UNIVERSITY of DELAWARE

East Coast Team: Benchmark Results

Jim Kirby, Stephan Grilli, Yong Sung Park,
Michael Shelby, Fengyan Shi, Babak Tehranirad

NTHMP Current Benchmark Workshop
February 9-10, 2015

NOAA NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION U.S. DEPARTMENT OF COMMERCE

Center for Applied Coastal Research

THE UNIVERSITY OF RHODE ISLAND

Model being benchmarked:

- Funwave-TVD (Shi et al (2012), *Ocean Modelling*)
  - Fully nonlinear Boussinesq equations of Chen (2006)
  - No extra boundary layer/vorticity corrections
  - Hybrid finite-volume/finite-difference scheme
  - MUSCLE-TVD finite volume scheme (3d order preferred, van Leer flux limiters, HLL Reimann reconstruction
  - 3d order SSP Runge-Kutta time integration, adaptive time stepping based on fixed CFL criterion
  - Either eddy viscosity or hybrid Boussinesq/NLSWE for breaking
  - Model previously benchmarked for NTHMP inundation mapping, used for all East Coast propagation and inundation modeling.

Governing equations (volume)

$$\eta_t + \nabla \cdot \mathbf{M} = 0 \qquad \mathbf{M} = H\{\mathbf{u}_\alpha + \bar{\mathbf{u}}_2\}$$

$$\bar{\mathbf{u}}_2 = \frac{1}{H}\int_{-h}^{\eta} \mathbf{u}_2(z)dz$$

$$= \left(\frac{z_\alpha^2}{2} - \frac{1}{6}(h^2 - h\eta + \eta^2)\right)\nabla B + \left(z_\alpha + \frac{1}{2}(h-\eta)\right)\nabla A$$

$$A = \nabla \cdot (h\mathbf{u}_\alpha)$$

$$B = \nabla \cdot \mathbf{u}_\alpha$$

Governing equations (momentum)

$$\mathbf{u}_{\alpha,t} + (\mathbf{u}_\alpha \cdot \nabla)\mathbf{u}_\alpha + g\nabla\eta + \mathbf{V}_1 + \mathbf{V}_2 + \mathbf{V}_3 + \mathbf{R} = 0$$

$$\mathbf{V}_1 = \left\{\frac{z_\alpha^2}{2}\nabla B + z_\alpha \nabla A\right\}_t - \nabla\left[\frac{\eta^2}{2}B_t + \eta A_t\right]$$

$$\mathbf{V}_2 = \nabla\left\{(z_\alpha - \eta)(\mathbf{u}_\alpha \cdot \nabla)A + \frac{1}{2}(z_\alpha^2 - \eta^2)(\mathbf{u}_\alpha \cdot \nabla)B + \frac{1}{2}[A + \eta B]^2\right\}$$

$$\mathbf{V}_3 = \omega_0 \mathbf{i}^z \times \bar{\mathbf{u}}_2 + \omega_2 \mathbf{i}^z \times \mathbf{u}_\alpha$$

$$\omega_0 = (\nabla \times \mathbf{u}_\alpha) \cdot \mathbf{i}^z = v_{\alpha,x} - u_{\alpha,y}$$

$$\omega_2 = (\nabla \times \bar{\mathbf{u}}_2) \cdot \mathbf{i}^z = z_{\alpha,x}(A_y + z_\alpha B_y) - z_{\alpha,y}(A_x + z_\alpha B_x)$$

Frictional effects:

Quadratic friction with drag coefficient $C_{D,}$ or Manning's n

$$\tau_b^{x,y} = \frac{1}{H} C_D |\mathbf{u}|(u,v)$$

Either C_D or n can be spatially variable (not used here) and input as gridded data.

Breaking algorithms

(1) Eddy viscosity formulation: Kennedy et al (2000)

$$\mathbf{R}_{bx} = \frac{1}{h+\eta}\left([\nu((h+\eta)u_\alpha)_x]_x + \frac{1}{2}[\nu((h+\eta)u_\alpha)_y + \nu((h+\eta)v_\alpha)_x]_y \right)$$

$$\mathbf{R}_{by} = \frac{1}{h+\eta}\left([\nu((h+\eta)v_\alpha)_y]_y + \frac{1}{2}[\nu((h+\eta)u_\alpha)_y + \nu((h+\eta)v_\alpha)_x]_x \right)$$

$$\nu = B\delta_b^2(h|+\eta)\eta_t \qquad B = \begin{cases} 1, & \eta_t \geq 2\eta_t^* \\ \dfrac{\eta_t}{\eta_t^*} - 1, & \eta_t^* < \eta_t \leq 2\eta_t^* \\ 0, & \eta_t \leq \eta_t^* \end{cases}$$

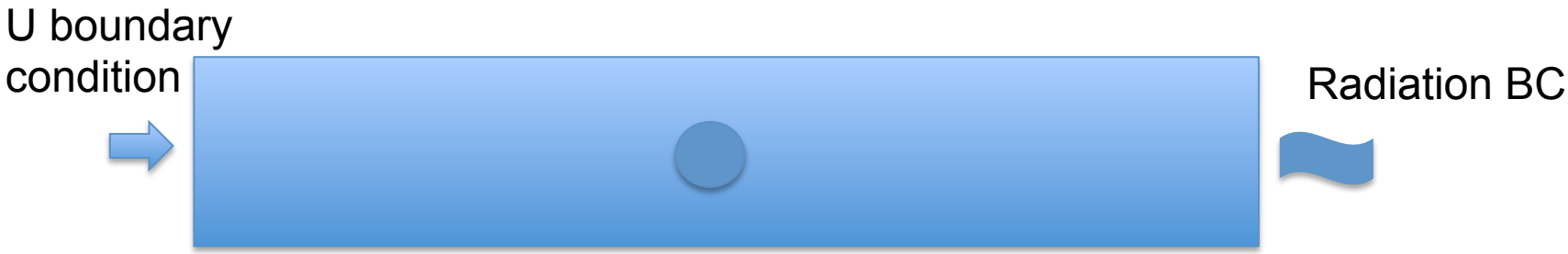
Breaking algorithms

(2) Hybrid formulation (Shi et al (2012), Tonelli and Petti, Roeber et al)

Switch from Boussinesq to Nonlinear Shallow Water Equations (i.e., turn off dispersion and let a shock form) if a criterion (or criteria) are exceeded.

Here, done when surface elevation/depth > 0.8

Benchmark Test # 1
Lloyd and Stansby experiment

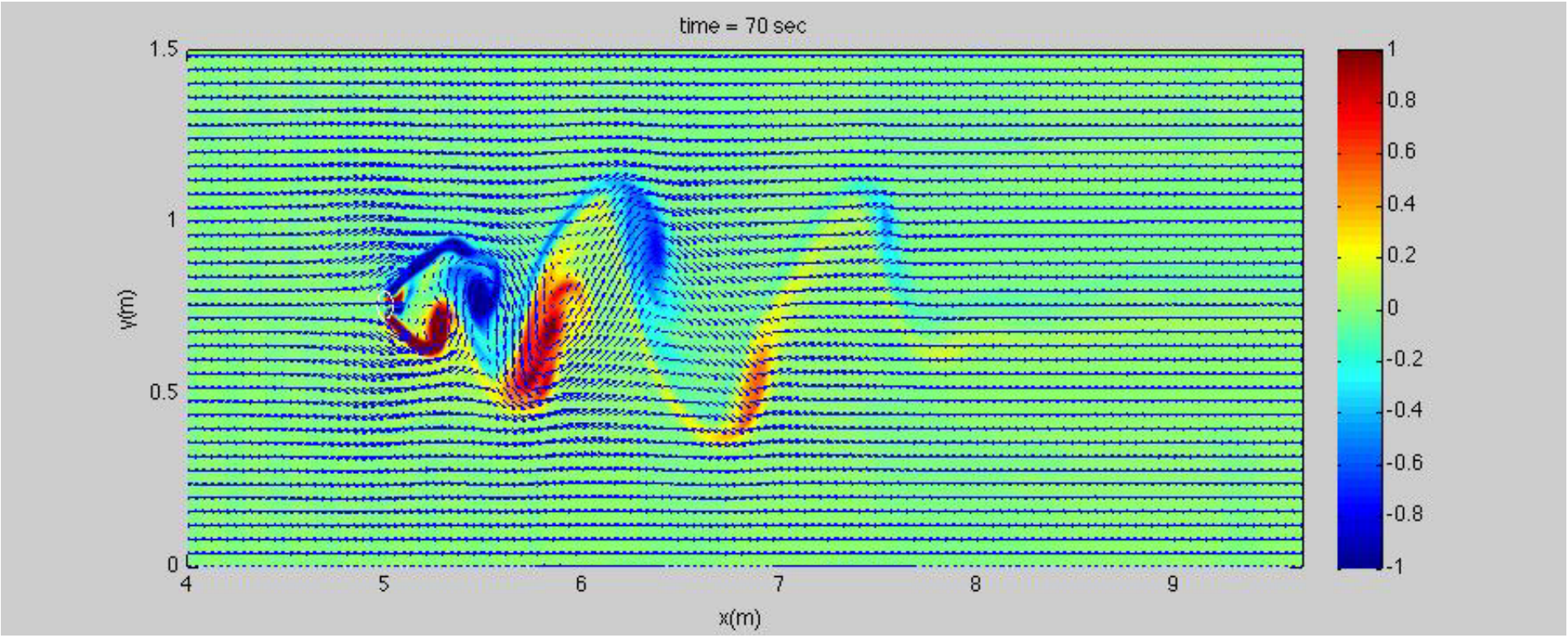


Radiation condition is simply a zero-gradient condition imposed on **η, u, v**

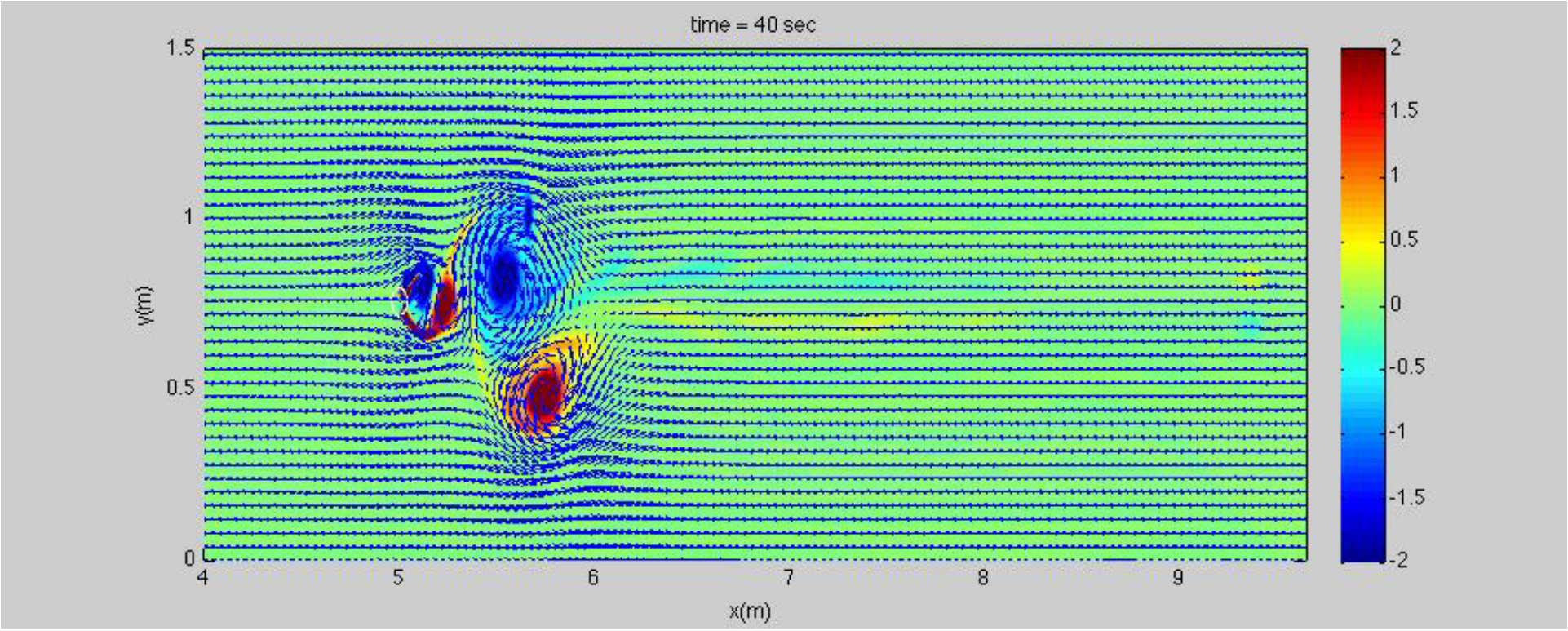
Model runs

	Dx(m)	Dy(m)	CFL	Cd
Cd test	0.01	0.01	0.5	0.0
Cd test	0.01	0.01	0.5	0.003
Cd test	0.01	0.01	0.5	0.006
Cd test	0.01	0.01	0.5	0.012
Coarse grid	0.03	0.0152	0.5	0.012
Coarse grid small Cd	0.03	0.0152	0.5	0.006
Fine grid	0.005	0.005	0.5	0.012
Small dt	0.01	0.01	0.25	0.012

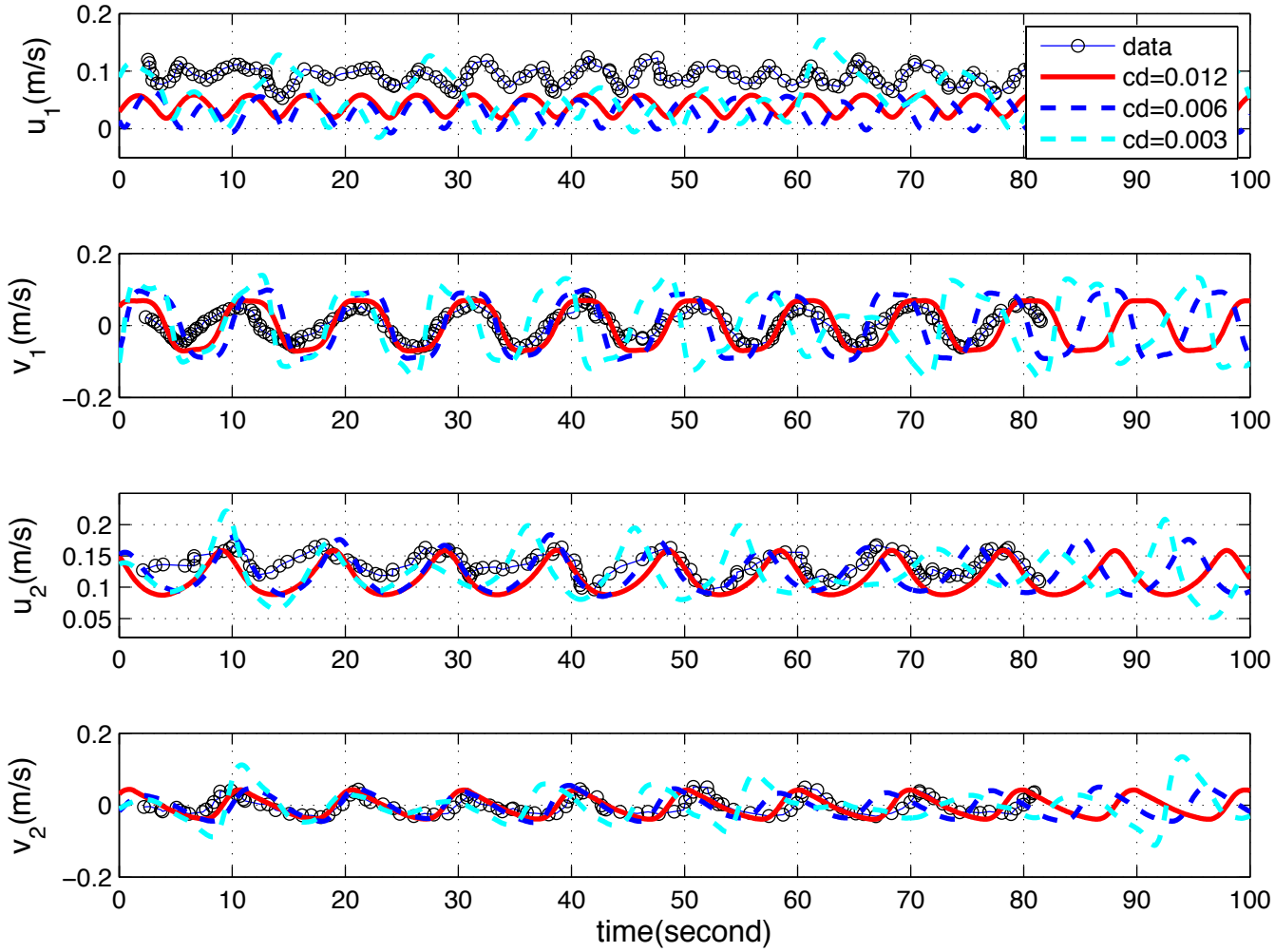
Baseline model: dx=dy=0.01m, CFL=0.5, Cd= 0.012



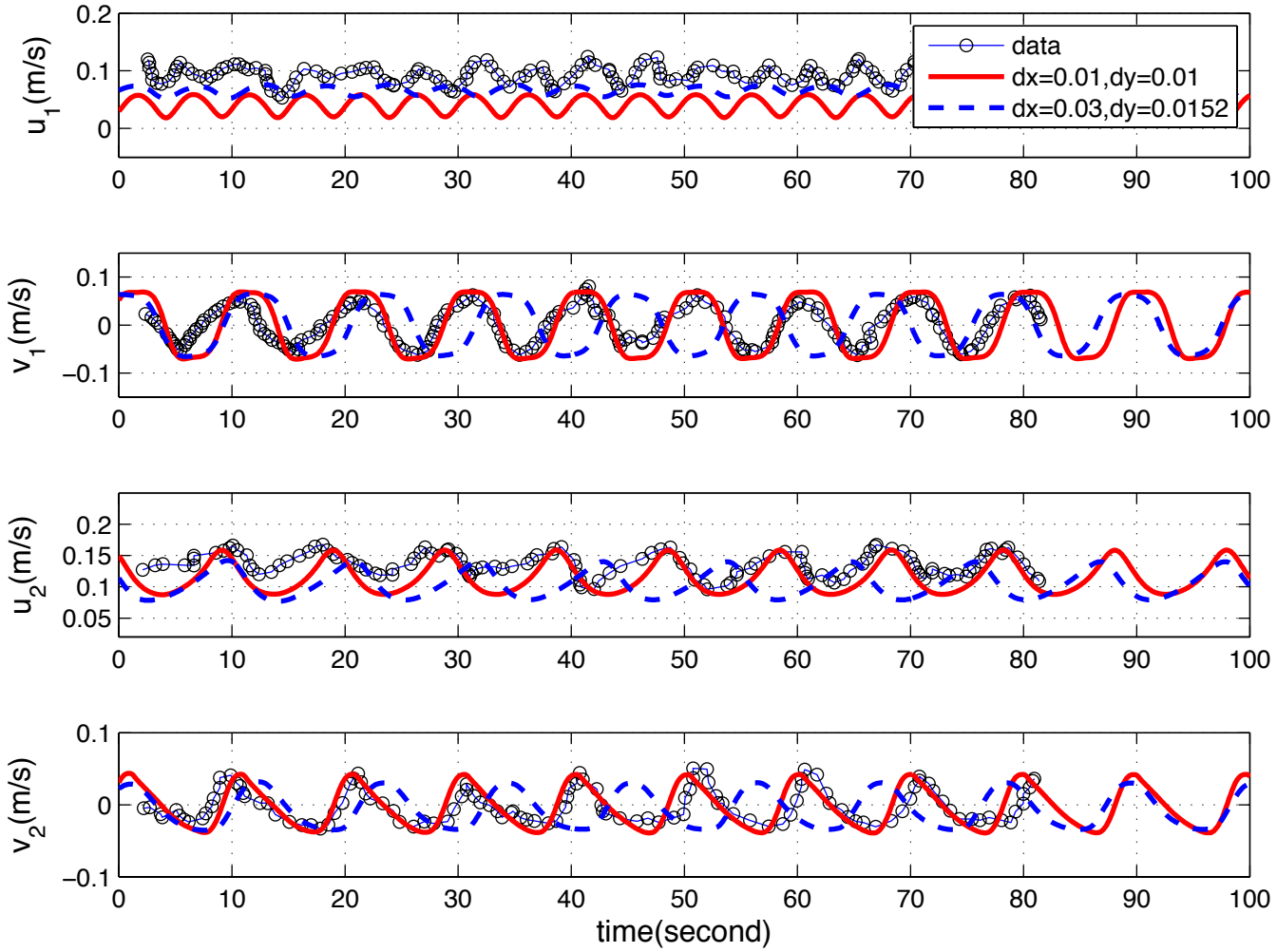
Non-friction model: dx=dy=0.01m, CFL=0.5, Cd= 0.0



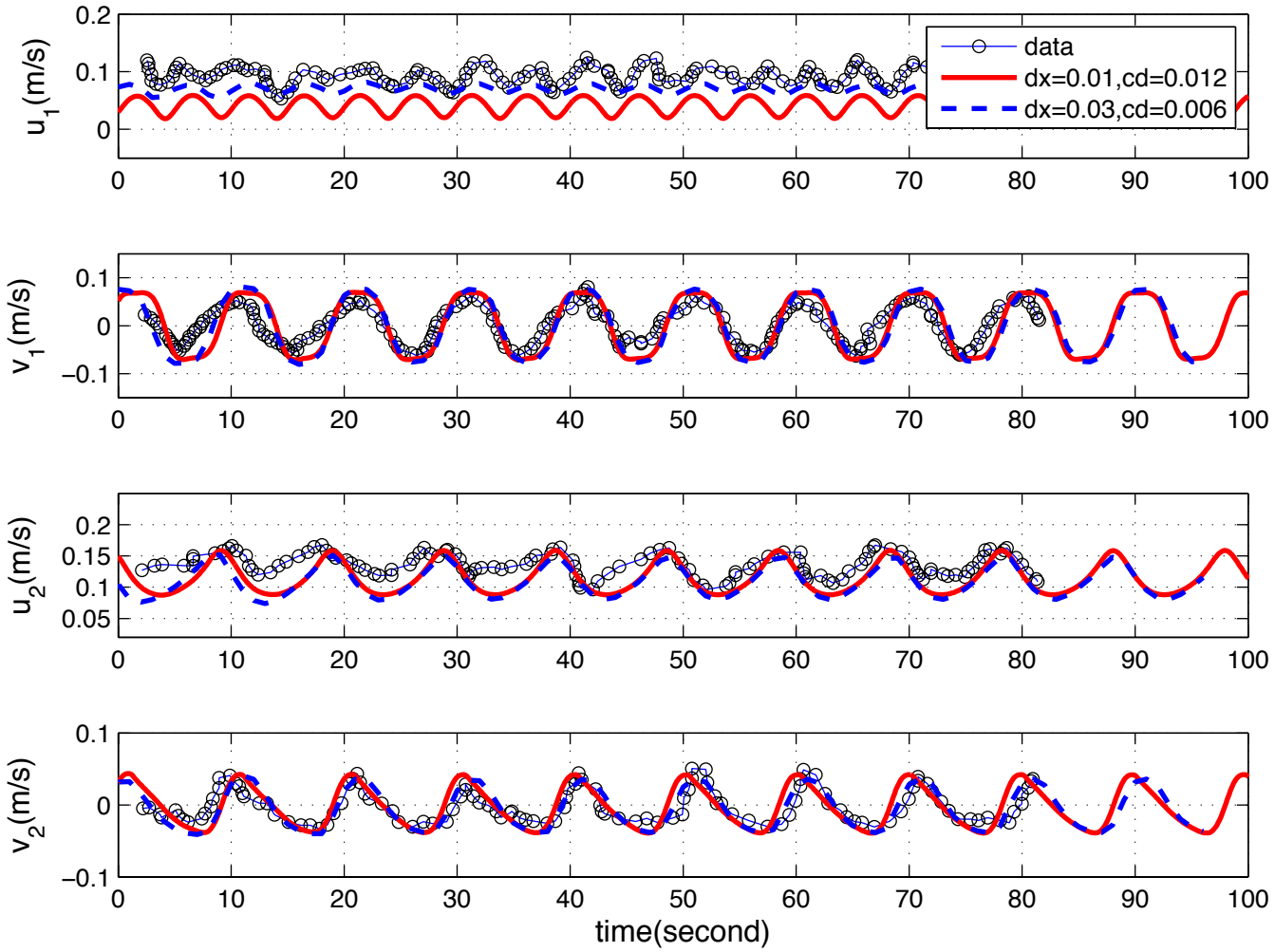
Tests with different C_d's at fixed resolution (dx=dy=0.01m)



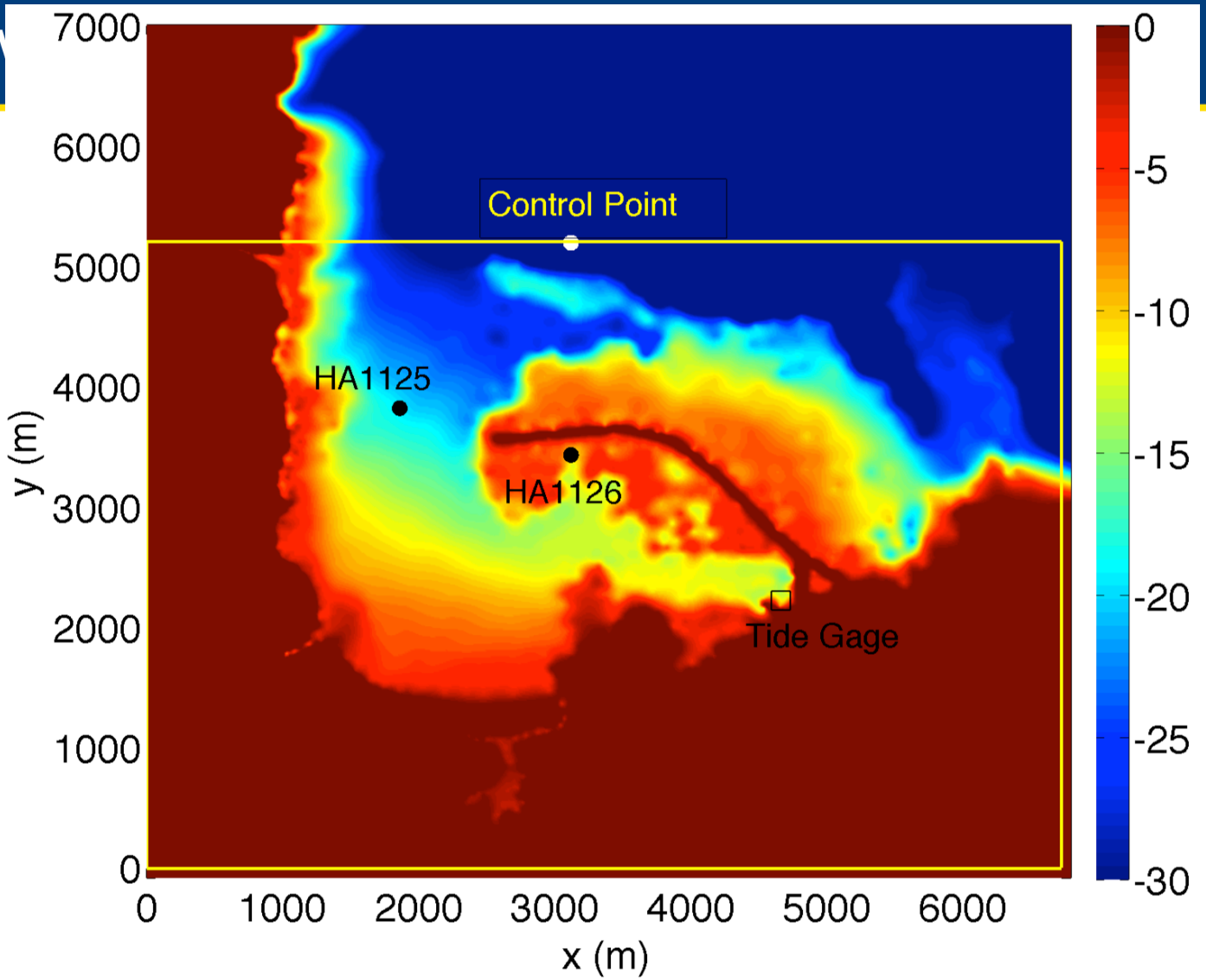
Baseline vs. a coarser grid, C_D= 0.012



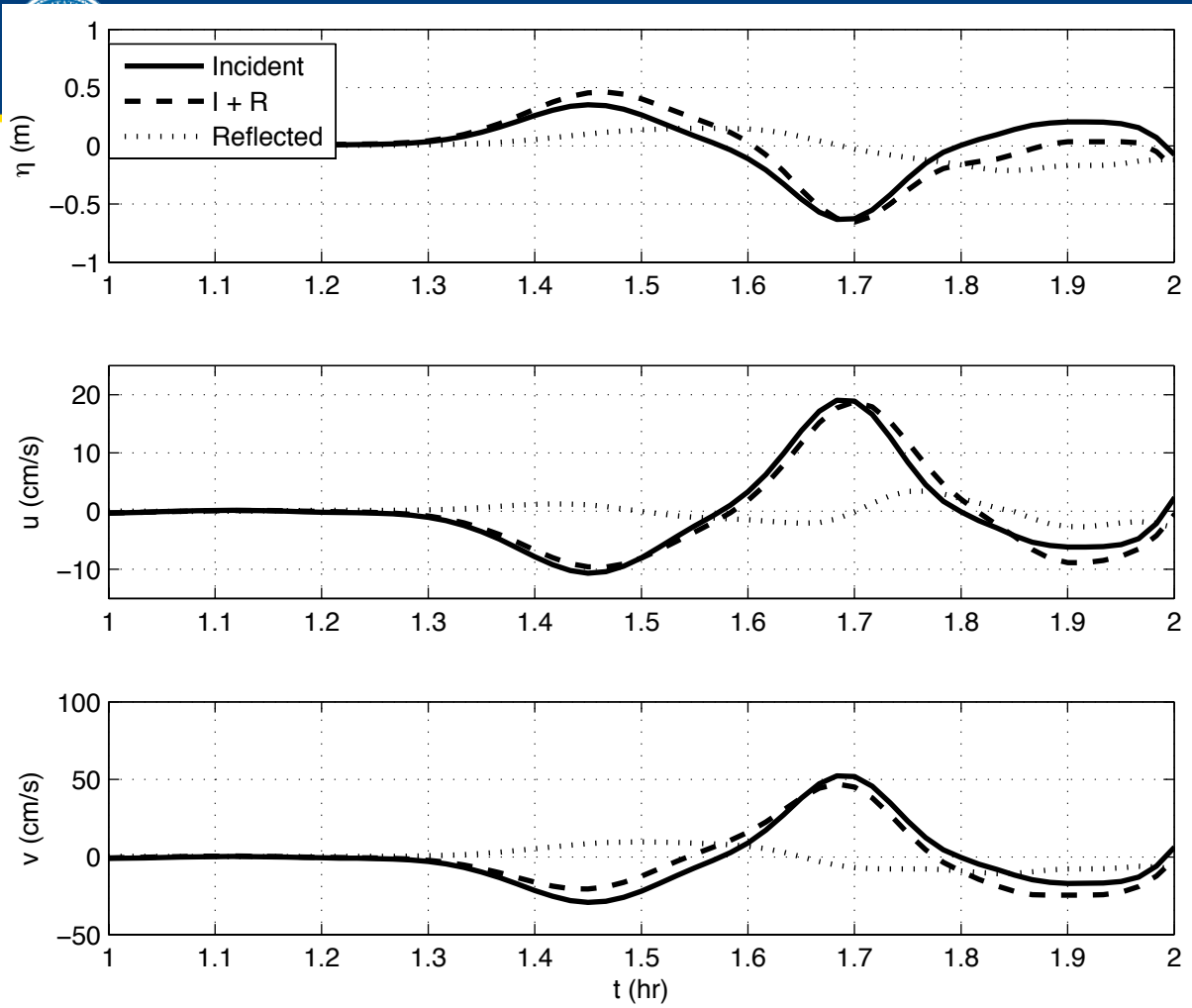
Baseline vs. a coarser grid but smaller Cd



Benchmark #2
Hilo Harbor



Bathymetry/topography (color scale in meter) in modeled area (model grids: 20, 10, 5 m resolution, footprint is yellow box). Yellow circle is input data point, black circles are ADCP, and black square is tide gage.



Upper boundary Condition:

$$\eta_i^k = \min\left(\hat{\eta}^k, 0.6h_i\right)$$

$$U_i^k = (1-R)\eta_i^k\sqrt{\frac{g}{h_i}}$$

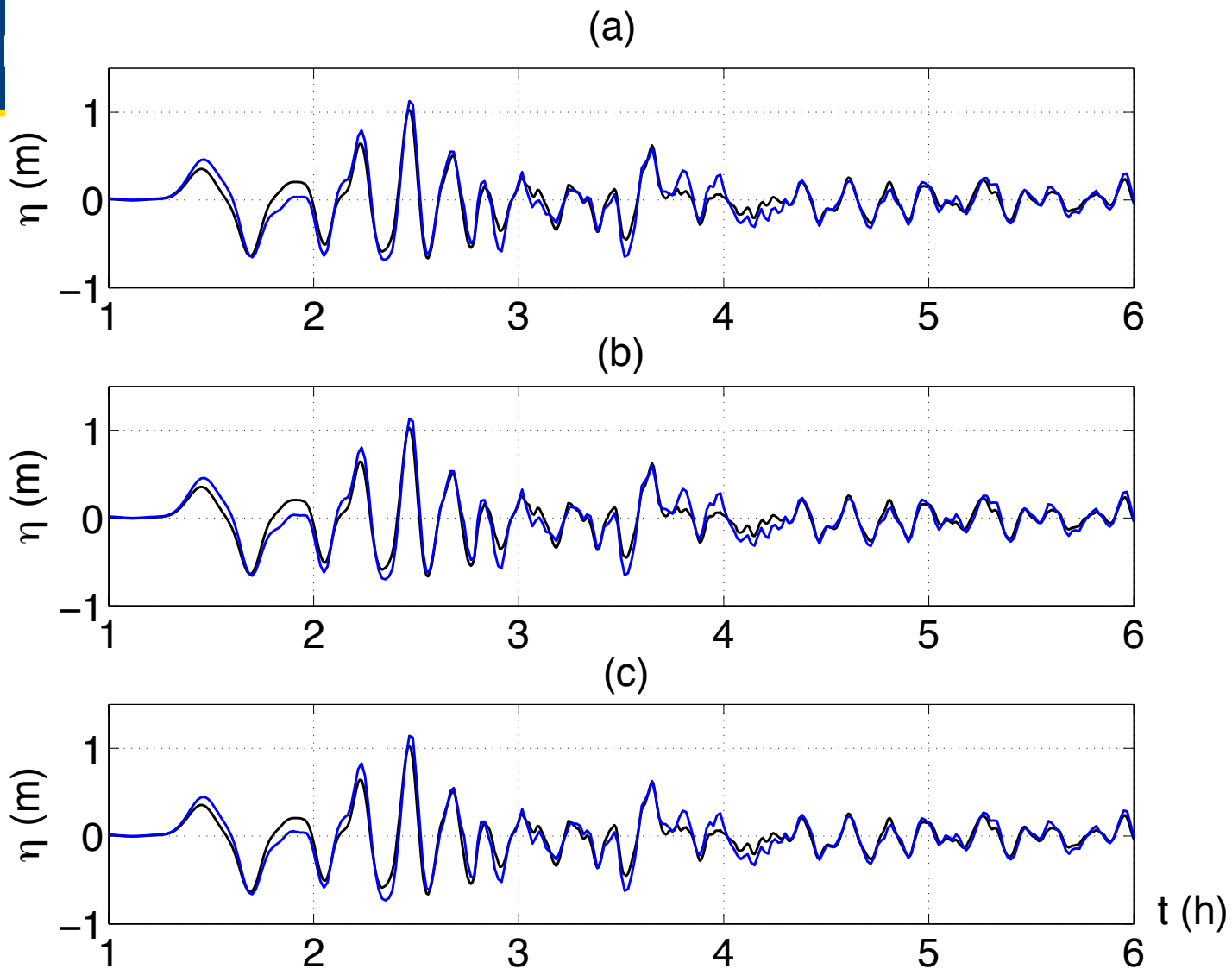
$$u_i^k = -U_i^k \sin\theta$$

$$v_i^k = -U_i^k \cos\theta$$

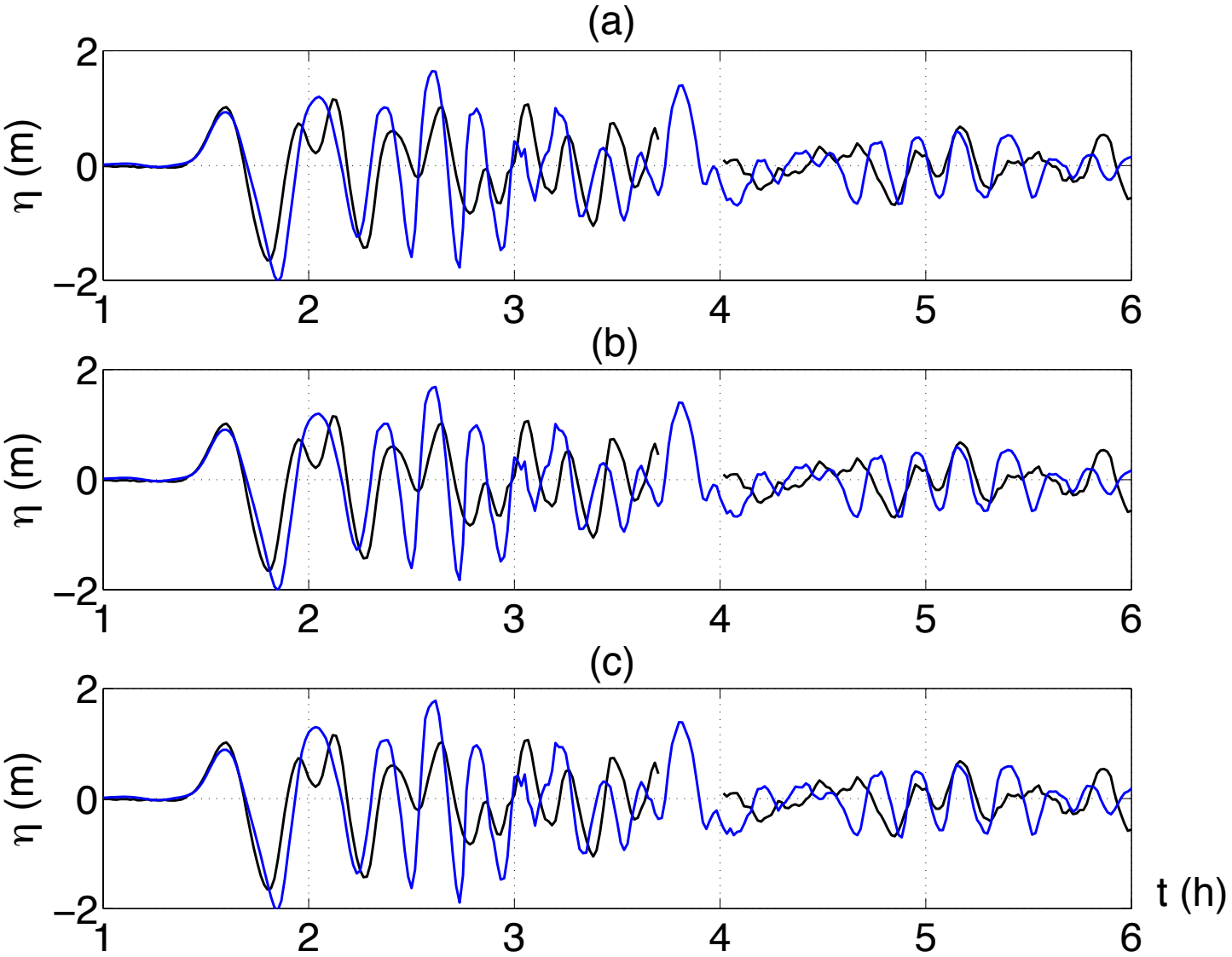
[Note correction for shallow water breaking]

Manning coeff: 0.025

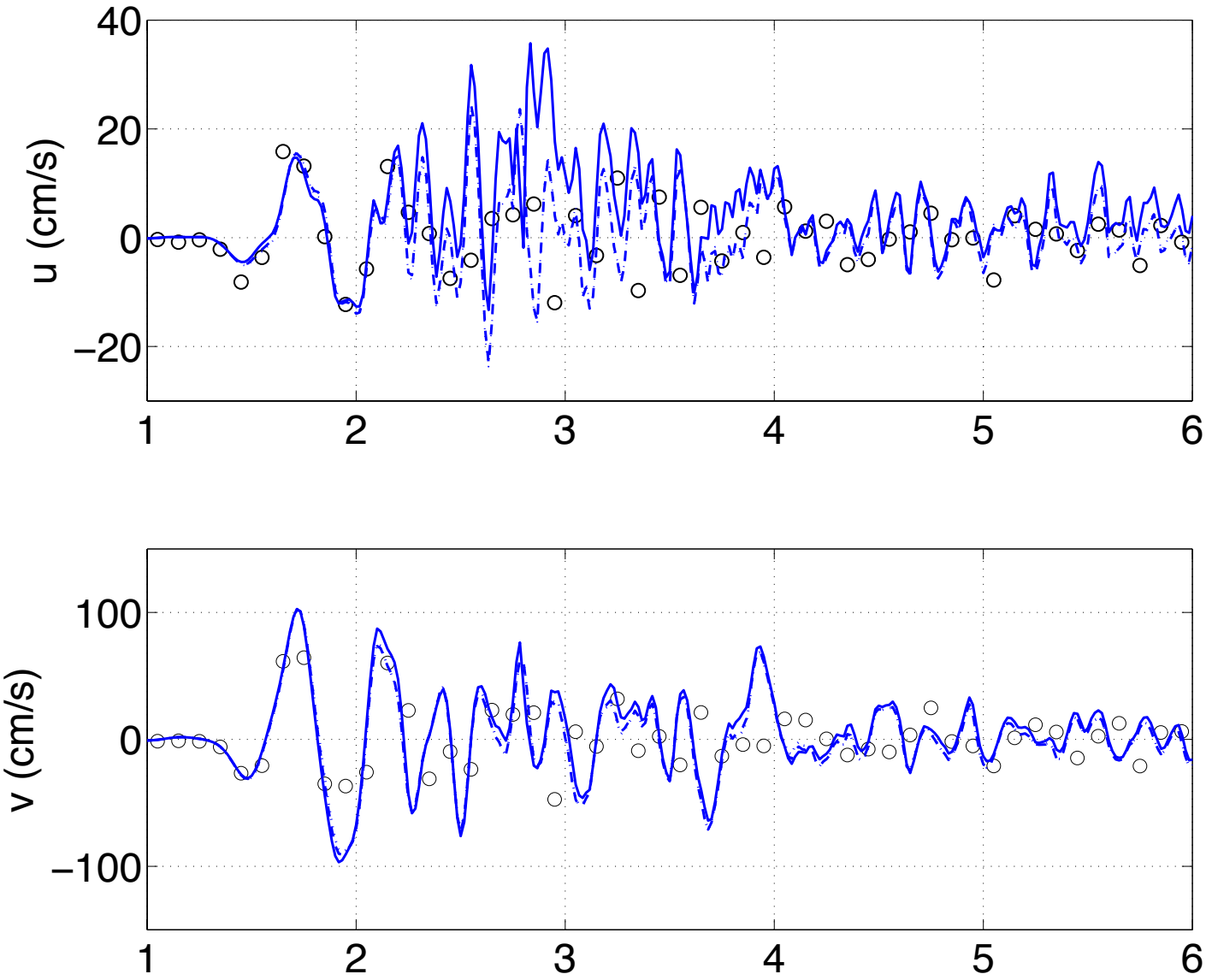
- **Iterations for correcting velocity input boundary condition to account for reflection in the model. Reflection coefficient *R*.**
- **Initially, *R* = 0 and $\theta = 0$; after *k* = 6 iterations => *R* = 0.4 and θ = 20 deg.**



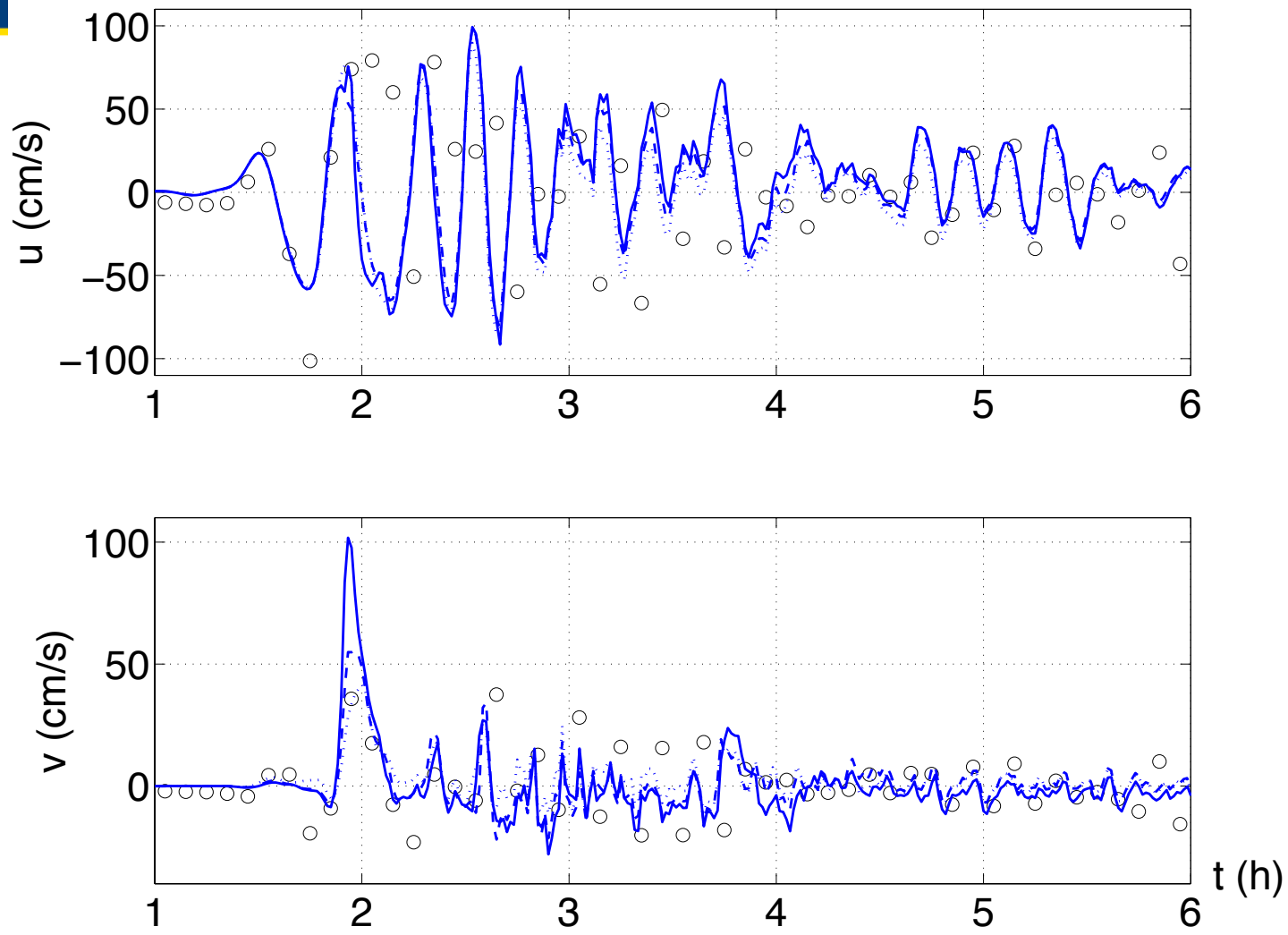
- **Surface elevation measured (black) and modeled (blue) at control point in: (a) 20 m, (b) 10 m; and (c) 5 m grids.**



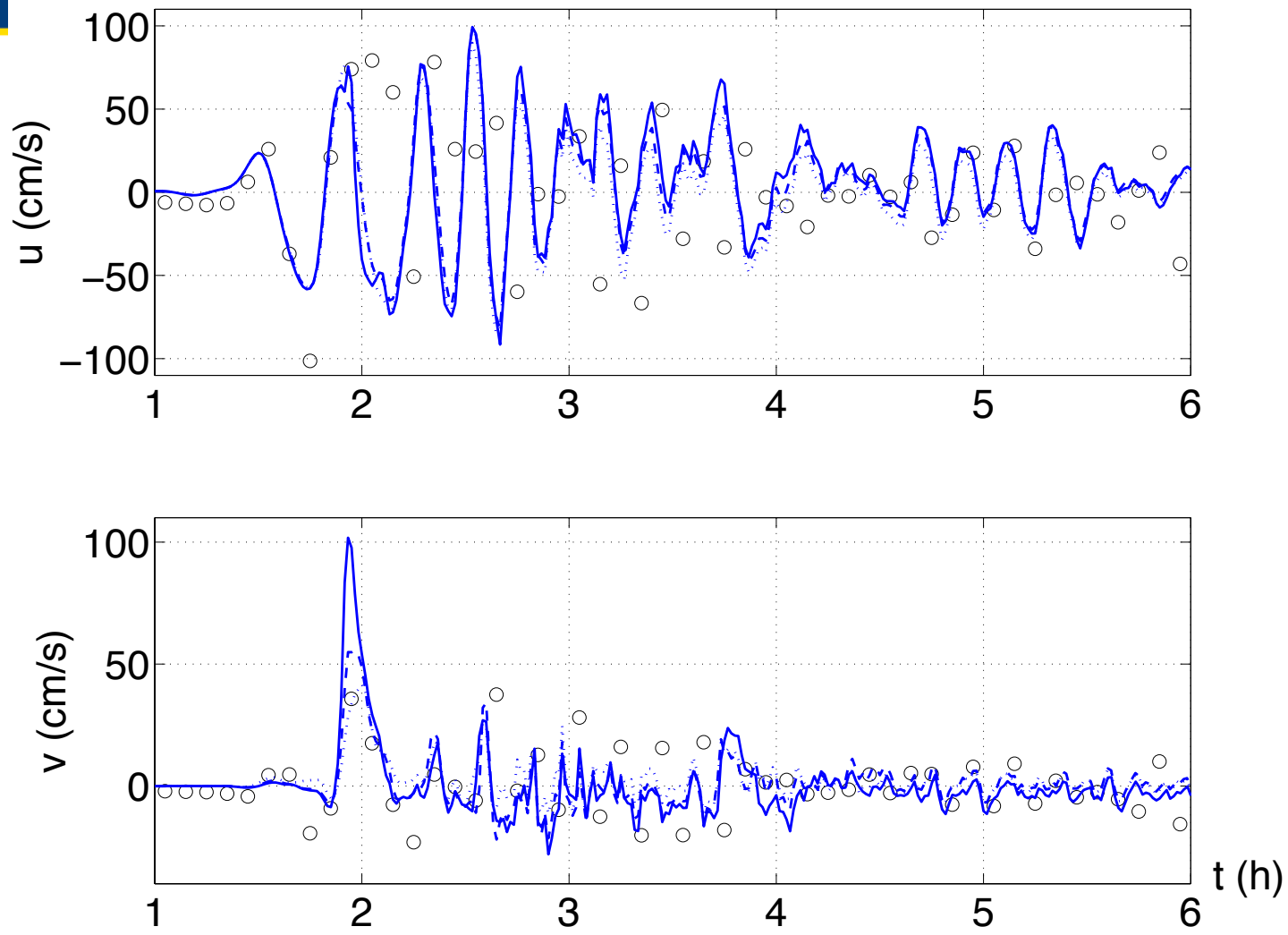
- **Surface elevation measured (black) and modeled (blue) at tide gage in: (a) 20 m, (b) 10 m; and (c) 5 m grids.**



- **Velocity components measured (black o) and modeled (blue) at ADCP 1125 in: (a) 20 m (dot blue), (b) 10 m (dash blue); and (c) 5 m (solid blue) grids.**



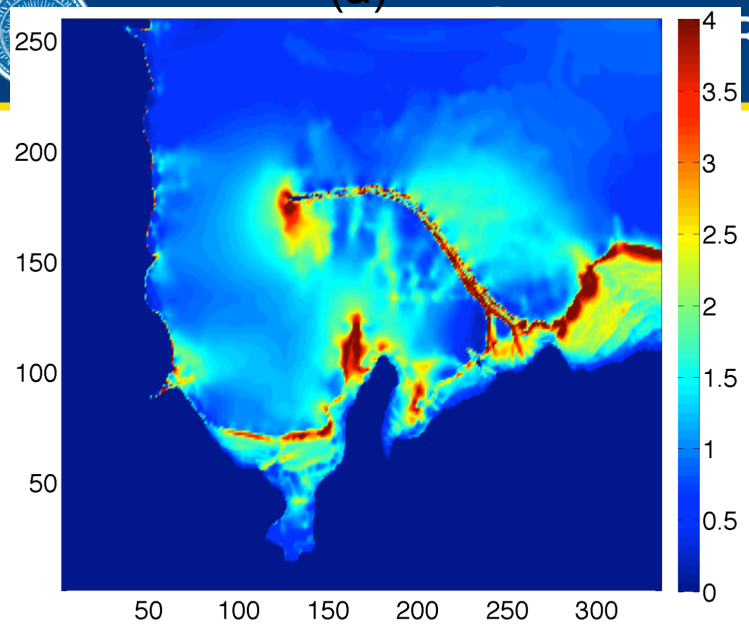
- **Velocity components measured (black o) and modeled (blue) at ADCP 1126 in: (a) 20 m (dot blue), (b) 10 m (dash blue); and (c) 5 m (solid blue) grids.**

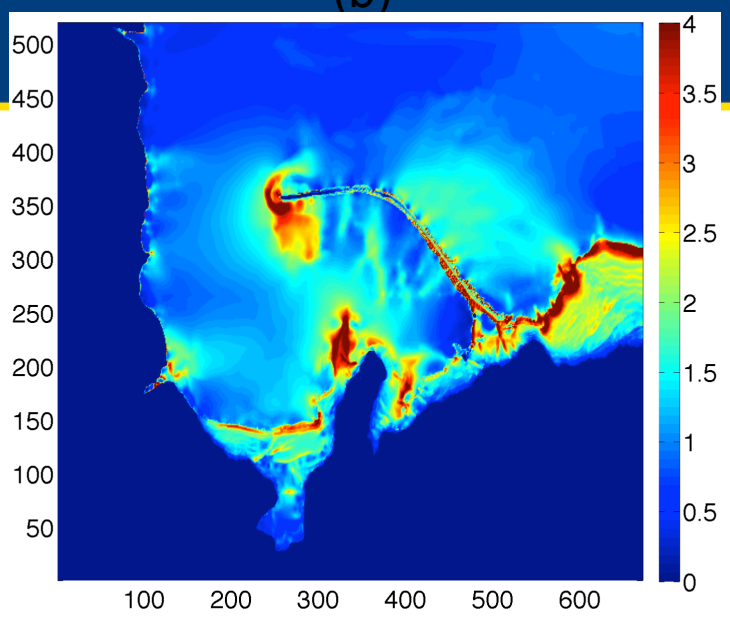


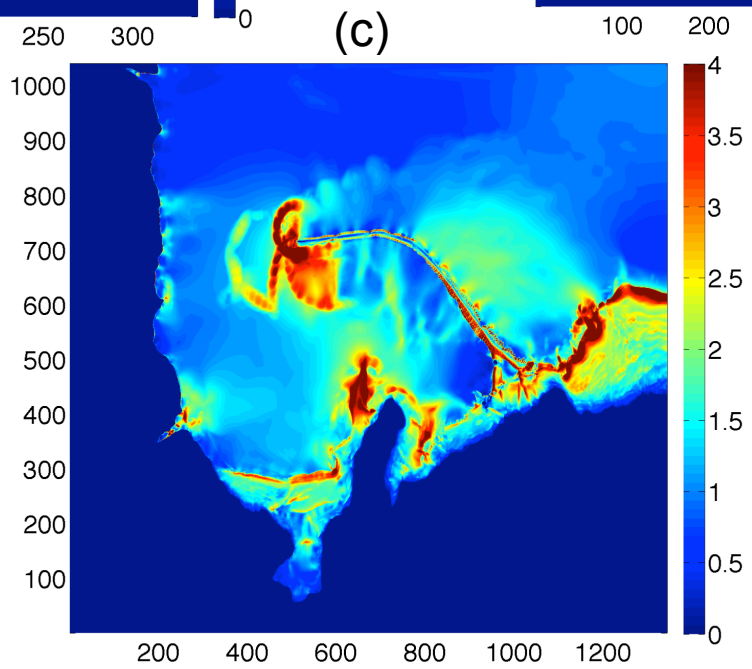
- **Velocity components measured (black o) and modeled (blue) at ADCP 1126 in: (a) 20 m (dot blue), (b) 10 m (dash blue); and (c) 5 m (solid blue) grids.**

Movies : Surface elevation (5 m grid)

Velocity magnitude (5 m grid)

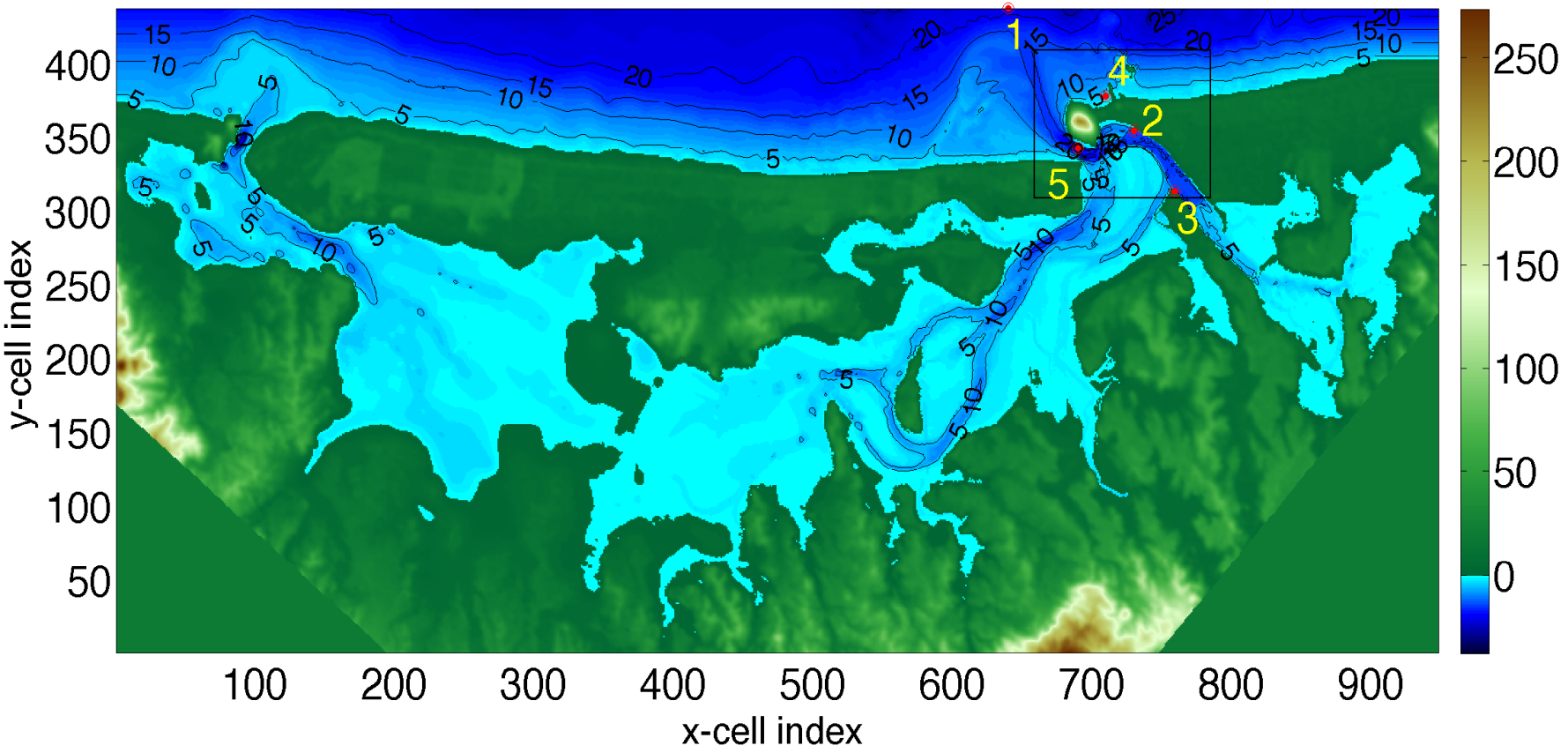




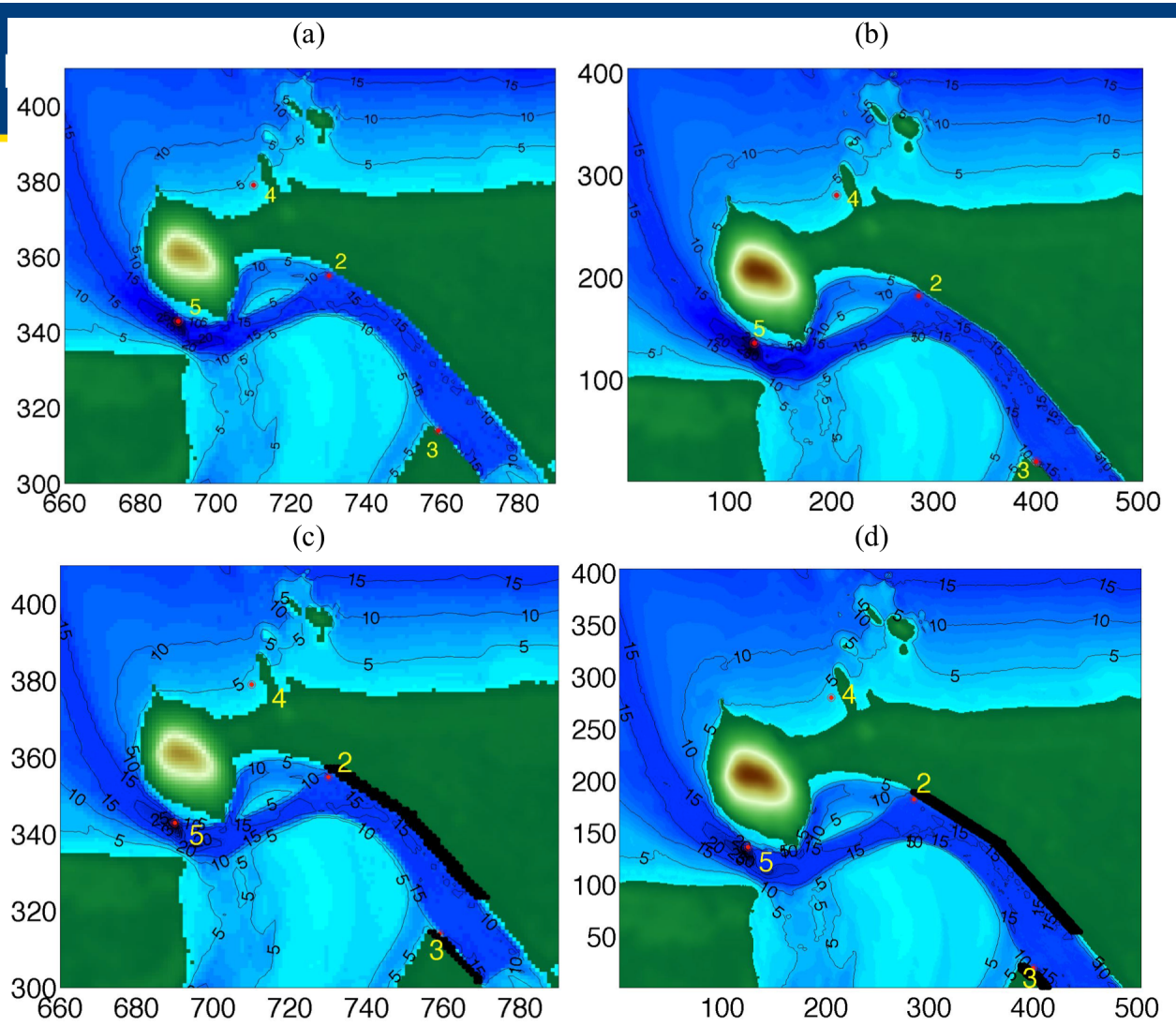


- **Maximum velocity magnitude (m/s) modeled in: (a) 20 m, (b) 10 m, (c) 5 m grids. Notice the small eddy shed at the tip of the breakwater in latter grid.**

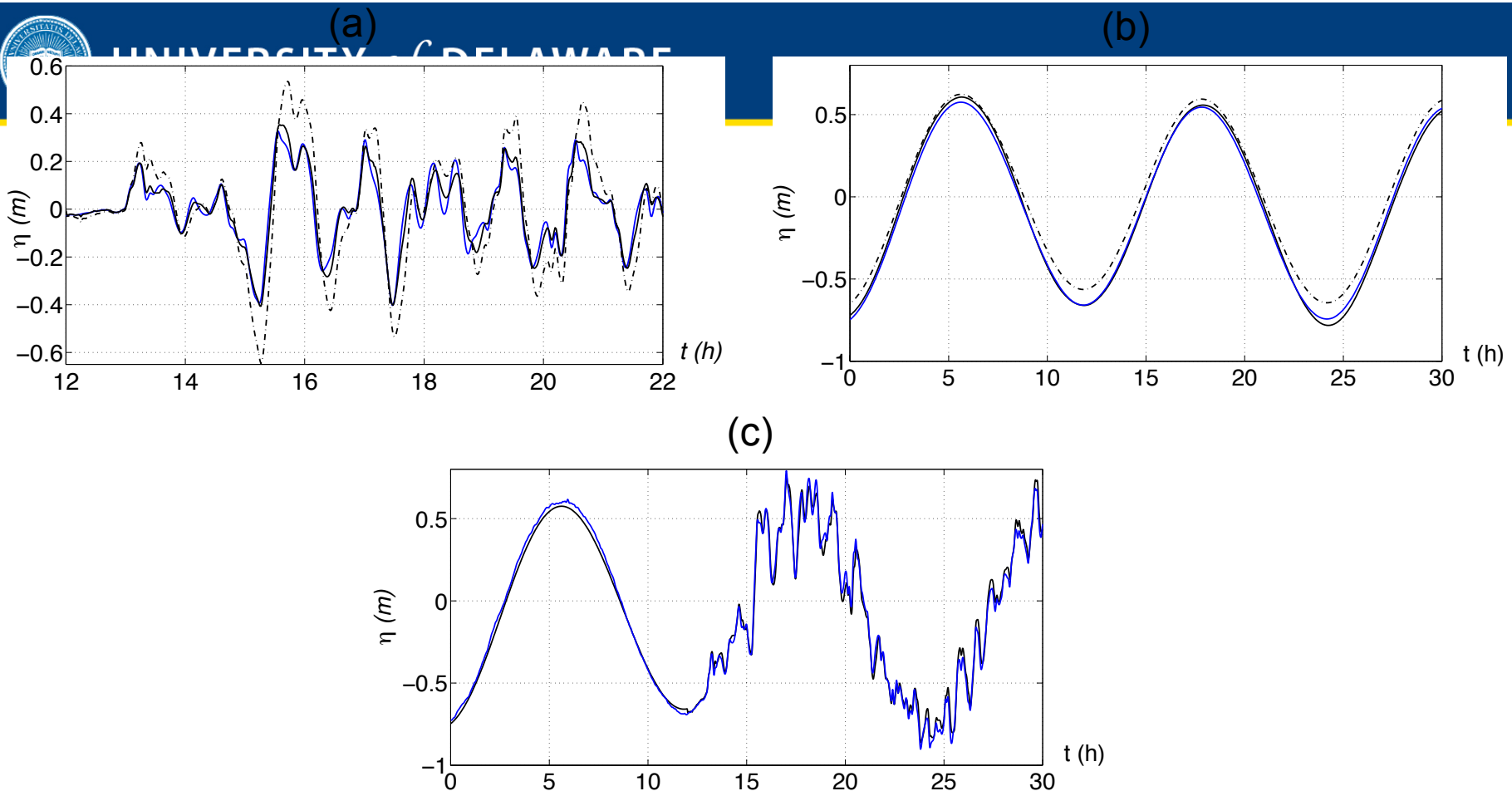
Benchmark #3
Taurangua Harbor



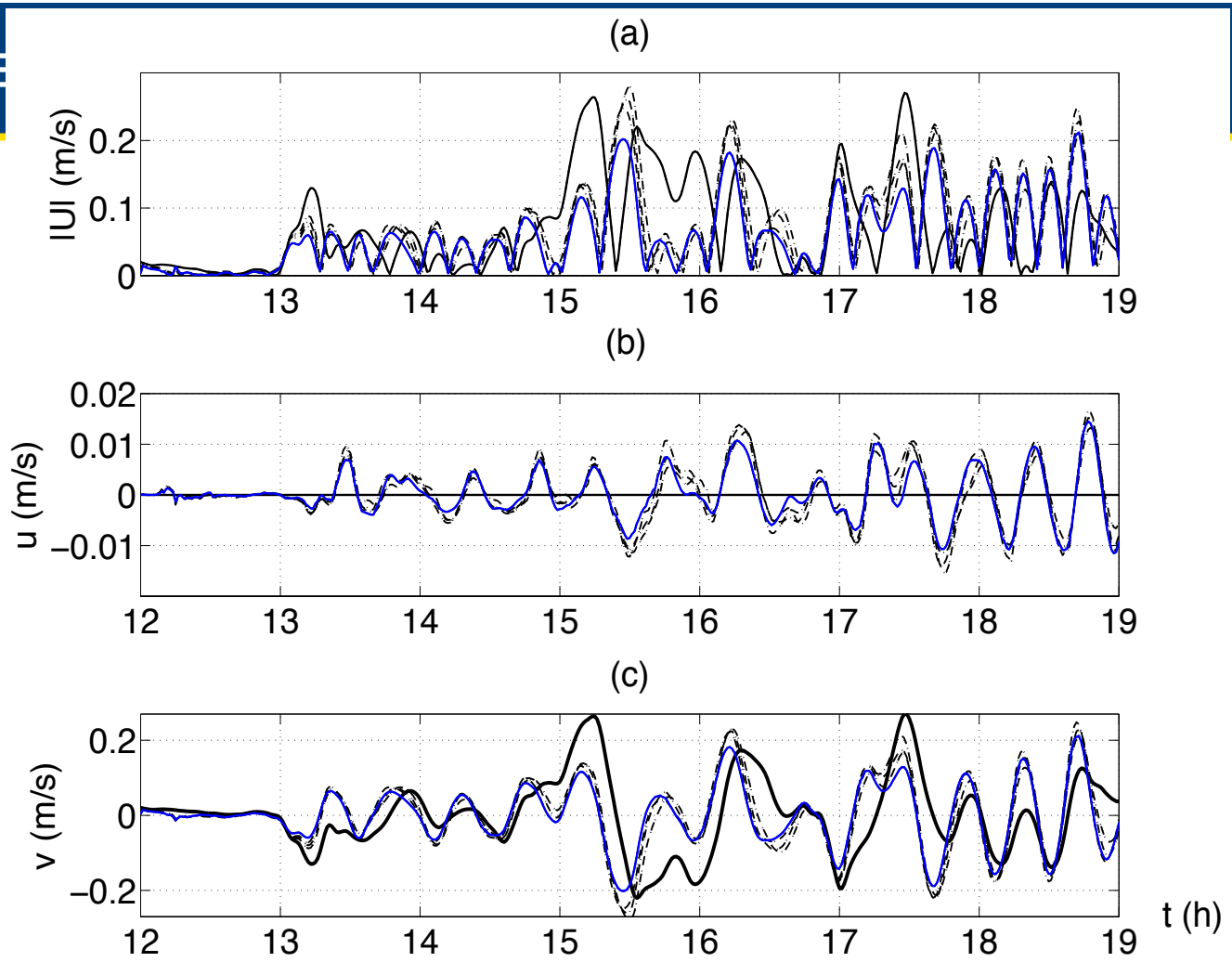
Bathymetry/topography (color scale/contours in meter) in modeled area. Large area is 40 m grid footprint with nested 10 m grid (black box). Numbered locations are: 1) A Beacon, 2) Tug Berth, 3) Sulfur Point and 4) Moturiki. An ADCP buoy is anchored in the middle of the inlet (slack mooring) at the point marked 5.



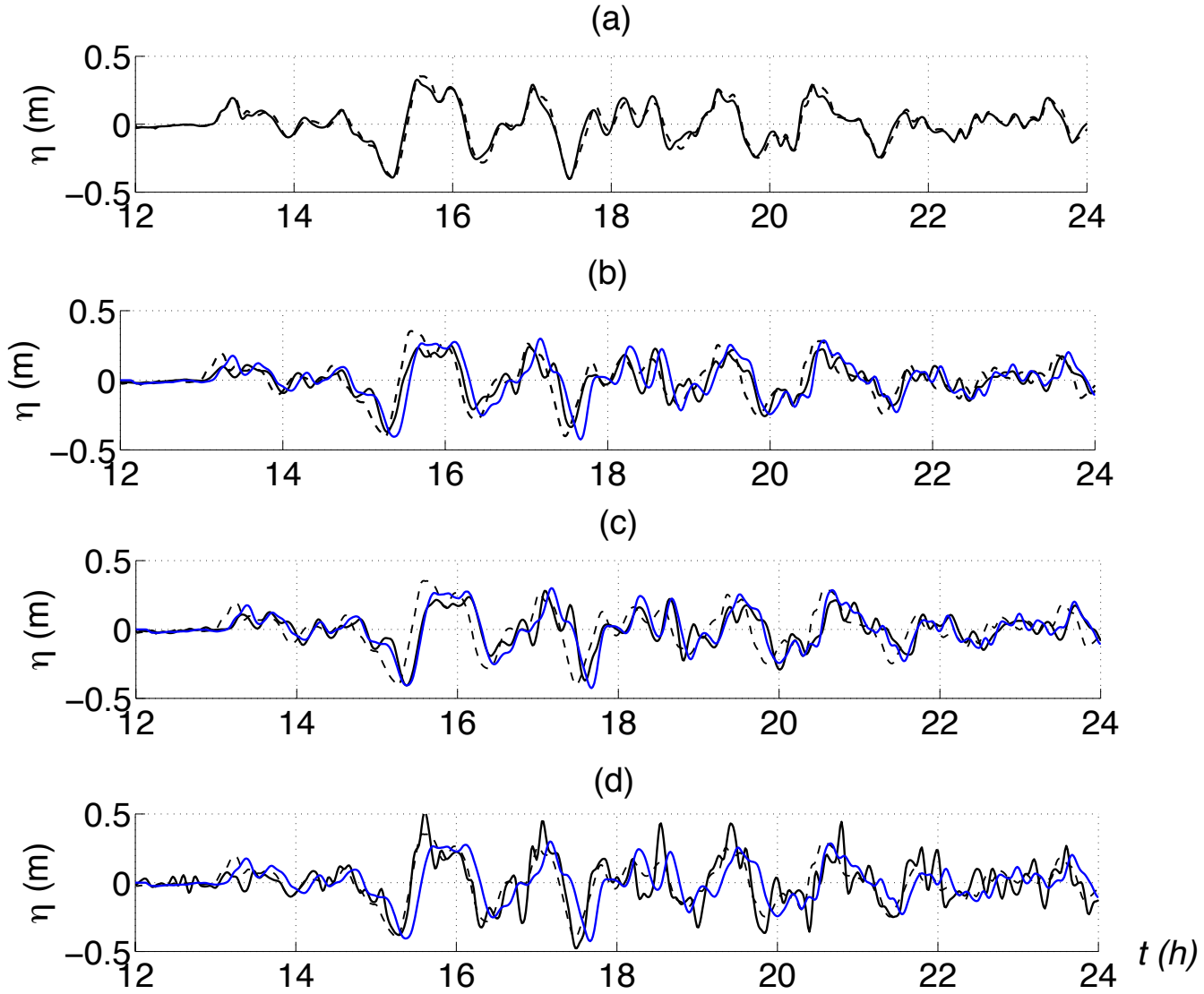
Zoom-in of (a,c) 40 meter; and (b,d) 10 m grids, without and with "obstacle boundary". The "obstacles" (no-flux boundary condition) were inserted in place of the steep bathymetry at the shore near the stations marked (2) and (3) (shaded in black).



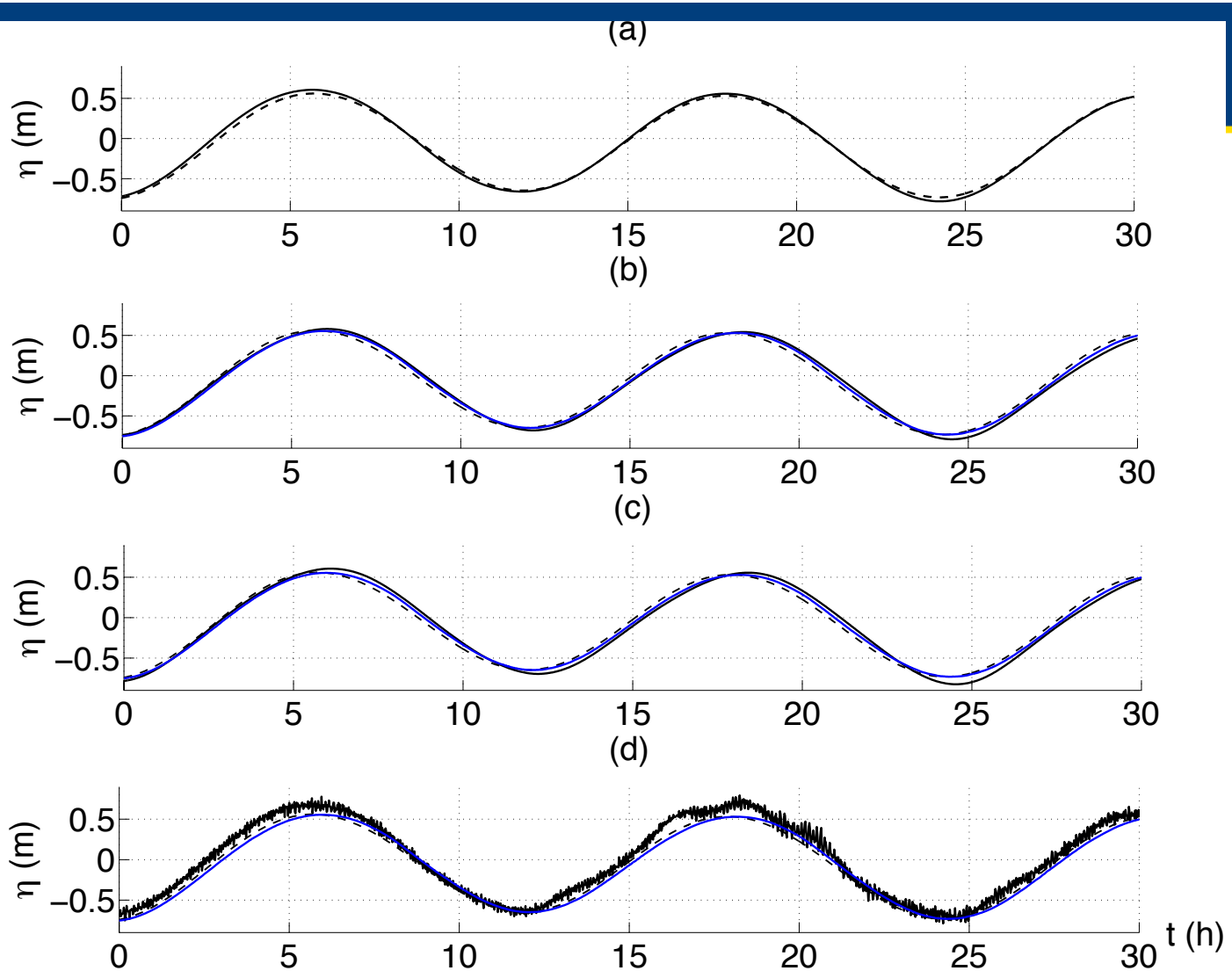
Surface elevation at "A Beacon" (offshore boundary). (a) Tsunami only simulations: initial discrepancy between assigned boundary surface elevation (black solid line) based on tsunami observations, and surface elevation (chained line); converged boundary condition (blue solid line line). (b) Tide only simulation: tide data (black solid line); OTPS (Oregon Tide Prediction Software, OSU) model prediction (chained line); and the same corrected by 4% (blue solid line) used as boundary condition. (c) Tsunami plus tide simulations: combined surface elevation specified as a boundary condition (black solid line).



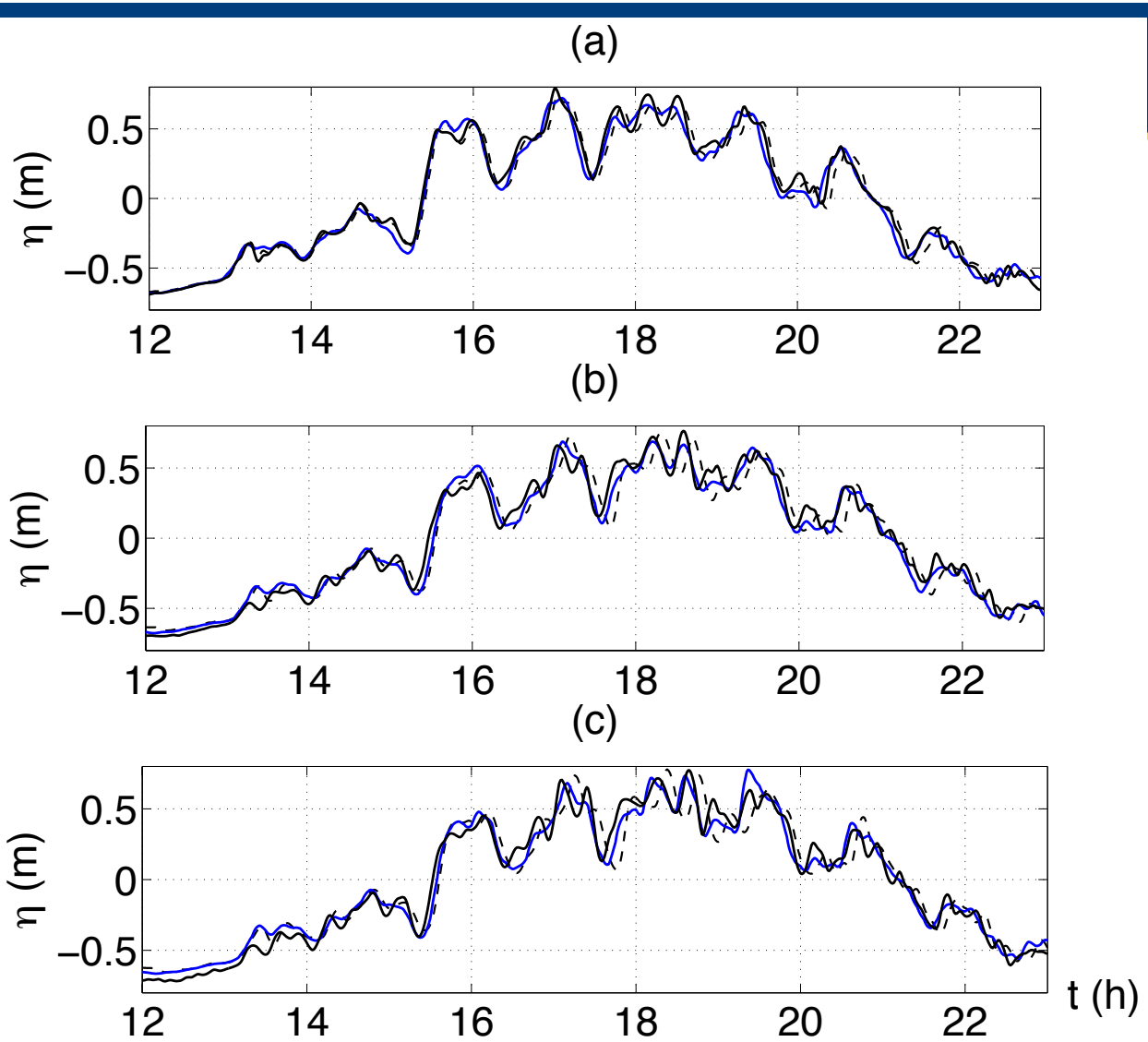
Tsunami only simulations, convergence of velocity boundary condition : (a) modulus |U| and components (b) u and (c) v, at "A Beacon", in successive simulations in 40 m grid. Initial input velocity, based on the linear long wave approximation (black solid line), successive computations (dashed line), and the final input boundary condition (blue solid line).



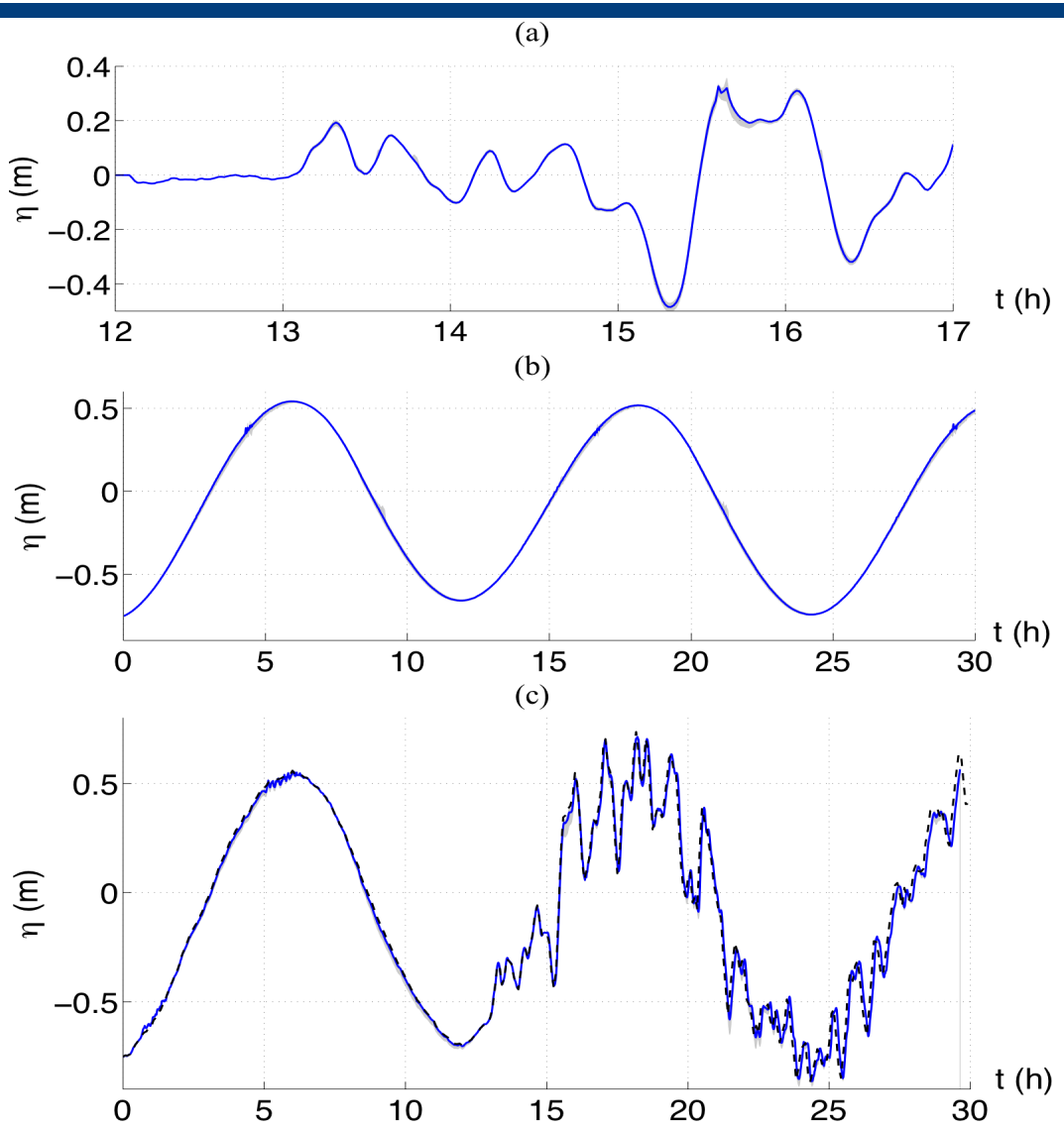
Tsunami only simulations. Measured tsunami surface elevations (solid line), detided and compared to 40 m grid results (dashed line) and 10 m grid results (blue solid line), at four locations: (a) A Beacon, (b) Tug Berth, (c) Sulfur Point, (d) Moturiki.



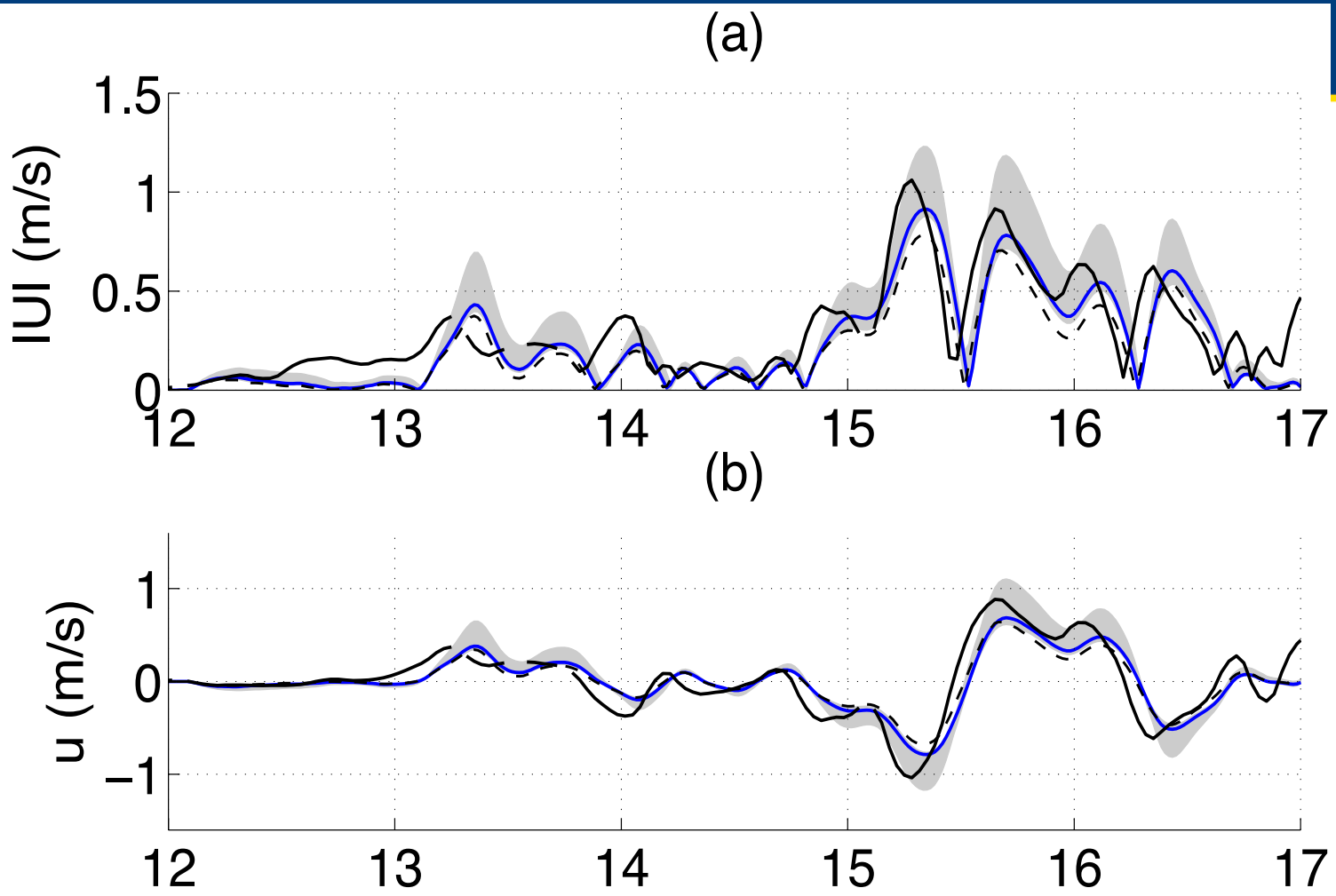
Tide only simulations. Measured tide surface elevations (solid line), compared to 40 m grid results (dashed line) and 10 m grid results (blue solid line), at four locations: (a) A Beacon, (b) Tug Berth, (c) Sulfur Point, (d) Moturiki.



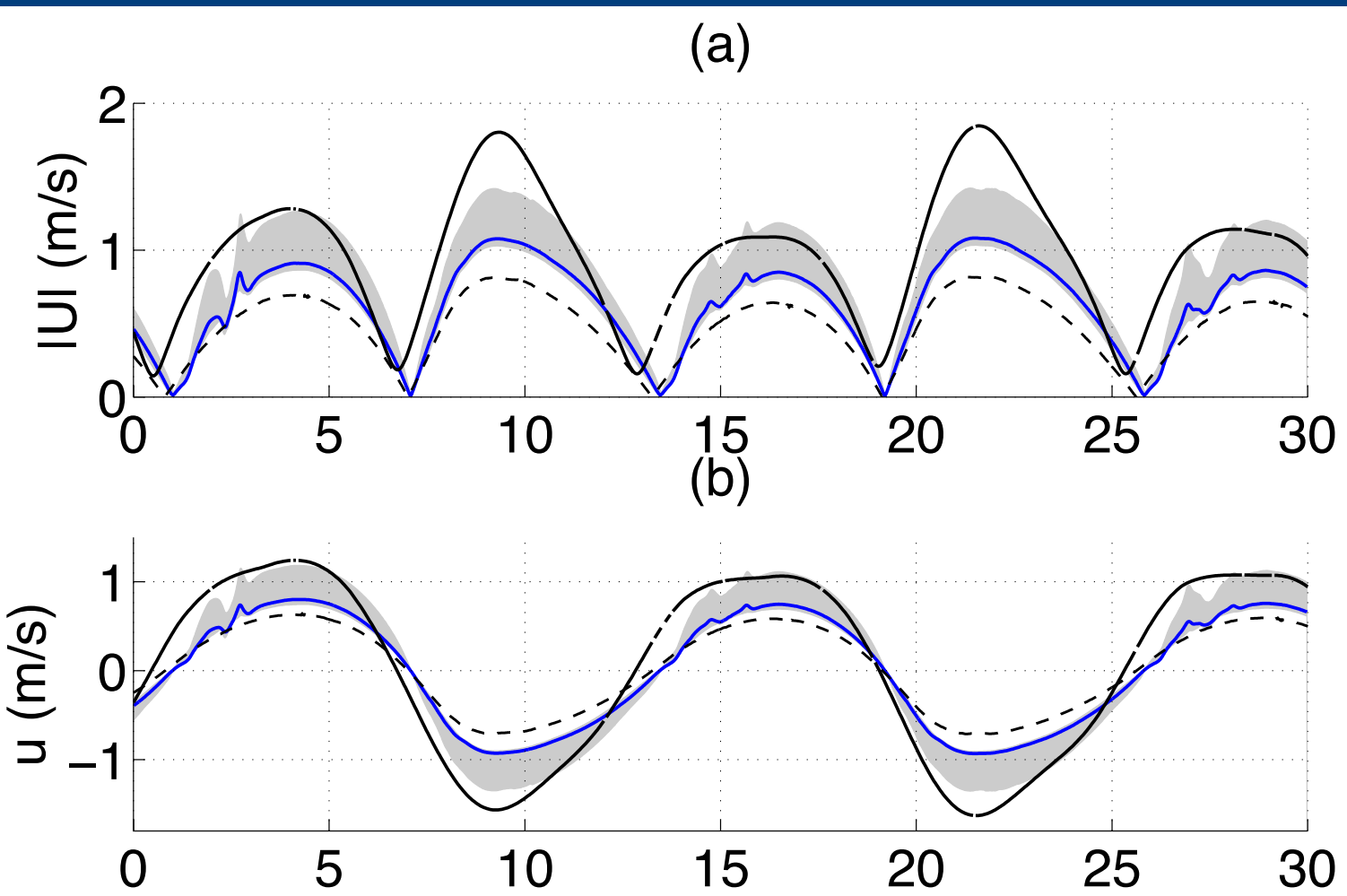
Tide-tsunami simulations. Measured surface elevations (solid line), compared to 40 m grid results of tide and tsunami alone linearly superimposed (dashed line) and results of simulations using a combined tide-tsunami boundary condition (blue solid line), at three locations: (a) A Beacon, (b) Tug Berth, (c) Sulfur Point.



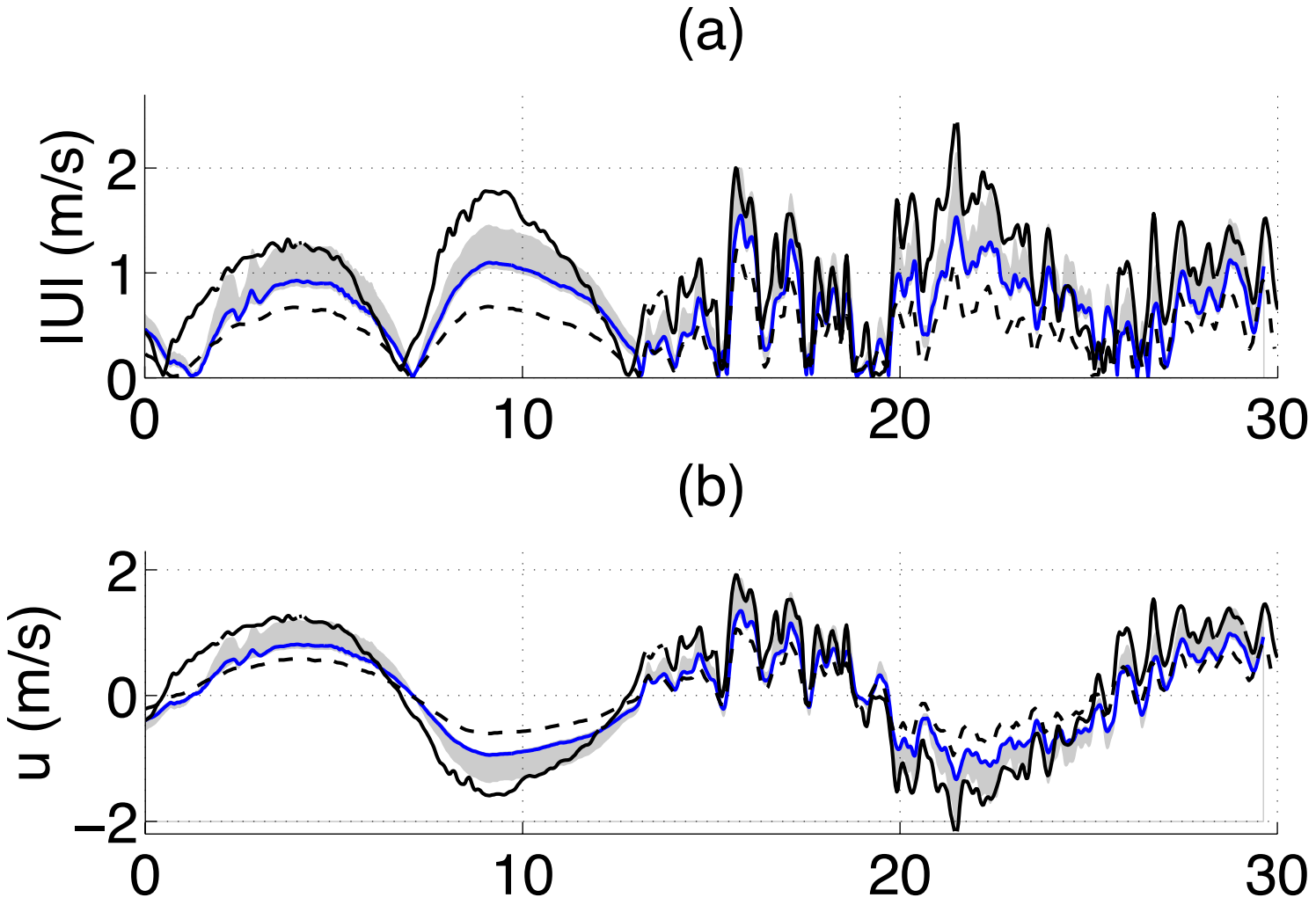
Surface elevations predicted in the 40 m (solid blue) and 10 m (dash black) grid, at the ADCP buoy location in: (a) tsunami only, (b) tide only; and (c) tide-tsunami simulations. The shaded gray region represents the range of surface elevations predicted within the buoy 40 m radius of gyration.



Tsunami only simulations. Measured tsunami current magnitude |U| and velocity component u at the ADCP buoy (solid line), detided and compared to 40 m grid results (dashed line) and 10 m grid results (blue solid line). The shaded region represents the range of values predicted in the 10 m grid, within the buoy 40 m radius of gyration.



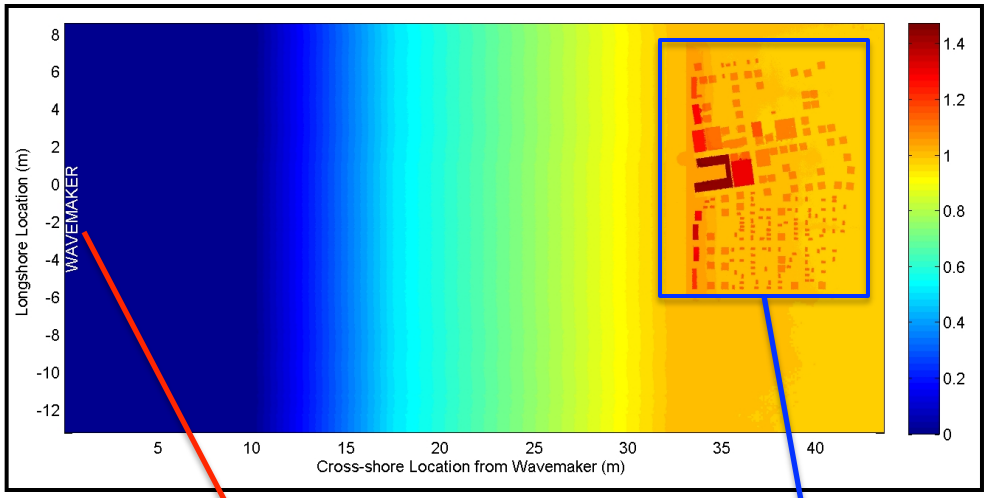
Tide only simulations. Measured tide current magnitude |U| and velocity component u at the ADCP buoy (solid line), compared to 40 m grid results (dashed line) and 10 m grid results (blue solid line). The shaded region represents the range of values predicted in the 10 m grid, within the buoy 40 m radius of gyration.

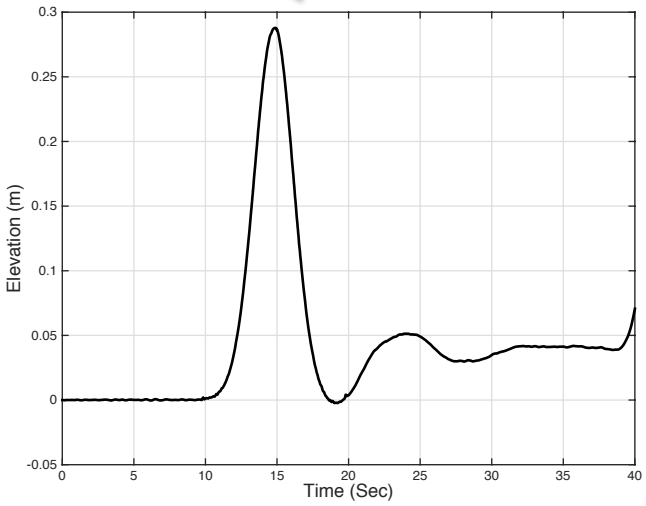


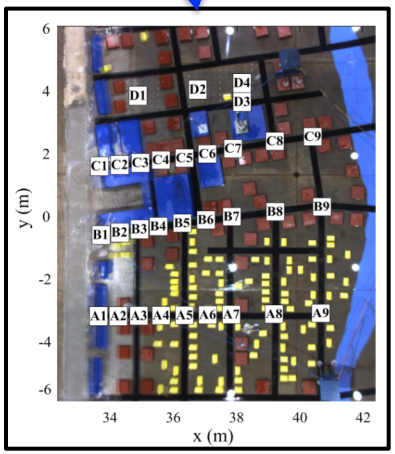
Tide-tsunami simulations. Measured tide current magnitude |U| and velocity component u at the ADCP buoy (solid line), compared to 40 m grid results (dashed line) and 10 m grid results (blue solid line). The shaded region represents the range of values predicted in the 10 m grid, within the buoy 40 m radius of gyration.

Benchmark 4

- A single long-period wave propagates over a combination of linear slopes and onto a model of the town of Seaside, Oregon.
- Main objective: provide a comparison of calculated momentum flux, velocity and inundation depth with measured data at B1, B4, B6 and B9 gauges.
- For simulation the wave was generated by forcing the boundary condition on the left side of domain.

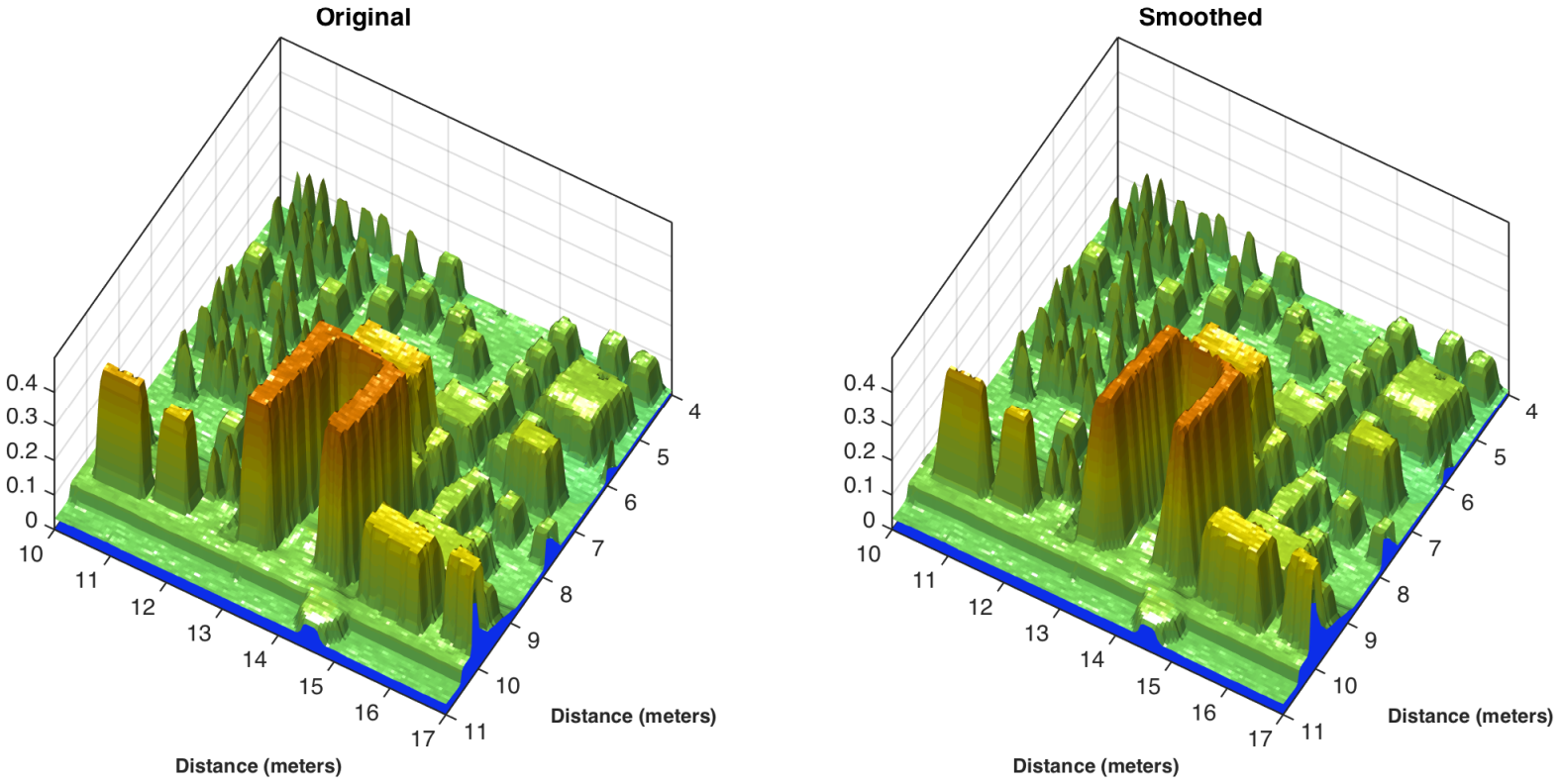




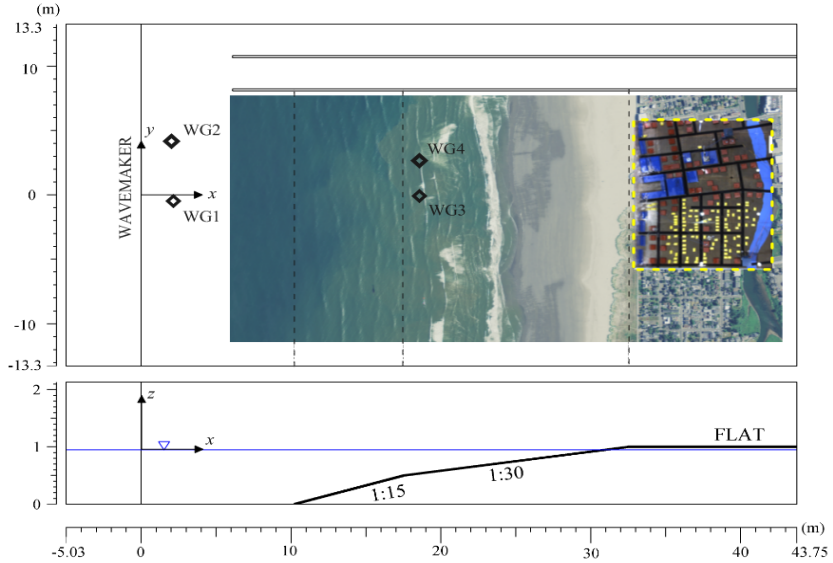


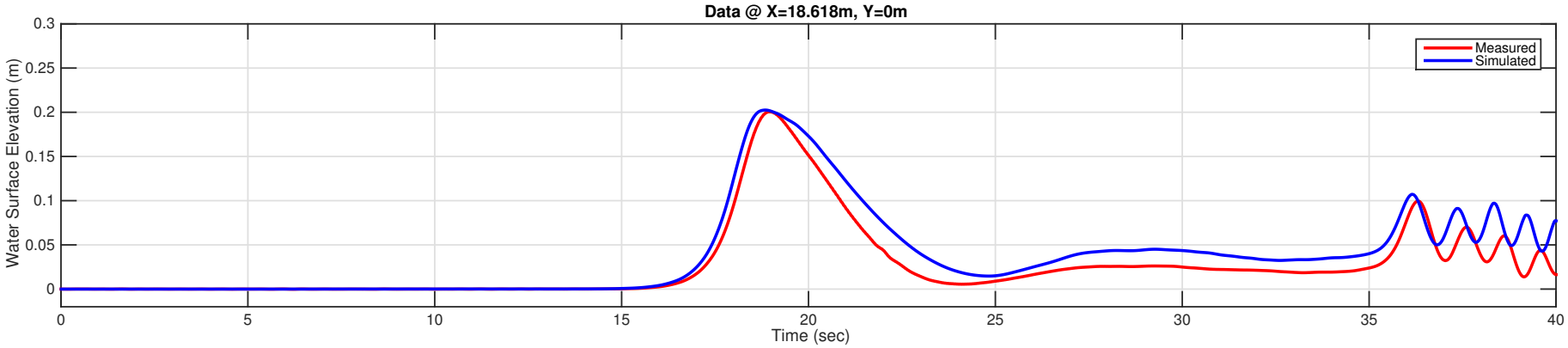
- Several tests were performed to evaluate convergence, the effect of bathymetry smoothing (maximum slope=1:2), and the best chosen value for the drag coefficient (C_d).

- As in Park et al. (2013), the grid size for the main run was 5 cm, and $C_d = 0.001$ produced the best fit to the measured data.

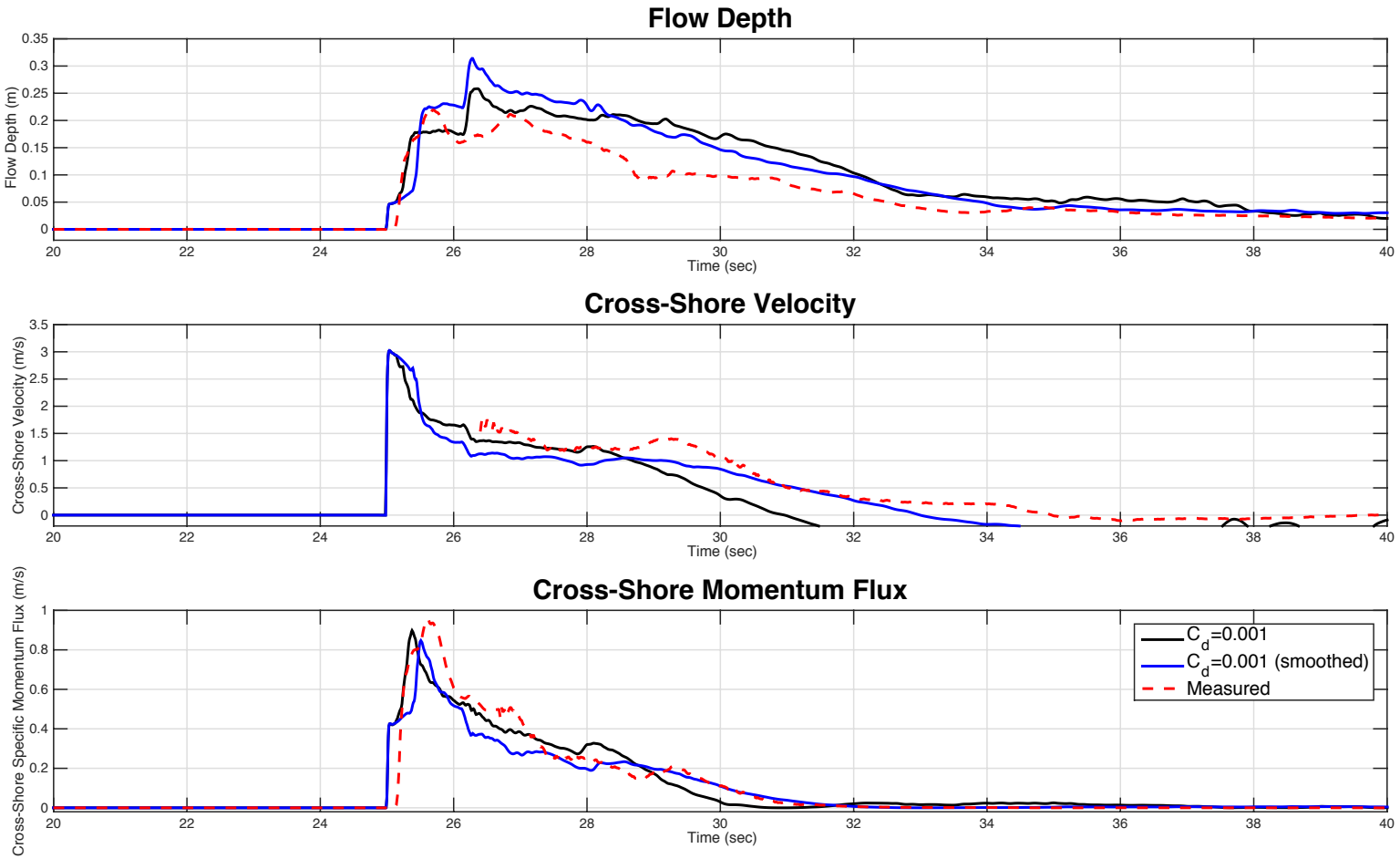


Comparison between measured and simulated data in the middle of the domain (WG3)

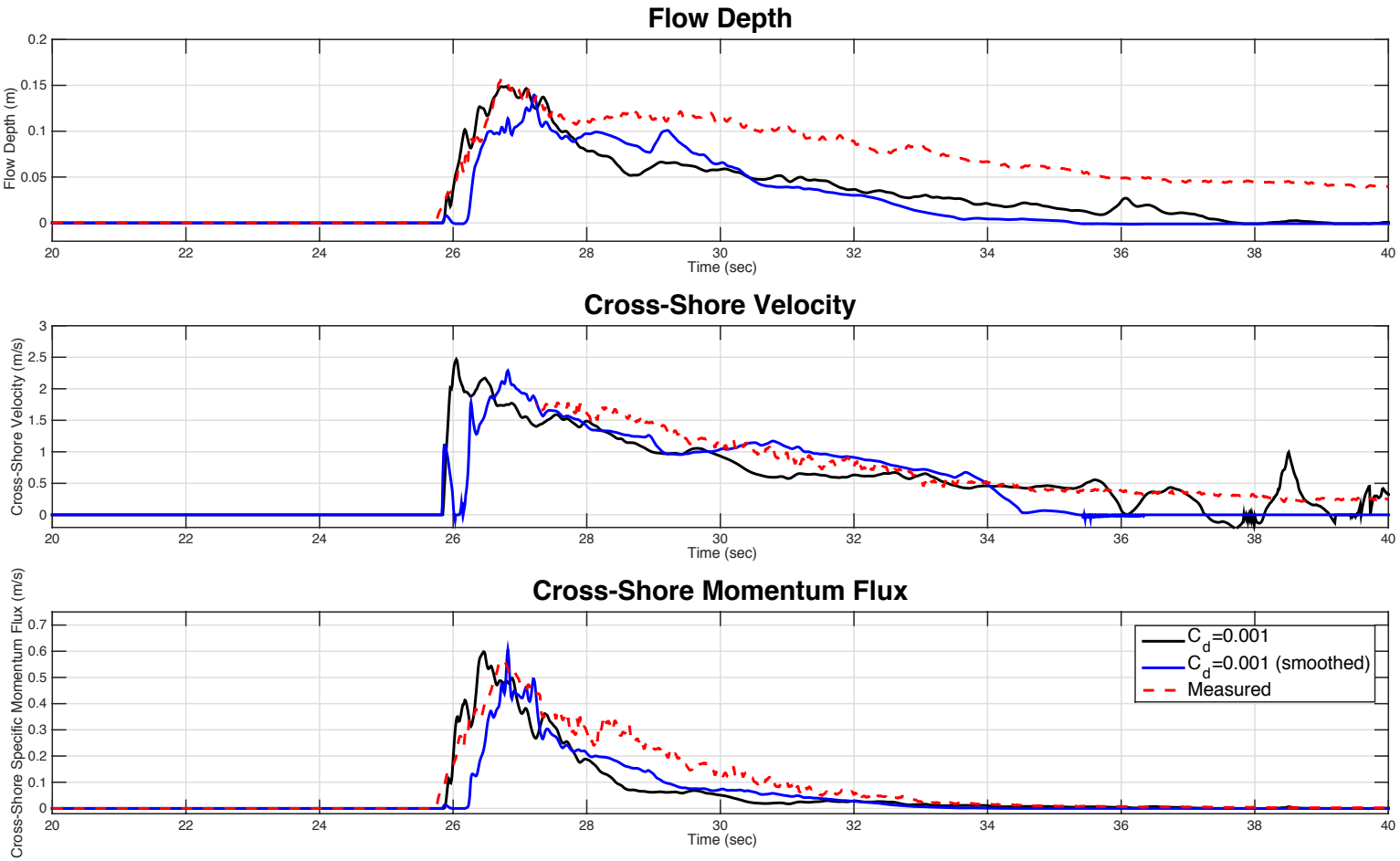




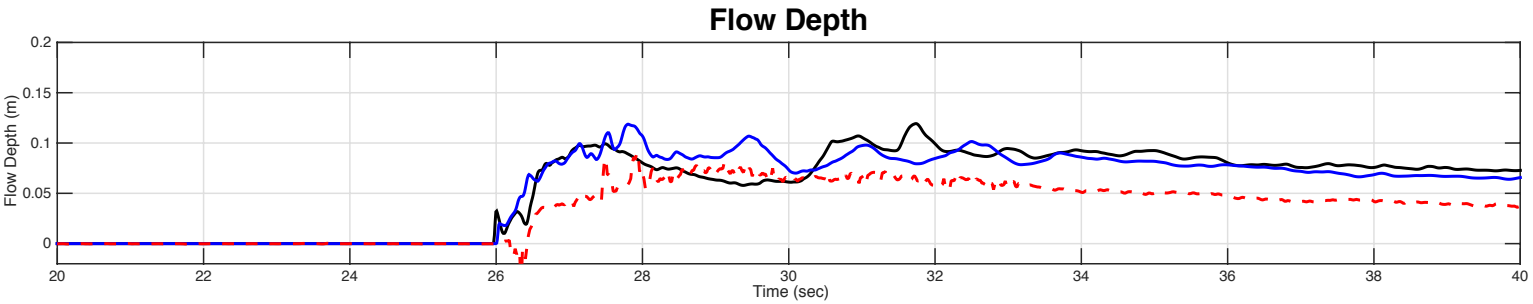
Gauge B1

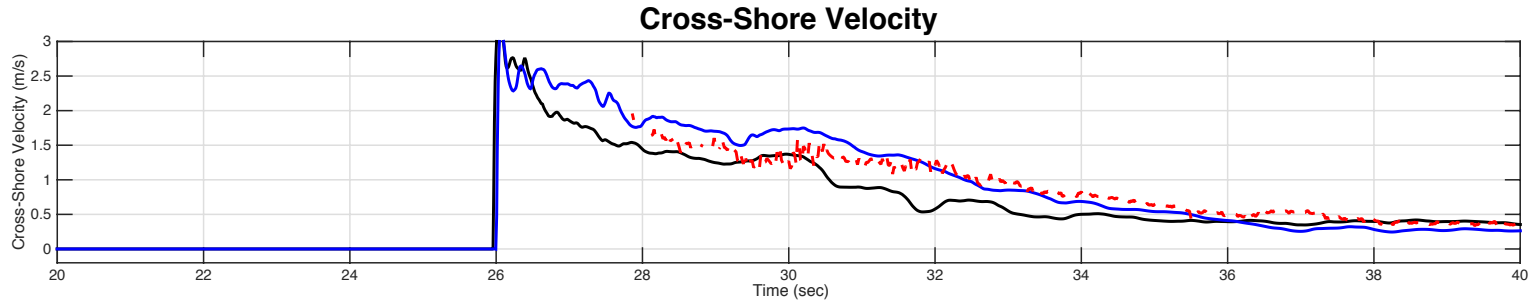

Flow Depth
Flow Depth (m)
Time (sec)
Cross-Shore Velocity
Cross-Shore Velocity (m/s)
Time (sec)
Cross-Shore Momentum Flux
Cross-Shore Specific Momentum Flux (m/s)
Time (sec)
C_d=0.001
C_d=0.001 (smoothed)
Measured

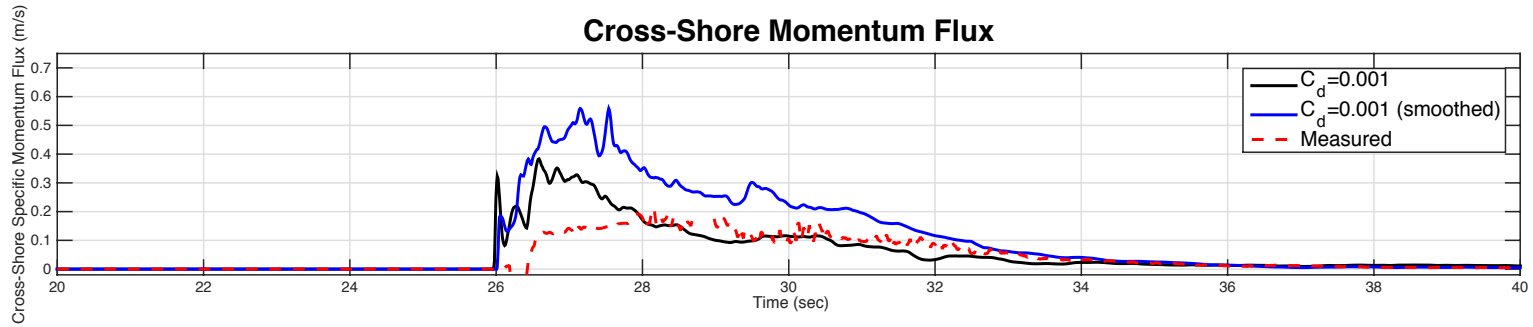
Gauge B4


Flow Depth
Flow Depth (m)
Time (sec)
Cross-Shore Velocity
Cross-Shore Velocity (m/s)
Time (sec)
Cross-Shore Momentum Flux
Cross-Shore Specific Momentum Flux (m/s)
Time (sec)
C_d=0.001
C_d=0.001 (smoothed)
Measured

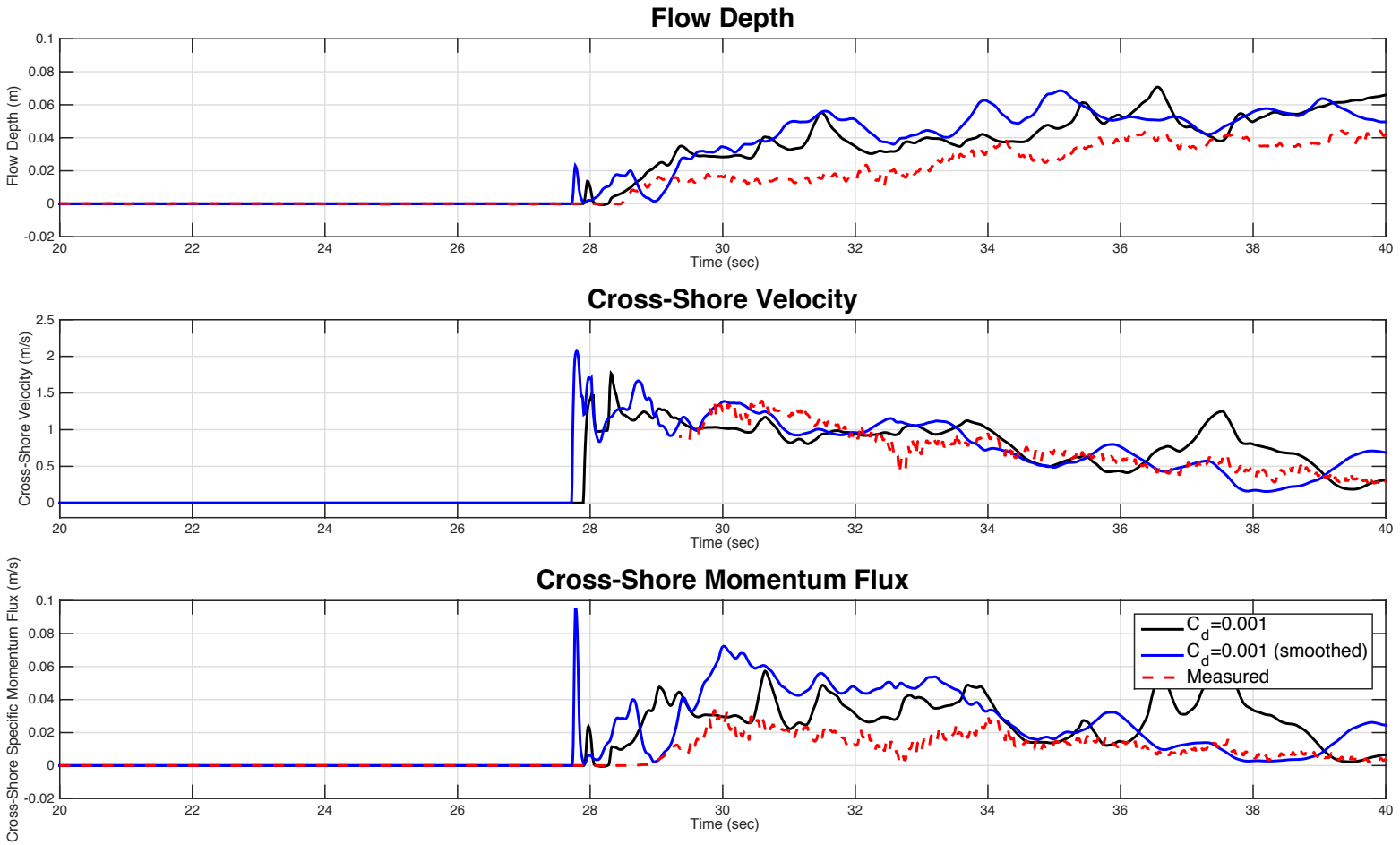
Gauge B6


Flow Depth
Flow Depth (m)
0.2
0.15
0.1
0.05
0
20
22
24
26
28
30
32
34
36
38
40
Time (sec)


Cross-Shore Velocity
Cross-Shore Velocity (m/s)
3
2.5
2
1.5
1
0.5
0
20
22
24
26
28
30
32
34
36
38
40
Time (sec)


Cross-Shore Momentum Flux
Cross-Shore Specific Momentum Flux (m/s)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
20
22
24
26
28
30
32
34
36
38
40
Time (sec)
C_d=0.001
C_d=0.001 (smoothed)
Measured

Gauge B9


Flow Depth
Flow Depth (m)
Time (sec)
Cross-Shore Velocity
Cross-Shore Velocity (m/s)
Time (sec)
Cross-Shore Momentum Flux
Cross-Shore Specific Momentum Flux (m/s)
Time (sec)
C_d=0.001
C_d=0.001 (smoothed)
Measured

Benchmark Test # 5
Solitary wave runup on a shelf with a conical island

The bathymetry grid was generated using the bathymetry data recorded in 'TWB 071708_5CM_XYZ_METERS.txt'.

The grid sizes for the data are
dx_data=0.04379 m
dy_data= 0.02658 m

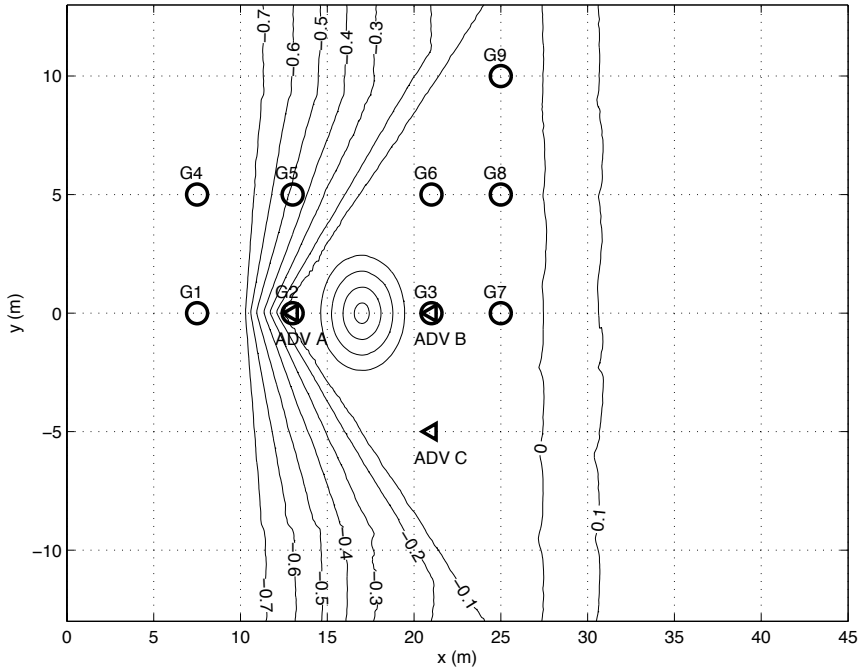


Figure: locations of WGs and ADVs

Model setup

MODEL GRIDS

Two sets of model grid sizes were used in the simulations. One is called the fine grid which doubled data grid sizes, that is (0.0876,0.1063). The other is called the coarse grid, which quadrupled the data grid sizes, that is (0.1752,0.2126).

The bathymetry data was shifted downward to get 0.78m at the left edge of the basin.

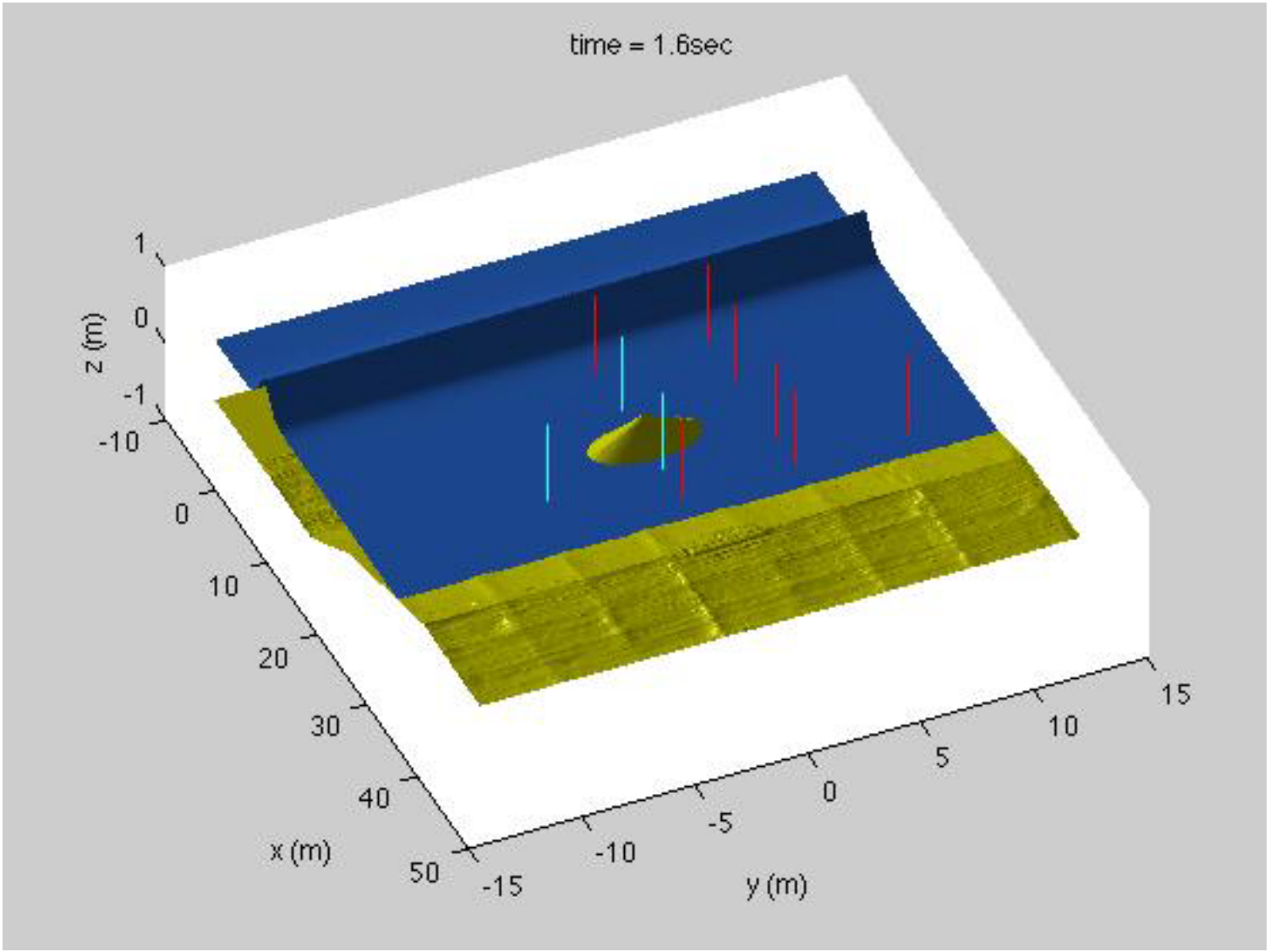
In order to initialize the solitary wave on the left side, the model domain was extended to the left by 17.7 m (101 points in the fine grid). The model dimensions are 600x250 and 300x125, respectively, for the fine grid and coarse grid.

Model RUNS

The bottom friction coefficient is 0.001 in all cases.

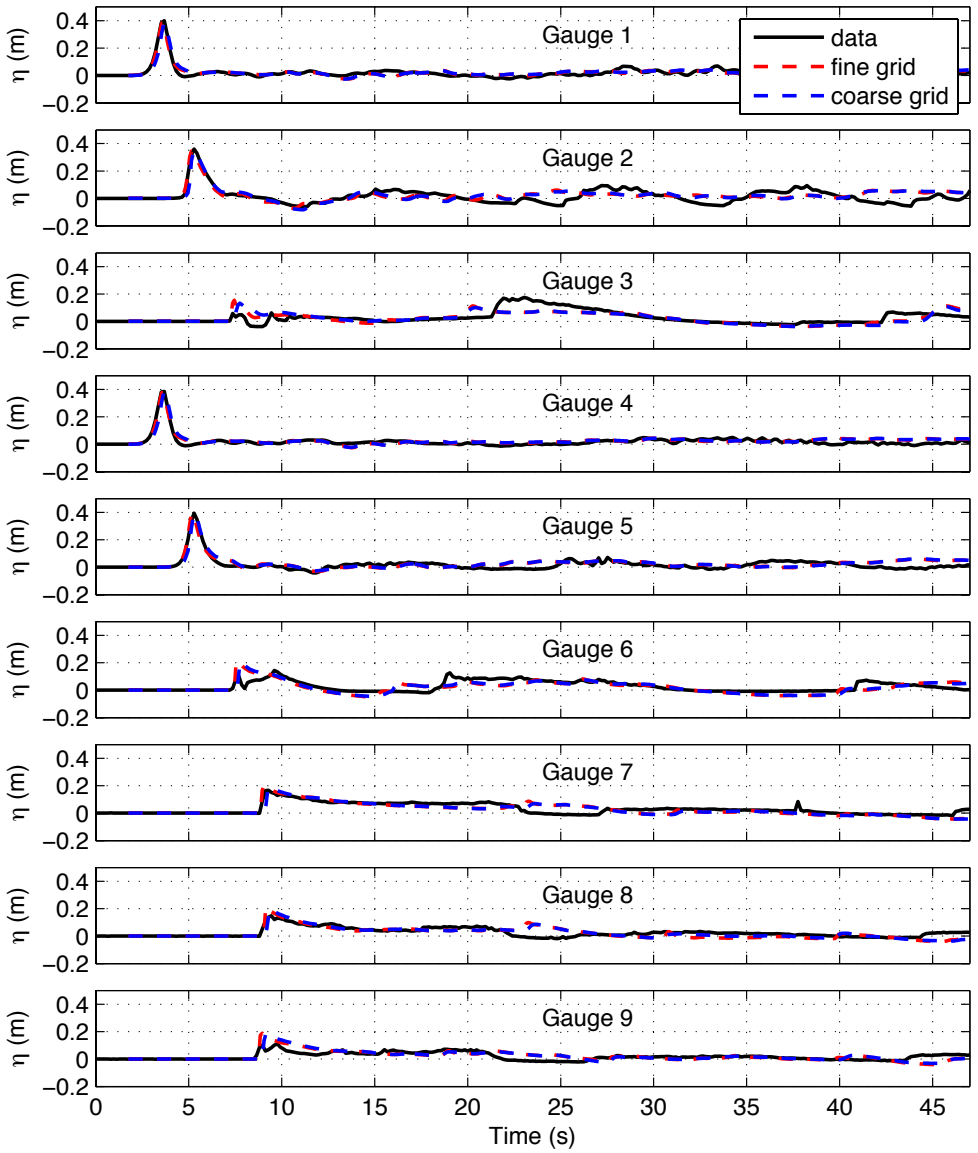
	Dx(m)	Dy(m)	breaking
Baseline	0.0876	0.1063	Eddy viscosity
Breaker test	0.0876	0.1063	Hybrid SWE
Coarse grid	0.1752	0.2126	Eddy viscosity

Baseline model



Fine grid v

Figure: Comparison of surface elevation between the fine grid model, coarse grid model and data.



Fine grid vs. coarse grid

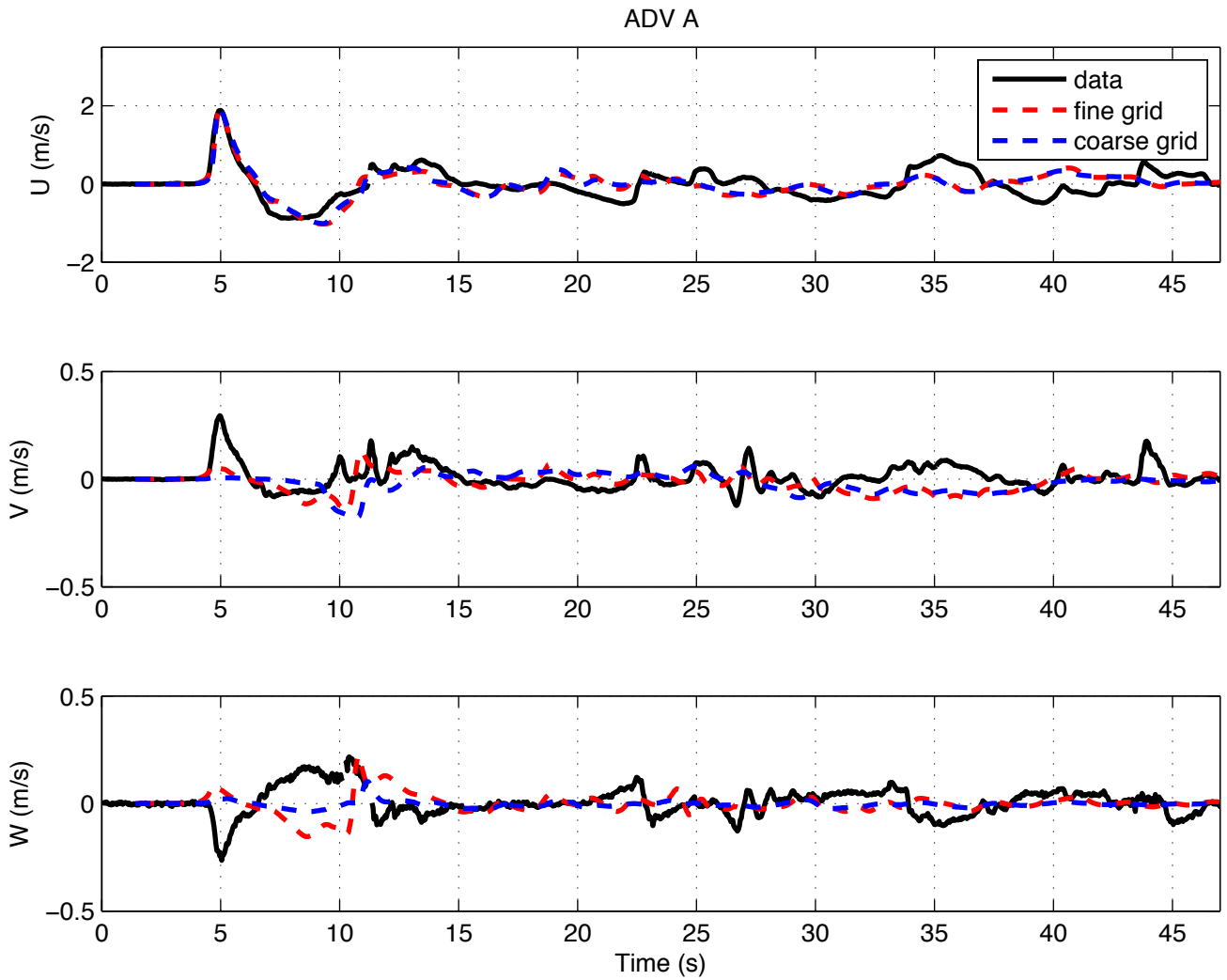
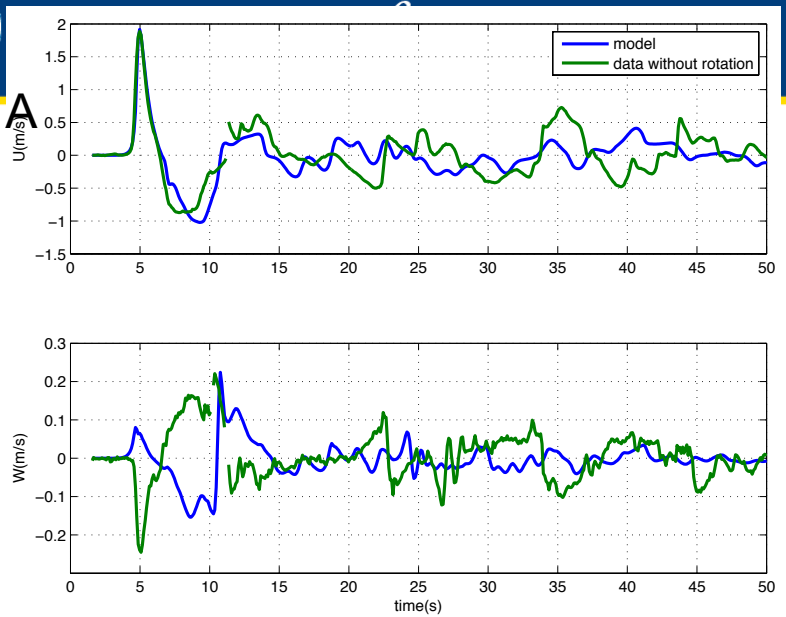
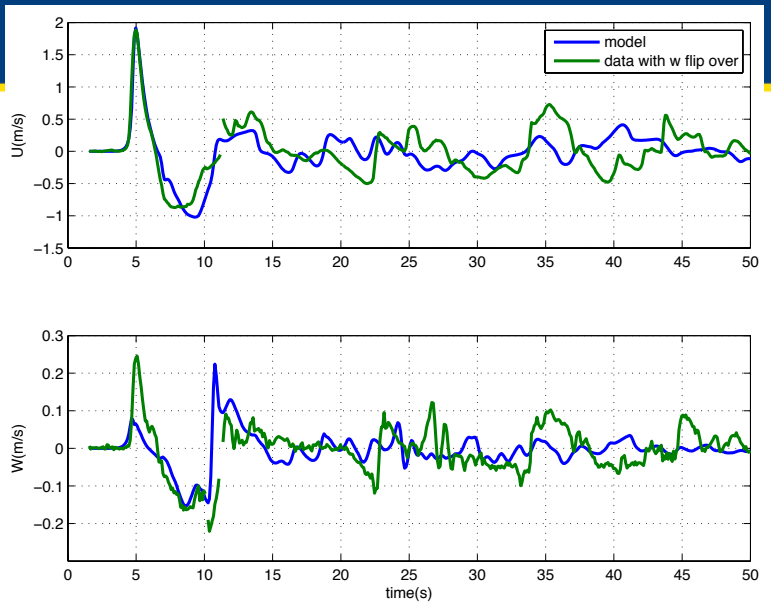


Figure: comparison of (U,V,W) at ADV A. (measured W NOT flip over)

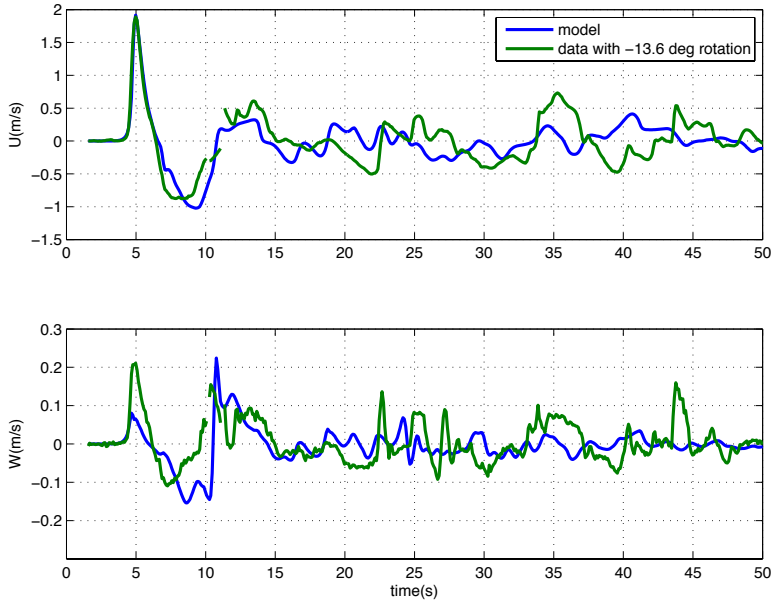
ADV A



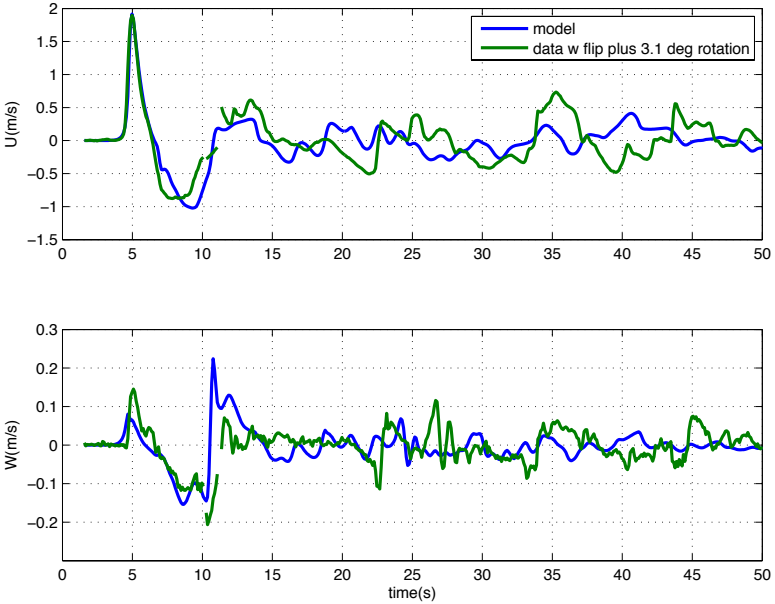
No rotation



W flip over



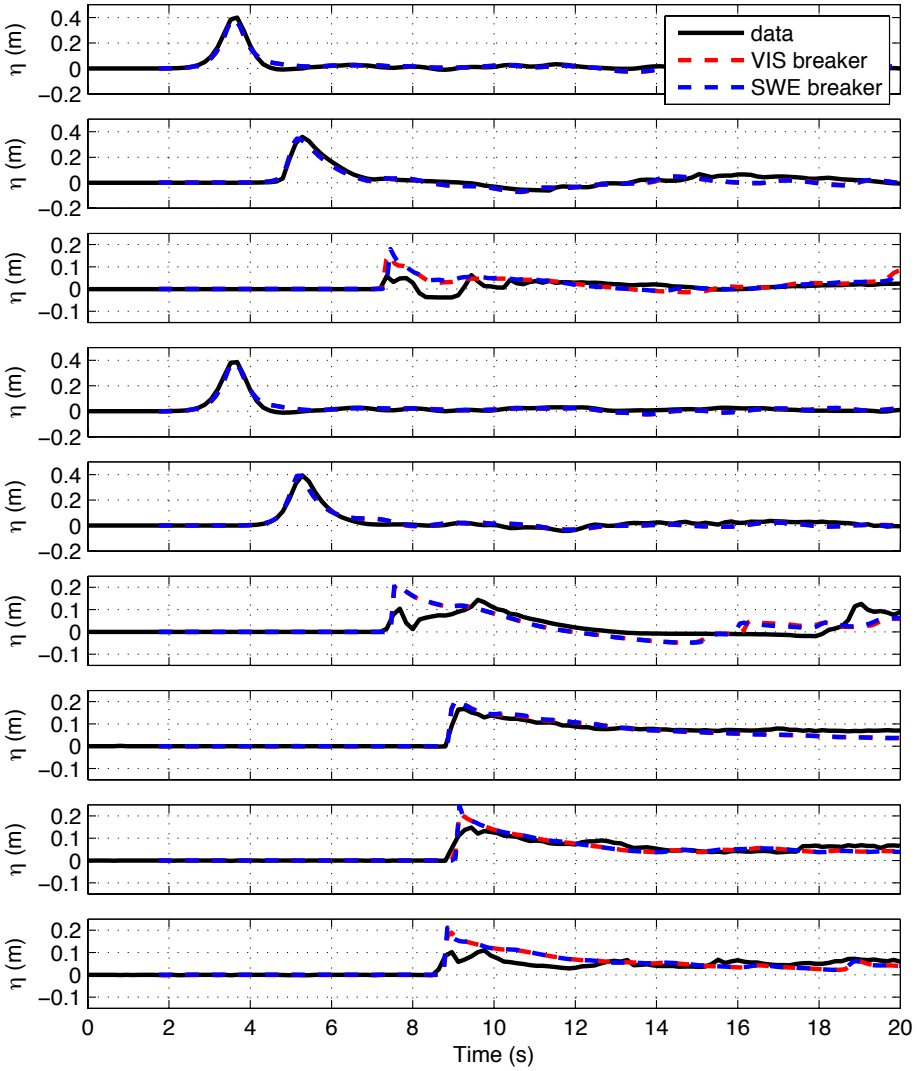
-13.6 deg rotation



W flip-over and 3 deg rotation

Eddy viscosity breaking vs. Hybrid SWE

Figure: Comparison of surface elevation between the VIS breaker model, SWE breaker model and data.



Eddy viscosity breaking vs. Hybrid SWE

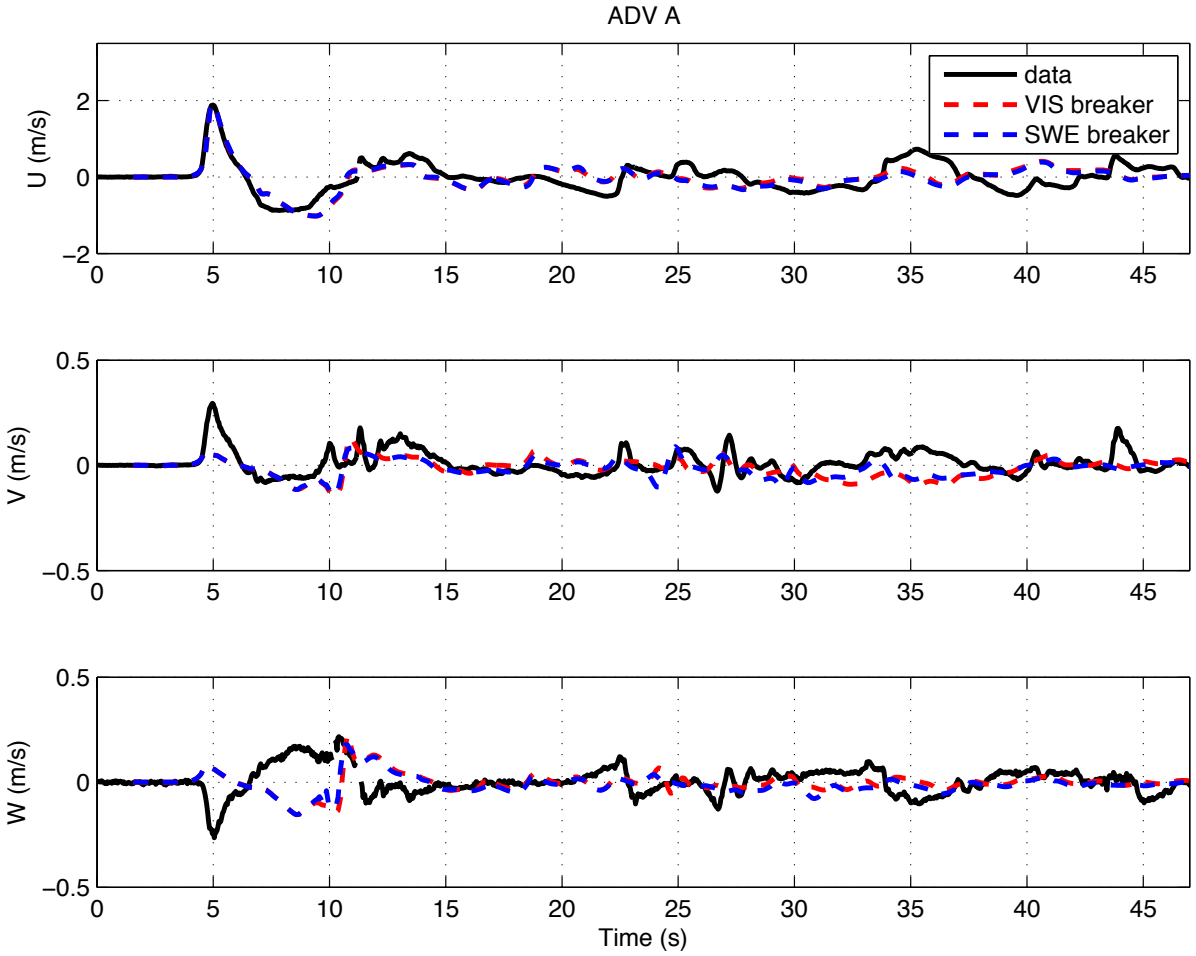
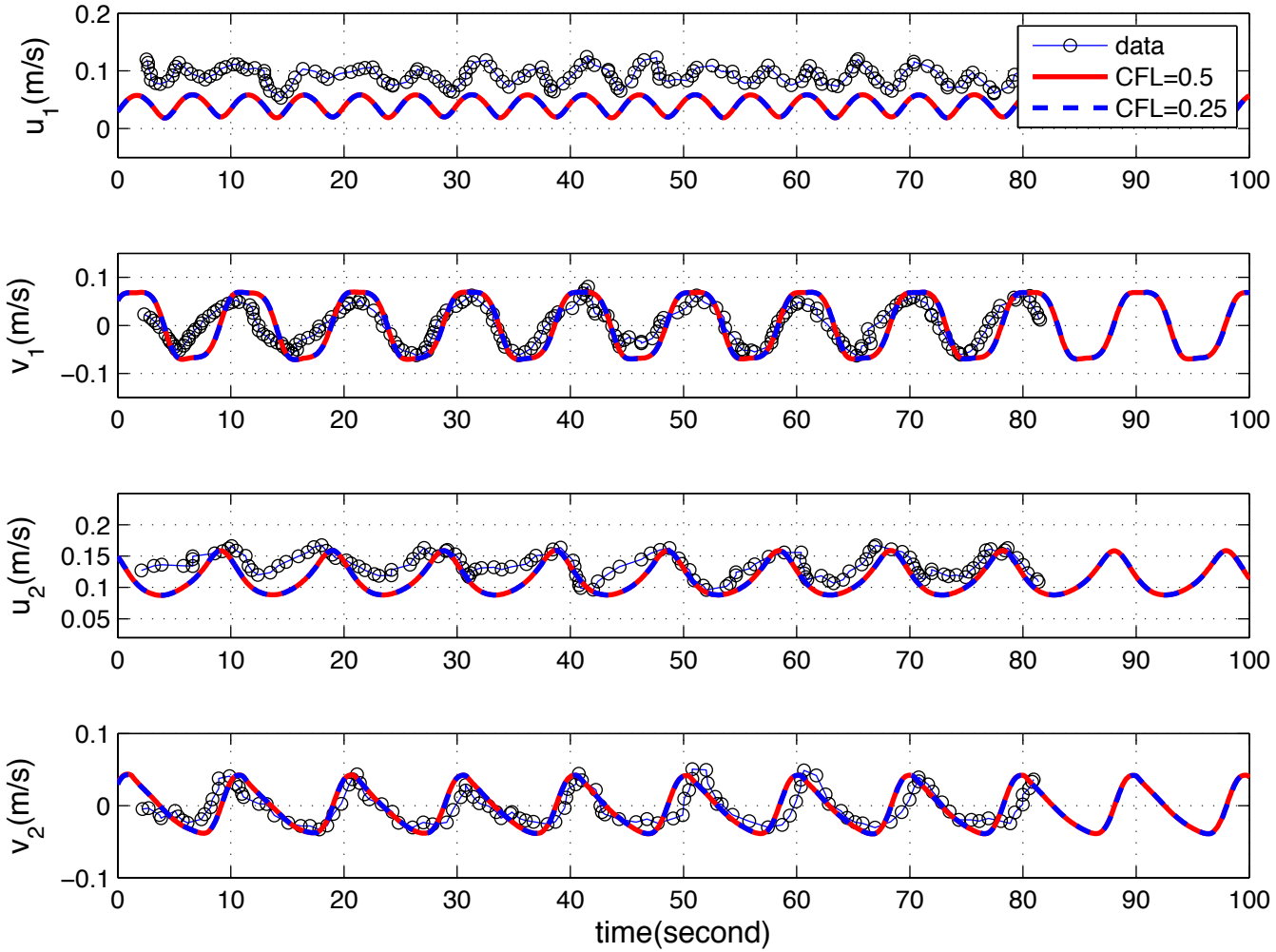


Figure: comparison of (U,V,W) at ADV A. (measured W NOT flip over)

EXTRAS

CFL tests



VIS breaker vs. SWE grid

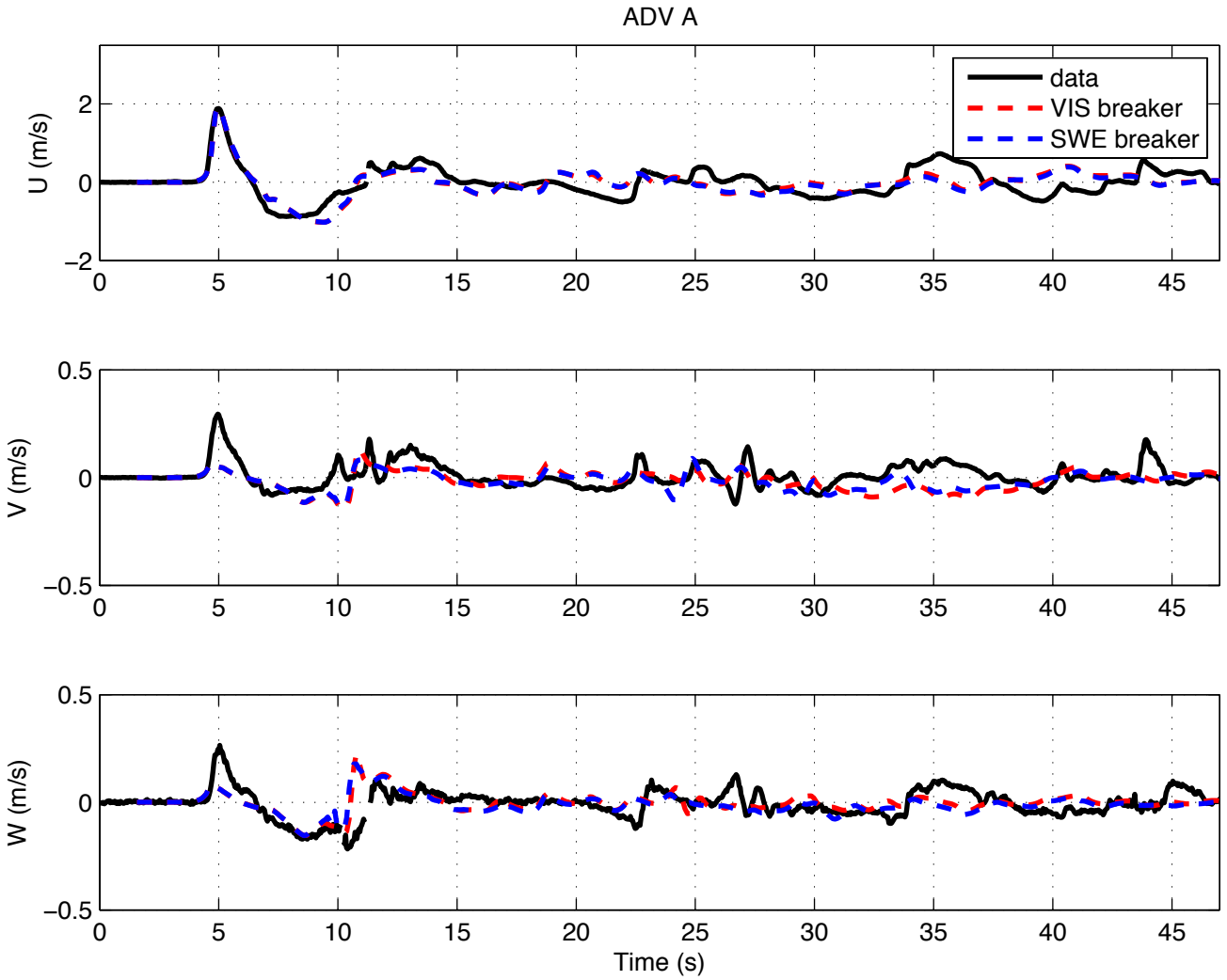


Figure: comparison of (U,V,W) at ADV A. (measured W flip over)

Fine grid vs. coarse grid

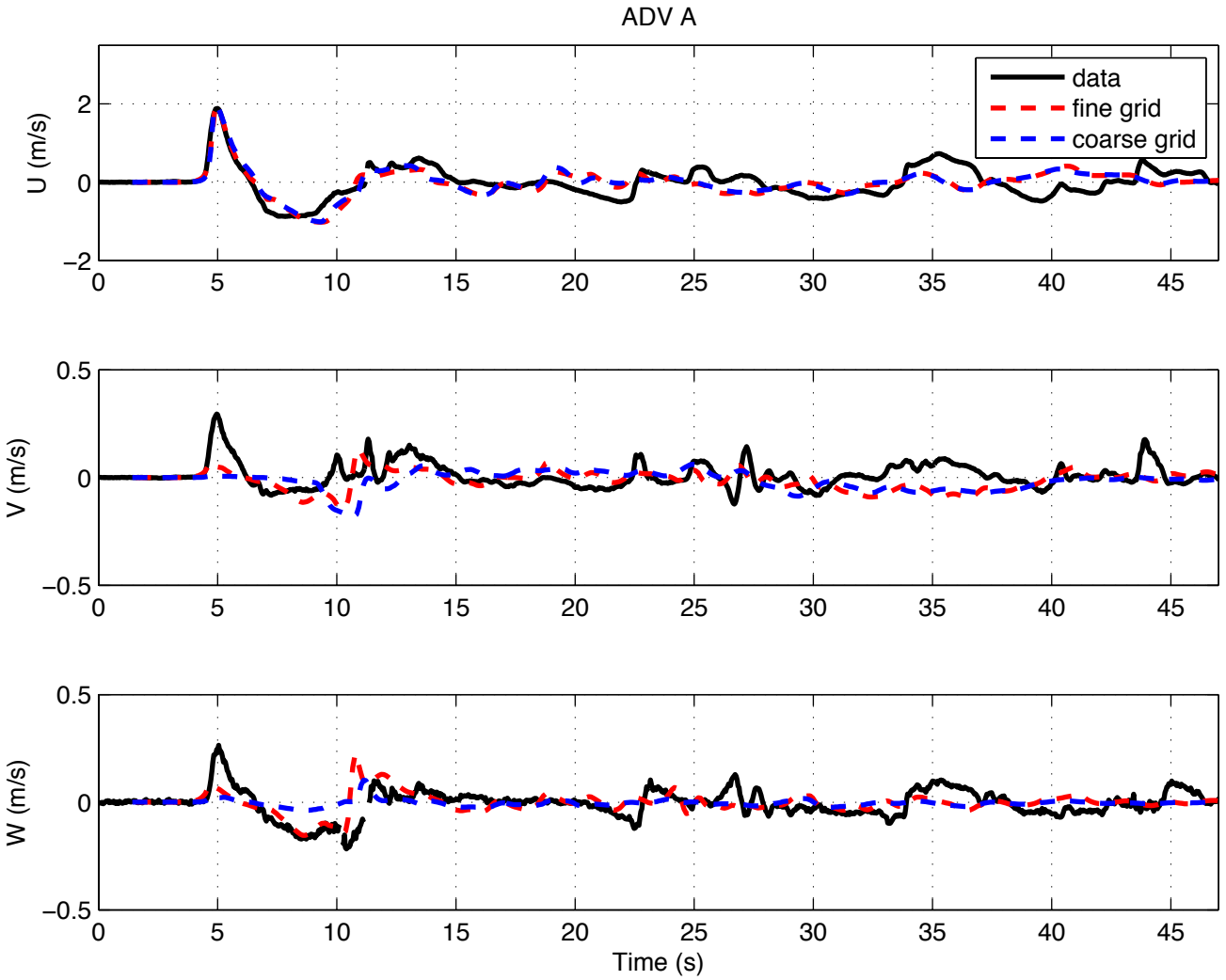


Figure: comparison of (U,V,W) at ADV A. (measured W flip over)

VIS breaker vs. SWE grid

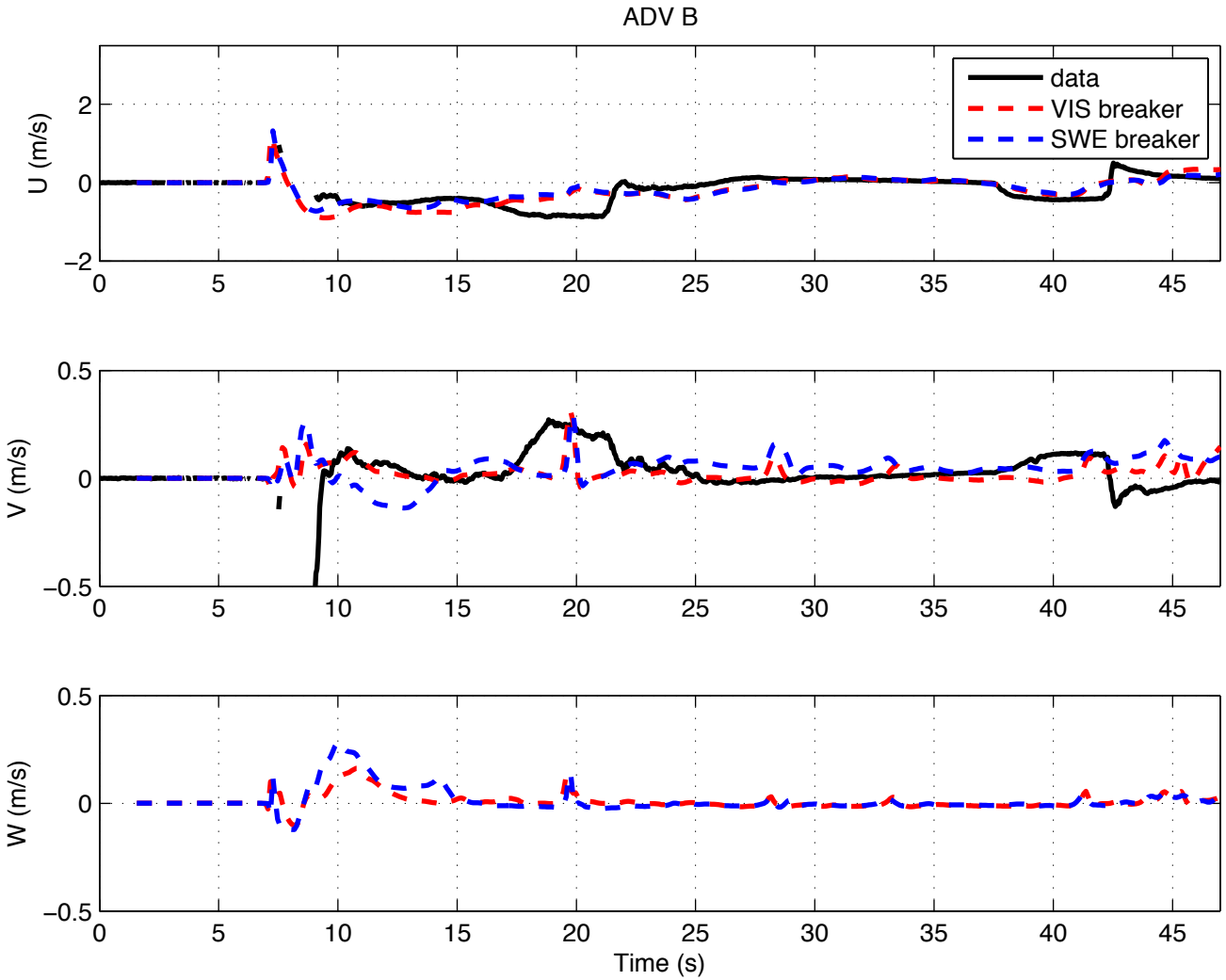


Figure: comparison of (U,V,W) at ADV B.

Fine grid vs. coarse grid

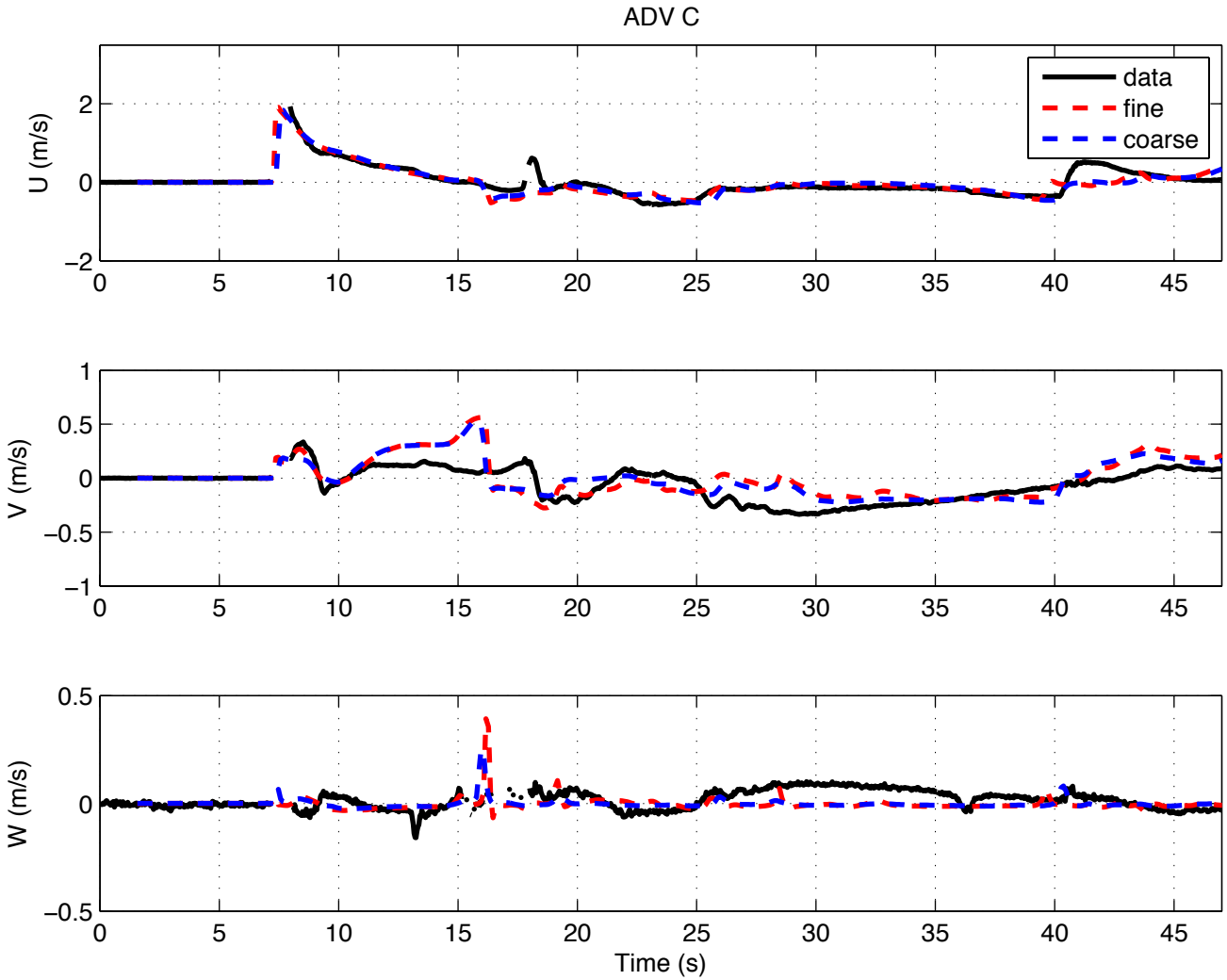


Figure: comparison of (U,V,W) at ADV C.

VIS breaker vs. SWE grid

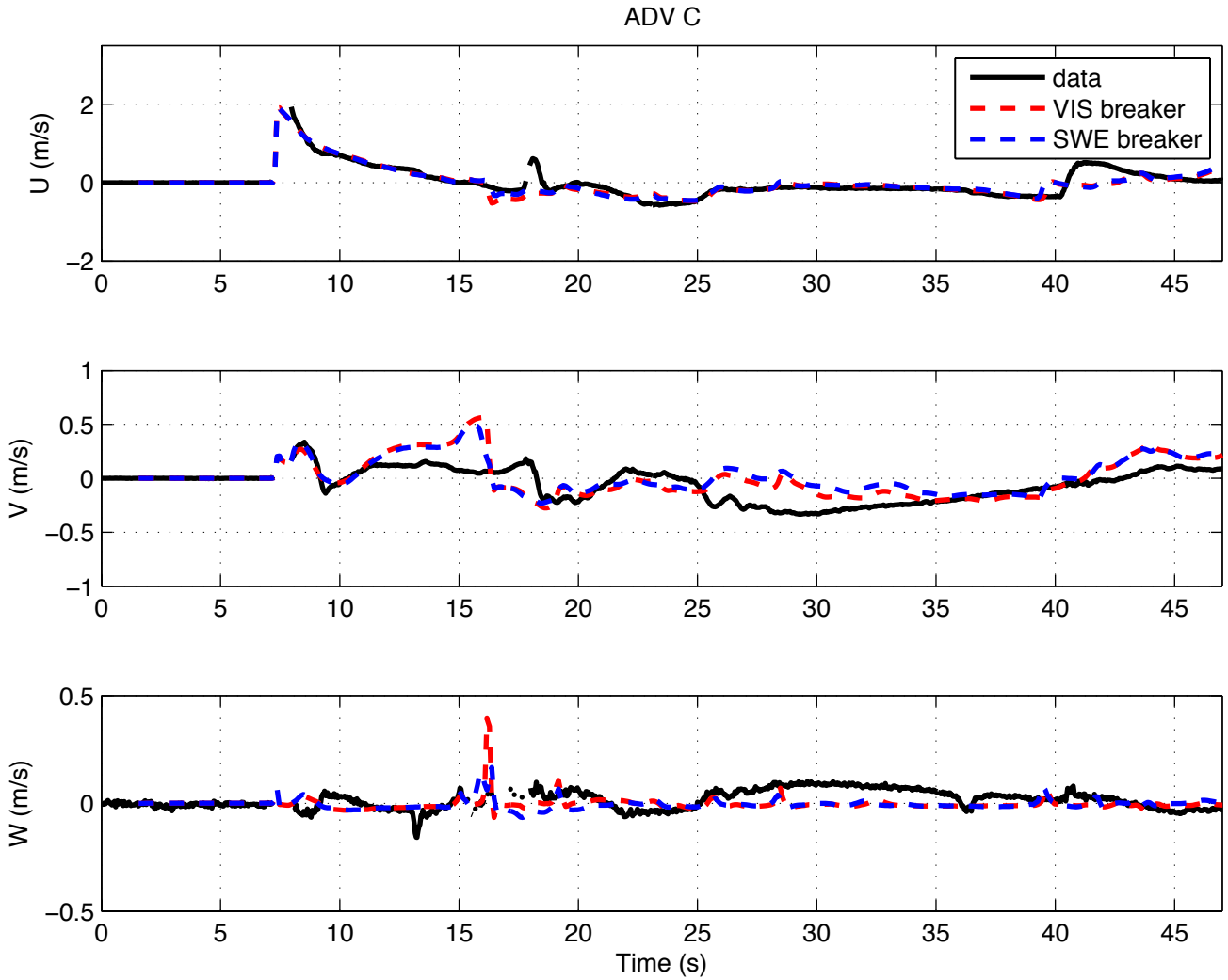
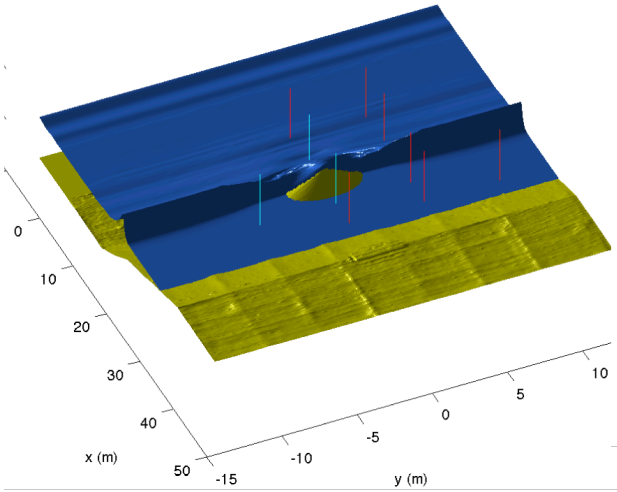
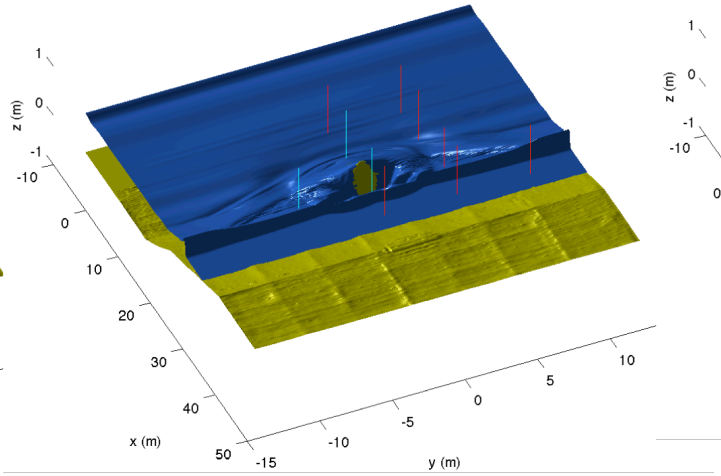


Figure: comparison of (U,V,W) at ADV C.

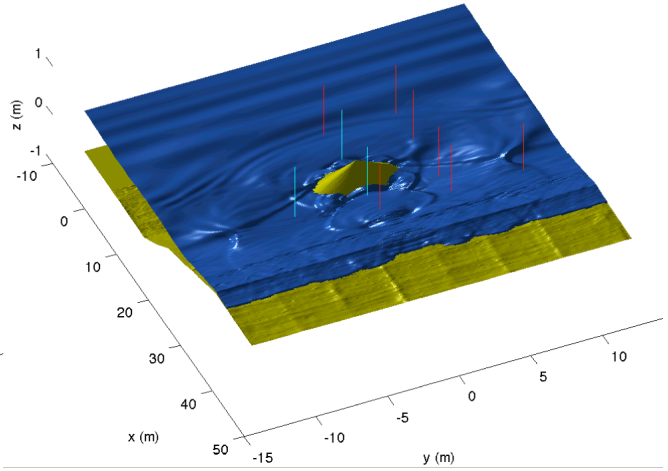
time = 6.0sec



time = 7.7sec



time = 13.0sec



Fine grid vs. coarse grid

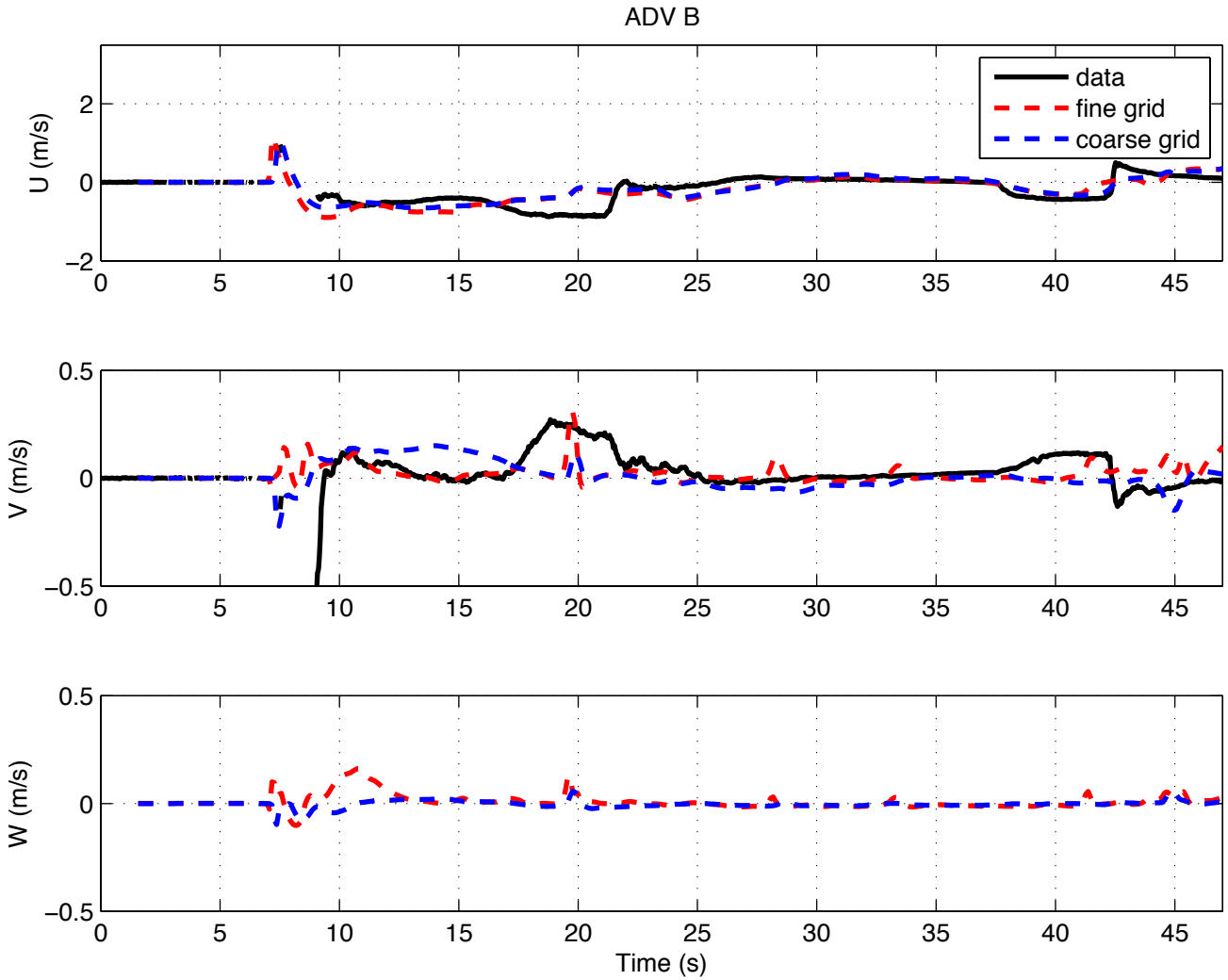


Figure: comparison of (U,V,W) at ADV B.