Seamless Modeling from Creek to Ocean on Unstructured Grids

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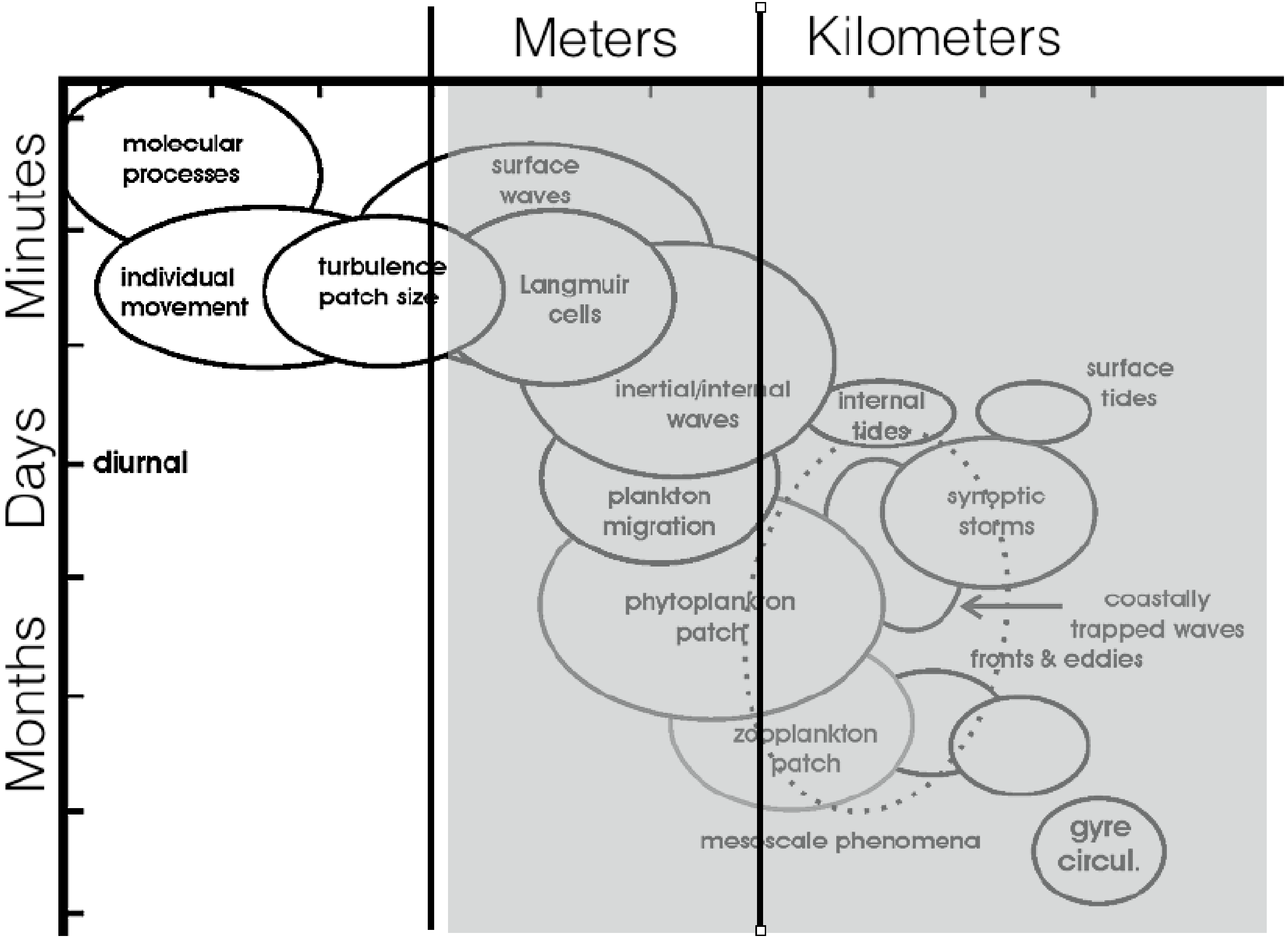
Course outline

- Day 1: Introduction to SCHISM modeling system; physical formulation; numerical formulation
- Day 2
  - Morning: simple set-up and grid generation; modelling system
  - Afternoon: tutorial for barotropic model; presentations by German colleagues
- Day 3
  - Morning: model set-up for baroclinic model; advanced topics (LSC^2 grid; eddying options)
  - Afternoon: tutorial for baroclinic model set-up

Introduction to seamless cross-scale modeling: go small, go big

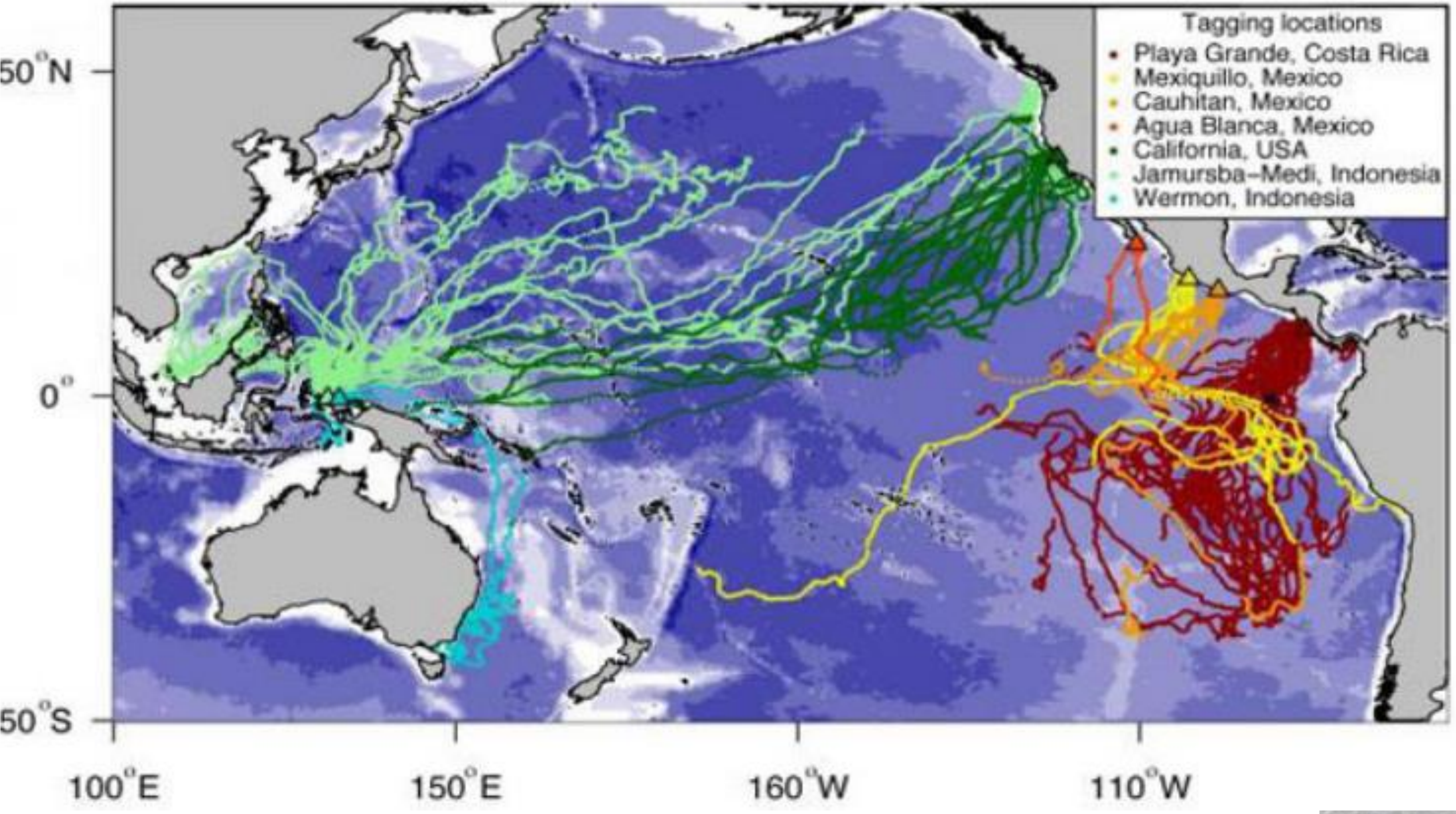
Matter of scales in GFD (Geophysical Fluid Dynamics)



Most GFD processes are multi-scale in nature

c/o: Luke van Roeke

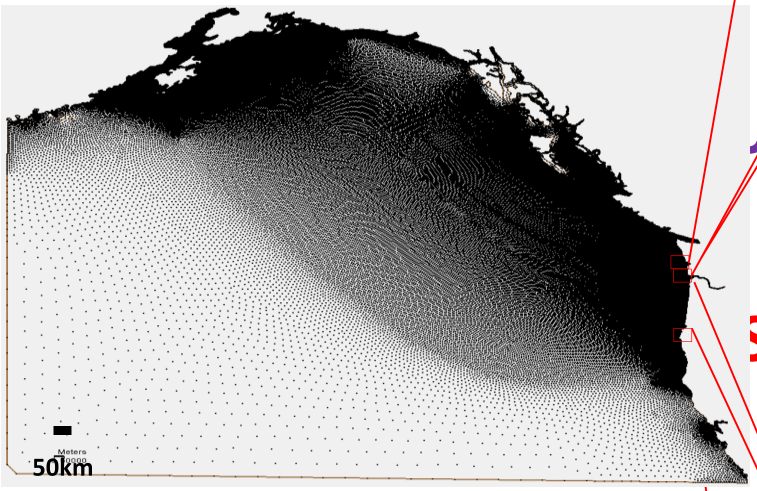
The messy reality of fish

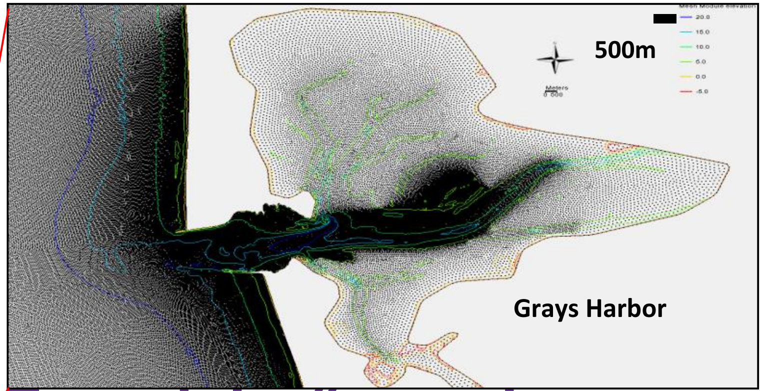


- Fish migration respects no border/boundary
- Best to be modeled using a large domain that encompasses the entire pathway

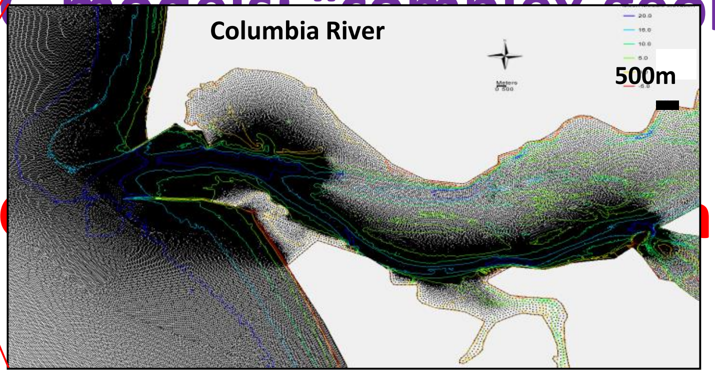
The great disappearing act of UG models

Tsunami

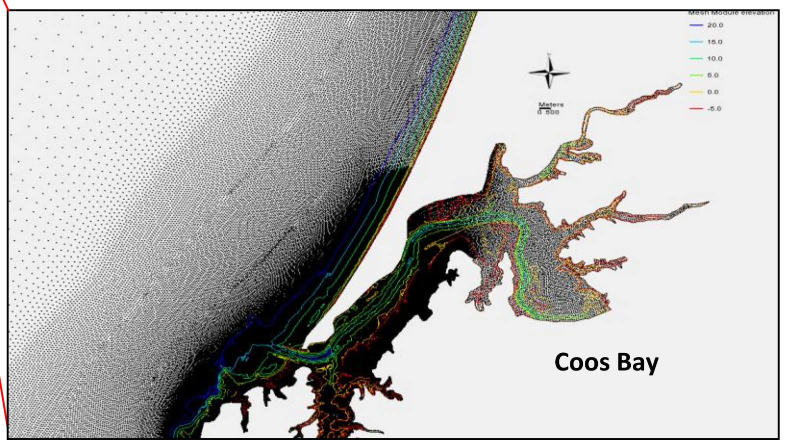


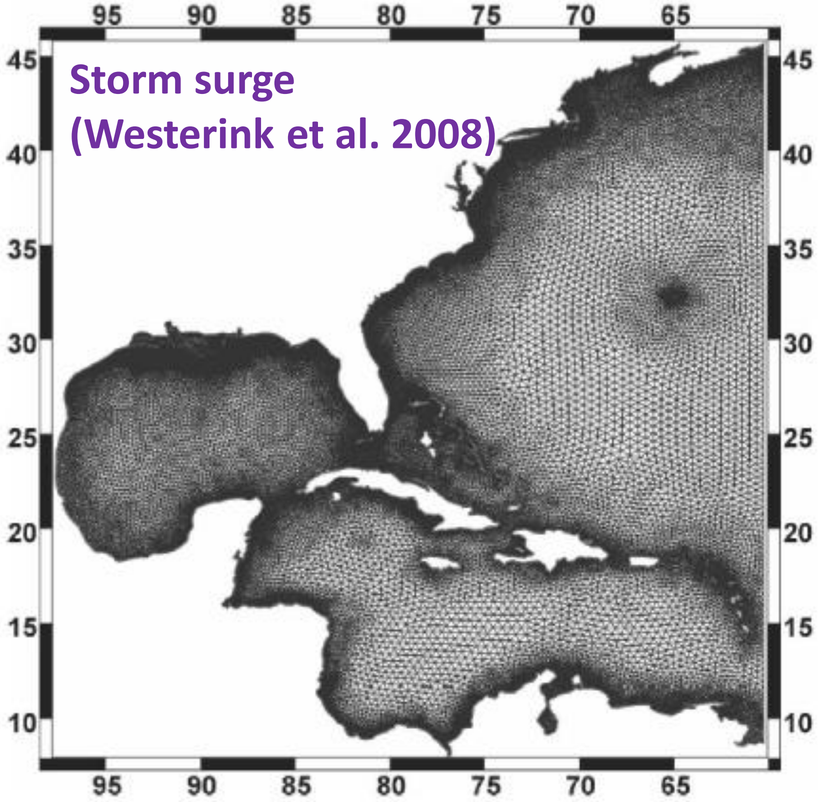


UG models: "complex geometry, sim

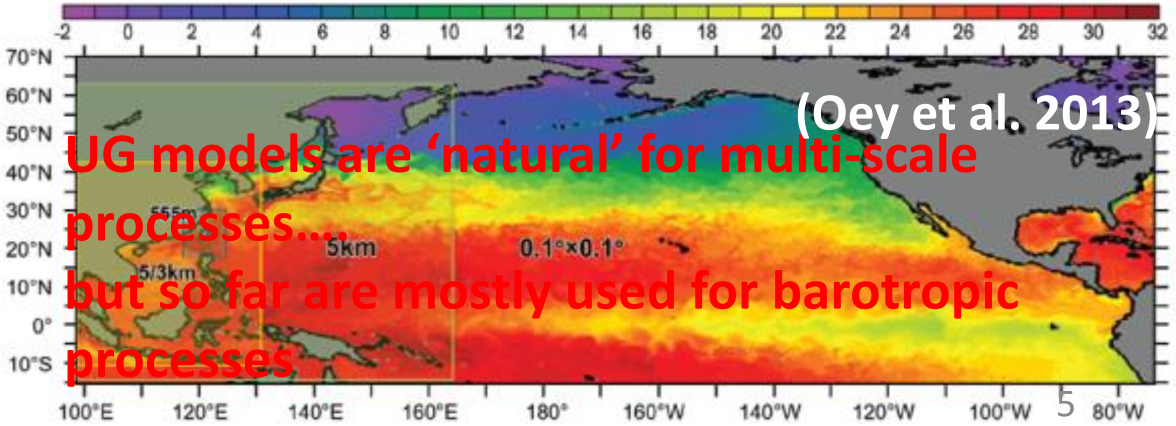


S etry, comp





Baroclinic circulation is still mostly done using SG models with grid nesting



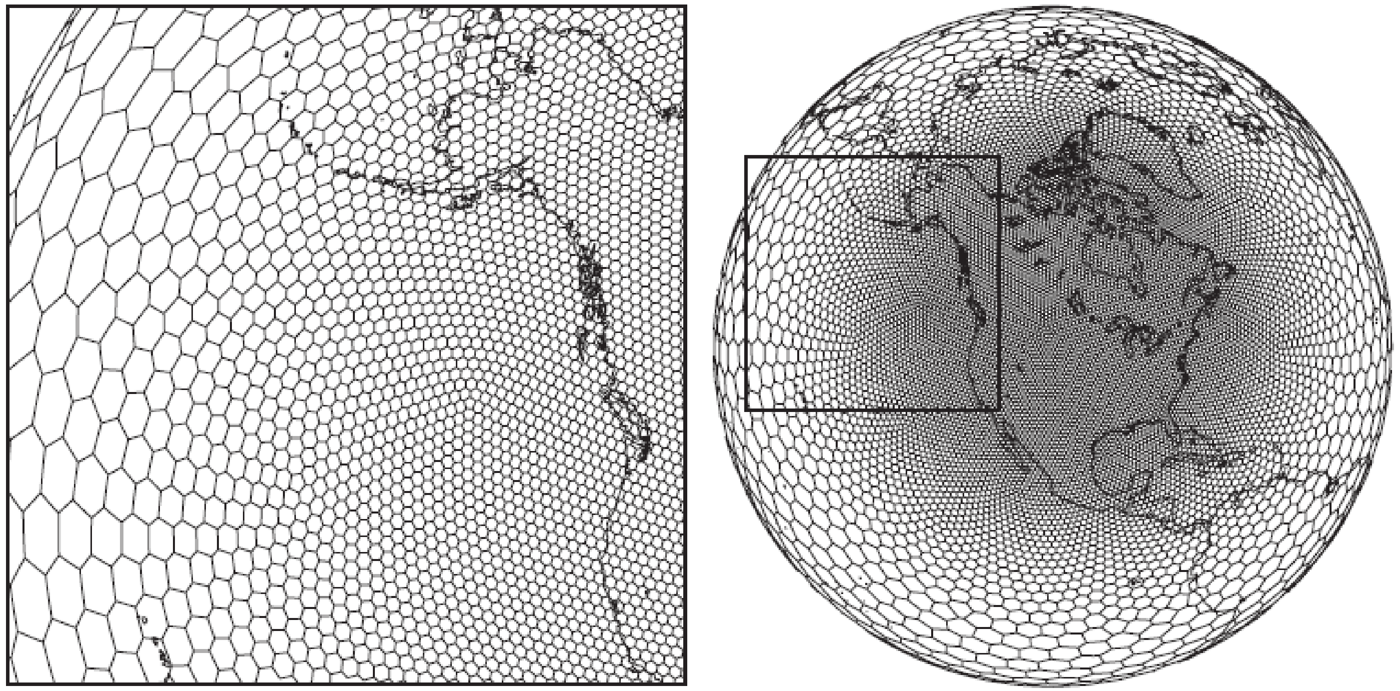
UG models are 'natural' for multi-scale processes…

but so far are mostly used for barotropic processes

Can we build a *baroclinic* unstructured-grid model from river to ocean?

Progress in the large-scale UG modeling…

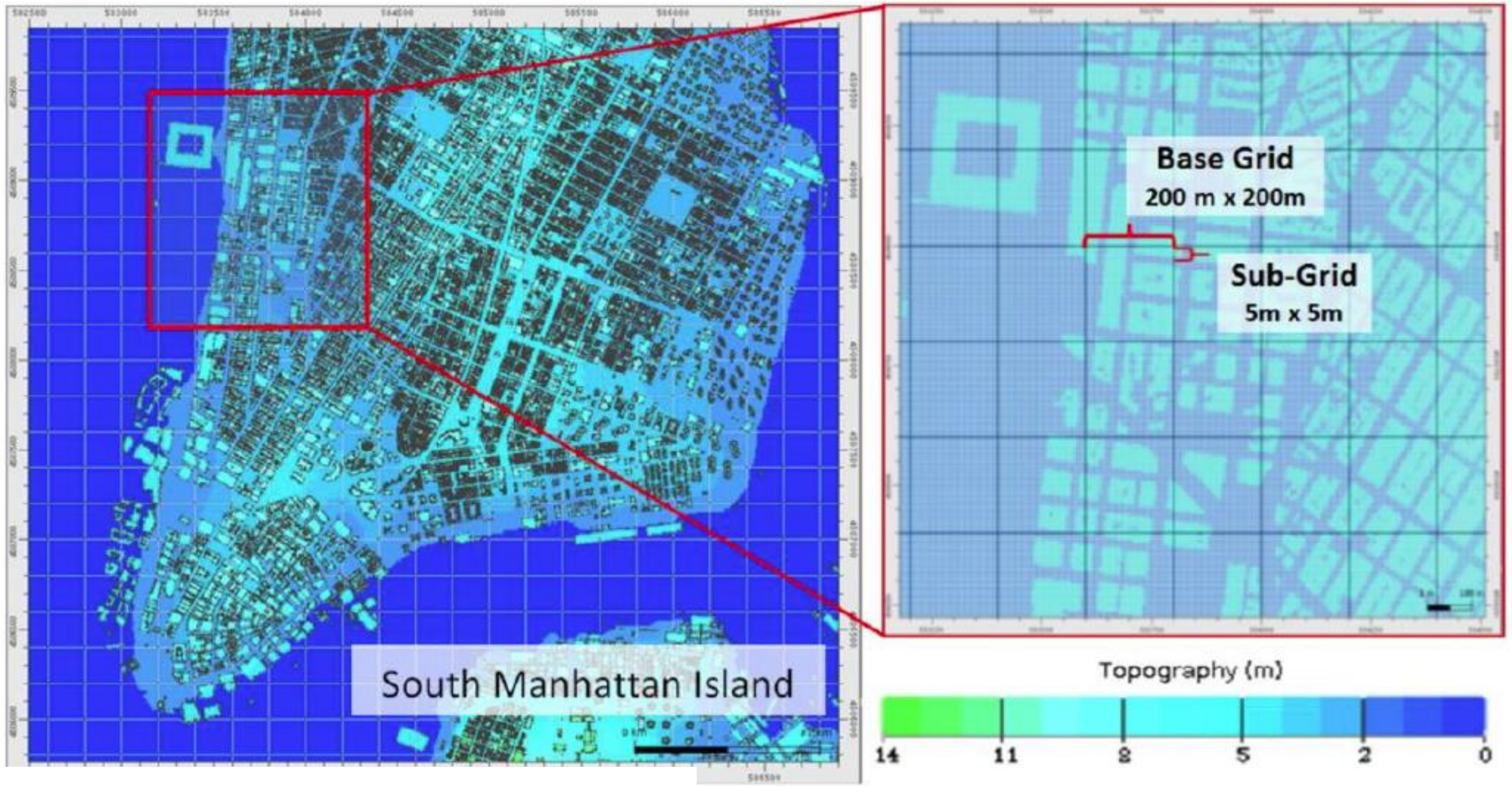
- MPAS
  - on Spherical Centroidal Voronoi Tessellations (SCVT), Arakawa-C grid (orthogonal), global
  - FV formulation (vector invariant)
  - Mostly free of spurious numerical ‘modes’
  - Ocean, seaice, landice, atmosphere…
- FESOM2
  - on hybrid triangle-quads
  - FV formulation
- ICON
  - on orthogonal triangles
  - FV formulation
- However, significant challenges remain from deep ocean into shallow waters
  - Part of these challenges are due to physics (e.g., scale differences =>different parameterizations)
  - Scale-aware parameterization is an active research area
  - However, underlying numerics are lacking even if we restrict ourselves to hydrostatic regime

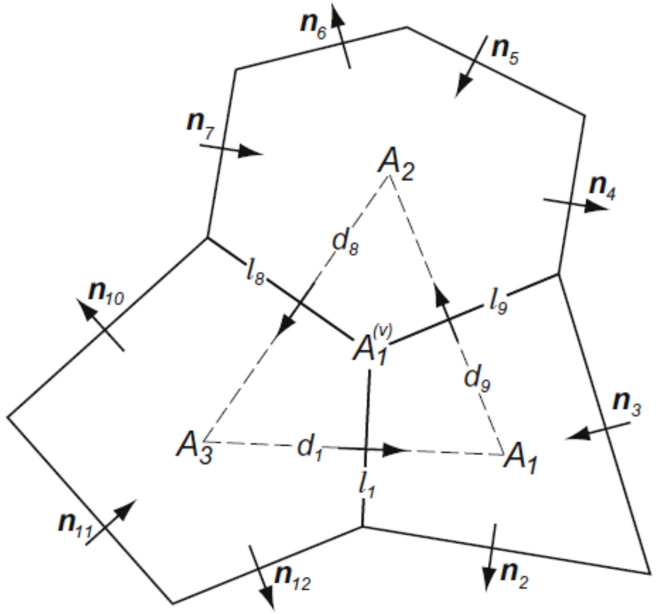


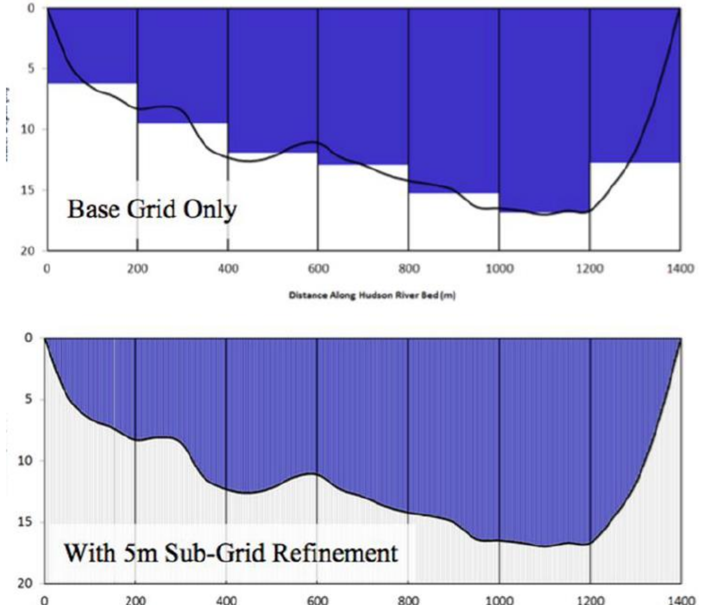
Skamarock et al. (2012)

Sister model, MPAS-OI: a nearshore component of global MPAS-Ocean

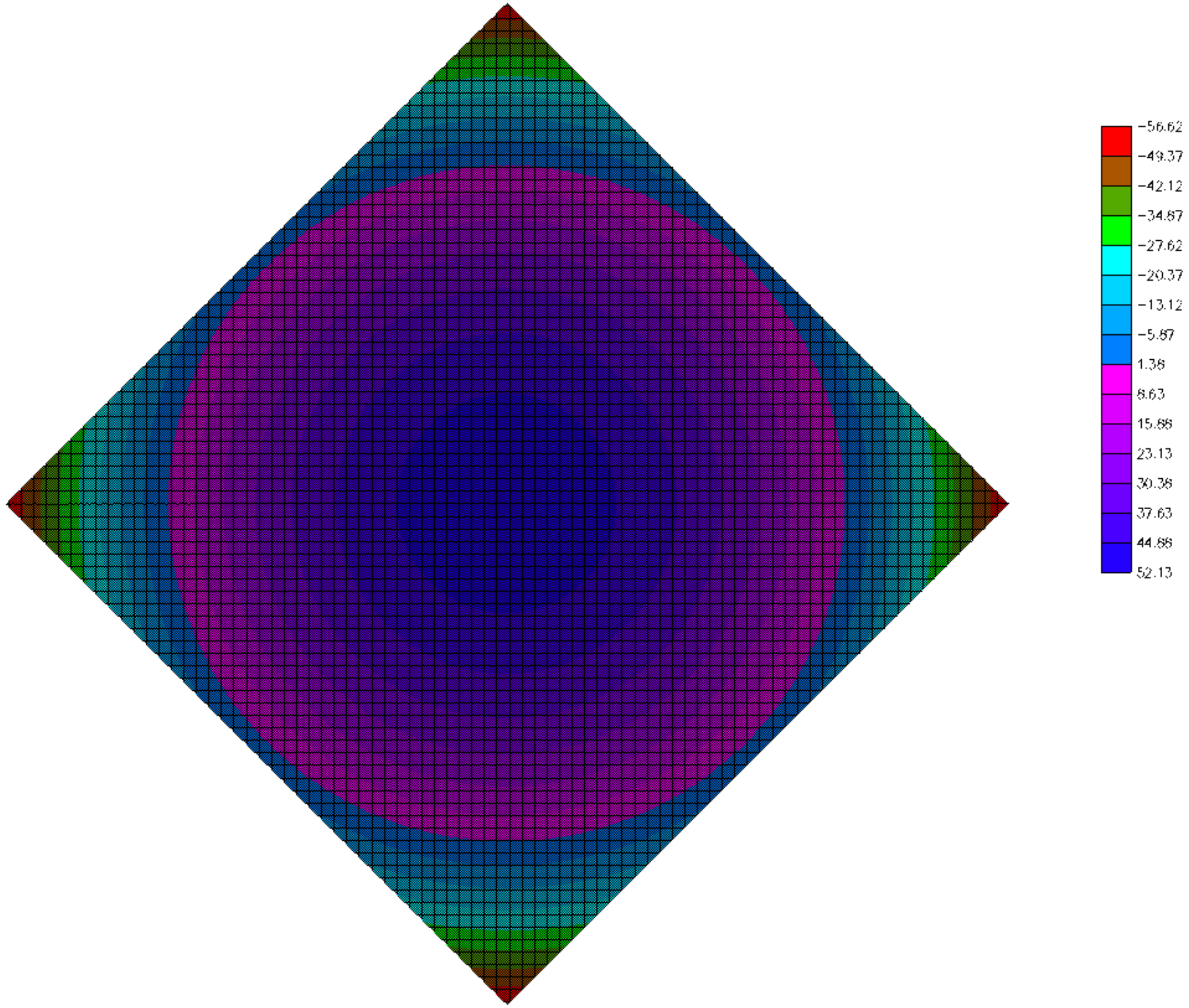
- Funded by US Dept. of Energy to bridge the gap between global ocean model and rivers
  - Both SCHISM and MPAS-OI will be fully coupled to MPAS-O
- Formulation based on the subgrid, FV solver of UnTRIM (Casulli 2009), but with MPAS' approach for conservation of mass, energy and potential vorticity (Thuburn et al. 2009)
- The core is a semi-implicit, nonlinear solver for coupled continuity and momentum equation
  - The convergence of the nonlinear solver is always guaranteed
  - Enables mass conservative wetting and drying with any time step used
- Subgrid capability for better representation of bathymetry



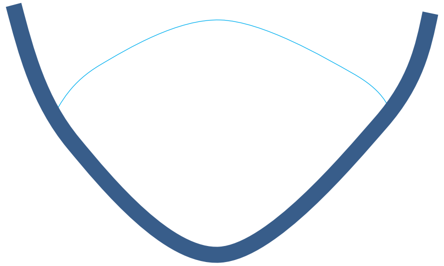


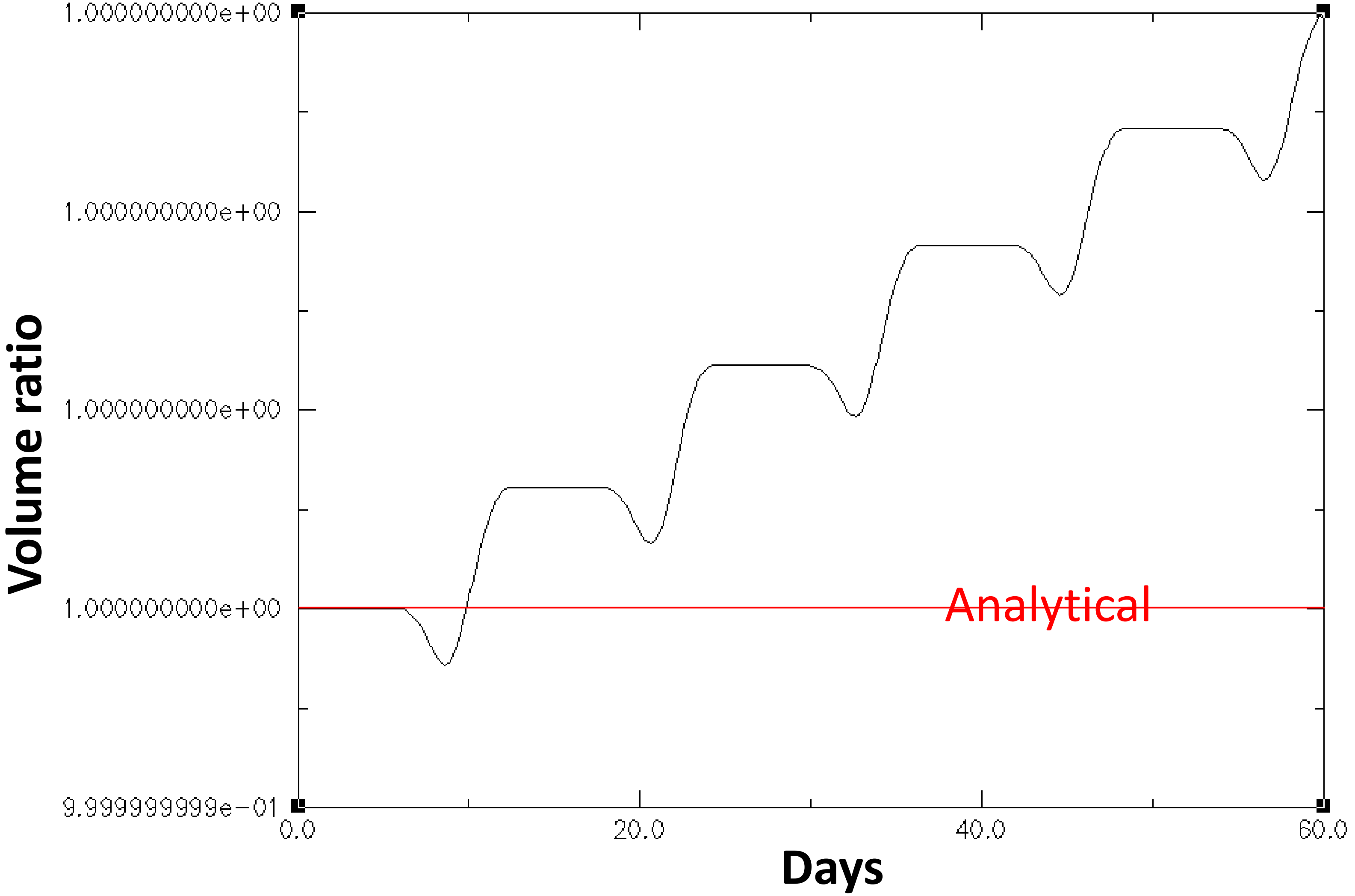


MPAS-OI: inundation test on a parabolic bowl



Rotated symmetric bowl to test robustness

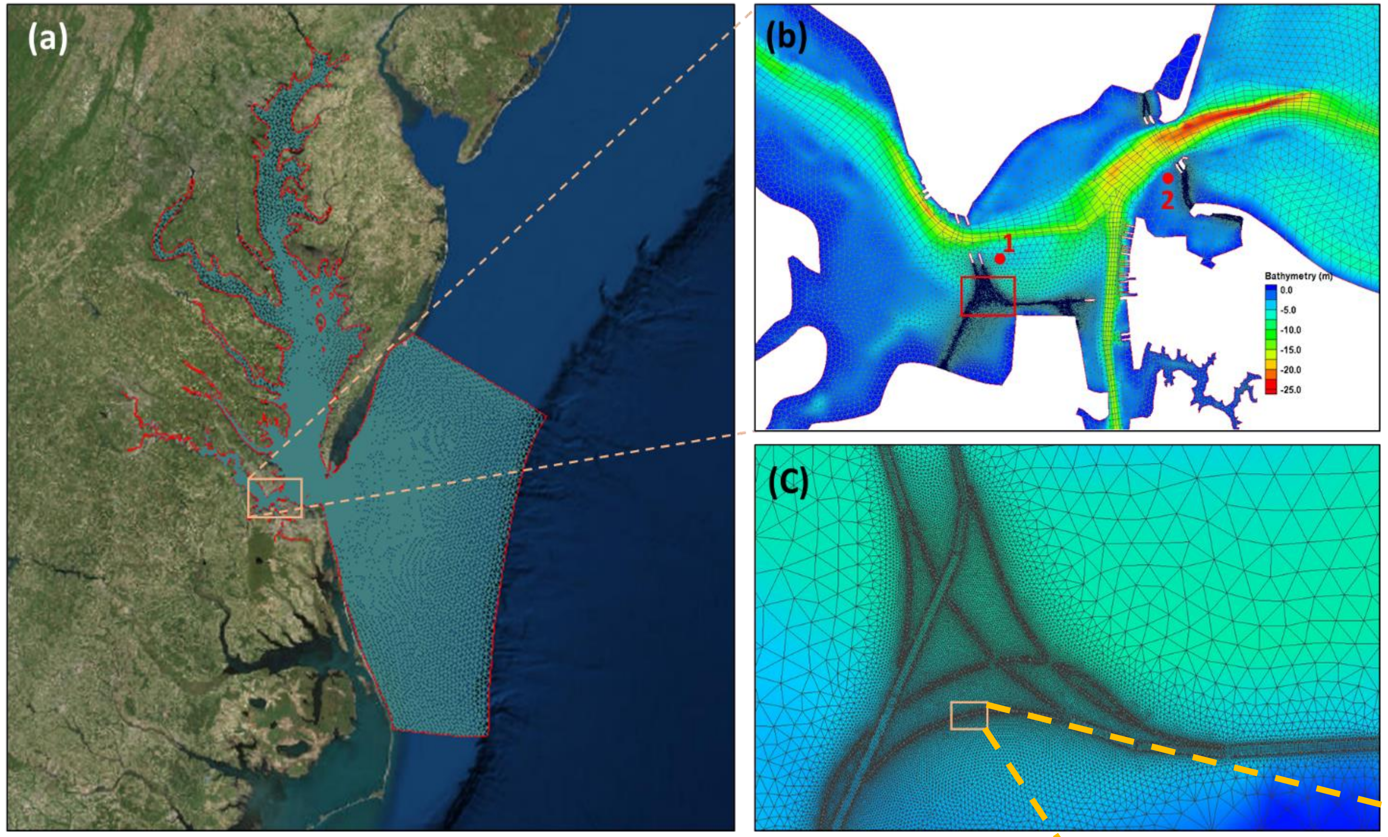




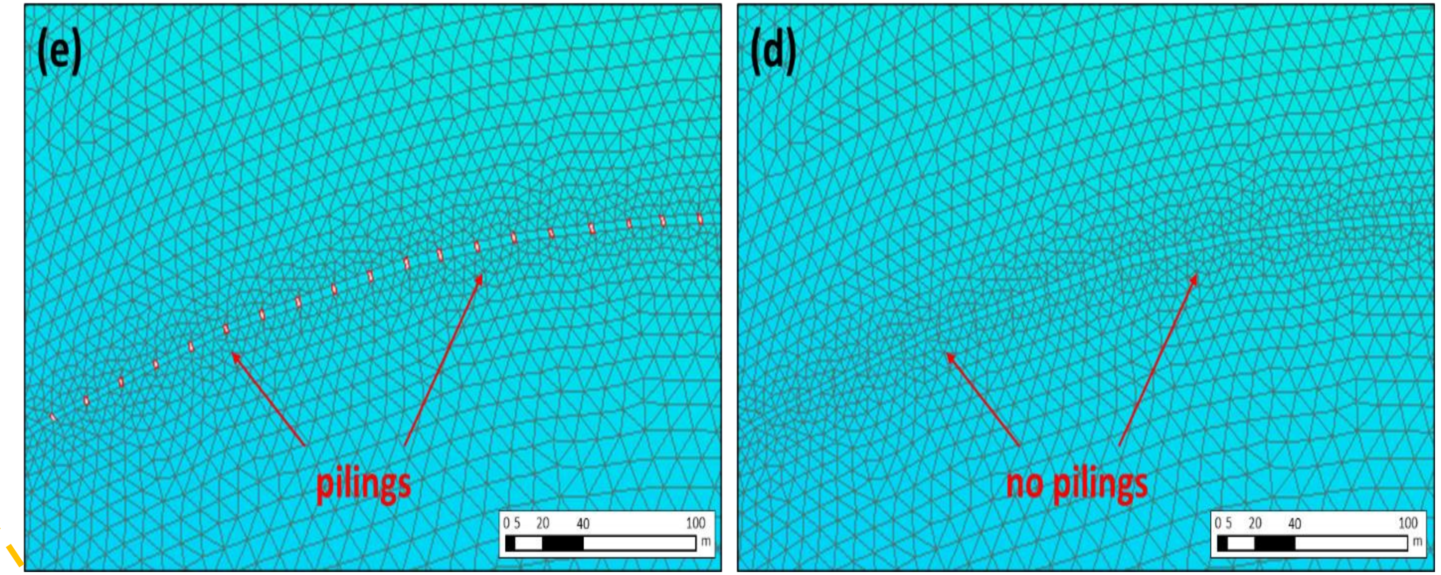
Seamless cross-scale modeling with SCHISM

San Francisco Bay & Delta

Seamless cross-scale modeling with SCHISM



- Bridge crossings on James River, Chesapeake Bay
- Bridge pilings of 1-2m in diameter
- ~1840 pilings located in the middle of salt intrusion path



SCHISM: Semi-implicit Cross-scale Hydroscience Integrated System Model

- A derivative product of SELFE v3.1, distributed with open-source Apache v2 license
  - Substantial differences now exist between the two models
  - Free svn access to release branch for general public

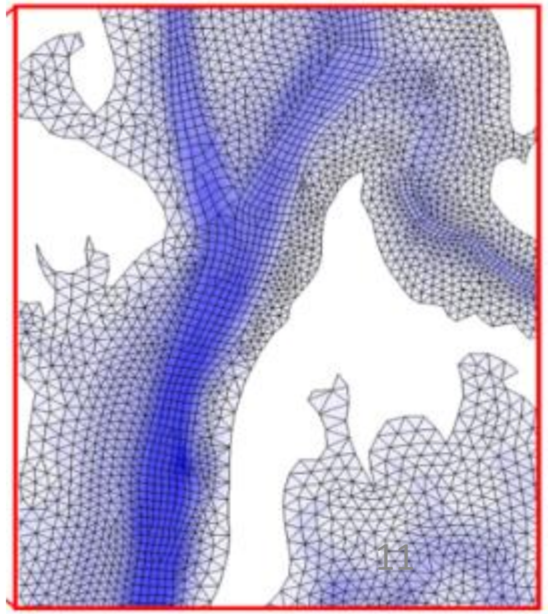
SELFE

- Galerkin finite-element and finite-volume approach: ***generic*** unstructured triangular grids
  - ELCIRC (Zhang et al. 2005), UnTRIM (Casulli 1990; 2010), SUNTANS (Fringer 2006): finite-difference/volume approach →orthogonal grid
  - Hydrostatic or non-hydrostatic options
- **Semi-implicit** time stepping: no mode splitting → large time step and no splitting errors
- **Eulerian-Lagrangian** method (ELM) for momentum advection → more efficiency & robustness
- Major differences from SELFE v3.1

SCHISM

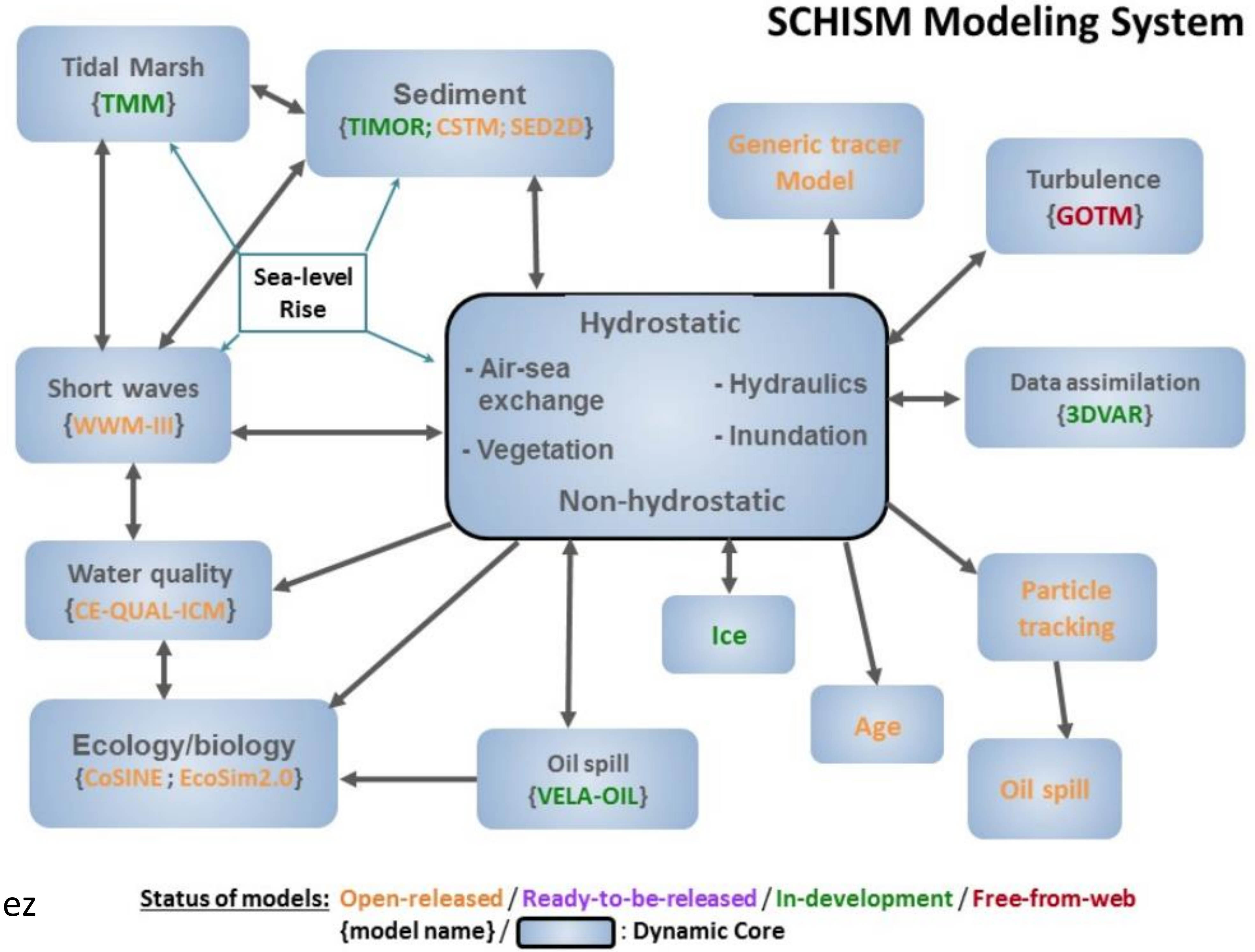
  - Apache license
  - Mixed grids (tri-quads)
  - **LSC^2** vertical grid (Zhang et al. 2015)
  - Implicit TVD transport (**TVD^2**) & WENO^3
  - Higher-order ELM with ELAD
  - Bi-harmonic viscosity

Eddying regime (Zhang et al. 2016)



visit schism.wiki

SCHISM



c/o Karinna Nunez

Why SCHISM?

- Major differentiators from peer models
  - No bathymetry smoothing or manipulation necessary: faithful representation of bathymetry is key in nearshore regime (Ye et al. 2018, OM)
  - Implicit FE solvers → superior stability → very tolerant of bad-quality meshes (at least in non-eddying regime)
  - Accurate yet efficient: implicit + low inherent numerical dissipation; flexible gridding system
  - Need for grid nesting is minimized
- Well-benchmarked; certified inundation scheme for wetting and drying (NTHMP)
- Fully parallelized with domain decomposition (MPI+openMP) with strong scaling (via PETSc solver)
- Operationally tested and proven (DWR, EPA, NOAA, CWB …)
- Open source, with wider community support (210+ registered user groups)

Underlying numerics matter!

- **Explicit** ‘mode-splitting’ models
  - Solves the hydrostatic equations in external and internal mode separately (splitting errors)
  - Easy to implement (with possible exception of filters), and well understood
  - 99% of the existing models
  - Subject to CFL constraints (severe in shallow water)
  - Structured and unstructured grids
  - Excellent parallel scaling
- **Implicit** models: the *cross-scale* models?
  - Solve the HS equations in one time step (no mode splitting errors)
  - Difficult to formulate (and parallelize)
  - No CFL constraints; superior stability
  - Mostly on unstructured grids
  - Parallel scaling not as good
  - Numerical diffusion needs to be carefully controlled

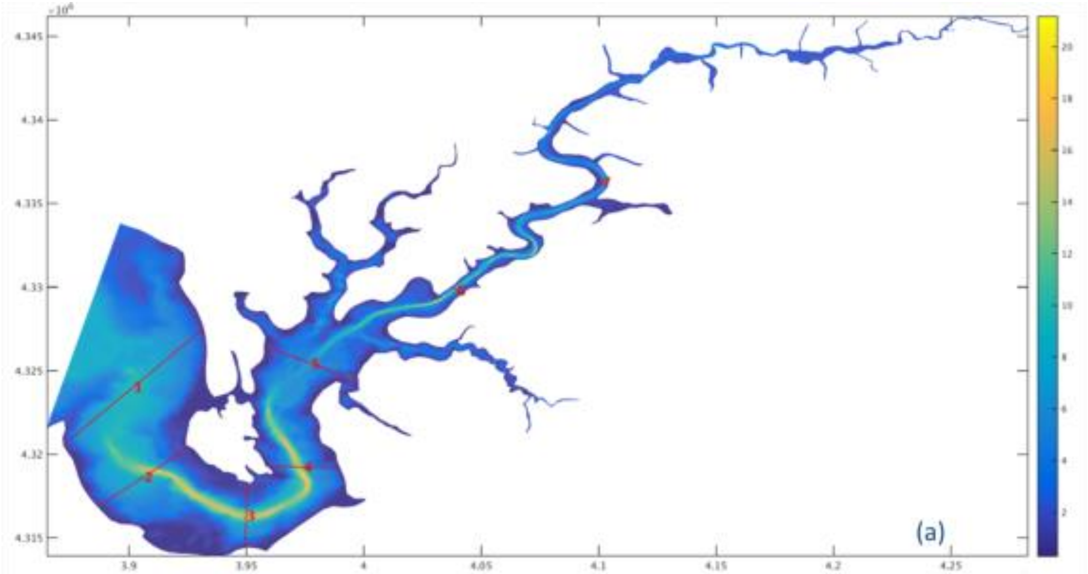
- BOM (Bergen Ocean Model)
- COHERENS (COupled Hydrodynamical Ecological model for REgioNal Shelf seas
- Dartmouth Circulation Models for the Gulf of Maine and Georges Bank
- DieCAST (Dietrich Center for Air Sea Technology)
- ECBILT/CLIO and ECBILT
- ECOM-si: Estuarine, Coastal and Ocean Model (semi-implicit)
- ELCIRC (Eulerian-Lagrangian CIRCulation)
- FMS (Flexible Modeling System)
- FRAM (Fine Resolution Antarctic Model)
- FVCOM (Finite Volume Comunnity Ocean Model)
- GMODEL
- GOTM (General Ocean Turbulence Model)
- HIM (Hallberg Isopycnal Model)
- HOPE (Hamburg Ocean Primitive Equation Model)
- HOPS (Harvard Ocean Prediction System)
- HYCOM (Hybrid Coordinate Ocean Model)
- LOAM (Lamont Ocean-AML Model)
- Ocean Dynamics and Prediction Branch: LSM (Large Scale Models)
- MICOM (Miami Isopycnic Coordinate Ocean Model)
- MITgcm (MIT General Circulation Model)
- The GFDL Modular Ocean Model (MOM)
- NCOM (NCAR CSM Ocean Model)
- NEMO (Nucleus for European Modelling of the Ocean) formerly OPA
- NLOM (Navy Layered Ocean Model)
- OCCAM (Ocean Circulation and Climate Advanced Modelling Project)
- OCCOMM
- OPNML (Ocean Processes Numerical Modeling Laboratory)
- PEQMOD (Primitive EQuation Model)
- POCM (Parallel Ocean Circulation Model)
- POGCM (Poseidon Ocean General Circulation Model)

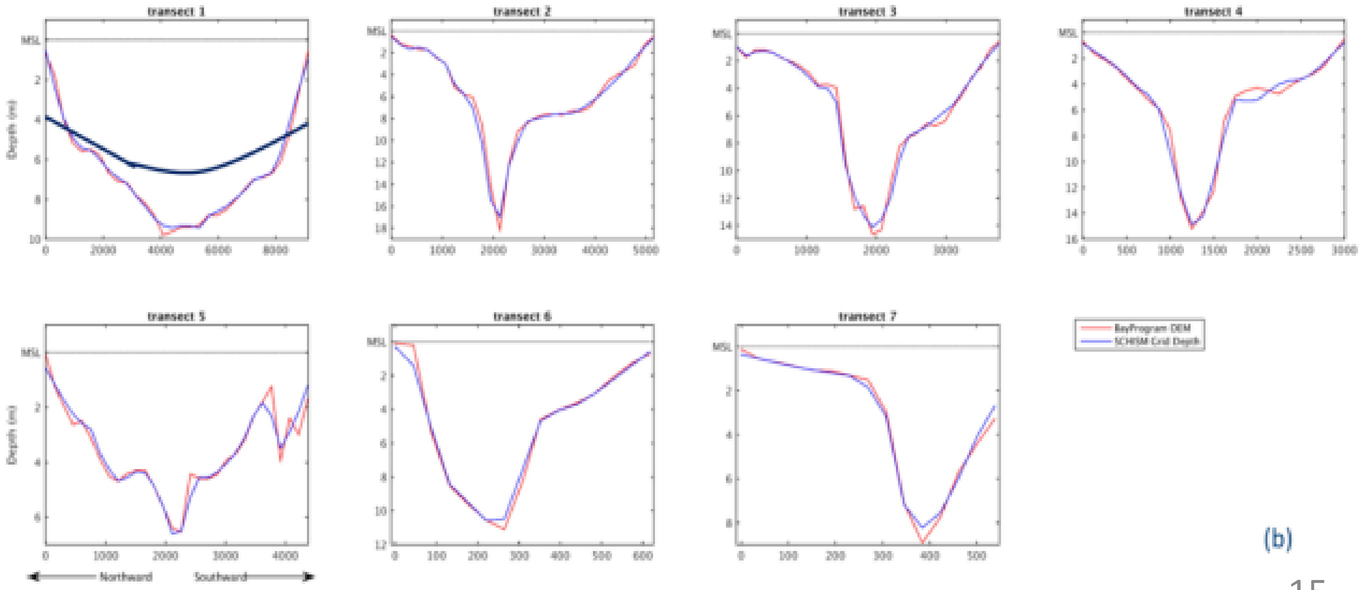
UnTRIM **SUNTANS** **ELCIRC**
SHYFEM **ECOM-si**
SELFE/SCHISM

In short, SCHISM is a very different type of beast from other conventional models, which has implications for usage! *Unlearning* prior experience with other models is required!

Underlying bathymetry *matters even more*: respect the bathymetry!

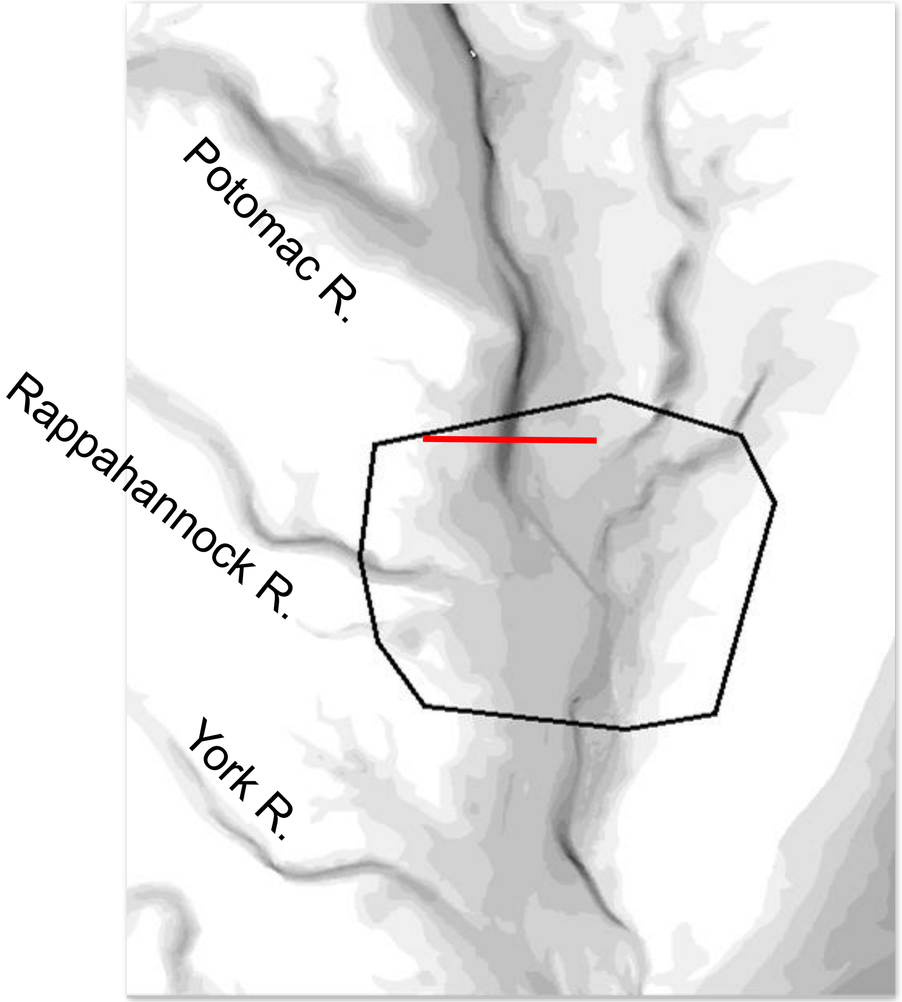
- **Faithful representation of bathymetry is of fundamental importance especially in nearshore**
- **Two types of bathymetric errors**
  - **Type I: Finite grid resolution; bathymetry survey errors; smoothing of DEM for unresolved sub-grid scales - not a convergence issue**
  - **Type II: Smoothing or other manipulations (e.g. as in terrain-following coordinate models) - a divergence error as refining grid generally makes it worse!**
- **SCHISM's representation of the bathymetry is piece-wise linear**
- **Very skew elements are allowed in non-eddying regime; implicit scheme guarantees stability**
  - **Facilitates feature-tracking in grid generation**
- **There is no need for bathymetry smoothing to stabilize the model**



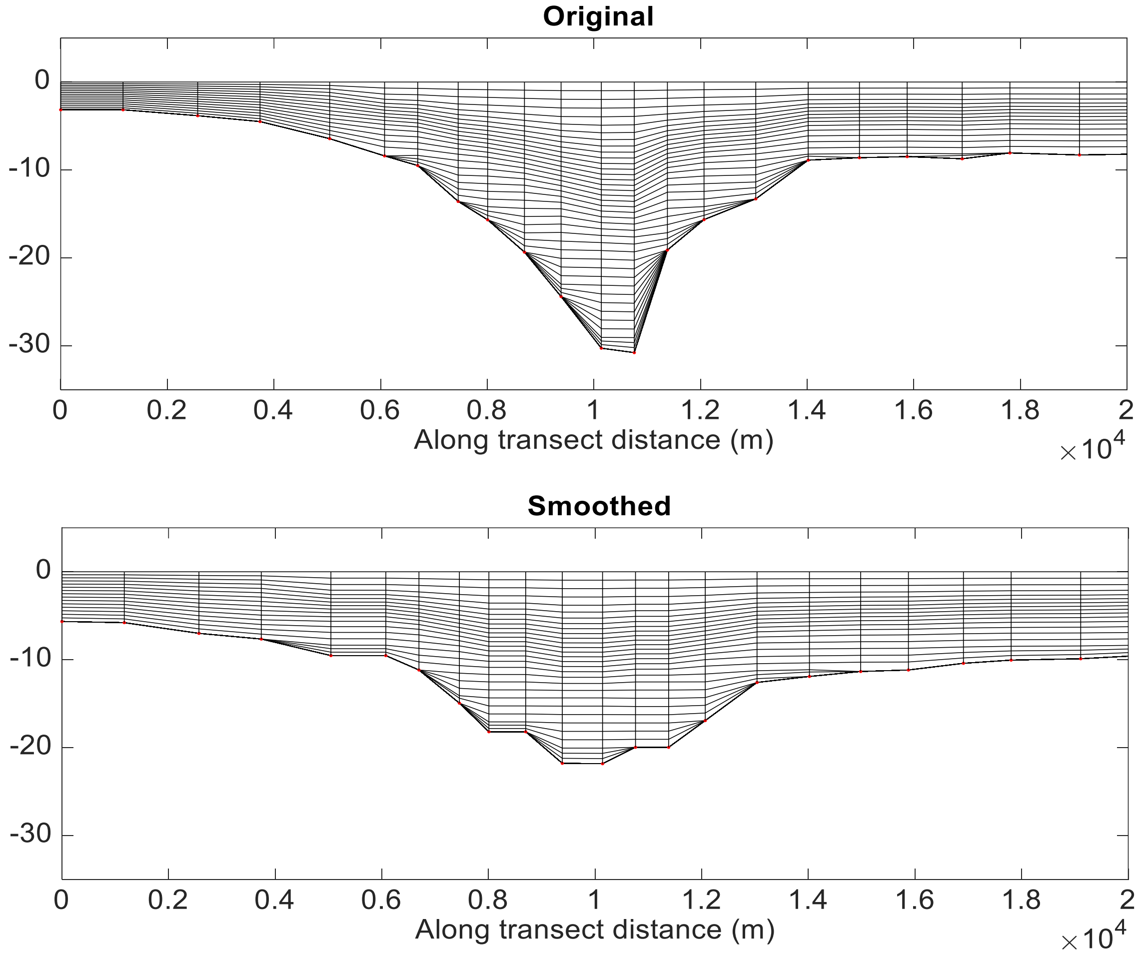


Detrimental effects of bathymetry smoothing

Smoothing in a critical region where the center channel constricts and bends, with multi-channel configurations



Cross-channel transect with deep center channel

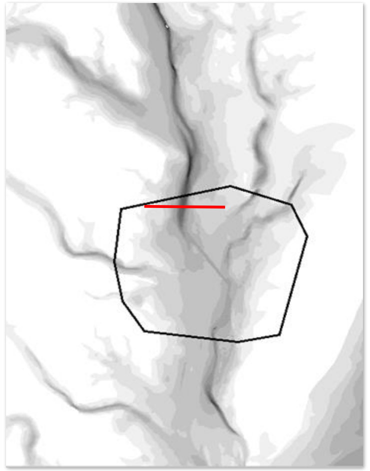


Volume is conserved during smoothing

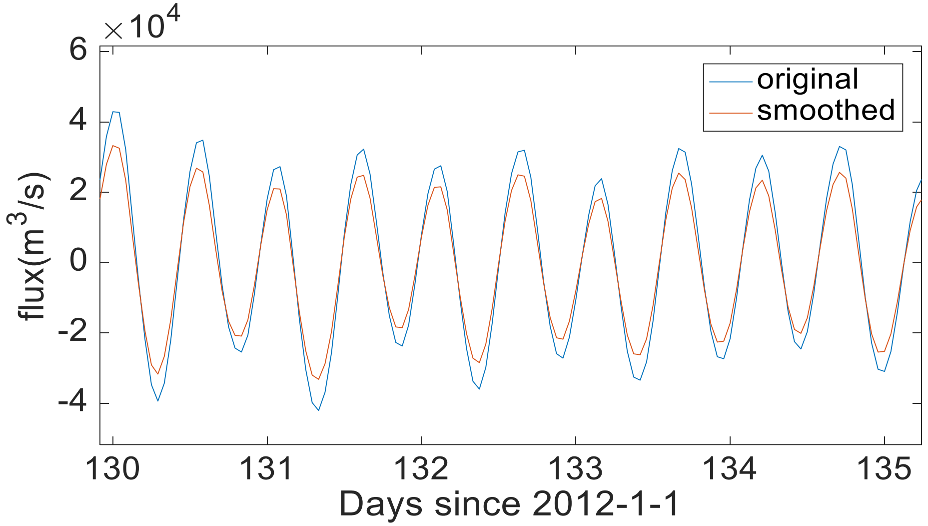
Ye et al. (2018)

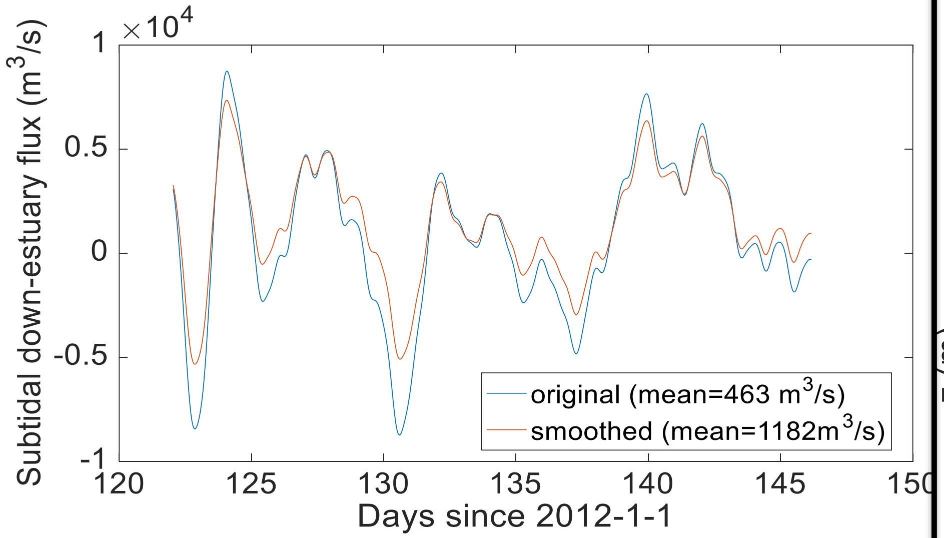
Bathymetry smoothing effectively masks true numerical dissipation!

Focusing on the cross transect on the west part of the main stem, the smoothing effects include:



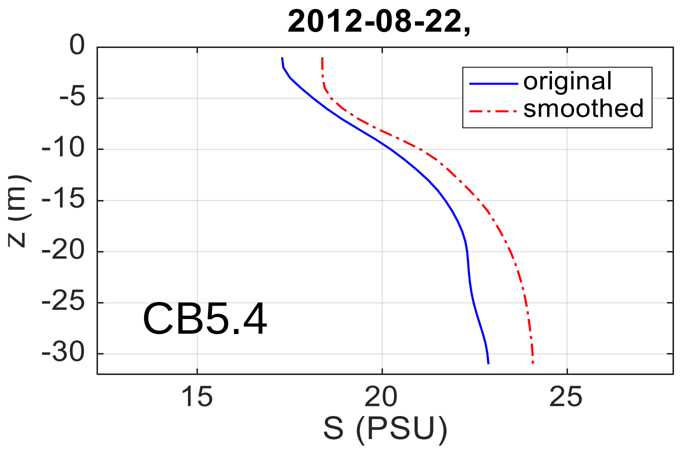
Smaller amplitude of tidal volume flux: smoothed = 79% original





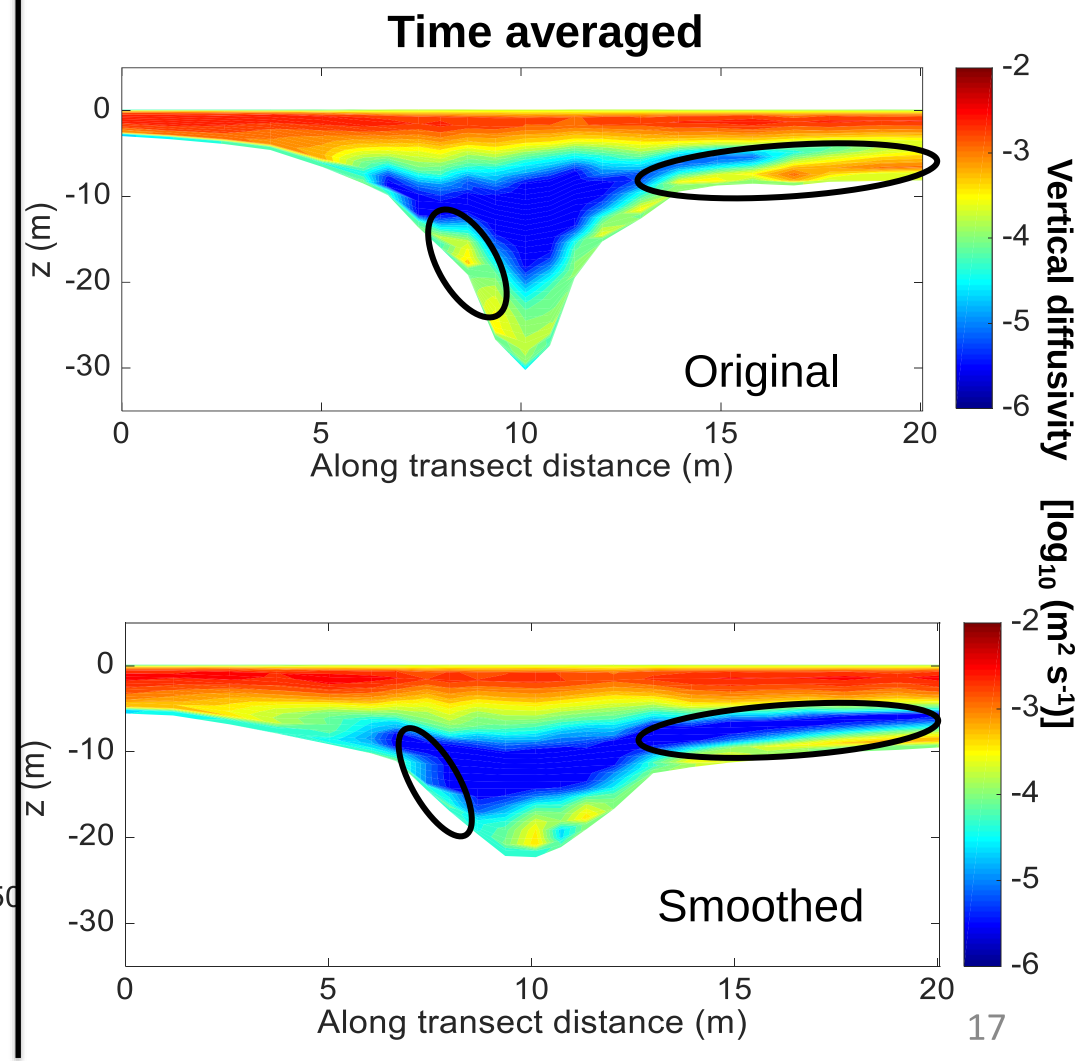
Larger sub-tidal volume flux

More salt, about +1 PSU in the smoothed region, 2-3 PSU upstream



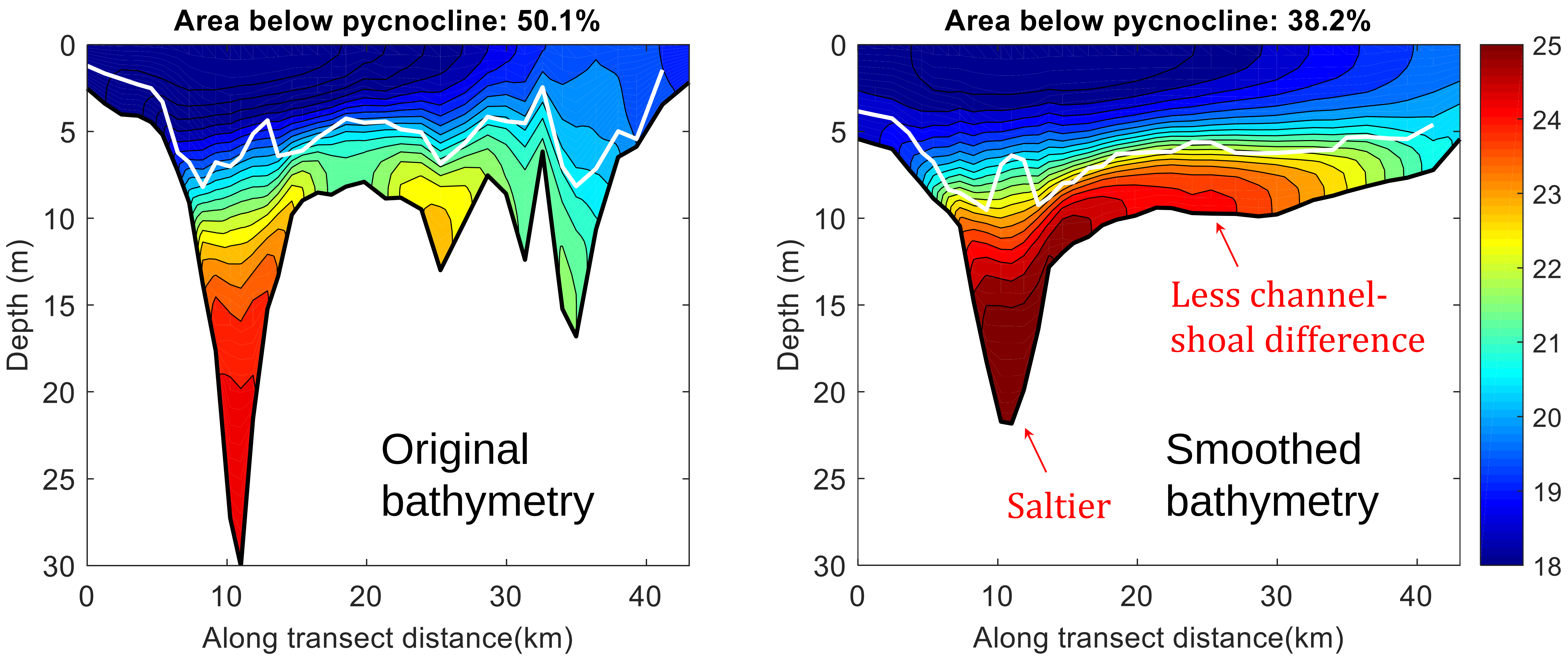
Ye et al. (2018)

The effect of smoothing on turbulent mixing: less mixing overall and less contrast between shoal and channel



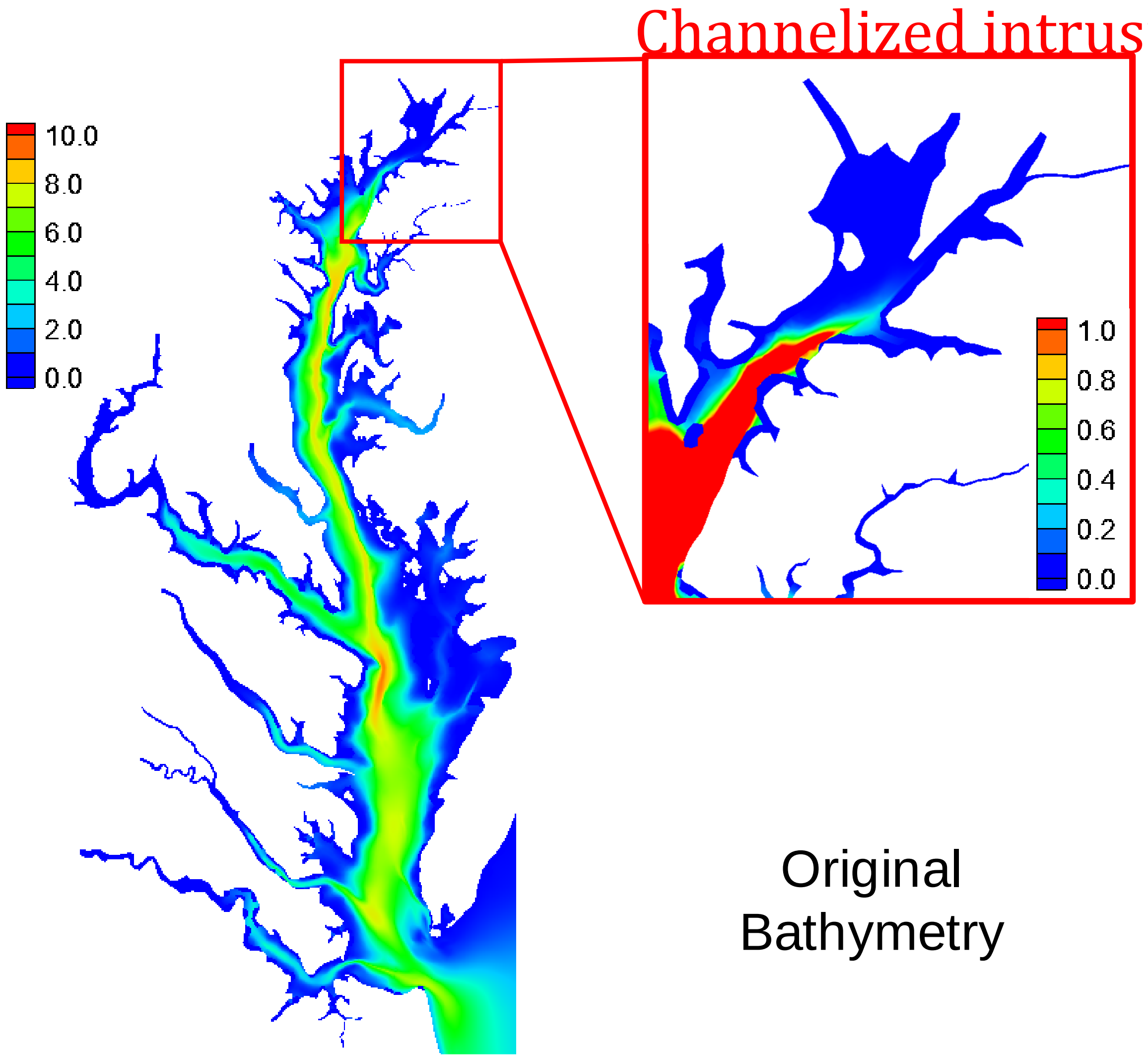
Sensitivity test 1: mid-Bay smoothing

Cross-sectional salinity distribution

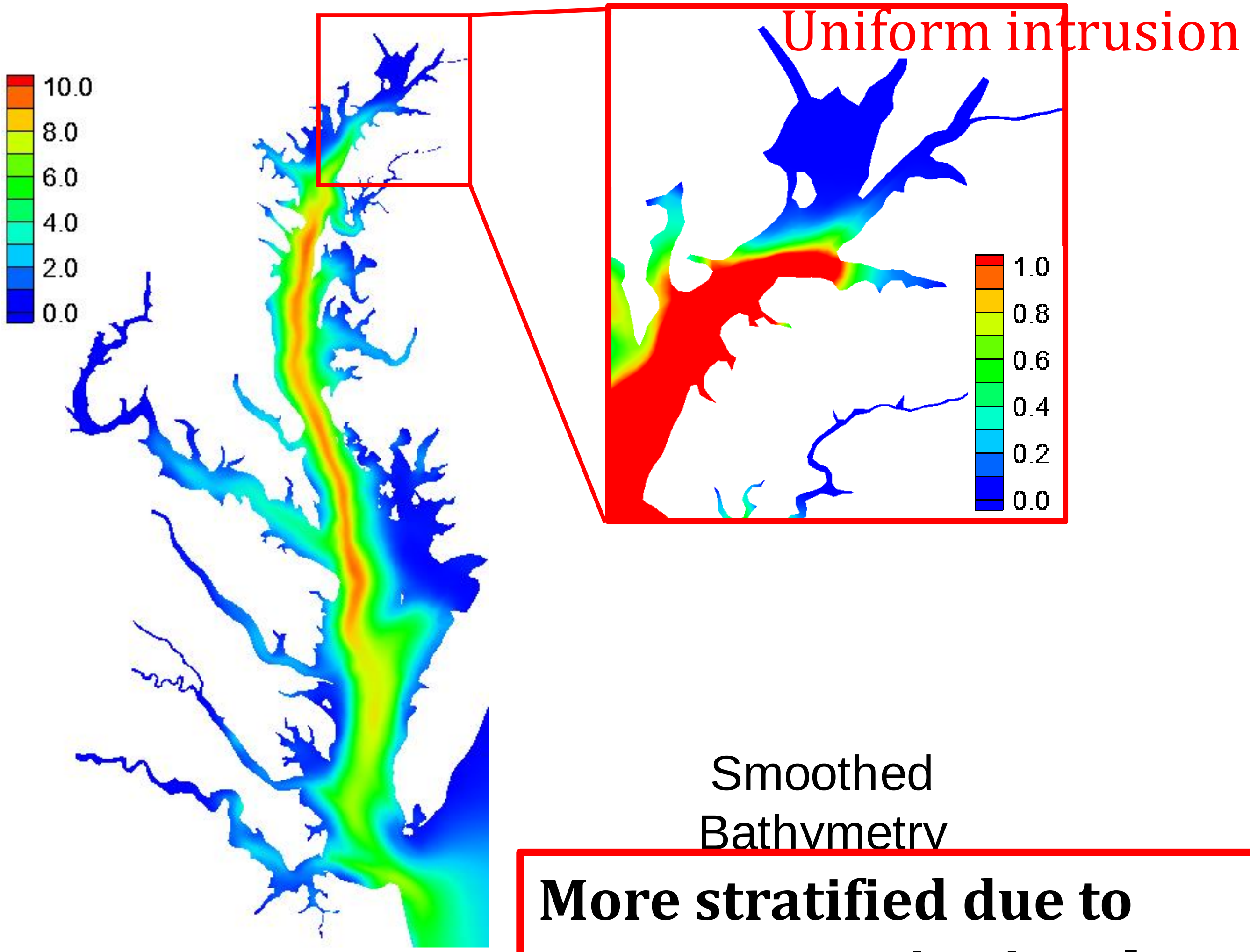


Sensitivity test 2: whole-Bay smoothing

Stratification



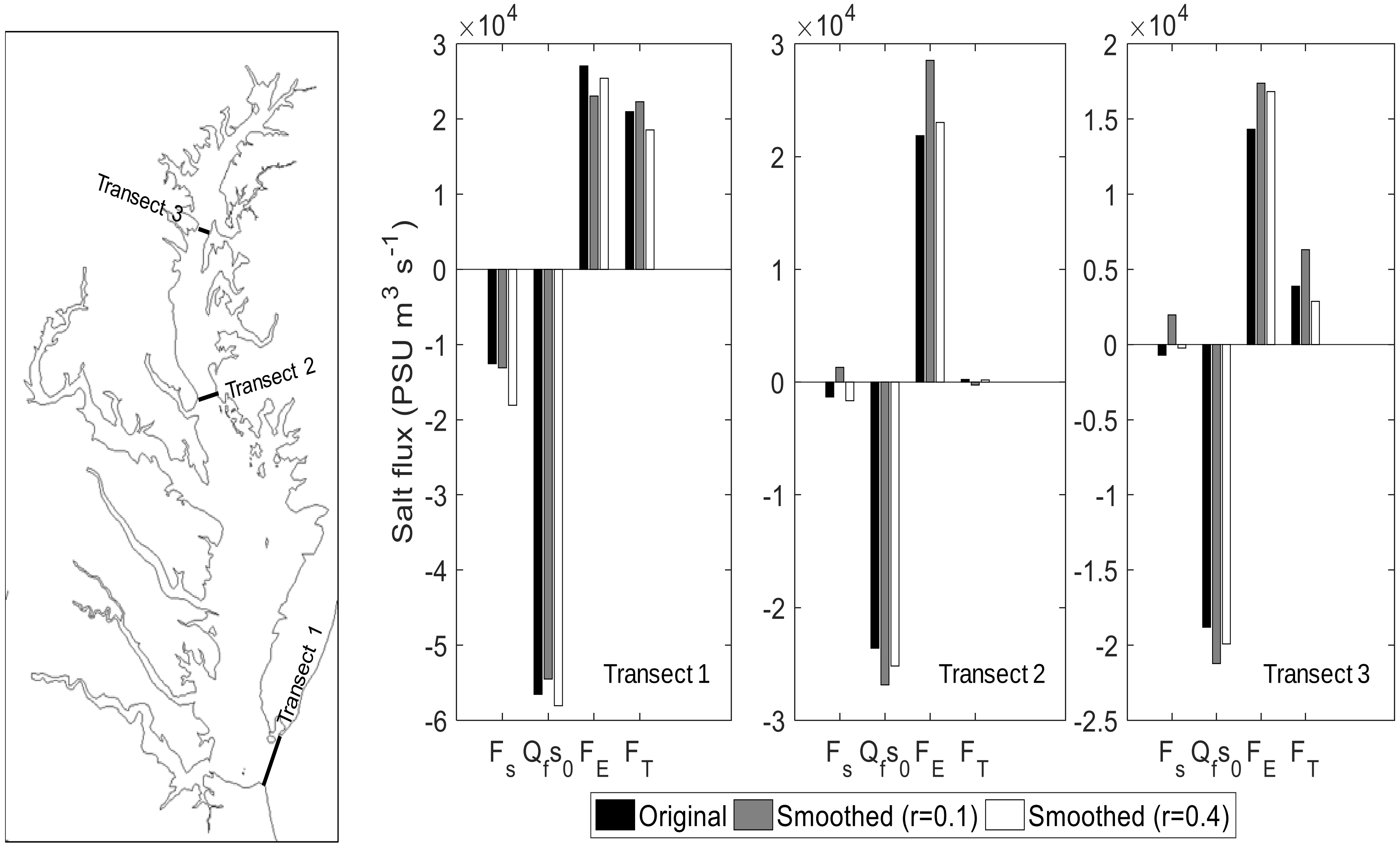
Original
Bathymetry



Smoothed
Bathymetry

More stratified due to stronger gravitational circulation

Sensitivity test 2: whole-Bay smoothing



Salt budget

(Lerczak et al., 2006)

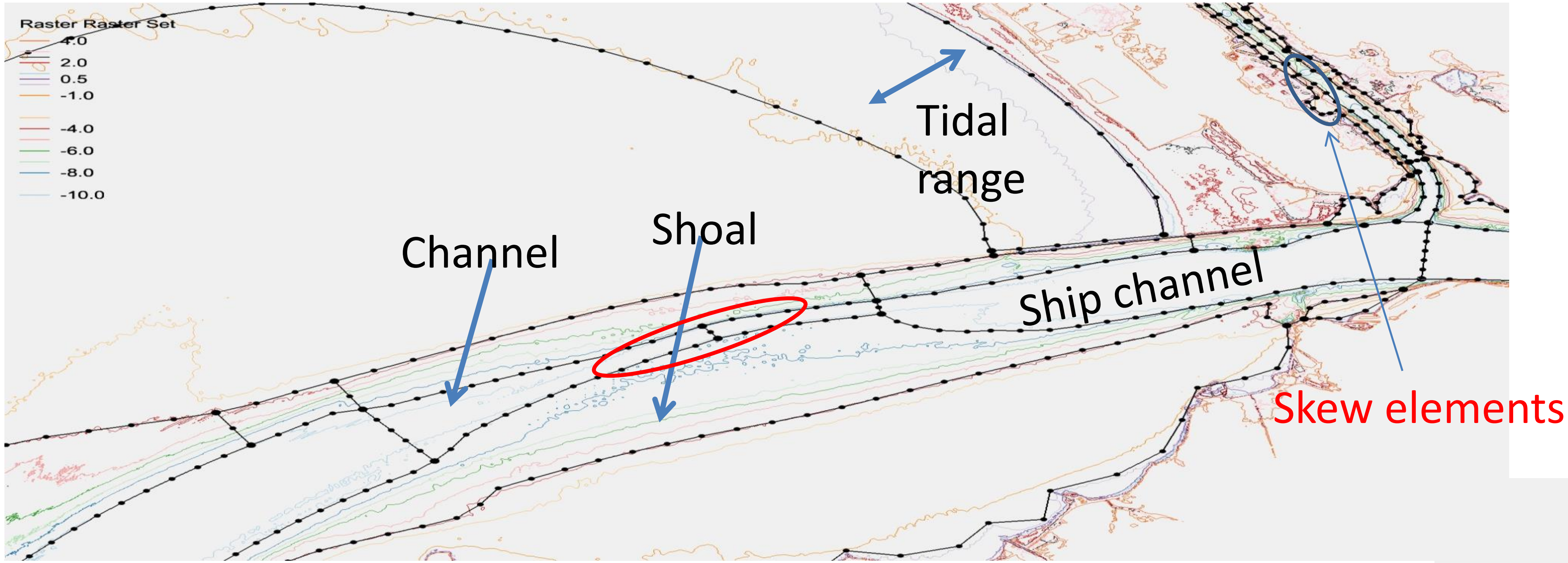
$$F_s \approx Q_f s_0 + F_E + F_T$$

F_S: total salt flux;
F_E : estuarine circulation flux;
F_T: tidal oscillatory flux;
$Q_f s_0$: salt flux from river discharge and Stokes transport

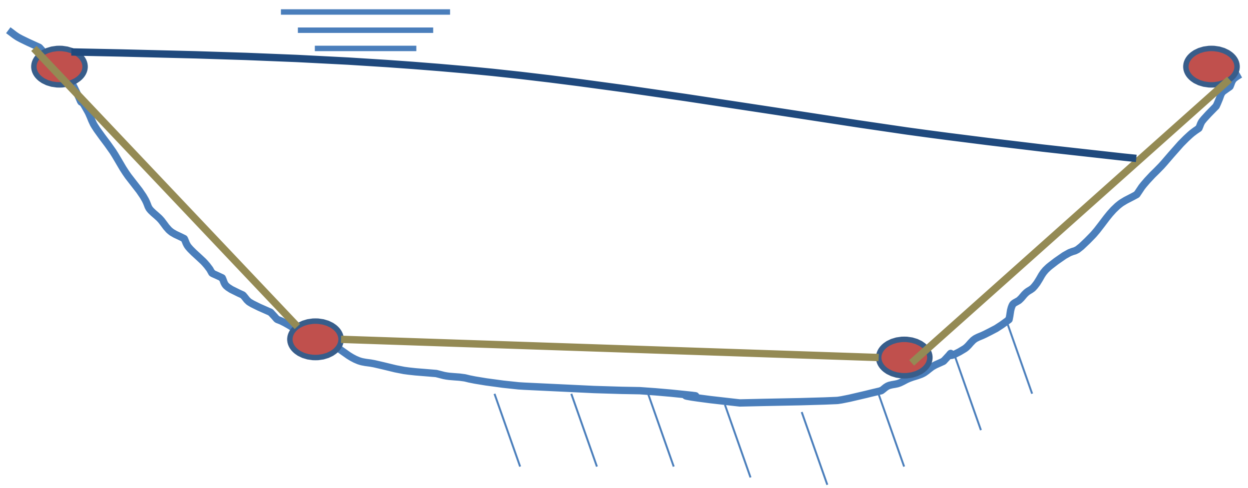
Larger salt flux due to estuarine circulation and tidal oscillation, leading to larger total flux

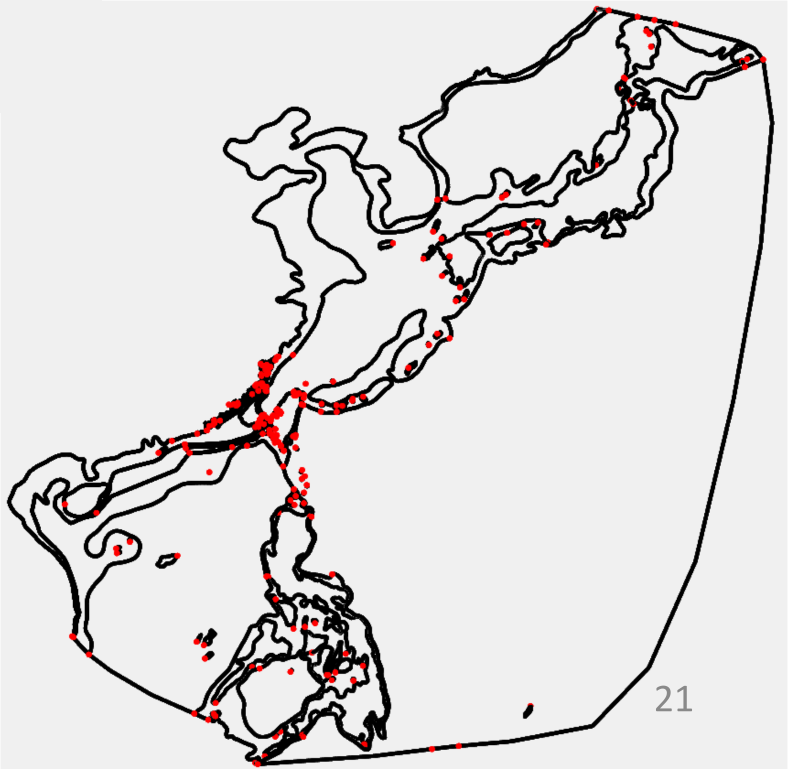
Ye et al. (2018)

Grid generation in SCHISM: less numerics, more physics

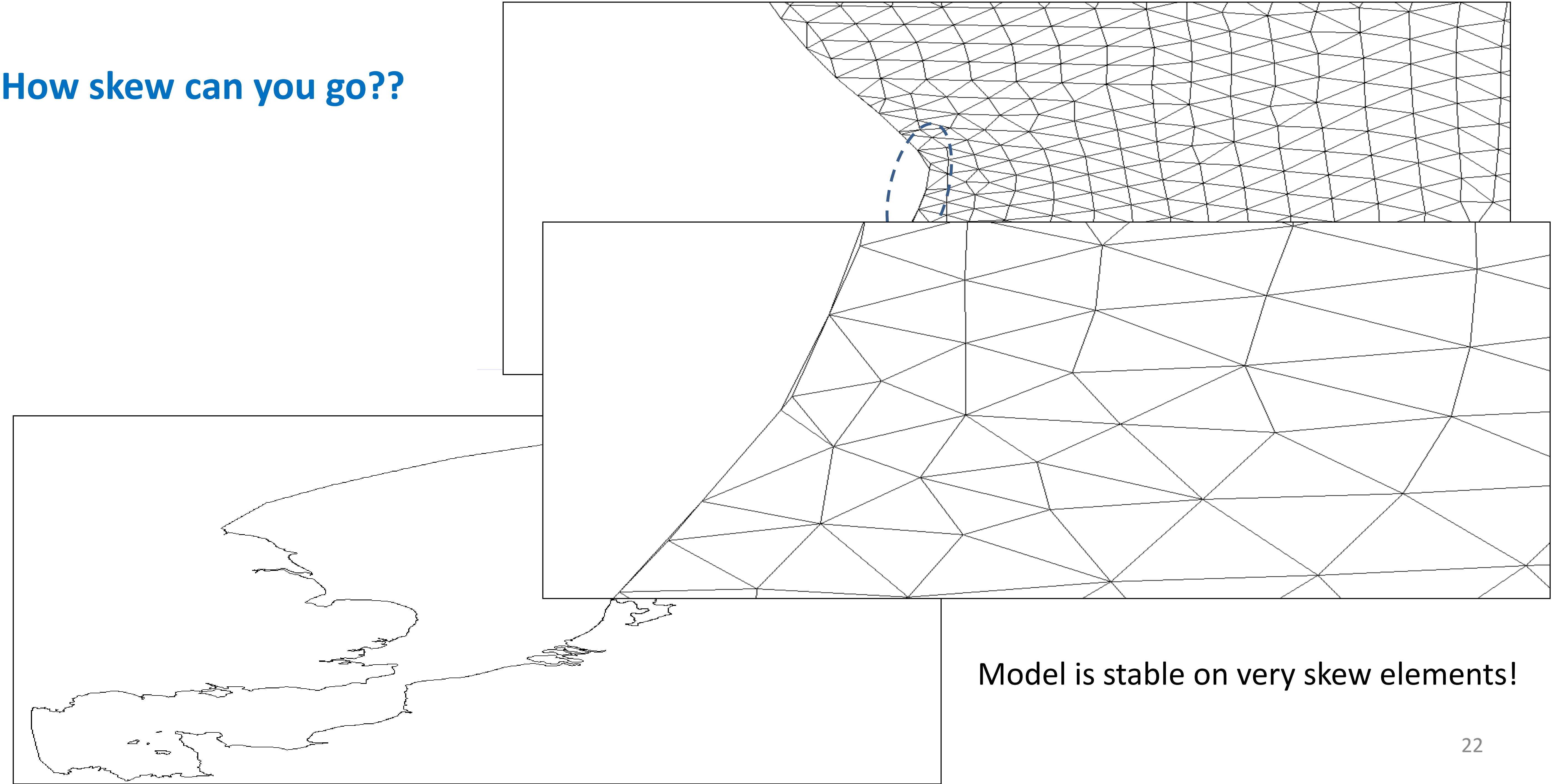


Channel representation



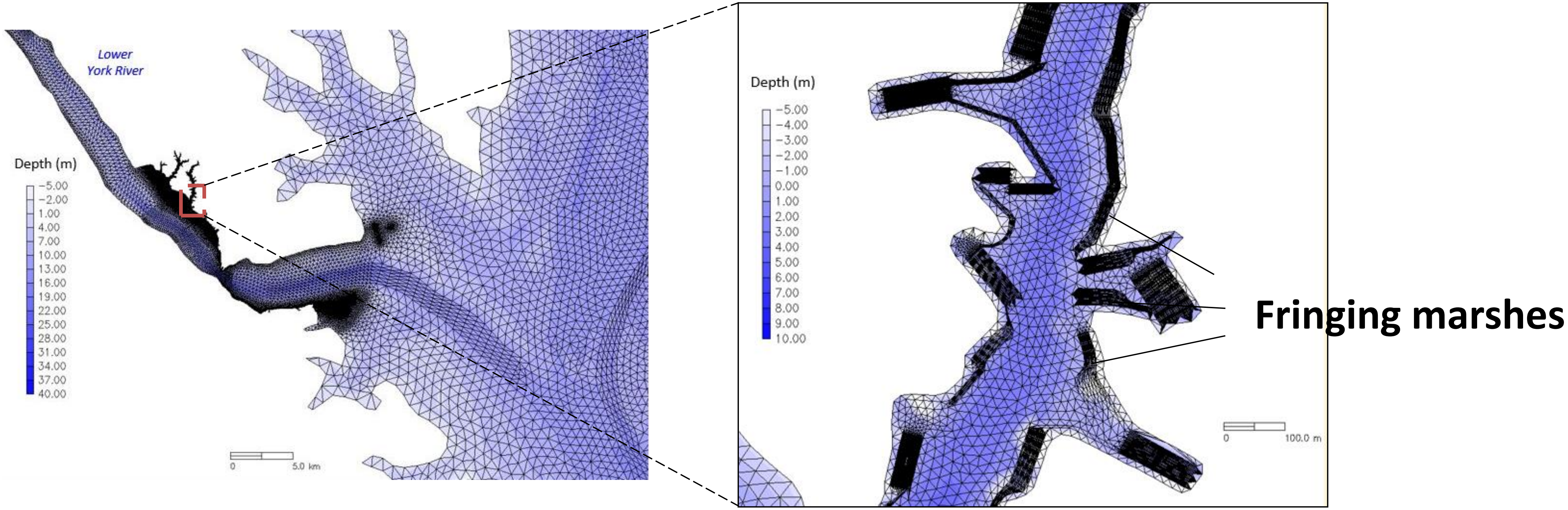


How skew can you go??



Model is stable on very skew elements!

Extreme case #1: skew elements are a boon in nearshore applications

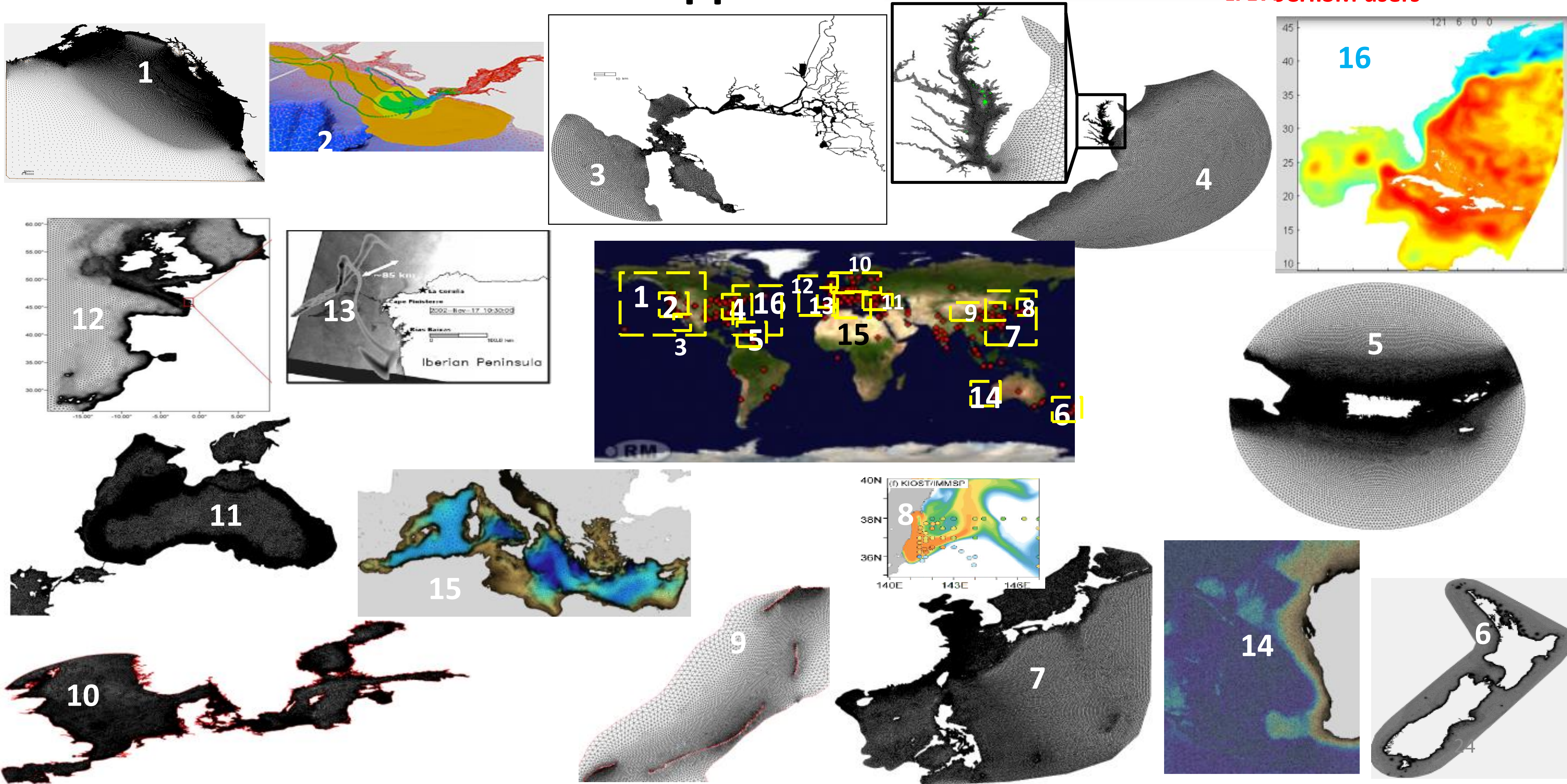


Smooth-transitioning grid would be 10x larger!

- **In the non-eddying regime, skew elements can save a lot of computational cost!**
- **Fringing marshes need fine resolution (1m cross, 15m along)**
- **The implicit FE formulation in SCHISM makes it very tolerant of ‘bad’ meshes**
- **Fully coupled SCHISM-SED-WWM-Marsh model runs stably on this type of meshes**
- **Marsh migration in 30 years, with 4mm/yr sea-level rise**
- **Flow/wave impedance by marsh vegetation is incorporated in the implicit solver**

Applications

c/o: SCHISM users

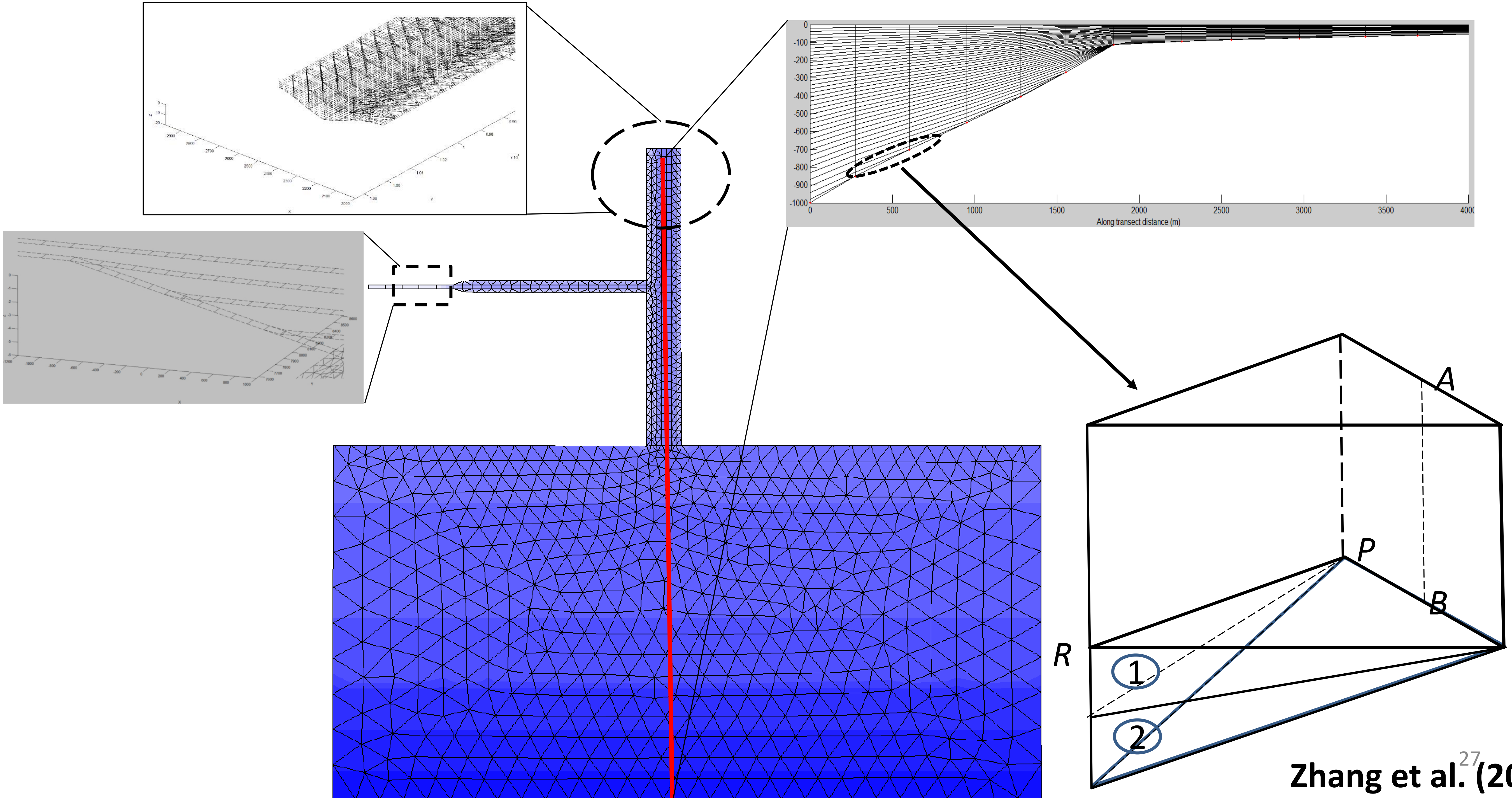


San Francisco Bay & Delta

Extend the model to large scale: from estuary to shelf and beyond

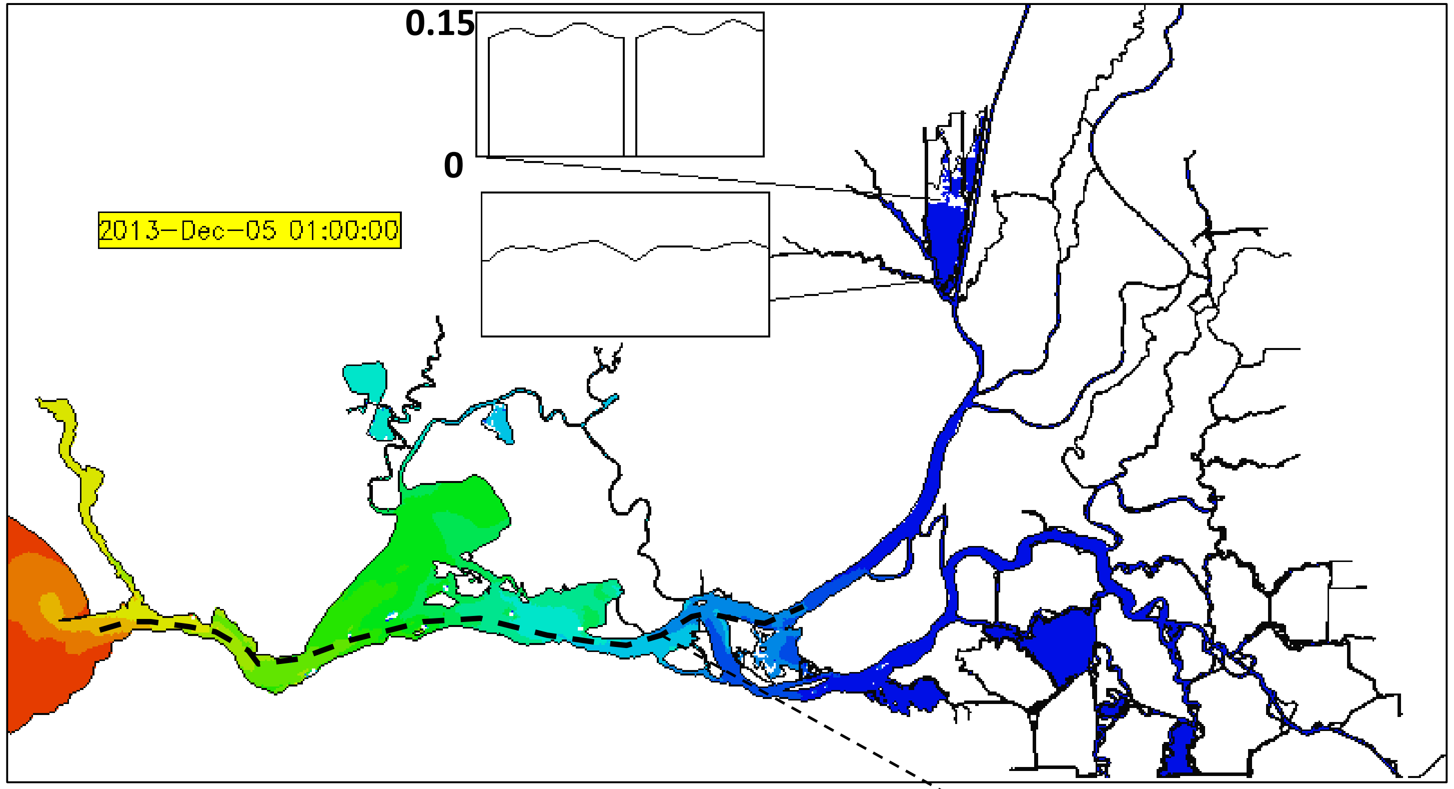
- Main motivation is the errors & uncertainties at the ocean boundary often strongly influence the solution interior
- Numerical challenges for cross-scale processes
  - Efficiency: mainly related to higher-order transport solver (explicit TVD)
  - Performance in eddying regime (baroclinic instability): PGE, spurious numerical modes/mixing….
    - UG models make some old issues more urgent
      - Grid transition in SG models is always smooth
      - Coarser resolution in SG models masks issues with steep bathymetry
- Strategy (for eddying and non-eddying regimes)
  - Reduce inherent numerical dissipation by combining the FE (dispersive) and implicit scheme (diffusive)
  - Make the higher-order transport solver implicit (in the vertical), without introducing excessive numerical diffusion
  - Make the grid system flexible (good for shallow depths also!)
  - Rework momentum advection and viscosity schemes to control dissipation

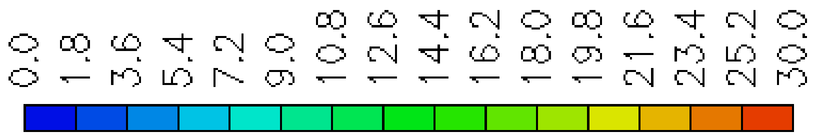
Model polymorphism



Zhang et al. (2015)

Polymorphism in action

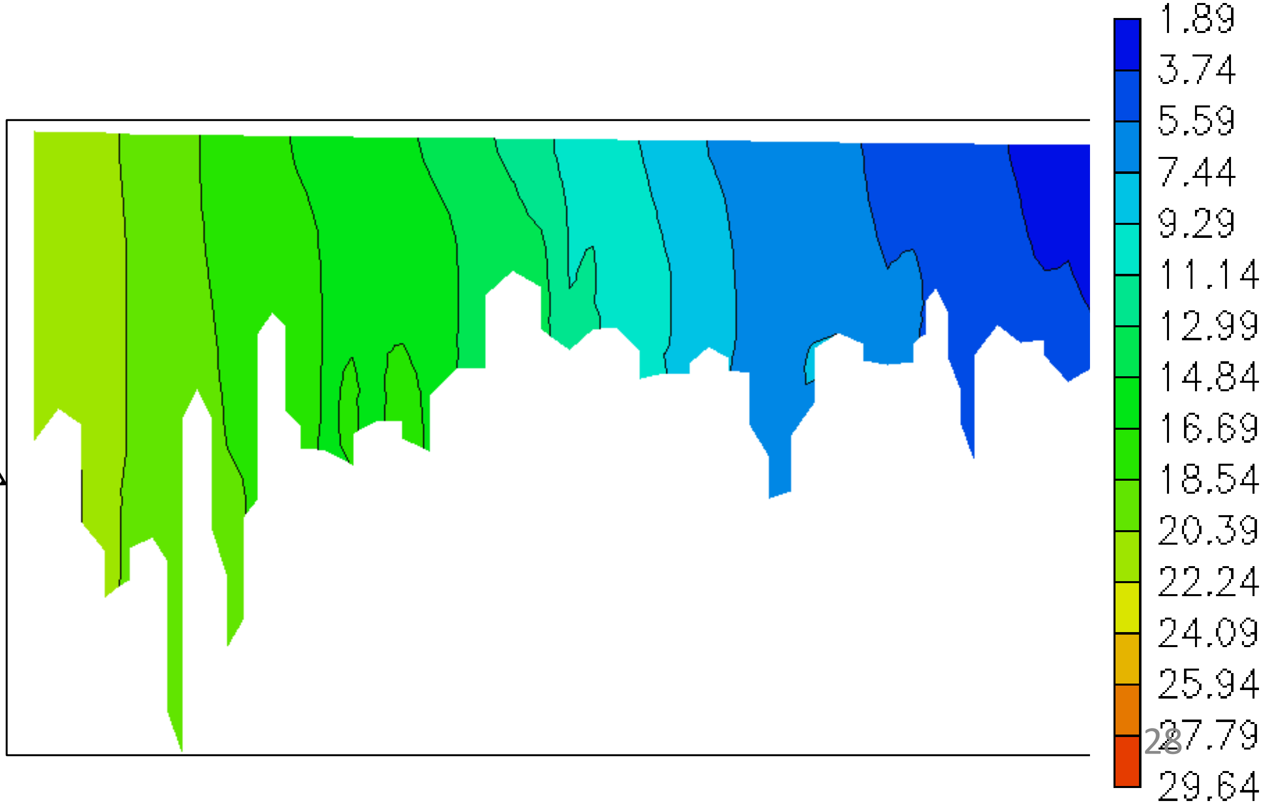




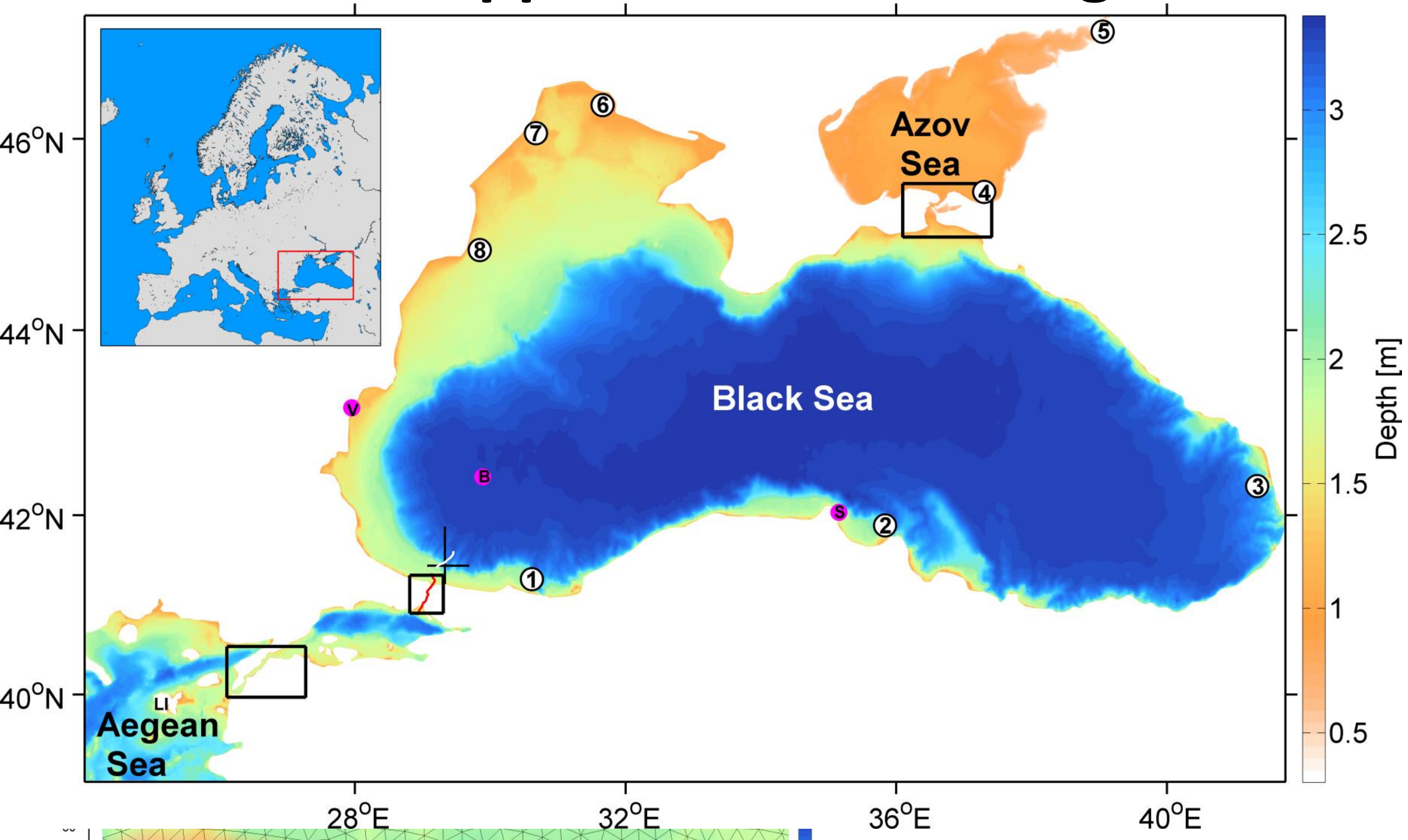
S(PSU)

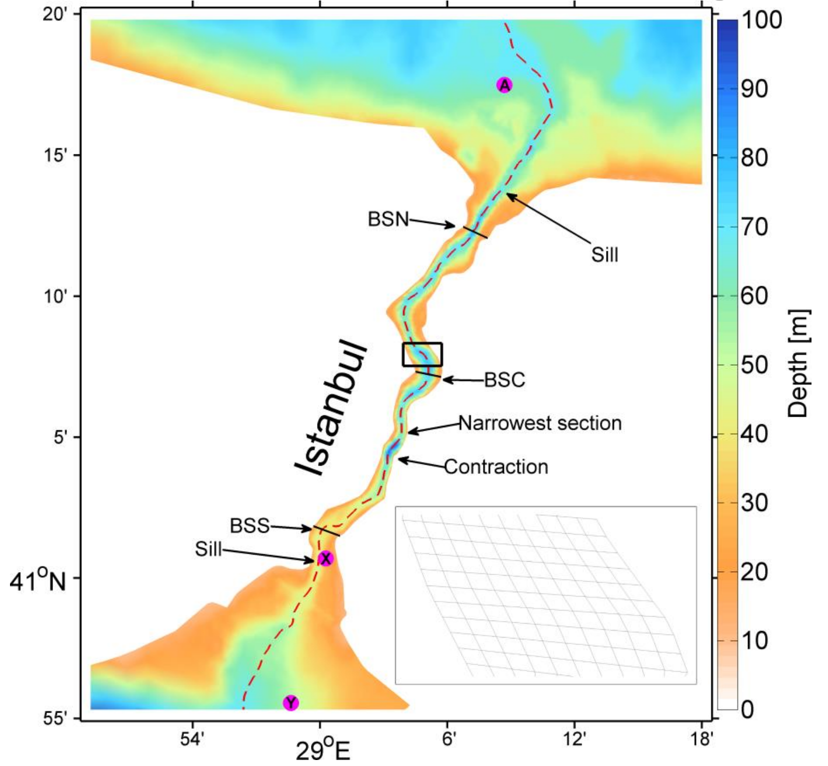
- The stratified Bay is represented by 3D grid
- The shallow Delta region is mostly represented as 2D
- There are only ~**10** layers on average

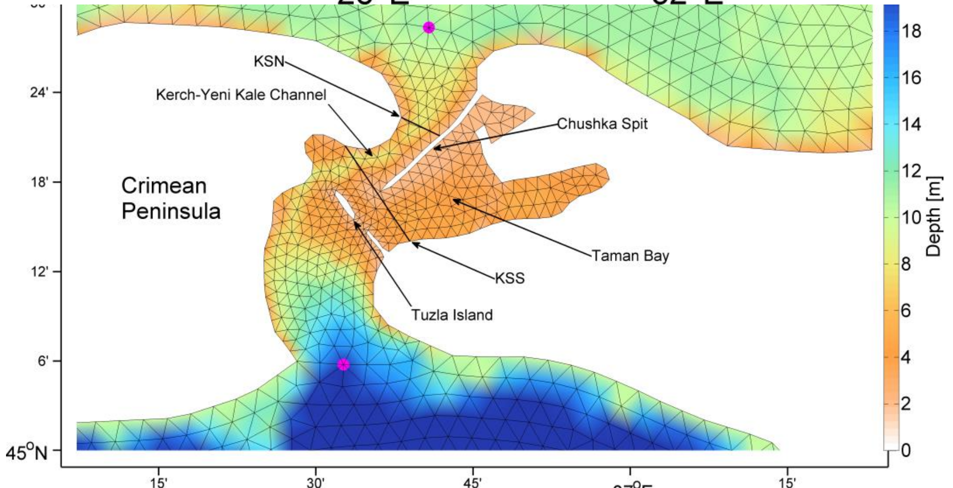
S(PSU)

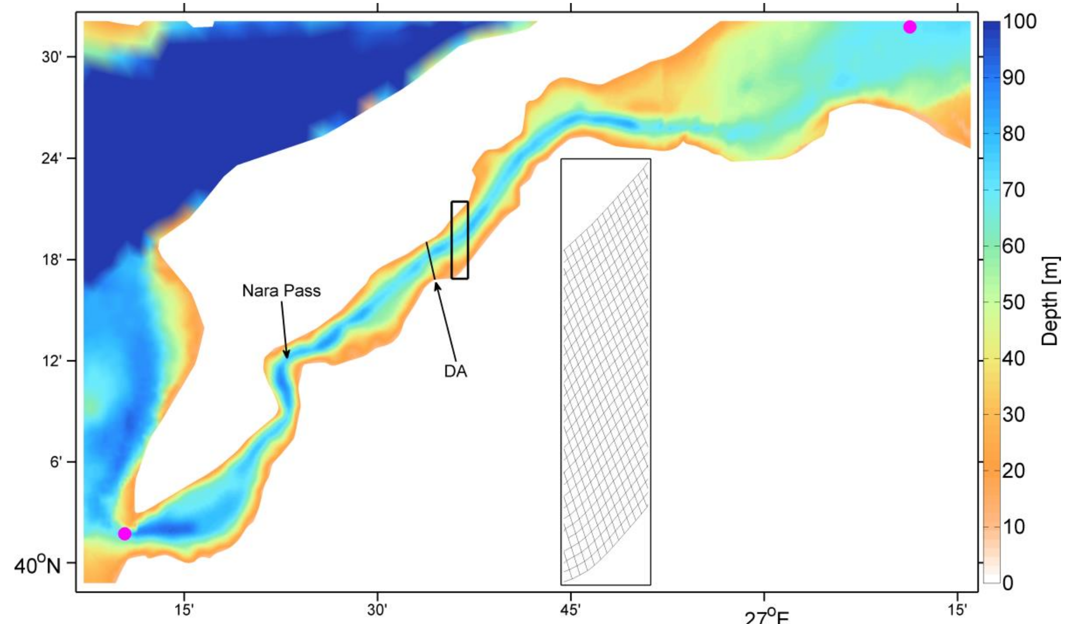


Multi-scale application: cascading basins in Azov-Black-Marama-Aegean Sea



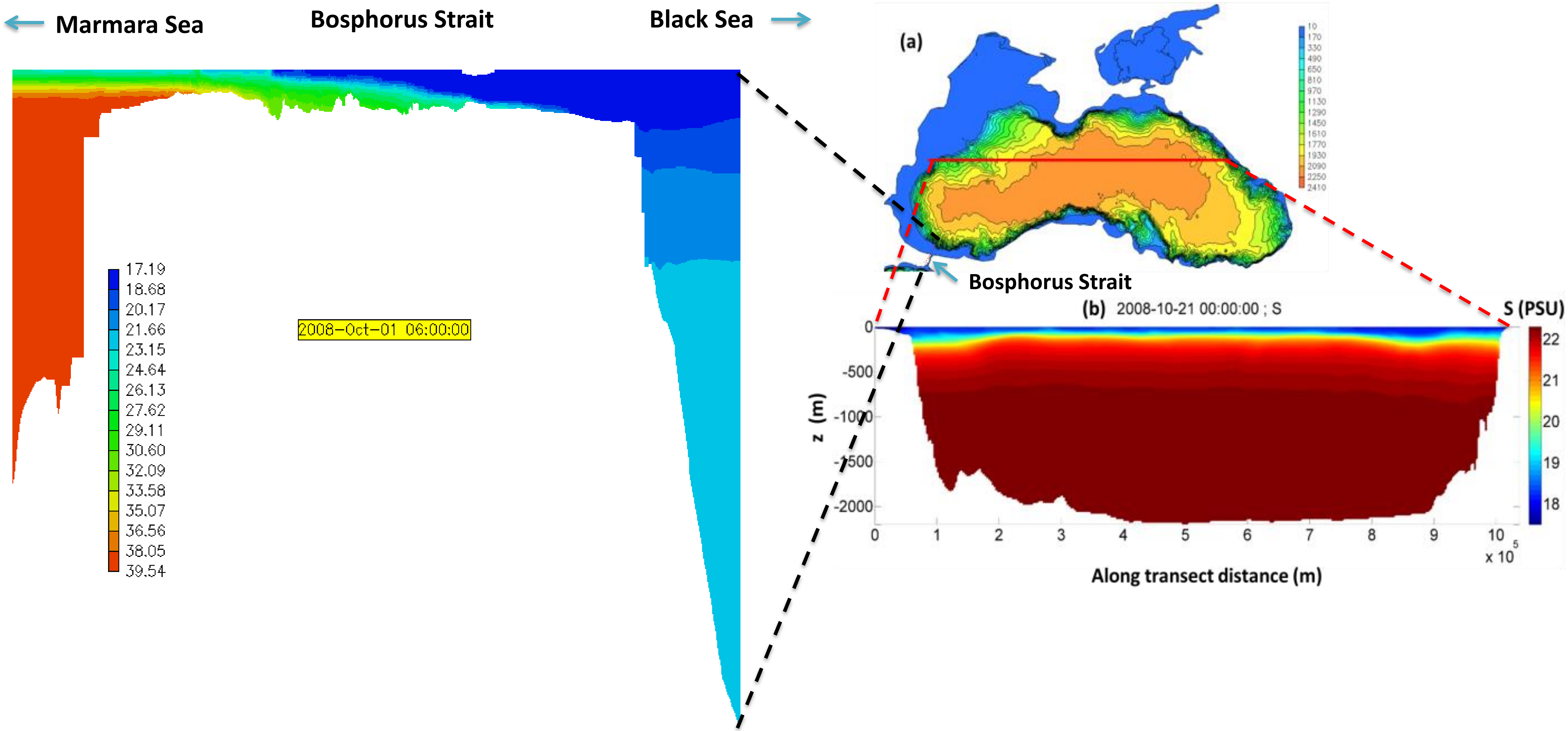






Stanev et al. (2017)

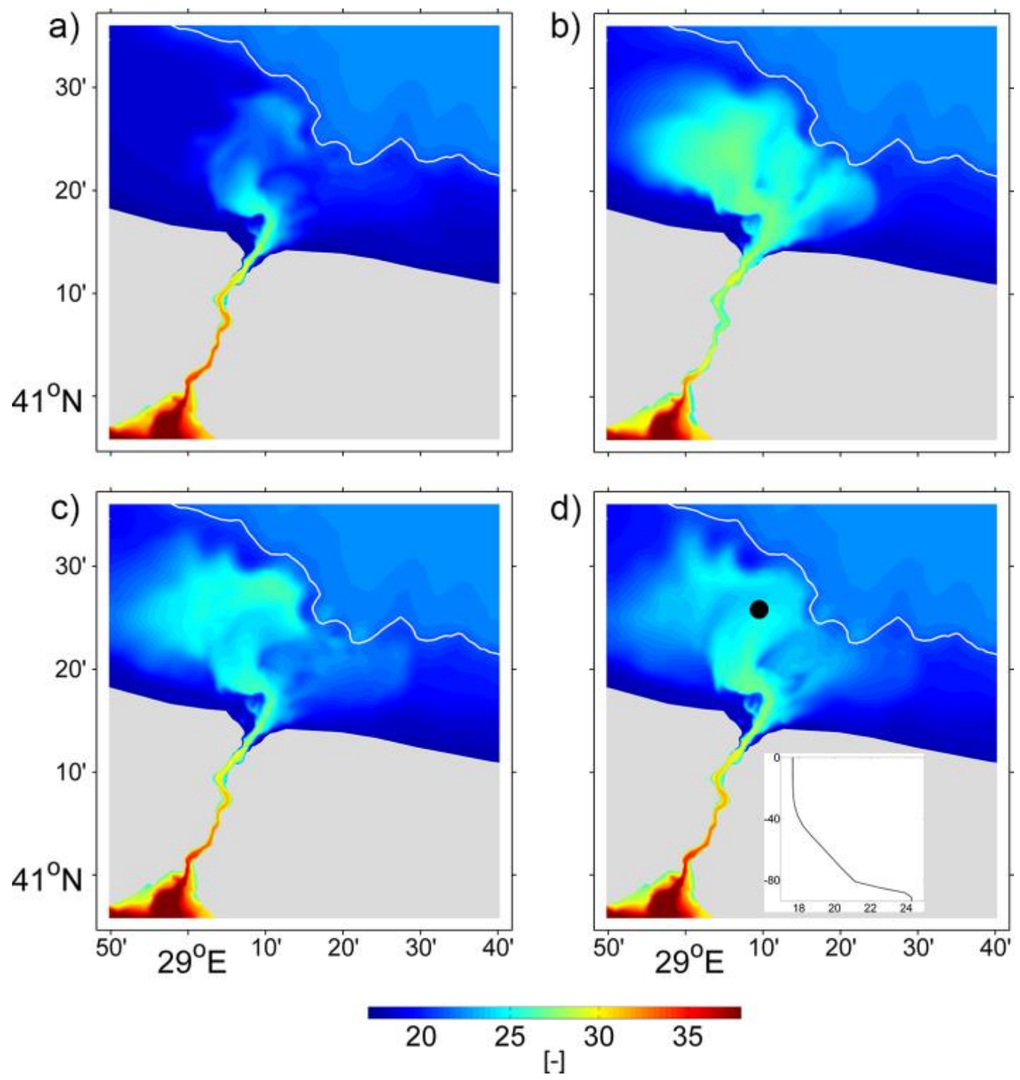
An extreme case…



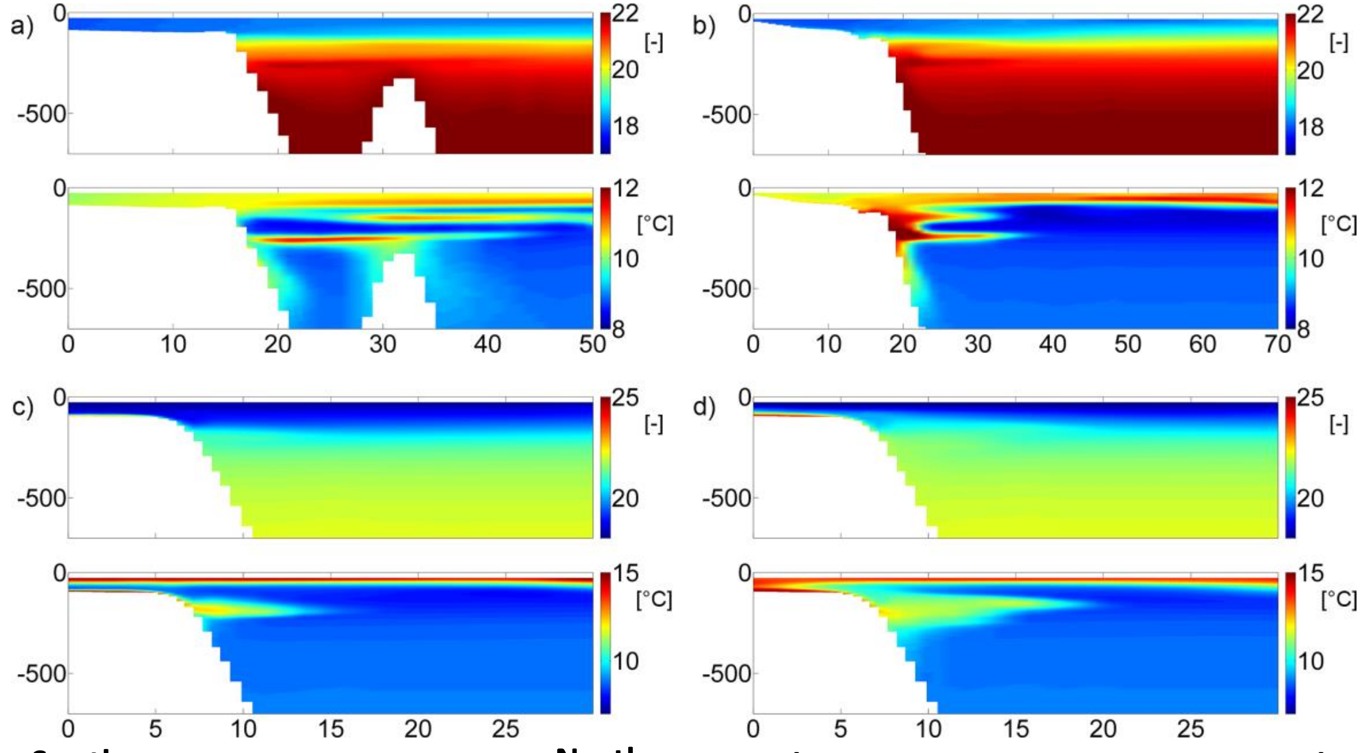
Either Z or terrain-following grid will have issues here…

Black Sea: overflow

'Negative plume'



Salinity

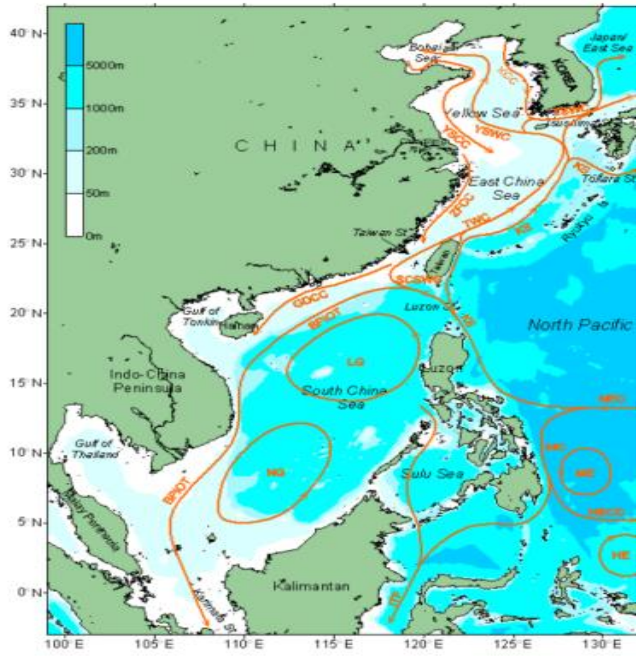


Distance along transect (km)

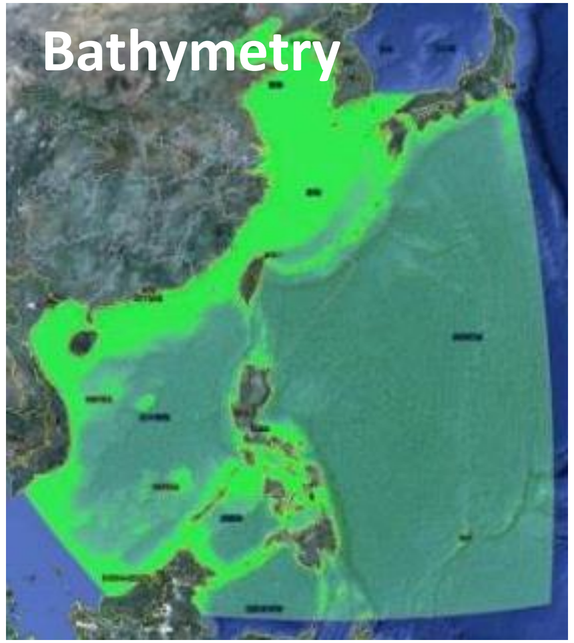
Stanev et al. (2017)

Multi-scale application: Northwestern Pacific around Taiwan

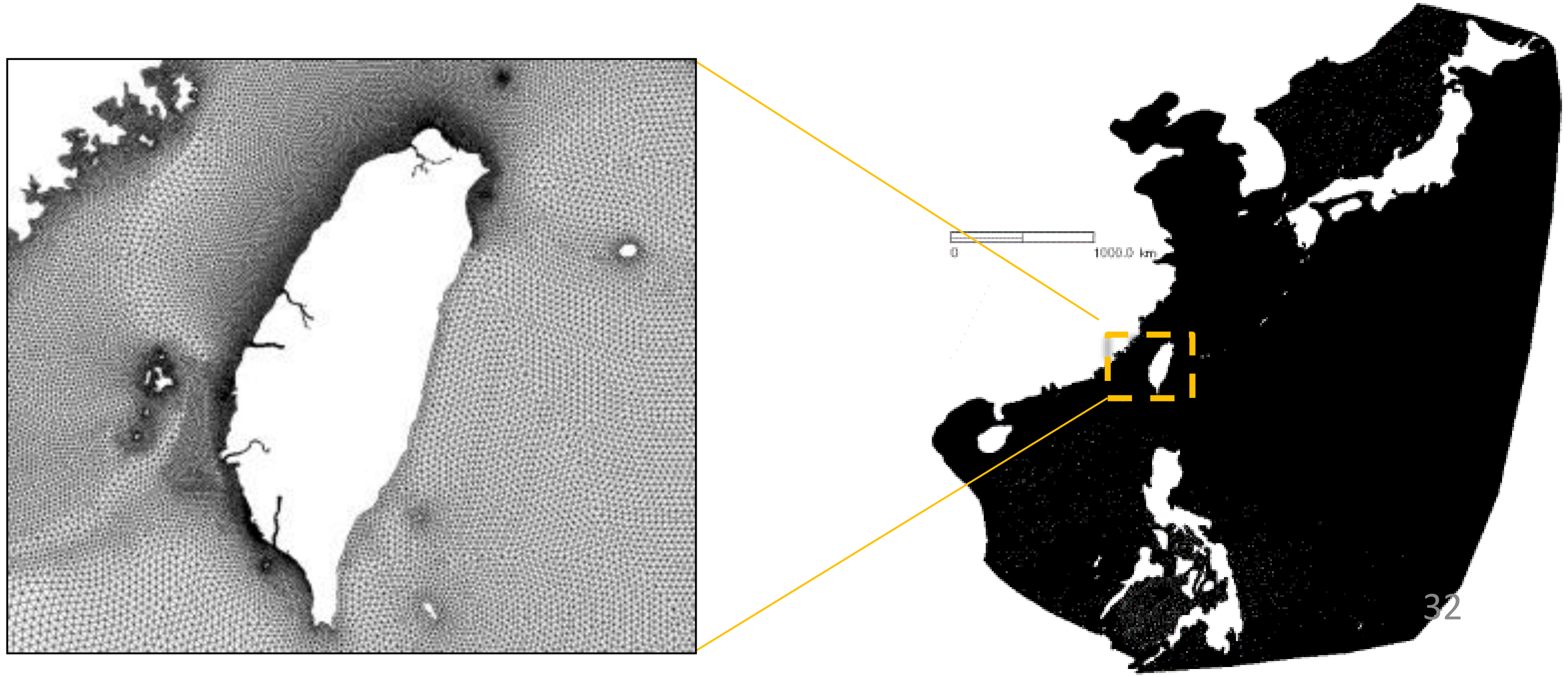
- Model set-up
  - Horizontal grid: 480K nodes, 960K elements. Quasi-uniform resolution in open seas (5-9km), 100-200m around Taiwan, 50m nearshore, 5m min resolution (in ports/harbors)
  - Vertical grid: LSC^2, max 41 layers (@10km depth), average 29 layers
  - ***No bathymetry smoothing/clipping (c/o LSC^2)***
  - Δt=120s, bi-harmonic viscosity
  - I.C. and B.C. from HYCOM
- Model performance: 120x RT on 480 Intel cores



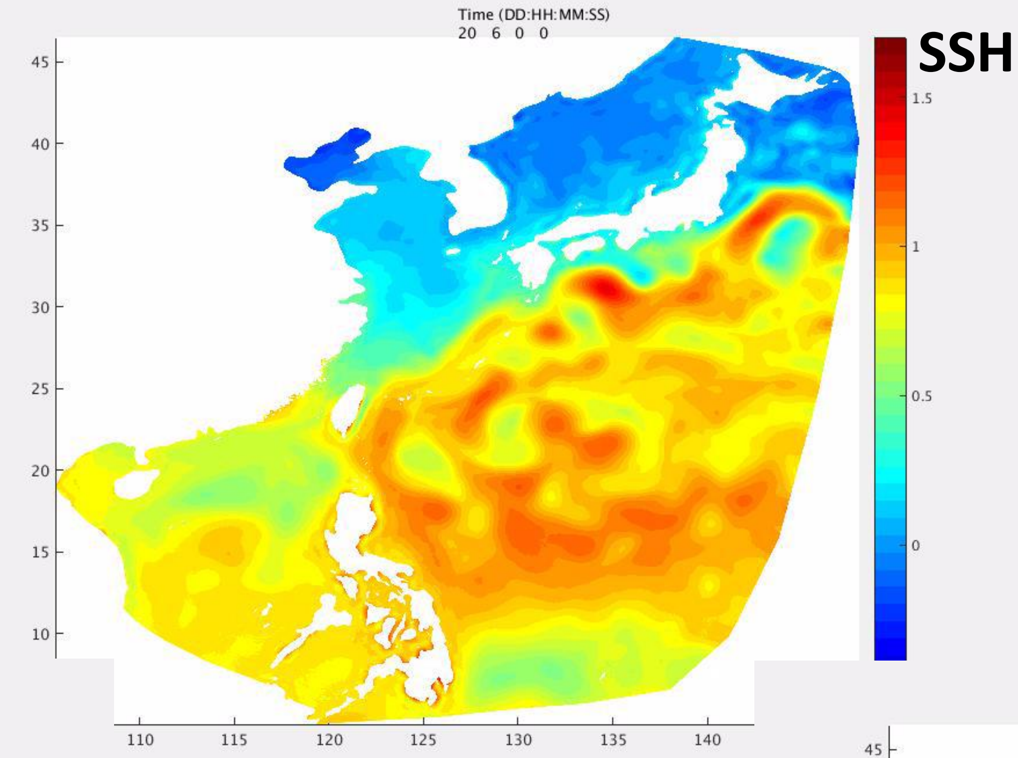
Zheng *et al.* (2006)

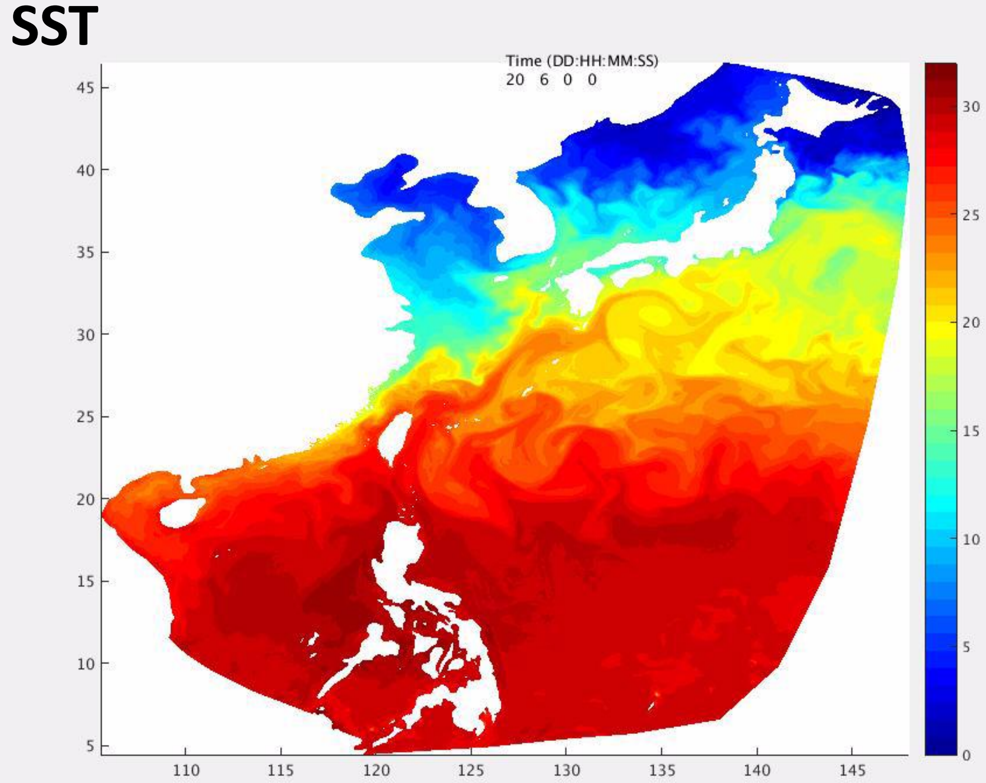


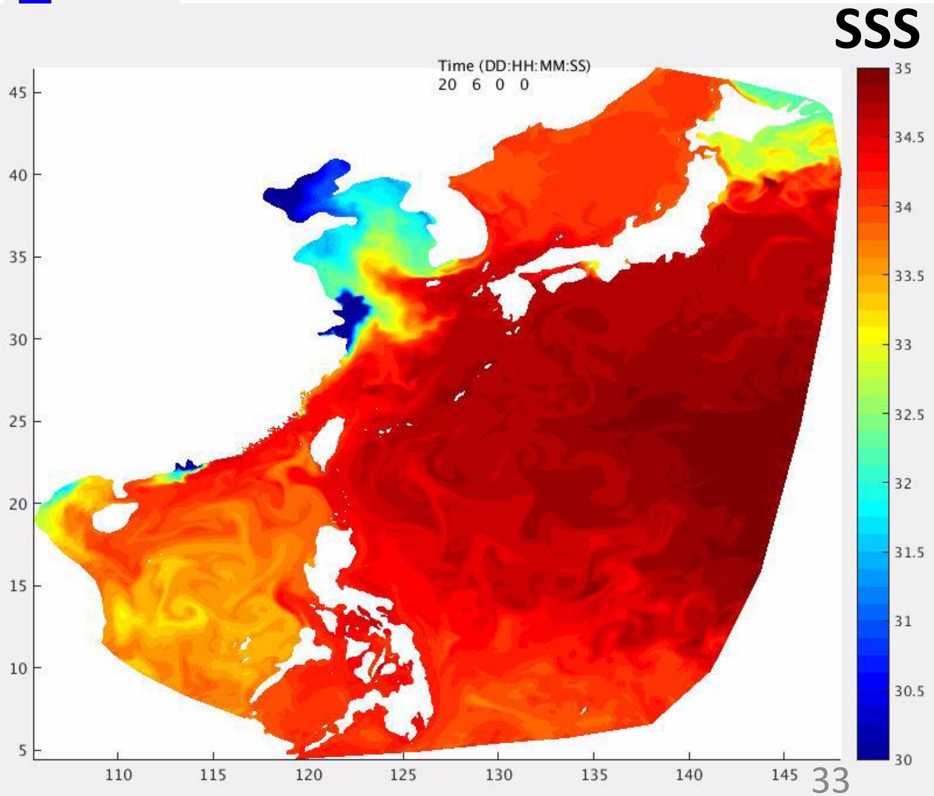
Yu et al. (2017)



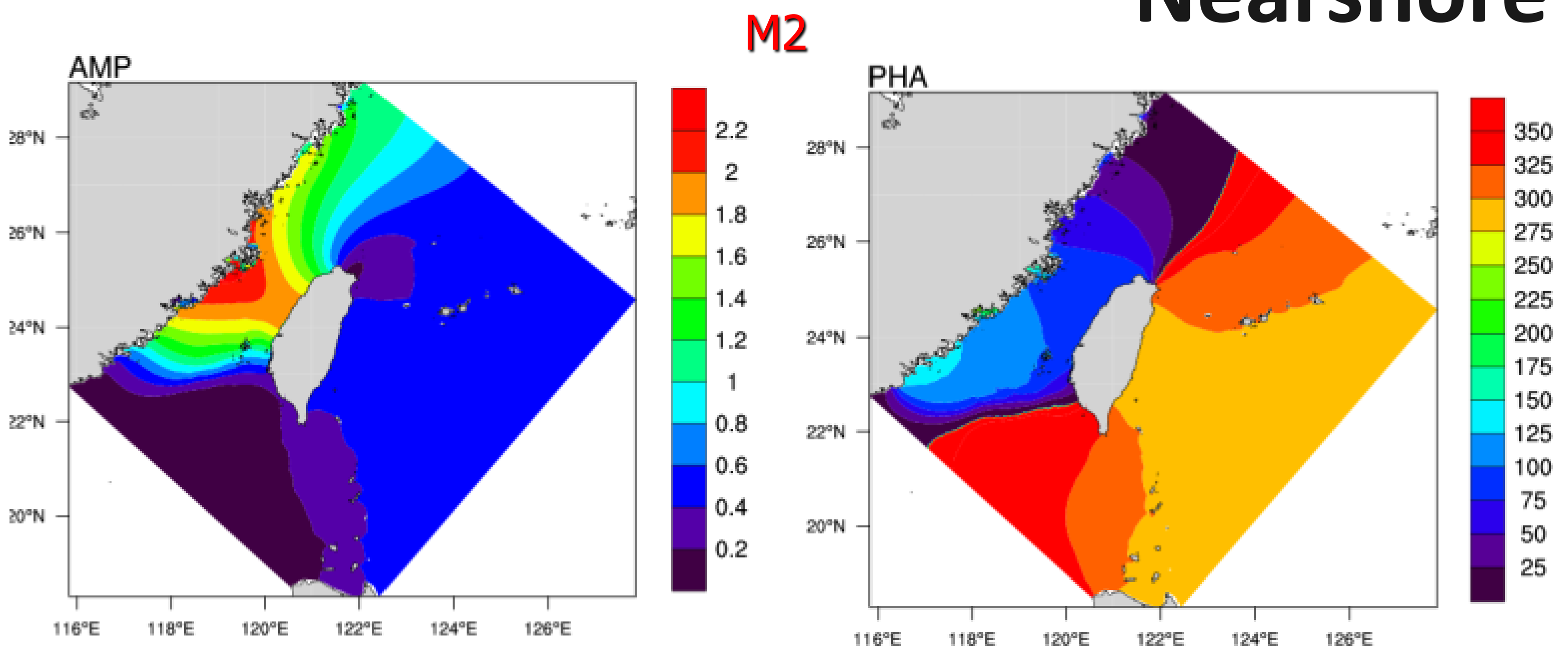
Large-scale skill: Kuroshio (Zhang et al. 2017)

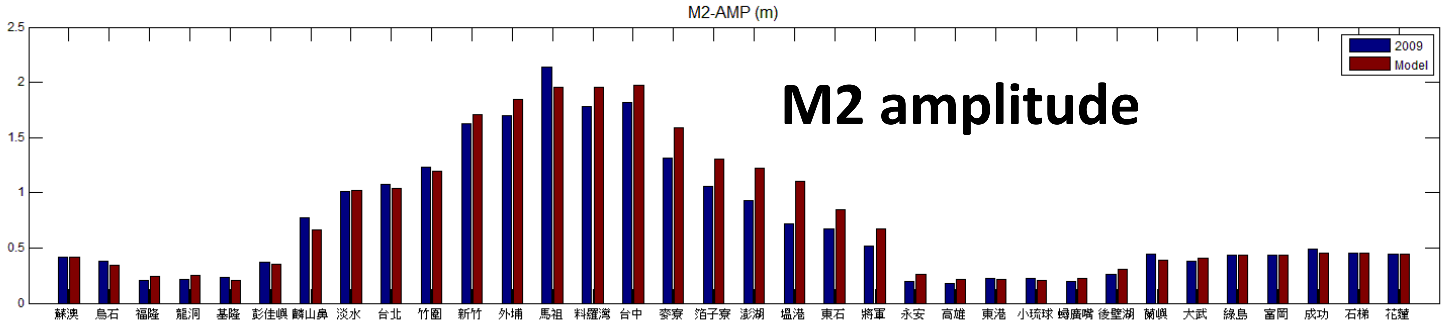


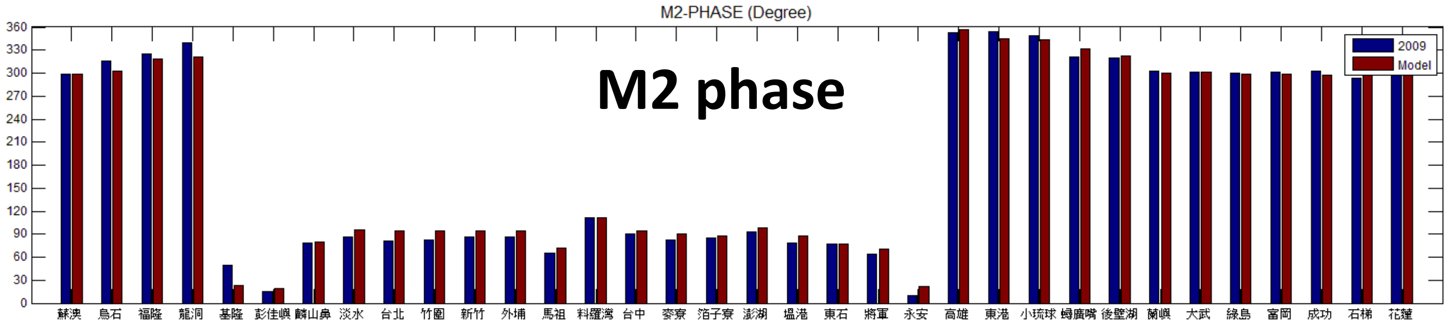




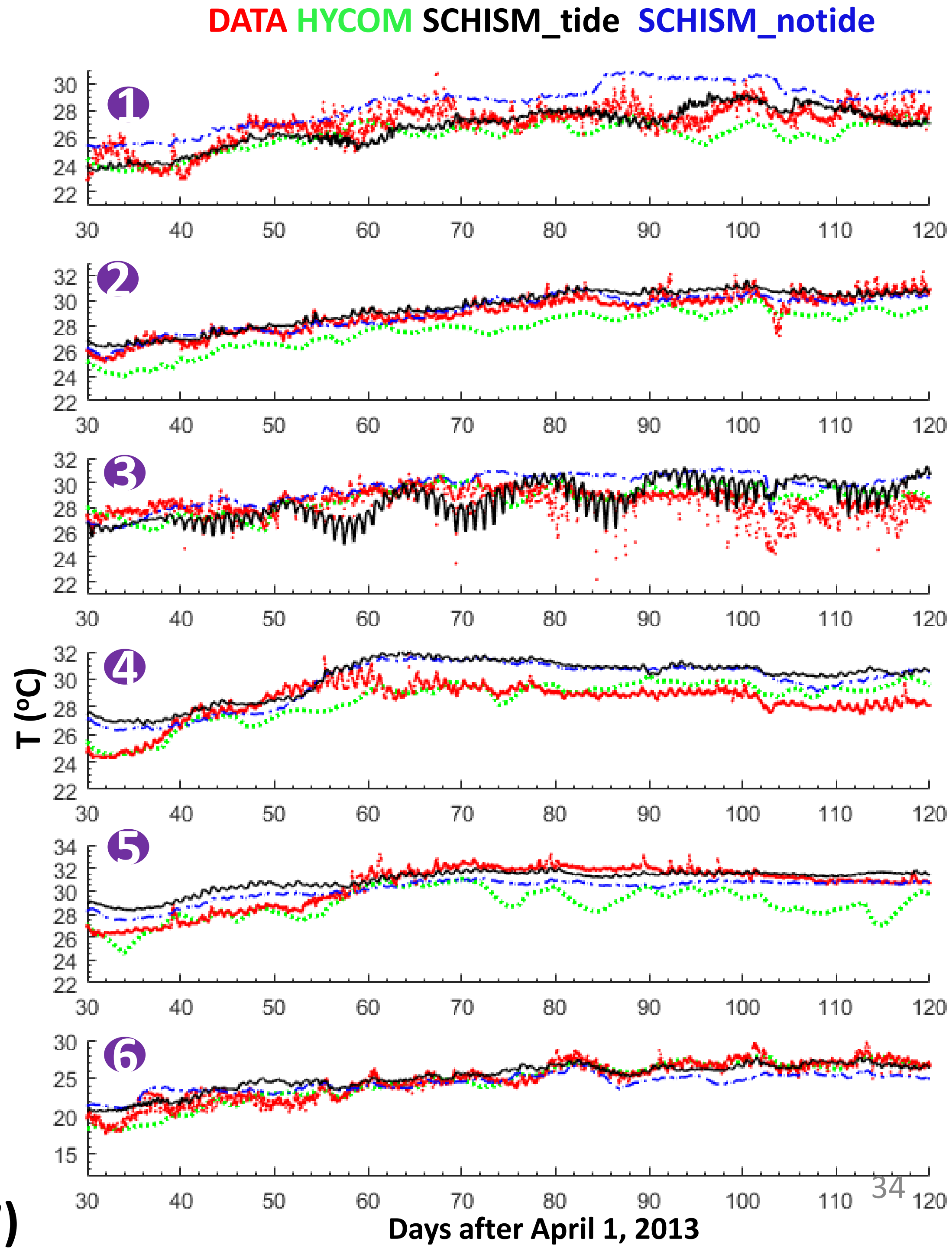
Nearshore skill







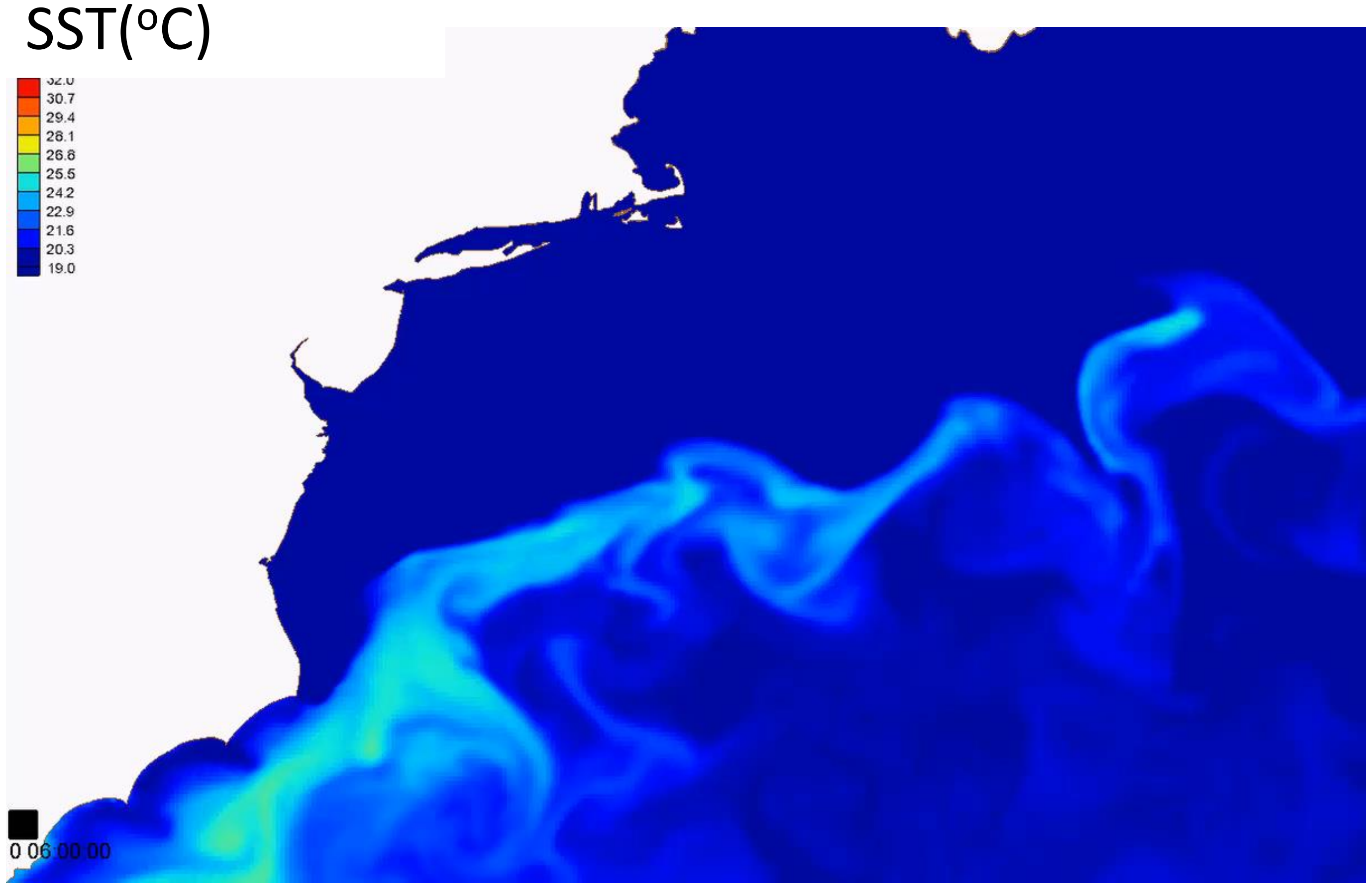
Stations



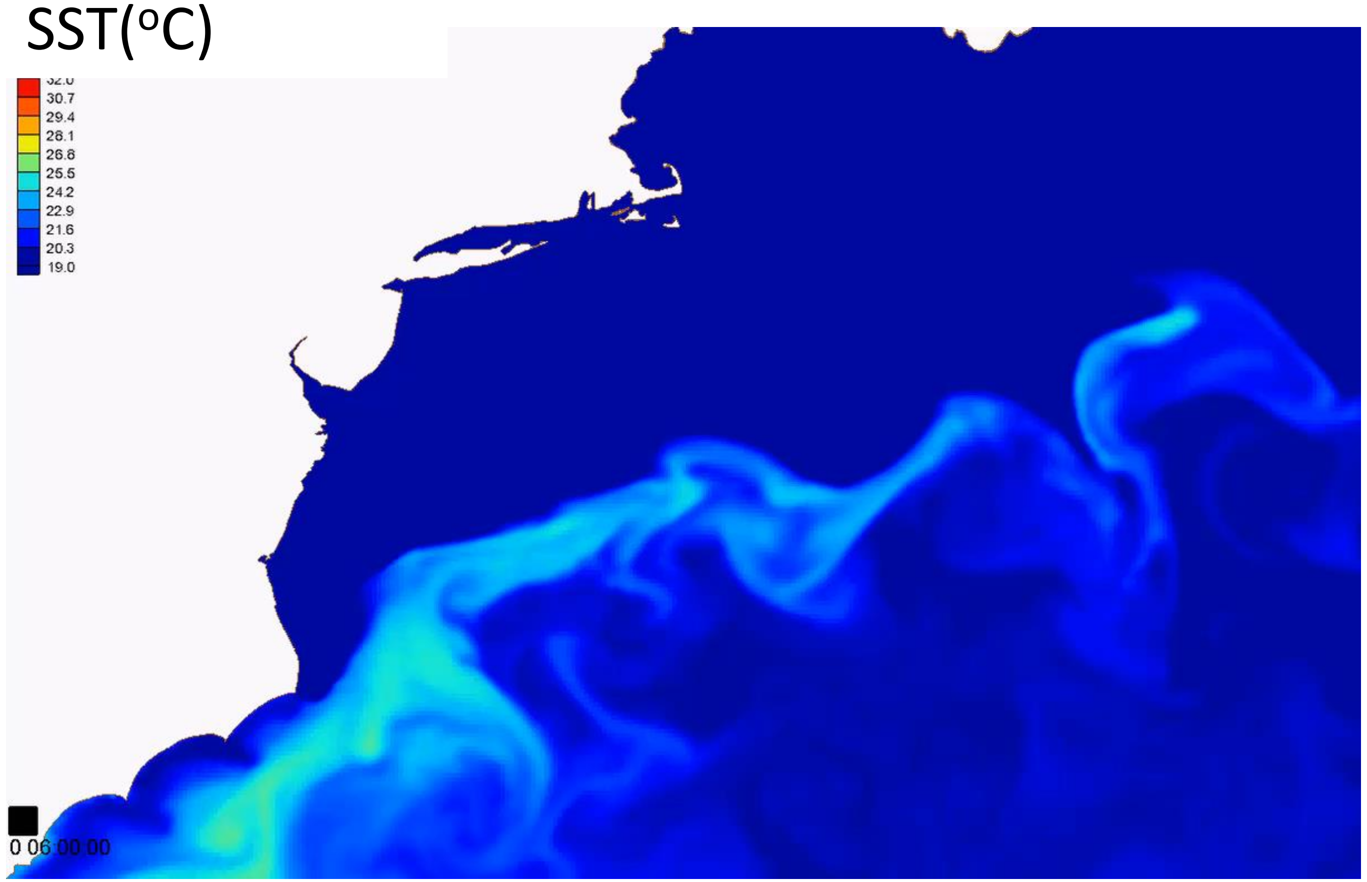
Yu et al. (2017)

Importance of higher-order scheme in eddying regime: Gulf Stream meandering

2nd order TVD



3rd order WENO



- Grid resolution: 2~7 km; 388K nodes and 766K elements; 27 LSC^2 vertical levels on average
- Time step=150 seconds
- No bathymetry smoothing

(Ye et al. in prep)

SCHISM web

Home	Manual & Download	Publications	Case study	Join SCHISM mailing list	News	Forum	Team SCHISM

SCHISM modeling system is a derivative work from the original SELFE model (v3.1dc as of Dec. 13 , 2014). SCHISM has been implemented by Dr. Joseph Zhang (College of William & Mary) and other developers around the world, and licensed under Apache. SELFE was developed at the Oregon Health Sciences University. However, there are now significant differences between the two models.

SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model) is an open-source community-supported modeling system based on unstructured grids, designed for seamless simulation of 3D baroclinic circulation across creek-lake-river-estuary-shelf-ocean scales. It uses a highly efficient and accurate semi-implicit finite-element/finite-volume method with Eulerian-Lagrangian algorithm to solve the Navier-Stokes equations (in either hydrostatic and non-hydrostatic form), in order to addresses a wide range of physical and biological processes. The numerical algorithm judiciously mixes higher-order with lower-order methods, to obtain stable and accurate results in an efficient way. Mass conservation is enforced with the finite-volume transport algorithm. It also naturally incorporates wetting and drying of tidal flats.

The SCHISM system has been extensively tested against standard ocean/coastal benchmarks and applied to a number of regional seas/bays/estuaries around the world (see 'Case study') in the context of general circulation, tsunami and storm-surge inundation, water quality, oil spill, sediment transport, coastal ecology, and wave-current interaction. SCHISM now includes many upgrades of the original SELFE code (v3.1dc); the major differences are summarized in Zhang et al. (Seamless cross-scale modeling with SCHISM, Ocean Modelling, 2016; see Publications).

The source code and user manual can be downloaded from this web site. The plot to the right shows a snapshot of various modules inside SCHISM.

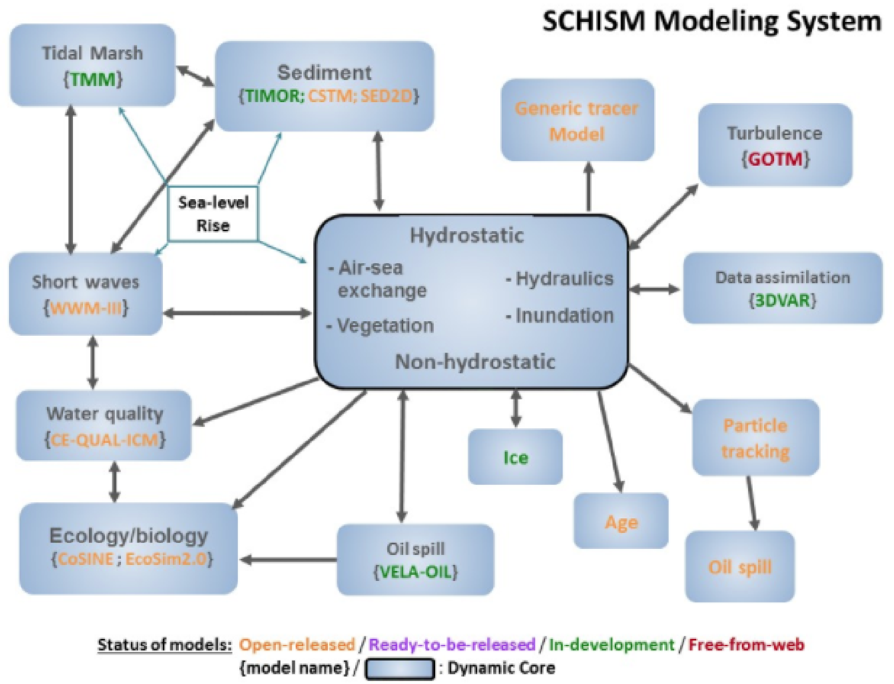
Major Characteristics of SCHISM

- Finite element/volume formulation
- Unstructured mixed triangular/quadrangular grid in the horizontal dimension
- Hybrid SZ coordinates or new LSC^2 in the vertical dimension
- Polymorphism: a single grid can mimic 1D/2DV/2DH/3D configurations
- Semi-implicit time stepping (no mode splitting): no CFL stability constraints → numerical efficiency
- Robust matrix solver
- Higher-order Eulerian-Lagrangian treatment of momentum advection (with ELAD filter)
- Natural treatment of wetting and drying suitable for inundation studies
- Mass conservative, monotone, higher-order transport solver: TVD^2; WENO
- **No bathymetry smoothing necessary**
- **Very tolerant of bad-quality meshes in the non-eddying regime**

Modeling system & application areas

- 3D baroclinic cross-scale lake-river-estuary-plume-shelf-ocean circulations
- Tsunami hazards
- Storm surge
- Sediment transport
- Biogeochemistry/ecology/water quality
- Oil spill
- Short wave-current interaction

Citation



Summary: how far can we push the cross-scale model?

- We have made good progress on seamless cross-scale modelling during the past 17 years
- Seamless cross-scale modeling can be effectively done with ***unstructured grids*** and ***implicit time stepping***
  - Besides accuracy consideration, efficiency, flexibility and robustness are also important factors in this endeavor
  - Balance between lower- and higher-order schemes is important
  - A seamless platform with 1D/2D/3D capability leads to efficiency
  - SCHISM is well demonstrated for nearshore and estuarine applications
  - We have extended SCHISM to large scale, in order to better handle the boundary condition
- How far can we go?
  - Nearshore: upstream rivers/creeks
  - Offshore: regional scale
  - Ultimate goal is to build a model that covers ocean-shelf-estuary-river-creek system without nesting (or at least minimize its use)