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Progress in the development and use of a finite element hydrospheric model

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Are adaptive- and unstructured-mesh GEFD models coming of age?

GEFD = Geophysical and Environmental Fluid Dynamics

- Classical structured-mesh GEFD models with (almost) constant resolution or grid nesting systems may be getting obsolete.

- Time may be ripe for developing models in which resolution may be enhanced **where** and **when** needed.

- For an eddy propagating in the Gulf of Mexico as an idealised internal Rossby wave packet, Bernard et al. (*Ocean Dynamics*, 2007) showed that a finite-element simulation with an adaptive grid (made up of triangles) was **one order of magnitude cheaper** (in terms of CPU time) than a constant-resolution one of the same accuracy, hence the motivation to develop SLIM.

The Second-generation Louvain-la-Neuve Ice-ocean Model (SLIM, www.climate.be/slim)

- SLIM's development started about 12 years ago, aiming at the **multi-scale/physics** modelling of (some of the components) of the **hydrosphere**.

- Key steps:
  - Collaboration of mechanical engineers and GEFD specialists;
  - Programming in C++;
  - Adopting the finite element (FE) method, then switching to Discontinuous Galerkin FE (DG FE ≈ hybrid of FE and FV);
  - Inserting SLIM in the FE software built around the source code of Gmsh (www.geuz.org/gmsh) ⇒ durability of SLIM.

What SLIM can and cannot do (I)

• SLIM solves **partial differential equations** in 1, 2 or 3 space dimensions for unknowns of the form $\psi(t,\mathbf{x})$. The generic form of (most of) these equations is:

$$\underbrace{\frac{\partial \psi}{\partial t} + \nabla \bullet (\overbrace{\mathbf{v}\psi - \mathbf{K} \bullet \nabla \psi}^{\text{advect.+diff. flux}})}_{} = \overbrace{P - D}^{\text{"reactions"}}$$

Dealt with by SLIM on an unstructured mesh by means of the discontinuous Galerkin finite element method in a C++ code

Dealt with by SLIM or by external modules interfaced with SLIM

We are not (always) reinventing the wheel...

What SLIM can and cannot do (II)

• SLIM is capable of being **interfaced** with well-established models/modules often based on (radically) **different numerical methods** (e.g. finite differences) and **programming languages** (e.g. FORTRAN):

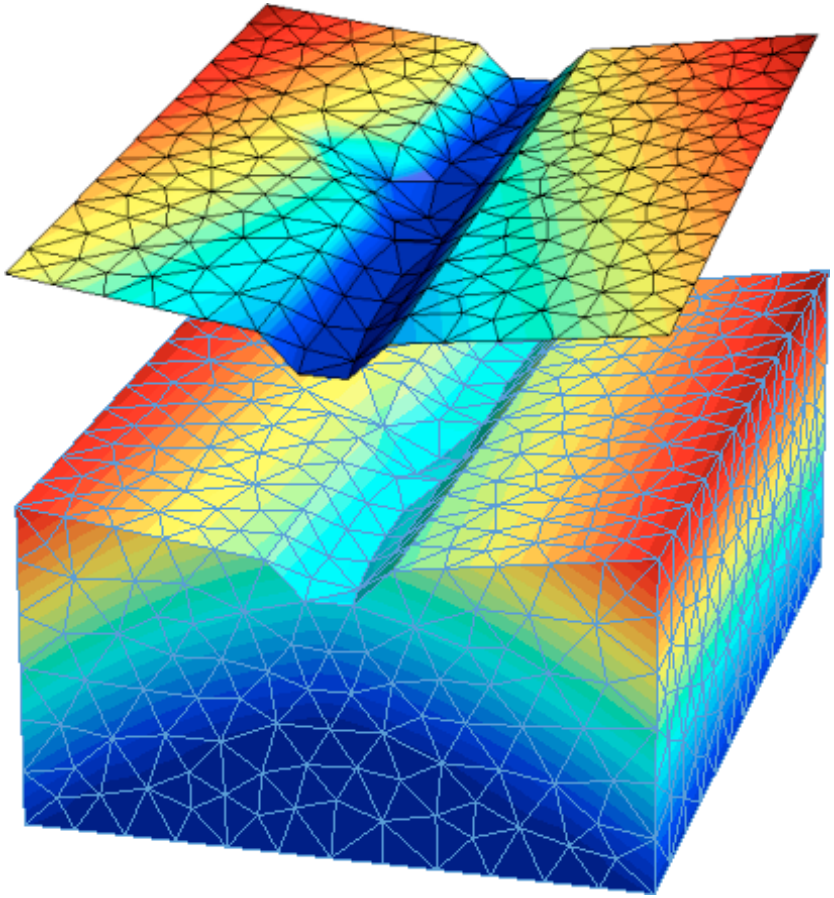
- in SLIM's hydrodynamic module, the turbulence closure is GOTM (General Ocean Turbulence Model, www.gotm.net);

- the sea ice thermodynamics is now that of LIM3 (Louvain-la-Neuve Sea Ice Model, version #3, www.climate.be/lim);

• SLIM solves CART's equations (www.climate.be/cart), to obtain diagnostic timescales (age, residence time, exposure time, etc.).

• Most in- and out-put files are to be dealt with by means of specific routines, owing to the unstructured nature of the mesh.

Groundwater and surface water



This worked started about 2 years ago

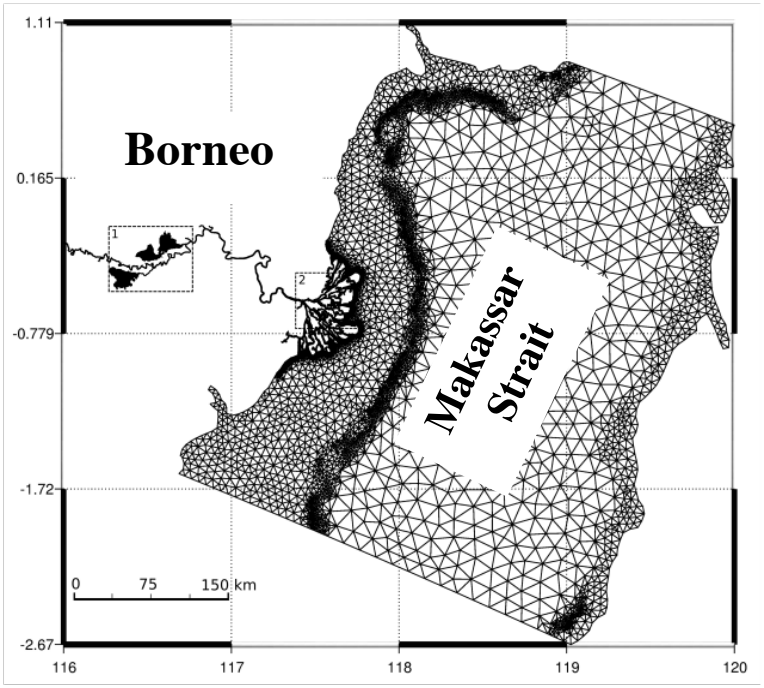
Surface flows:
diffusive wave approximation of
the shallow-water equations
(solved with DG FEM)

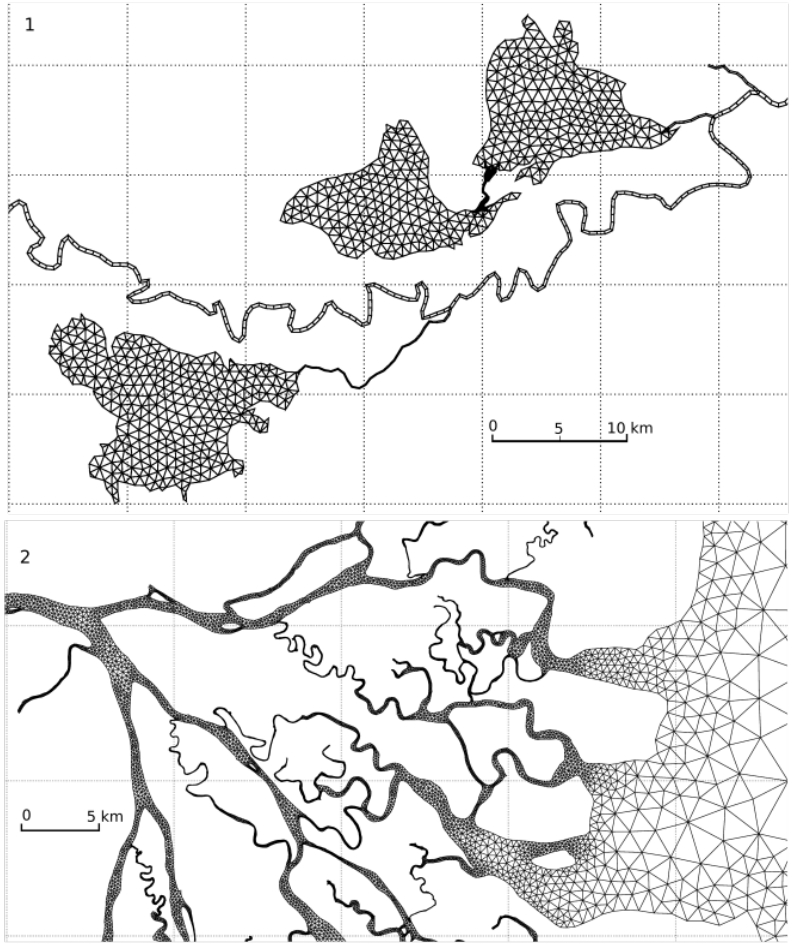
Outline:

1. 3D subsurface flows
2. 2D runoff
3. coupling between surface/subsurface

Subsurface flows:
Richards equation
(soved with DG FEM)

The Mahakam river-sea continuum (Indonesia)



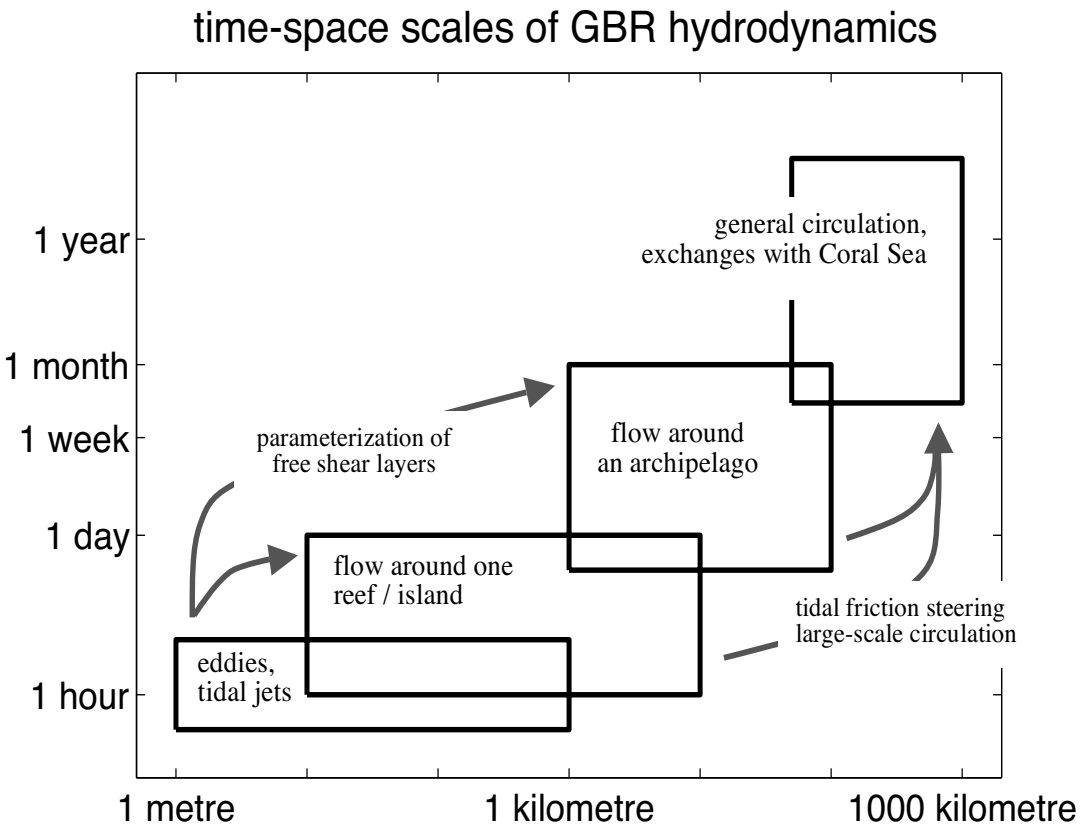


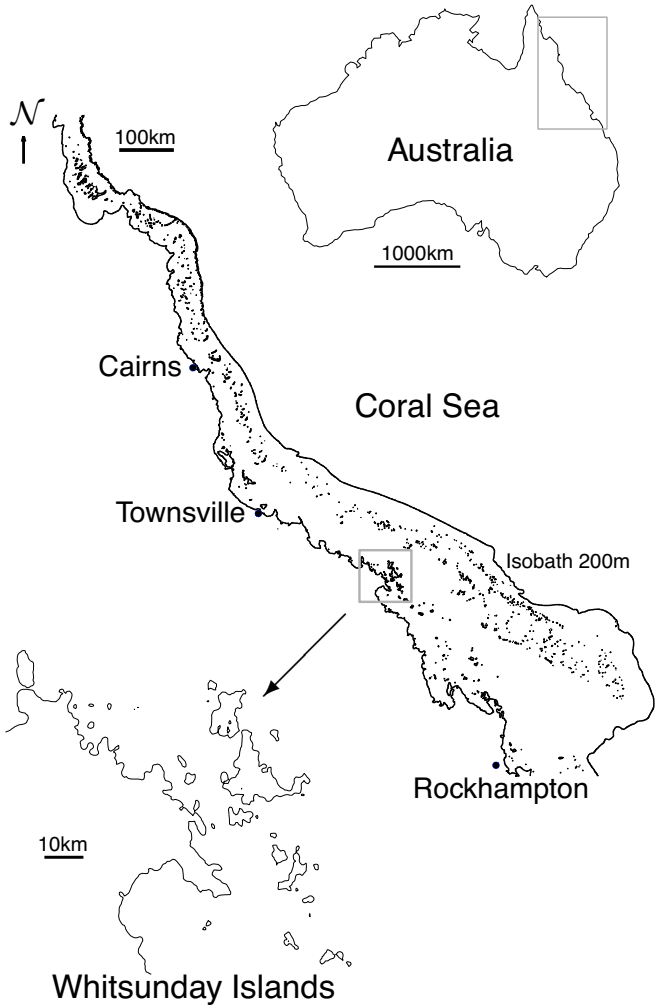
de Brye et al. (*Ocean Dynamics*, 2011)
Sassi et al. (*Ocean Dynamics*, 2011)

Hydrodynamics in 1D + 2D (tides, river discharge)
Tidal impact on the division of river discharge over distributary channels
Hydraulic geometry of the delta (under review)
Modelling salinity intrusion (work in progress)

The Great Barrier Reef, Australia (GBR) (I)

See Wolanski et al. (2003, in: *Advances in Coastal Modeling*, V.C. Lakhan (Ed.))





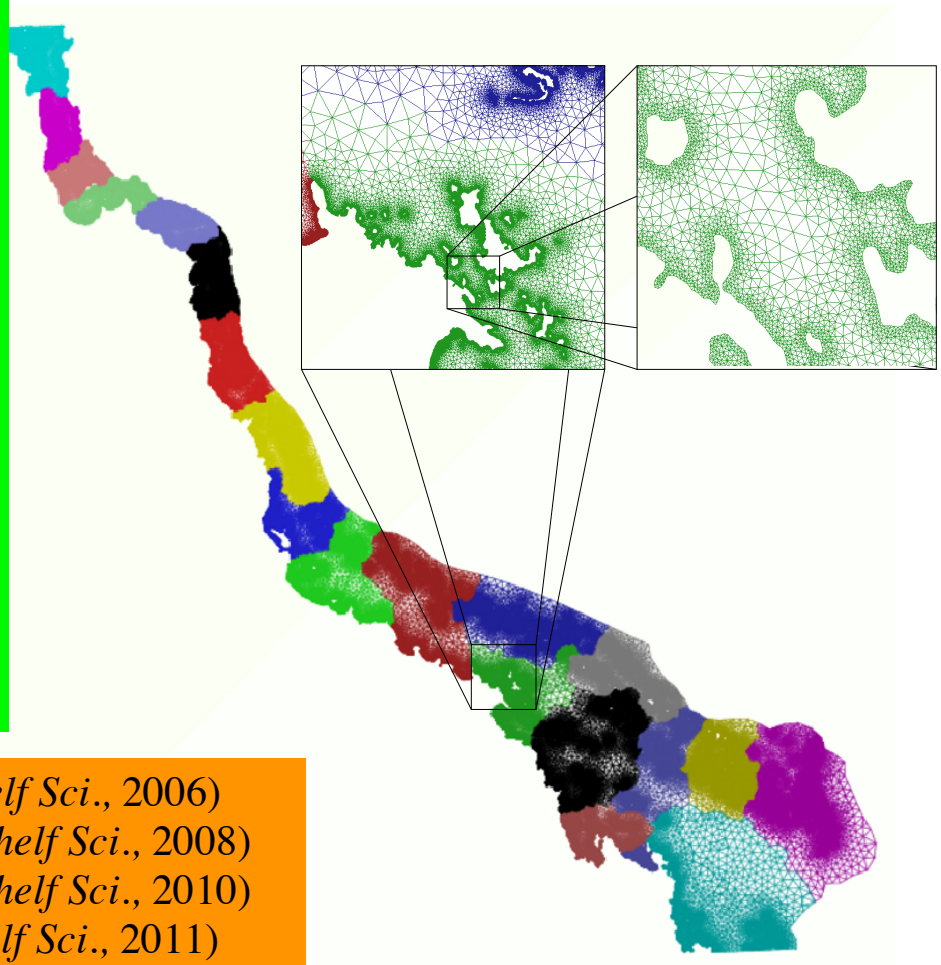
The widest range of time and space scales we have addresses so far!

The Great Barrier Reef, Australia (GBR) (II)

- $O(10^6)$ triangles, with

$\Delta x_{\max} / \Delta x_{\min} \approx 10^2$

- Forcings: wind, tides, Coral Sea inflow
- A wide spectrum of hydrodynamic processes simulated (eddies, tidal jets, "sticky waters", general circulation)
- Modelling of sediment transport, turtle hatchlings, etc.

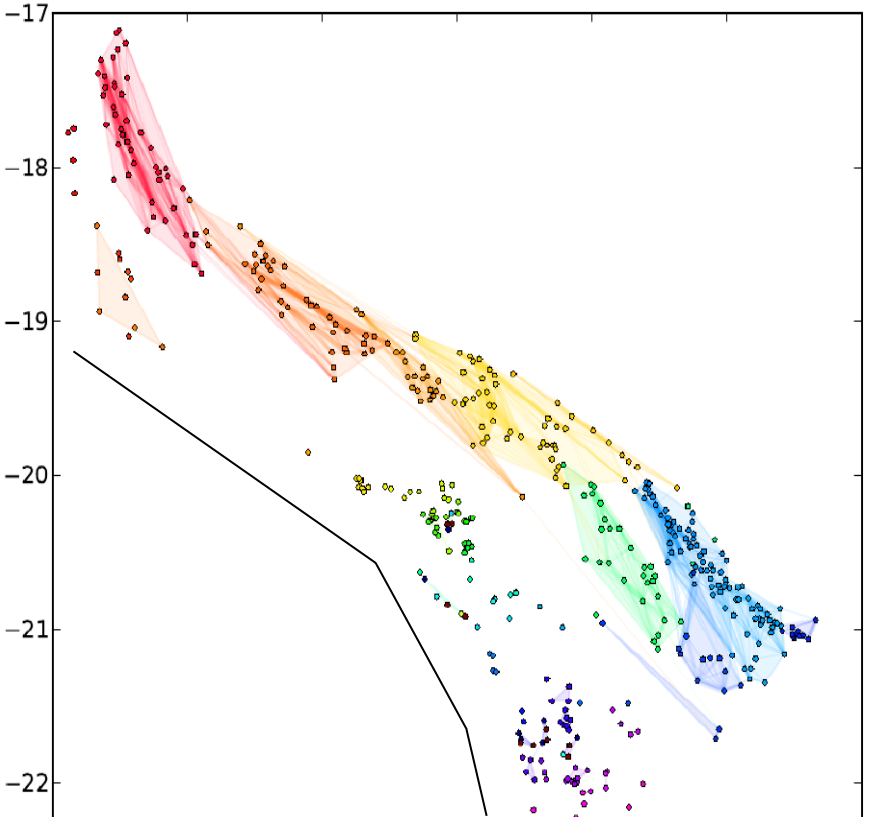


Legrand et al. (*Est., Coast. and Shelf Sci.*, 2006)
Lambrechts et al. (*Est., Coast. and Shelf Sci.*, 2008)
Lambrechts et al. (*Est., Coast. and Shelf Sci.*, 2010)
Andutta et al. (*Est., Coast. and Shelf Sci.*, 2011)
Hamann et al. (*Ecological Modelling*, 2011)

The Great Barrier Reef, Australia (GBR) (III)

- Modelling the transport of coral and fish eggs/larvae with a Lagrangian transport module.
- Assess inter-reef **connectivity**.
- Use tools from graph theory to identify clusters of highly connected reefs (sites.uclouvain.be/networks).
- Identify reef clusters **weakly connected** to the rest of the GBR, i.e. the most **vulnerable** reefs.

Work in progress, with preliminary results to be presented at the 12th International Coral Reef Symposium (Cairns, July 2012, www.icrs2012.com)

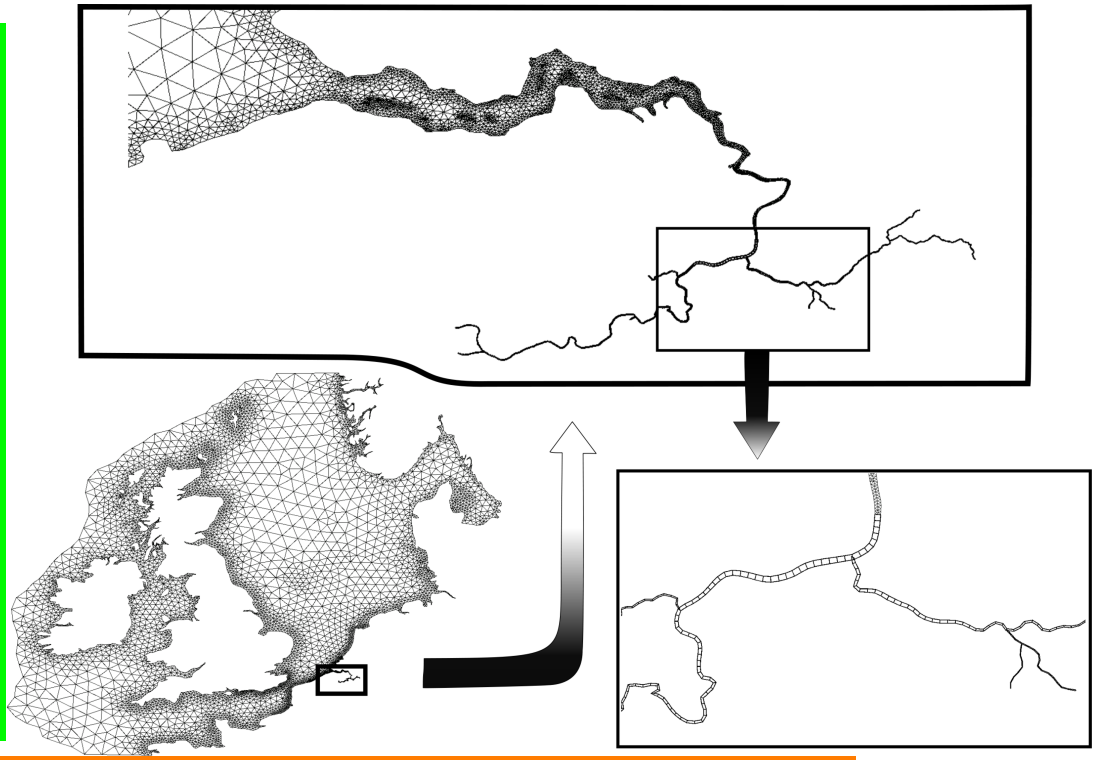


Map of reefs in the central GBR with reefs grouped into clusters (colours).
Solid line shows approximate position of coastline.

The Scheldt river-sea continuum (I)

The main advantage of unstructured meshes probably is that multi-scale modelling is rendered easier. Example: the Scheldt tributaries, River, Estuary and the adjacent coastal zone.

- 40% of the meshes in the estuary, which represents 0.3% of the computational domain.
- No major problem with open boundary conditions (for tides, storms, river discharge).

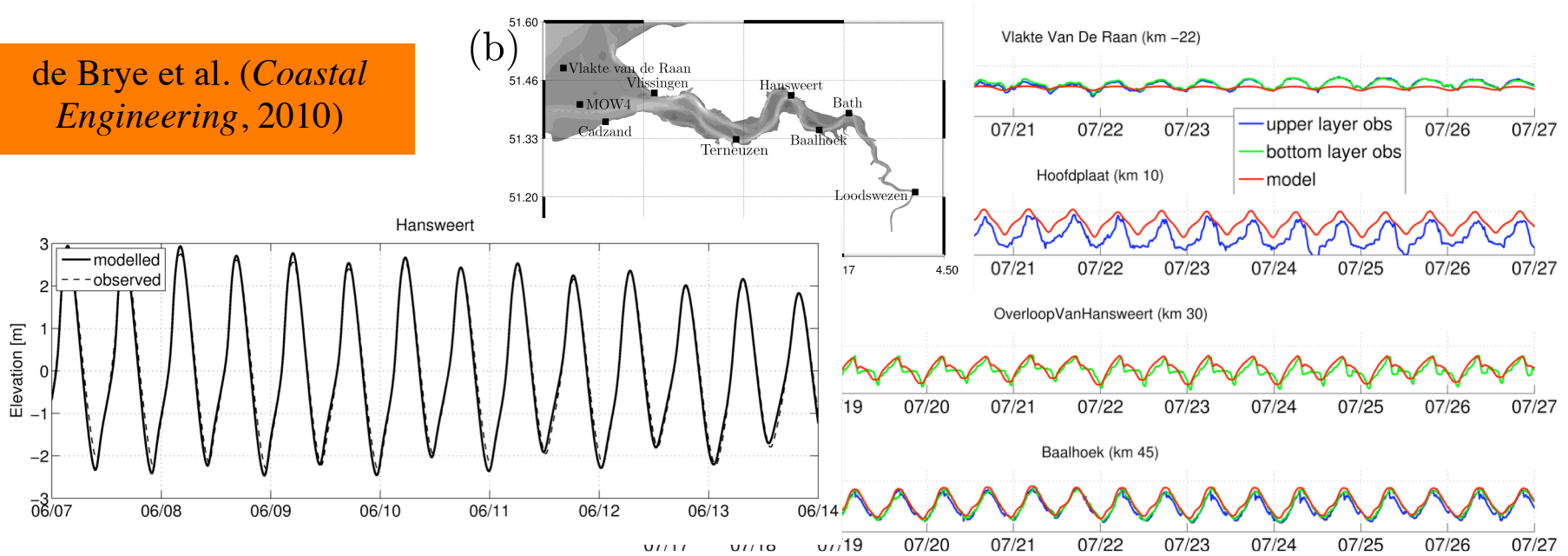


SLIM's DG FEM wetting-drying schemes:
Gourgue et al. (*Advances in Water Research*, 2009)
Kärnä et al. (*Computer Methods in Applied Mechanics and Engineering*, 2011)

The Scheldt river-sea continuum (II)

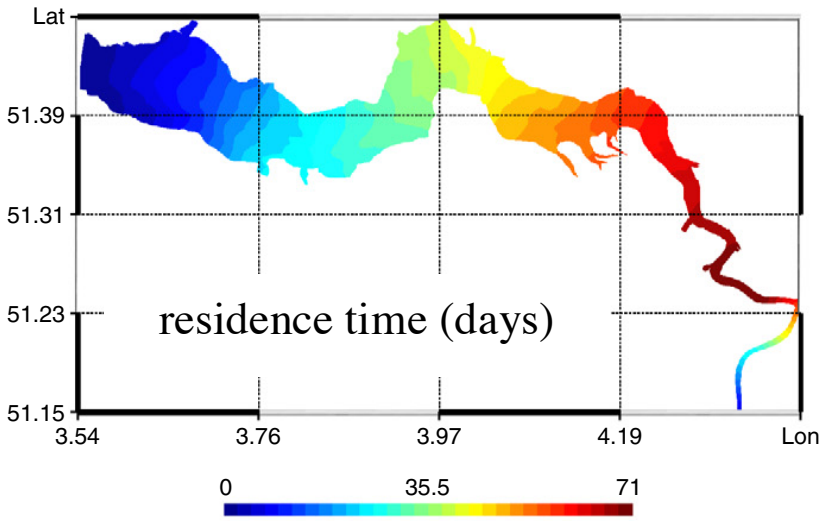
- Hydrodynamics is forced by tides (prescribed and the shelf break) and wind stress.
- Tidal components (amplitude and phase) are well represented, as well as salinity (treated as a passive tracer).

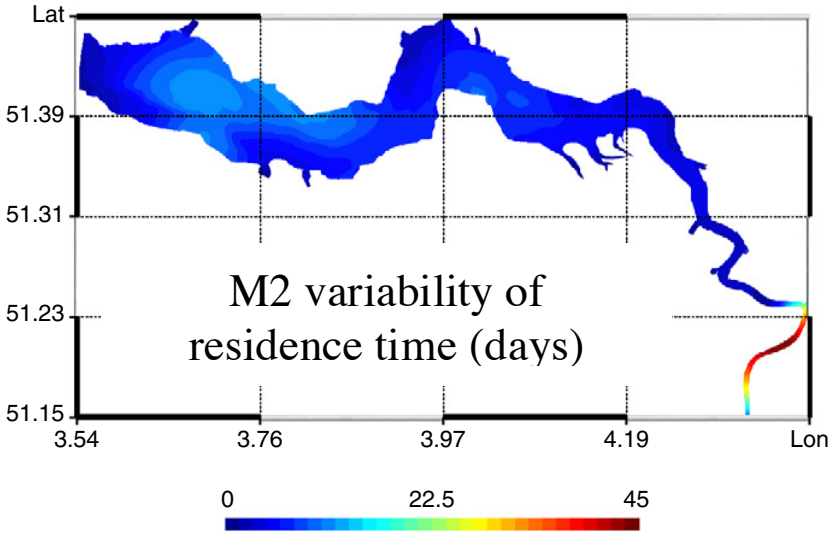
de Brye et al. (*Coastal Engineering*, 2010)



The Scheldt river-sea continuum (III)

- CART's water renewal timescales (age, residence time, exposure time) and return coefficient for the estuary have been simulated at any time and position.



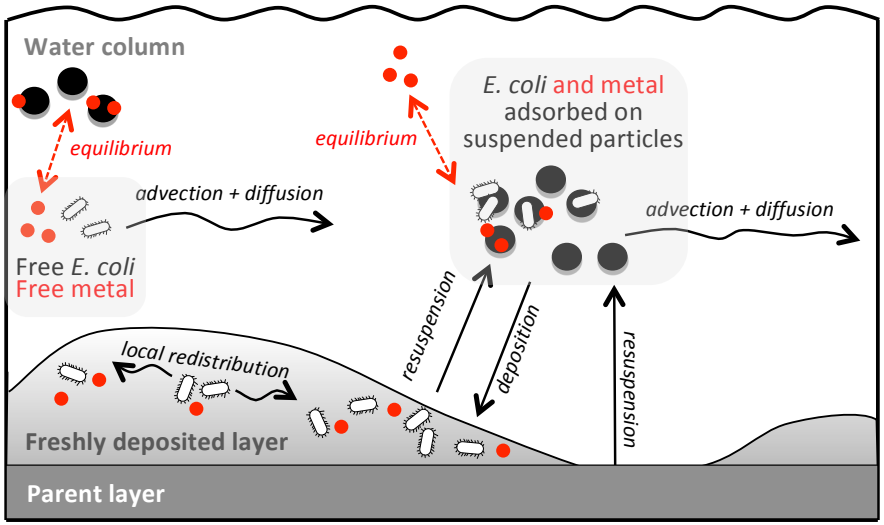


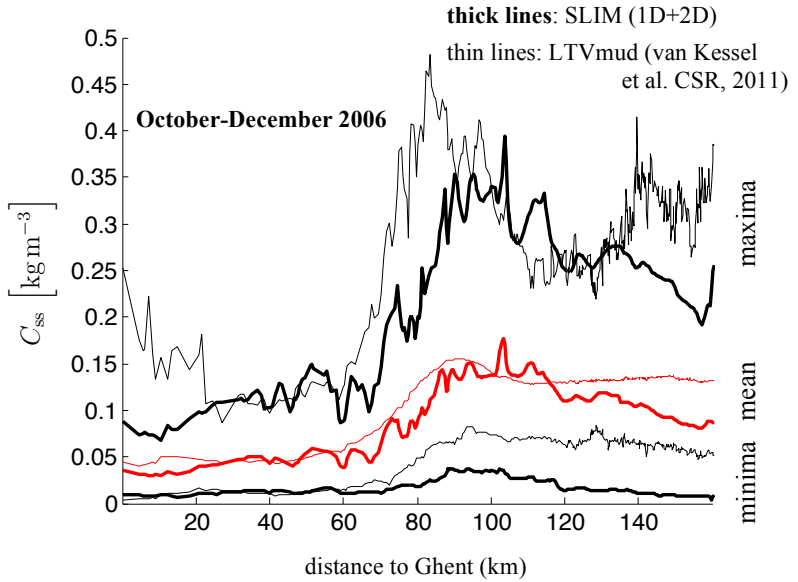
- Surprising result: the large time variability of the residence time.

Blaise et al. (*Ocean Dynamics*, 2010), de Brauwere et al. (*Journal of Marine Systems*, 2011)
de Brye et al. (*Journal of Marine Systems*, 2012)

The Scheldt river-sea continuum (IV)

• We are developing a simple sediment module, which is a prerequisite for simulating the fate of several classes of contaminants (fecal bacteria, trace metals).





de Brauwere et al. (*Env. Model. & Soft.*, 2009)
de Brauwere et al. (*Water Research*, 2011)

Suspended sediment concentration:
results of SLIM (1D+2D) are not that different from those of the 3D, much more complex LTVmud model

SLIM's three-dimensional baroclinic component (I)

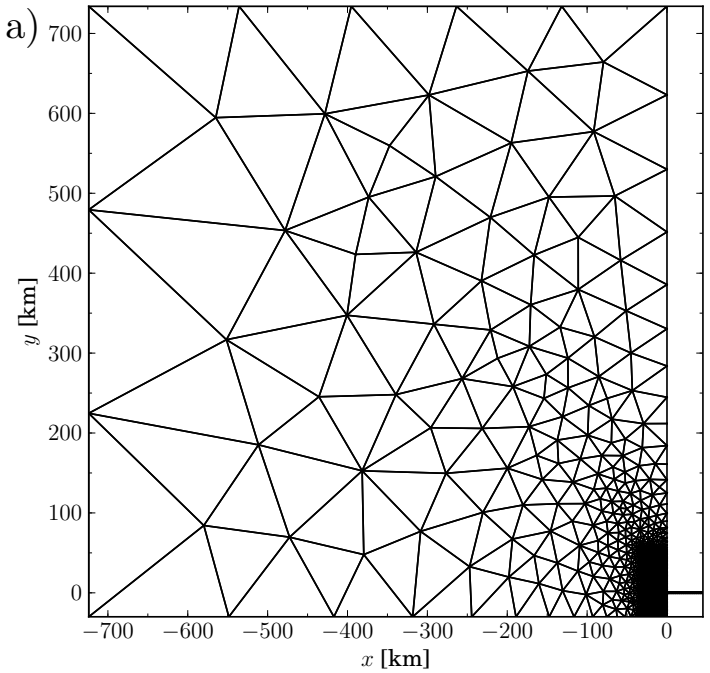
- Several attempts have been made to obtain a 3D, baroclinic module.

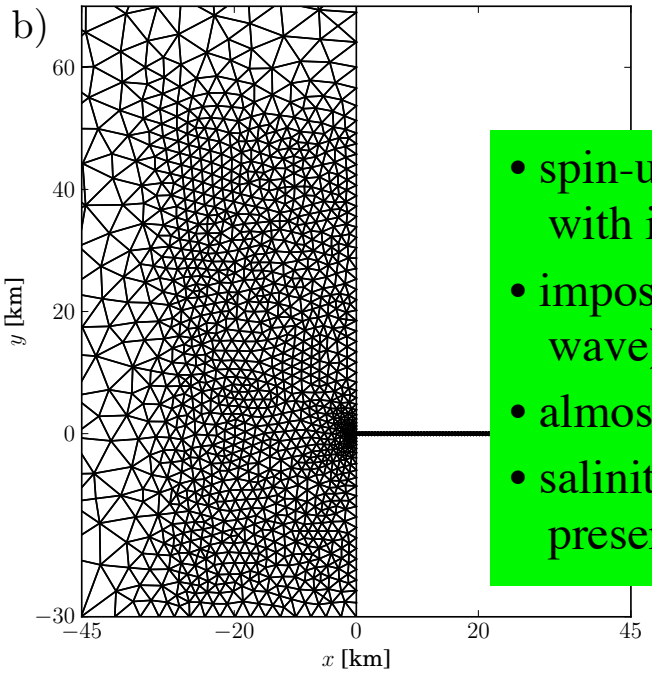
- The present version seems very promising (prismatic elements, DG FEM with flux limiters, split explicit, GOTM turbulence closure). It has been applied successfully to several test cases
  - wind-driven deepening of surface mixed (Kato and Phillips, *Journal of Fluid Mechanics*, 1969)
  - idealised estuarine circulation (Warner et al., *Computers & Geosciences*, 2010)
  - adjustment of a density front (Wang, *Journal of Physical Oceanography*, 1984)

Kärnä et al. (*Ocean Modelling*, 2012)
Kärna et al. (*Ocean Modelling*, submitted)

SLIM's three-dimensional baroclinic component (II)

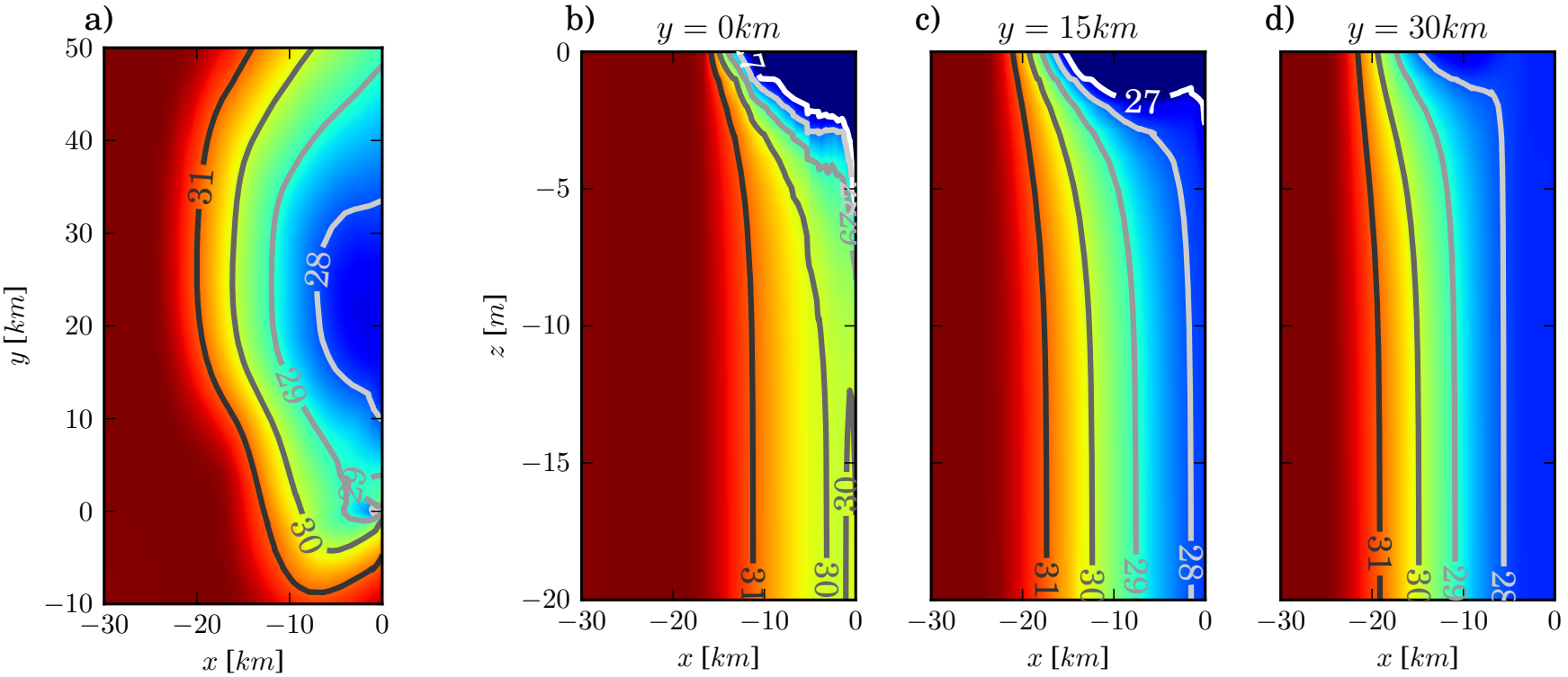
• SLIM's results compare very well to other 3D models (Delft3D, GETM) on the classical ROFI test case of de Boer et al. (*Ocean Dynamics*, 2006).





- spin-up of 30 tidal cycles, with initial salinity of 32 PSU
- imposed M2 tide (Kelvin wave) at the souther boundary
- almost periodic regime
- salinity gradient well preserved

SLIM's three-dimensional baroclinic component (III)



Tidally-averaged salinity distribution: depth average (a), and vertical transects at river mouth (b), 15 km downstream of it (c) and 30 km downstream (d).

Conclusion

- SLIM already has some of the building blocks of a multi-scale/physics hydrospheric model, which are progressively coupled with eachother.

- The computational efficiency must be increased significantly (e.g. by resorting to multi-rate schemes).

Seny et al. (*Int. J. Num. Meth. Fluids.*, in press)

- Which existing models/modules should be interfaced with SLIM (rather than developed by ourselves within SLIM's framework)?

- The (relative lack of) availability of multi-scale data is a key problem.

www.climate.be/slim

Thank you for your attention!