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SLIM: a numerical model for the land-sea continuum and beyond

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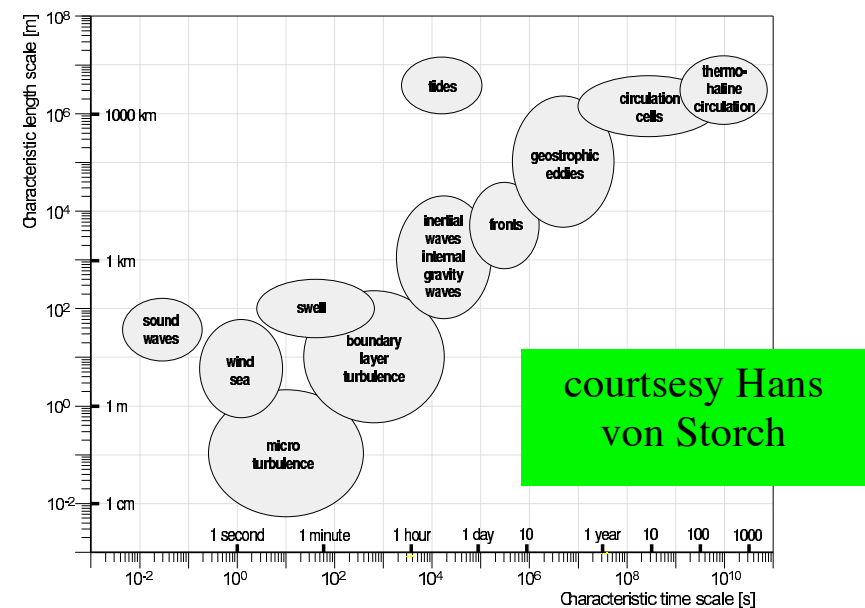
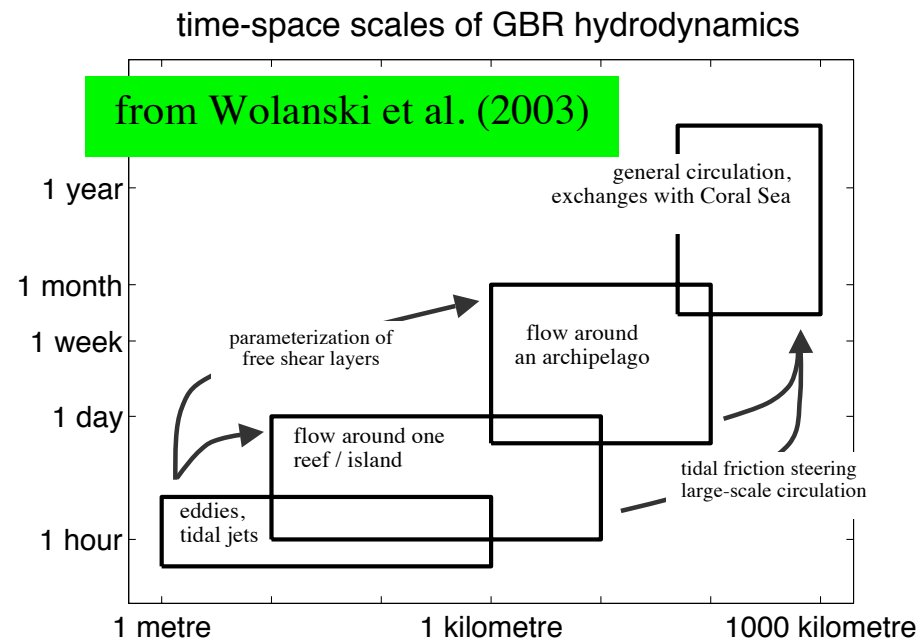
SLIM has been developed and used by a number of colleagues, including

Fernando Pinheiro Andutta, Paul-Emile Bernard, Sébastien Blaise, Sylvain Bouillon, Hans Burchard, Richard Comblen, Anouk de Brauwere, Benjamin de Brye, Thomas De Maet, Philippe Delandmeter, Eric Delhez, Thierry Fichefet, Olivier Gourgue, Emmanuel Hanert, Hidayat Hidayat, Ton Hoitink, Ozgur Karatekin, Tuomas Kärnä, Jonathan Lambrechts, Yoann Le Bars, Vincent Legat, Sébastien Legrand, Olivier Lietaer, Samuel Mechior, Jaya Naithani, Alice Pestiaux, Chien Pham Van, Jean-François Remacle, Maximiliano Sassi, Bruno Seny, Sandra Soares Frazao, Benoît Spinewine, Christopher Thomas, Martin Vancoppenolle, Valentin Vallaeys, Bart Vermeulen, David Vincent, Laurent White, Eric Wolanski.

Their numerous, valuable contributions are gratefully acknowledged.

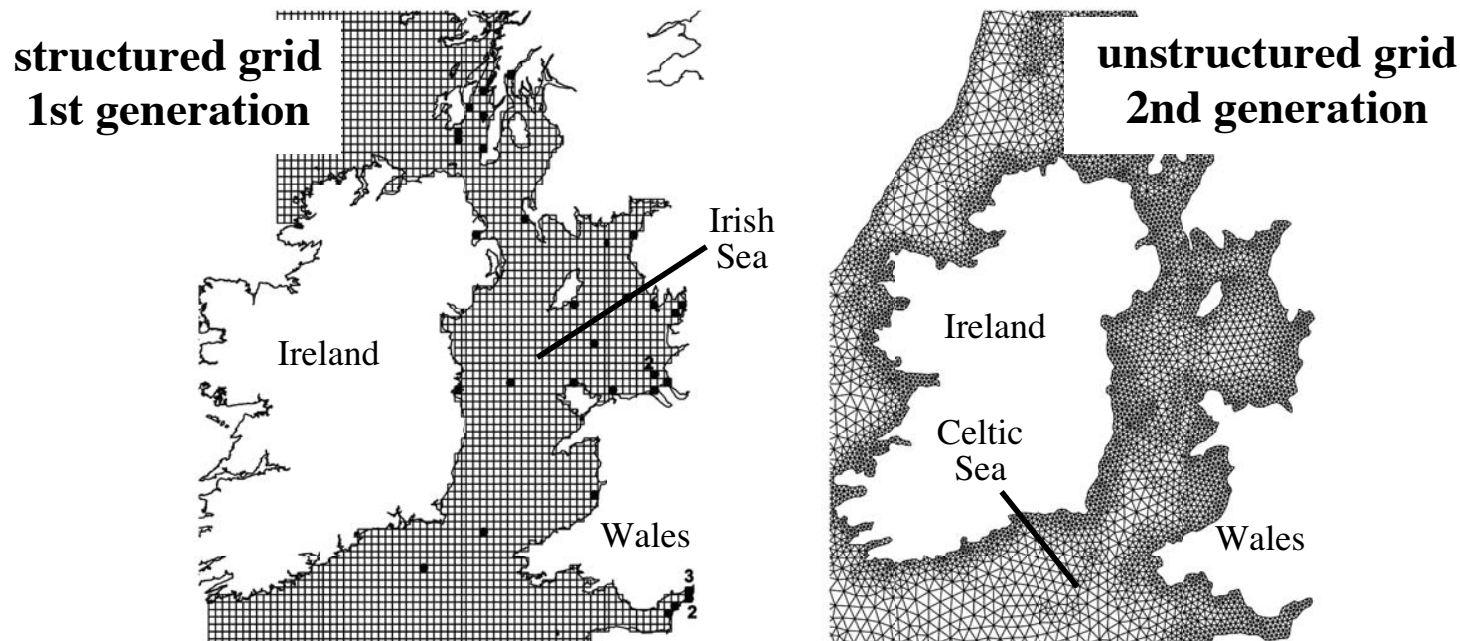
The need for multi-scale/physics models

- Phenomena occurring in geophysical and environmental fluid flows span an enormous range of space and time scales.



- One of the greatest challenges modellers are currently faced with is to widen the range of explicitly resolved phenomena.

Structured vs unstructured grids in geophysical and environmental fluid dynamics (GEFD) models



Impossible to transform step by step a first generation dynamical core into a second generation one.

A tough choice is to be made!

This not a mere “technical” detail, since the flows to be dealt with are intrinsically multi-scale.

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

- 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. **⇒ movie1**
- Encouraging example: reduced-gravity simulation of a baroclinic eddy (e.g. Lewis and Kirwan, *JGR* 1987) in the Gulf of Mexico by means of a Discontinuous Galerkin (DG), finite-element, adaptive-mesh model (Bernard et al., *Ocean Dynamics*, 2007).

This simulation is **one order of magnitude cheaper** than a constant-resolution one of the same accuracy!

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

- SLIM's development started about 15 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 $\approx$ hybrid of FE and FV);
 - Inserting SLIM in the FE software built around the source code of Gmsh (www.geuz.org/gmsh) $\Rightarrow$ 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:

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

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

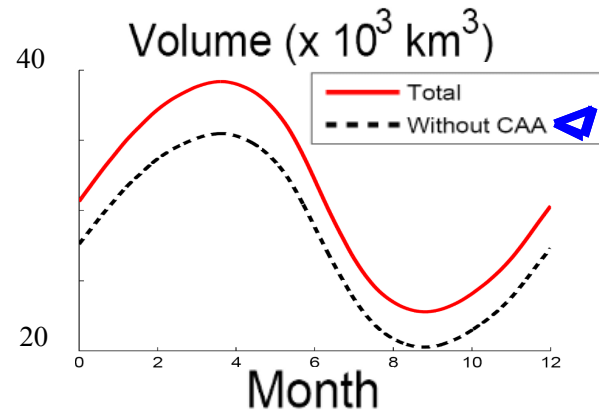
Dealt with by SLIM or by external modules interfaced with SLIM

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

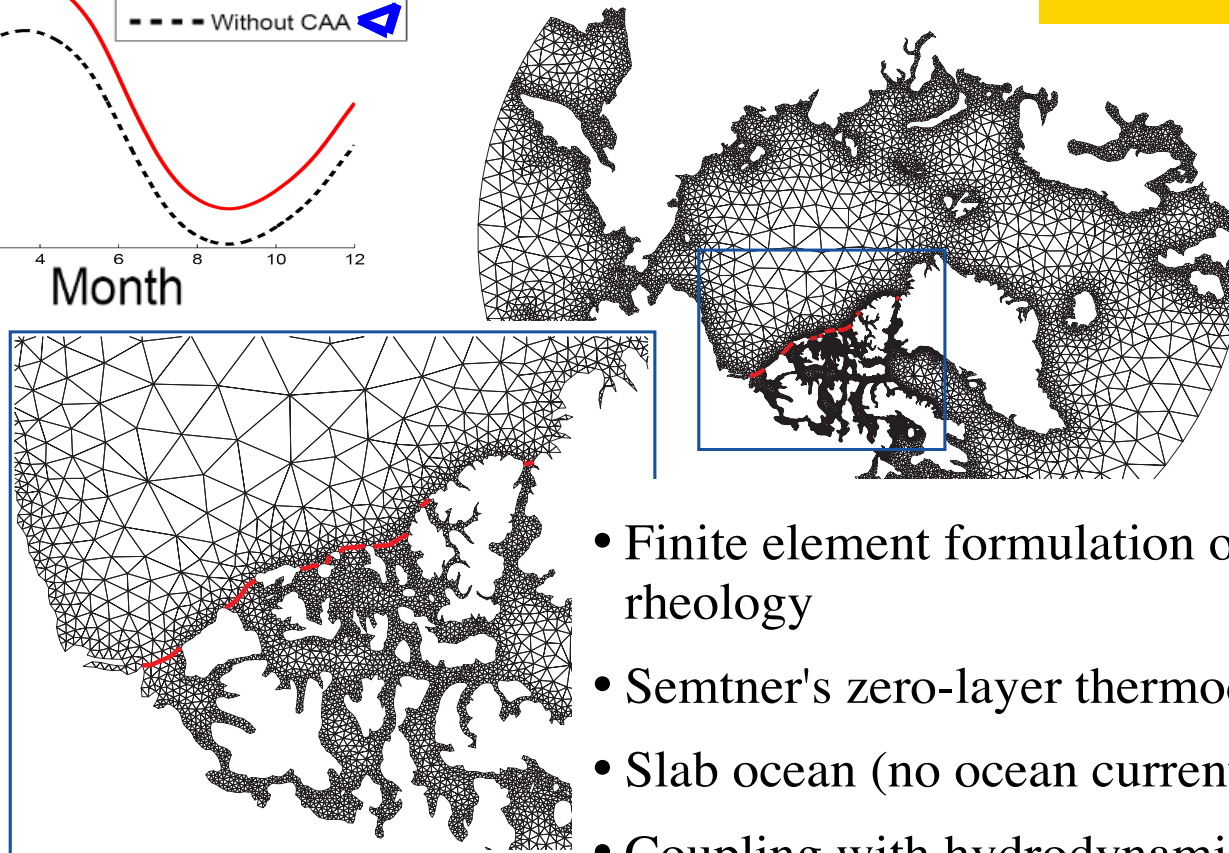
What SLIM can and cannot do (II)

- 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.

Sea ice in the Arctic



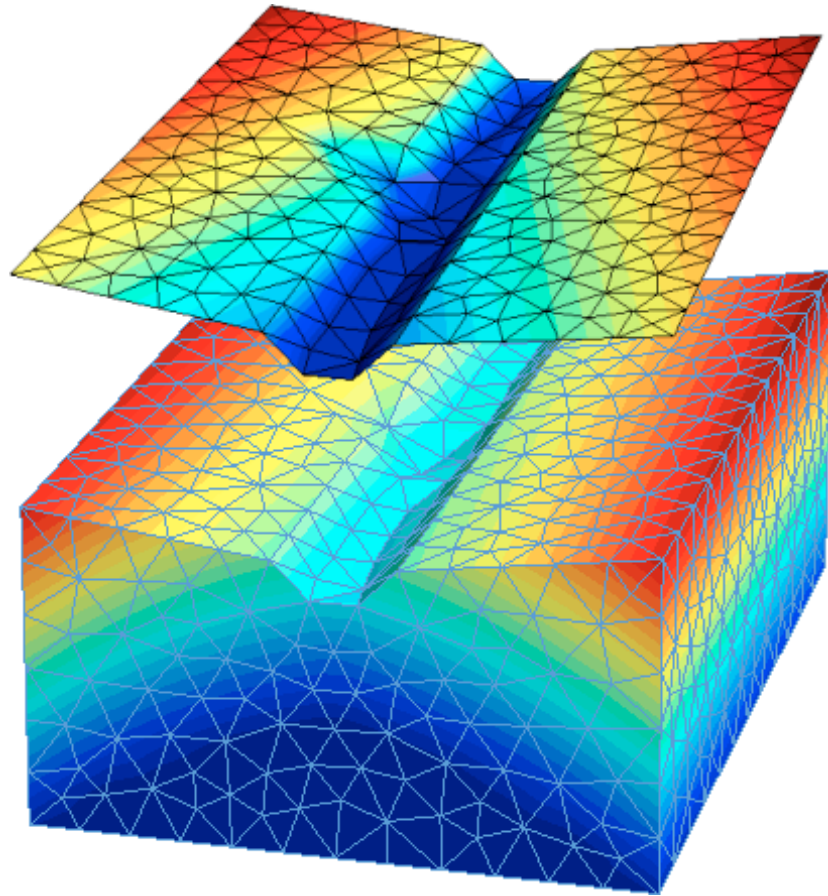
⇒ movie2



- Finite element formulation of Hibler's rheology
- Semtner's zero-layer thermodynamics
- Slab ocean (no ocean current)
- Coupling with hydrodynamic module in progress

Lietaer et al. (*Ocean Modelling*, 2008)
Vancoppenolle et al. (*Ocean Modelling*, 2009)

Groundwater and surface water



de Maet et al. (*Journal of Hydrodynamics*, 2014)

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

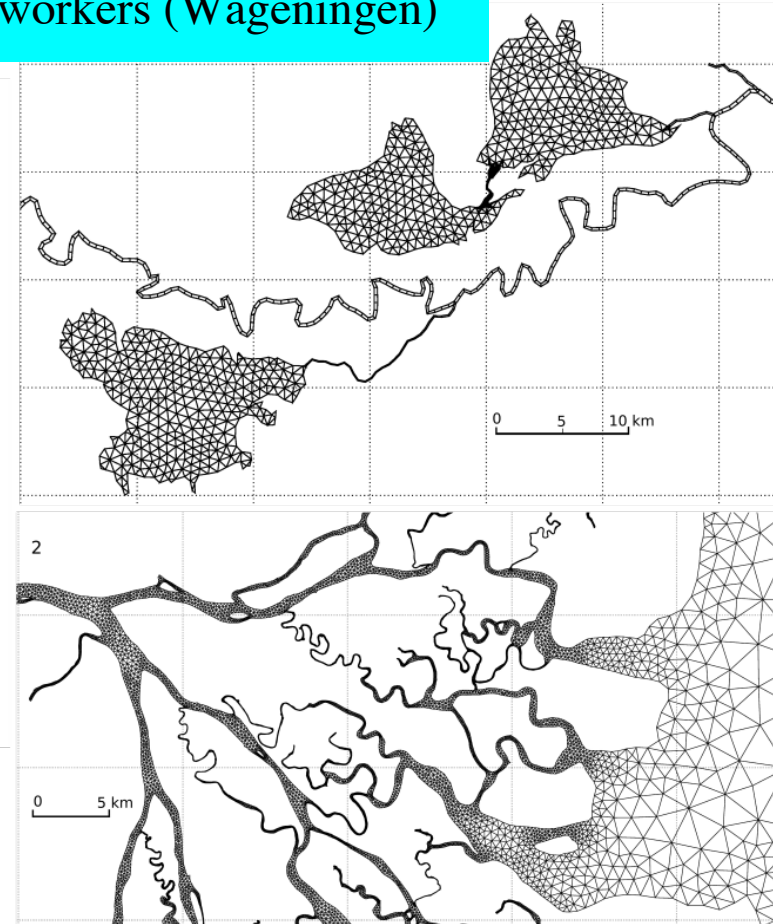
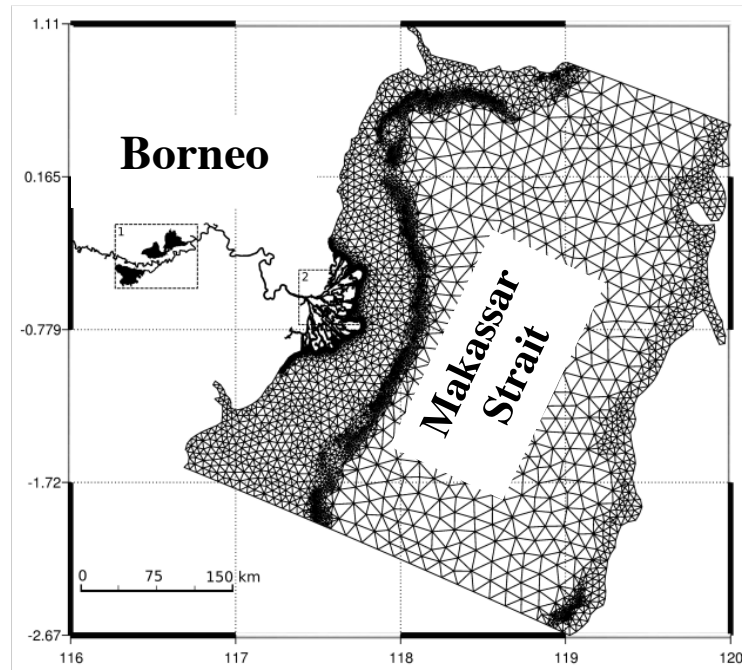
Outline:

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

Subsurface flows:
Richards equation
(solved with DG FEM)

The Mahakam river-sea continuum (Indonesia) (I)

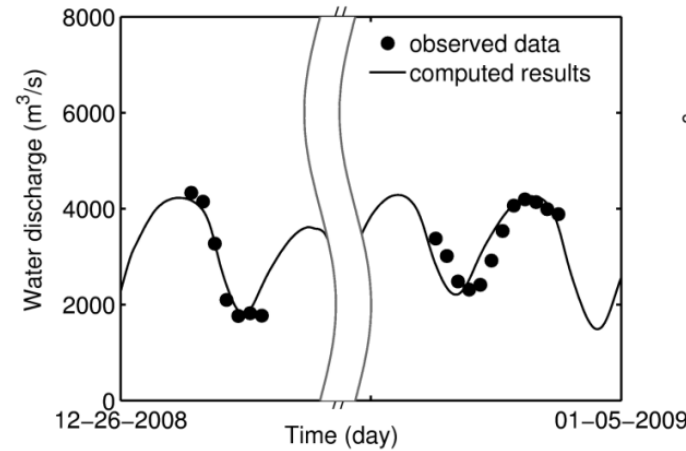
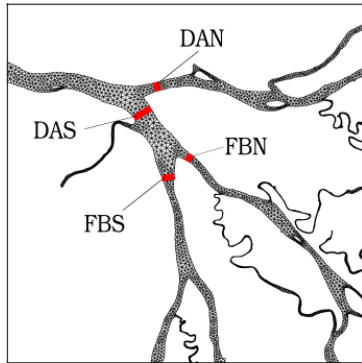
Work carried out with Prof Ton Hoitink and coworkers (Wageningen)



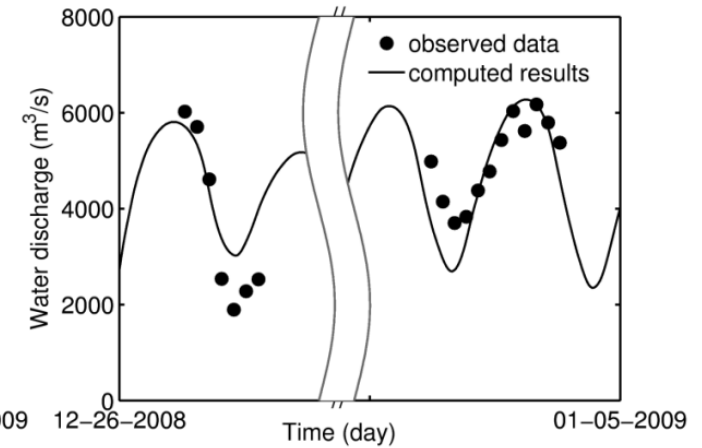
de Brye et al. (*Ocean Dynamics*, 2011)
Sassi et al. (*Ocean Dynamics*, 2011)
Sassi et al. (*JGR Earth Surface*, 2012)

Hydrodynamics in 1D + 2D (tides, river discharge)
Tidal impact on the division of river discharge over distributary channels
Hydraulic geometry of the delta
Modelling fine-grained sediment transport

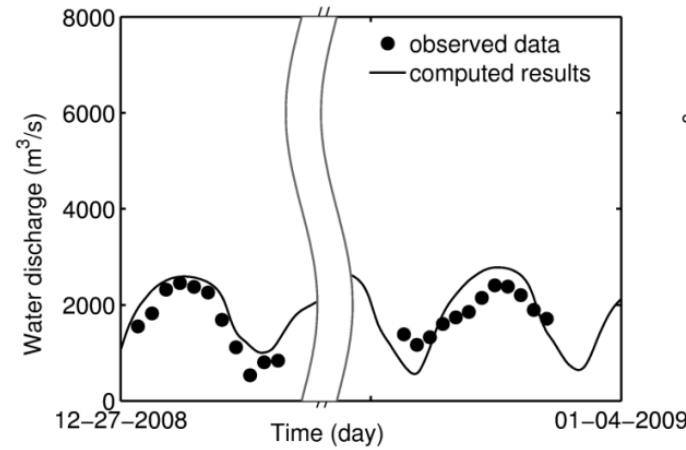
The Mahakam river-sea continuum (Indonesia) (II)



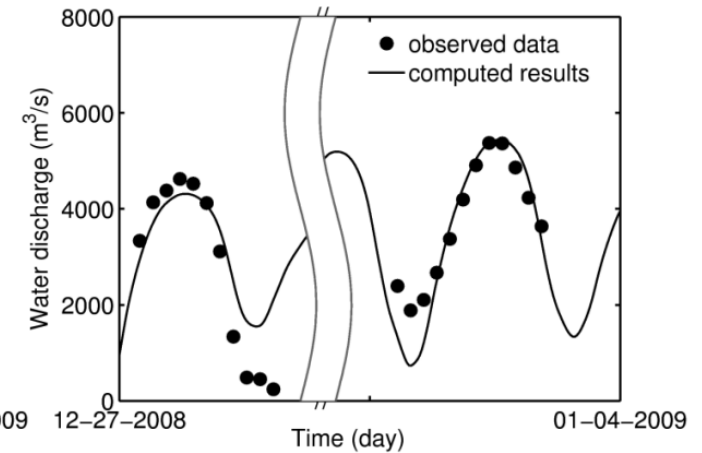
(a) DAN



(b) DAS



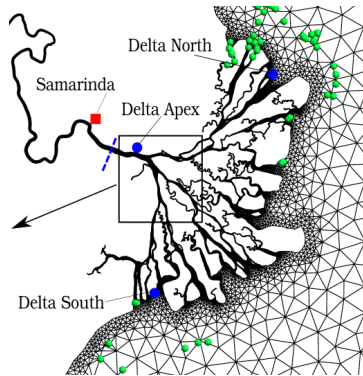
(c) FBN



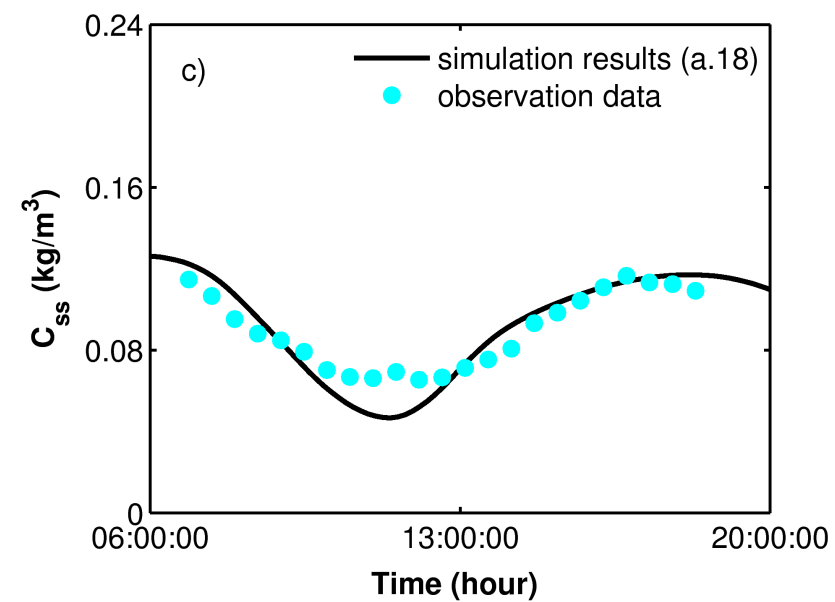
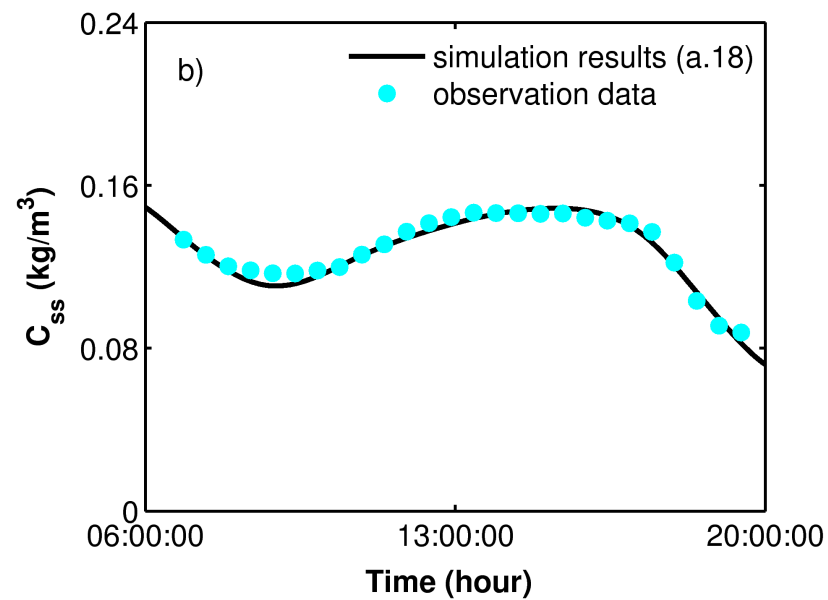
(d) FBS

Water discharge
in the delta

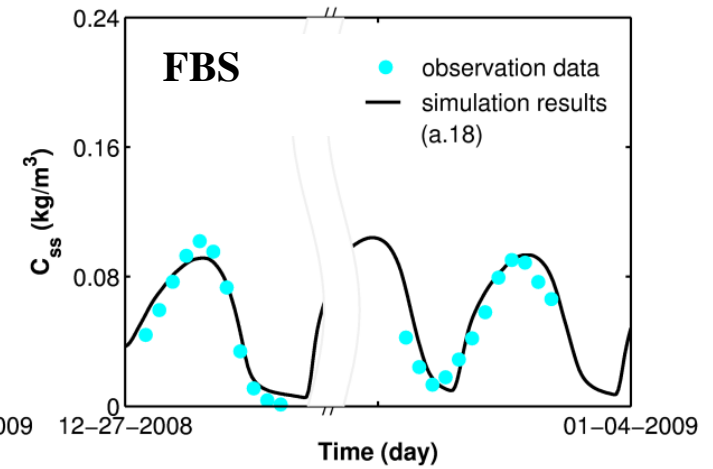
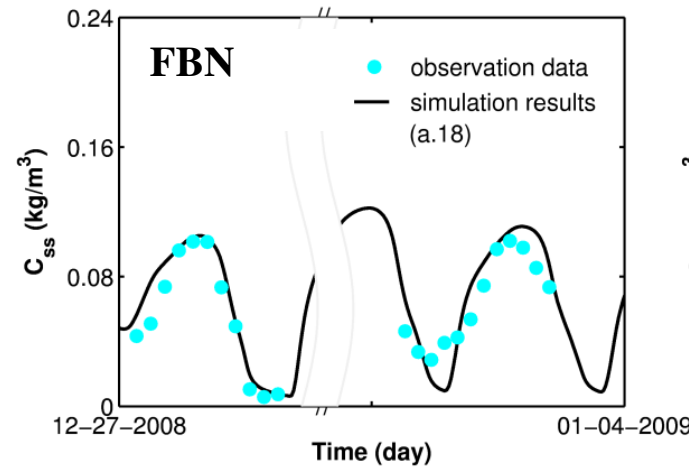
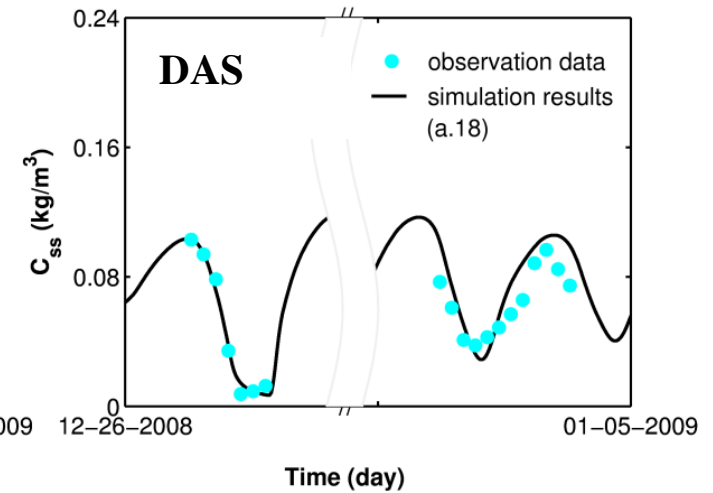
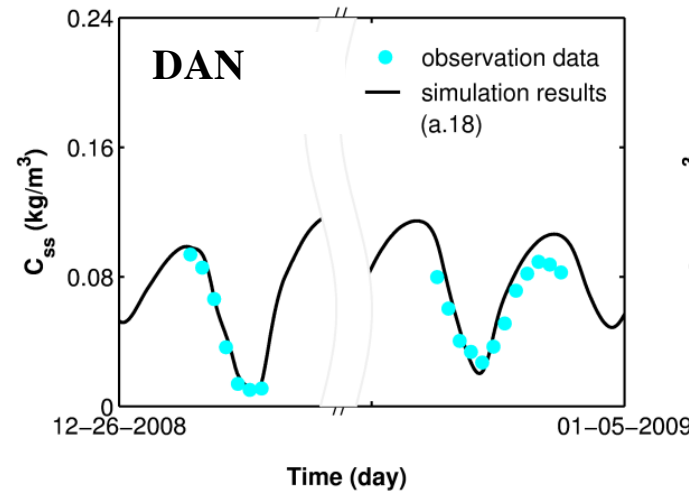
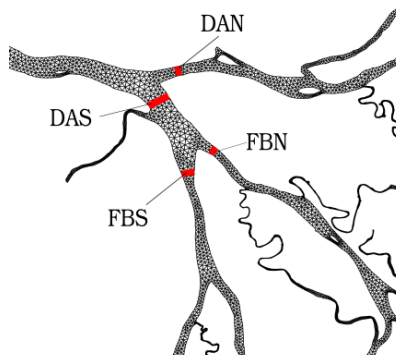
The Mahakam river-sea continuum (Indonesia) (III)



Suspended sediment concentration (SSC)
at Samarinda
(a little upstream of the delta apex)



The Mahakam river-sea continuum (Indonesia) (IV)

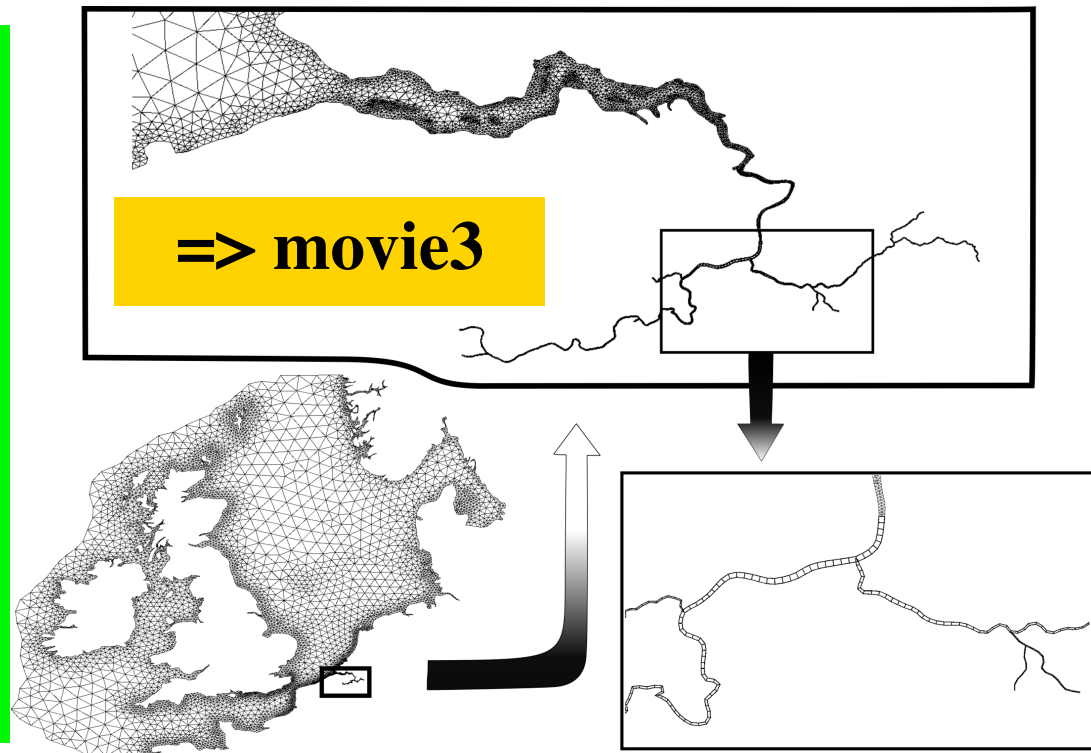


**SSC in
the delta**

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).

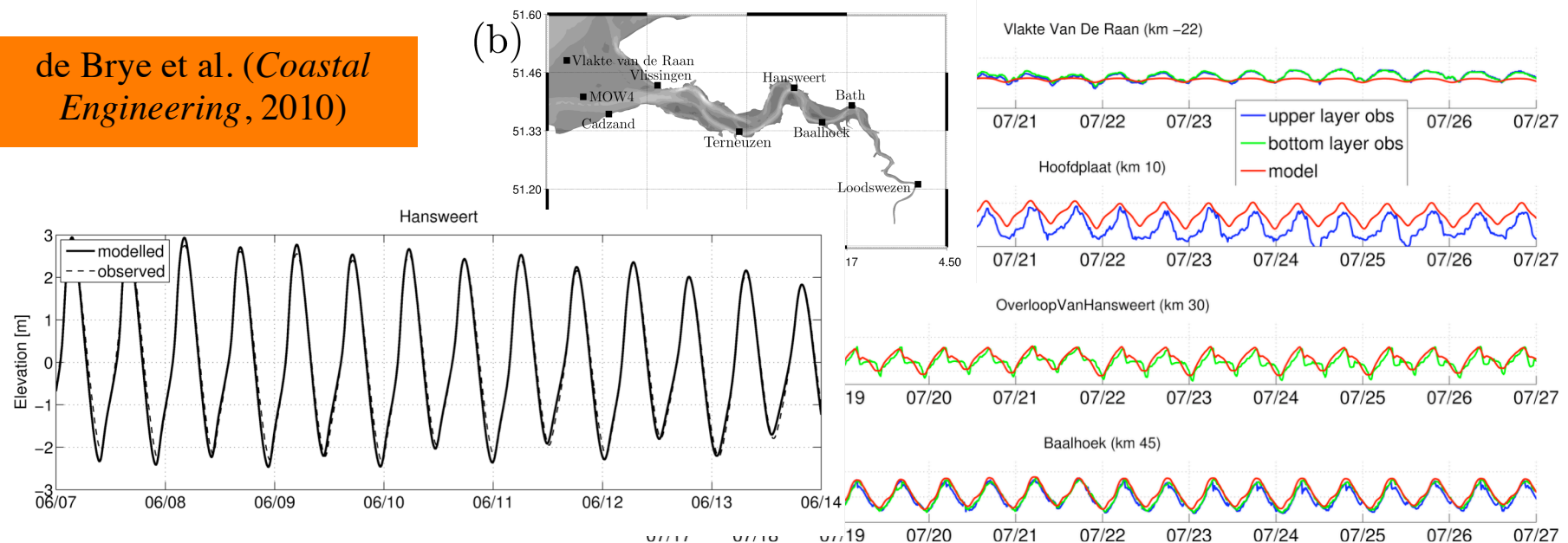


SLIM's DG FEM wetting-drying schemes:
Gourgue et al. (*Advances in Water Research*, 2009)
Kärnä et al. (*Computer Methods in Applied Mechanics and Engineering*, 2011)

The Scheldt river-sea continuum (II)

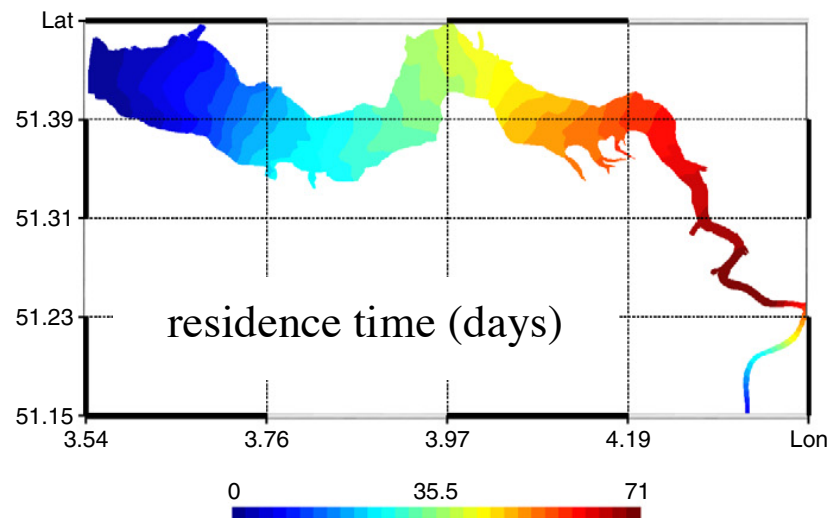
- Hydrodynamics is forced by tides (prescribed at the shelf break) and wind stress.
- Tidal components (amplitude and phase) are well represented, as well as salinity (treated as a passive tracer).

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

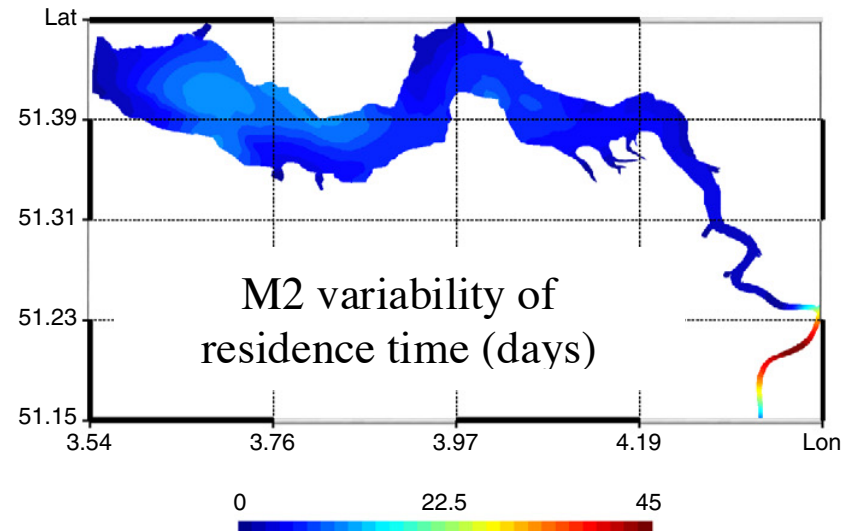


The Scheldt river-sea continuum (III)

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



www.climate.be/cart

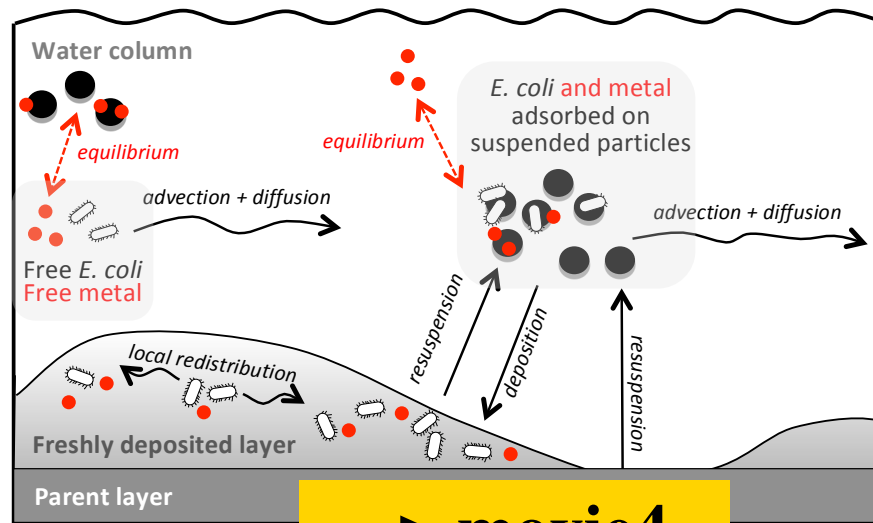


- Surprising result: the large time variability of the residence time.

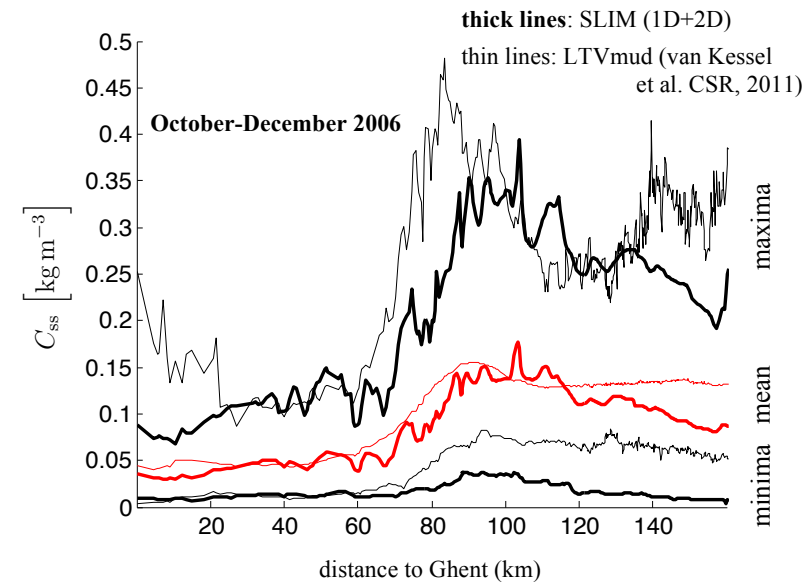
Blaise et al. (*Ocean Dynamics*, 2010), de Brauwere et al. (*Journal of Marine Systems*, 2011)
de Brye et al. (*Journal of Marine Systems*, 2012)

The Scheldt river-sea continuum (IV)

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



=> movie4



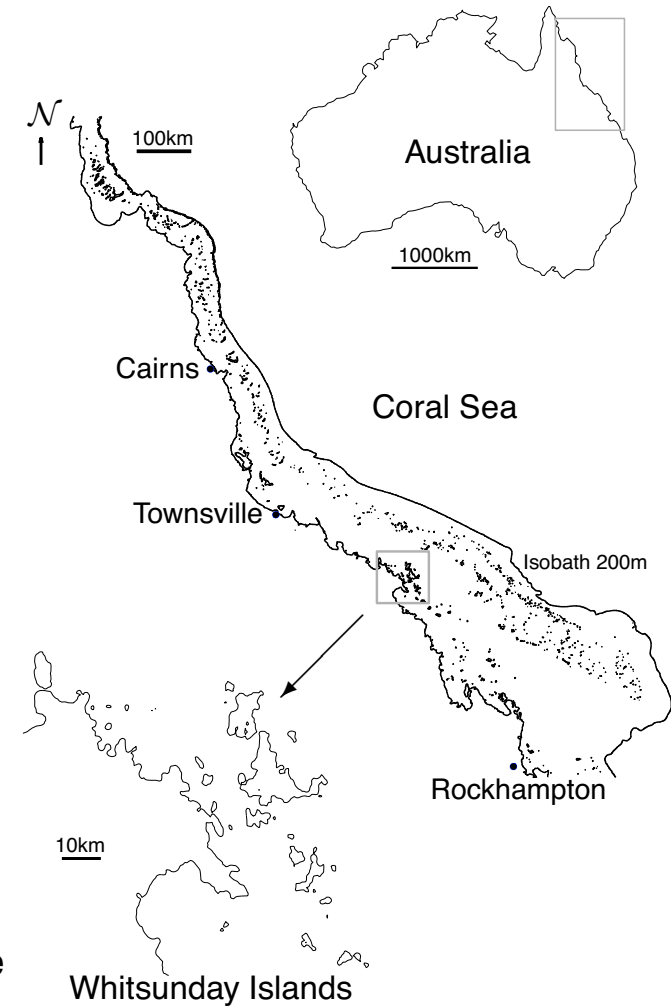
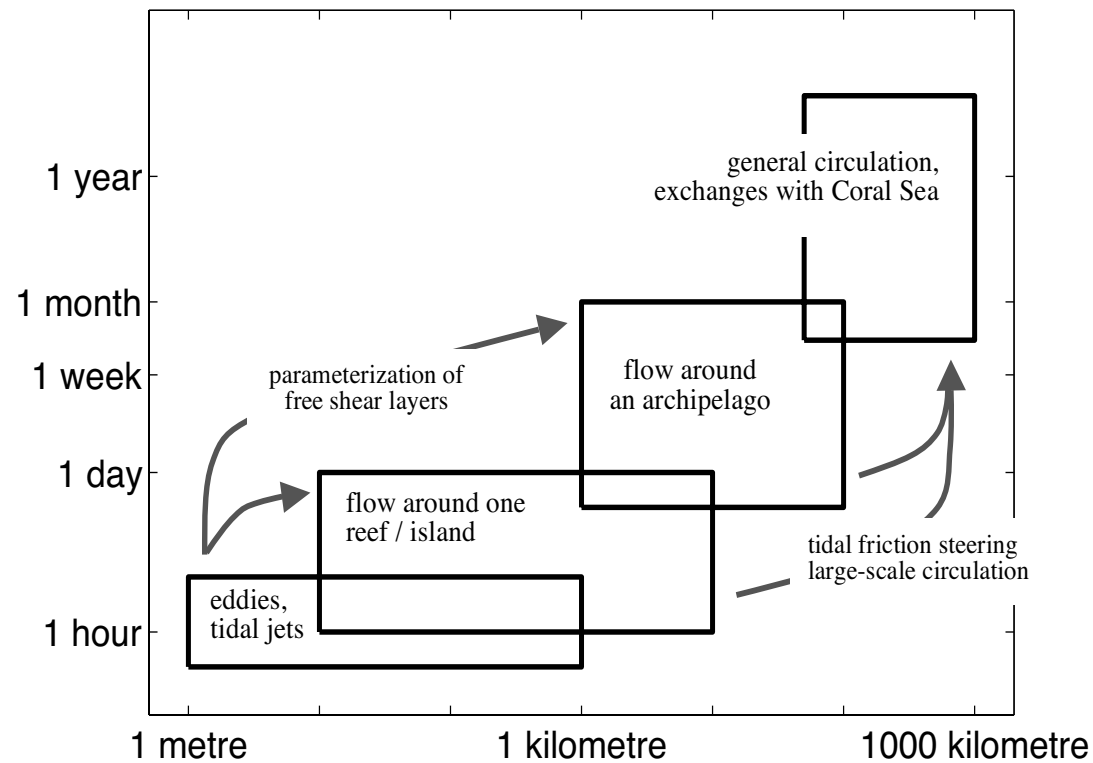
Suspended sediment concentration:
results of SLIM (1D+2D) are not that different
from those of the 3D, much more complex
LTVmud model

de Brauwere et al. (*Env. Model. & Soft.*, 2009)
de Brauwere et al. (*Water Research*, 2011)
Gourgue et al. (*J. Marine Systems*, 2013)
de Brauwere et al. (*STOTEN*, 2014)
Elskens et al. (*STOTEN*, 2014)

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

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

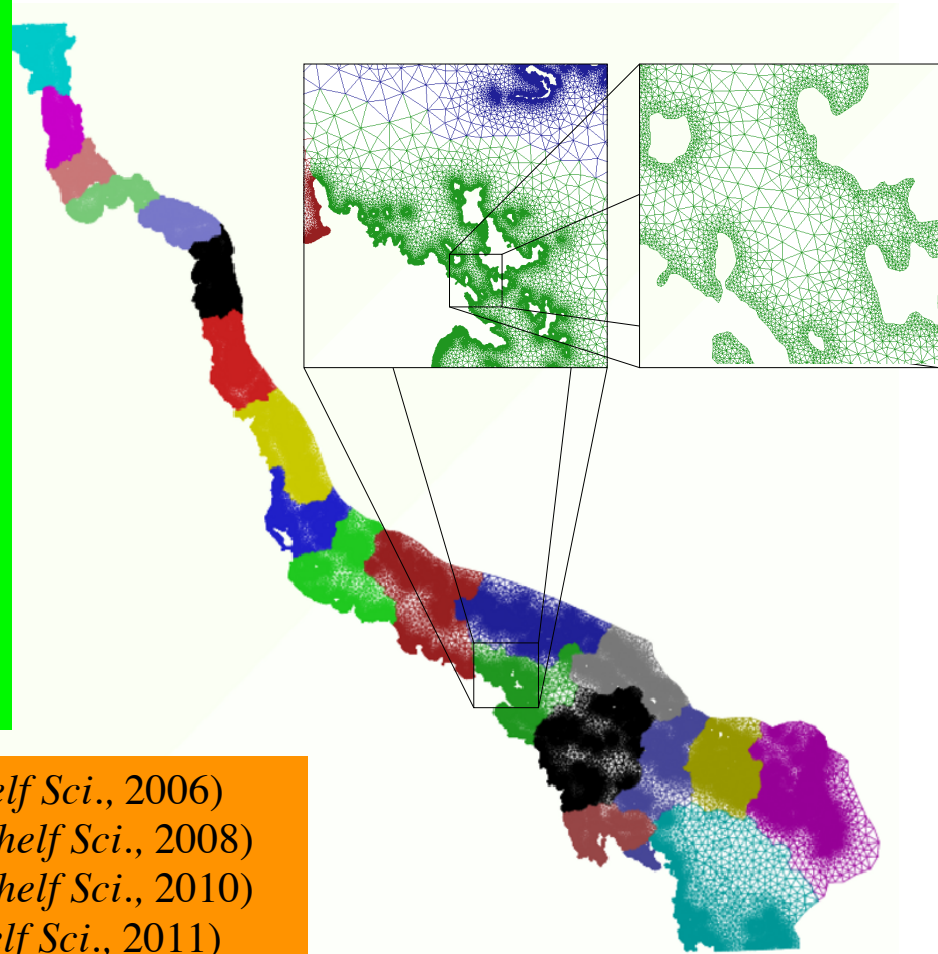
time-space scales of GBR hydrodynamics



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

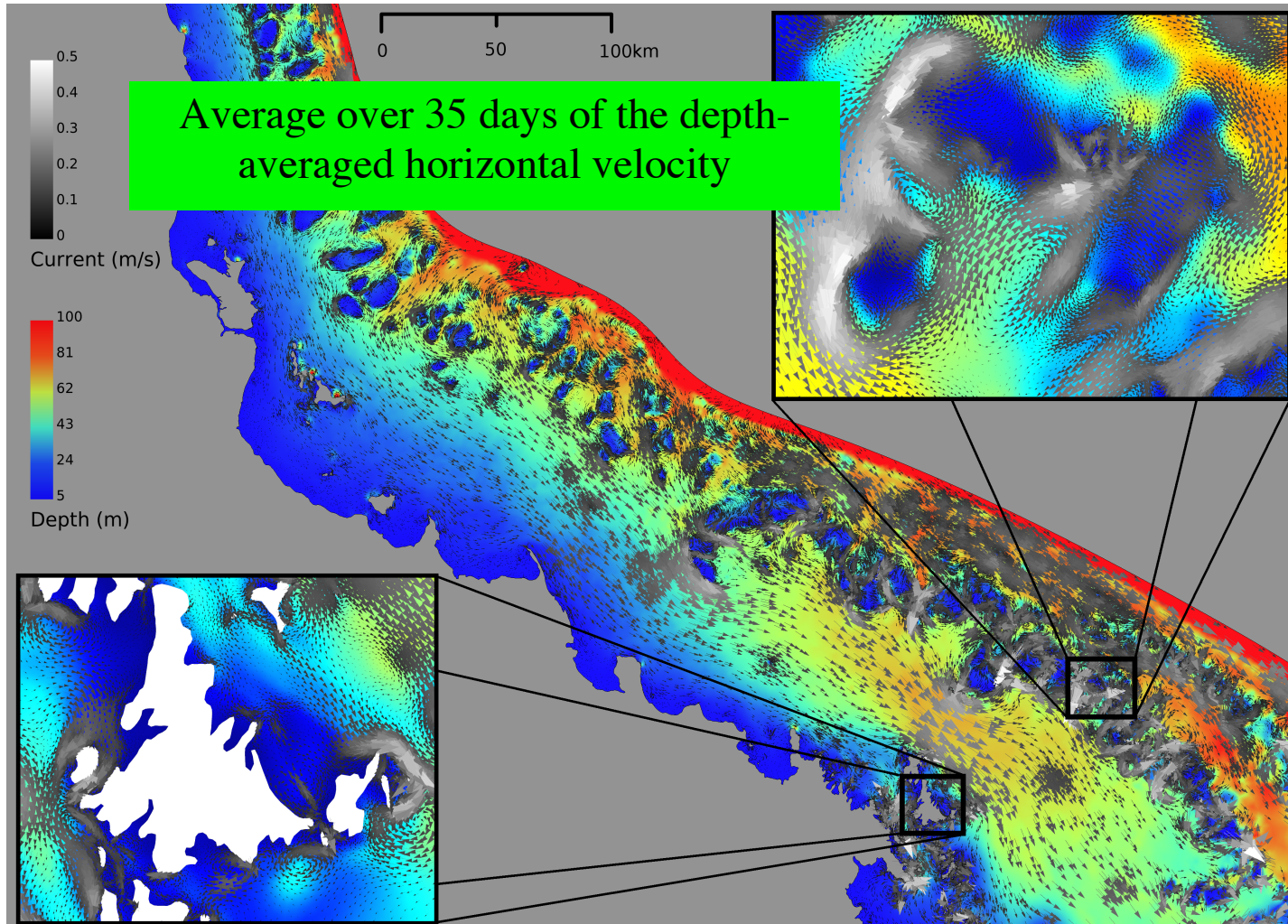
The Great Barrier Reef, Australia (GBR) (II)

- $O(10^6)$ triangles, with
$$\Delta x_{\max} / \Delta x_{\min} \approx 10^2 - 10^3$$
- 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)
Wolanski et al. (*Cont. Shelf Res.*, 2013)

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



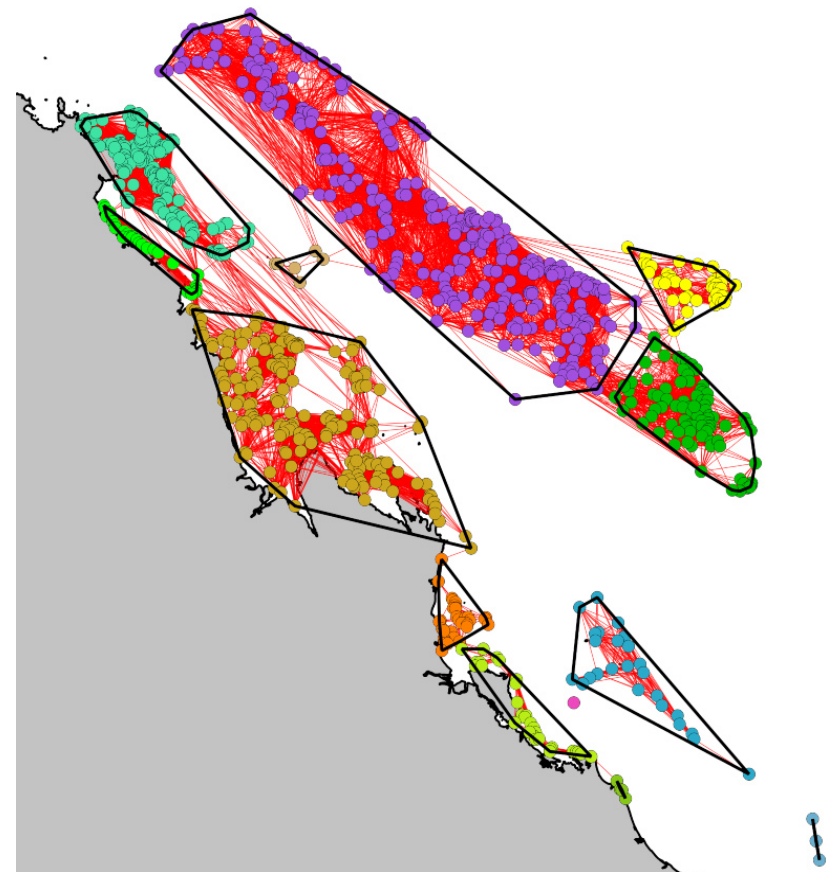
The Great Barrier Reef, Australia (GBR) (IV)

- Modelling the transport of coral 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.

Thomas et al. (*Ecological Modelling*, 2014)

Thomas (*Reef Encounter*, 2014)

Thomas et al. (*Diversity and Distributions*, submitted)



Map of reefs in the central GBR with reefs grouped into clusters (coloured dots).

Red lines represent connections between reefs.

Conclusion

- SLIM already has some of the building blocks of a multi-scale/physics hydrospheric model, which are progressively coupled with each other.
- The computational efficiency must be increased significantly

Seny et al. (*Int. J. Num. Meth. Fluids.*, 2013) - Seny et al. (*J. Comput. Physics*, 2014)
Seny et al. (*J. Comput. Physics*, submitted)

- Key numerical issues are yet to be addressed!

Isaac Newton Institute for Mathematical Sciences

Multiscale Numerics for the Atmosphere and Ocean

22 August - 21 December 2012



A number of SLIM-team members have participated in the Newton Institute workshop.





www.climate.be/slim