The University of Texas at Austin
Aerospace Engineering
and Engineering Mechanics
Cockrell School of Engineering

COMPUTATIONAL HYDRAULICS GROUP
THE UNIVERSITY OF TEXAS AT AUSTIN

Coupled atmospheric, hydrodynamic, and hydrologic models for simulation of complex phenomena

Defense: PhD in Engineering Mechanics

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Introduction

Overview

- Strongly coupled 2D and 3D shallow water and transport models
  - Theory
  - Applications
- Weakly coupled atmospheric, shallow water, and diffusive wave models
  - Application: Hindcasting flooding from Hurricane Harvey

Primitive equations

- Partial differential equations governing flows in the atmosphere and oceans
- Obtained from Reynolds-averaged Navier-Stokes by using scaling arguments and Boussinesq assumption
- Solve for 3D velocities (u, v, w) & depth (h)/surface elevation (η)
- Apply in case of temperature/salinity variations (baroclinicity)
- Constituent transport equations are additionally included

Primitive / 3D Shallow water equations

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} + \frac{1}{\rho_0}\left(\frac{\partial p}{\partial x}\right) - fv - \frac{1}{\rho_0}(\nabla \cdot \boldsymbol{T}_x) = 0$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + \frac{1}{\rho_0}\left(\frac{\partial p}{\partial y}\right) + fu - \frac{1}{\rho_0}(\nabla \cdot \boldsymbol{T}_y) = 0$$

$$p = p_a + \int_z^{\eta} g\rho dz$$

+ Boundary and initial conditions

2D Shallow water equations

- Partial differential equations governing flows in rivers, estuaries and oceans
- Solve for 2D velocities $(\bar{u}, \bar{v})$ & depth (h)/surface elevation(η)
- Apply where water is well-mixed (density variations are negligible)
- Constituent transport equations may be additionally included

2D Shallow water equations

$$\frac{\partial h}{\partial t} + \frac{\partial h\bar{u}}{\partial x} + \frac{\partial h\bar{v}}{\partial y} = 0$$

$$\frac{\partial h\bar{u}}{\partial t} + \frac{\partial h\bar{u}\bar{u}}{\partial x} + \frac{\partial h\bar{v}\bar{u}}{\partial y} + \frac{\partial}{\partial x}\left(\frac{1}{2}gh^2\right) - fh\bar{v} - \nabla \cdot \left(\frac{h}{\rho_0}\bar{\boldsymbol{T}}_x\right) + \left(gh\frac{\partial b}{\partial x} + S_x\right) = 0$$

$$\frac{\partial h\bar{v}}{\partial t} + \frac{\partial h\bar{u}\bar{v}}{\partial x} + \frac{\partial h\bar{v}\bar{v}}{\partial y} + \frac{\partial}{\partial y}\left(\frac{1}{2}gh^2\right) + fh\bar{u} - \nabla \cdot \left(\frac{h}{\rho_0}\bar{\boldsymbol{T}}_x\right) + \left(gh\frac{\partial b}{\partial y} + S_y\right) = 0$$

+ Boundary and initial conditions

2D/1D Diffusive wave equations

- Partial differential equations governing overland/surface flow in watersheds
- Solve for 2D/1D velocities $(\bar{u}, \bar{v})/(\bar{u})$ and depth (h)
- Apply in case of gentle land slope and low Froude number $(\mathrm{Fr} = U/\sqrt{gh} \ll 1)$
- Constituent transport equations may be additionally included

2D/1D Diffusive wave equations

2D DW EQUATIONS

$$\frac{\partial h}{\partial t} + \frac{\partial h\bar{u}}{\partial x} + \frac{\partial h\bar{v}}{\partial y} = 0$$

$$g\frac{\partial h}{\partial x} + g\frac{\partial b}{\partial x} + S_x = 0$$

$$g\frac{\partial h}{\partial y} + g\frac{\partial b}{\partial y} + S_y = 0$$

+ Boundary and initial conditions

1D DW EQUATIONS

$$\frac{\partial h}{\partial t} + \frac{\partial h\bar{u}}{\partial s} = 0$$

$$g\frac{\partial h}{\partial s} + g\frac{\partial b}{\partial s} + S_s = 0$$

+ Boundary and initial conditions

3D/2D Advection-diffusion equations

- Partial differential equations governing transport of constituents in a fluid
- Solve for 2D depth-averaged or 3D concentrations $(\bar{c}, c)$
- 3D transport equations required to capture baroclinicity, i.e., transport of salinity and temperature that affect density
- 2D depth-averaged equations not suitable for baroclinicity

3D/2D Advection-diffusion equations

3D transport equations:

$$\frac{\partial c}{\partial t} + \boldsymbol{u} \cdot \nabla c - \nabla \cdot \left(\overline{\boldsymbol{D}}_{\mathrm{3D}} \nabla c\right) = 0$$

2D depth-averaged transport equations:

$$\frac{\partial h\bar{c}}{\partial t} + \overline{\boldsymbol{u}} \cdot \nabla_{\mathrm{2D}}(h\bar{c}) - \nabla \cdot \left(\overline{\boldsymbol{D}}_{\mathrm{2D}} \nabla_{\mathrm{2D}}(h\bar{c})\right) = 0$$

+ Boundary and initial conditions

Objective: Coupling

THE BEST OF ALL WORLDS

(OR THE WORST IF YOU DO NOT USE IT PROPERLY!)

Objectives

- Strongly coupled 2D and 3D shallow water and transport models
  - Theory
  - Test cases & applications
- Weakly coupled atmospheric, shallow water, and diffusive wave models
  - Application: Hindcasting flooding from Hurricane Harvey

Motivation: 2D-3D SW, Trans. coupling

2D SW MODELS

- Variety of ways to include wetting and drying; much easier than implementing in 3D
- Not applicable in baroclinic flows involving vertical mixing

3D SW MODELS

- Only a few σ-coordinate based 3D SW models have wetting and drying; extremely complicated and computationally expensive
- Can capture baroclinic flows and vertical mixing accurately

Motivation: 2D SW - 2D/1D DW coupling

2D SHALLOW WATER

- Applicable for flow in oceans
- Computationally expensive: Extremely small mesh size and time step required for flood simulations

2D DIFFUSIVE WAVE

- Applicable for overland flow in watersheds
- Computationally cheaper: Can be coupled to groundwater/infiltration for flood simulations

Why couple different models?

- Allows simulating complex phenomena that individual models may not be able to handle
- Computationally cheaper when simplified models are used where appropriately
- Saves time, effort, and money involved in developing new models
- Verification and validation are partly inherited

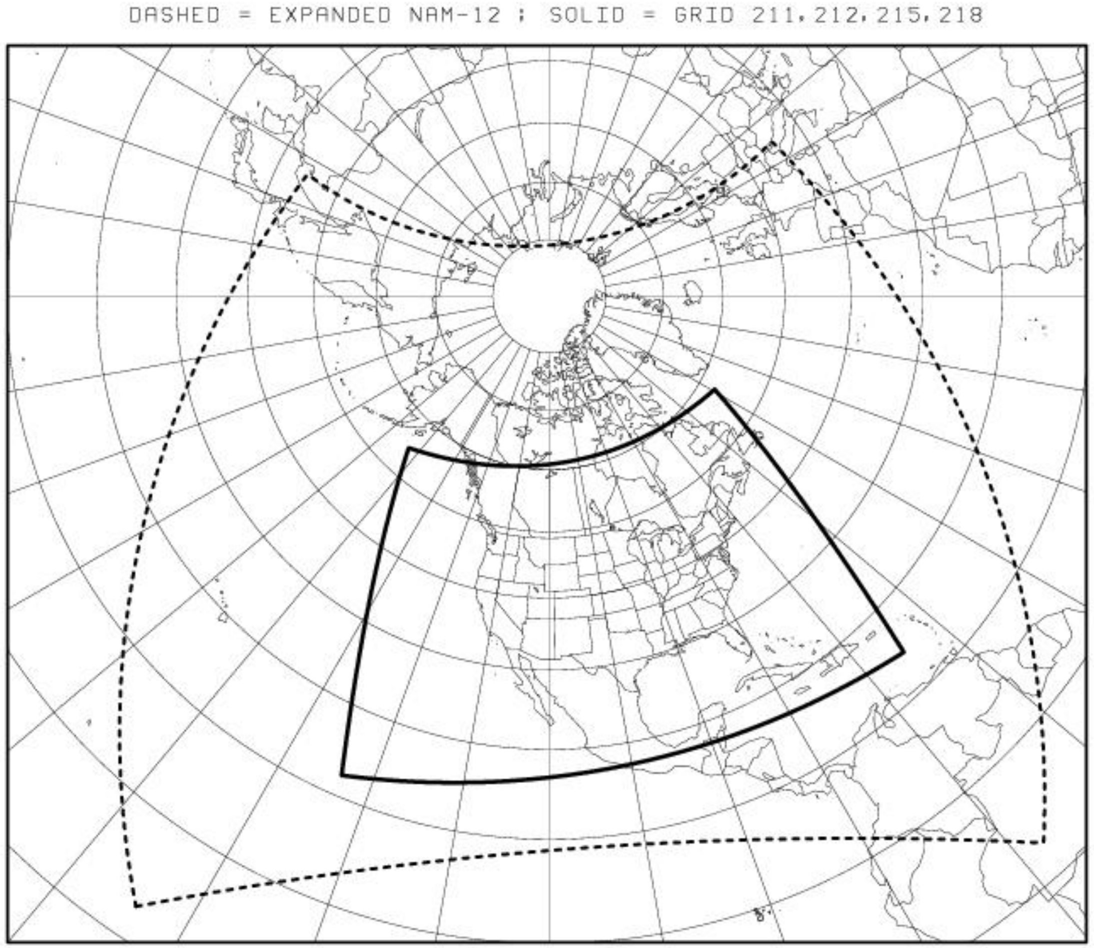
Models

Atmospheric model: NAM – Primitive Eq.

North American Mesoscale Forecast System (NAM) [1]

- Atmospheric model run by NCEP, NOAA
- Primitive equations, with non-hydrostatic effects and temperature transport
- NAM forecasts in *grib2* format available for download every 6 hours
- Contiguous over the United States (CONUS) domain, 12 km grid

NAM: CONUS domain



NAM 12 km Lambert Conformal CONUS domain (solid line) [2]

Hydrodynamic model: AdH – 3D/2D SW

Adaptive Hydraulics (AdH) [3]

- Software developed by ERDC, written in C programming language
- 3D and 2D shallow water (SW) and transport equations, among others
- Semi-discrete finite element method based code with SUPG stabilization
- First and second order implicit time stepping – backward difference formulas

[3] C. J. Trahan, G. Savant, R. C. Berger, M. Farthing, T. O. McAlpin, L. Pettey, **G. K. Choudhary**, and C. N. Dawson. *Formulation and application of the adaptive hydraulics three-dimensional shallow water and transport models*. Journal of Computational Physics, 374:47-90, 2018.

Hydrologic model: GSSHA – 2D/1D DW

Gridded Surface Subsurface Hydrologic Analysis (GSSHA) [4]

- Software developed by ERDC, written in C++ programming language
- 2D and 1D diffusive wave (DW) and transport equations, among others
- Finite volume method based code
- Explicit time-stepping

Approaches to coupling

Strong/algebraic coupling

- Solve a monolithic coupled system of equations once every time step
- Guarantees solution continuity at all times
- Guarantees conservation across coupling interface at all times
- Best used when:
  - Models are implemented within a single software
  - Access to source code is available, and significant modifications are permitted
  - Compatible discretization and time-stepping methods have been used

Weak/flux coupling

- Iterate between separate subsystems within each time step
- Allows subcycling, i.e., different models using different time step sizes
- Discontinuity in either solution or flux across coupling interface
- Best used when:
  - Models are implemented in different software
  - Little to no modification of source code allowed
  - Incompatible discretization and time-stepping methods are being used

Summary

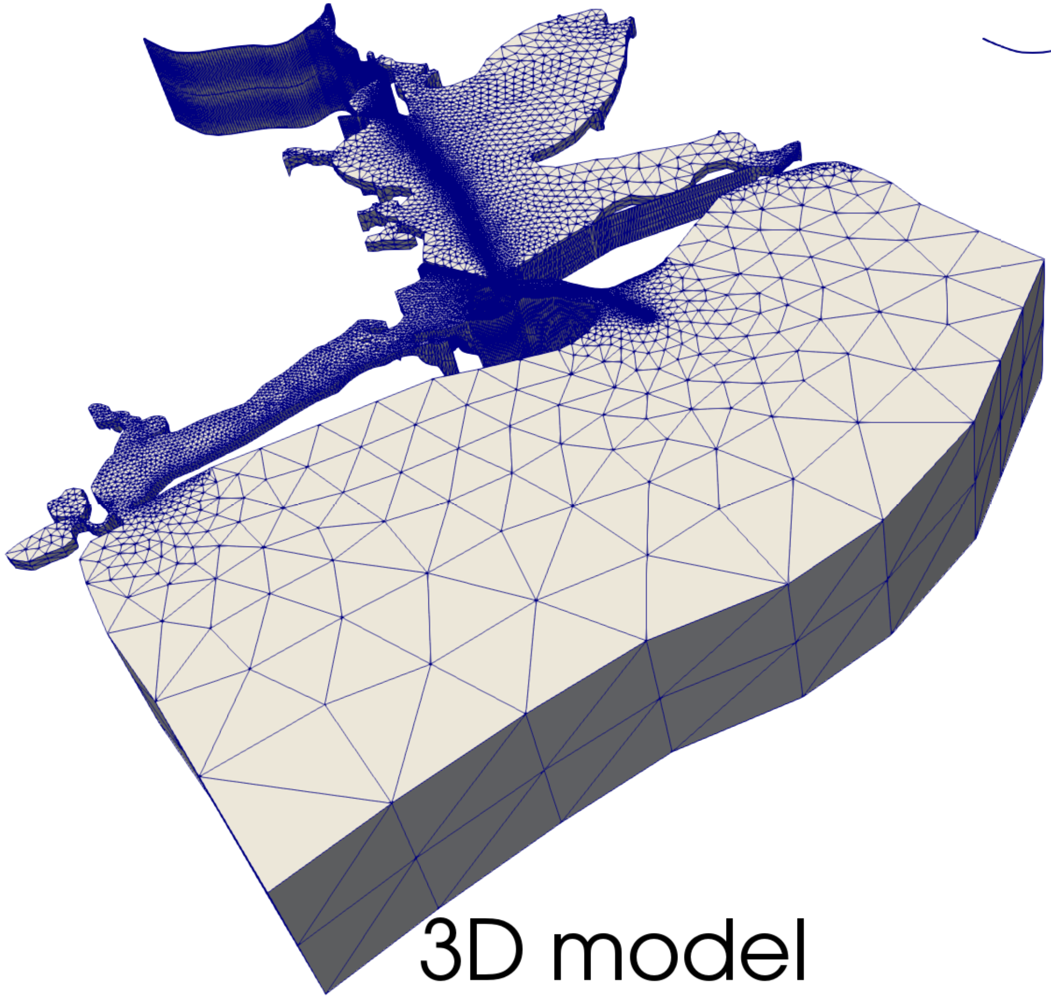
- Atmospheric model: NAM, solution includes wind and rainfall
- 3D, 2D Shallow water models: AdH, solves for $\{h, \boldsymbol{u}\}/\{h, \overline{\boldsymbol{u}}\}$
- 3D, 2D Transport models: AdH, solves for $\{c\}/\{\bar{c}\}$
- 2D, 1D Diffusive wave models: GSSHA, solves for $\{h, \boldsymbol{q} = h\overline{\boldsymbol{u}}\}$
- Objectives:
  - 2D, 3D shallow water and transport coupling: <u>Strong/algebraic</u>
  - Atmospheric, shallow water, diffusive wave coupling: <u>Weak/flux</u>

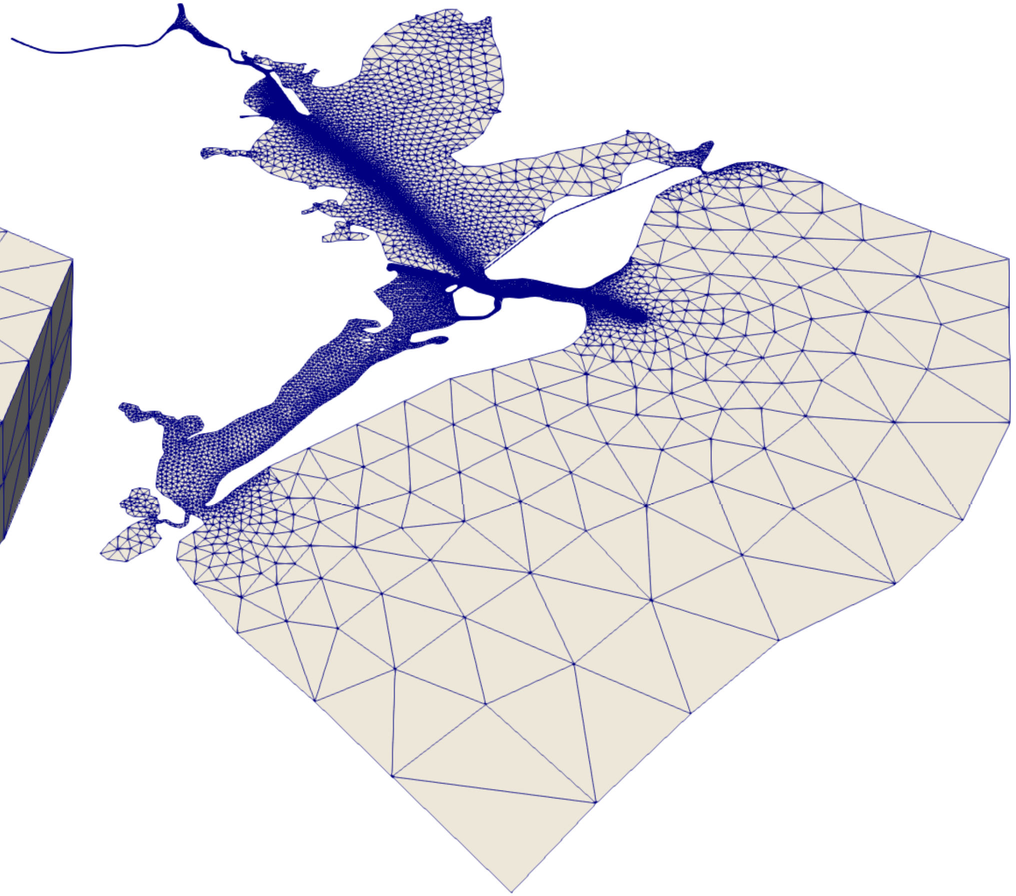
2D-3D Coupled SWE: Theory

Adaptive Hydraulics – SW models

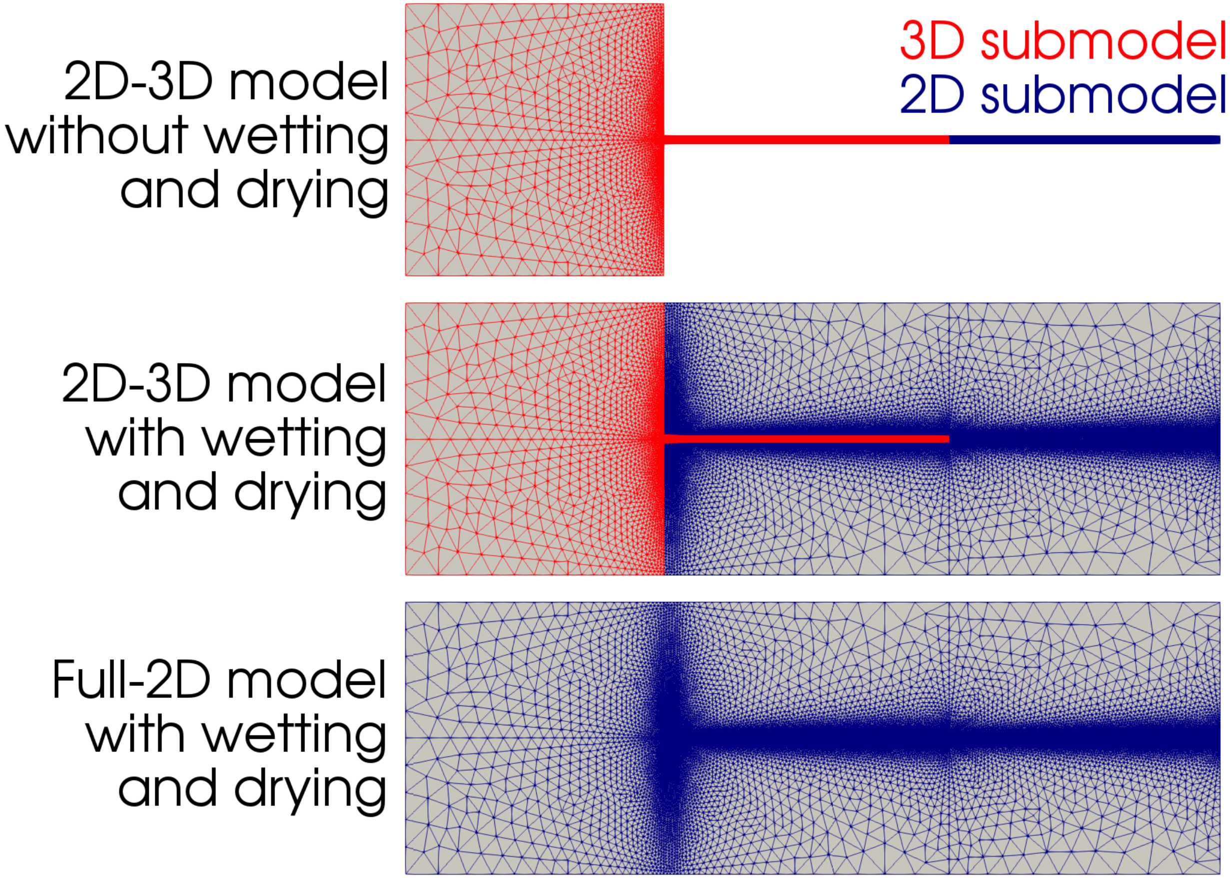
- AdH 2D SW and transport models:
  - Unstructured mesh
  - Linear triangular elements
- AdH 3D SW and transport models:
  - Semi-structured mesh: Unstructured in horizontal (x, y) directions extruded in the z direction, so that nodes are aligned vertically
  - Linear tetrahedral elements and bilinear wedge elements

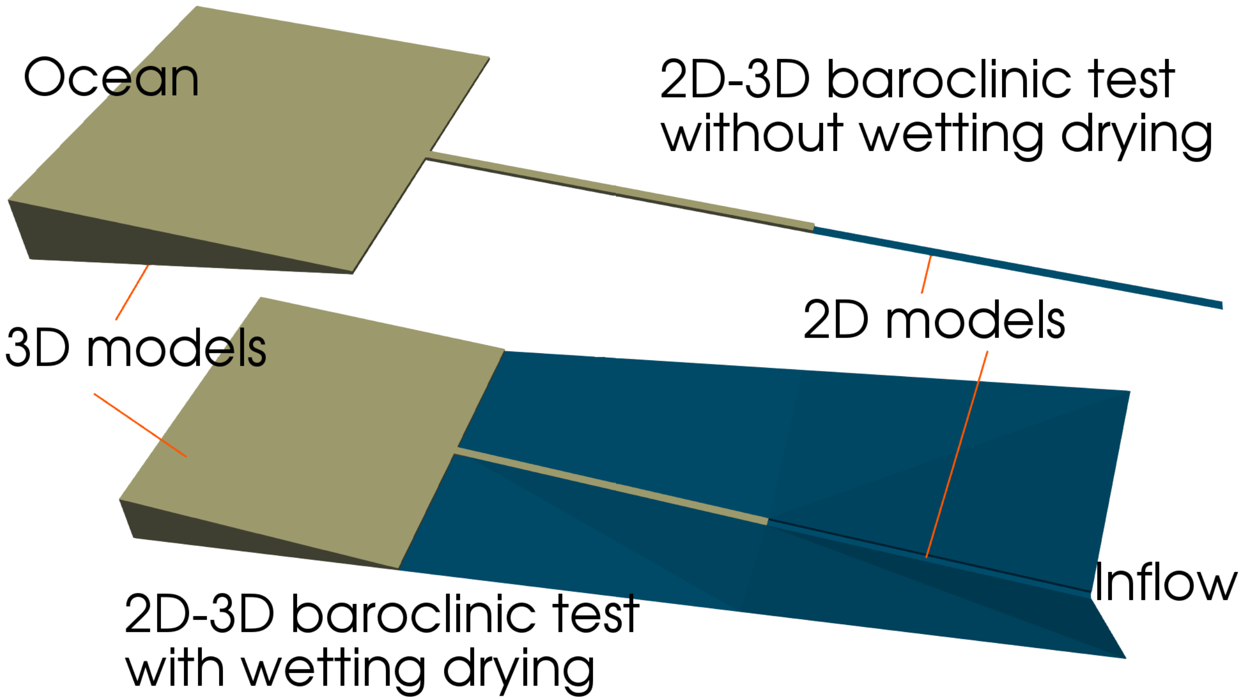
AdH Shallow water models





Goal: 2D-3D Estuaries





Strong coupling

- Assumptions:
  - Conformity: Require interface nodes, faces, edges to be aligned vertically
  - Interface placed in a region where physics is governed by 2D SW equations
- Method: Modify trial and test functions at the 2D-3D interface
  - One trial/test function per coupled column of interface nodes
- Result:
  - Generates a single coupled system of nonlinear equations
  - Solution continuity, and mass and momentum conservation at all times

Strong 2D-3D Coupling

Interface Nodes:

$\mathcal{J}^{2D} = \{1_{2D}, 2_{2D}, 3_{2D}\}$

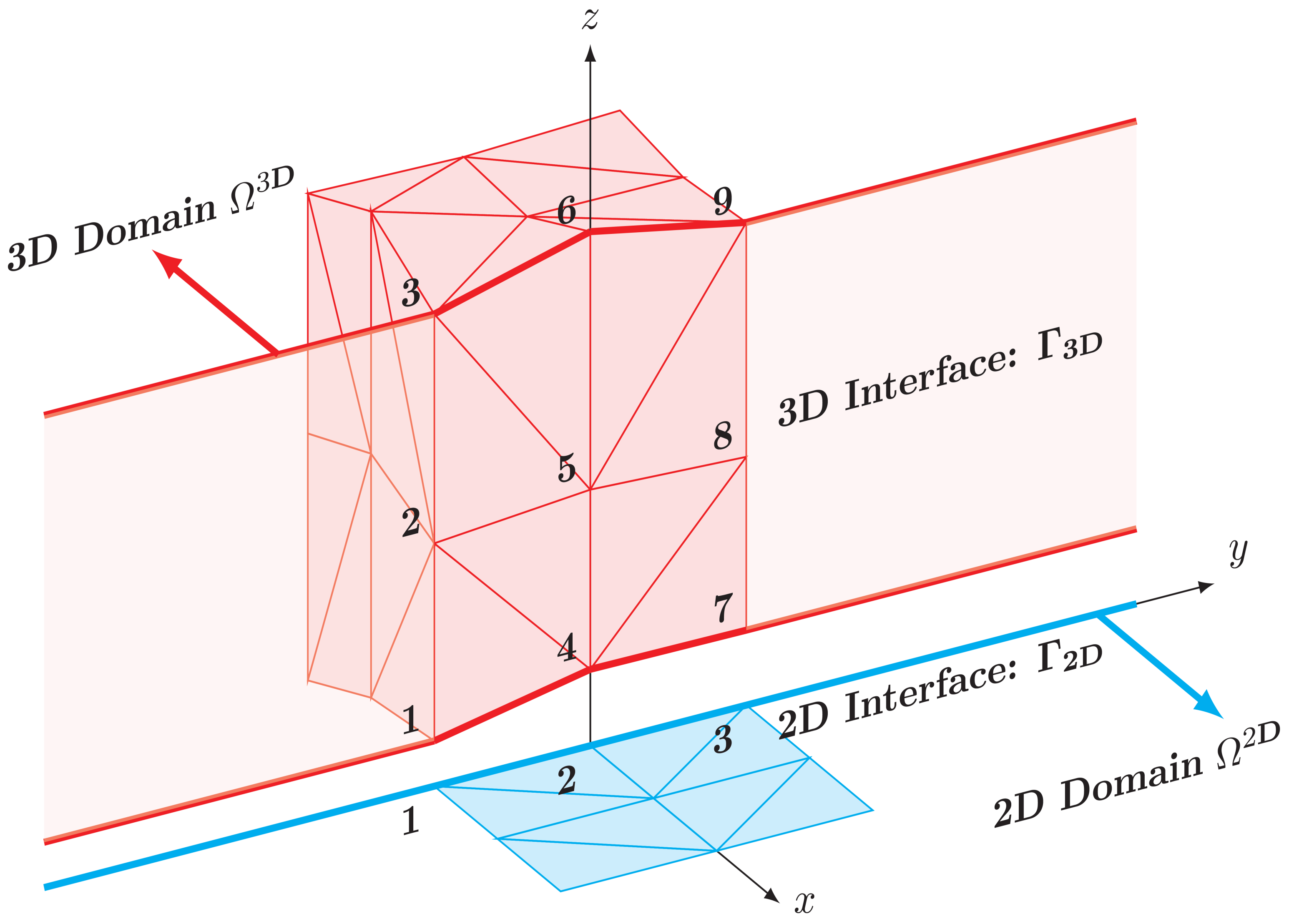
$\mathcal{J}^{3D} = \{1_{3D}, 2_{3D}, 3_{3D}, 4, \ldots, 9\}$

Coupled Node Columns:

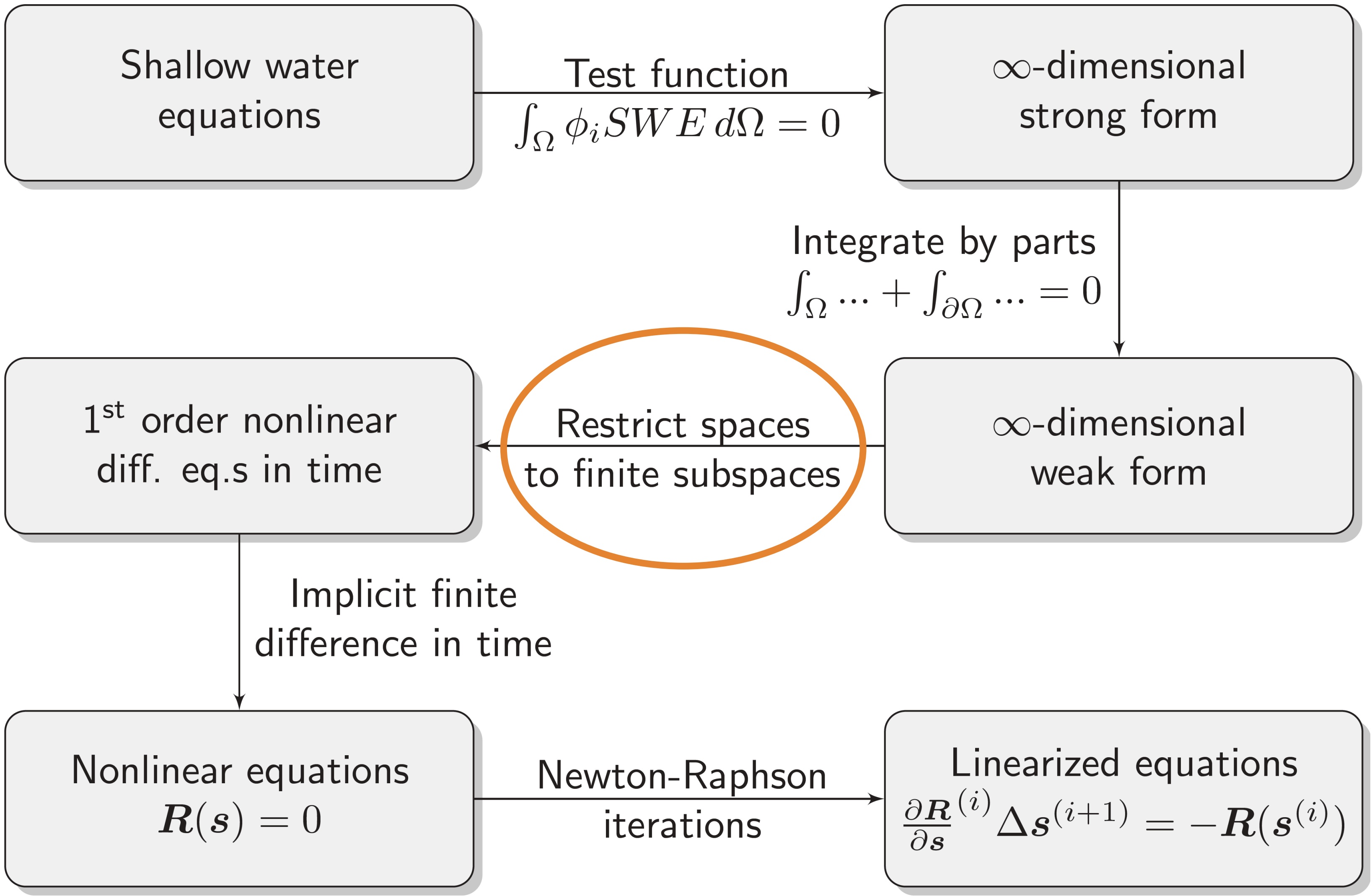
$\mathcal{C}(1_{2D}) = \{1_{3D}, 2_{3D}, 3_{3D}\}$

$\mathcal{C}(2_{2D}) = \{4, 5, 6\}$

$\mathcal{C}(3_{2D}) = \{7, 8, 9\}$



Semi-discrete finite element method



Strong 2D-3D Coupling

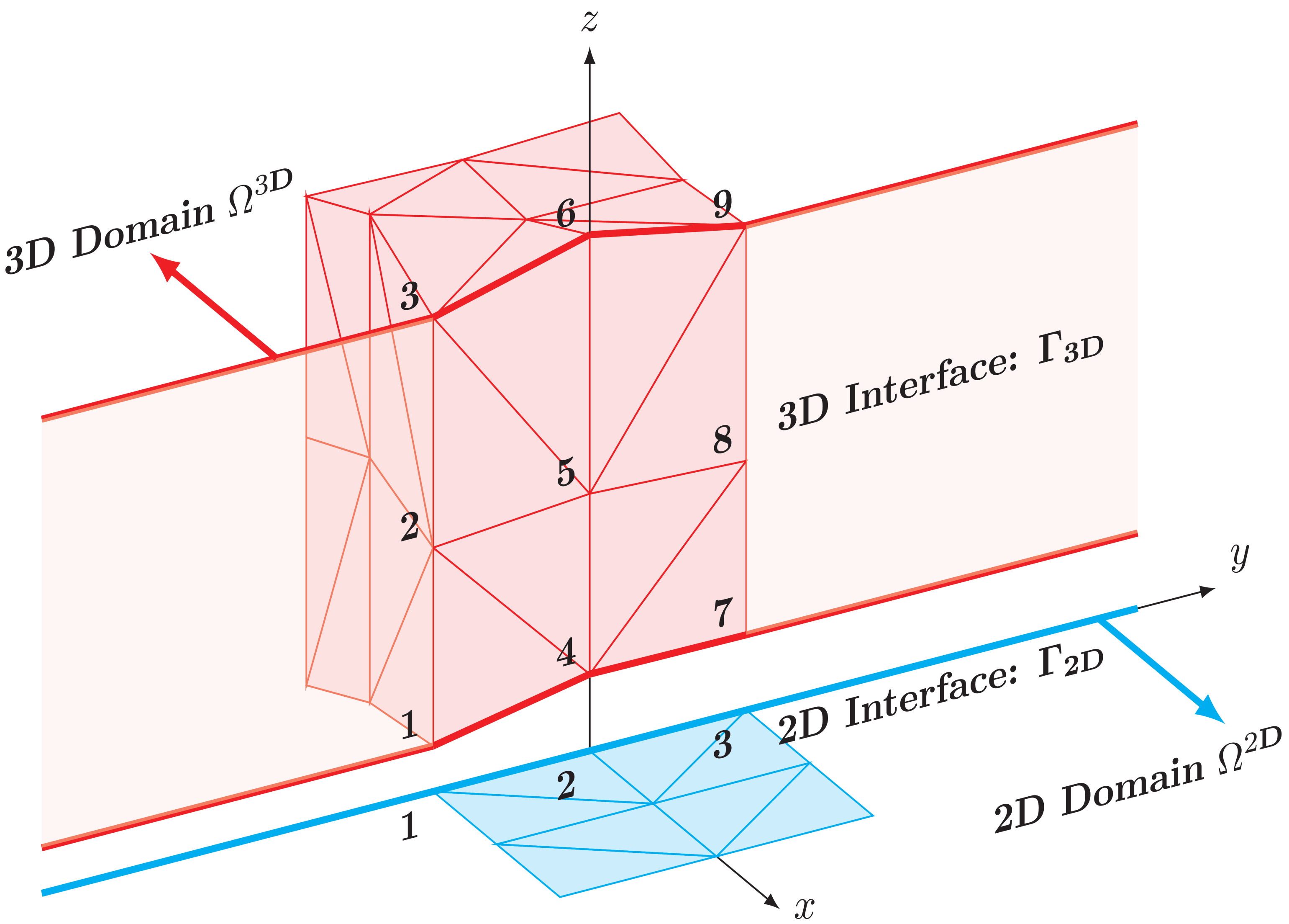
New trial functions (ϕ):

$$\phi_1 = \phi_{1_{2D}} \cup \left(\phi_{1_{3D}} + \phi_{2_{3D}} + \phi_{3_{3D}}\right)$$

$$\phi_2 = \phi_{2_{2D}} \cup (\phi_4 + \phi_5 + \phi_6)$$

$$\phi_3 = \phi_{3_{2D}} \cup (\phi_7 + \phi_8 + \phi_9)$$

Test functions: Analogous



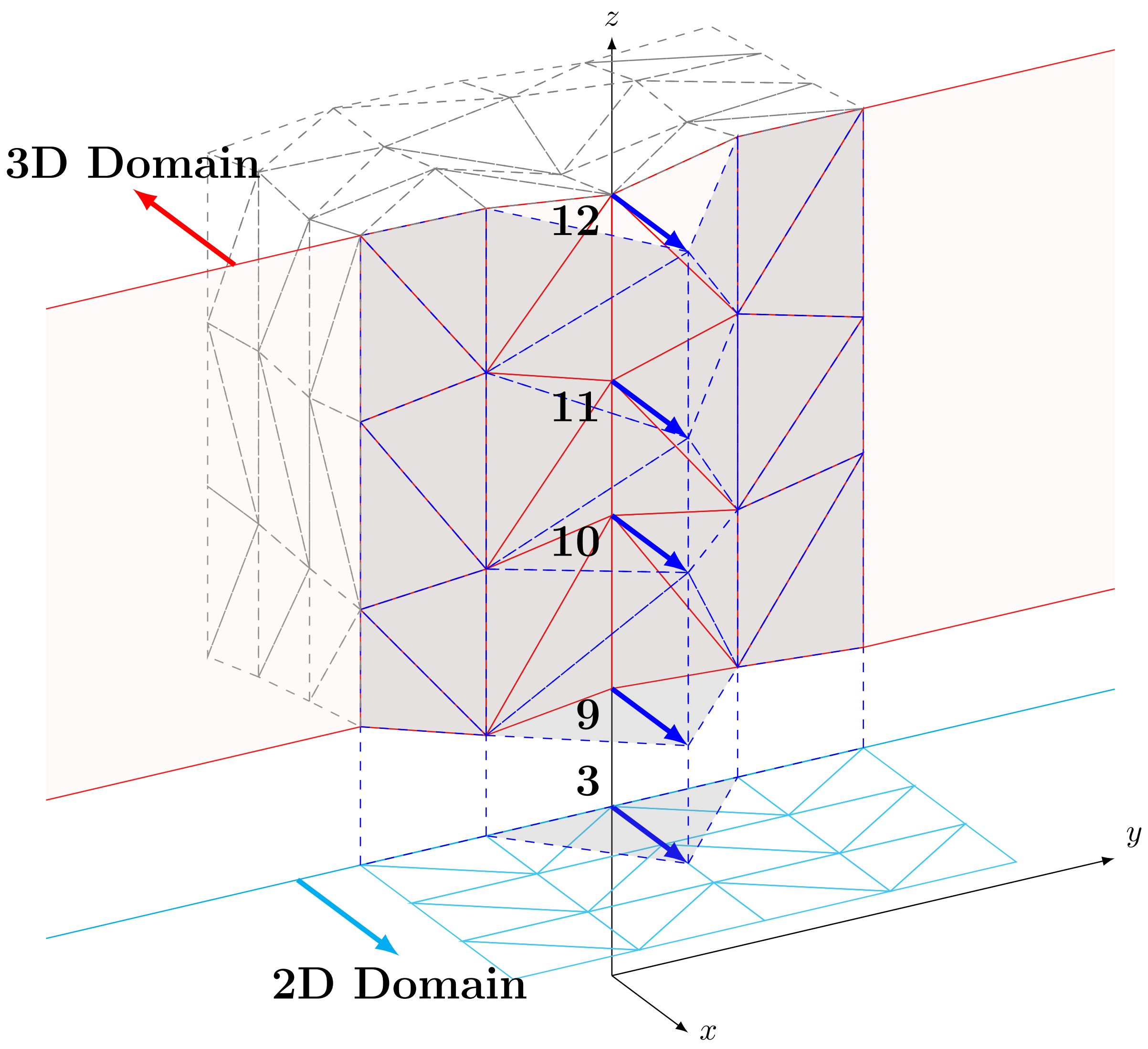
Strong 2D-3D Coupling

New trial functions (ϕ^{CPL}):

$$\phi_3^{CPL} = \phi_3^{2D} \cup \sum_{i=9}^{i=12} \phi_i^{3D}$$

Or equivalently,

$$\phi_3^{CPL}(\boldsymbol{x}) = \begin{cases} \phi_3^{2D}(\boldsymbol{x}), & \boldsymbol{x} \in \Omega^{2D} \\ \sum_{i=9}^{i=12} \phi_i^{3D}(\boldsymbol{x}), & \boldsymbol{x} \in \Omega^{3D} \end{cases}$$



2D-3D Coupled SWE: Verification

SMALL AMPLITUDE SLOSH TEST CASE

REFERENCE [5]

Verification – small amplitude slosh test

- Domain: $\Omega = (0, L)\times(0, B)\times(-H, 0)$
  - $L = 25.6km, B = 6.4km, H = 82.5m$, no friction, no viscosity
- Boundary conditions:
  - No-flow across all vertical boundaries
- Initial conditions:
  - Water at rest, i.e., $\boldsymbol{u}(x, y, z, 0) = 0m/s$
  - Depth perturbation: Cosine wave of amplitude $a_\eta = 0.01m$, and wave-length $2L$:

$$h(x, y, 0) = H + a_\eta \cos(\pi x/L)$$

Verification – small amplitude slosh test

- Analytical solution to linearized SW equations available: Sinusoidal oscillations
- Not the true solution to the full nonlinear SW equations
- Comparison with full-2D and full-3D solutions and the analytical solution
- Comparison against finest mesh solution, mesh size $\hbar = 50m$, $\Delta t = 1s$
- Convergence analysis with $\hbar = \{6400, 3200, 1600, 800, 400, 200, 100\}m$ and $\Delta t = \{30, 15, 10, 6, 3, 1\}s$
- Errors: $E^{lin,\hbar}$ against analytical solution, and $\tilde{E}^{\hbar}$ against fine mesh solution

Verification – slosh test case

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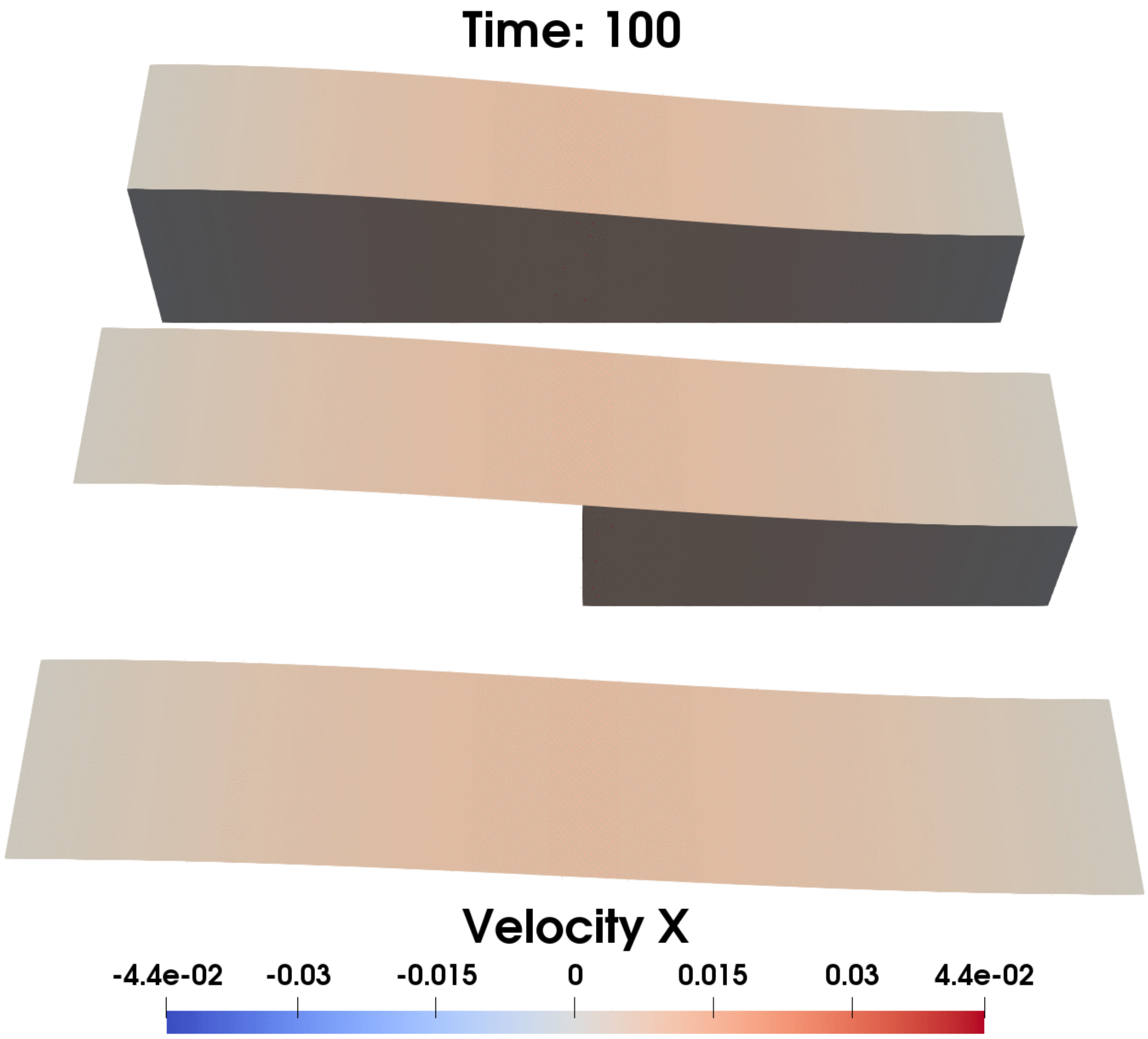
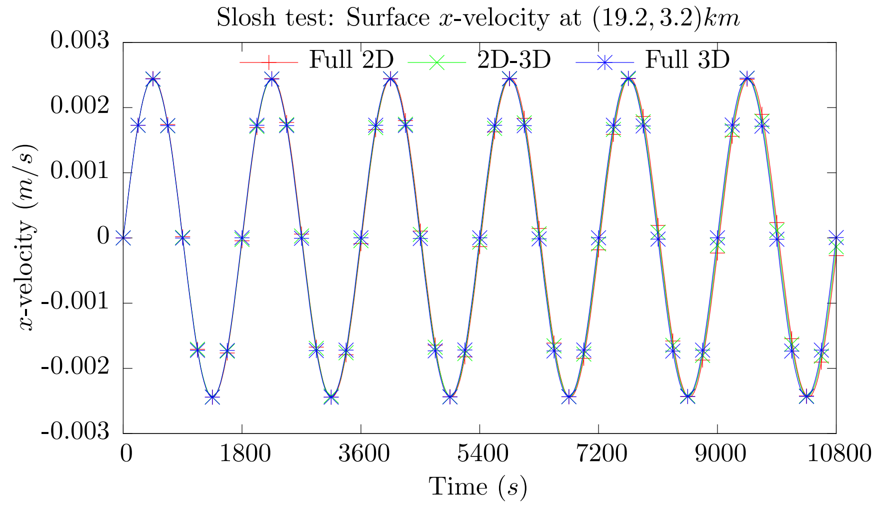
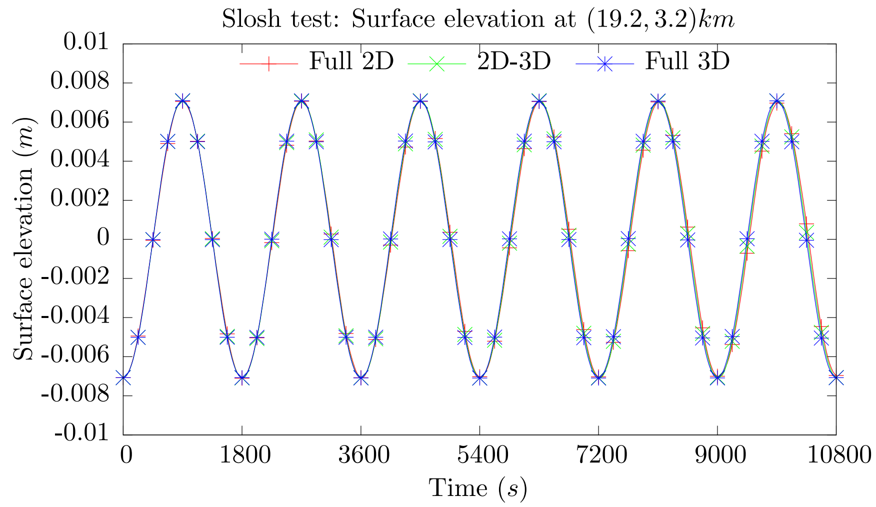
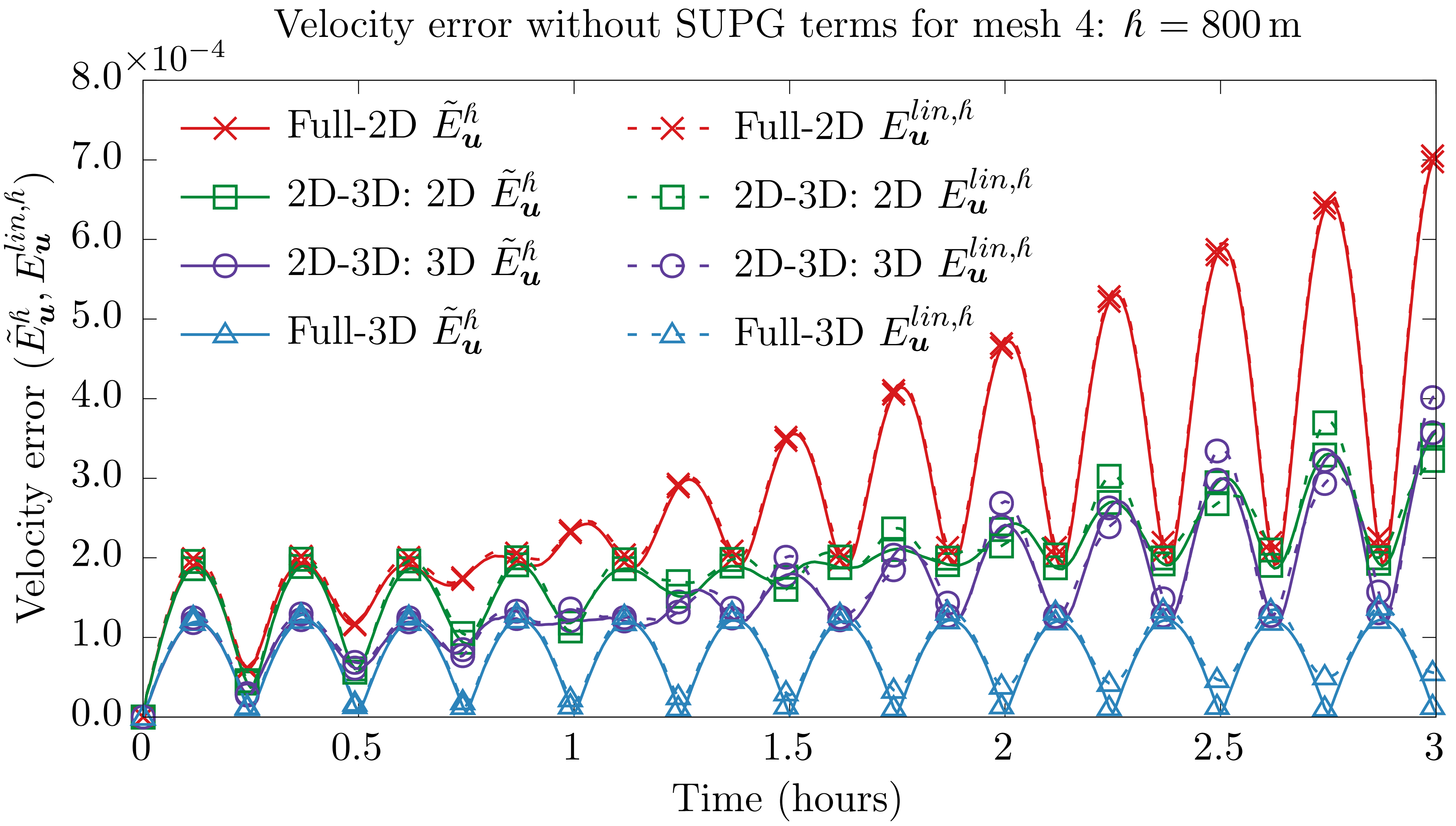


Time in s, velocity in m/s, meshes scaled in z direction

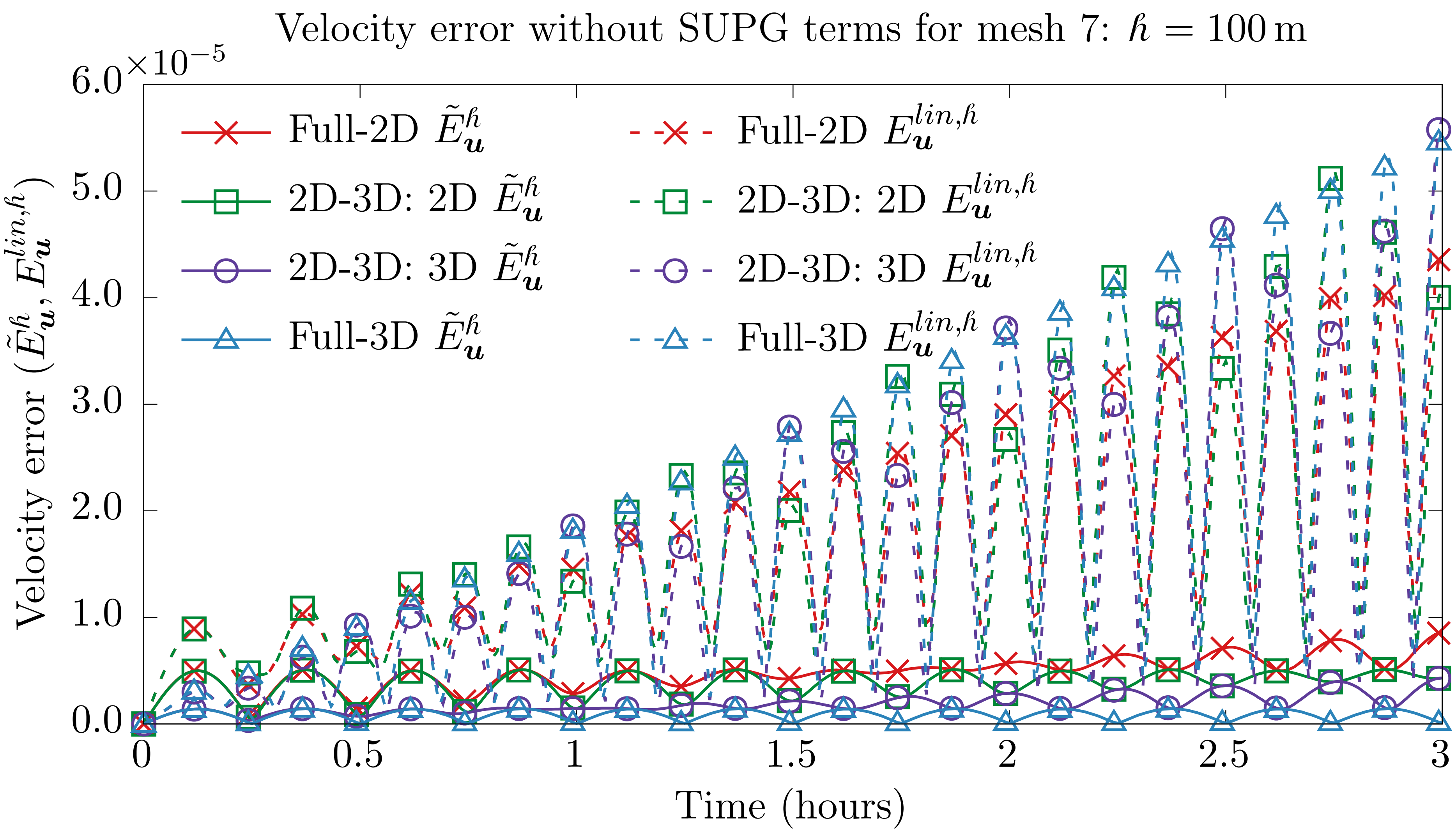




Velocity error: Coarse mesh



Velocity error: Fine mesh

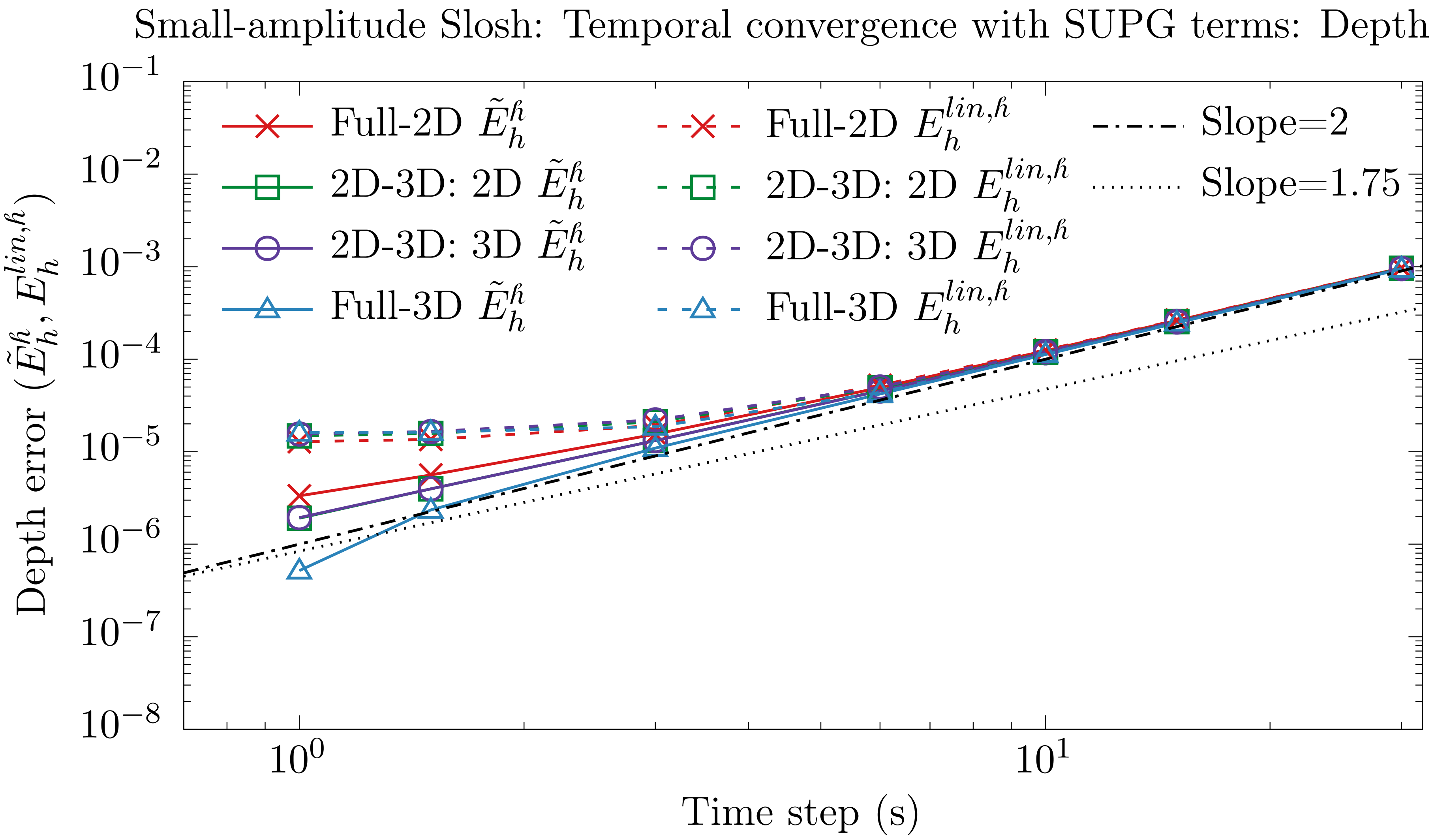


Temporal Convergence

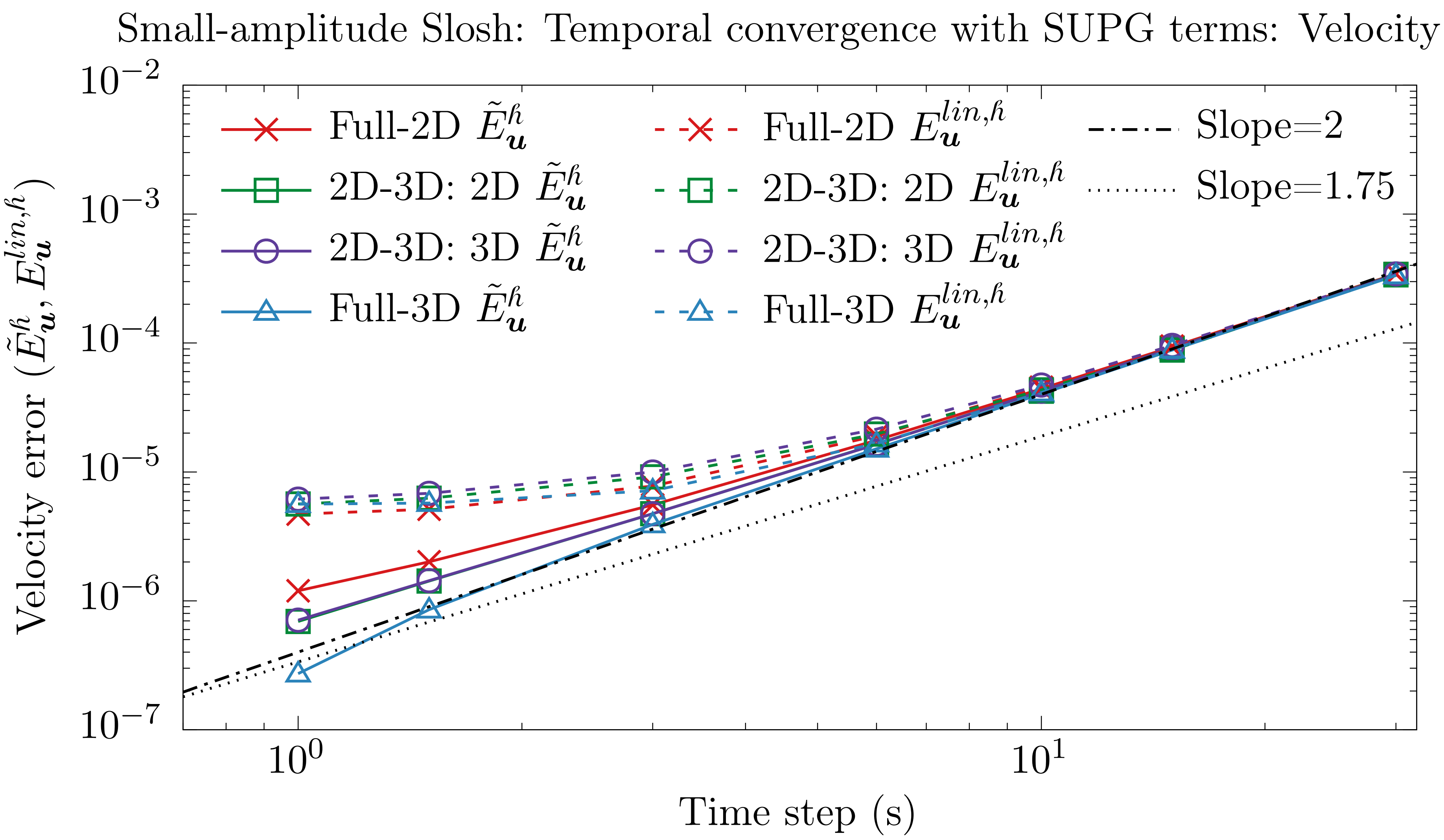
SMALL AMPLITUDE SLOSH TEST CASE

REFERENCE [5]

Temporal convergence with SUPG terms



Temporal convergence with SUPG terms

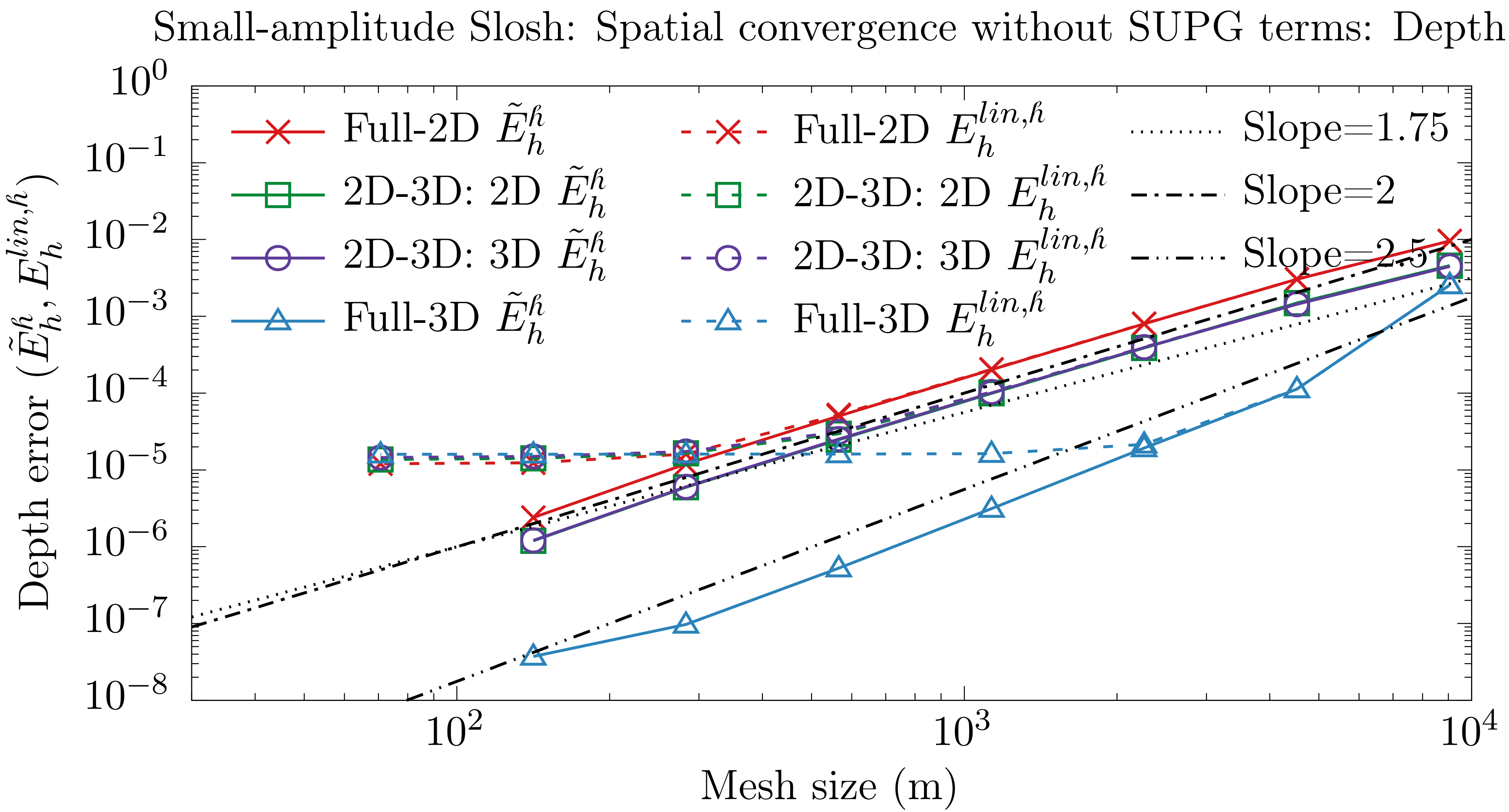


Spatial Convergence

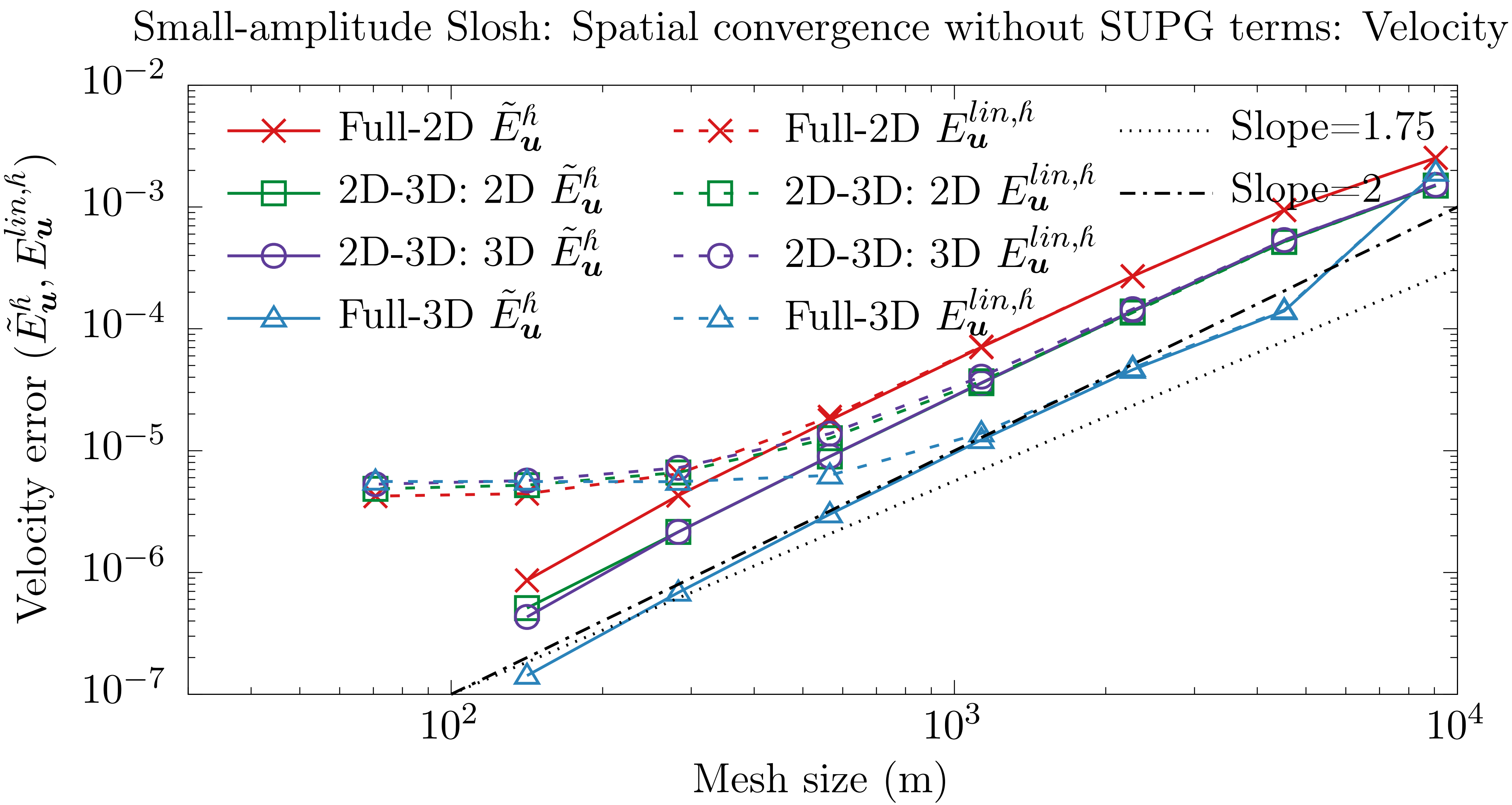
SMALL AMPLITUDE SLOSH TEST CASE

REFERENCE [5]

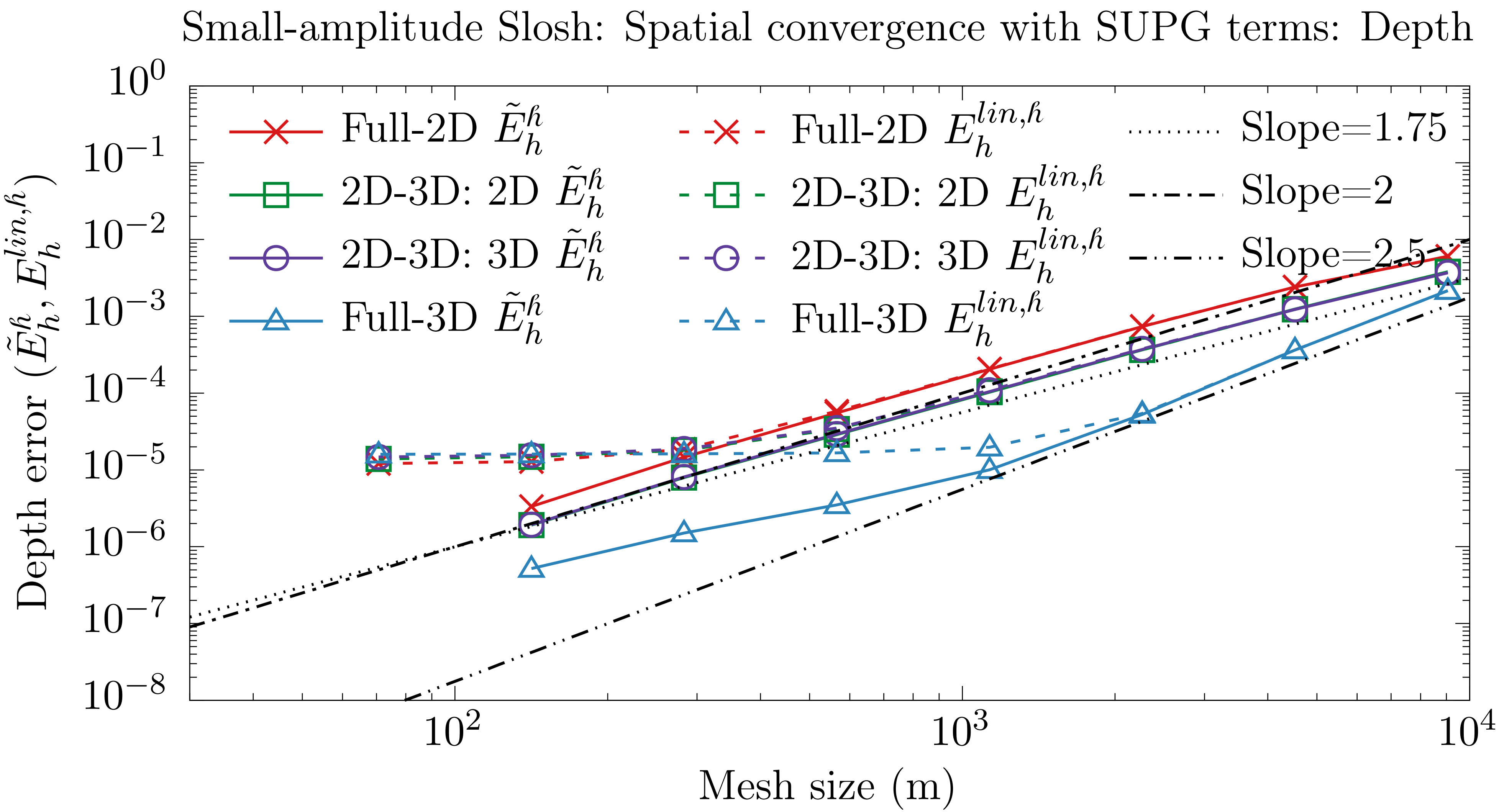
Spatial convergence without SUPG terms



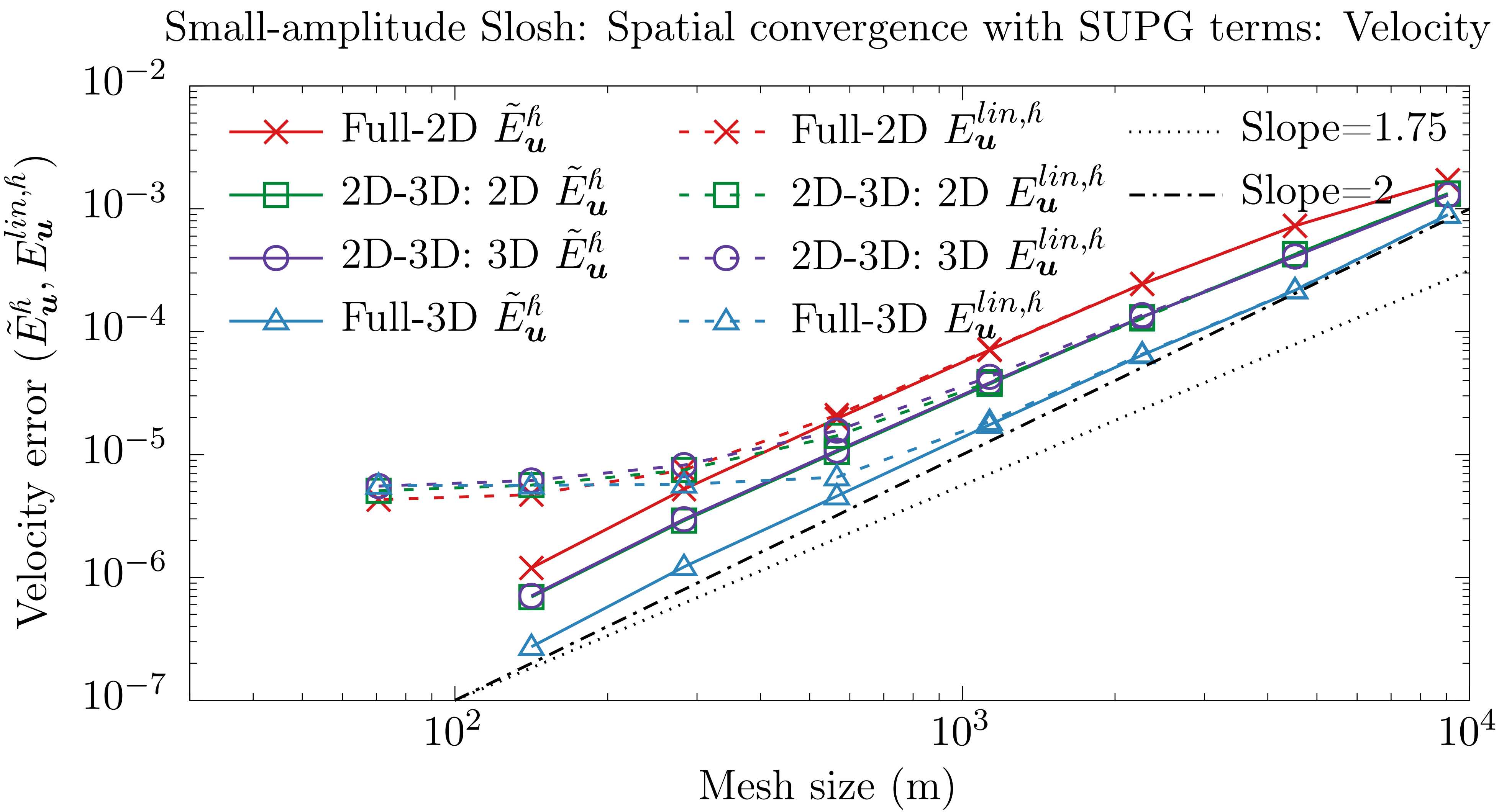
Spatial convergence without SUPG terms



Spatial convergence with SUPG terms



Spatial convergence with SUPG terms



Spatial Convergence

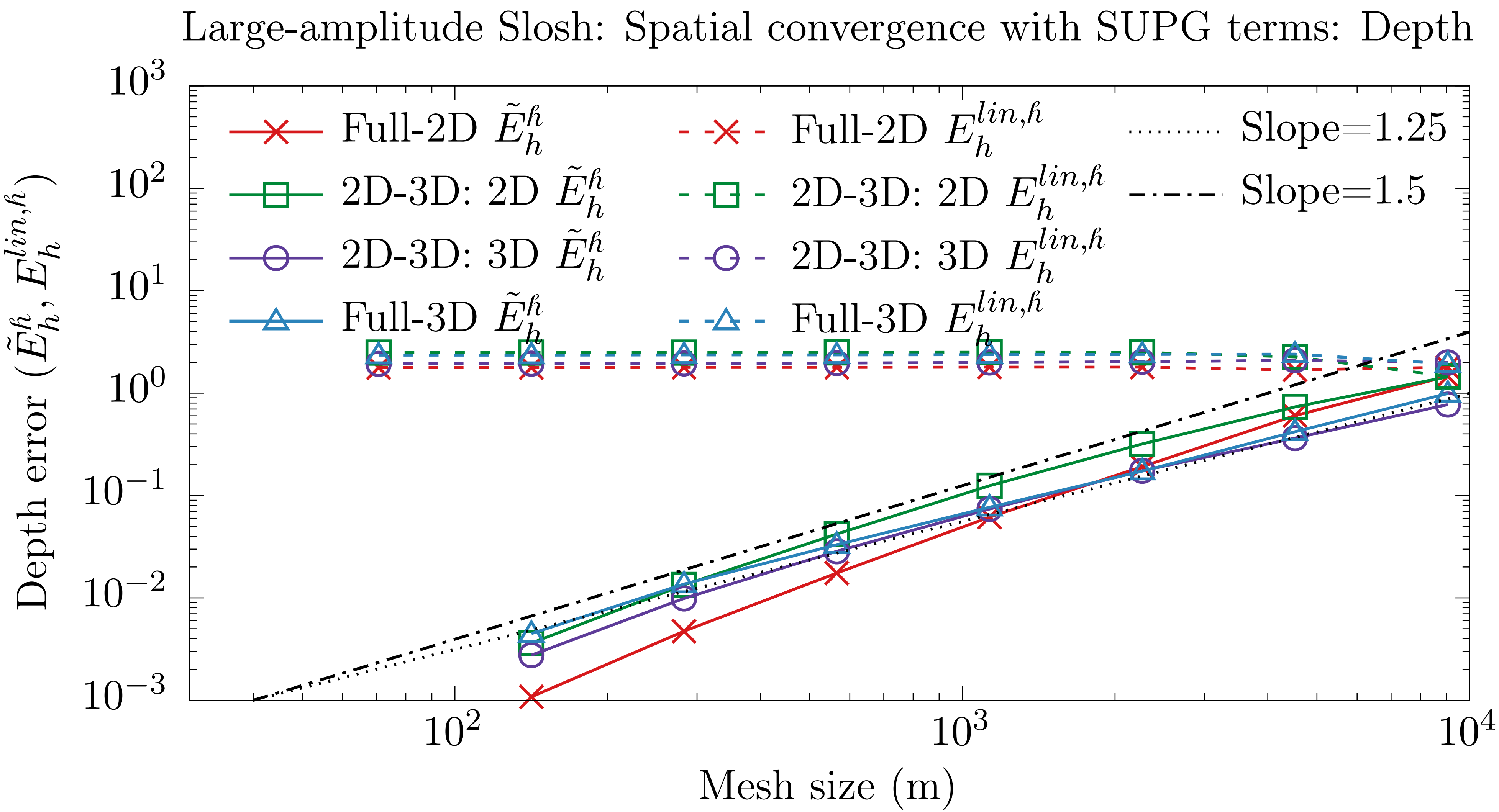
LARGE AMPLITUDE SLOSH TEST CASE

REFERENCE [5]

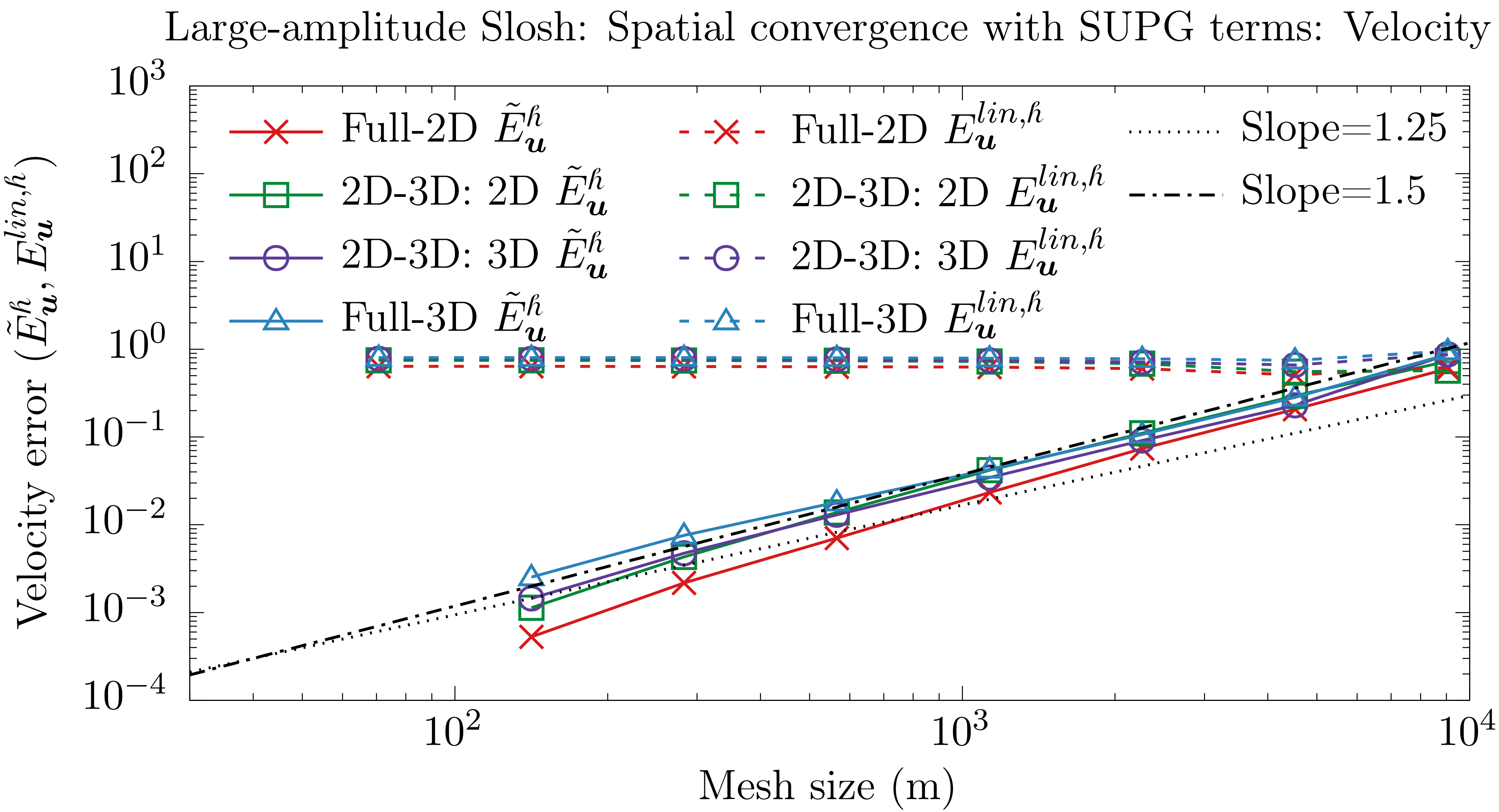
Verification – large amplitude slosh test

- Everything same as before, except depth perturbation amplitude increased to $a_\eta = 10.0m$ from $0.01m$
- Advection dominated case
- Analytical solution no longer applies
- Expected convergence rate according to [6, 7] is 1.5

Convergence: Large amplitude, SUPG



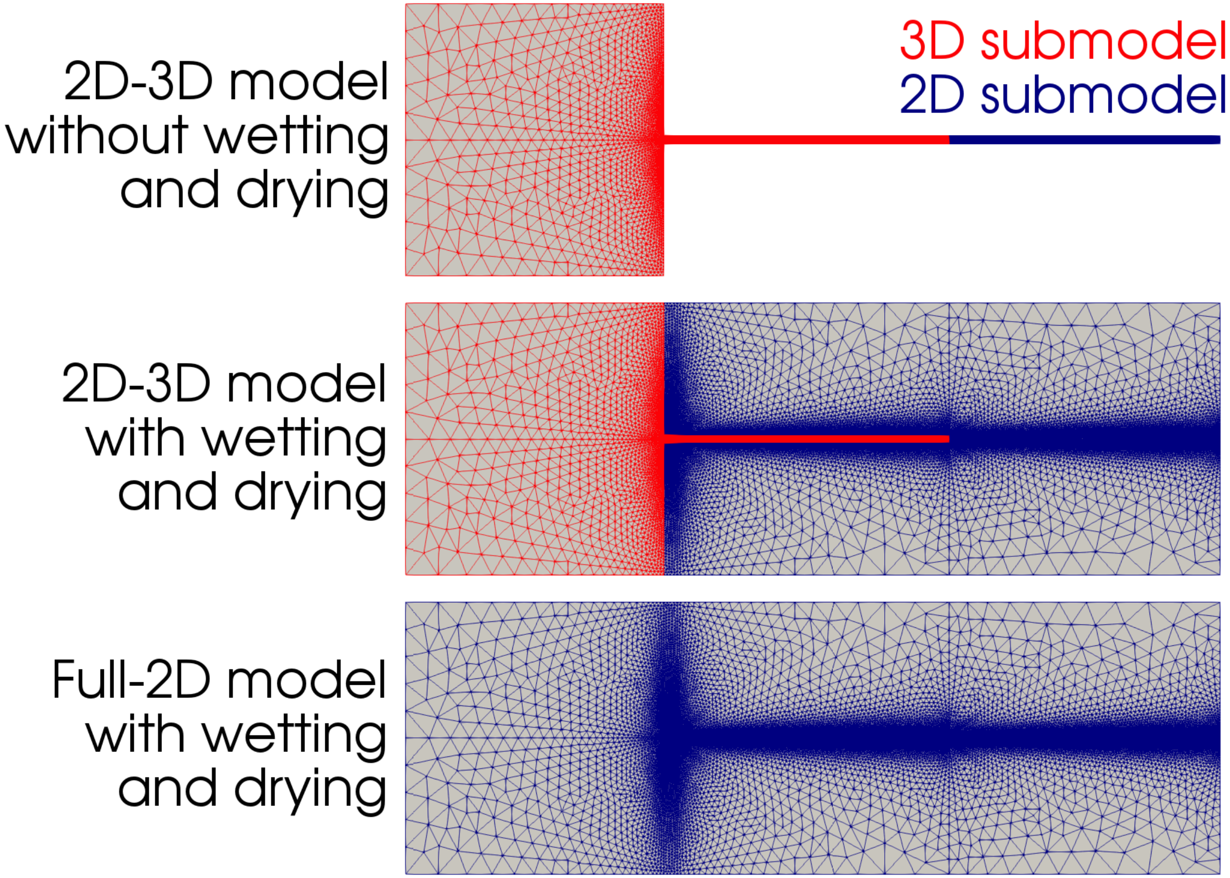
Convergence: Large amplitude, SUPG

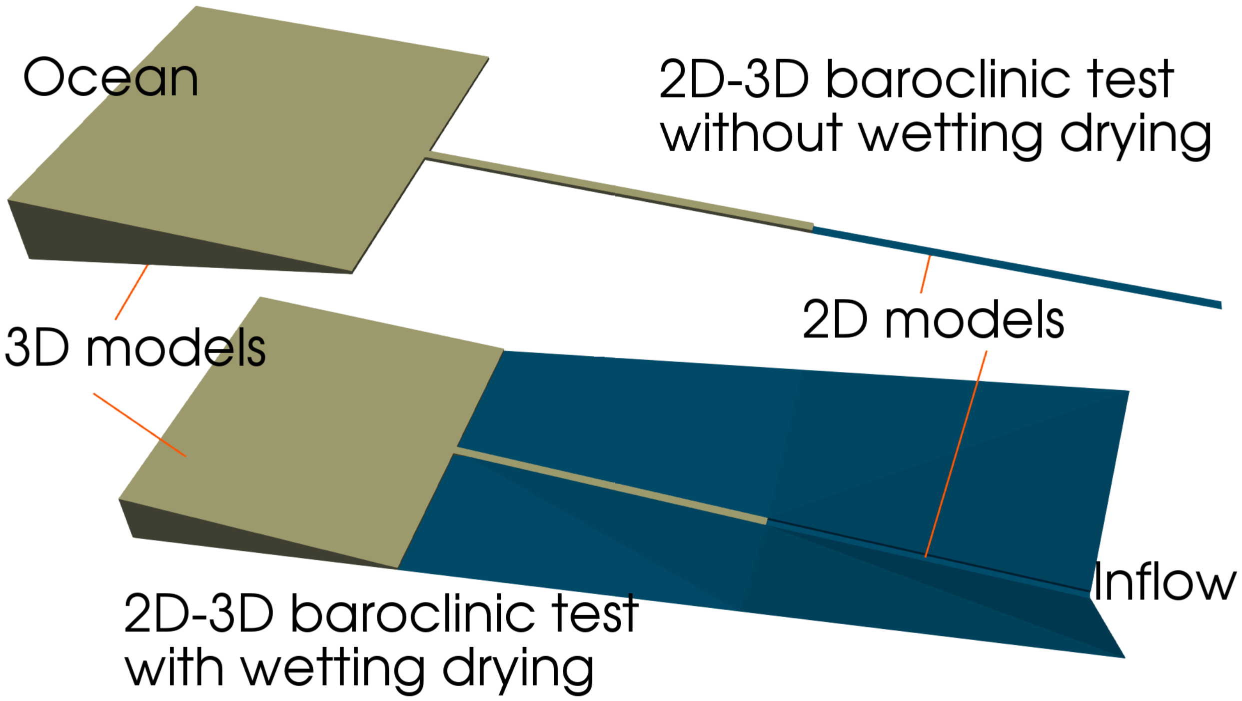


Application

IDEALIZED ESTUARY WITH BAROCLINICITY AND WETTING-DRYING

Idealized estuary – models





Idealized estuary - BC/IC

- Boundary conditions:
  - Ocean surface elevation specified: $\eta = 0.5m(1 - \cos 2\pi t/T)$, where $T = 1\ day$
  - Salinity specified at western deep ocean boundary, set to $35‰$
  - Inflow of $29800m^3/s$, salinity $1‰$ in east specified, and no-flow everywhere else
- Initial conditions:
  - Water at rest, i.e., $\boldsymbol{u}(\boldsymbol{x}, 0) = 0m/s$
  - Flat water surface, i.e., $\eta(\boldsymbol{x}, 0) = 0m$
  - Constant salinity, i.e., $c(\boldsymbol{x}, 0) = 35‰$

Idealized estuary – surface velocity

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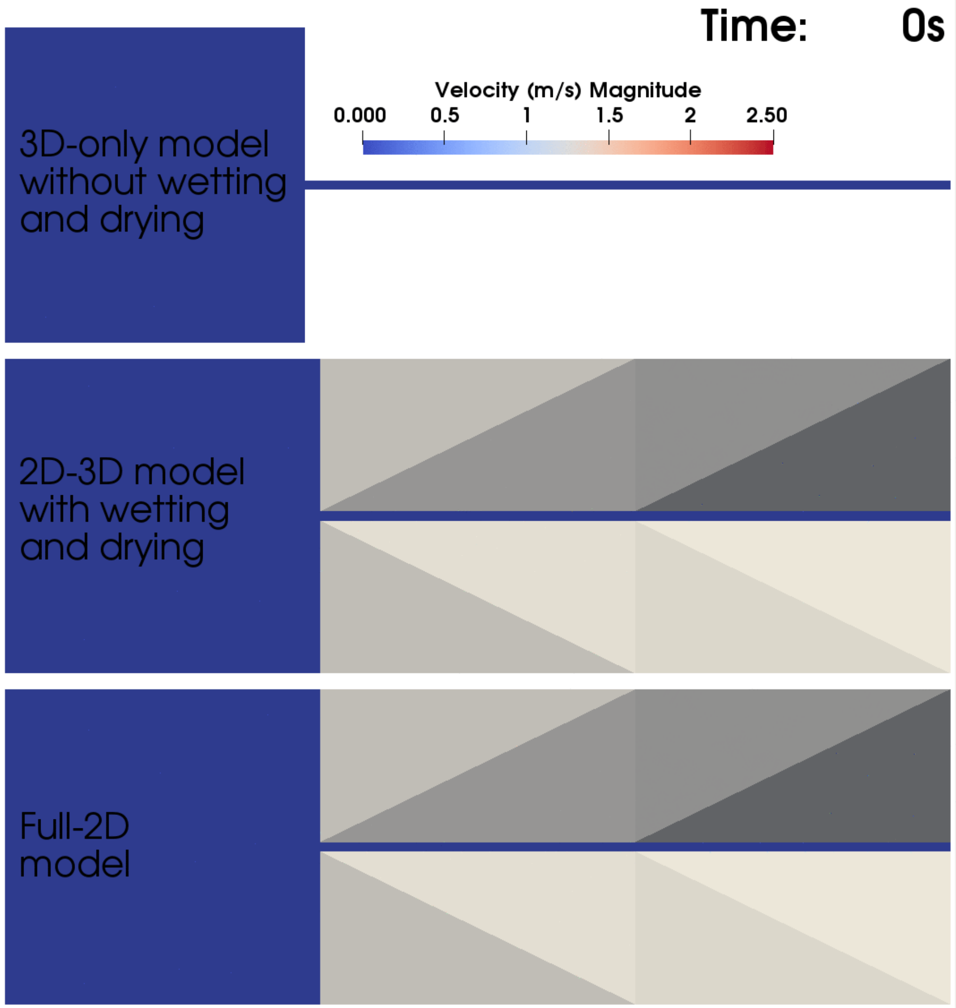

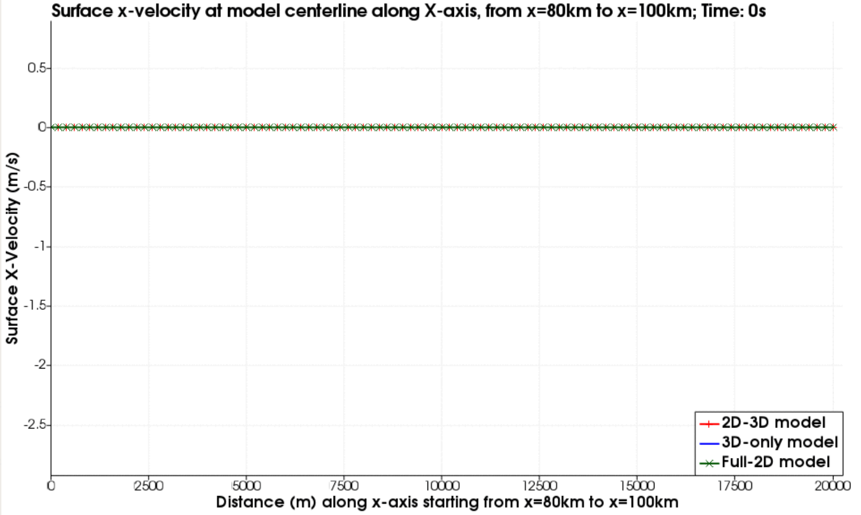

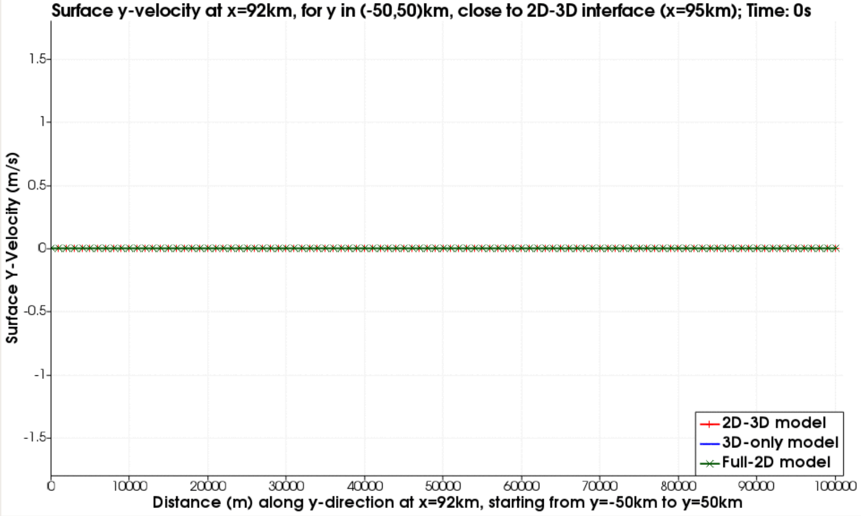

Idealized estuary – surface salinity

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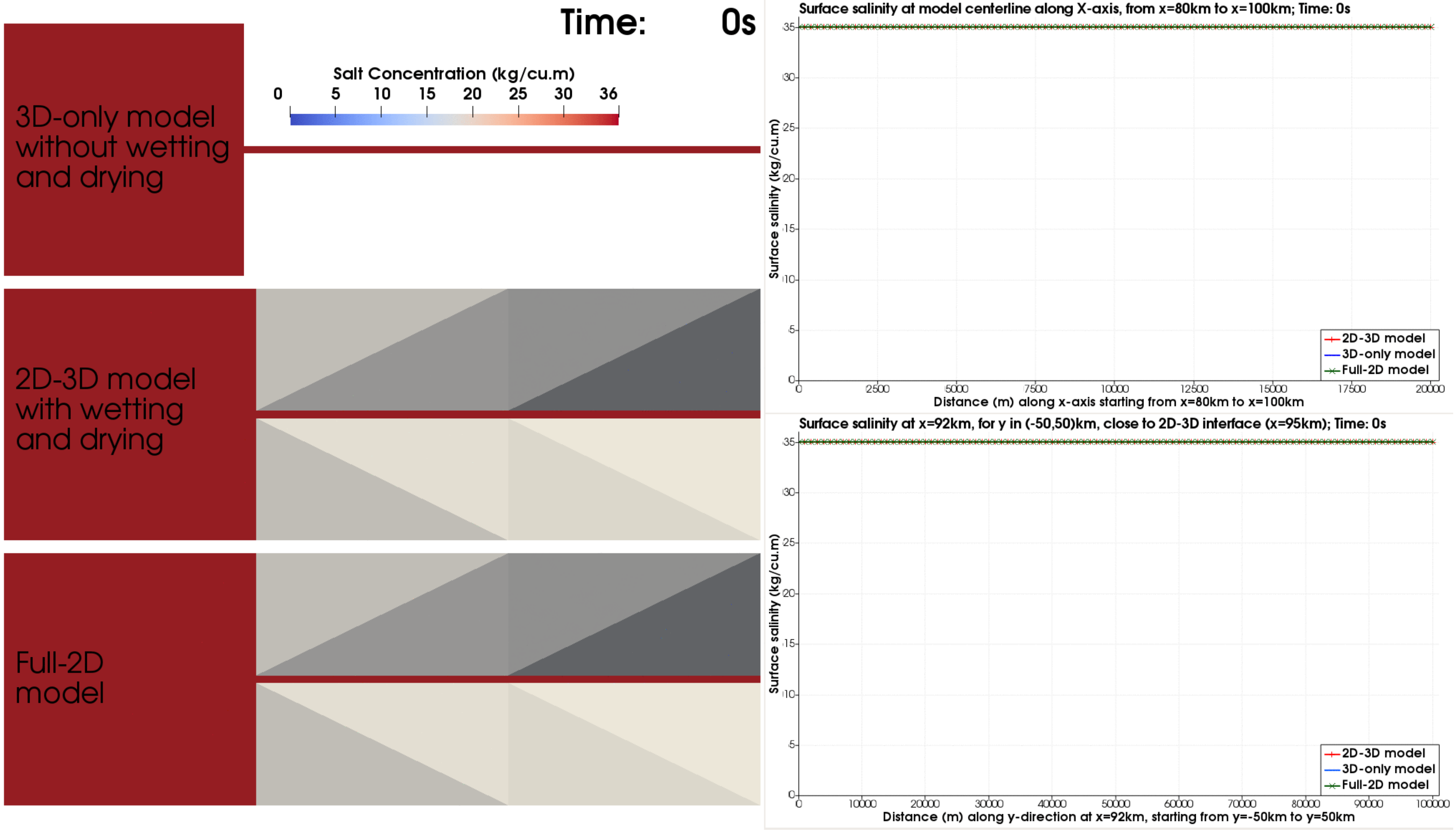

Wetting-drying + Baroclinic mixing

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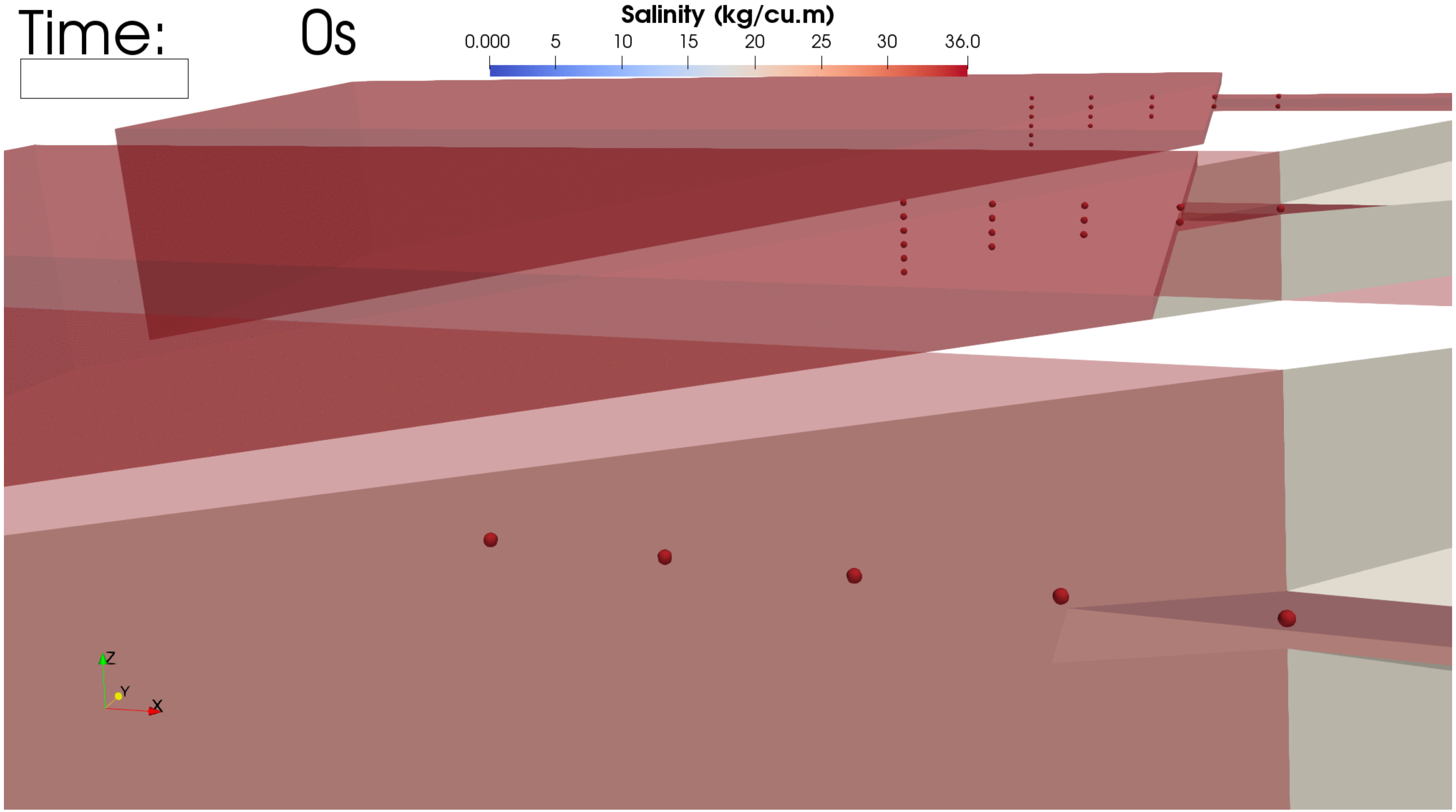
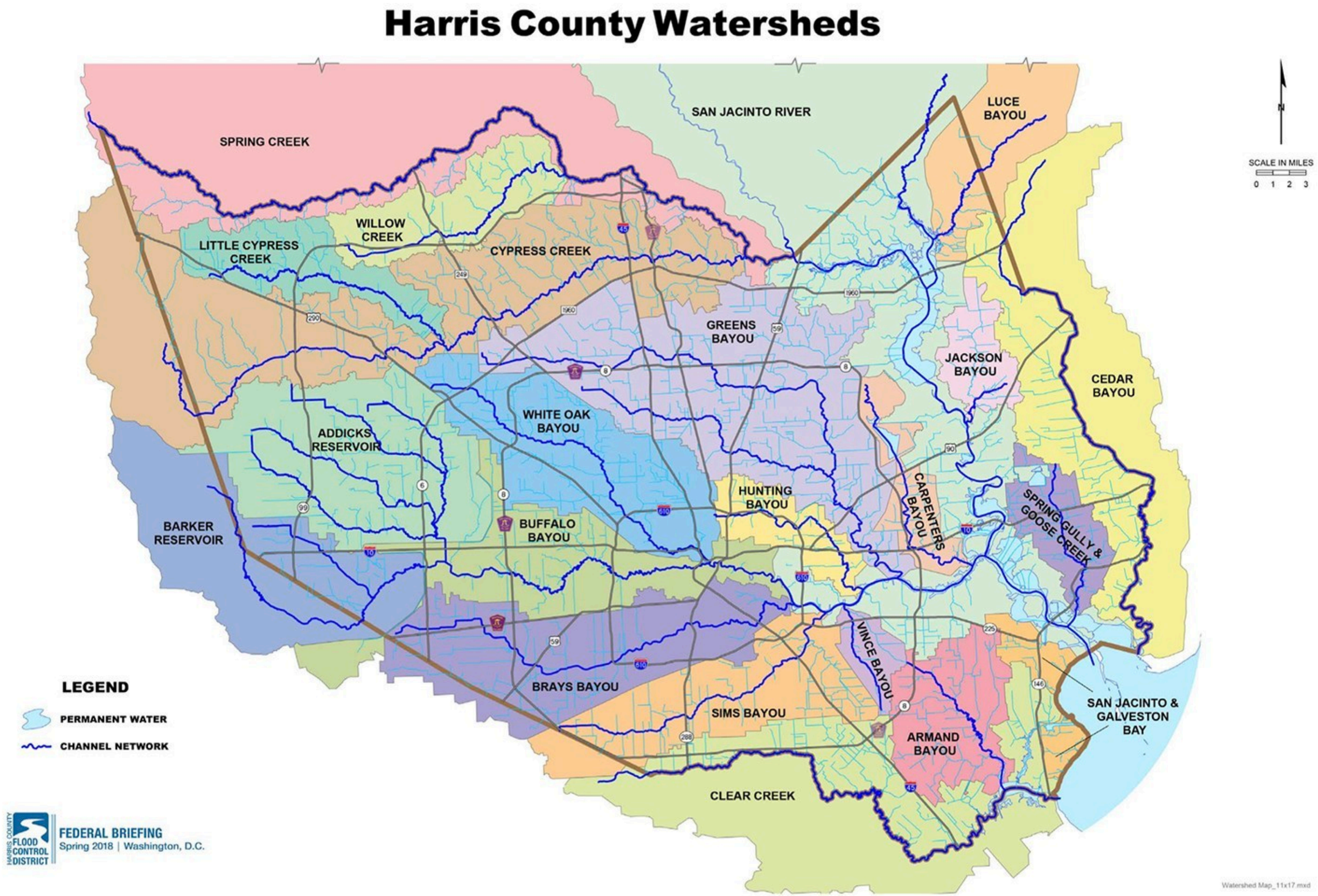


3D Atmospheric, 2D SW, 2D DW coupled models: Application

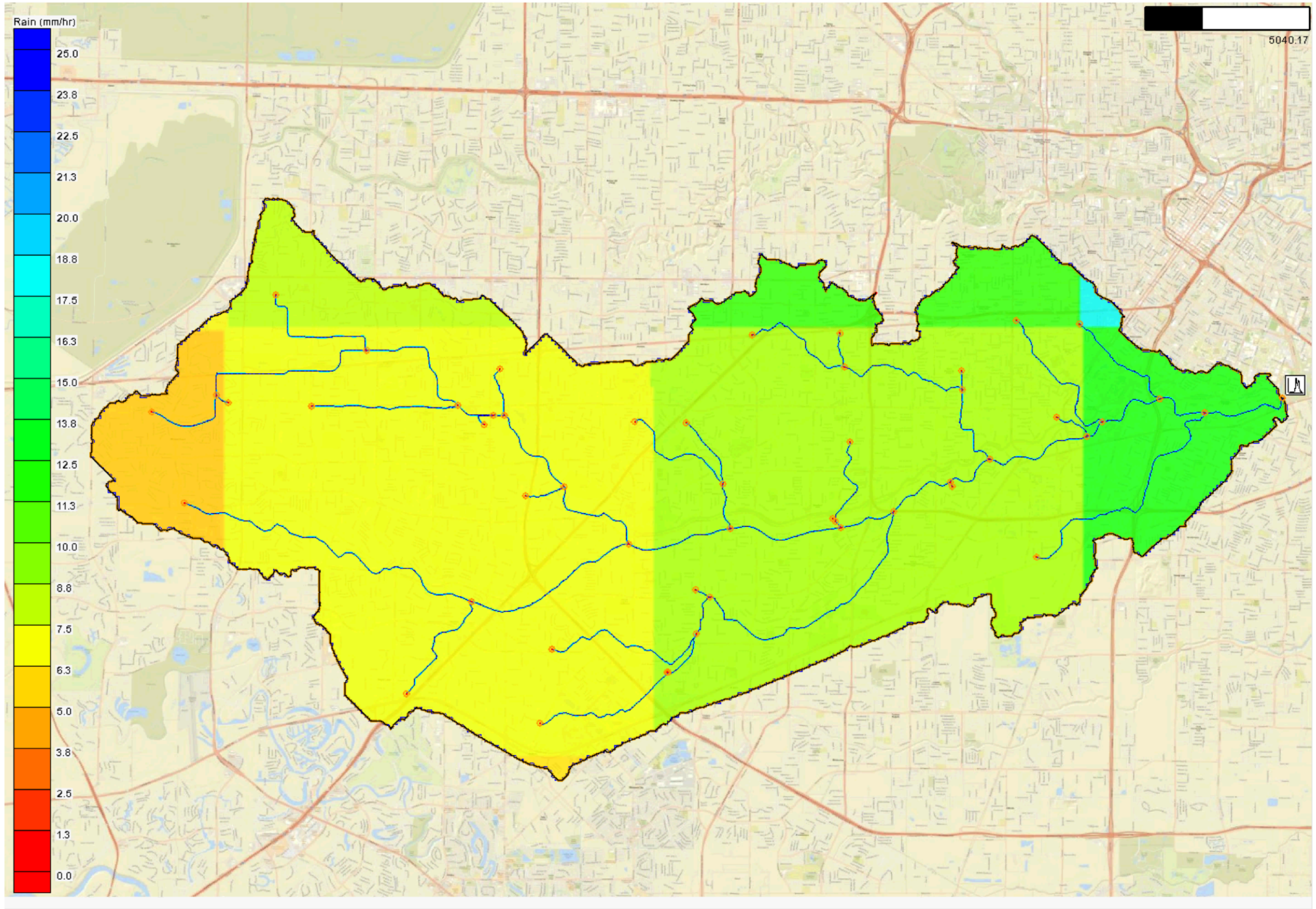
HURRICANE HARVEY, AUGUST 2017

ONE OF THE COSTLIEST HURRICANES TO HIT THE US

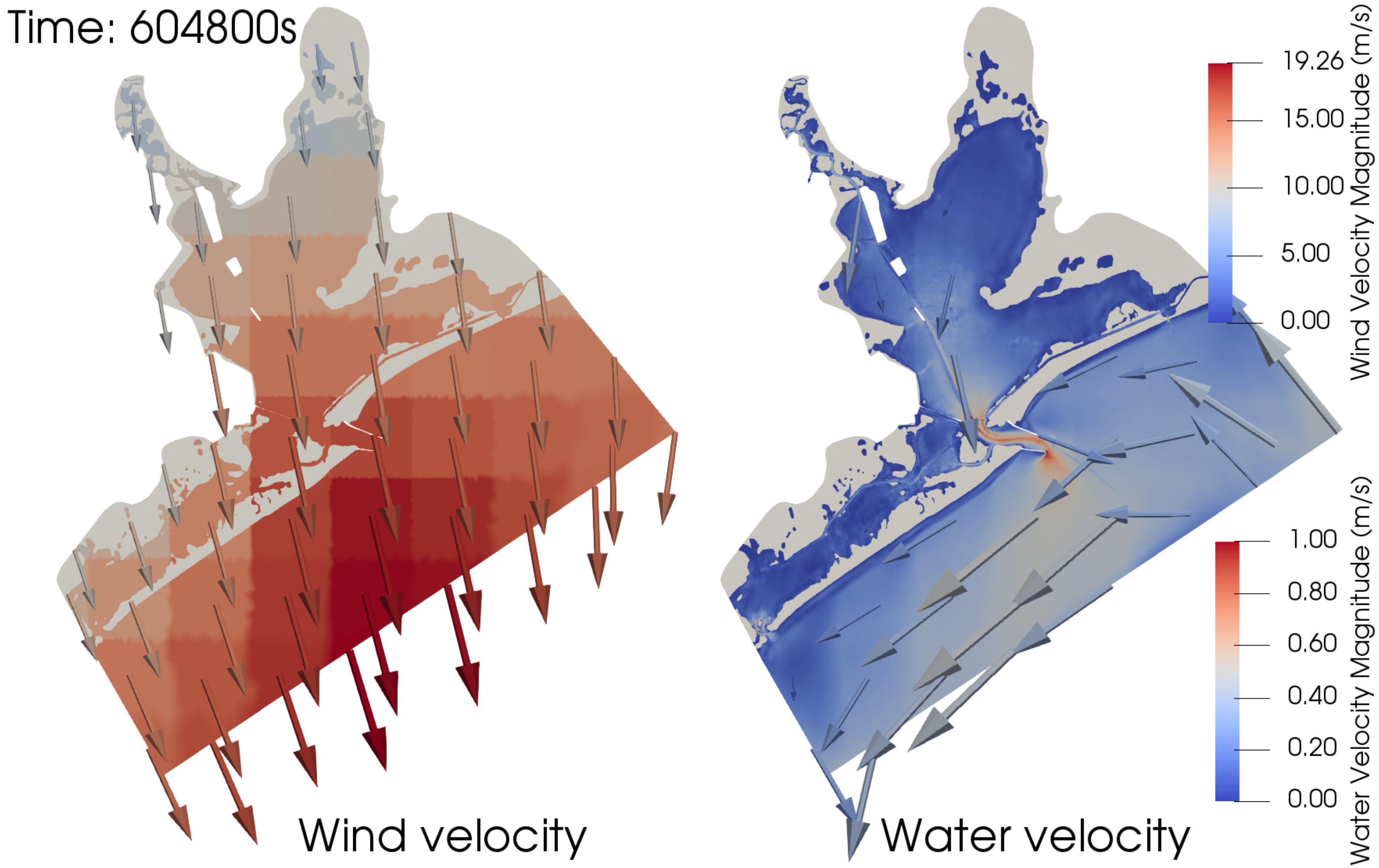
Harris County Watersheds



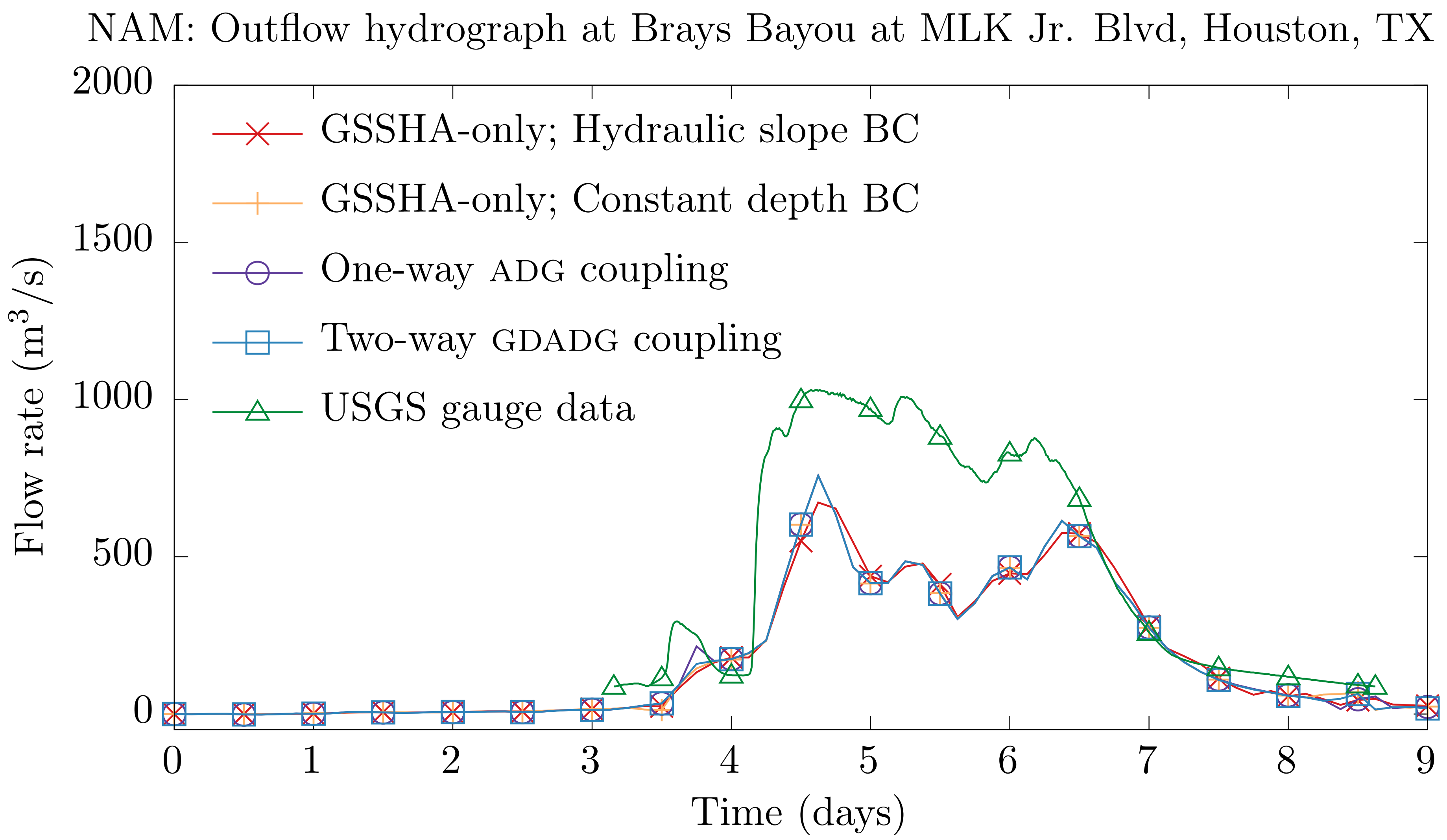
Brays Bayou Watershed model



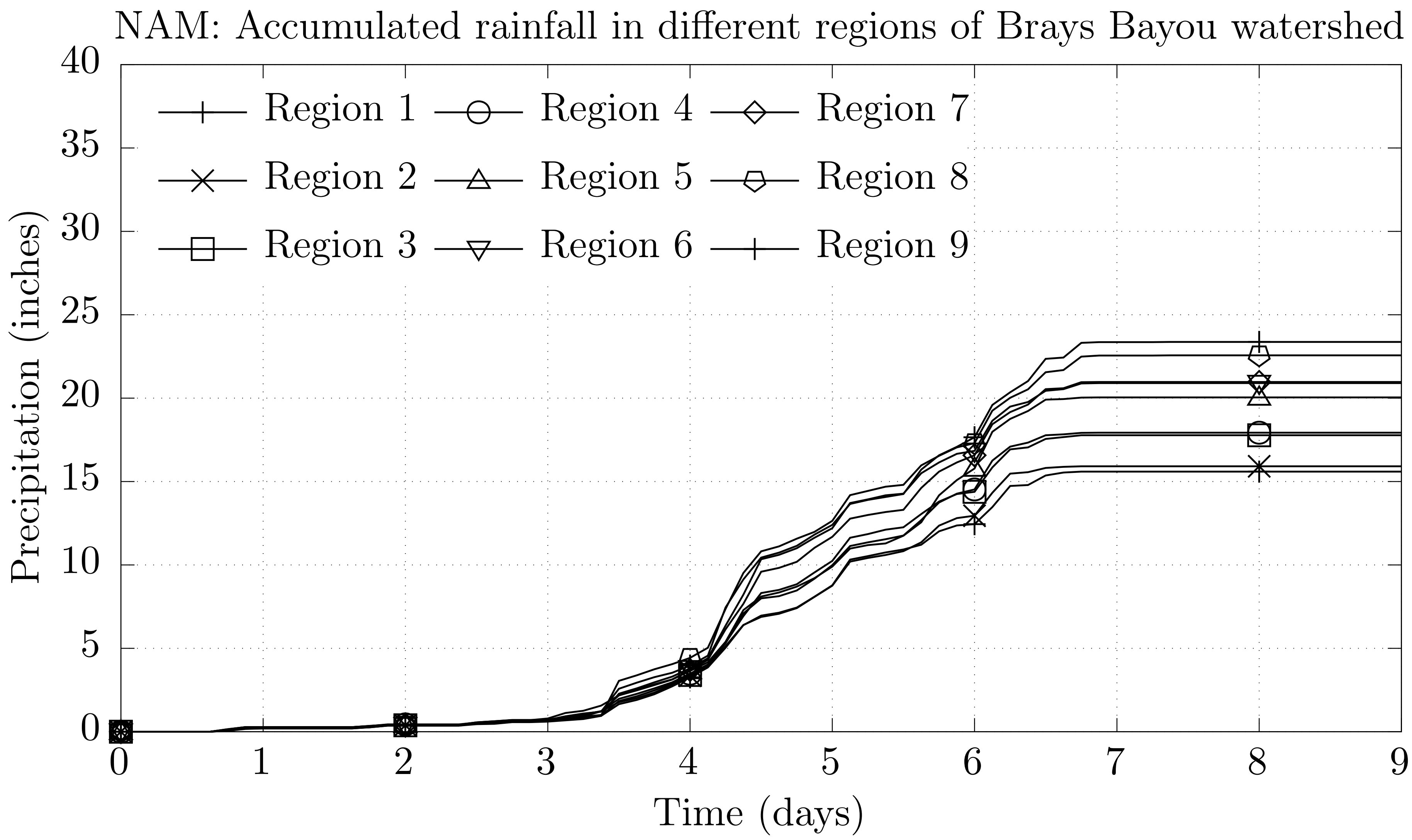
Galveston Bay model



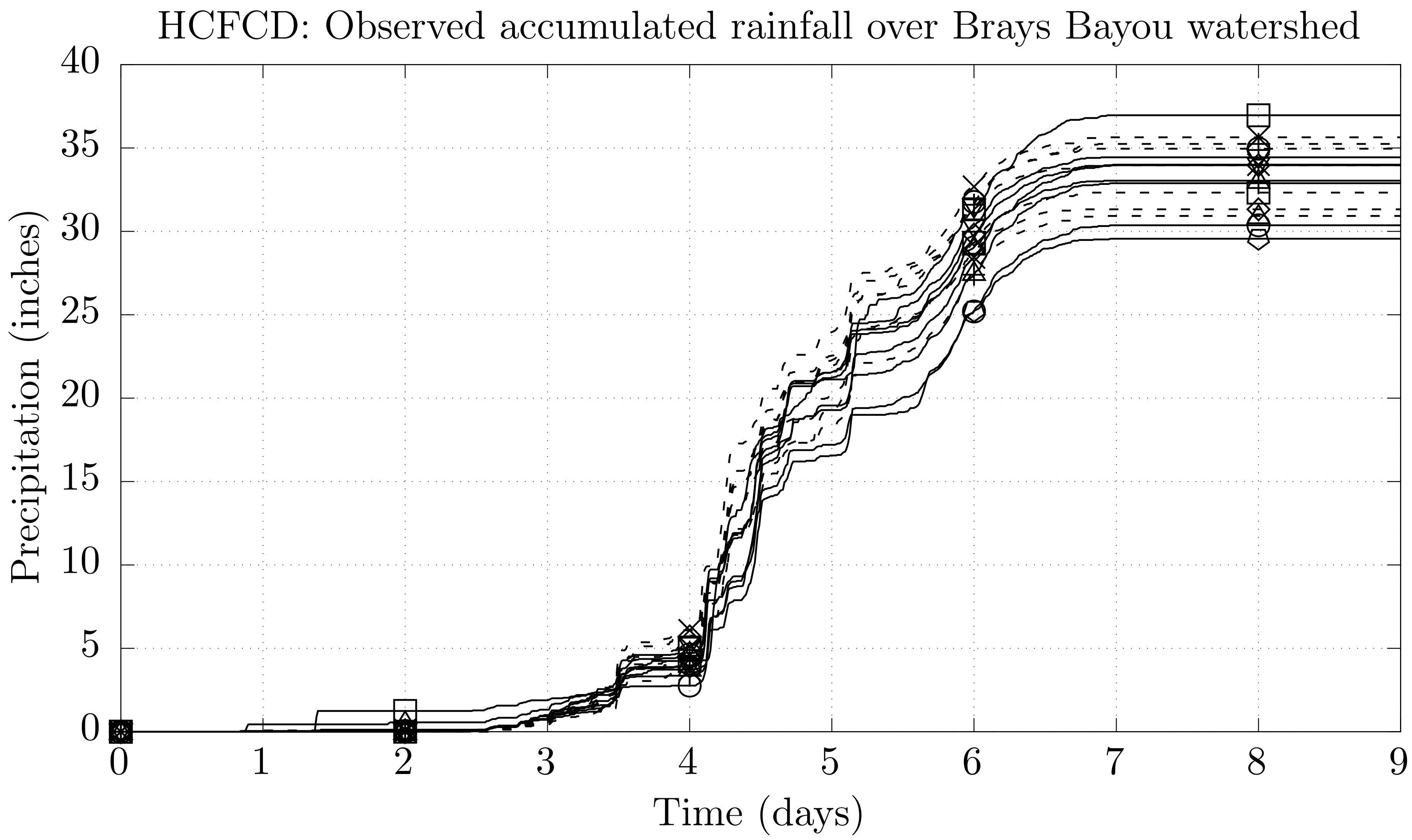
NAM-AdH-GSSHA coupling



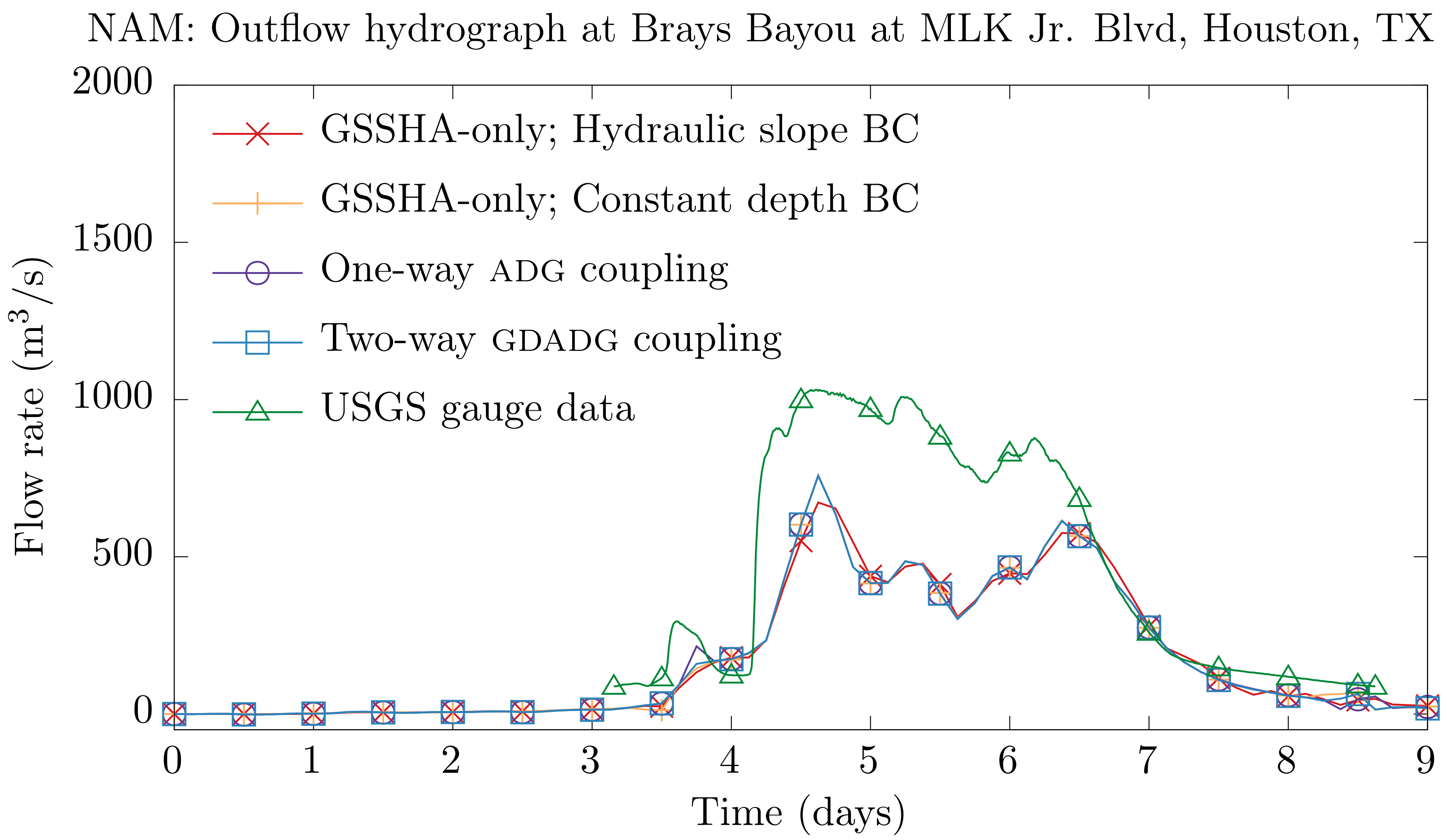
NAM: Rainfall during Harvey



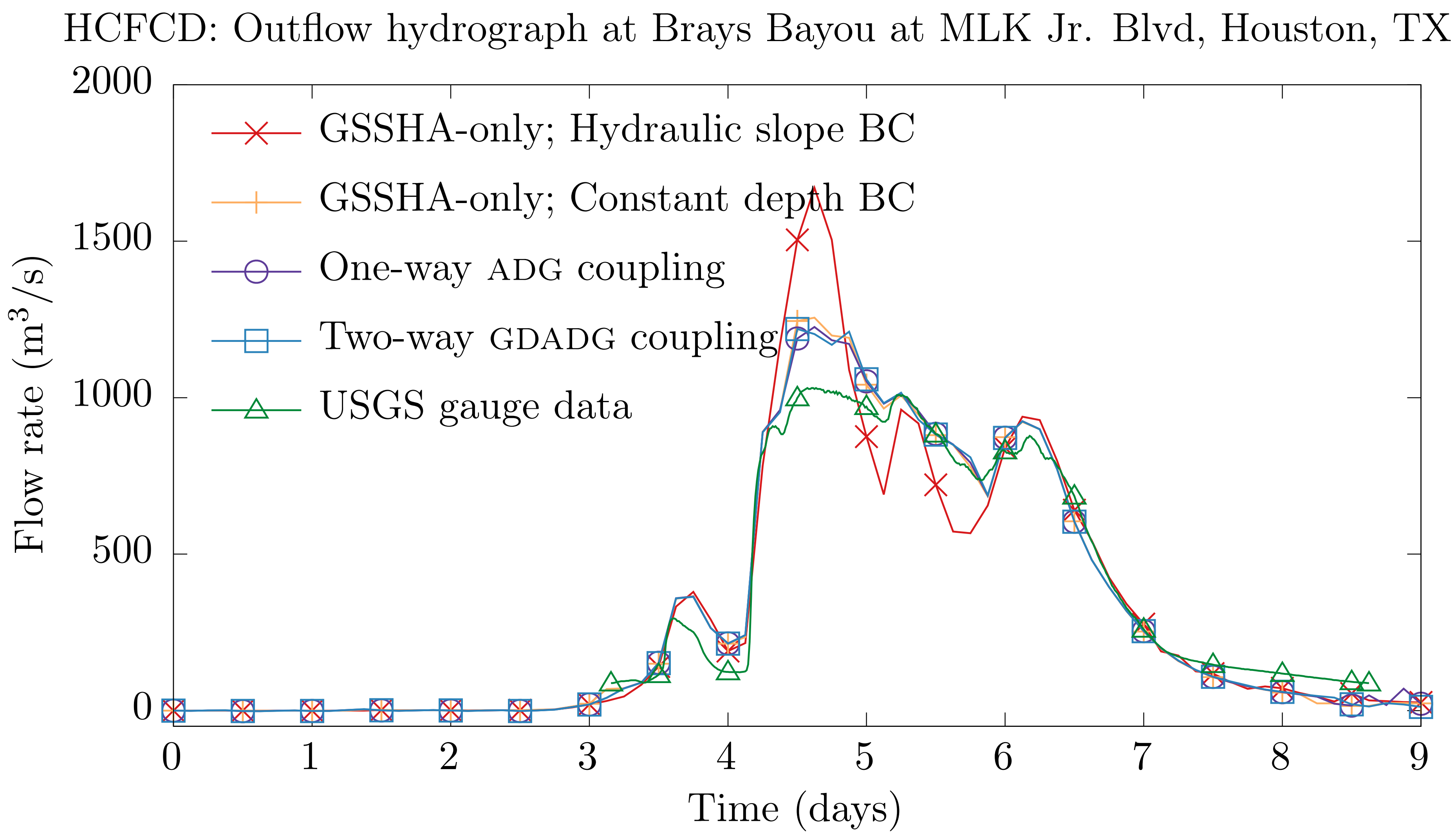
HCFCD: Observed rainfall during Harvey



NAM-AdH-GSSHA coupling



Observations-AdH-GSSHA coupling



Conclusion

Conclusions

- 2D-3D strong coupling of shallow water and transport models
- Temporal convergence rates in line with theory: Optimal rate of 2
- Spatial convergence rates in line with theory:
  - Optimal rate of 2 for negligible advection slosh test case
  - Suboptimal rate of 1.25-1.5 for advection-dominated slosh test case
- 2D-3D coupled model solutions lie ‘between’ solely 2D and 3D ones

Conclusions

- Coupled models are not just viable, but needed
- 2D-3D coupled solution lies ‘between’ 2D and 3D solutions
  - Salinity results of 3D submodels ≈ 3D-only models
  - Wetting-drying in 2D submodels ≈ full-2D models
- 2D SW models coupled to 2D/1D DW models, driving by one-way coupling from an atmospheric model
  - More work needed: better atmospheric model, more BCs, and more V&V

Future work

- More validation test cases OR theoretical guarantee needed
- How is the solution affected by the location and orientation of the coupling interface?
- Dynamically moving coupling interface to switch regions to run 3D SW, 2D SW, or 2D DW
- 3D SW coupled to 2D SW coupled to 2D/1D coupled DW to 2D GW, all driven by one-way coupling from an atmospheric model

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Any opinions, findings and conclusions or recommendations

expressed in this material are those of the author(s)

and do not necessarily reflect the views of the DoD HPCMP

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- Most important of all, parents Kalpana and Krishna, brother Abhinav and sister Supriya, without whom I would not be here

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[2] NOAA. NAM CONUS Domain. Available at https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-mesoscale-forecast-system-nam. Last accessed 09/29/2019.

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Thank You!

Additional Slides

Proof summary

CONSERVATION OF MASS/MOMENTUM ACROSS 2D-3D INTERFACE

Strong 2D-3D Coupling

Interface Nodes:

$\mathcal{J}^{2D} = \{1_{2D}, 2_{2D}, 3_{2D}\}$

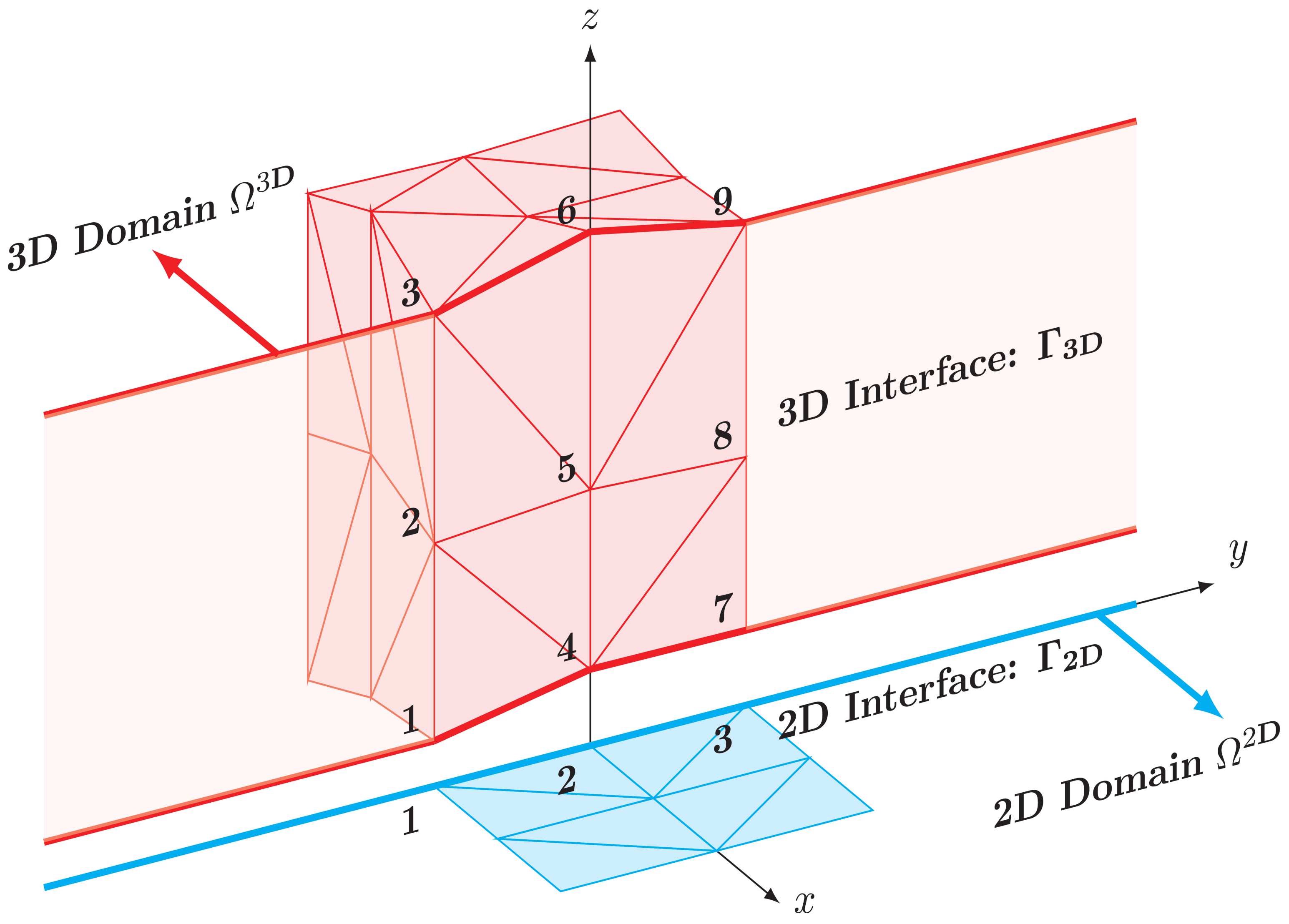
$\mathcal{J}^{3D} = \{1_{3D}, 2_{3D}, 3_{3D}, 4, \dots, 9\}$

Coupled Node Columns:

$\mathcal{C}(1_{2D}) = \{1_{3D}, 2_{3D}, 3_{3D}\}$

$\mathcal{C}(2_{2D}) = \{4, 5, 6\}$

$\mathcal{C}(3_{2D}) = \{7, 8, 9\}$



Example: Mass conservation

- Condition for mass conservation, for coupled node column $\{2^{2D}, 4, 5, 6\}$:
- To prove:

$$\int_{\Gamma^{2D}} \phi_{2_{2D}} h\bar{\boldsymbol{u}} \cdot \boldsymbol{n}_{2D} d\Gamma^{2D} = -\sum_{i=4}^{6} \int_{\Gamma^{3D}} \phi_i \boldsymbol{u} \cdot \boldsymbol{n}_{3D} d\Gamma^{3D}$$

- Proof uses:

$$(h, \bar{u}, \bar{v})\Big|_{\Gamma^{2D}} = (h, u, v)\Big|_{\Gamma^{3D}} \quad \text{… (choice of trial function)}$$

$$\phi_{2_{2D}}\Big|_{\Gamma^{2D}} = (\phi_4 + \phi_5 + \phi_6)\Big|_{\Gamma^{3D}} \quad \text{… (extrusion + conformity)}$$

$$\boldsymbol{n}_{2D}\Big|_{\Gamma^{2D}} = -\boldsymbol{n}_{3D}\Big|_{\Gamma^{3D}} \quad \text{… (no gaps in the interface)}$$

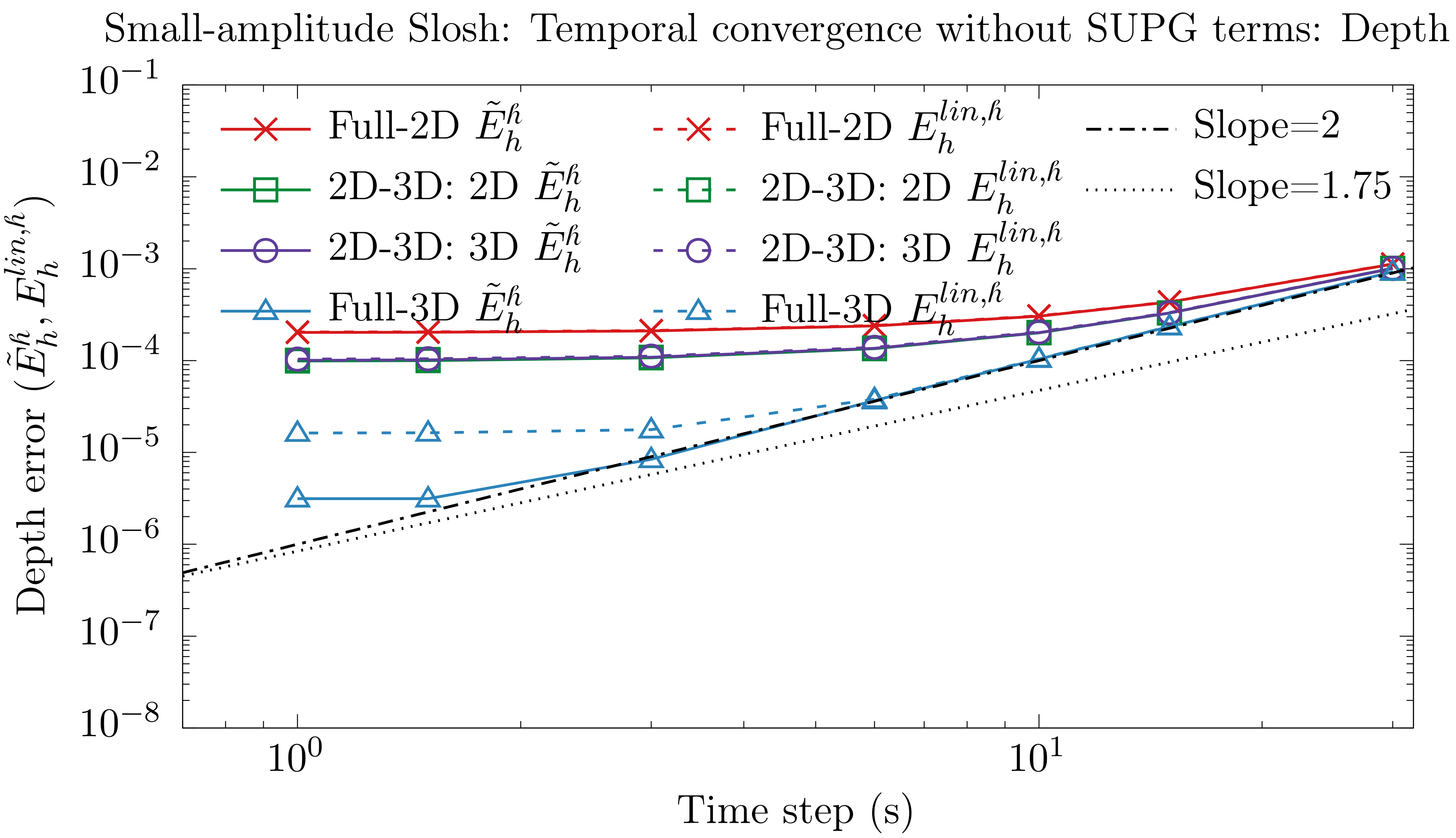
- Trivial after this. Momentum conservation likewise.

Temporal Convergence

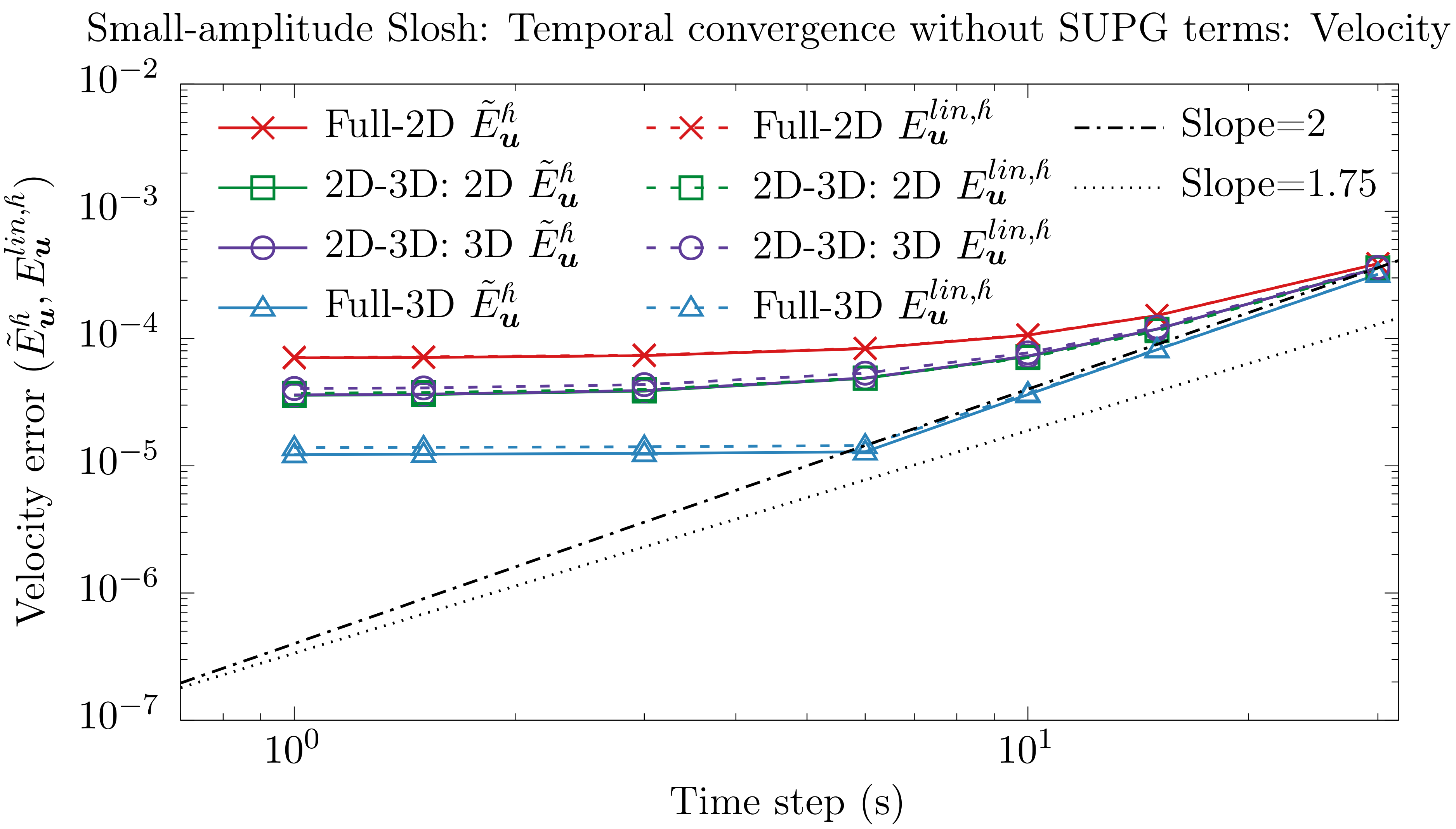
SMALL AMPLITUDE SLOSH TEST CASE

REFERENCE [1]

Temporal convergence without SUPG terms



Temporal convergence without SUPG terms



Spatial Convergence

SMALL AMPLITUDE SLOSH TEST CASE

REFERENCE [1]

2D-3D Coupled SWE: Verification

BAROCLINIC LOCK EXCHANGE TEST CASE

Lock exchange test

- Domain: $\Omega = (0, L)\times(0, B)\times(-H, 0)$
  - $L = 2m, B = 0.2m, H = 0.2m$; simulation time $48s$
- Boundary conditions:
  - No-flow across all vertical boundaries
- Initial conditions:
  - Water at rest, i.e., $\boldsymbol{u}(x, y, z, 0) = 0m/s$
  - Constant water depth, i.e., $h(x, y, 0) = H = 0.2m$
  - Salinity discontinuity at the center; $30‰$ in one half, and $10‰$ in the other

Lock exchange test

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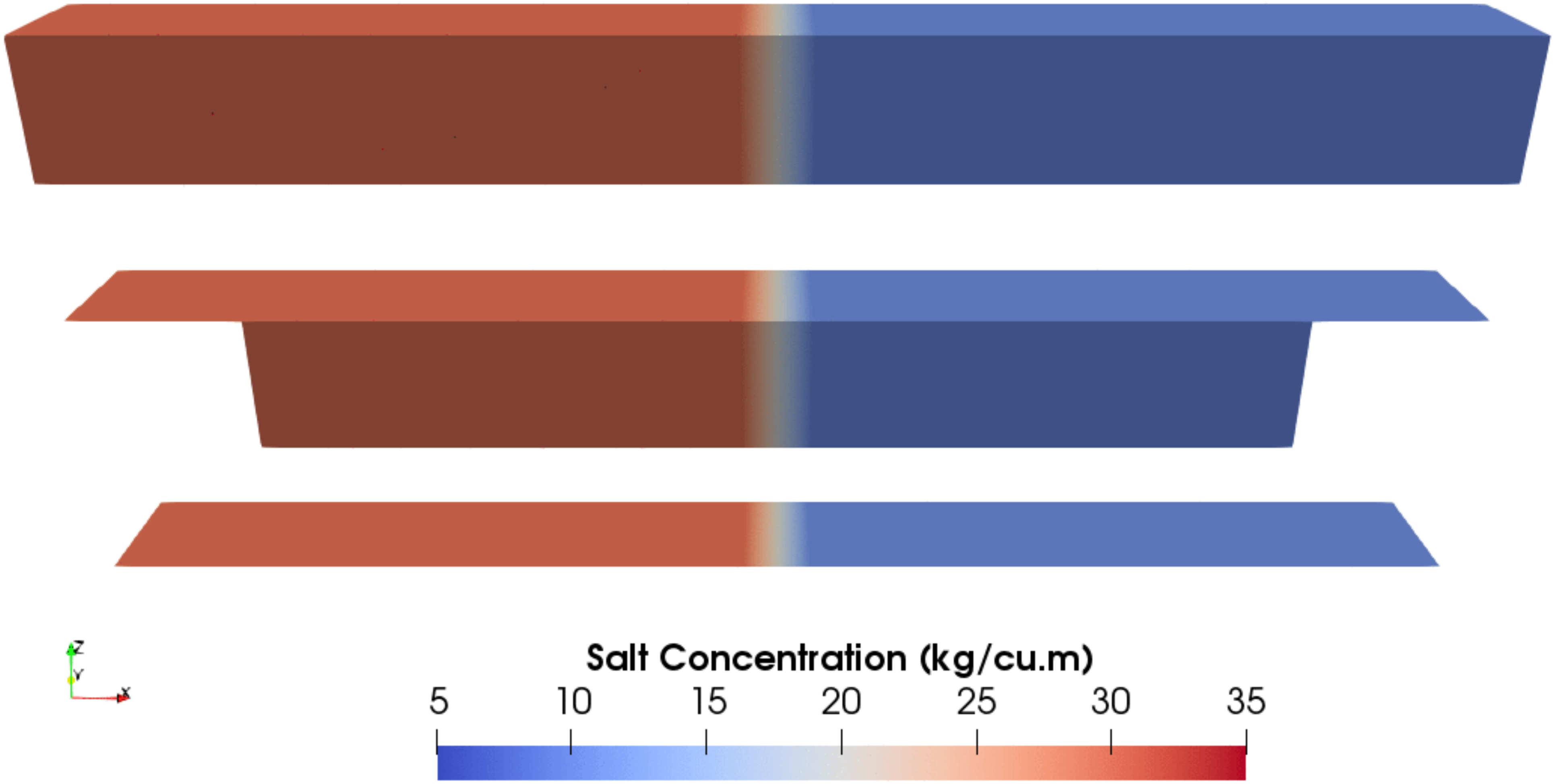
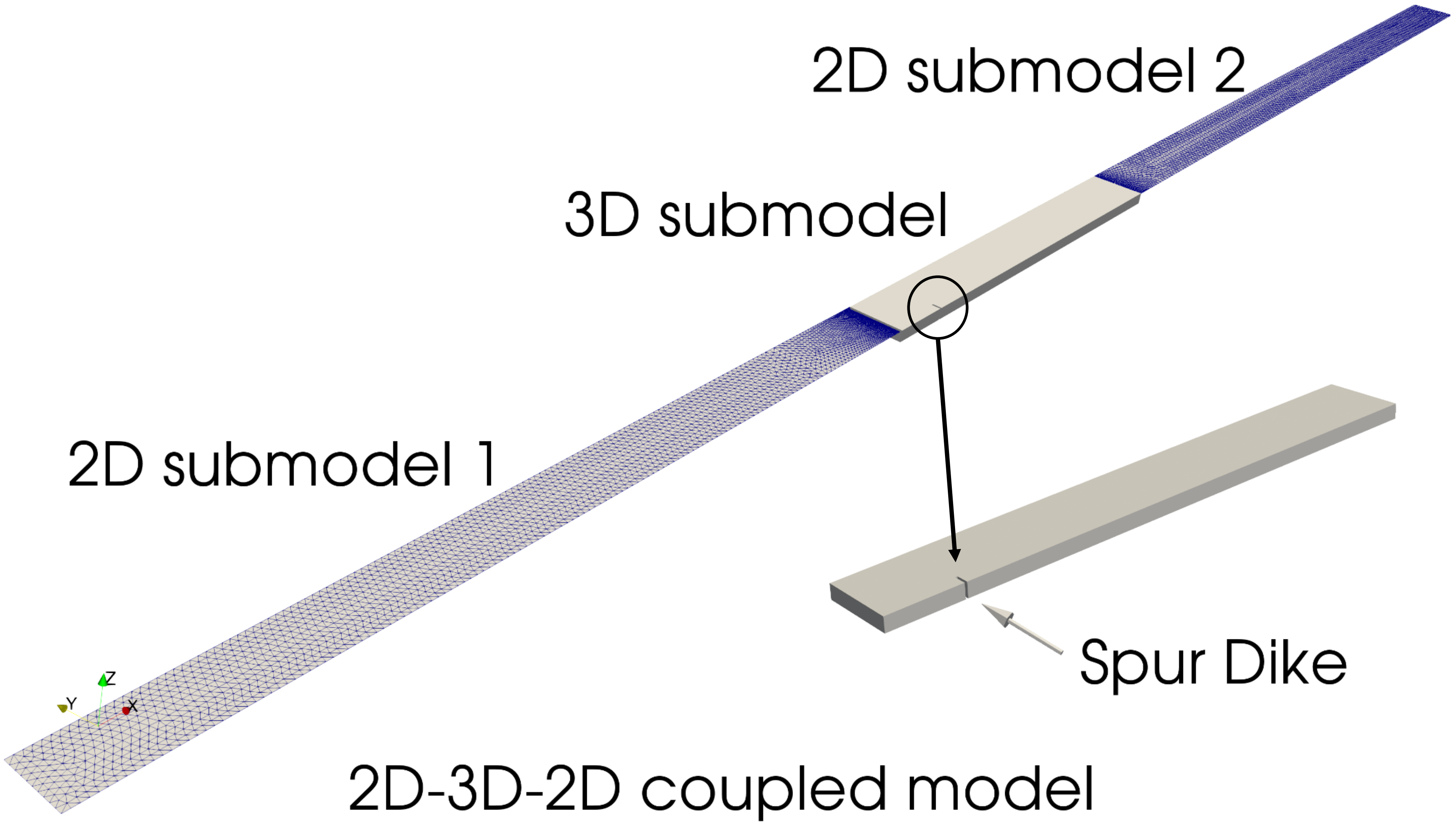


Validation

EMERGENT SPUR DIKE IN A RECTANGULAR CHANNEL

REFERENCE [4]

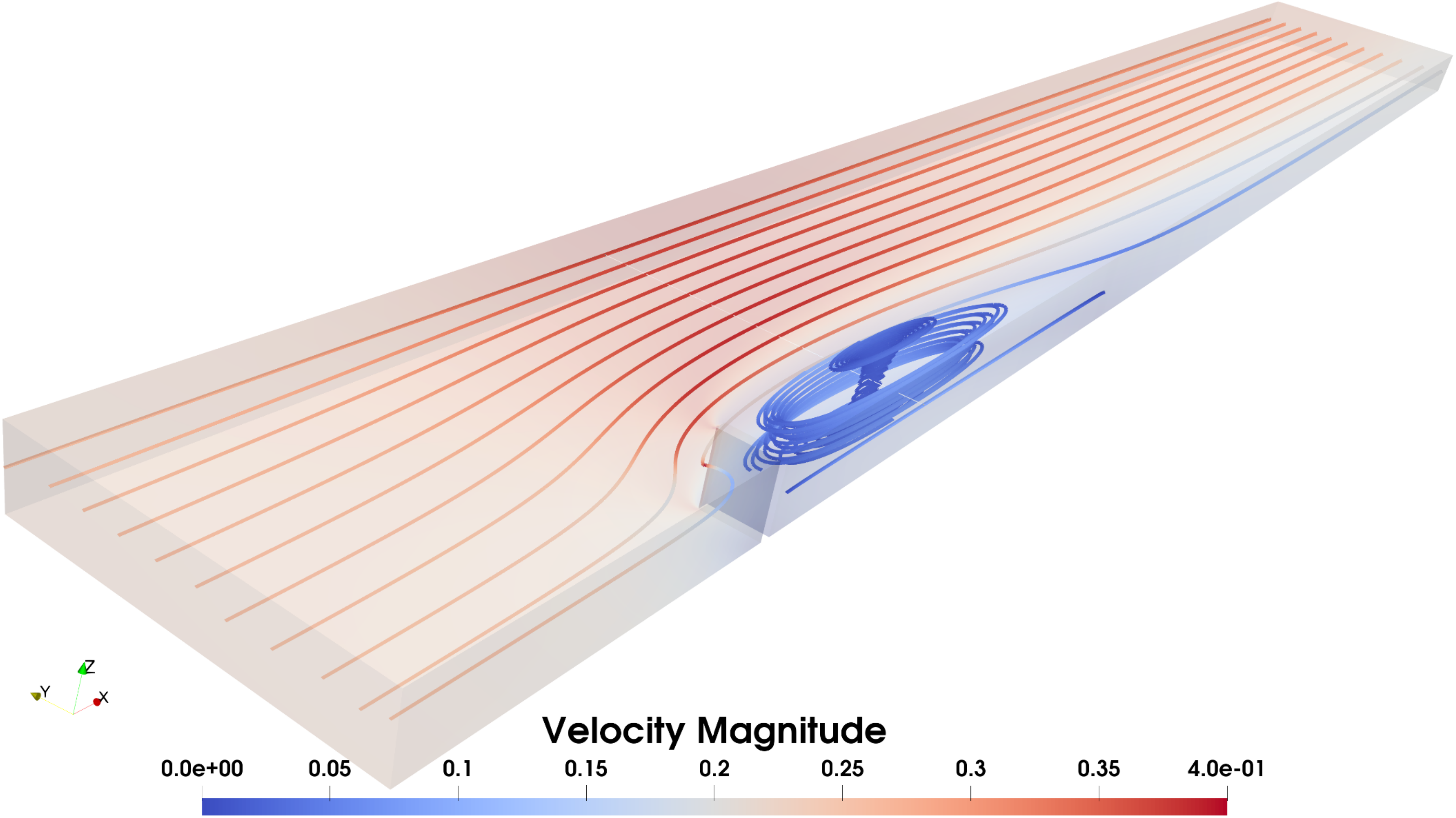
Model


2D submodel 2
3D submodel
2D submodel 1
Spur Dike
Z
Y
X
2D-3D-2D coupled model

Validation – emergent spur dike

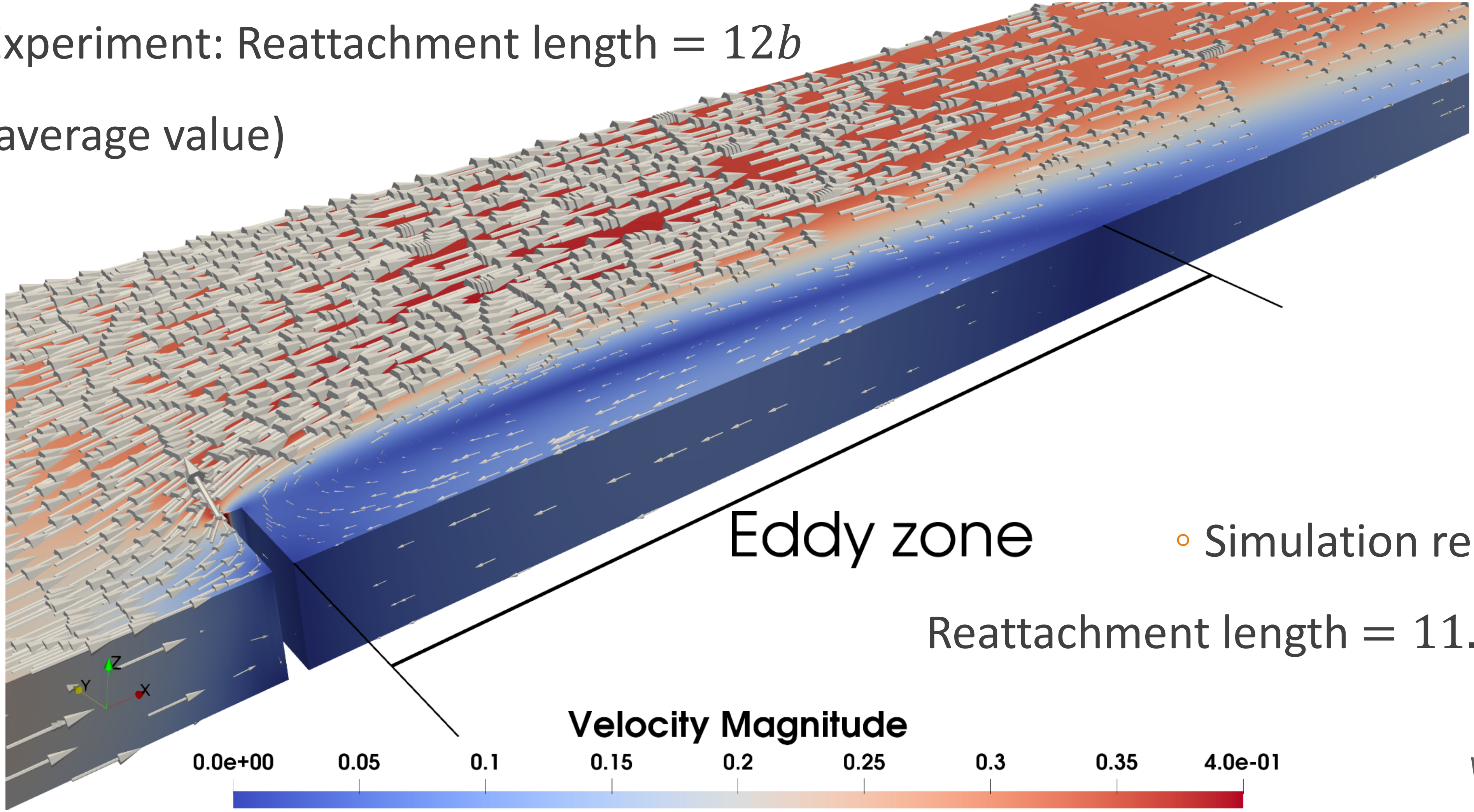
- Domain: $\Omega = (0, 37)m \times (0, 0.92)m \times (-0.189, 0)m$
- Dike location: $(14.00, 14.03)m \times (0, b = 0.152)m \times (-0.189, \infty)m$
- Boundary conditions:
  - No-flow across North and South vertical boundaries
  - Inflow from East boundary, flow rate $Q(t) = 0.0453 m^3/s$
  - Water depth fixed at the West boundary, $h(L, y, 0) = 0.189m$
- Initial conditions:
  - Water at rest and flat water surface, i.e., $\boldsymbol{u}(x, y, z, 0) = 0 m/s$, $\eta(x, y, 0) = 0m$

Streamlines



Validation - reattachment length

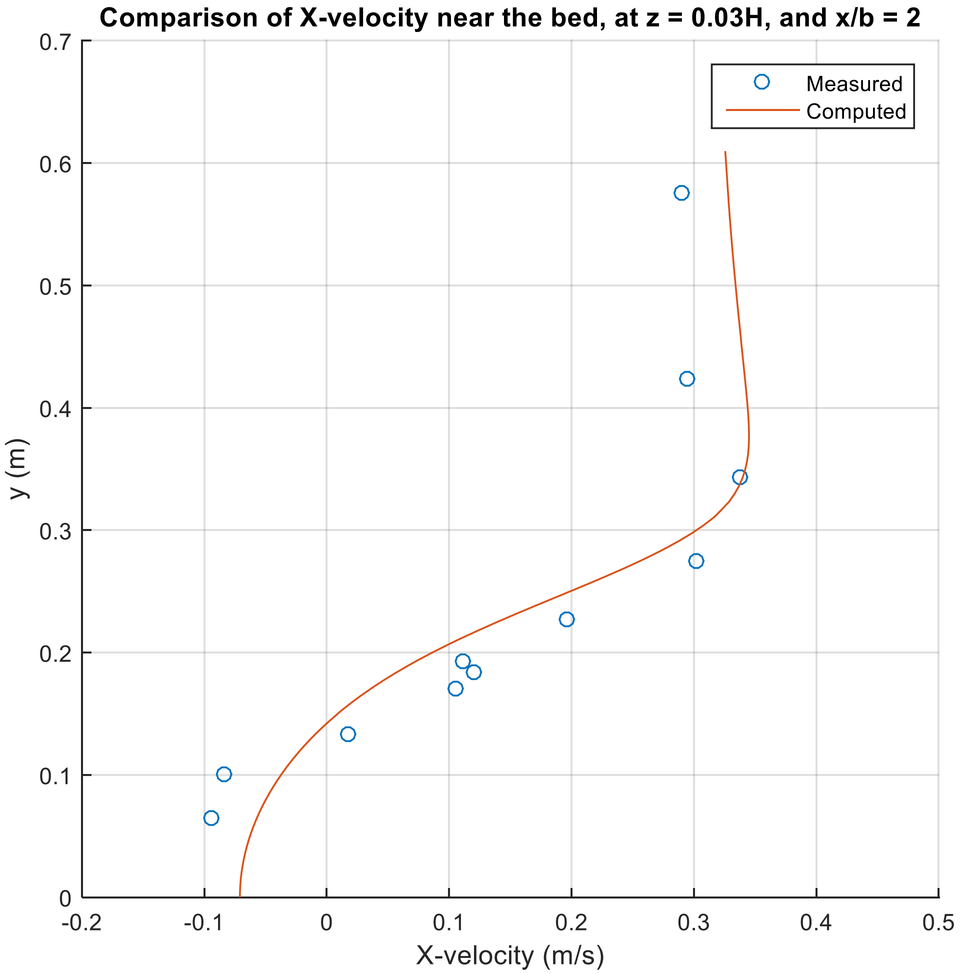
- Experiment: Reattachment length $= 12b$ (average value)

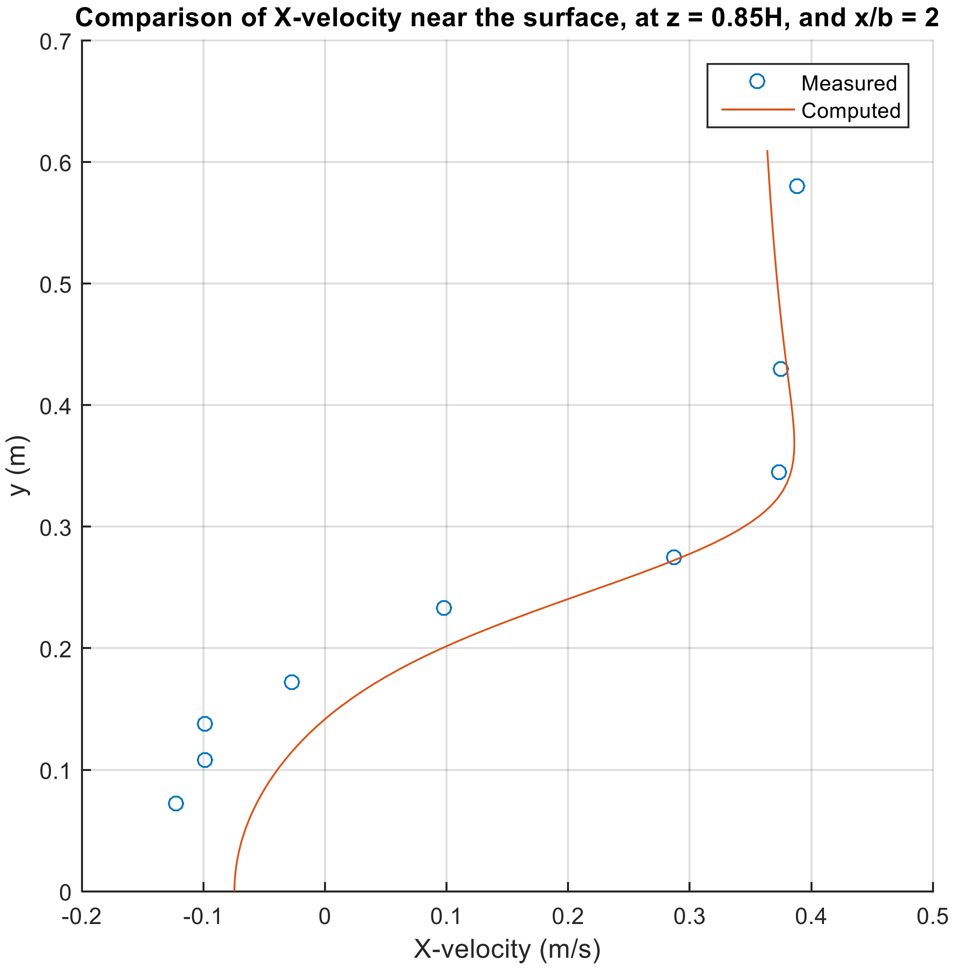


- Simulation result: Reattachment length $= 11.47b$

Velocity in m/s

Surface x-velocity profiles near the dike



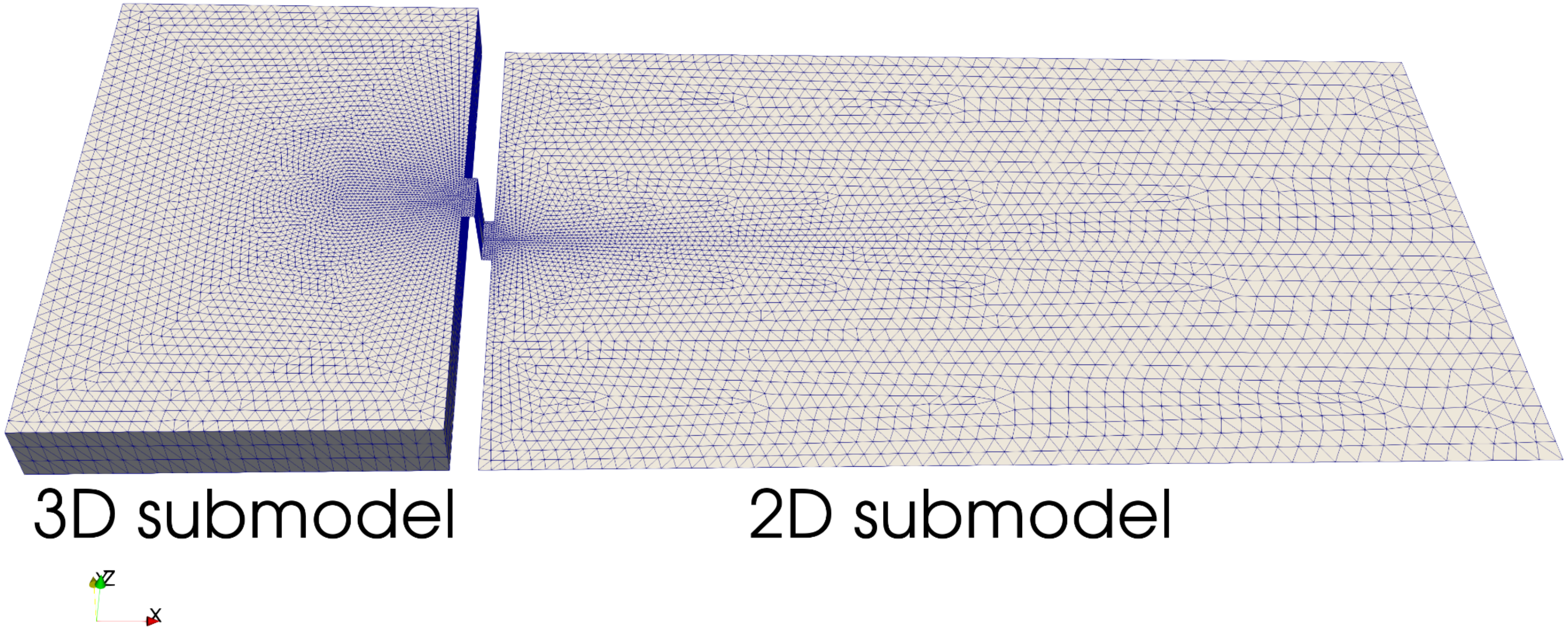


Validation

PARTIAL-BREACH DAM-BREAK SCENARIO

REFERENCE [2]

Model



3D submodel

2D submodel

2D-3D coupled model

Validation – dam break scenario

- Domain: $\Omega = (-3, 8.15)m \times (-2.15, 2.15)m$
- Dam: $(-0.15, 0.15)m \times (-2.15, 2.15)m$
- Gate: $(-0.0015, 0.0015)m \times (-0.2, 0.2)m$
- Boundary conditions:
  - No-flow across all boundaries
- Initial conditions:
  - Upstream of gate: water at rest and flat water surface with depth $h(x, y, 0) = 0.5m$
  - Downstream of gate: dry bed

Dam break simulation

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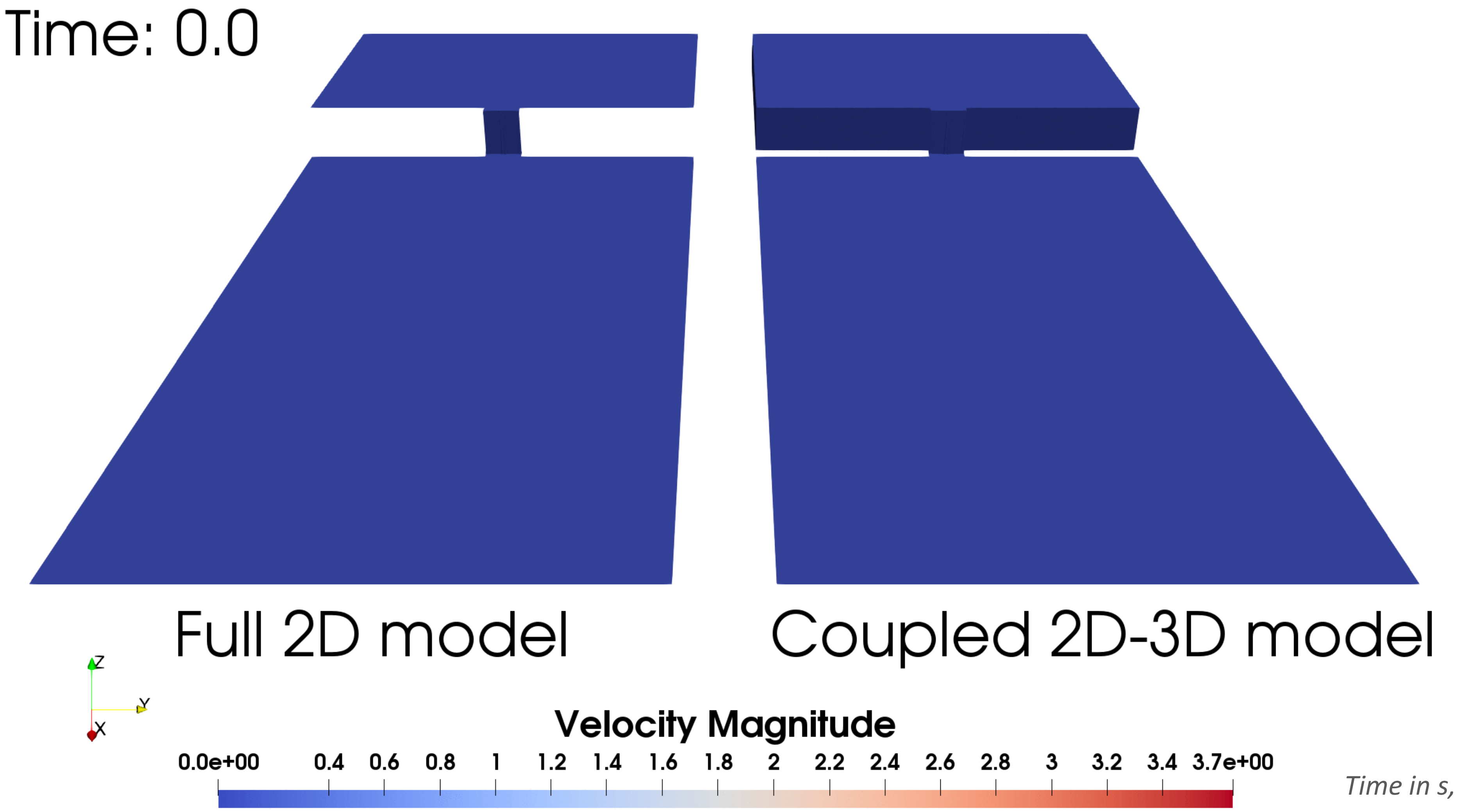
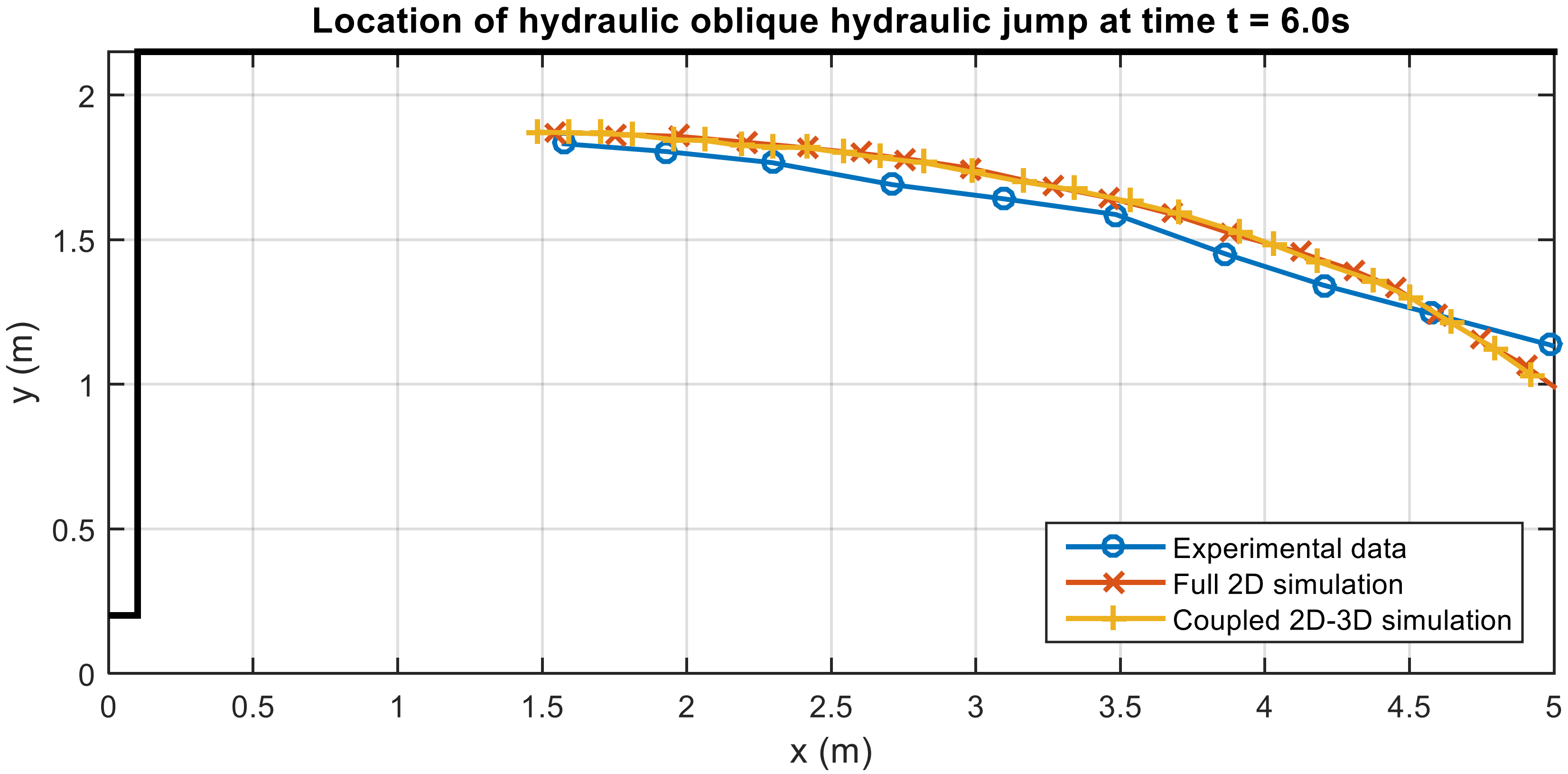


Time in s, velocity in m/s

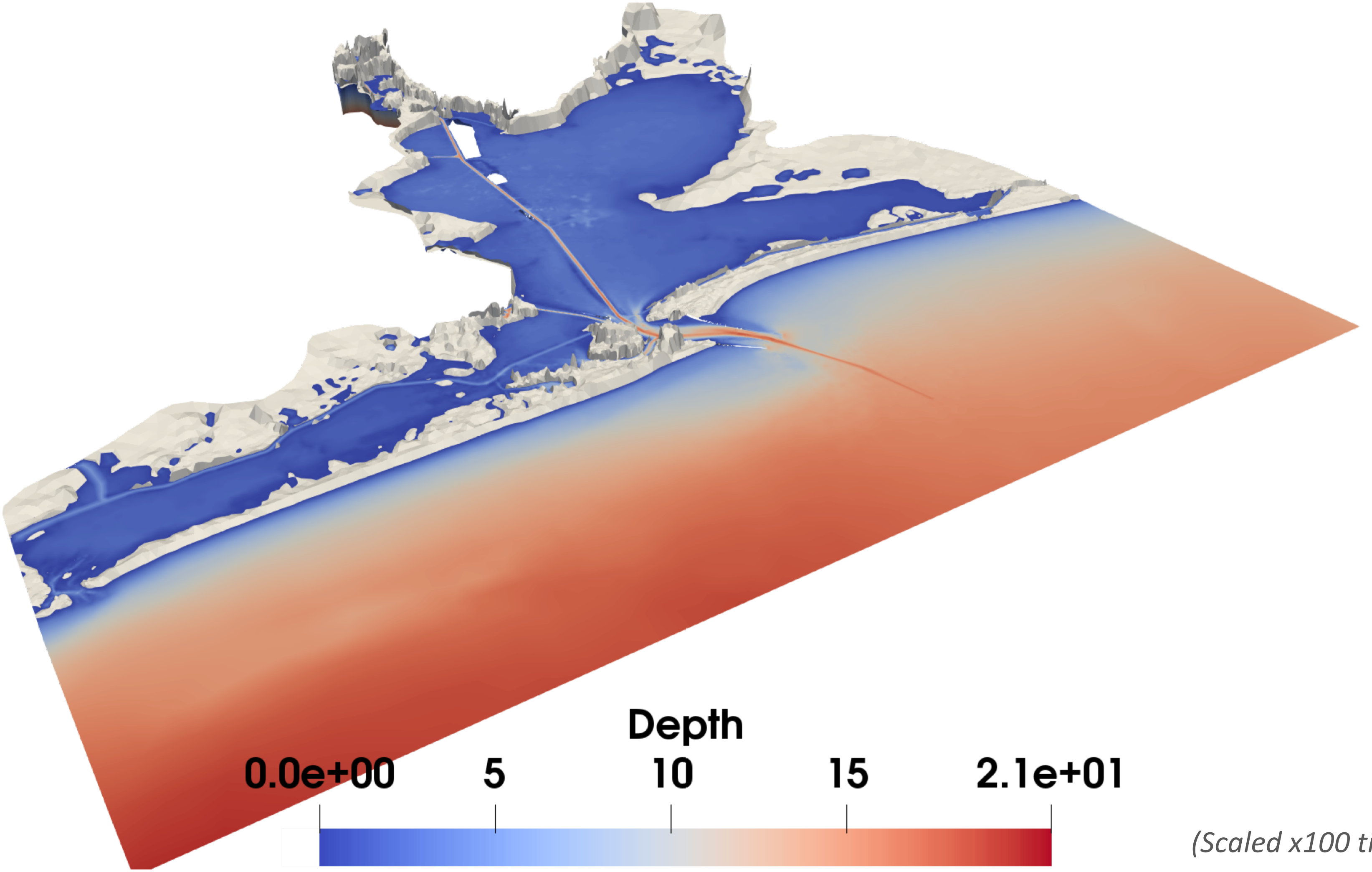
Hydraulic jump



Application

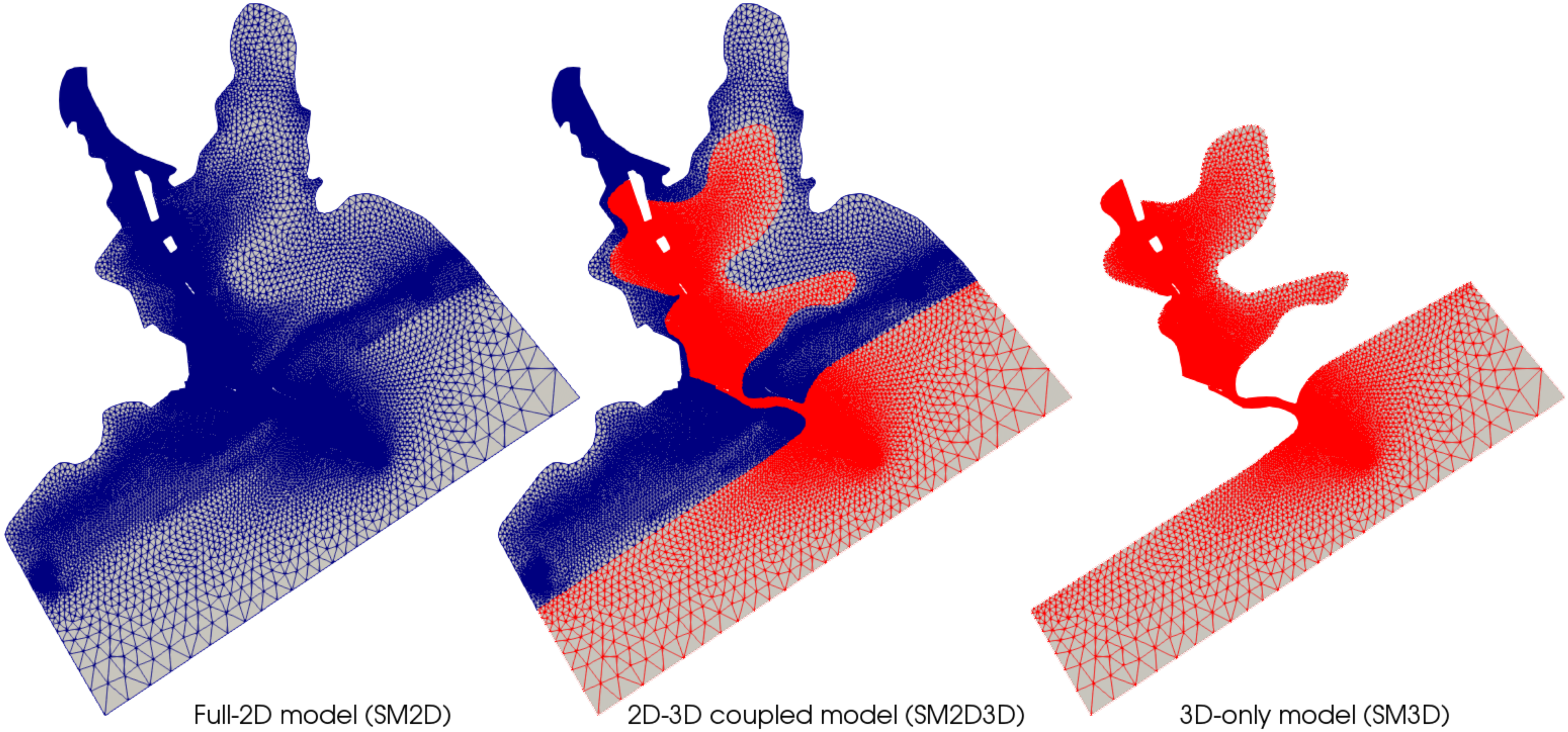
GALVESTON BAY

Galveston Bay - Bathymetry



(Scaled x100 times in the z-direction)

Galveston Bay - meshes



Galveston Bay - BC/IC

- Boundary conditions:
  - Ocean surface elevation specified: $\eta = 0.5m(1 - \cos 2\pi t/T)$, where $T = 1\ day$
  - Salinity specified at deep ocean, set to 35‰
  - No-flow everywhere else
- Initial conditions:
  - Water at rest, i.e., $\boldsymbol{u}(x, y, z, 0) = 0m/s$
  - Flat water surface, i.e., $\eta(x, y, z, 0) = 0m$
  - Salinity distribution specified

Galveston Bay – surface salinity

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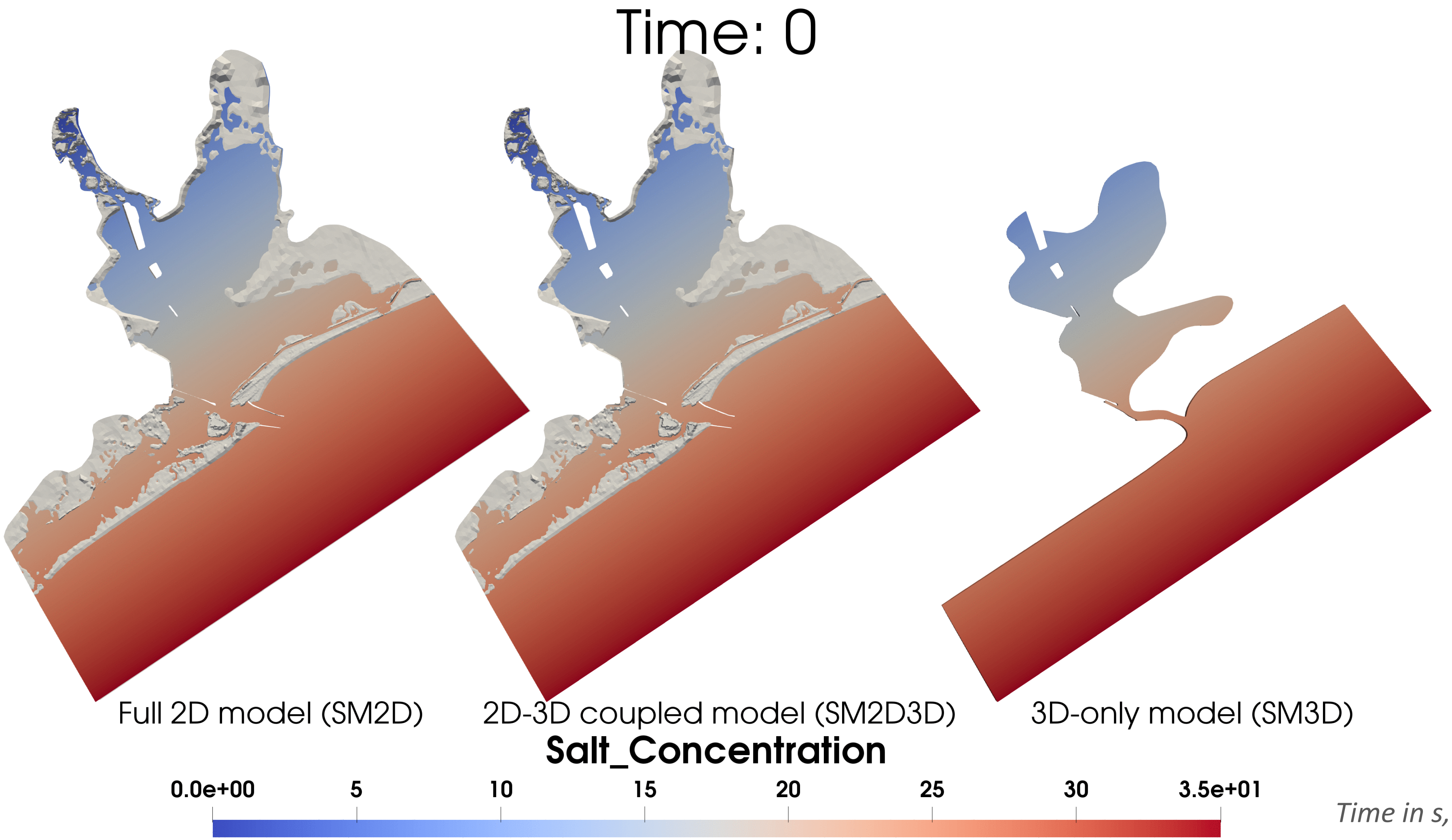

Time in s, salinity in kg/m³

Thank You!