# Chimera Grid Method for Coupling of Coastal Ocean Model and Computational Fluid Dynamics Model

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# Outline

I. Introduction: Needs and current status
II. Coastal ocean model and CFD model
III. Coupling strategies
IV. Examples of coupling
V. Concluding remarks

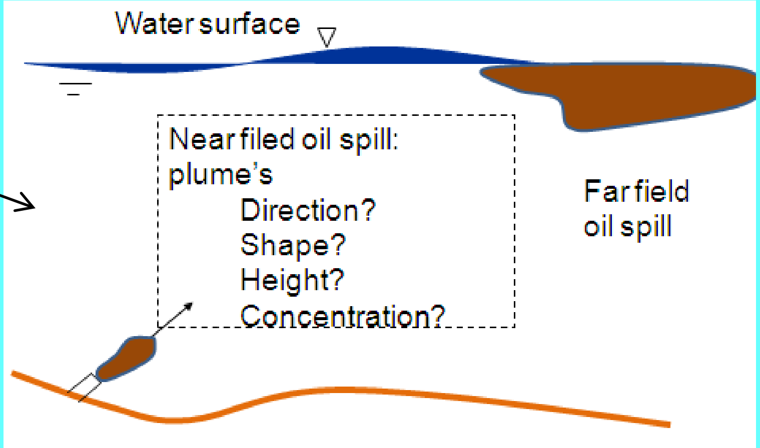
I. Introduction: Needs and current status

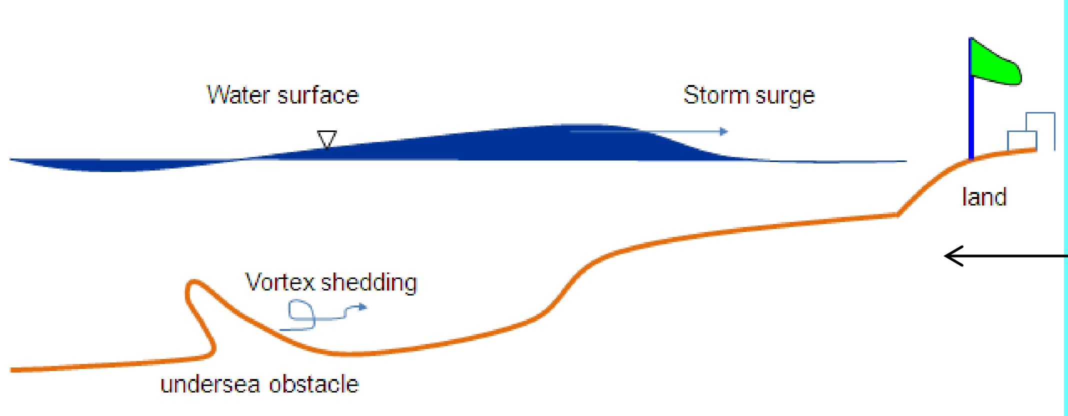
# Multi-scale and Multi-physics Flows: Example problems

A. Deepwater horizontal oil spill

1) small-scale plume of oil spill: initial mixing, momentum dominant

2) large scale ocean circulation: floating and dispersion, buoyancy prevalent



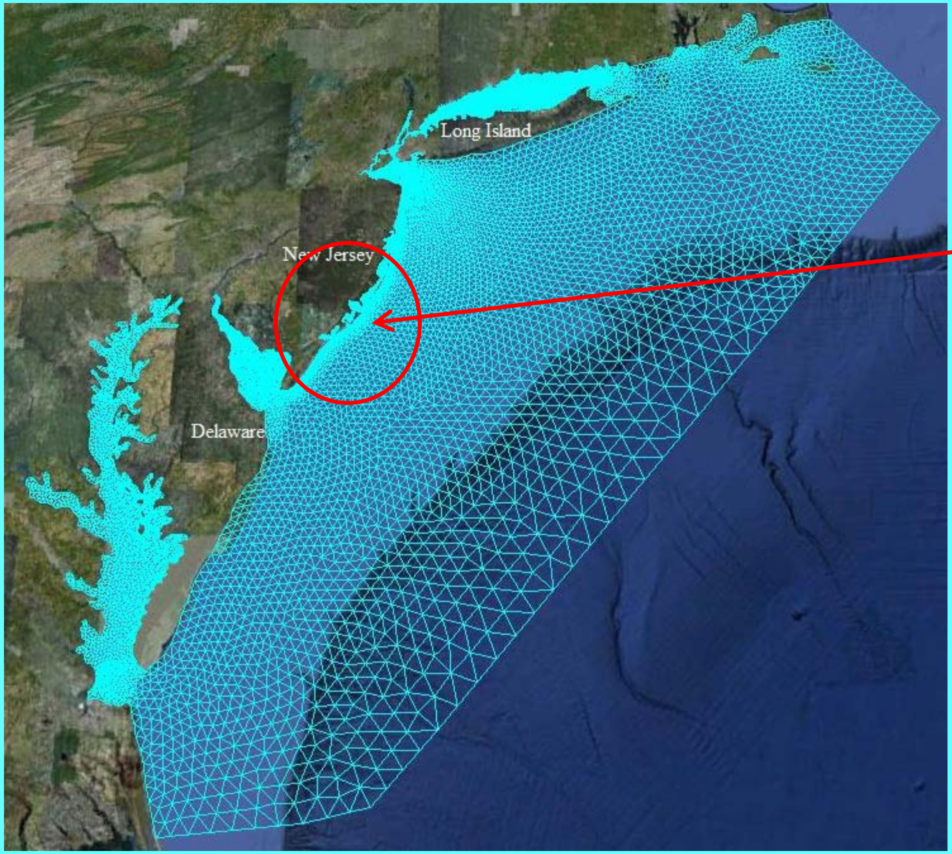

B. Coastal surface wave

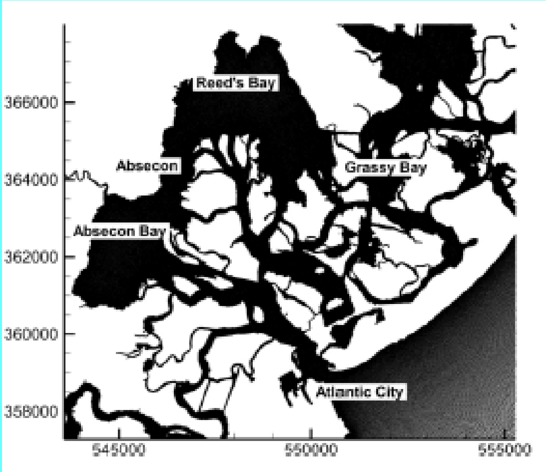
1) surge bore: wave, inviscid

2) underwater vortex flow: mixing & diffusion process

# Coastal Ocean Flow Modeling, Challenge, and Approach

- Large scales -- Computational Geophysics Dynamics (GFD):
  O(10)km – O (10,000) km
  O(1)hr – O (1) month




Atlantic City.

6 million elements (grid spacing 20 m --- 20 km)
Two week flow run takes:
15 days (800 cores)
7 days (2000 cores)

# Coastal Ocean Flow Modeling, Challenge, and Approach

- Smaller scales: computational fluid dynamics (CFD):
  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: Accurate simulation of coastal ocean flows,
  especially those at small scales.

Approaches: Hybrid GFD/CFD, or coupling of GFD/CFD models (with as change
in side the two models as less as possible)

# CFD Model and FVCOM

## CFD model

$$\Gamma\frac{\partial Q}{\partial t}+J\frac{\partial}{\partial \xi^k}(F^k-F_v^k)+H=0,\quad \Gamma=diag(0,1,1,1),\quad Q=(p,u,v,w)^T,$$

$$F^k=\frac{1}{J}(U^k,uU^k+p\xi_x^k,vU^k+p\xi_y^k,wU^k+p\xi_z^k)^T,$$

$$F_v^k=\frac{1}{J}\left(\frac{1}{\mathrm{Re}}+\nu_t\right)(0,g^{lk}\frac{\partial u}{\partial \xi^l},g^{lk}\frac{\partial v}{\partial \xi^l},g^{lk}\frac{\partial w}{\partial \xi^l})^T\qquad H=-\frac{T}{Fr^2}e$$

Curvilinear coordinates
Overset grids
2nd-order artificial compressible method
……..
Ref: Sotiropoulos, et al. JCP, 1991
Tang, et al., JCP, 2003
Paik, et al., Phys Fluids, 2008
…..

## FVCOM (hydrostatic assumption, p=gamma*h, ….)

External mode (shallow water eqs)

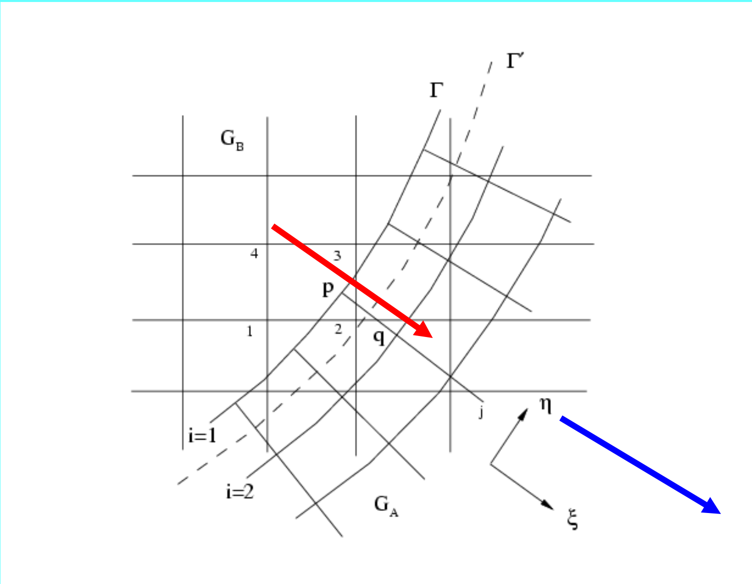
$$\frac{\partial \eta}{\partial t}+\frac{\partial DU_l}{\partial x_l}=0\qquad \frac{\partial U_iD}{\partial t}+\frac{\partial U_iU_lD}{\partial x_l}=-gD\frac{\partial \eta}{\partial x_i}-\frac{gD}{\rho_0}\left(\int_{-1}^{0}\frac{\partial}{\partial x_i}\left(D\int_{\sigma}^{0}\rho d\sigma'\right)d\sigma+\frac{\partial D}{\partial x_i}\int_{-1}^{0}\sigma\rho d\sigma\right)$$
$$+(-1)^i fU_jD+\frac{\tau_{sx_i}-\tau_{bx_i}}{\rho_0}+D\tilde{F}_i+G_i,$$

Internal mode

$$\frac{\partial \eta}{\partial t}+\frac{\partial Du_l}{\partial x_l}+\frac{\partial \omega}{\partial \sigma}=0,\quad \frac{\partial u_iD}{\partial t}+\frac{\partial u_iu_lD}{\partial x_l}+\frac{\partial u_i\omega}{\partial \sigma}=-gD\frac{\partial \eta}{\partial x_i}-\frac{gD}{\rho_0}\left(\frac{\partial}{\partial x_i}\left(D\int_{\sigma}^{0}\rho d\sigma'\right)+\sigma\rho\frac{\partial D}{\partial x_i}\right)$$
$$+(-1)^i fu_j+\frac{1}{D}\frac{\partial}{\partial \sigma}\left(K_m\frac{\partial u_i}{\partial \sigma}\right)+DF_i,$$

Triangle mesh and σ coordinate
2nd-order finite volume method
Mode splitting solution
……..
Ref: Chen, et. al., JAOT, 2003
Lai, et al., JGR, 2010
……

# Overset Method of CFD Model

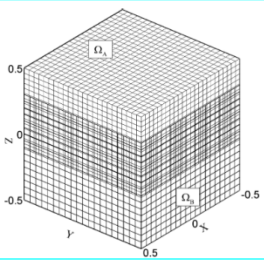


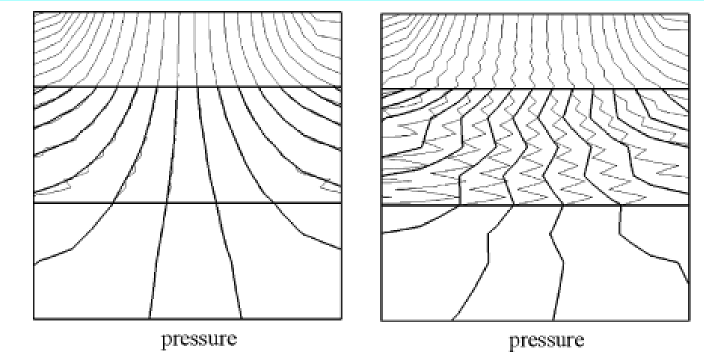

Implicit interface conditions implemented using Schwarz alternative iteration

A mass conservative interpolation MFBI (e.g., Tang, et al., JCP, 2003)

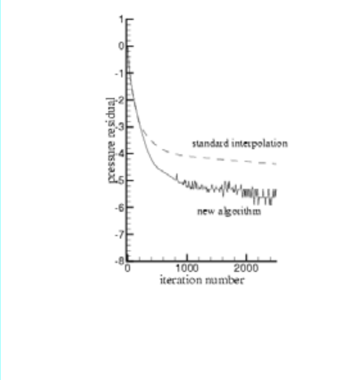
$$\sum_j \tilde{F}^1_{3/2,j}(U_p^A, U_q^A)\Delta\Gamma'_j = \sum_j \tilde{F}^1_{3/2,j}(U_p^B, U_q^B)\Delta\Gamma'_j,$$

Unsteady cavity flow

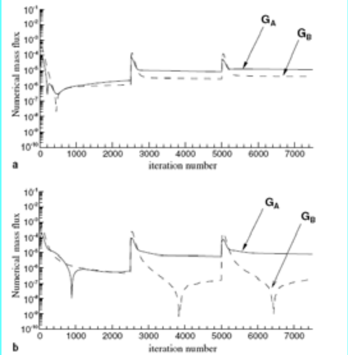



Direct interpolation Conservative interpolation



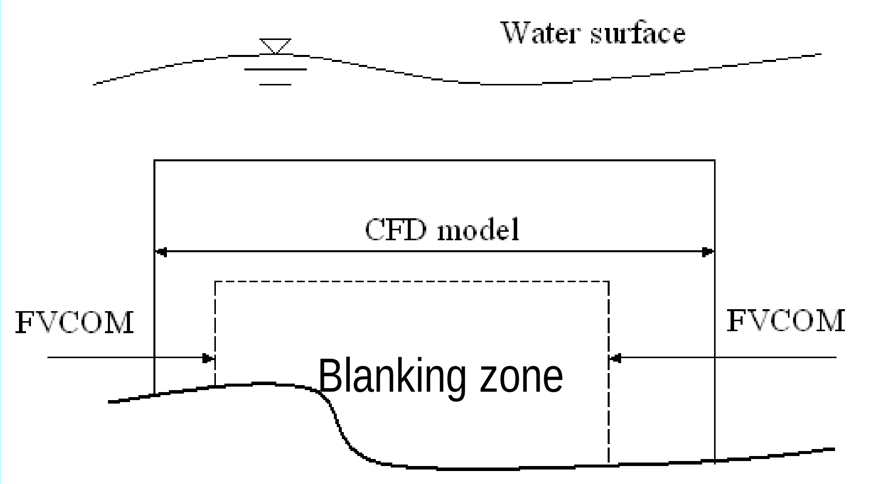

Convergence history for periodic cavity flow

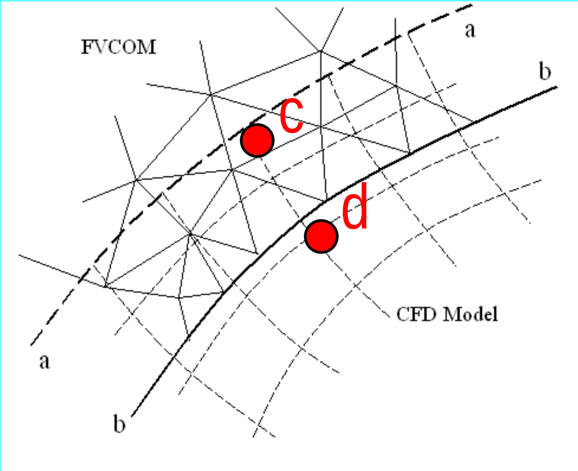



Numerical mass flux across the boundary of grid $G_B$. (a) MFBI and (b) SI

Convergence, conservation error

# Outline of Coupling




CFD/FVCOM coupling:

--- Domain decomposition, overlapping regions, and Schwarz alternative iteration

--- Coupling between CFD and internal mode of FVCOM : exchange of solution for u, v, w

--- Tri-linear interpolation, FVCOM → CFD: one point (c) or two point interpolation (c & d)

CFD → FVCOM: all points in the blanked region

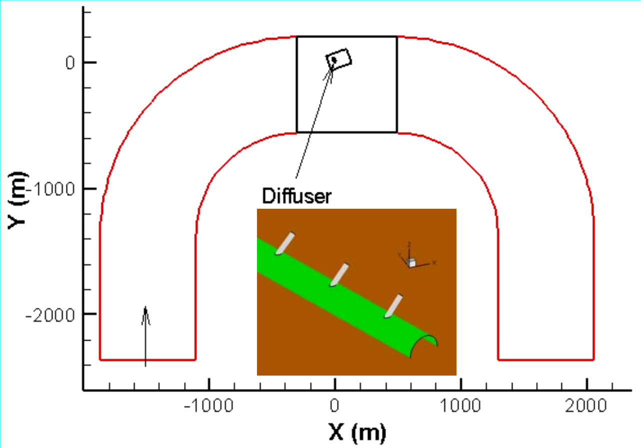
One – point interpolation ---- natural, conventional (FVCOM, CFD 2nd order)

Two – point interpolation ---- unusual, seems abundant / unnecessary, an approximation of derivatives, … ?

Focus of this presentation: 1) Feasibility and solution quality of approach

2) Interface algorithm, e.g., performance of one- and two-point interpolation

# Thermal Discharge in Steady Curved Channel Flow




Channel and diffuser

Mesh:

coupling – FVCOM: 115,000 nodes each layer,11 layers

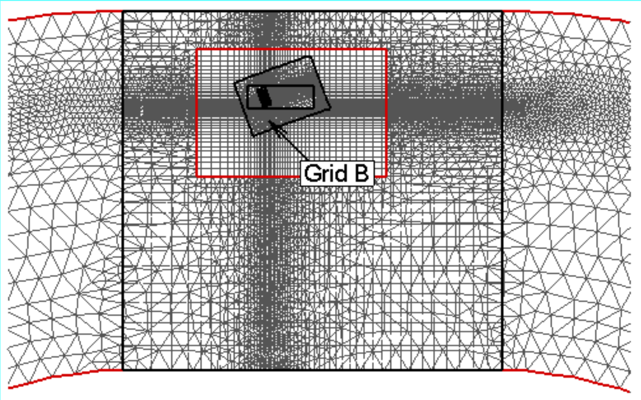
CFD -- 220,000 nodes

Diffuser:

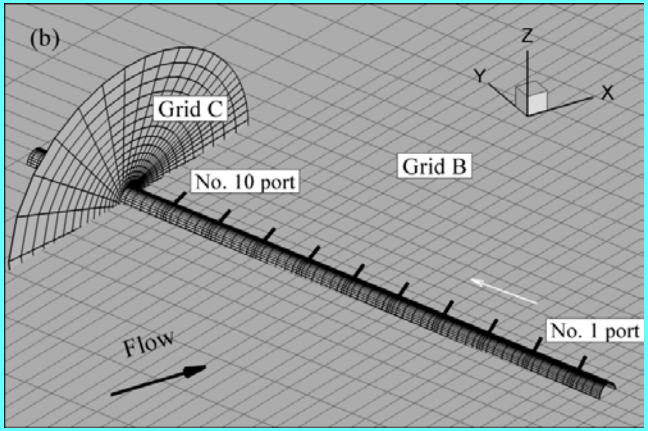
Diameter of ports: 0.17 m

Discharge plume: 3.9 m/s, 32 $^{o}$C

Ambient flow: 20.5 $^{o}$C




Mesh. Structured mesh – CFD
unstructured mesh – FVCOM



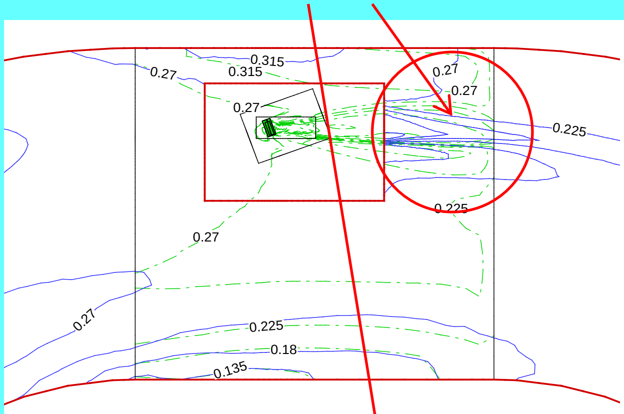

Mesh around the diffuser

IV. Examples of CFD/FVCOM coupling

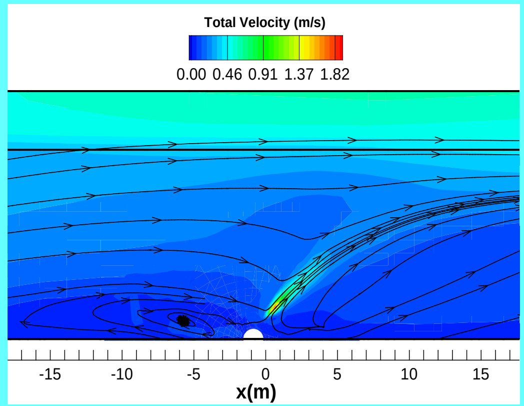
# Computed Solutions

Discrepancy in contours

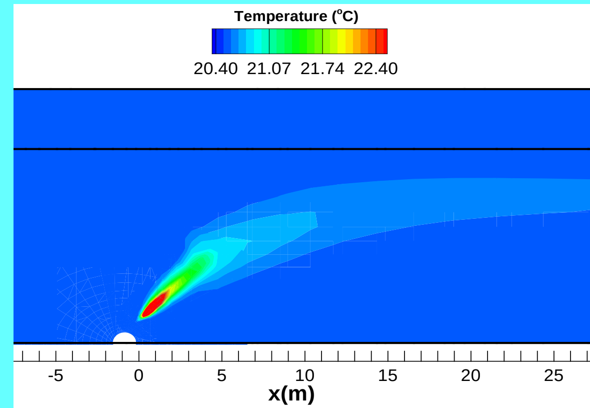
## Two-point interpolation



Total velocity

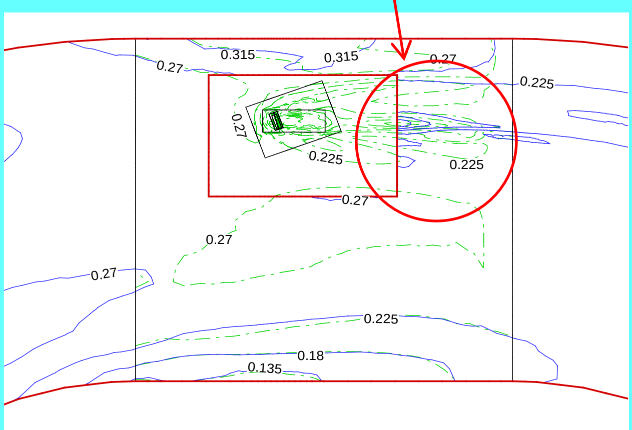


Total velocity

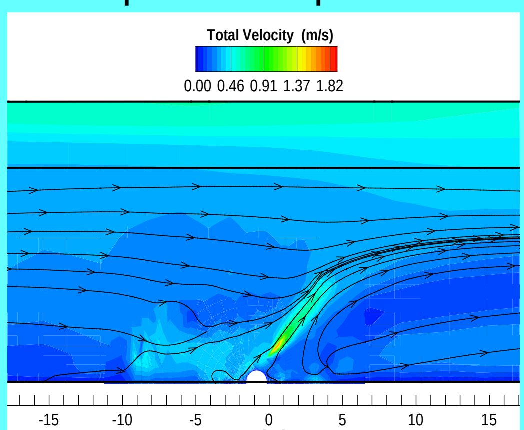


Temperature

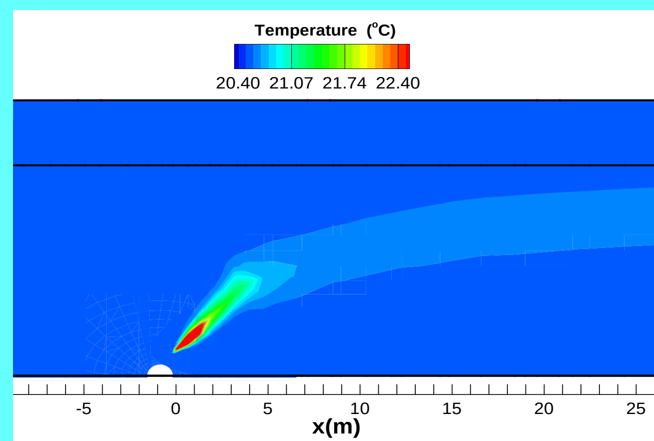
## one-point interpolation



Total velocity

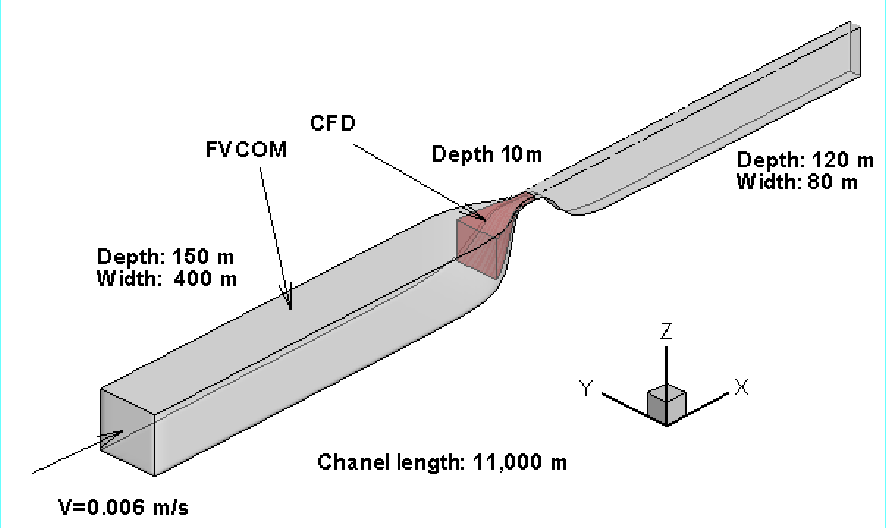


Total velocity

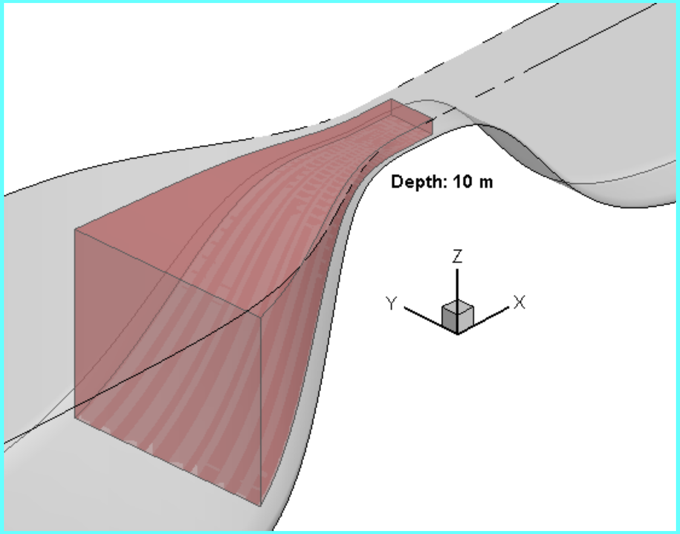


Temperature

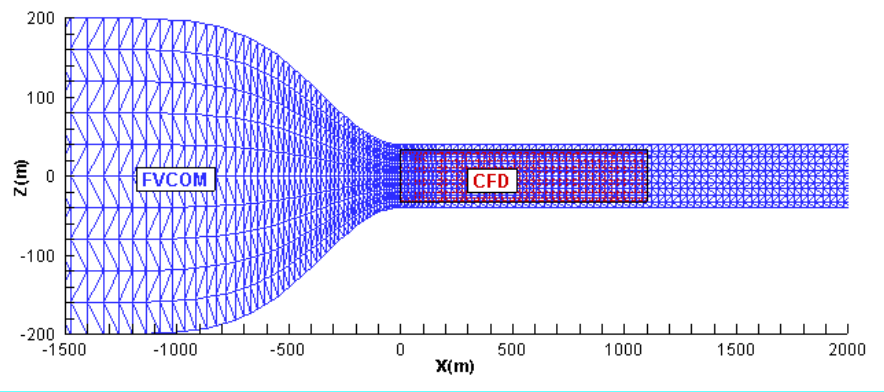
# Unsteady Sill Flow



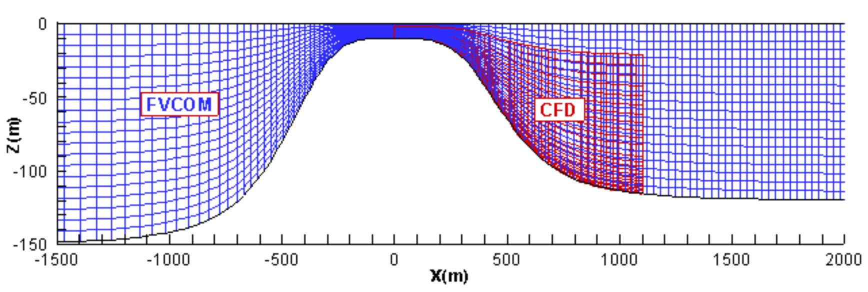

Configuration




Convergence section



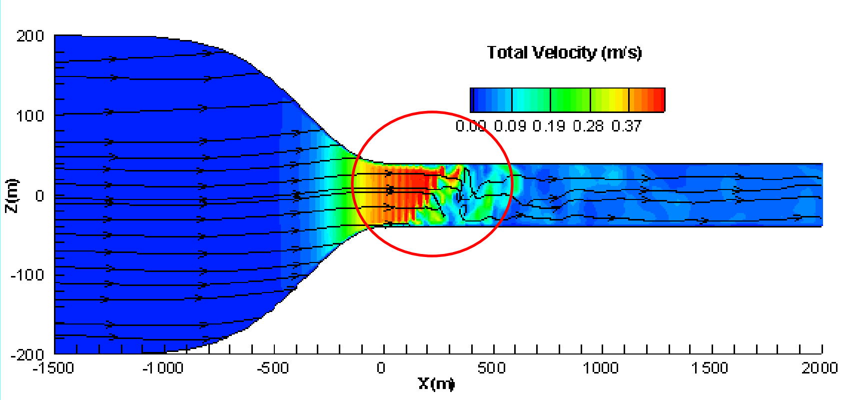

Horizontal mesh



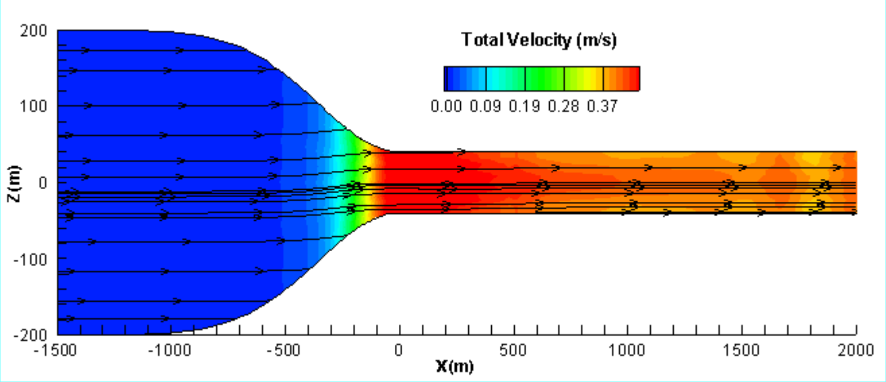

Vertical mesh

IV. Examples of CFD/FVCOM coupling

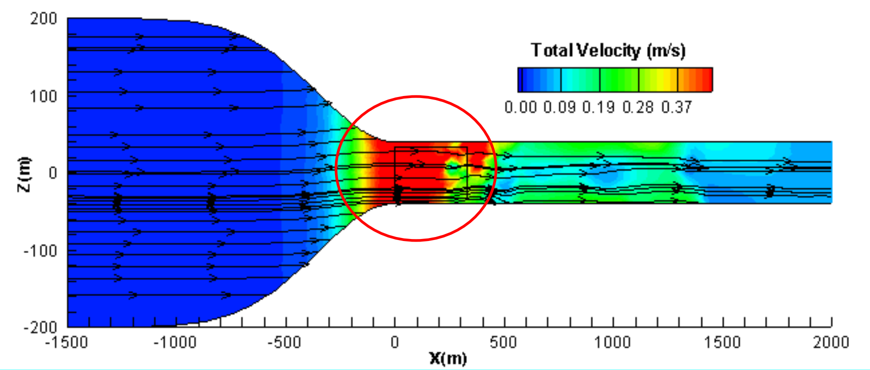
# Computed Solution in Horizontal Plane



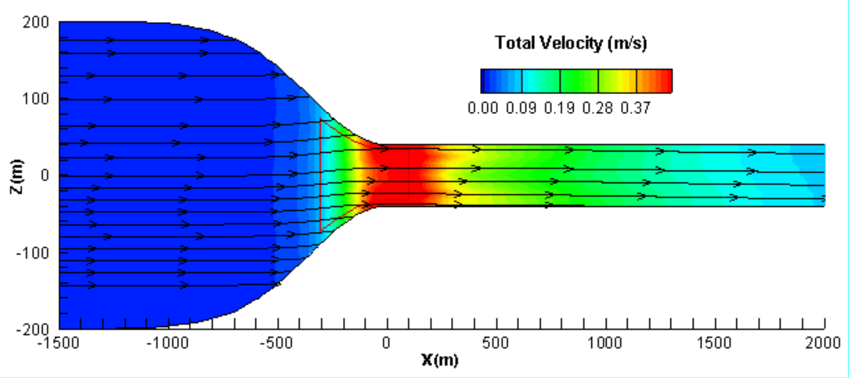

CFD




FVCOM

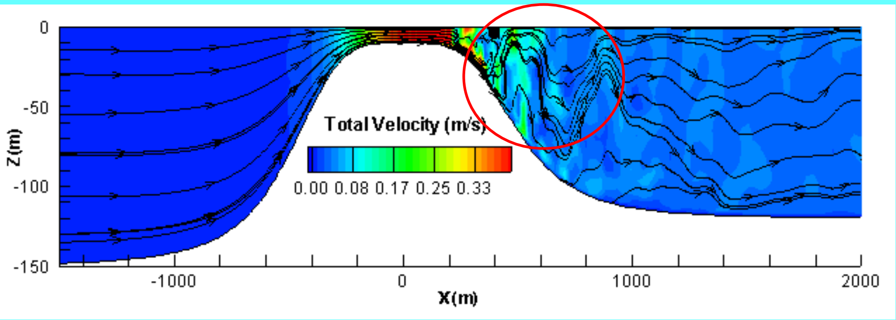



CFD/FVCOM at divergence section

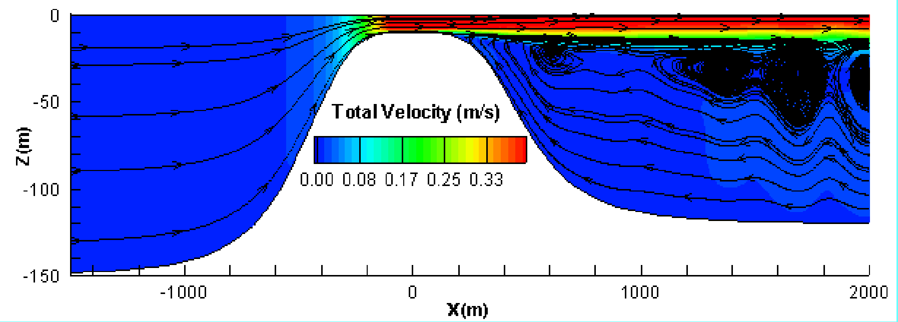



CFD/FVCOM at convergence section

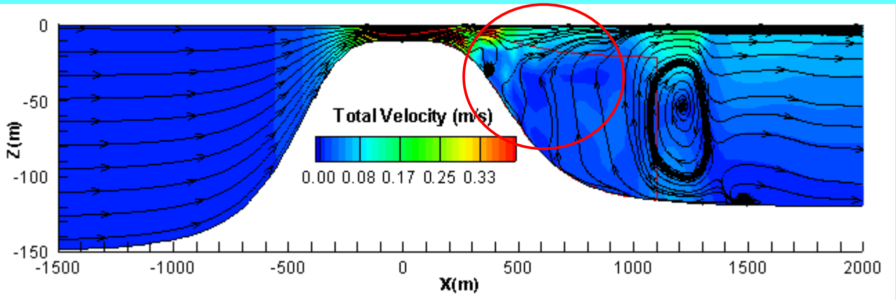
# Computed Solution in Vertical Plane



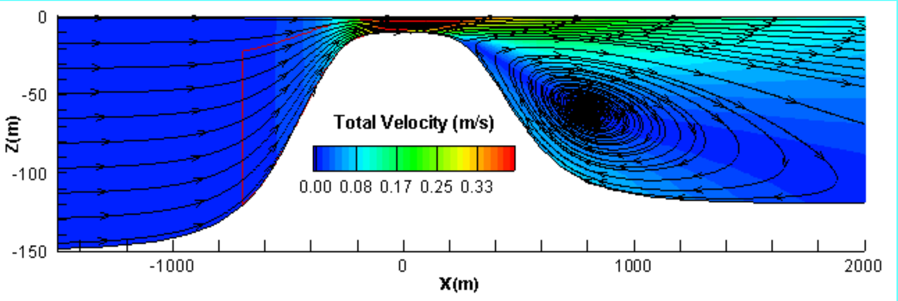

CFD




FVCOM




CFD/FVCOM at divergence section

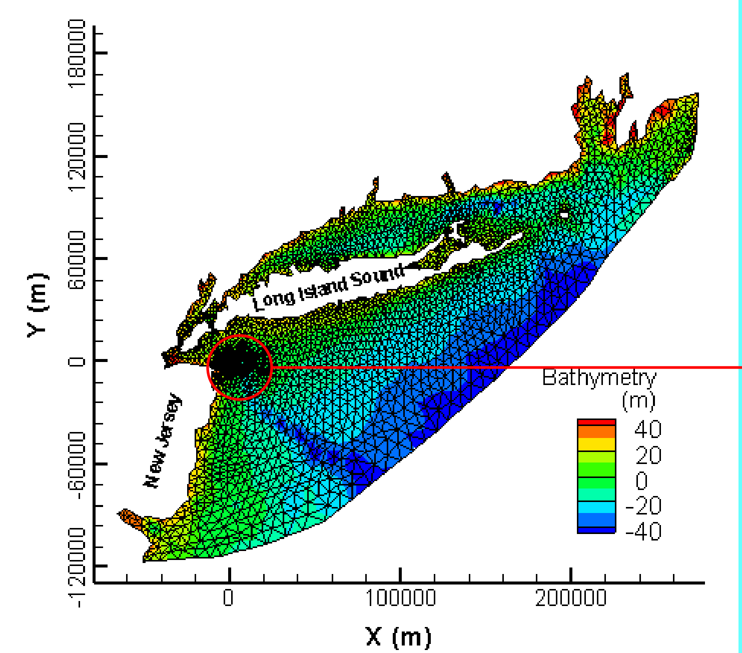



CFD/FVCOM at convergence section

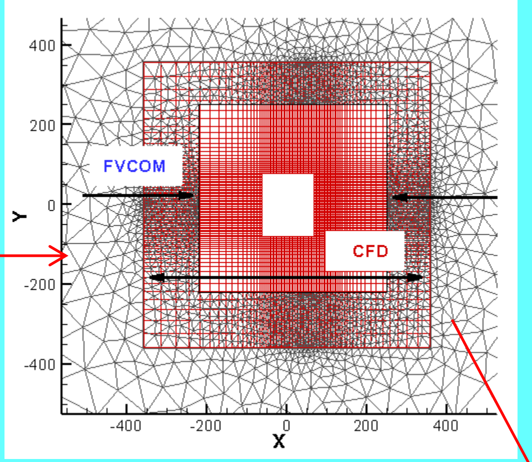
IV. Examples of CFD/FVCOM coupling

# Coastal flow at Sea Mount

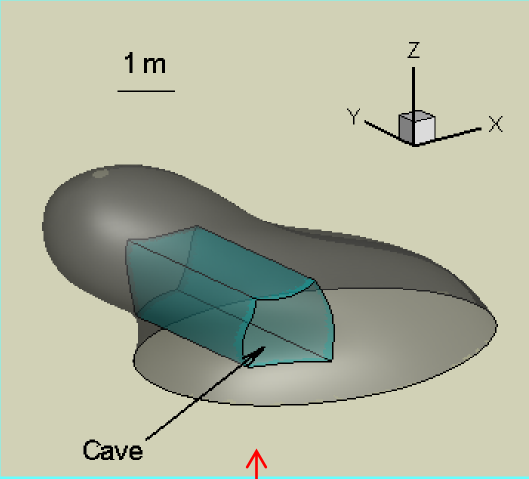
FVCOM mesh

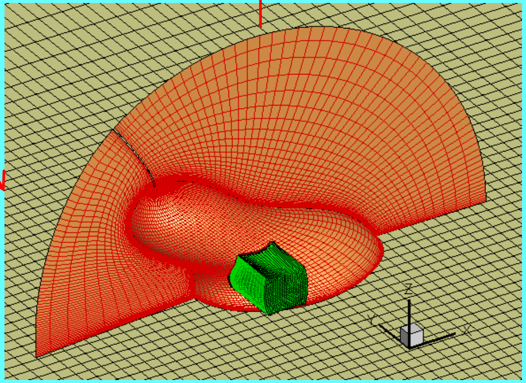



FVCOM/CFD mesh




Sea mount



mesh sea mount

IV. Examples of CFD/FVCOM coupling

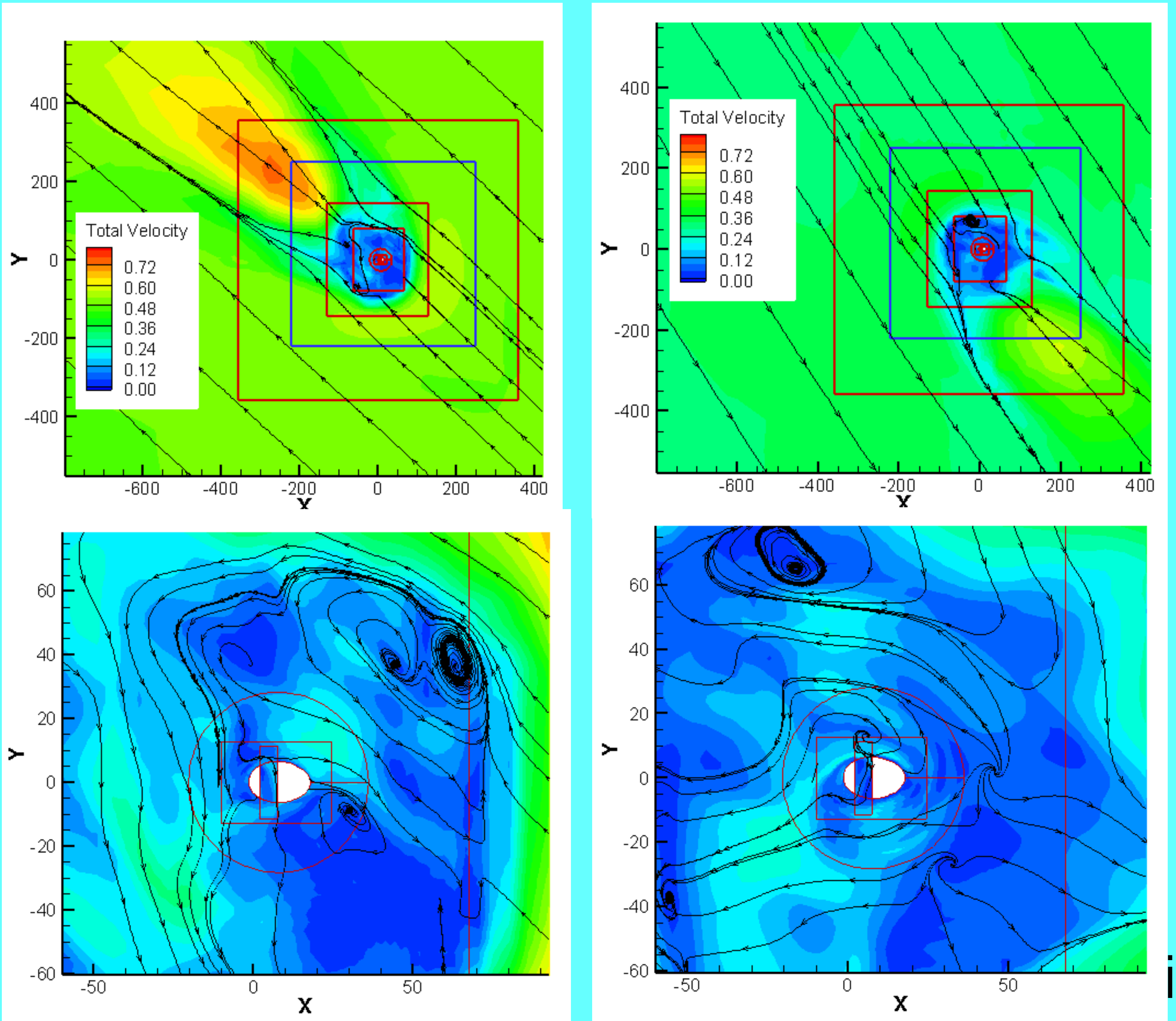
# Solution in horizontal Plane

Flood tide

Ebb tide

FVCOM/CFD solution

CFD solution

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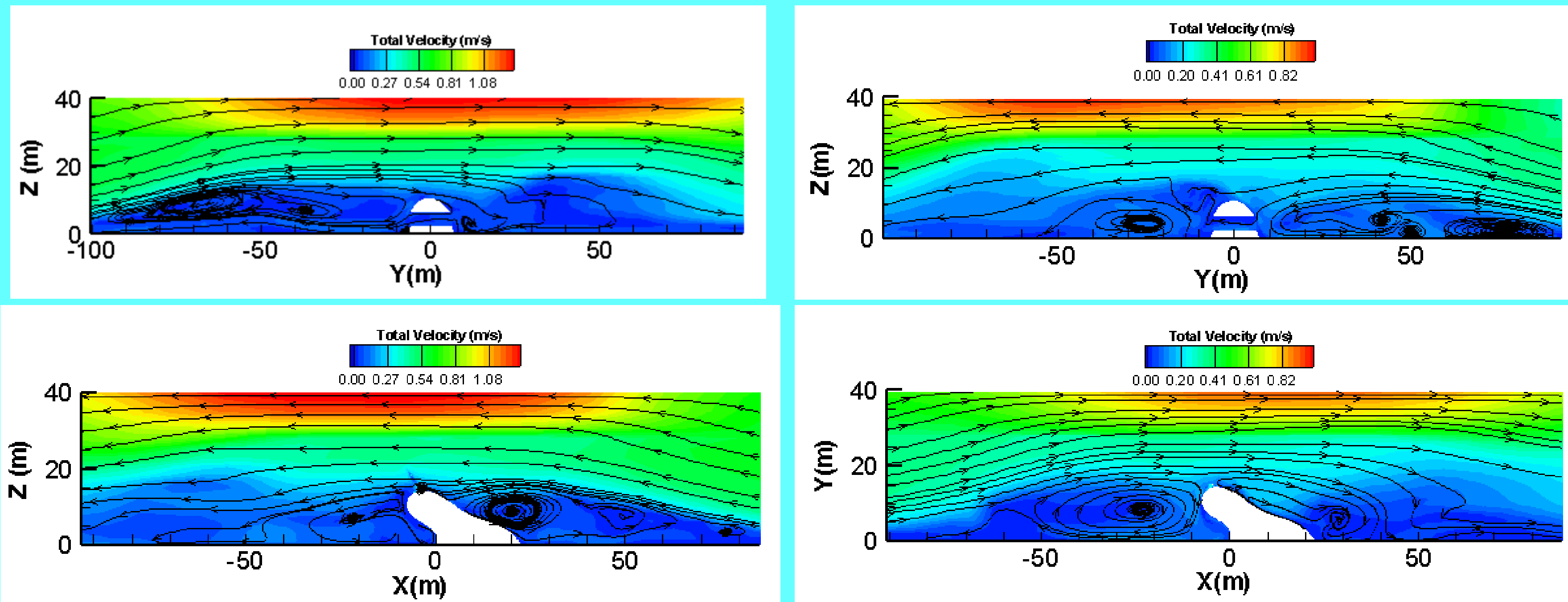
# Solution in Vertical Plane

Flood tide

Ebb tide



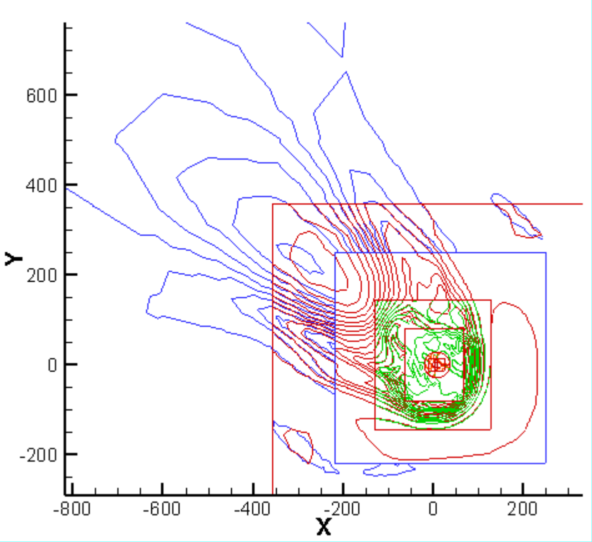
IV. Examples of CFD/FVCOM coupling

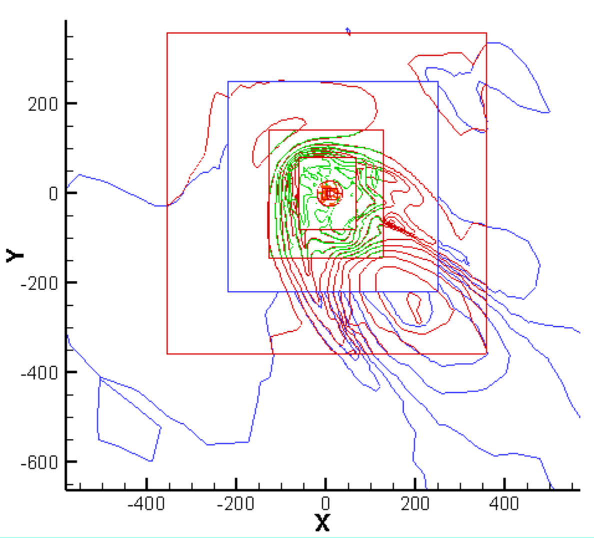
# Comparison of Two- and One Point Interpolation

Velocity of flood tide

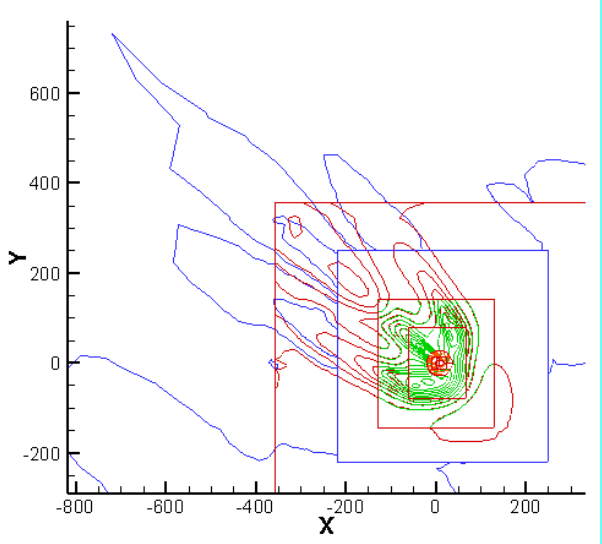
Velocity of ebb tide

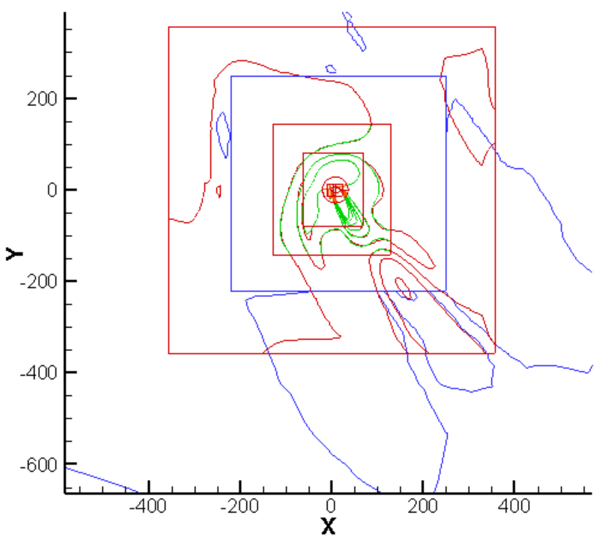
Two-pt interpolation
More details,
Smoother solu transition




One-pt interpolation

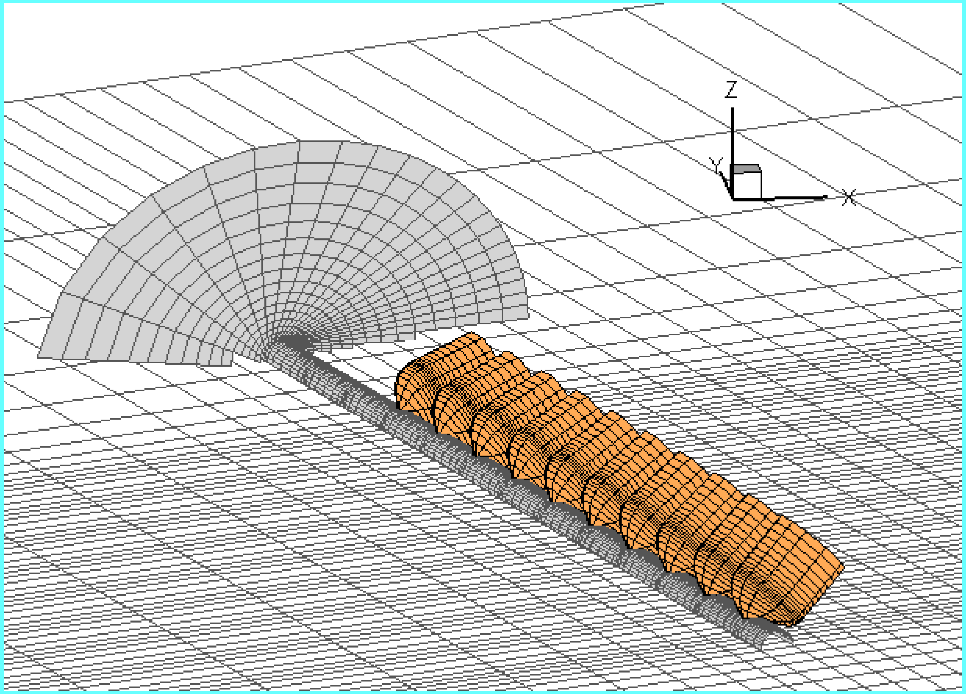


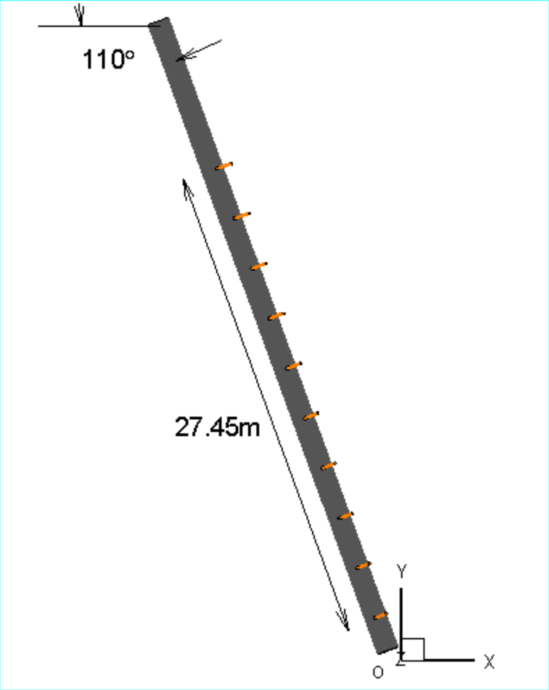
IV. Examples of CFD/FVCOM coupling

# Thermal Discharge in Coastal Environment

Diffuser mesh



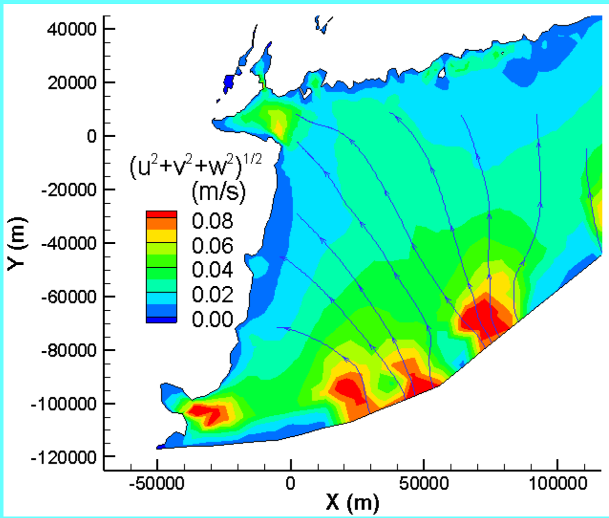

Diffuser configuration



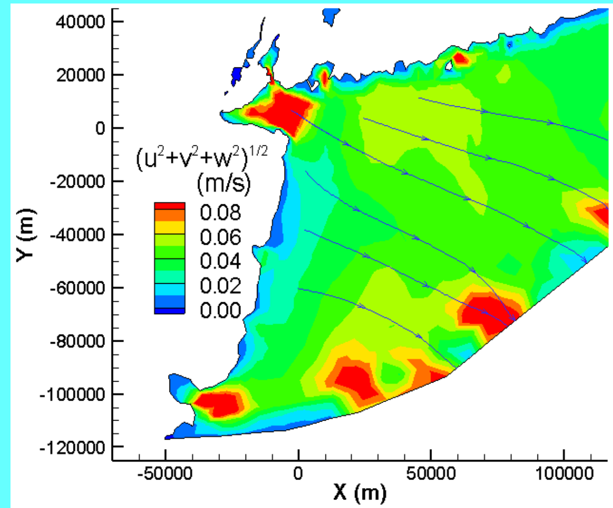

Discharge temperature: 32 $^{o}$C
Ambient temperature: 25 $^{o}$C

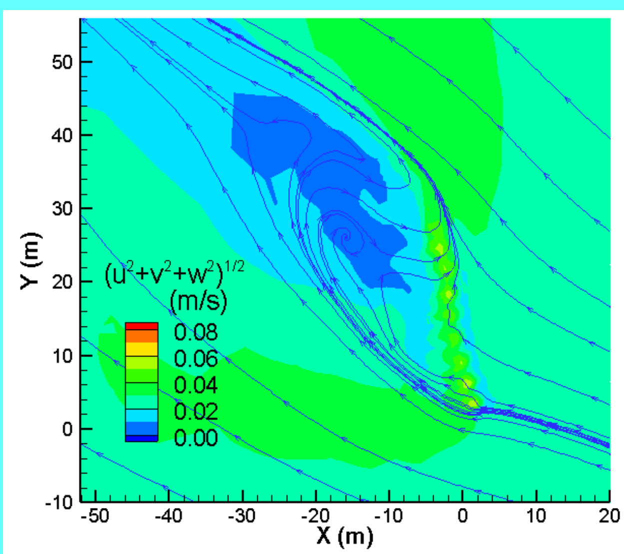
# Computed Velocity Field

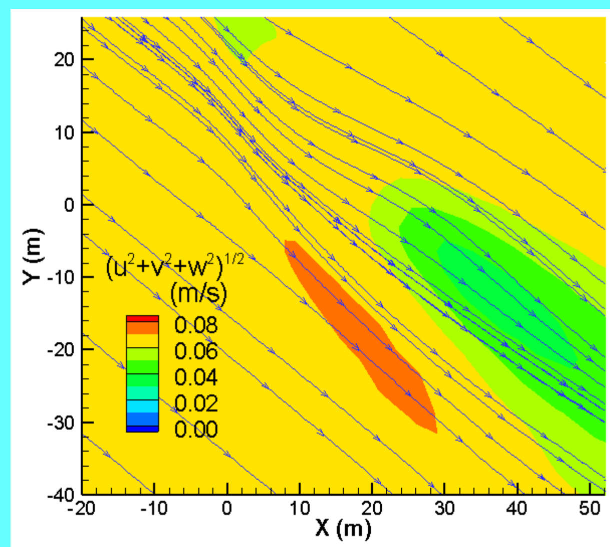
Flood tide




Ebb tide



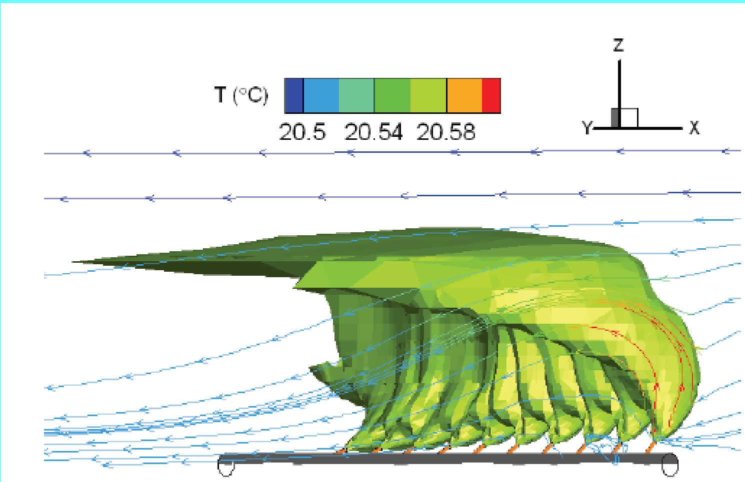



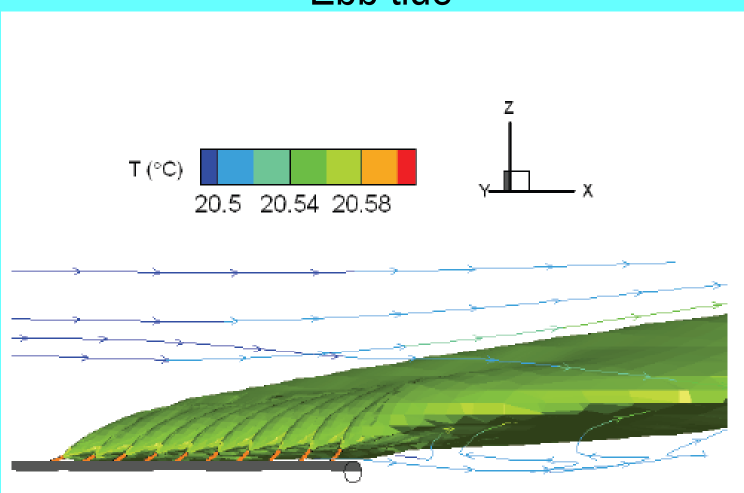
IV. Examples of CFD/FVCOM coupling

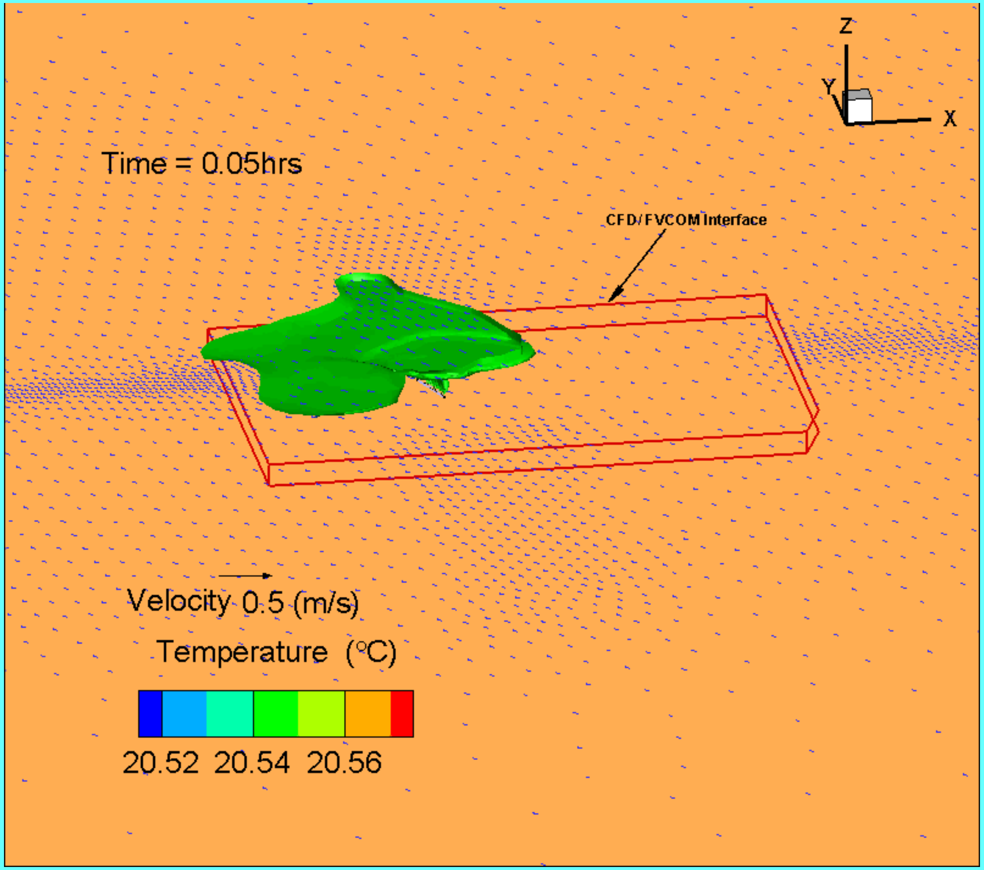
# 3D Thermal Plume (Movie)

Flood tide




Ebb tide




3D plume movie

IV. Examples of CFD/FVCOM coupling

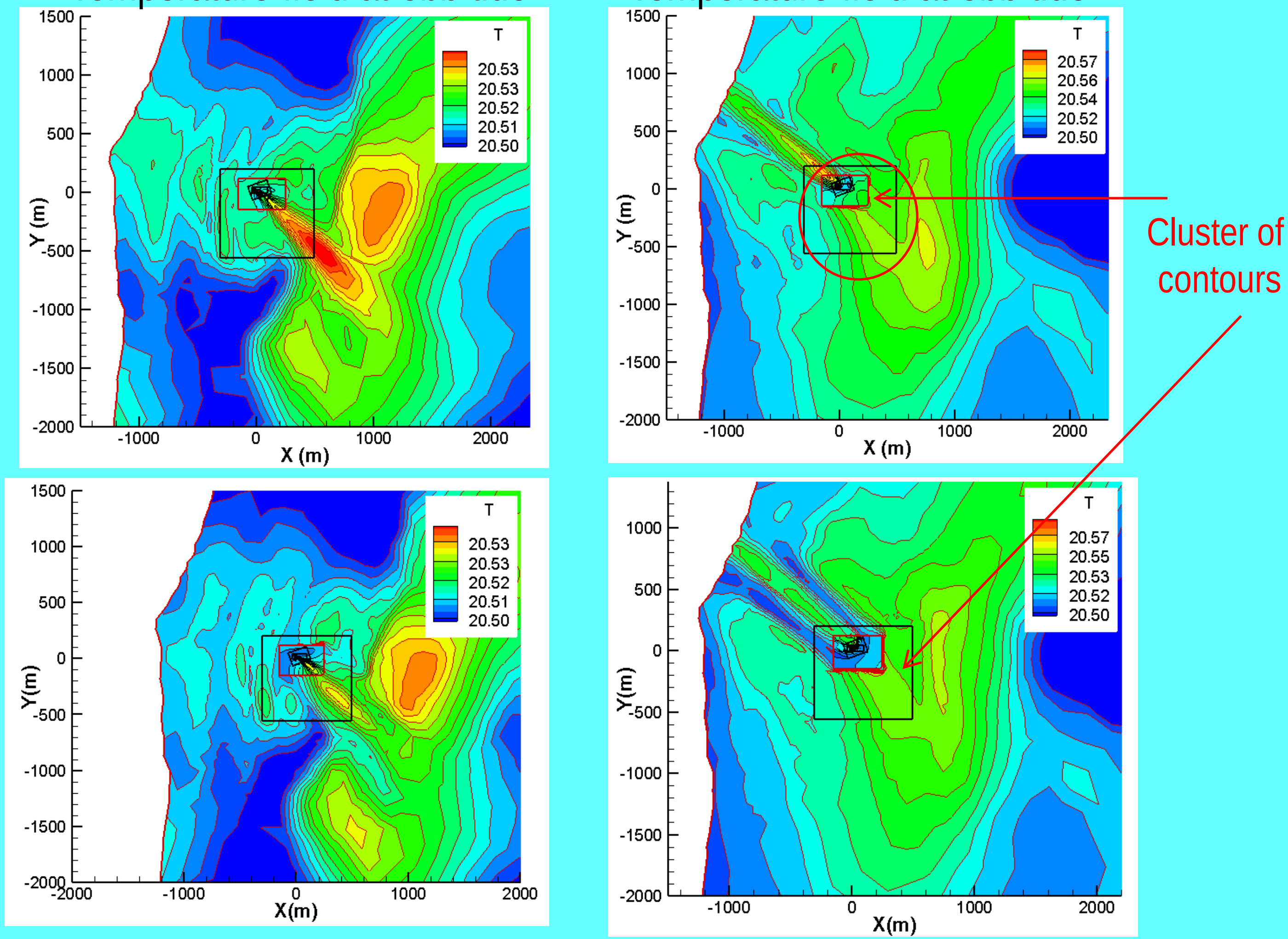
# Comparison of Two- and One Point Interpolation

Temperature field at ebb tide

Temperature field at ebb tide

Two point interpolation
Stronger temperature field

One point interpolation



# Discussions

## Questions

1) Why one- and two-point interpolations perform differently, hint and analysis?

2) Governing equations of two models are different, they may tend to different solutions as grid spacing goes to zero. Then, how we define interface conditions?

3) Schemes of the two models are different, how to minimize nonphysical solutions at the interfaces?

4) How to integrate the two models so the system work efficiently?

5) …..

# Conclusions

## Conclusion and Future work

1) Overset grid techniques are powerful in resolving multi-scale and multi-physics problems
2) A systematic investigation on accurate and stable model interface algorithms is necessary
3) Challenges: coupling between different sets of PDE and flow models

## Acknowledgement

We are grateful to the FVCOM group at UMASS for their help.

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------ Questions??? Thanks !!! ------