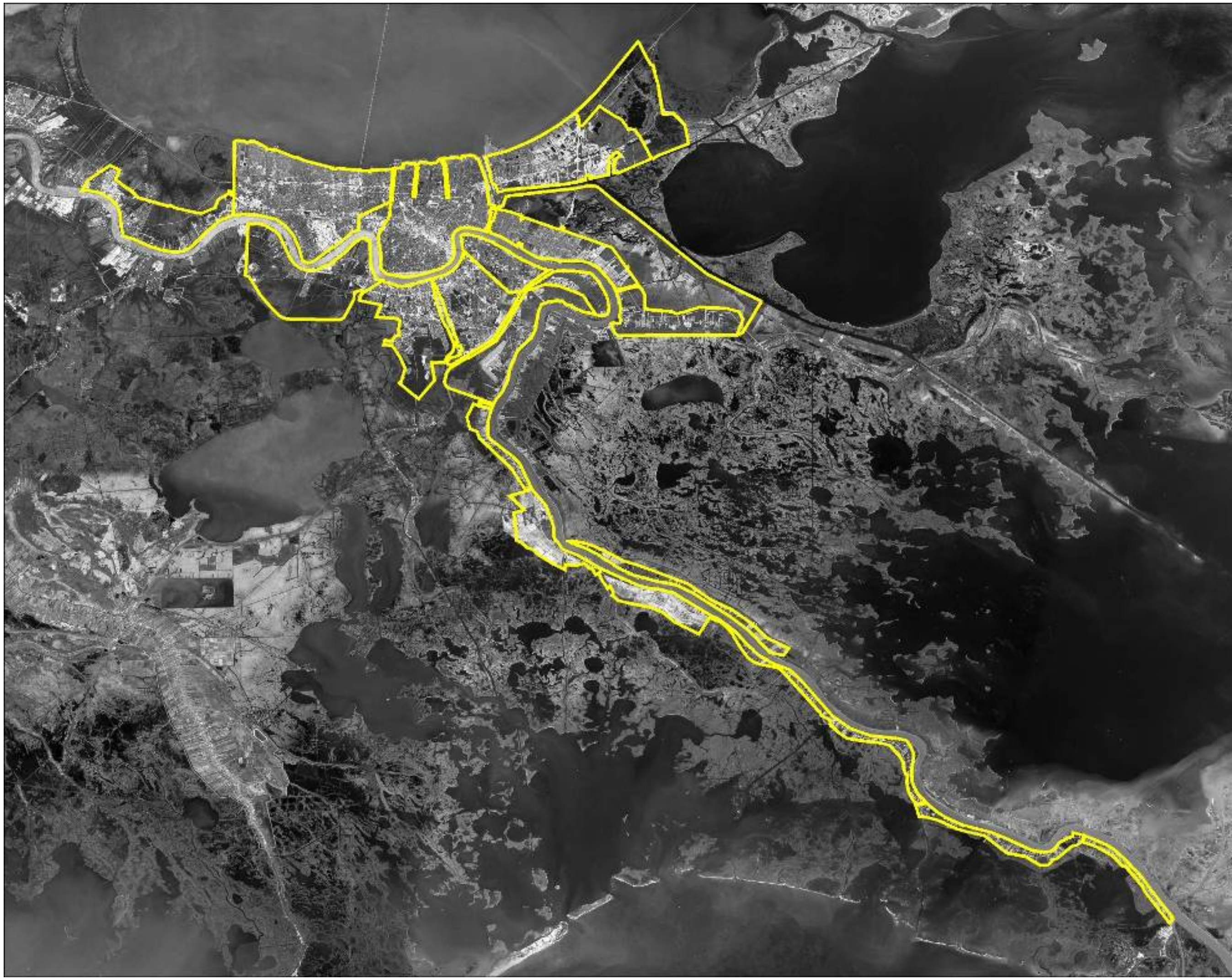
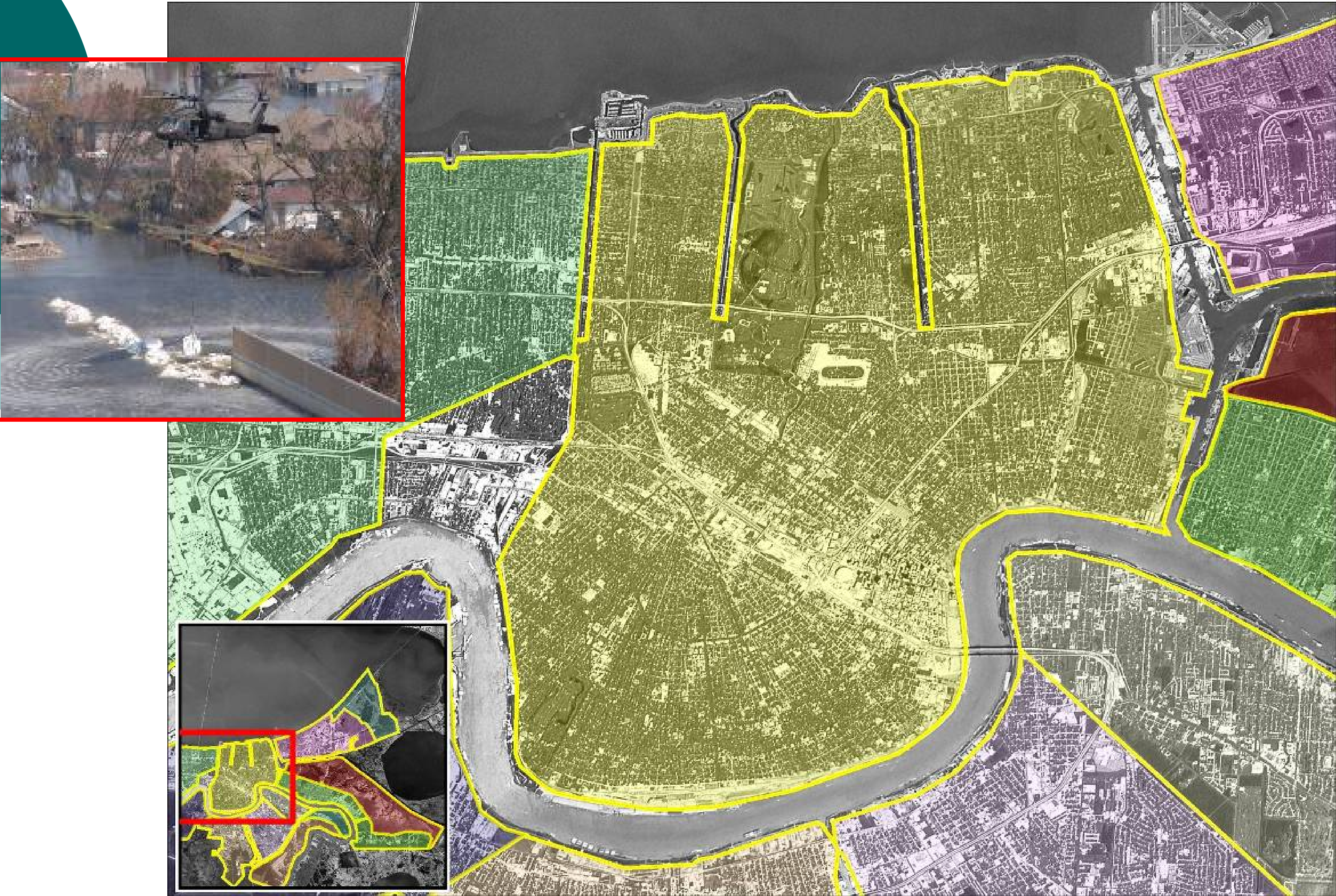
Hurricane Katrina – Damage in New Orleans

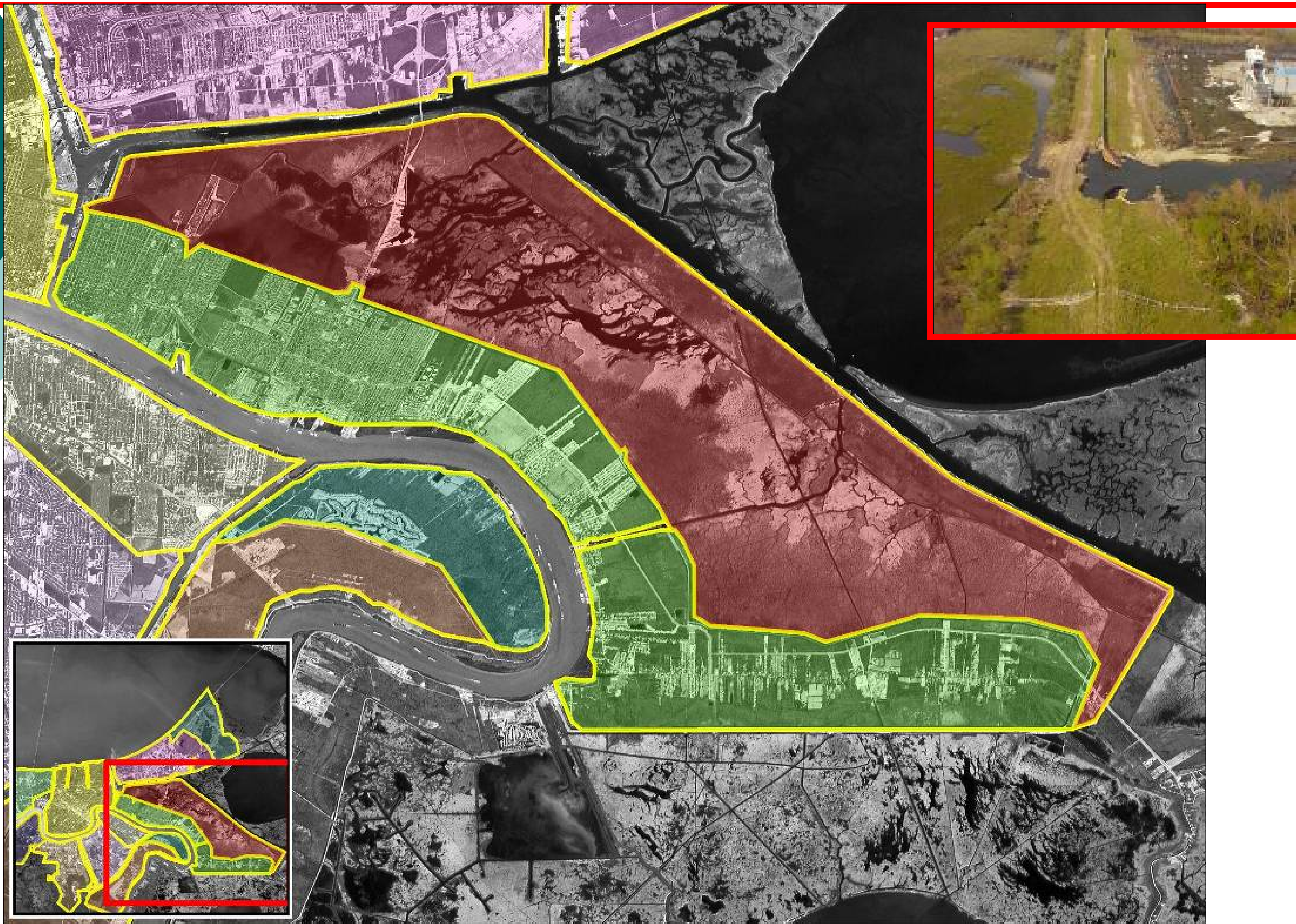
- Most of New Orleans is below sea level, and requires a complex system of flood walls and levees to protect against hurricane surges



Hurricane Katrina – Damage in New Orleans

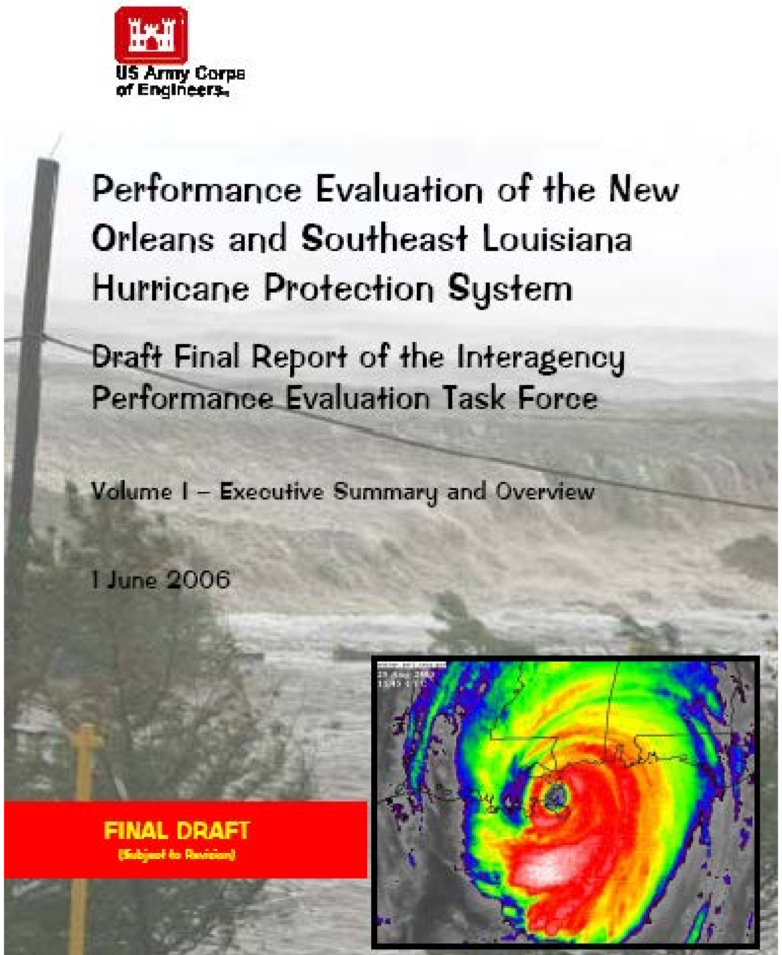


Hurricane Katrina – Damage in New Orleans



Hurricane Katrina – Damage in New Orleans

- U.S. Army Corps of Engineers organized a large forensic study of Katrina & its impact
  - Interagency Performance Evaluation Task Force (IPET)
  - Goals were to examine:
    - The System
    - The Storm
    - The Performance
    - The Consequences



- Many different aspects, hydrodynamic, structural, geotech, social science,…
- Nearshore wave forces & impact through detailed hydrodynamic modeing

Hurricane Katrina – IPET Hydrodynamics

- Multi-model, multi-scale simulation approach:
  - Surge predicted by ADCIRC, based on the observed/simulated wind and pressure field
    - Resolution ~100m, but as low as ~1m in certain areas
  - Wave generation predicted by STWAVE, based on wind and water levels
    - Coupled with ADCIRC
    - Resolution ~100m, cannot resolve nearshore hydrodynamics
  - For the nearshore, Boussinesq is used
    - Water level provided by ADCIRC
    - Incident waves provided by STWAVE
    - Resolution ~1m
- Simulate the entire Gulf of Mexico (1 million square miles = $2.5*10^{12}$ m^2) with refined resolution ~ 1m

Damage in New Orleans - IPET

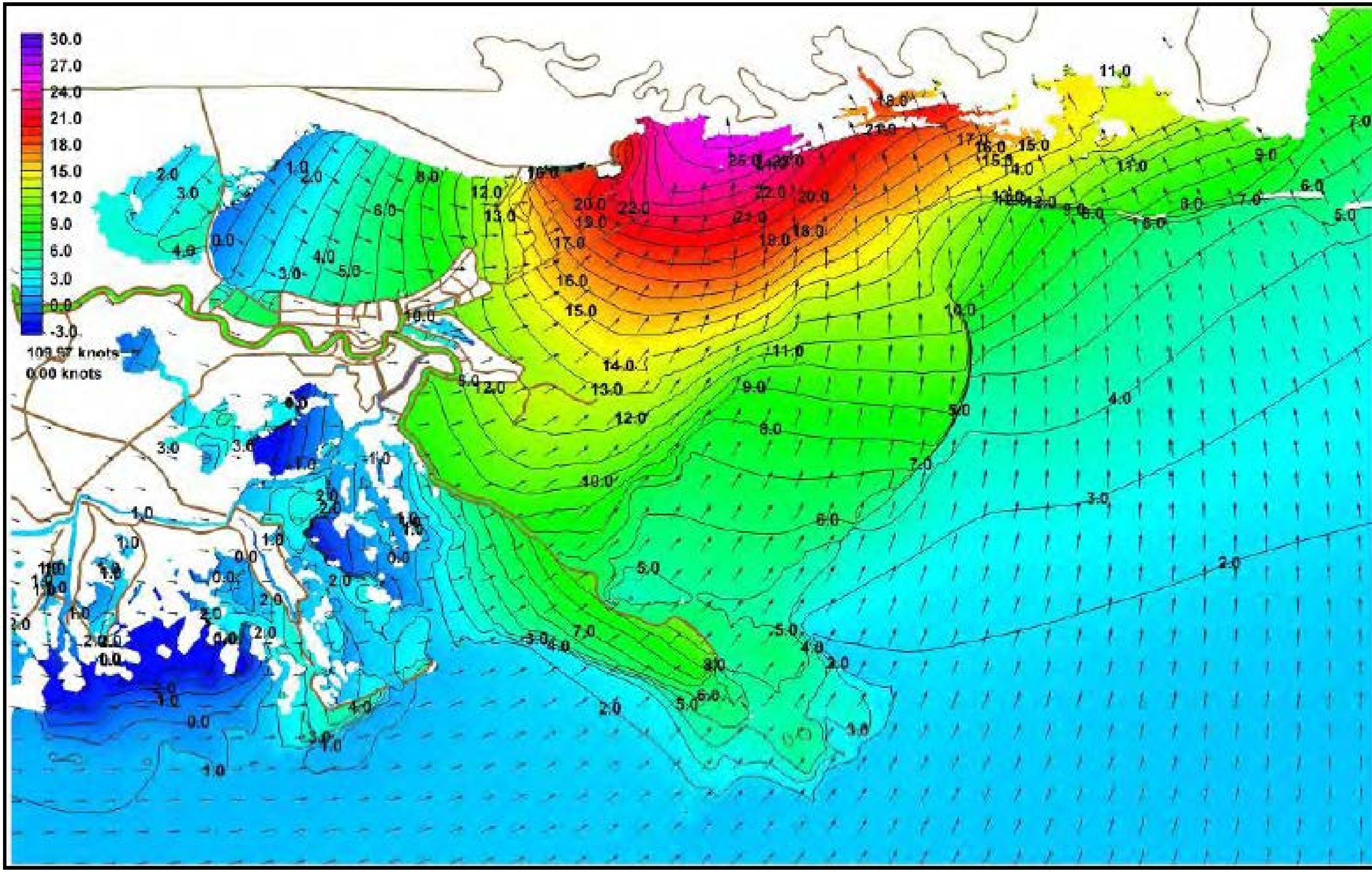
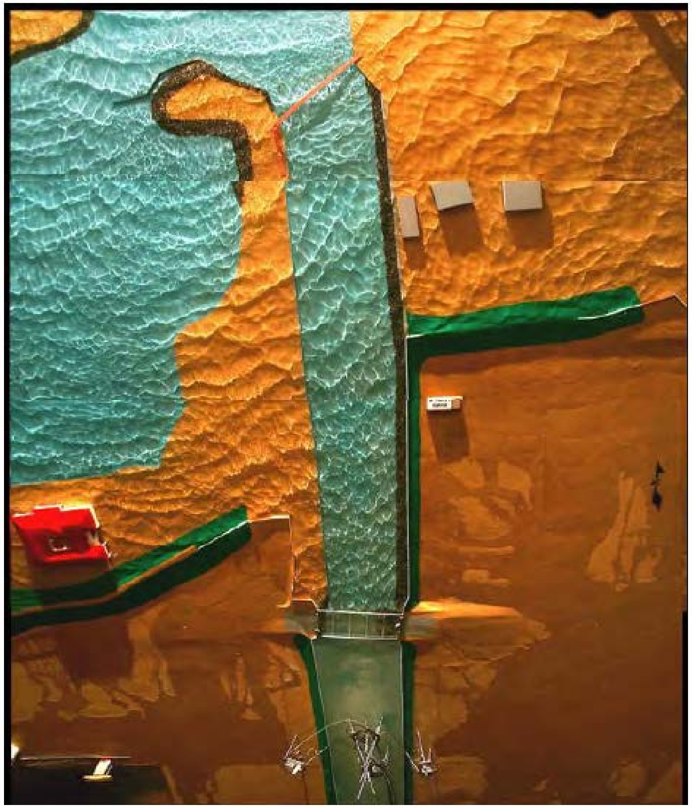


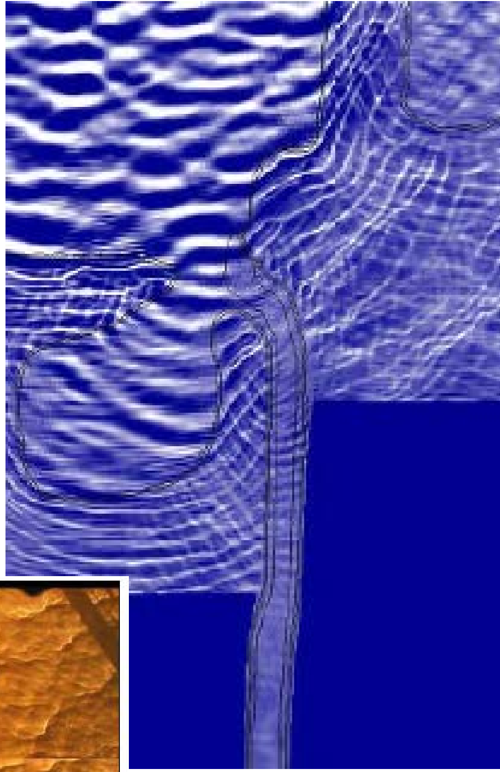
Figure 5-7h. Water surface elevation with respect to the NAVD 88 (ft) with boundary layer adjusted wind velocity vectors (knots) during Hurricane Katrina on August 29, 2005 at 1600UTC

Damage in New Orleans - IPET

Figure 12-1. 17th Street Canal entrance region, Hammond Highway Bridge, and breach location

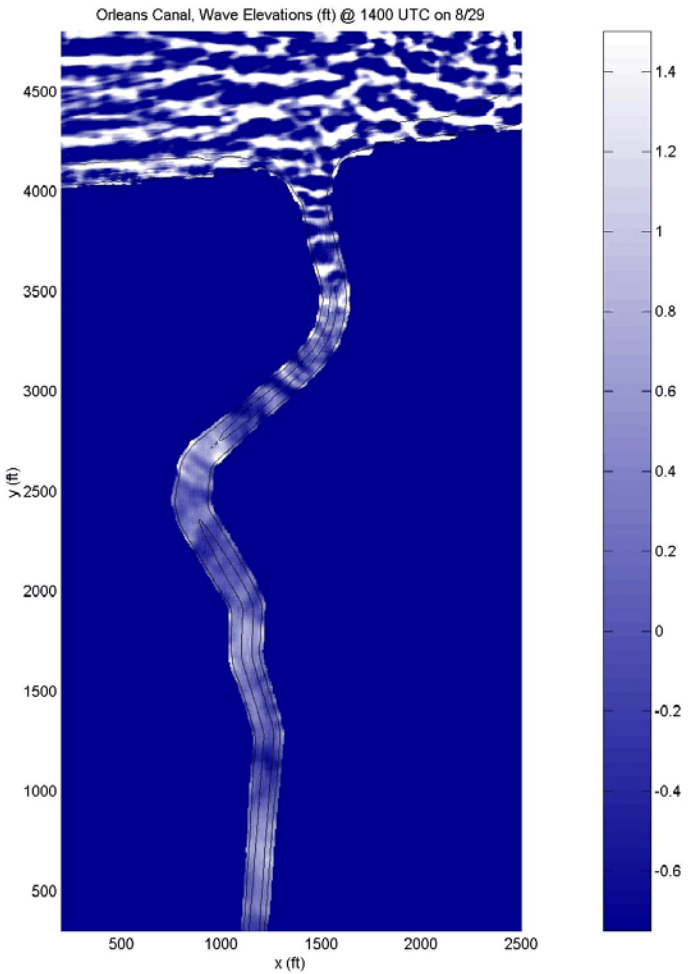
Physical &
Numerical Models

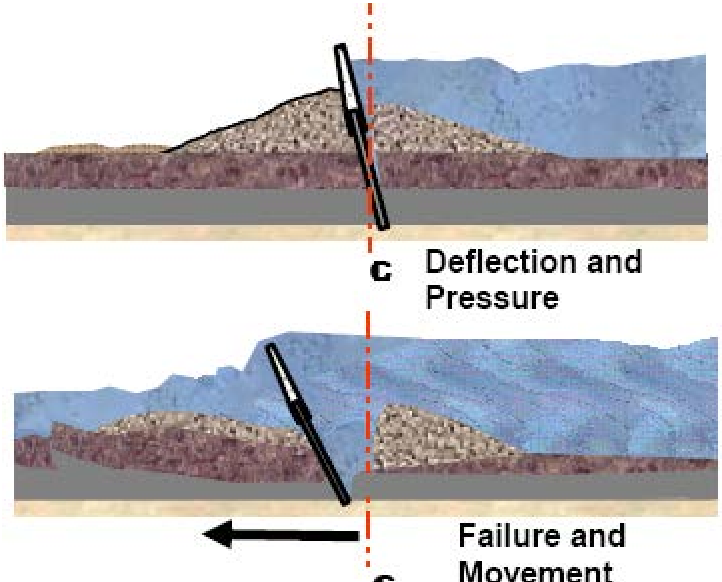




Damage in New Orleans

- Failures in the some of the canals occurred well before the water level reached the top of the wall
- Observations and simulations indicate that waves near the failures were very small ~0.3-0.5m
  - Walls *should not* have failed
- Study showed that failures were geotechnical based

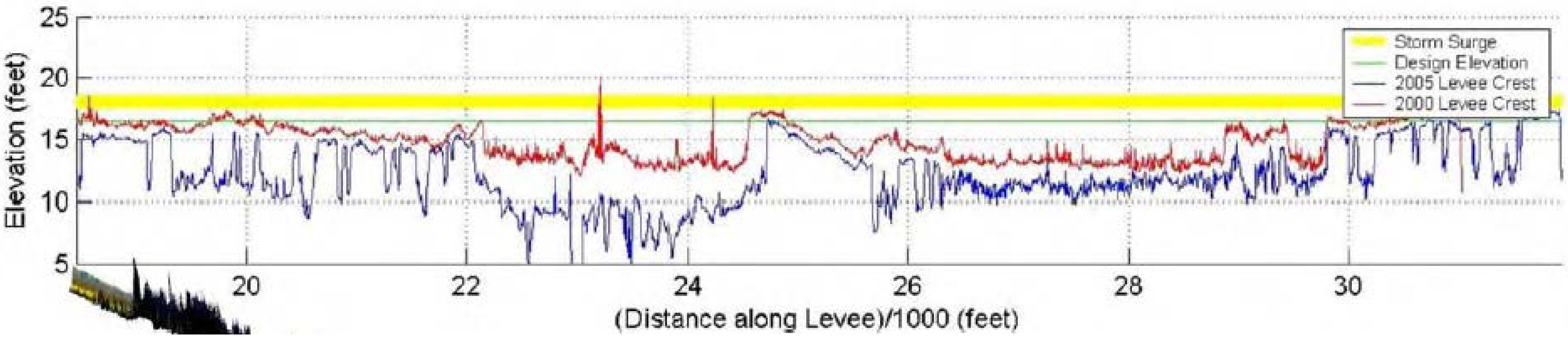




Porous or weak underlying soils allowed for gaps to be created between the panels

Damage in New Orleans- IPET

- Failures on the eastern levees were numerous
- Surge ~14-18’, design elevation of the levees was 17.5’
  - In addition, serious subsidence in this area, some levees were only 12.5’ before Katrina



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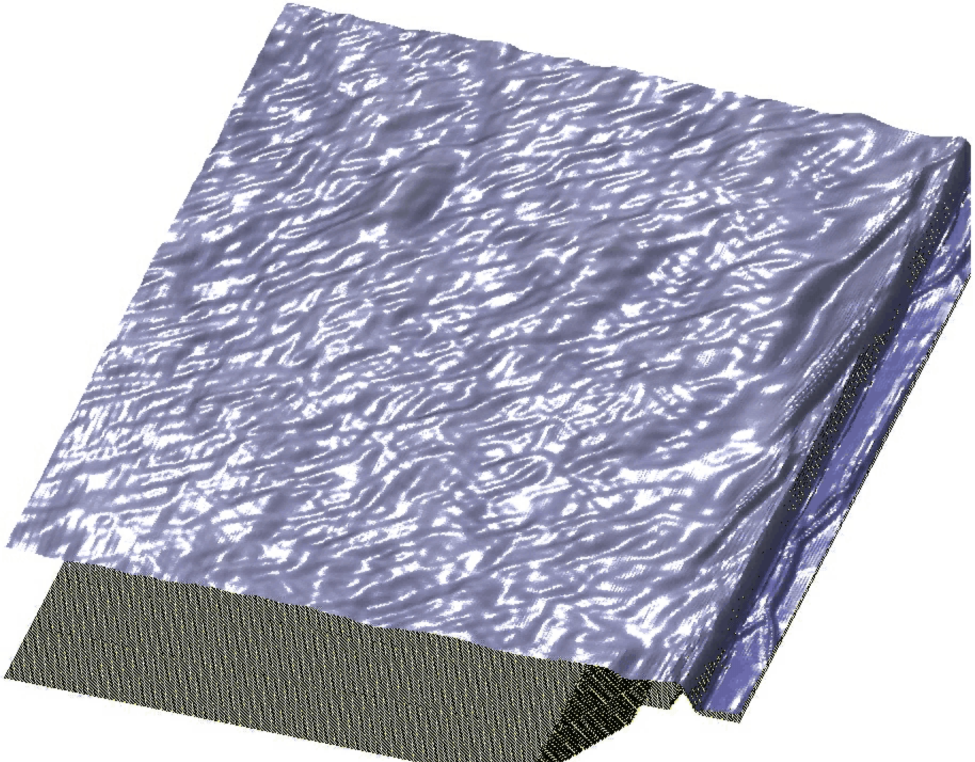
“Magic Number” for levee failure ~0.1 $ft^3/s/ft$ (0.01 $m^3/s/m$)



This value taken from detailed hydrodynamic simulations, and appears to have a high correlation with damaged levees

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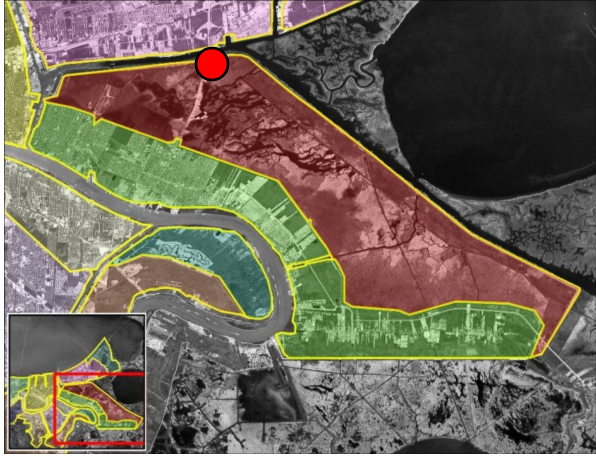


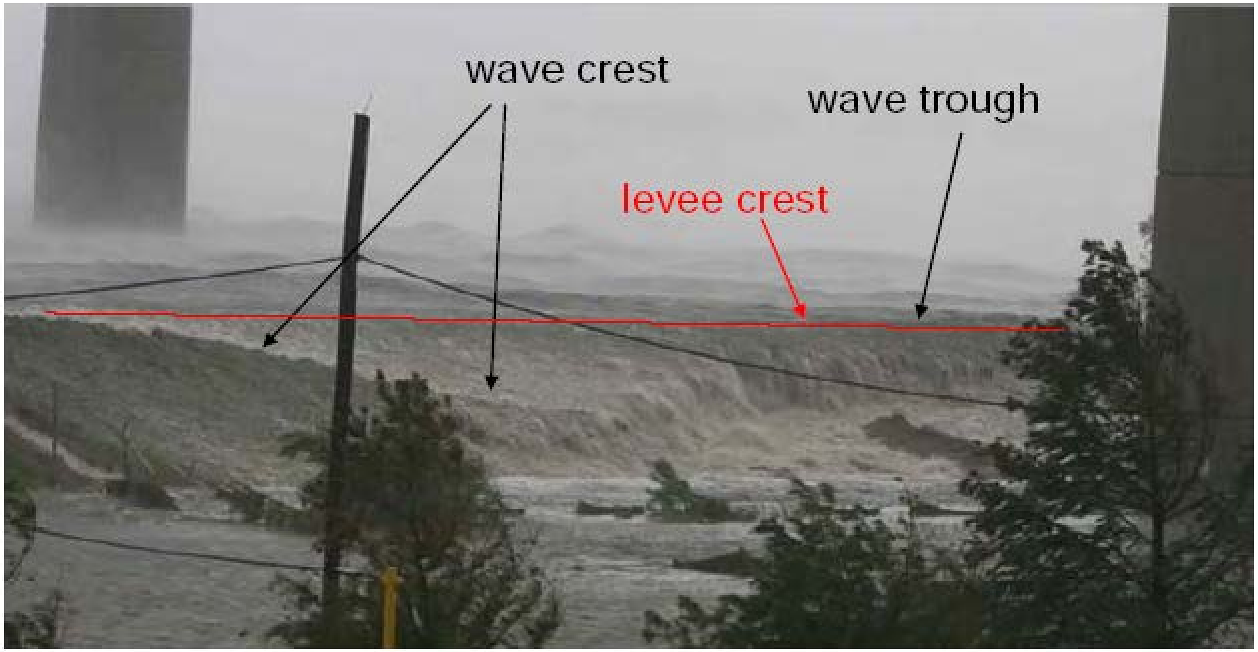
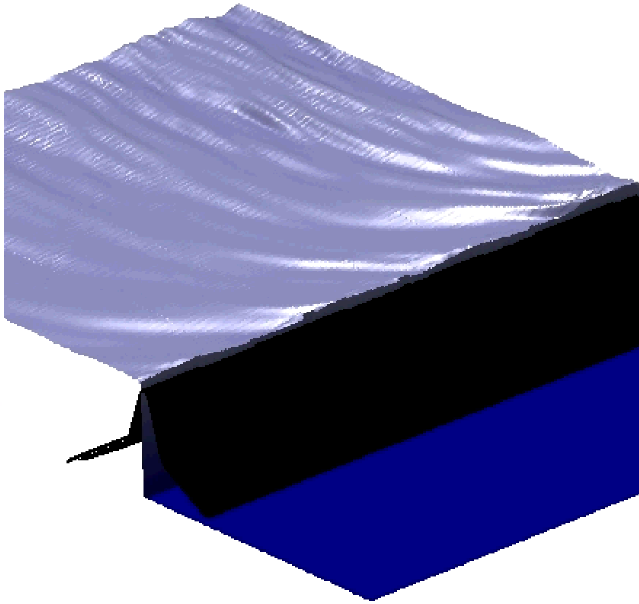


Figure 15-39. Photograph showing overtopping of levee under the Paris Road Bridge. Time of the photo is not known with certainty. View is from the north side of the levee, looking towards the southwest. Waves are traveling from the east (left side of photo) towards the IHNC



Damage in New Orleans- IPET

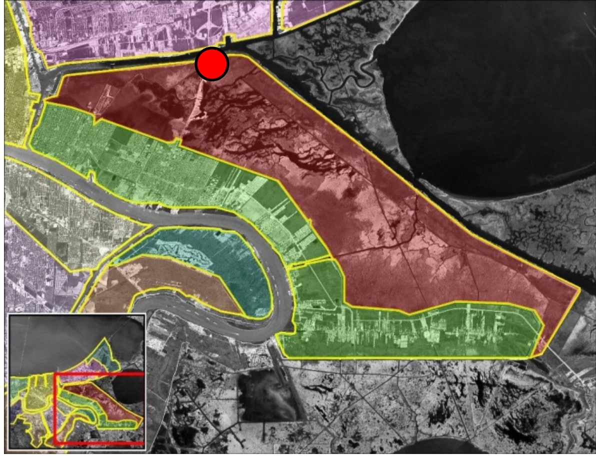


Figure 15-39. Photograph show
not known with certa
southwest. Waves a

Hurricane Sandy

movie

- Max sustained winds 110 mph (175 km/h)
- Made landfall in southern New Jersey with winds of 80 mph (130 km/h)
- Max storm surge was 13-16 ft (4-5 m)
- Surge in New York City ~14’ (4.2m) occurring within 30 minutes of high (Spring) tide
- Waves offshore of NYC ~30’ (9 m)

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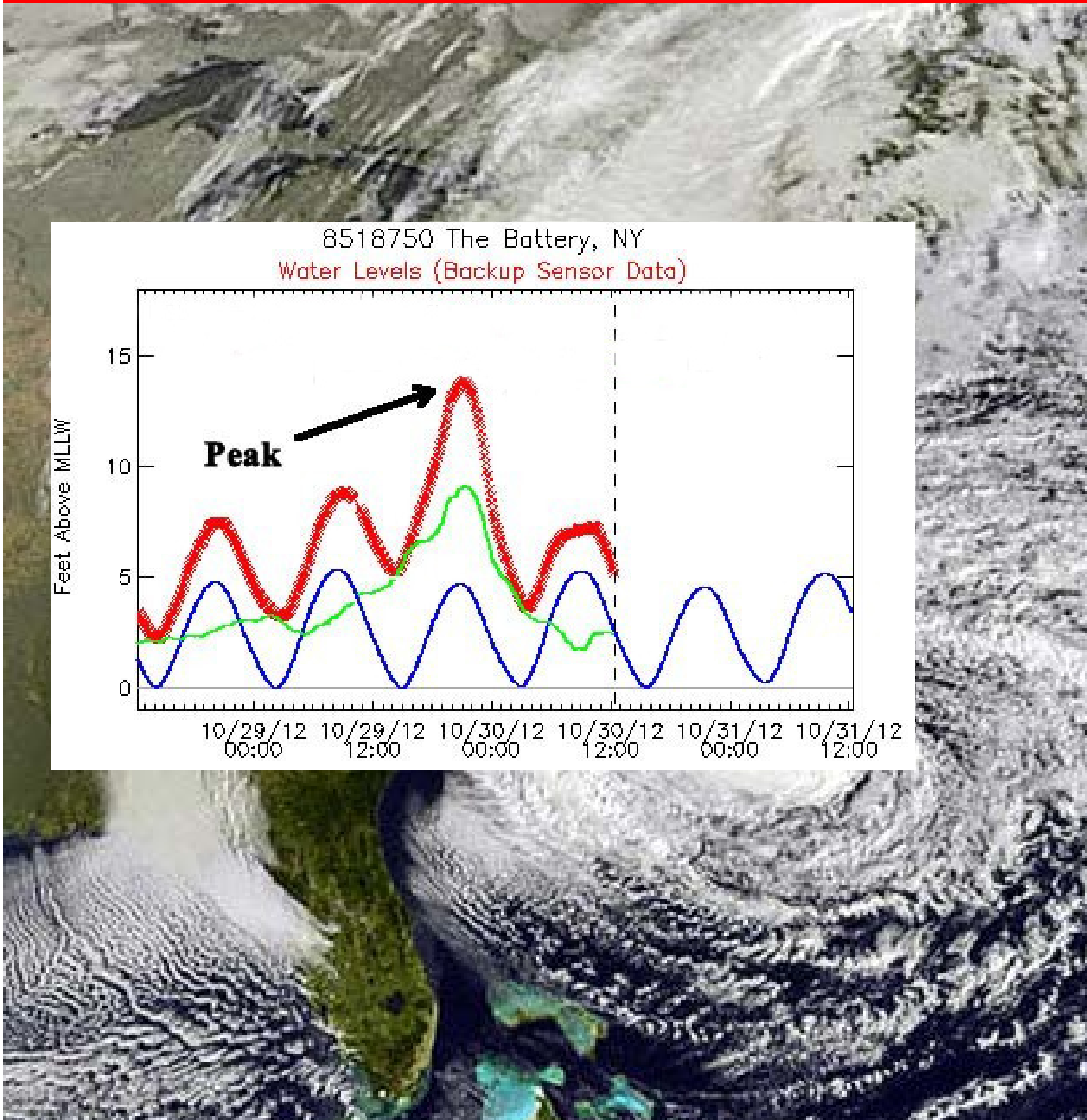

Hurricane Sandy -Damage in New Jersey

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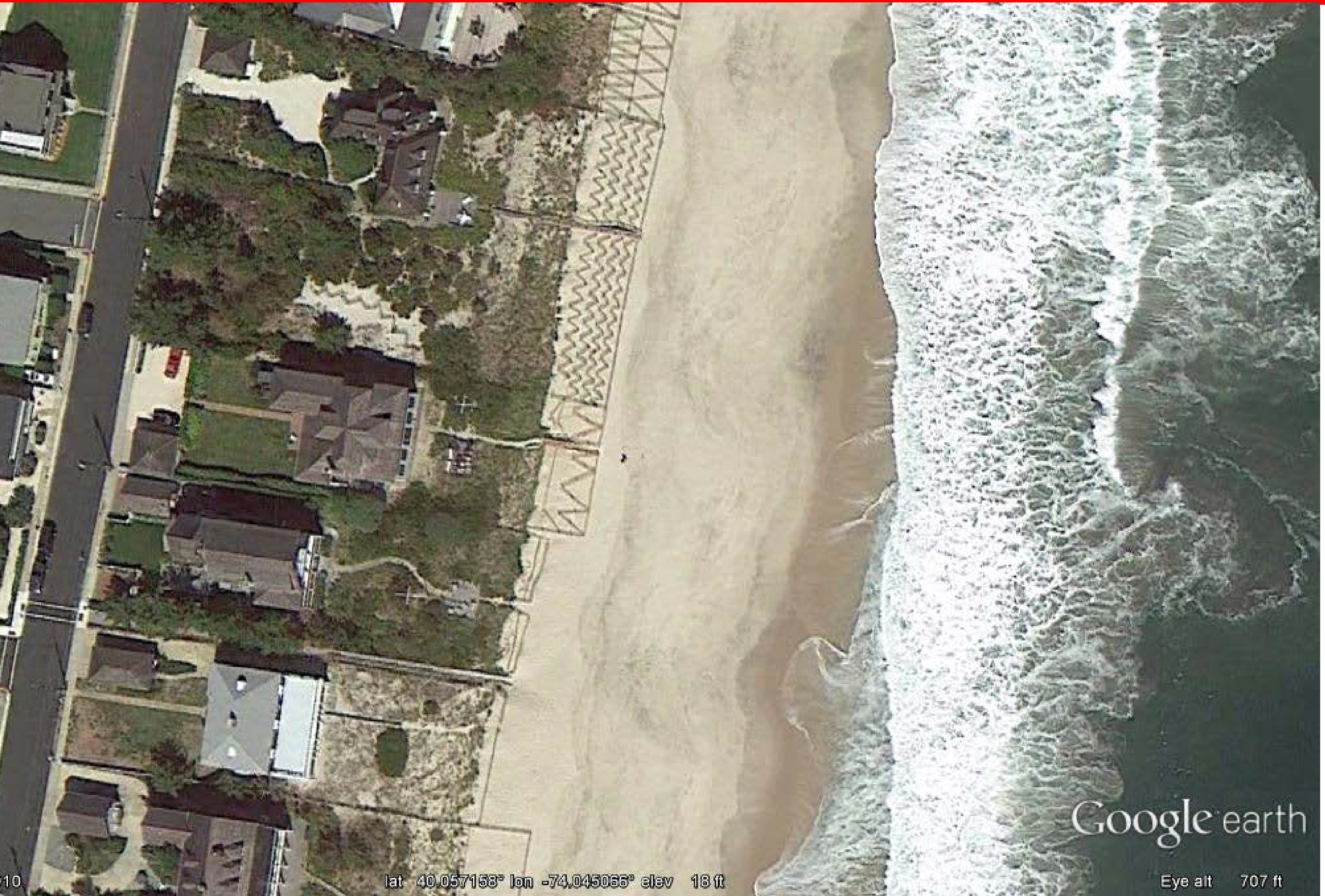

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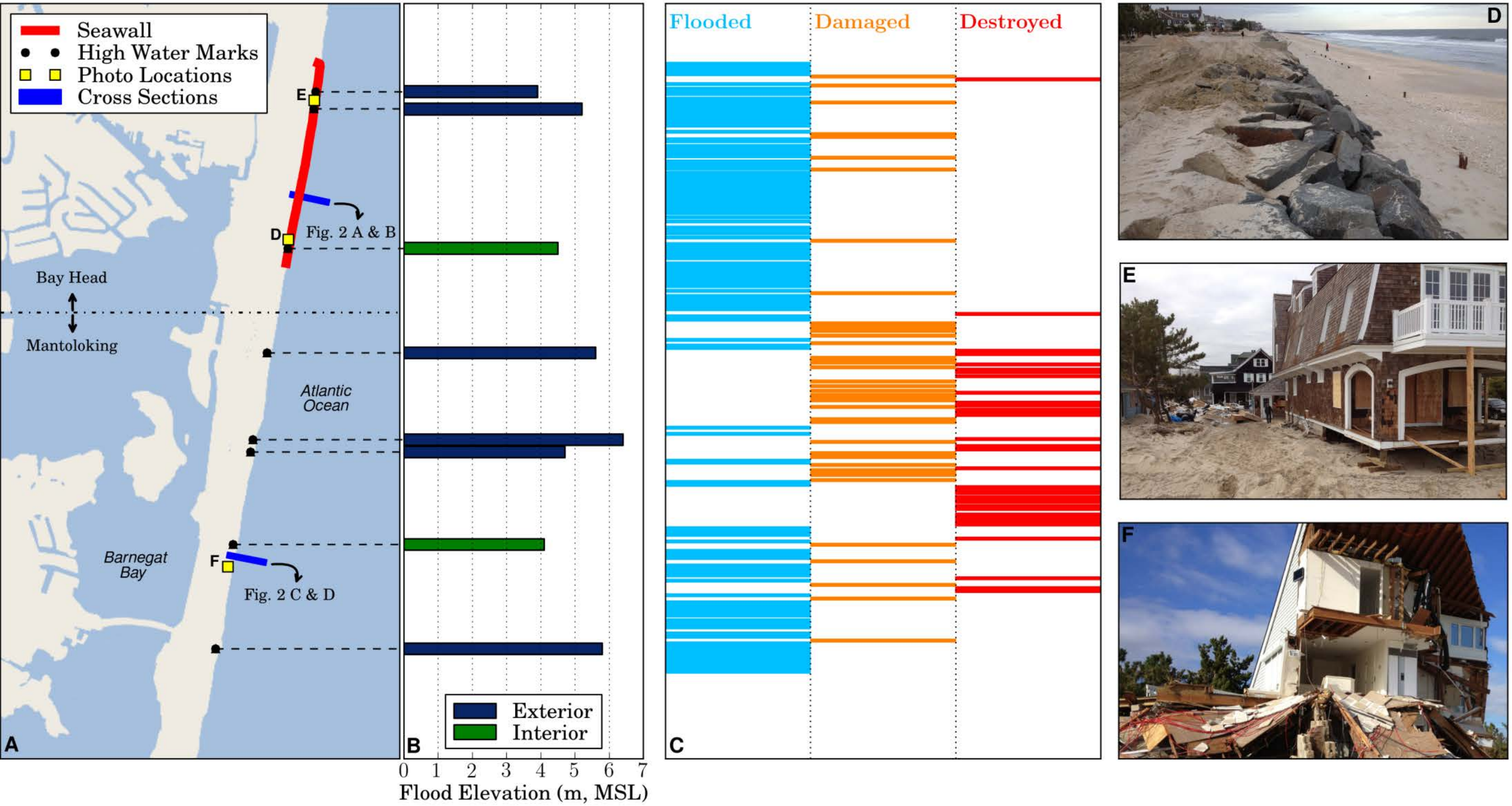

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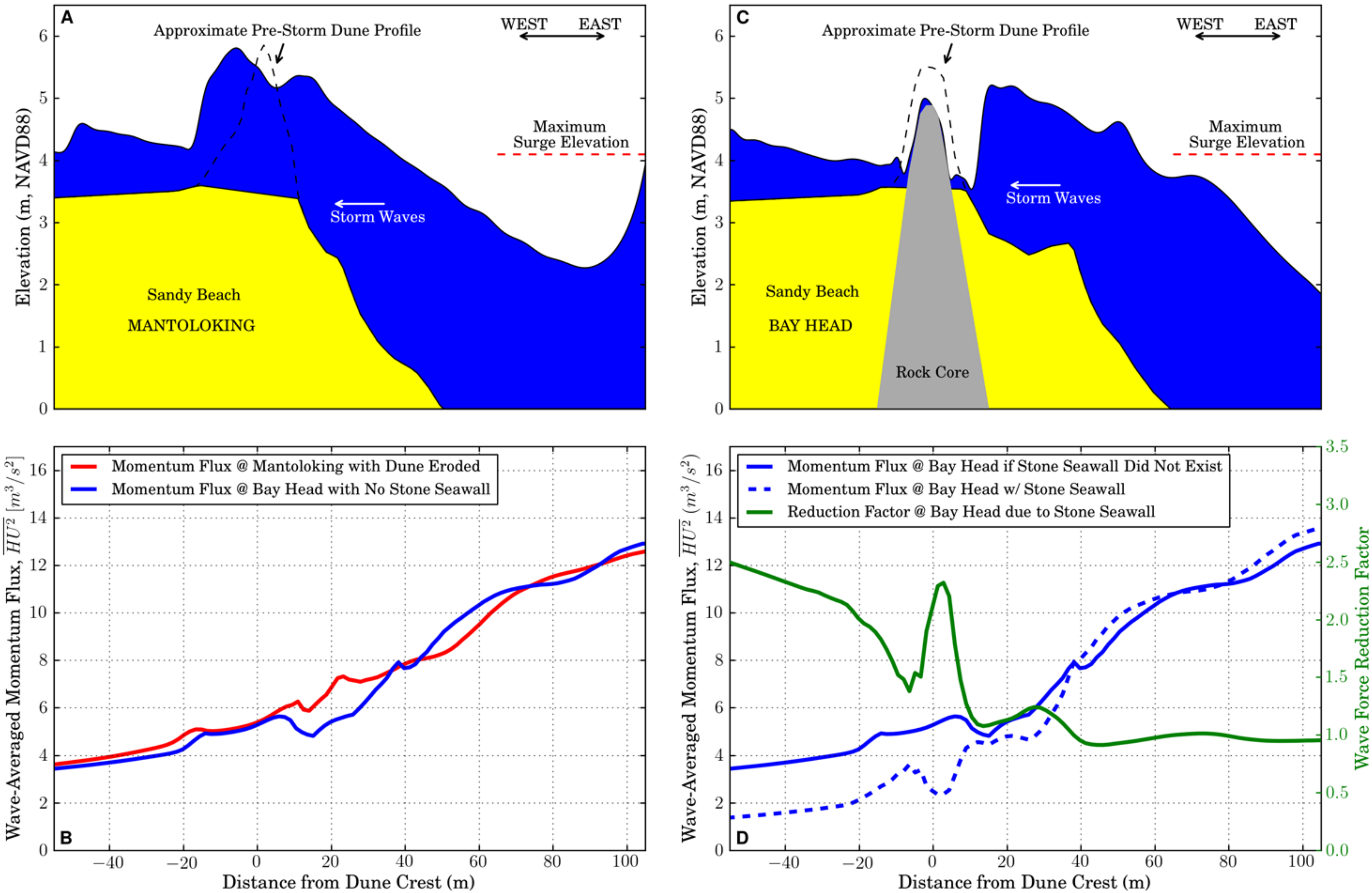
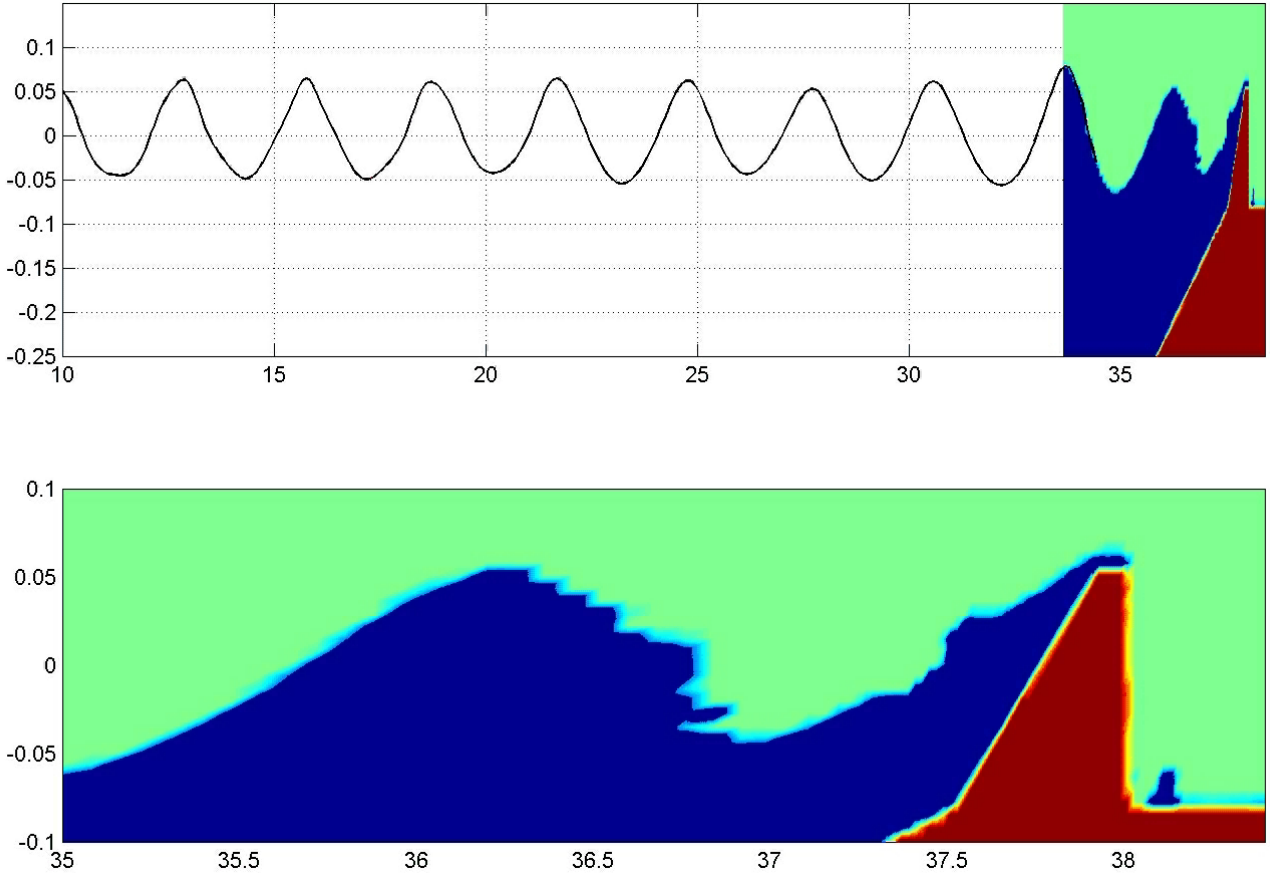


Wave Overtopping – Limitations with Boussinesq

- Wave overtopping is a turbulent, 3D problem
  - Strong vertical velocity and acceleration components



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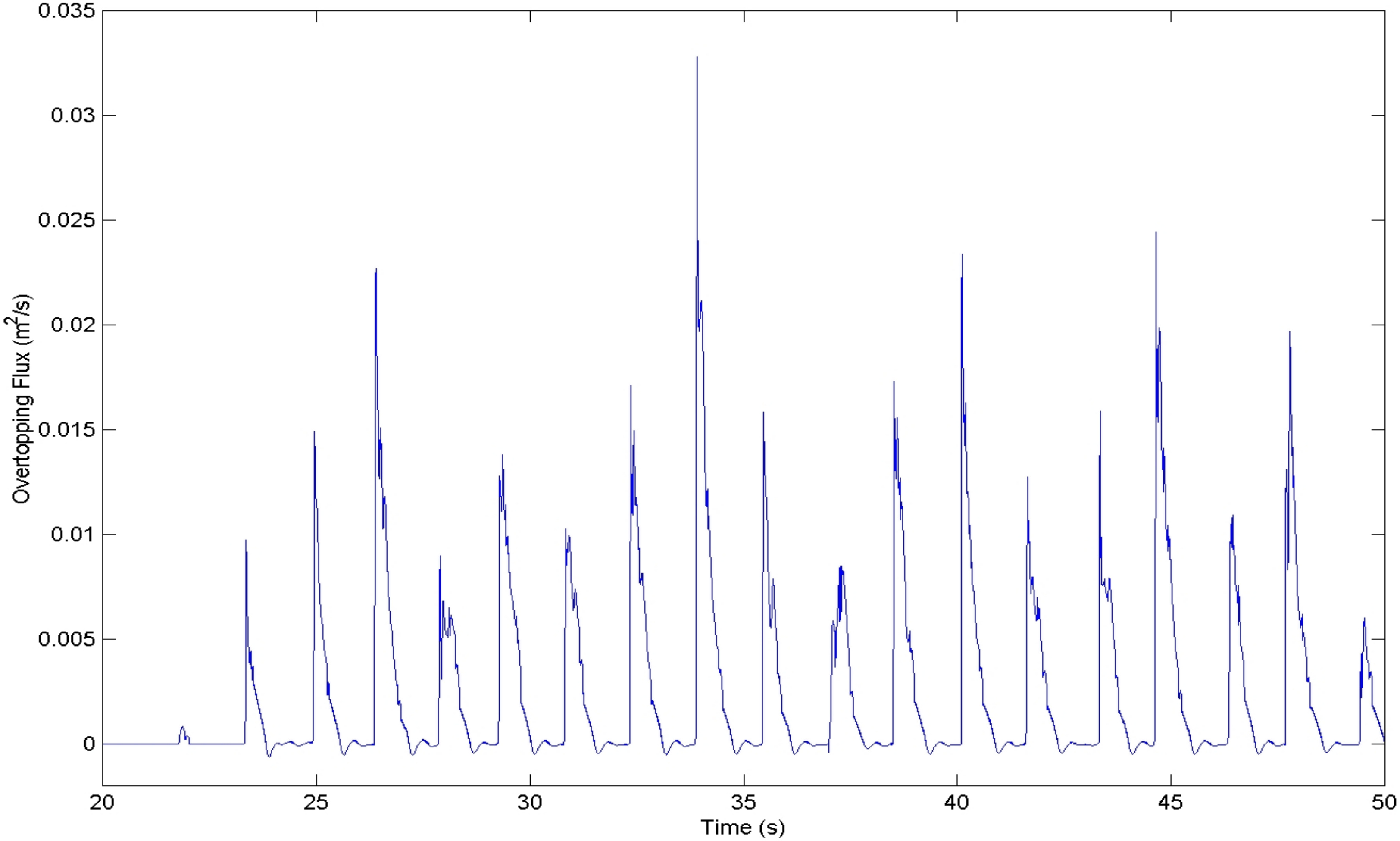
  - Strong vertical velocity components

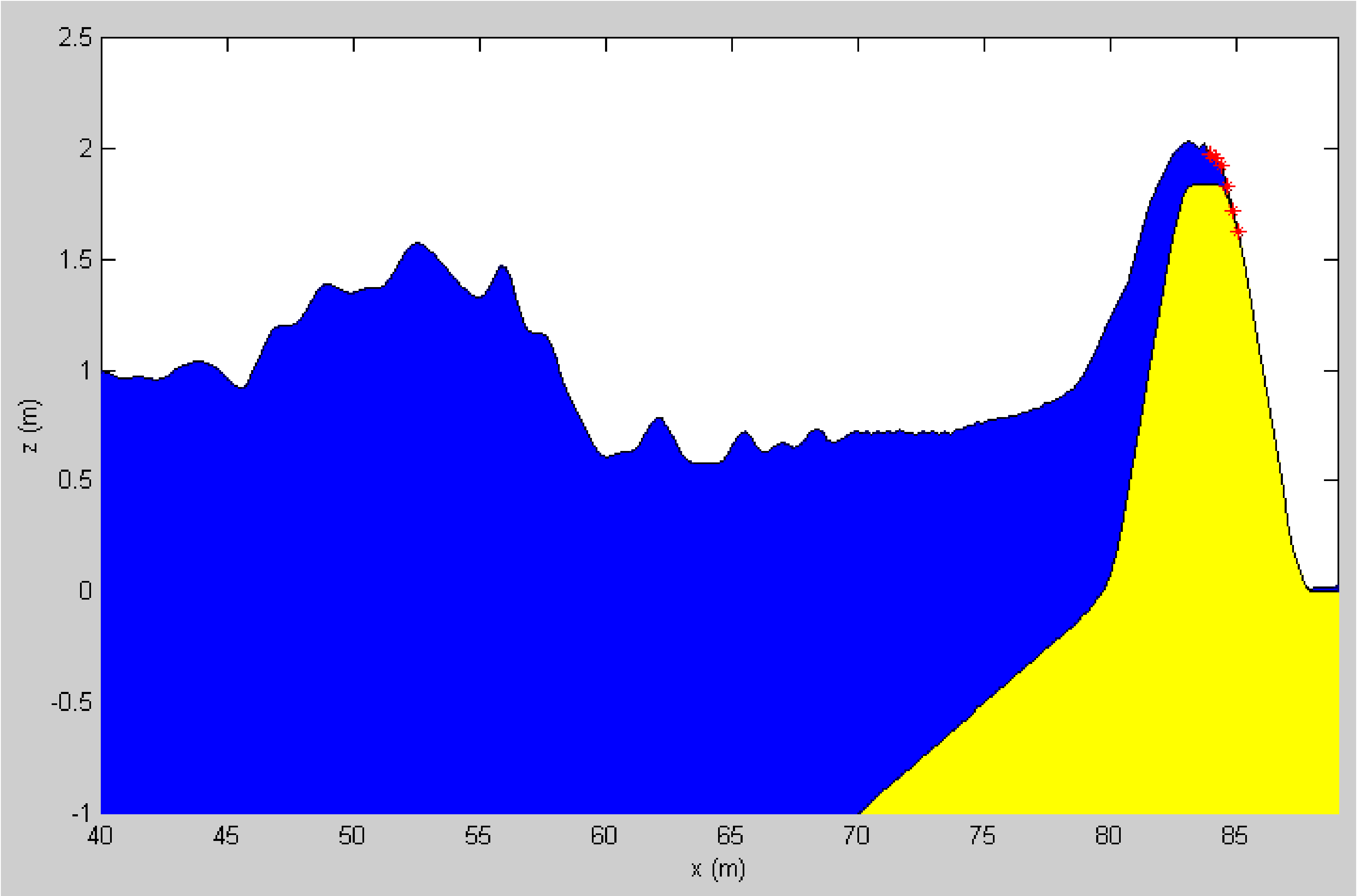
Wave Overtopping – Limitations with Boussinesq

- Turbulent interaction with reflected wave leads to a non-uniform overtopping time series, even for regular incident waves



Wave Overtopping – Limitations with Boussinesq

- Now, with the Boussinesq, we cannot model this turbulent 3D interaction
  - How important is this phenomenon to predicting overtopping???



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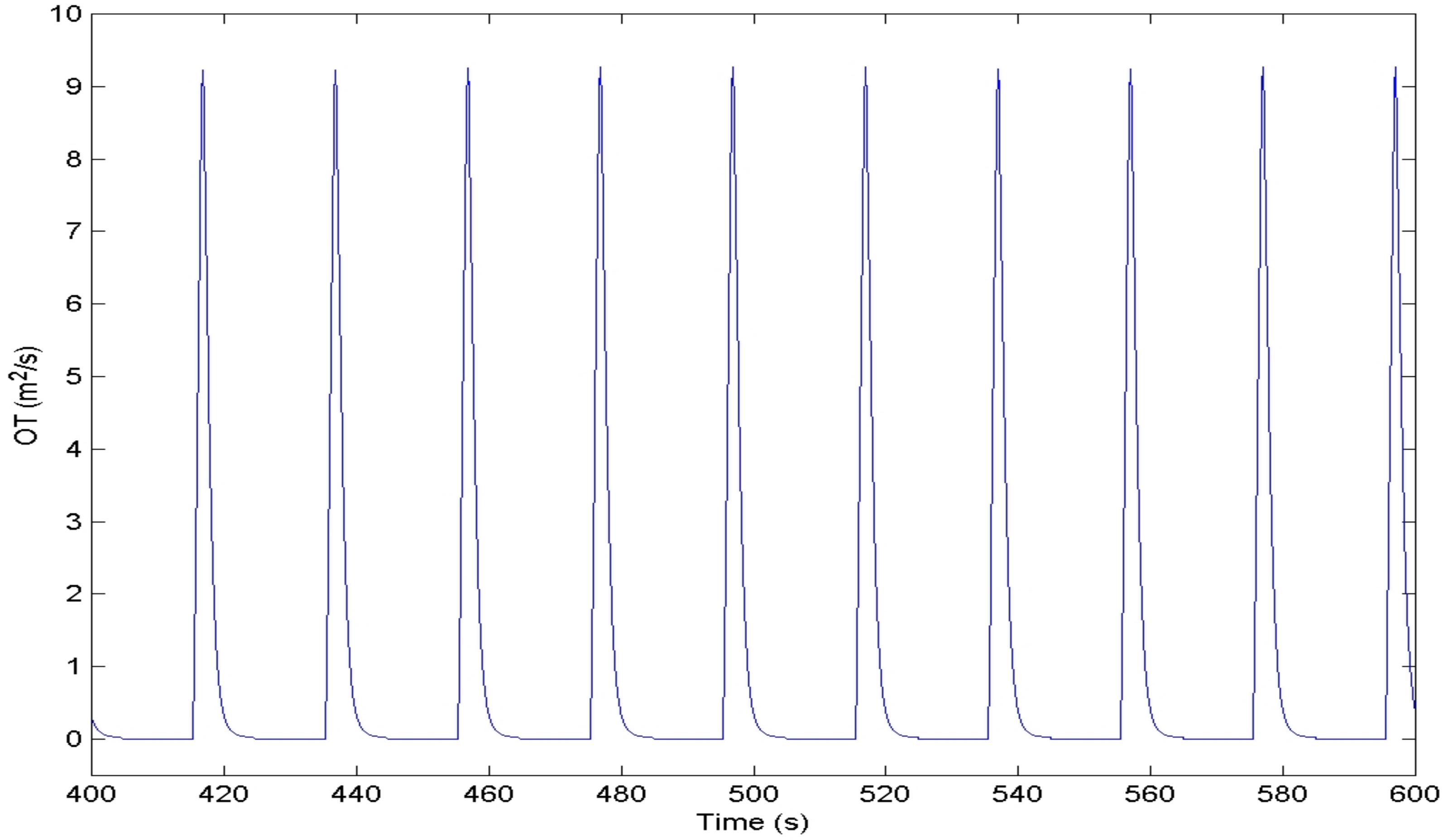
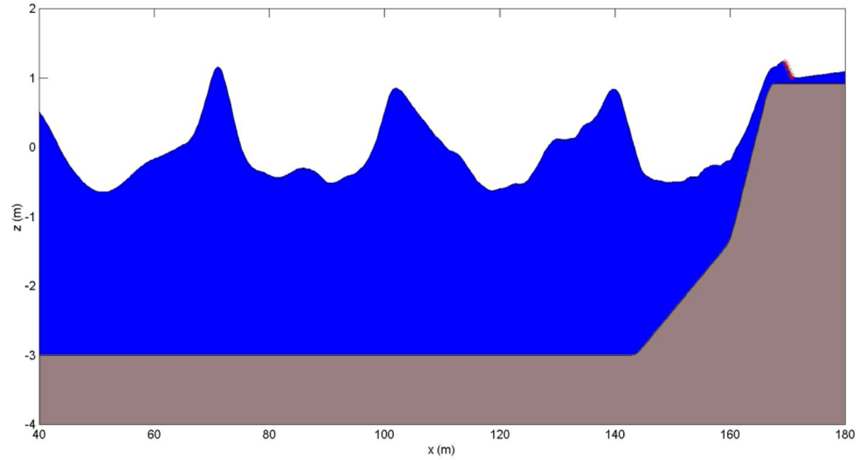
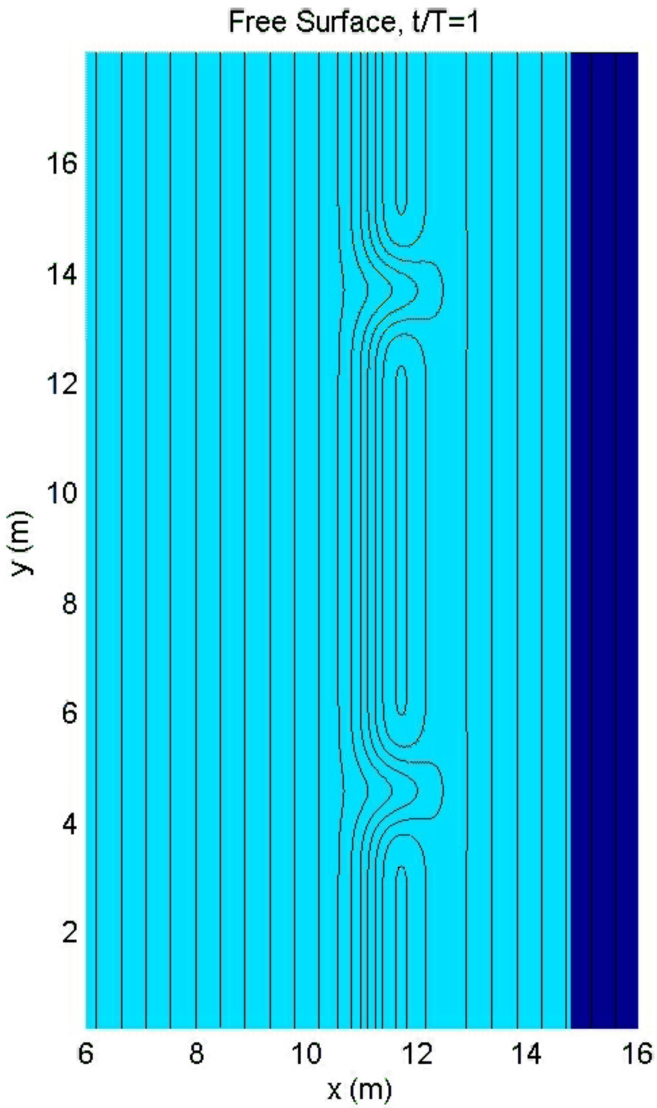


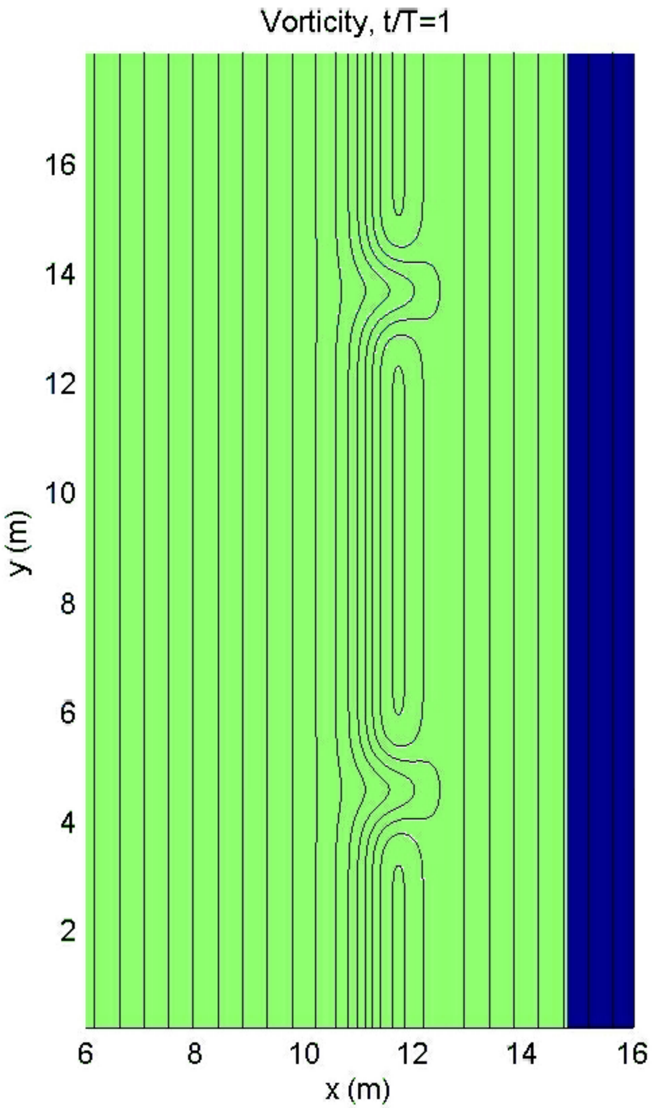
Wave Overtopping – Limitations with Boussinesq

- Now, with the Boussinesq, we cannot model this turbulent 3D interaction
  - How important is this phenomenon to predicting overtopping???
    - Experimental data comparisons indicate that, in the time-averaged sense, the Boussinesq provides reasonable results
    - Mean OT rate = OK
    - Variance statistics = not OK
      - Would need to use physical modeling or N-S modeling

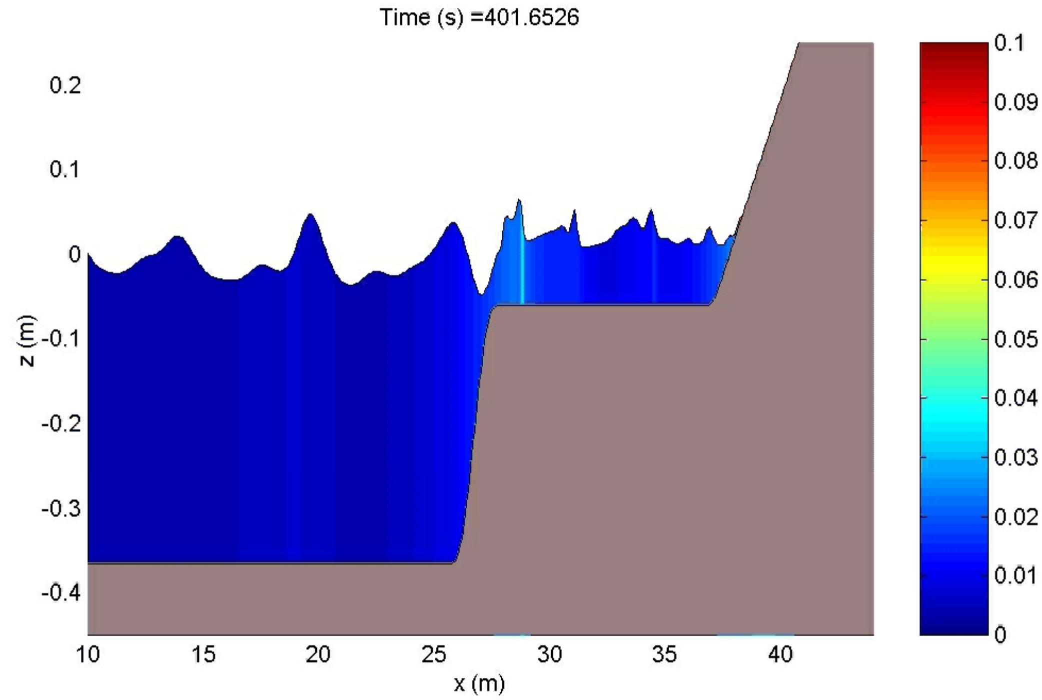


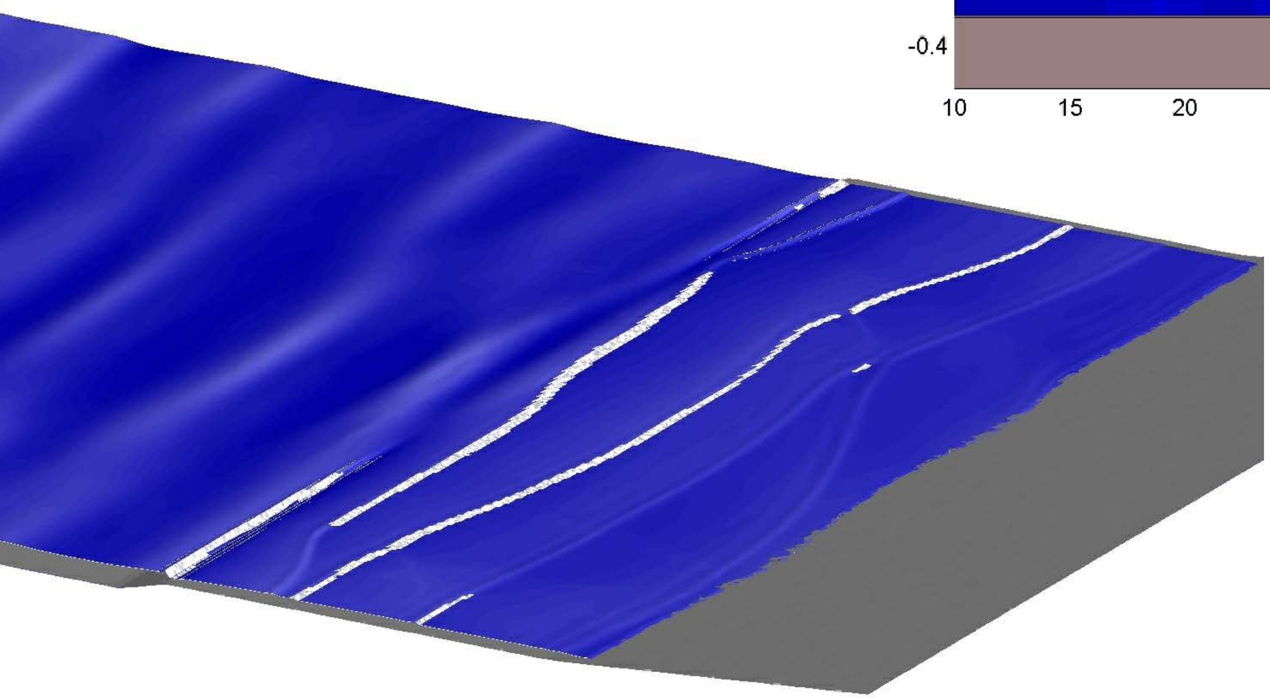
Generation of Rip Currents



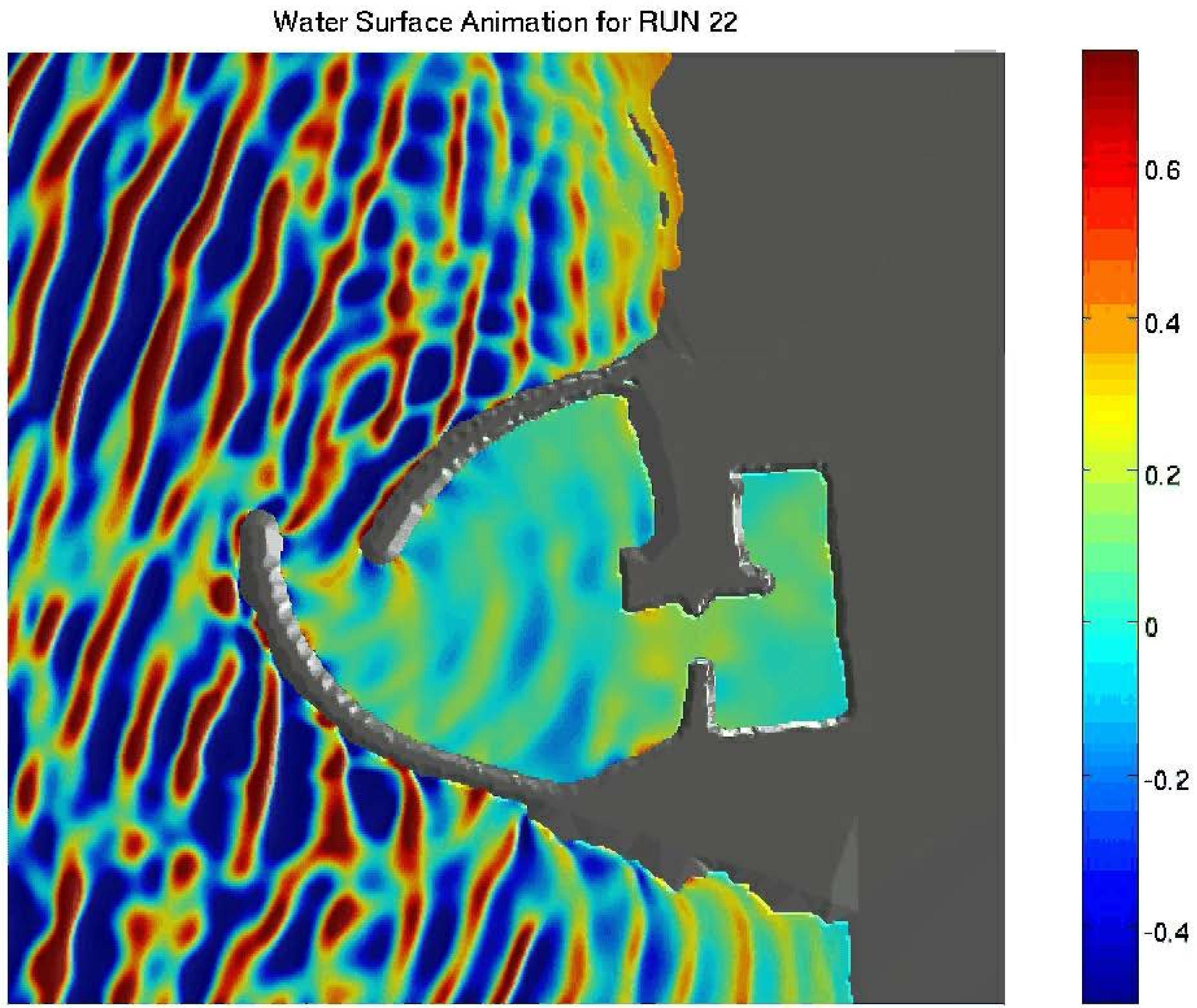


Wave Evolution of Reefs and Shelves





Harbor Resonance



Nearshore application of the Boussinesq on the large scale - Conclusions

- What can we do now?
  - Field scale simulation of waves in the time domain
    - Large domains (>100 km^2, 50 million grid points)
    - Long time simulations (days)
  - Wave induced currents
  - Tidal/river flows, inlets
  - Wind wave & tsunami interaction with nearshore structures and complex bathymetry
- What we want to do in the future…
  - Sediment transport (storm erosion AND recovery)
  - Coupled/hybrid modeling with fully 3D models
  - Think stochastic (need to decrease wall clock time)