Simulations of Coastal Ocean Flows Using Chimera Grids

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Outline

I. Introduction: Needs and current status
II. Modeling framework
III. Coupling strategies
IV. Application examples
V. Concluding remarks

I. Introduction: Needs and current status

Coastal Flows: Example Problems

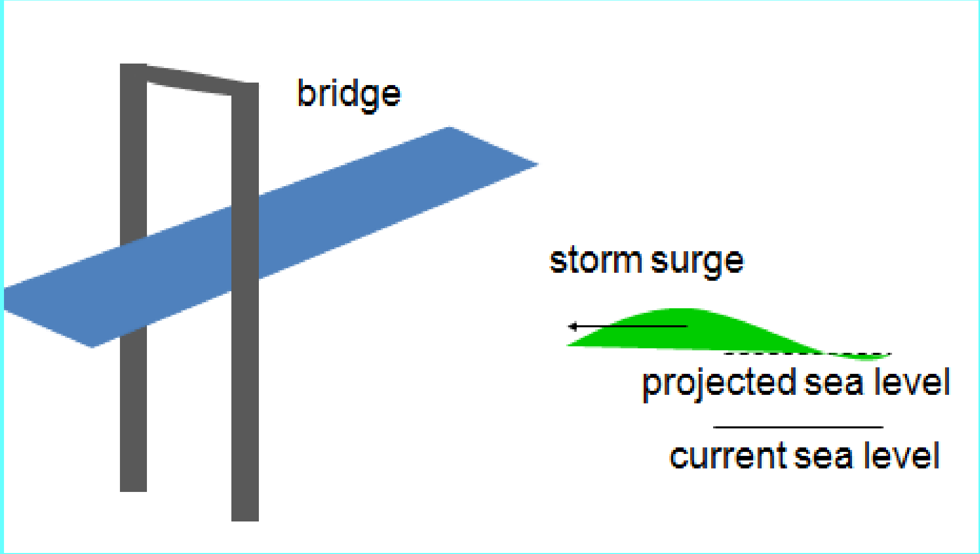
Bridge carrying US-90 damaged during Hurricane Katrina (Douglass et al. 2006)

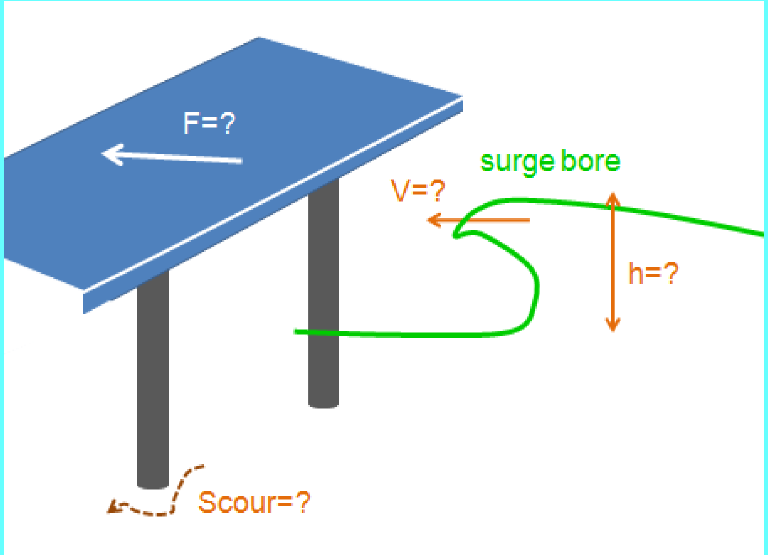
A destroyed section of boardwalk at Long Beach, NY (Photo by Bruce Bennett/Getty Images)

Multi-scale and Multi-physics Coastal Ocean Flows

A modeling question:

How can we make a high fidelity, detailed simulation of such phenomena, considering actual settings, forcing, etc.?





Other problems: oil spill, ……

Current Status, Challenge, and Approach

- Large-scales: geophysical fluid dynamics (GFD): O(10) – O (10,000) km, O(1) min – O (1) month
- Smaller scales: fully 3D fluid dynamics (F3DFD): O(10) cm – O (10) km, O(1) ms – O (1) hr
- Challenges: coastal ocean flows are multi-scale, multi-physics, most current models are designed for individual phenomena: circulation, wave, etc.
- Objective: high-fidelity, detailed simulation of coastal ocean flows, especially those at small scales.
- Approaches: Hybrid GFD/F3DFD (with change in the two models as less as possible)
- References of this presentation:

Tang, Wu, and Qu, JCP 2014

Tang, Qu, Wu, and Zhang, DD22, Lugano, Switzerland, 2013.

Tang and Wu, IEMSS, Ottawa, Canada, 2010

Tang, Comput. & Fluids, 2006

Tang, Jones, and Sotiropoulos, JCP 2003

II. Modelling framework

Fully 3D Fluid Dynamics and Coastal Ocean Model

$$\nabla \cdot \mathbf{u} = 0,$$

$$\mathbf{u}_t + \nabla \cdot \mathbf{u}\mathbf{u} = -\frac{1}{\rho_0}\nabla p + \nabla \cdot \left((\nu + \nu_t)\nabla \mathbf{u}\right) - g\big(1 - \alpha(T - T_0) - \beta(C - C_0)\big)\mathbf{k},$$

⟵ Gravity & buoyancy

$$T_t + \nabla \cdot (\mathbf{u}T) = \nabla \cdot \left(\left(\frac{\nu}{Pr} + \frac{\nu_t}{Pr_t}\right)\nabla T\right).$$

SIFOM -- solver for incompressible flow on overset meshes (Tang et al. 2003; Ge and Sotiropoulos 2005, …)

External mode

$$\eta_t + \nabla_H \cdot (\mathbf{V}D) = 0,$$

$$(\mathbf{V}D)_t + \nabla_H \cdot (\mathbf{V}\mathbf{V}D) = -gD\nabla_H \eta + \frac{\boldsymbol{\tau}_s - \boldsymbol{\tau}_b}{\rho_0} + \mathbf{G}.$$

FVCOM – finite volume method coastal ocean model (Chen et al., 2003; …)

Internal mode

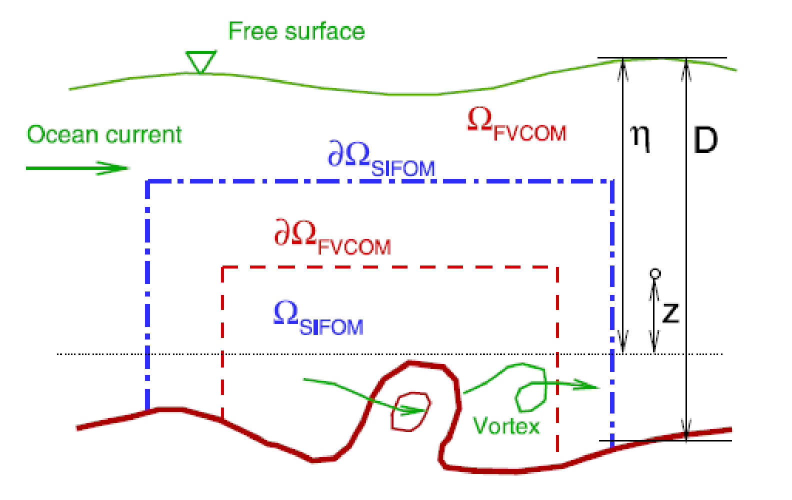
$$\eta_t + \nabla_H \cdot (\mathbf{v}D) + \omega_\sigma = 0,$$

$$(\mathbf{v}D)_t + \nabla_H \cdot (\mathbf{v}\mathbf{v}D) + (\mathbf{v}\omega)_\sigma = -gD\nabla_H \eta + \nabla_H \cdot (\kappa \mathbf{e}) + \frac{1}{D}(\lambda \mathbf{v}_\sigma)_\sigma - \frac{gD}{\rho_0}\left(\nabla_H\left(D\int_\sigma^0 \rho\, d\sigma'\right) + \sigma\rho\nabla_H D\right) + \mathbf{H},$$

$$(TD)_t + \nabla_H \cdot (TD\mathbf{v}) + (T\omega)_\sigma = \nabla_H \cdot (\theta \nabla_H T) + \frac{1}{D}(\vartheta T_\sigma)_\sigma + \mathbf{I}.$$

II. Modelling framework

Outline of Coupling

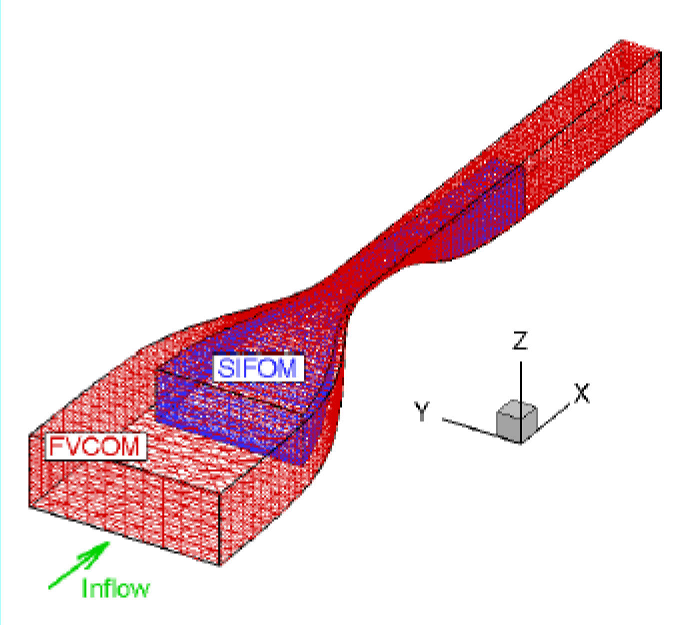


SIFOM/FVCOM coupling:

--- Domain decomposition, Chimera grids, overlapping regions, and Schwarz alternative iteration
--- Coupling between SIFOM and FVCOM : exchange of solution for η, u, v, w
--- Tri-linear interpolation, FVCOM ➔ SIFOM, SIFOM → FVCOM

Focus of this presentation: 1) Treatments of coupling
2) Demonstration of feasibility and performance

Test1 --- Flow over Sill



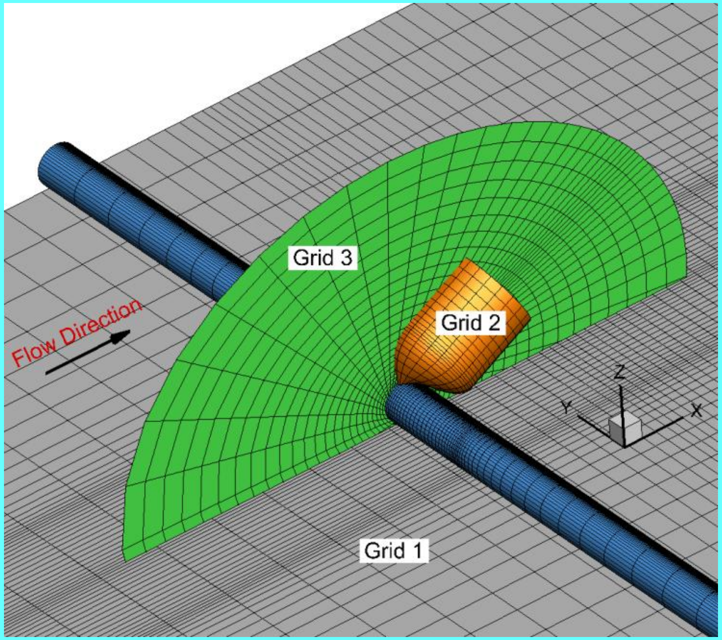
$$\begin{cases} -1500 < x < 2000, \\ y = \pm 200(1 - 0.8e^{-4\times10^{-6}x^2}), \quad x < 0; \;\; y = \pm 40, \;\; x > 0, \\ z = -150 + \dfrac{140}{1 + (x/500)^4}, \;\; x < 0; \;\; z = -120 + \dfrac{110}{1 + (x/500)^4}, \;\; x > 0, \end{cases}$$

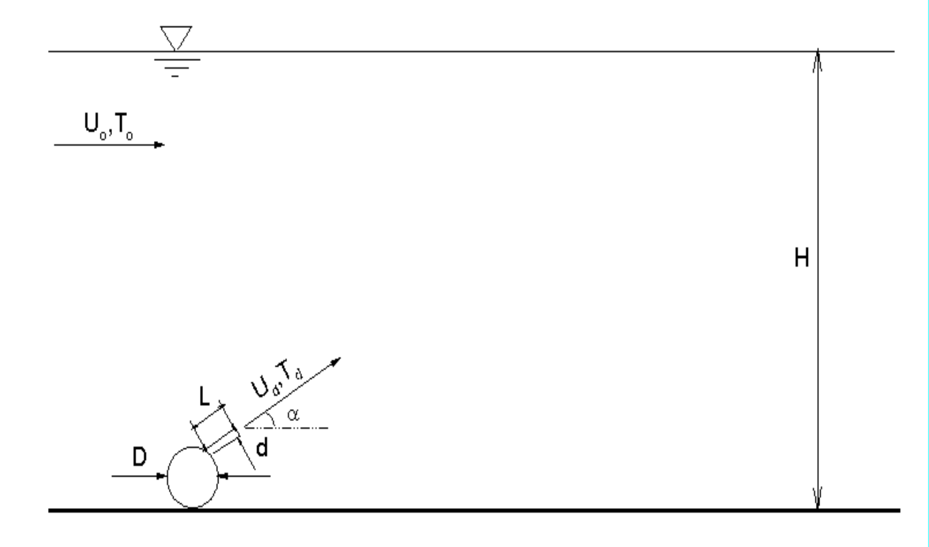
Configuration of channel and sill

$$\begin{cases} u, v, w = 0, \;\; t = 0, \\ \eta u = 0.9175(1 - e^{-0.01t}), \;\; x = -1500; \;\; \eta = 0, \;\; x = 2000. \end{cases}$$

IC & BC

Test2 --- Thermal Discharge Flow

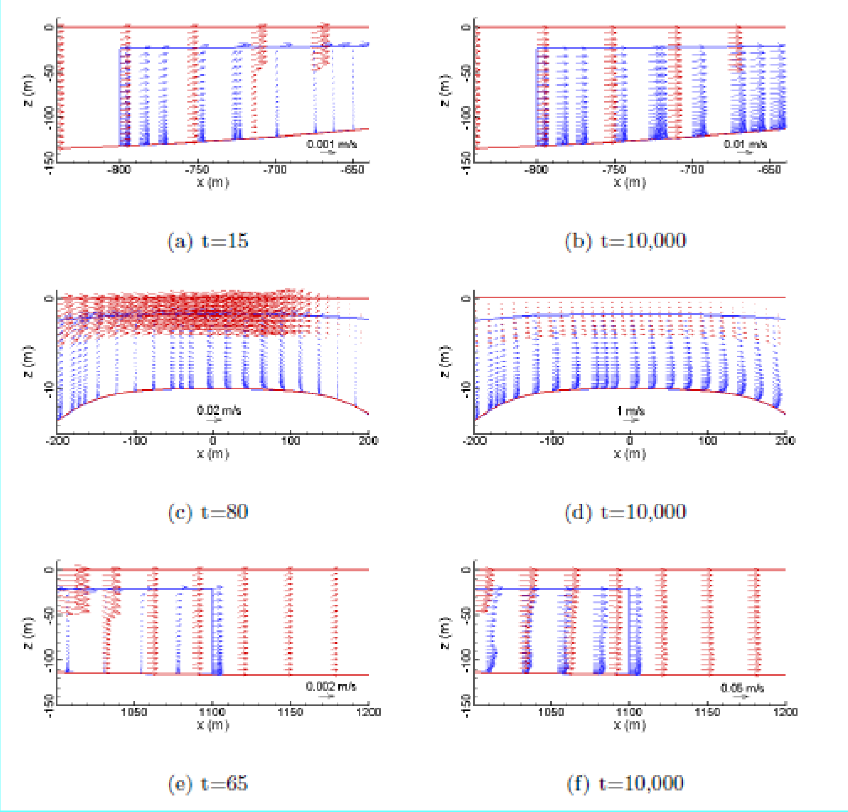




Ambient parameter		
Velocity, U_a (m/s)	Temperature, T_a (°C)	Channel depth, H (m)
0.05	20.5	12.3

Effluent parameter					
Velocity, U_d (m/s)	Temperature, T_d (°C)	Port diameter, d (m)	Port length, L_d (m)	Port angle, α (degree)	Pipe diameter, D (m)
3.92	32.0	0.175	0.91	30°	1.32

Treatment of Hydrostatic Pressure

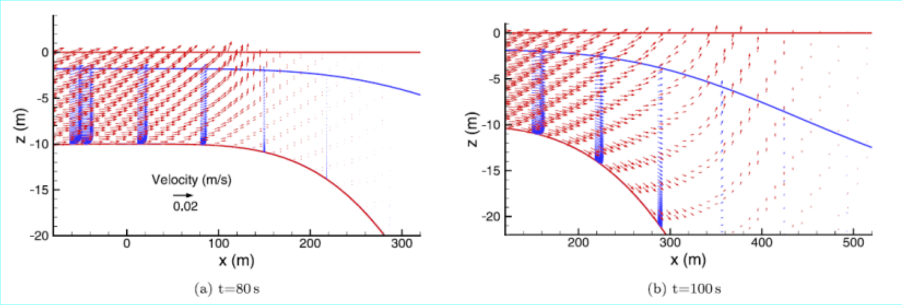


(a) t=15 (b) t=10,000

(c) t=80 (d) t=10,000

(e) t=65 (f) t=10,000

SIFOM-FVOCM



(a) t=80 s (b) t=100 s

SIFOM1-FVOCM

SIFOM and SIFOM1 perform differently. Why?

SIFOM1

$$p = p_h + p_d.$$

$$-\frac{1}{\rho_0}\nabla_z p_h = g\big(1-\alpha(T-T_0)-\beta(C-C_0)\big)\mathbf{k},$$

Differential-integral equation

$$\mathbf{u}_t + \nabla\cdot\mathbf{u}\mathbf{u} = -\frac{1}{\rho_0}\nabla p_d + \nabla\cdot\big((\nu+\nu_t)\nabla\mathbf{u}\big) - g\nabla_H\left(\eta - \int_z^{\eta}\big(\alpha(T-T_0)+\beta(C-C_0)\big)d\zeta\right),$$

Treatment of Buoyancy

$$p = p_h' + p_d',$$

$$-\frac{1}{\rho_0}\nabla_z p_h' = g\mathbf{k},$$

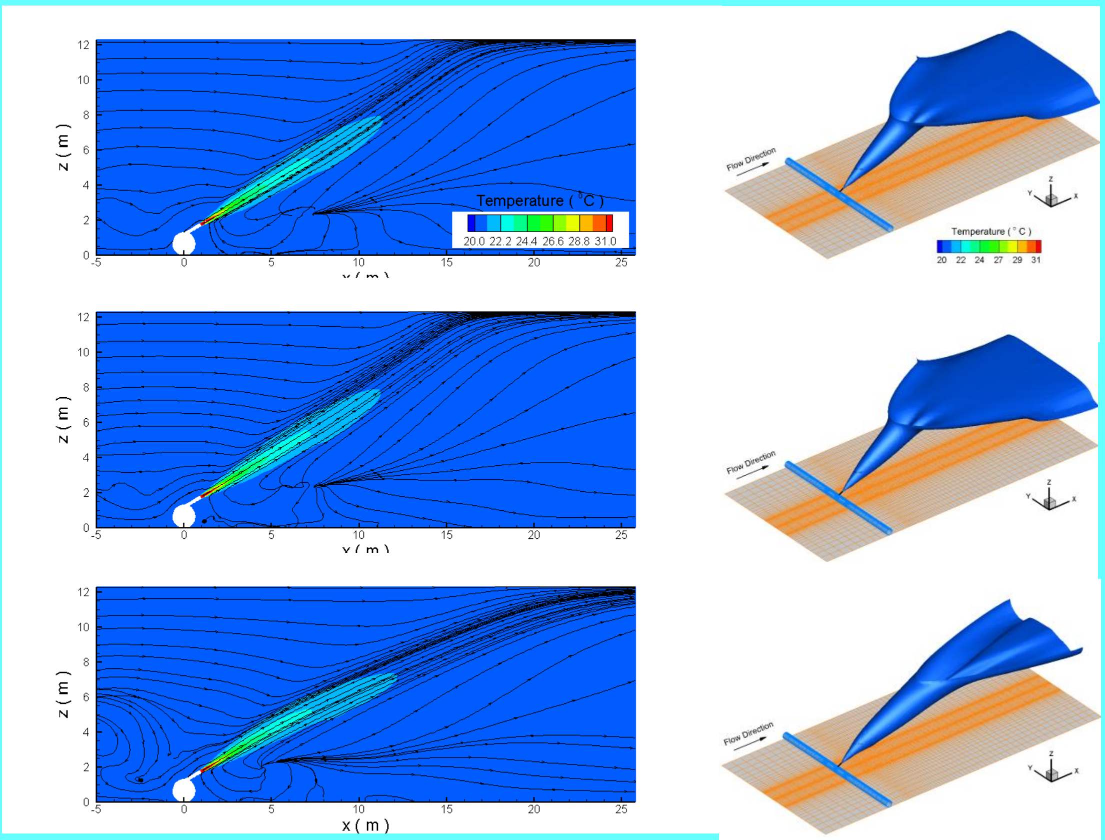
SIFOM2

$$\mathbf{u}_t + \nabla\cdot\mathbf{u}\mathbf{u} = -\frac{1}{\rho_0}\nabla p_d' + \nabla\cdot\left((\nu+\nu_t)\nabla\mathbf{u}\right) - g\nabla_H\eta + g\big(\alpha(T-T_0) - \beta(C-C_0)\big)\mathbf{k},$$

SIFOM1

SIFOM2

No buoyancy



0.4 million nodes

CPU time comparison

Model	CPU
SIFOM 1	300%
SIFOM2	100%

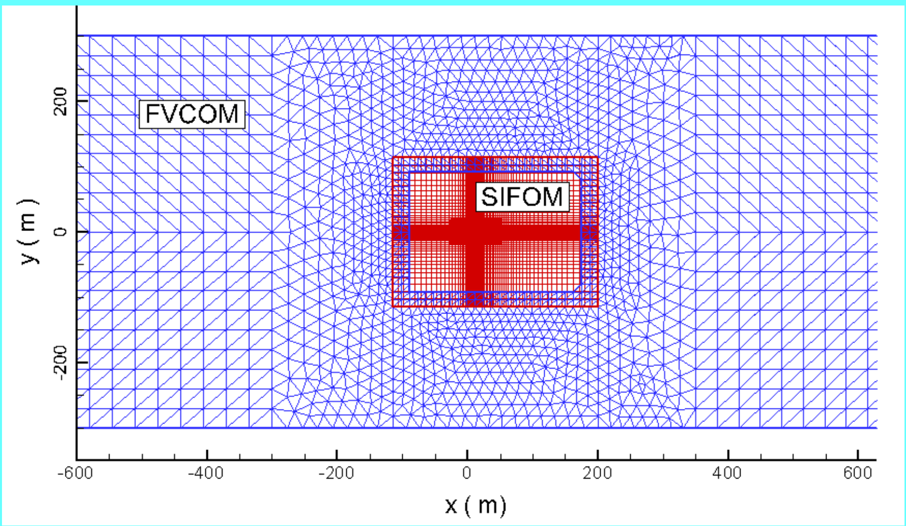
Treatment of Buoyancy

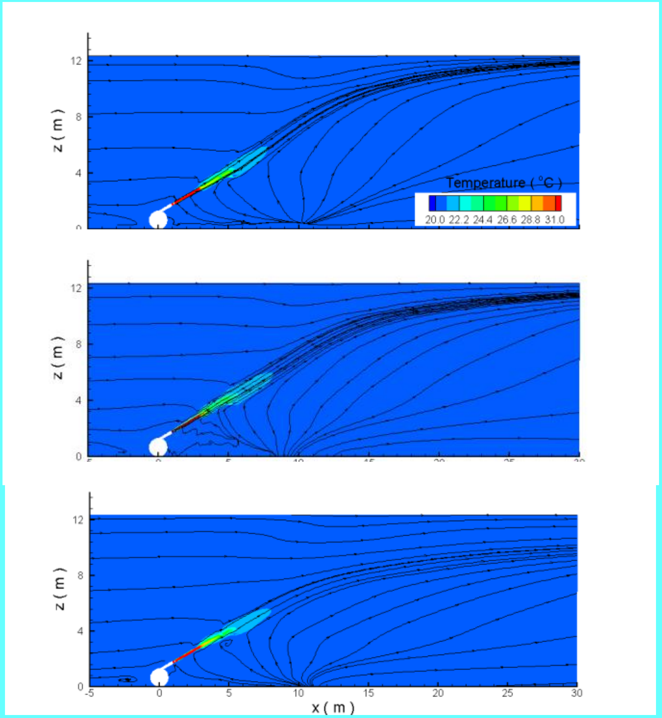
$$p = p_h' + p_d',$$

$$-\frac{1}{\rho_0}\nabla_z p_h' = g\mathbf{k},$$

SIFOM2

$$\mathbf{u}_t + \nabla \cdot \mathbf{uu} = -\frac{1}{\rho_0}\nabla p_d' + \nabla \cdot \left((\nu + \nu_t)\nabla \mathbf{u}\right) - g\nabla_H \eta + g\big(\alpha(T - T_0) - \beta(C - C_0)\big)\mathbf{k},$$





SIFOM1-FVCOM

SIFOM2-FVCOM

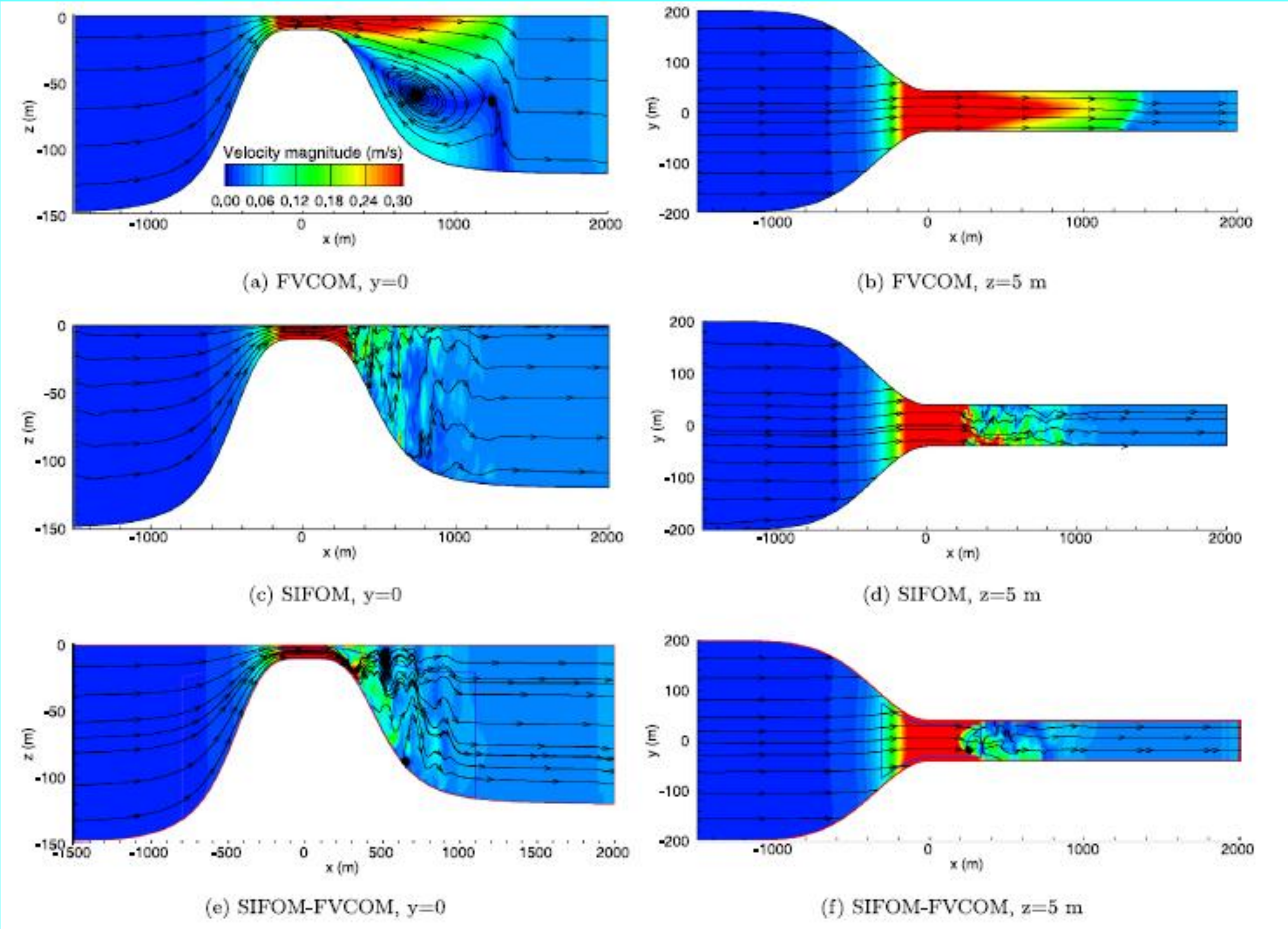
No buoyancy

CPU time

	SIFOM1	SIFOM2
SIFOM-FVCOM	123%	100%

SIFOM: 0.4 million nodes
FVCOM: 70k elements

Simulations and Convergence Test



(a) FVCOM, y=0
(b) FVCOM, z=5 m
(c) SIFOM, y=0
(d) SIFOM, z=5 m
(e) SIFOM-FVCOM, y=0
(f) SIFOM-FVCOM, z=5 m

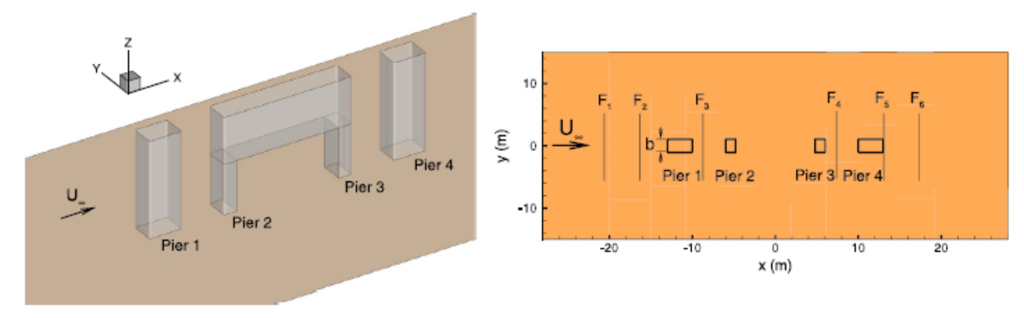
T=10,000 s

Estimated order of solution accuracy.

Accuracy order k	p	η	u	v	w
SIFOM model	0.96		1.75	2.12	1.63
FVCOM		1.08	1.53	2.73	1.68

t=100 s

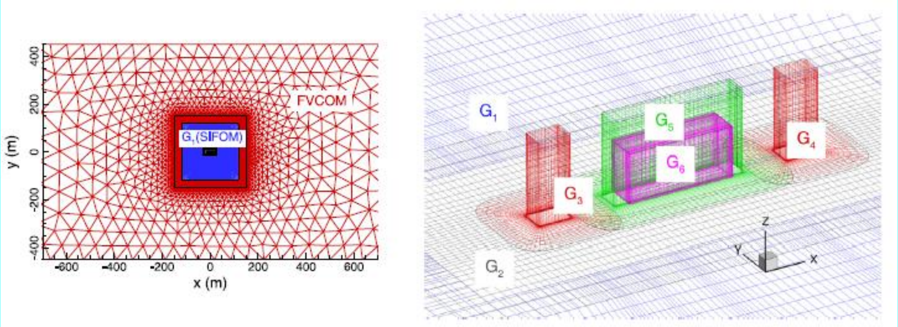
Flow past Bridge Peers in Channel



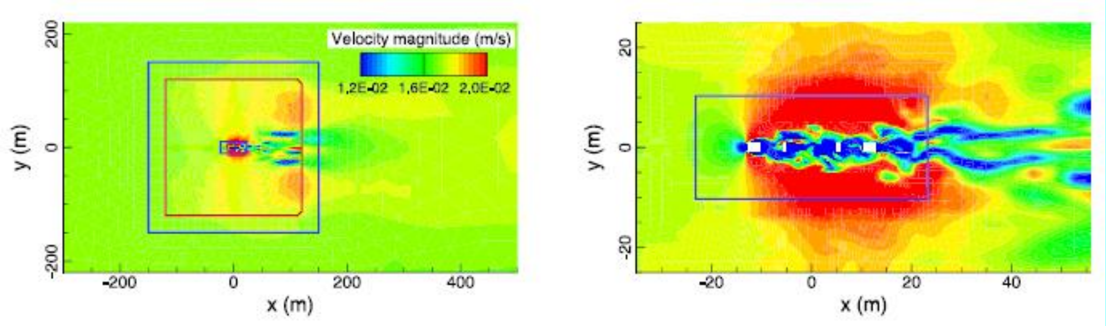
(a) 3D view (b) Top view

Peer configuration

mesh



(a) (b)

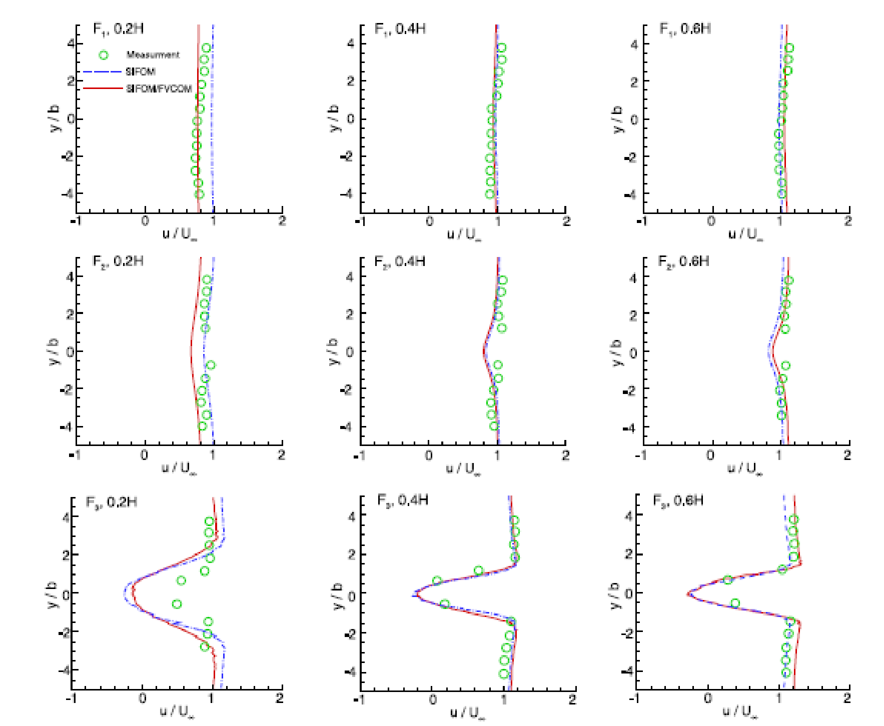


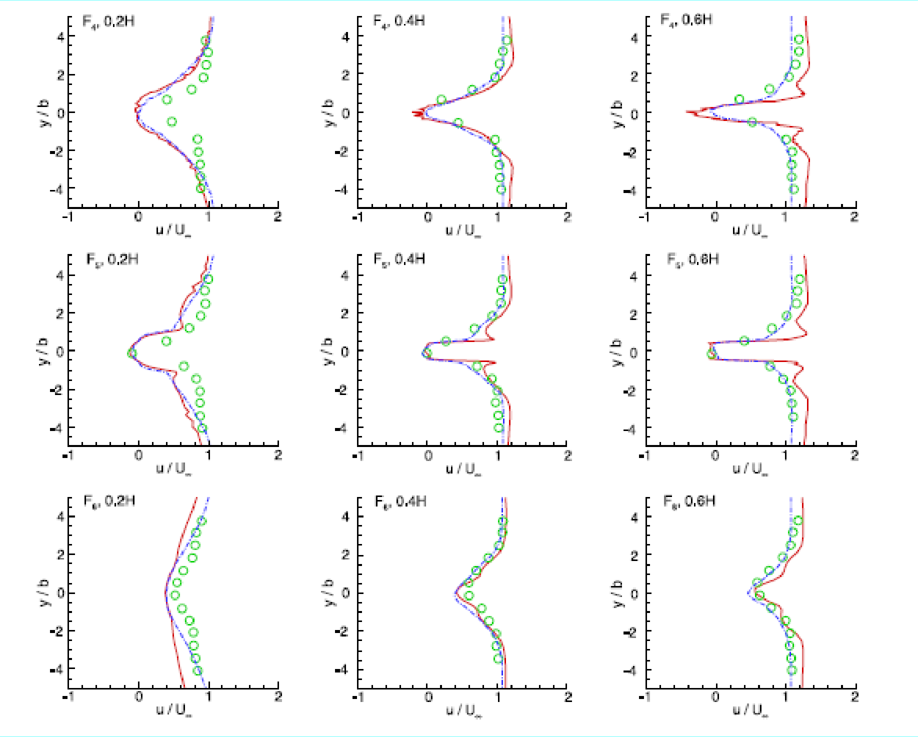
(a) (b)

Simulation

IV. Application examples

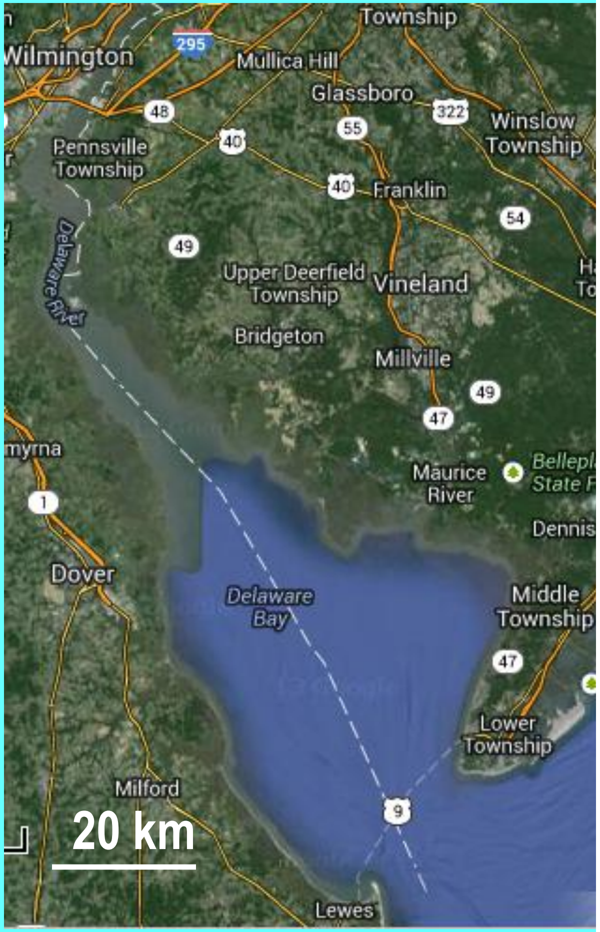
Comparison with Measurement

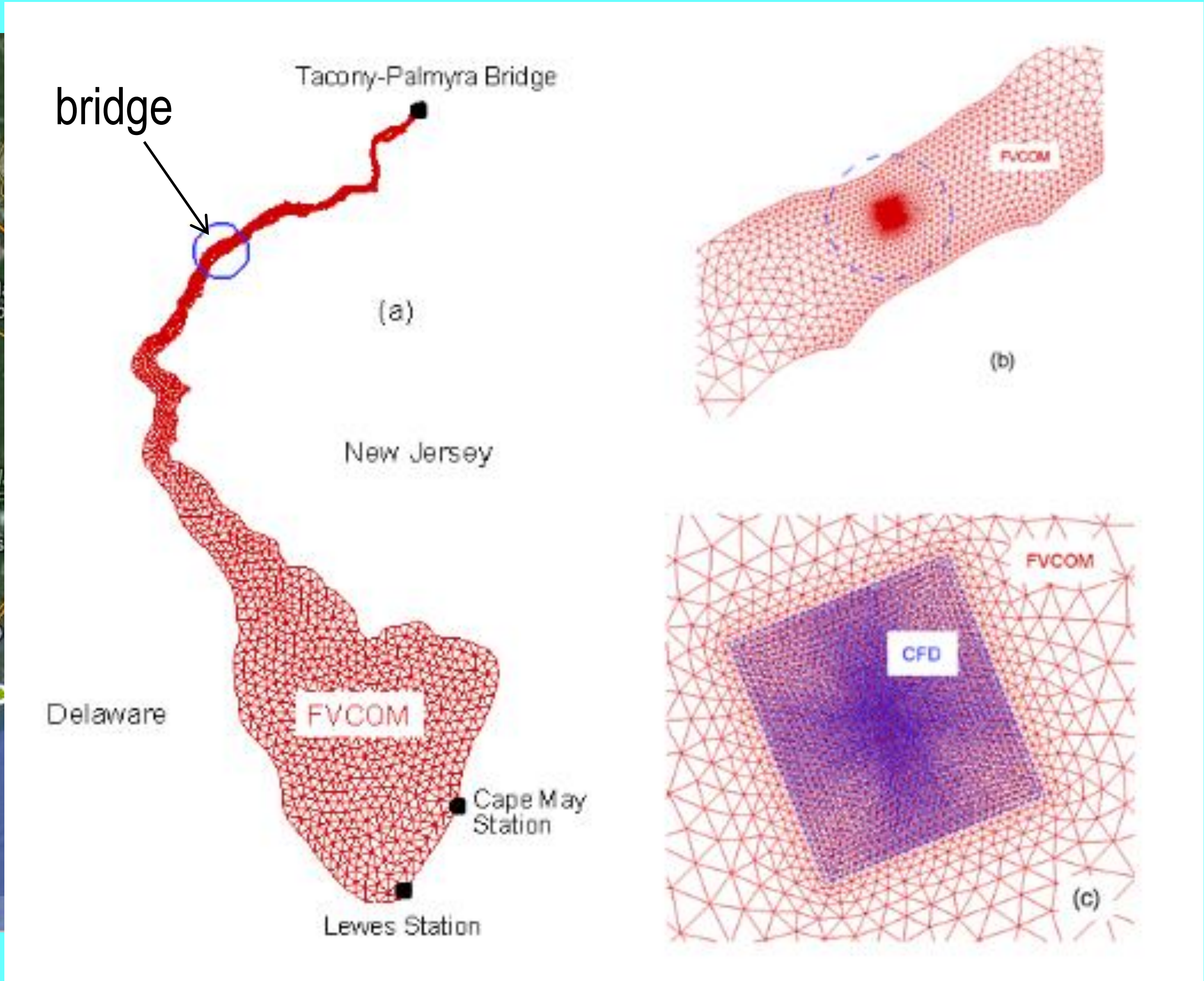




Velocity profiles at different locations

Flow Past Coastal Bridge – Model Setup



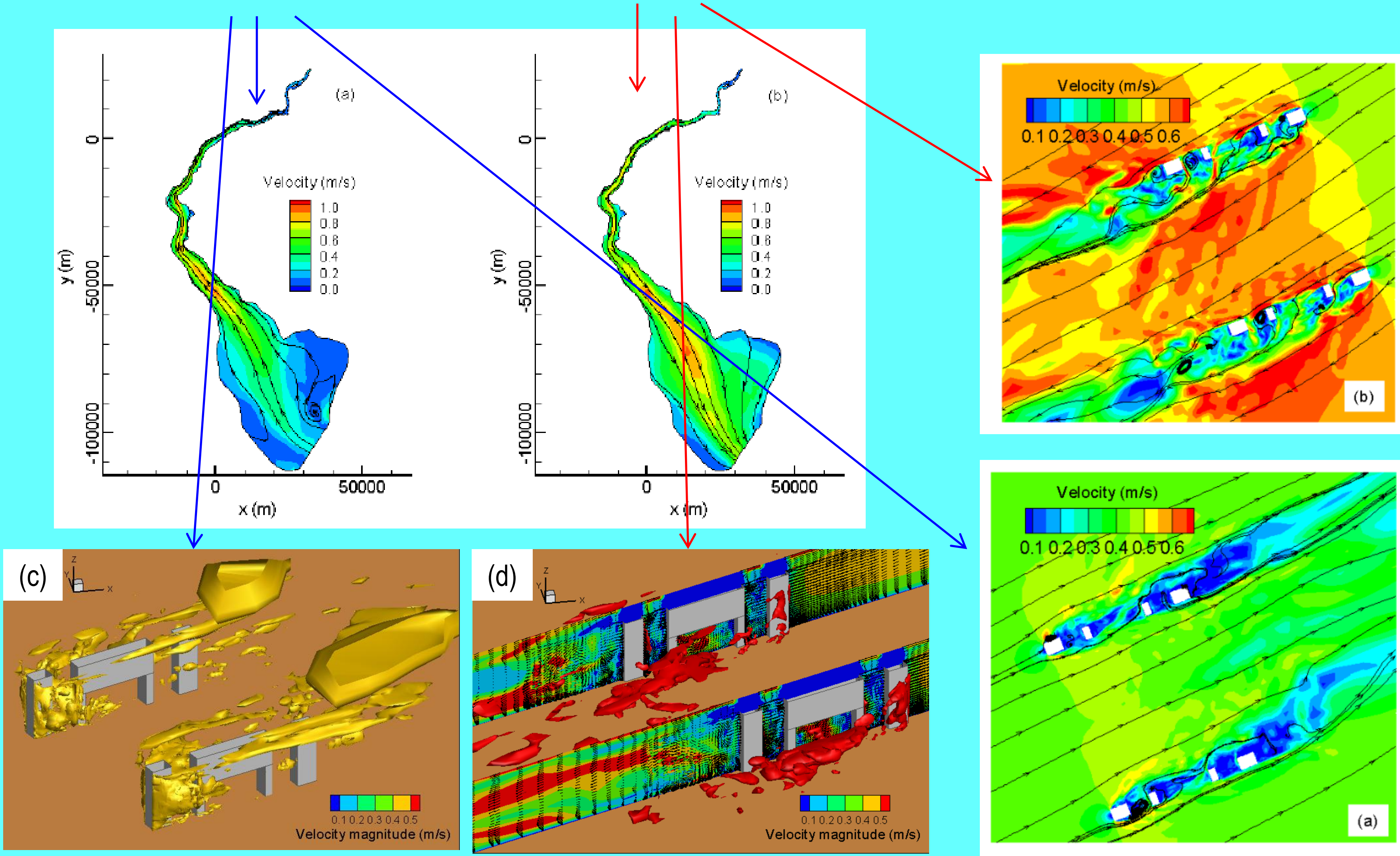


Meshes of FVCOM and CFD model

IV. Application examples

Simulated Flows

Flood tide Ebb tide



Discussions

Conclusion:

1) Chimera grid method is promising in coupling fully 3D fluid dynamics and coastal ocean models, which is challenging; it integrates different governing equations, distinct numerical systems, and dissimilar meshes.
2) SIFOM-FVCOM works well, and it can be applied to actual problems.

Future work:

1) More validation and experiment of the modeling system
2) Better model interface algorithms
3) Improve computational efficiency of the system
4) ……

Question?

Thanks!