Imperial College London

中国科学院大气物理研究所
Institute of Atmospheric Physics, Chinese Academy of Sciences

Ensemble Data Assimilation Applied to An Unstructured Mesh Ocean Model

Juan DU[1], Jiang ZHU[1], **Fangxin FANG**[2], Chris Pain[2], Xiaobao YOU[1,2]

[1] *Institute of Atmospheric Physics, Chinese Academy of Sciences, China*,

[2] *AMCG,* Department of Earth Science and Engineering, *Imperial College London, United Kingdom*

f.fang@imperial.ac.uk

3. Sept. 2015, COSS-TT, Lisbon

Outlines

- **Introduction to an unstructured mesh ocean model (ICOM-Fluidity)**

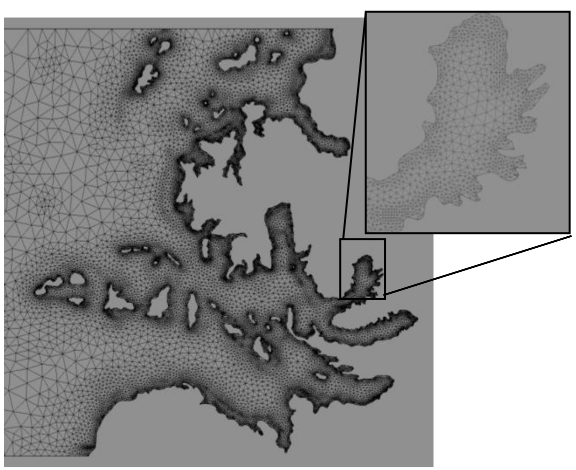
  Mesh adaptivity and the supermesh technique

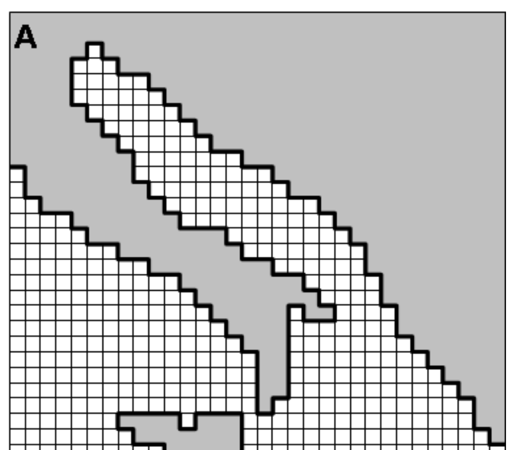
- **Implementation of Ensemble Kalman Filter (EnKF) in the adaptive mesh model and case study (Gyre)**

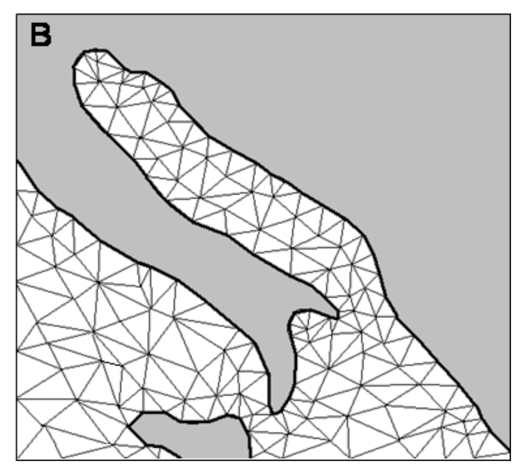
- **Adaptive observations (optimal sensor locations)**

Motivation for Geophysical Fluid Dynamics model utilising unstructured and adaptive mesh methods

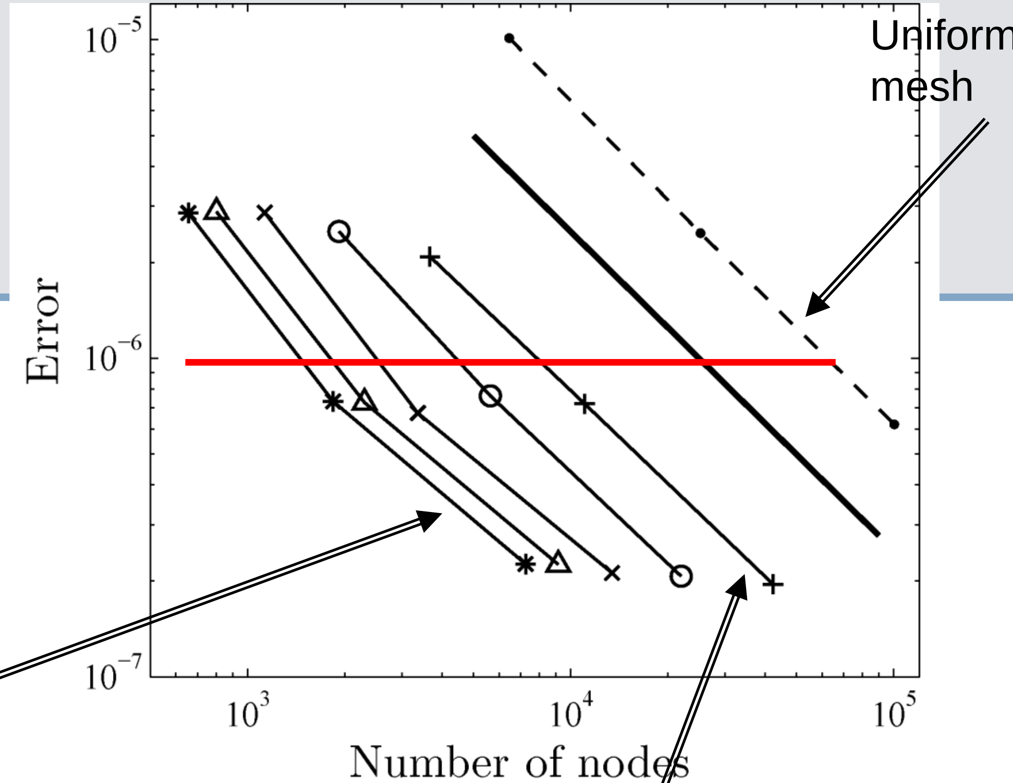
- Wide range of critical spatial and temporal scales present in oceanographic dynamics
- A need to resolve boundary currents, eddies, overflows, convection events and so on accurately and efficiently within a global and coupled context
- Improved predictions and understanding of the highly nonlinear coupled system (turblence, boundary local flows, eddy etc.)
- Need for accurate and efficient representation of highly complex domains, bathymetry etc.
- Ability to model interaction of flow with small scale topography, shelf seas, coastal regions, islands, estuaries, harbours,…
- Take advantage of recent developments in CFD, numerical analysis, scientific computing, …



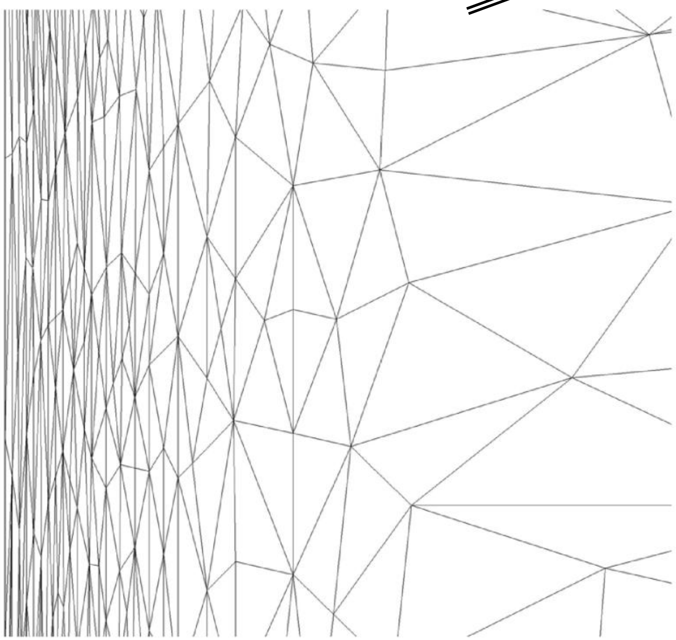


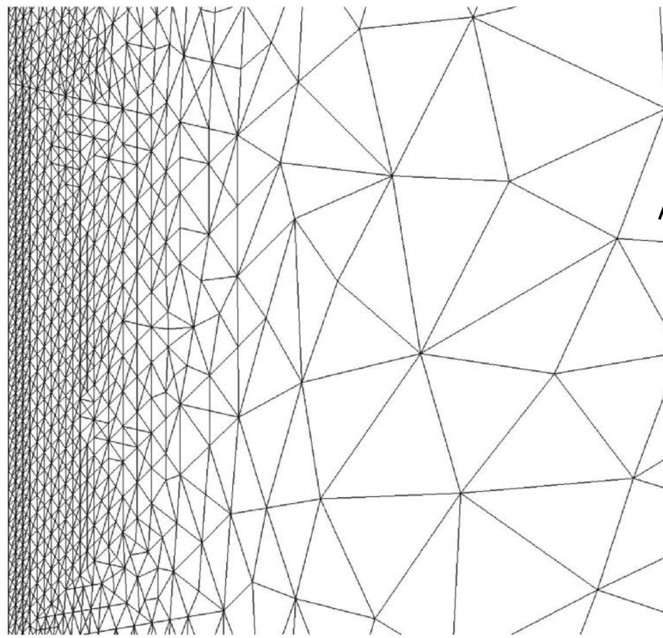


Effect of varying the maximum allowed aspect ratio in the adapted mesh



Approximately a two orders of magnitude improvement in the error/cost relationship between uniform and anisotropic adaptive refinement





Unstructured Mesh Ocean Model: ICOM-FLUIDITY

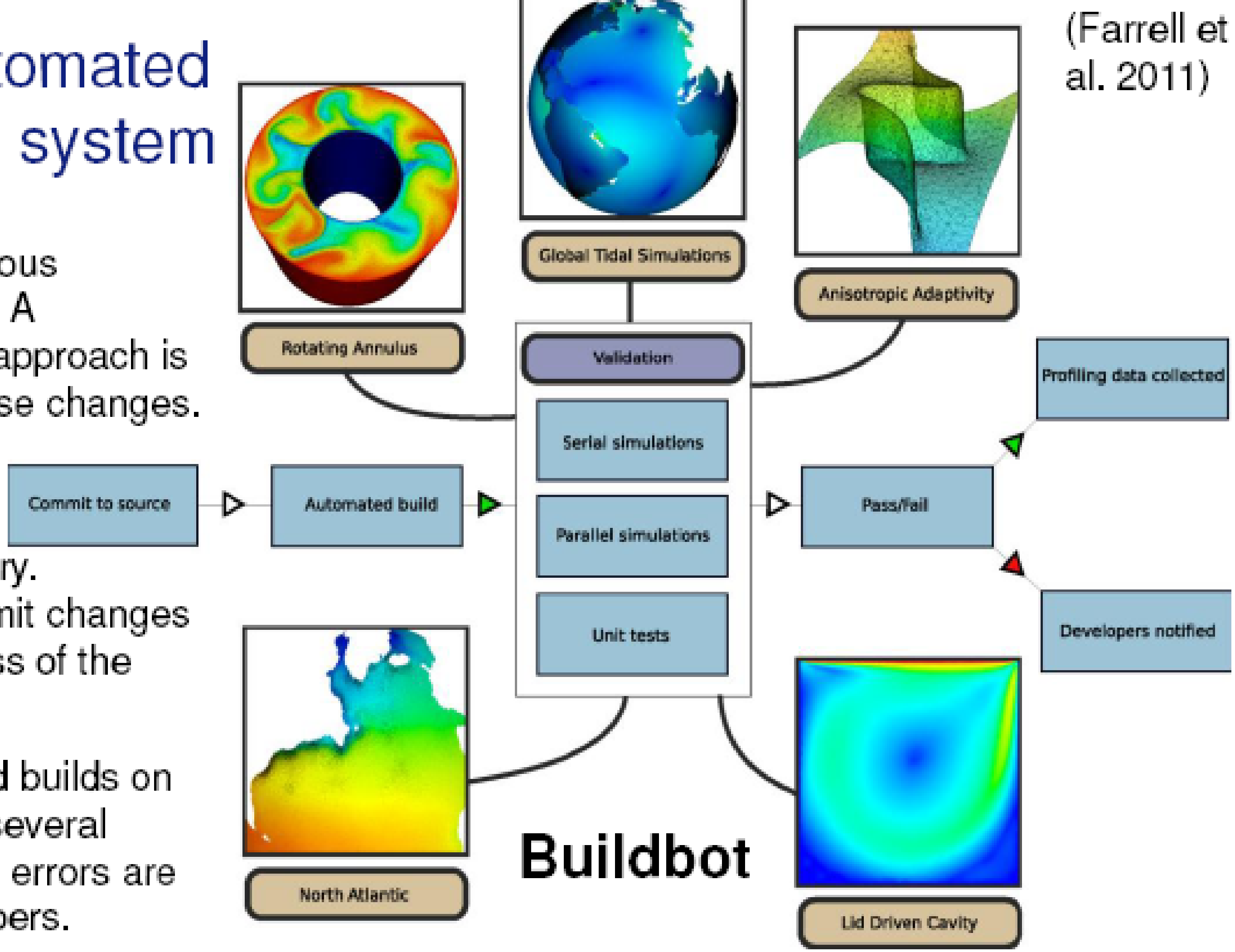
- **Adaptive meshes in 3D space and time** so that regions of steep topography, high dynamical activity or specific interest can be modelled at a high horizontal and vertical resolution;
- 3D Navier-Stokes (**being non-hydrostatic**, to cope with steep topography) flow solver with a range of CV-FEM discretisation methods;
- New finite element types (P1DG-P2 and DG) designed to optimally represent ocean flows (e.g. tracers, sanility, temperature);
- Conservative mesh-to-mesh interpolation;
- Parallel computing;
- Reduced order modelling for rapid responses;
- Data assimilation technologies for uncertainty analysis, improving accuracy of numerical modelling and optimisation of uncertainties in models.

http://amcg.ese.ic.ac.uk/FLUIDITY

Robustness: automated code verification system

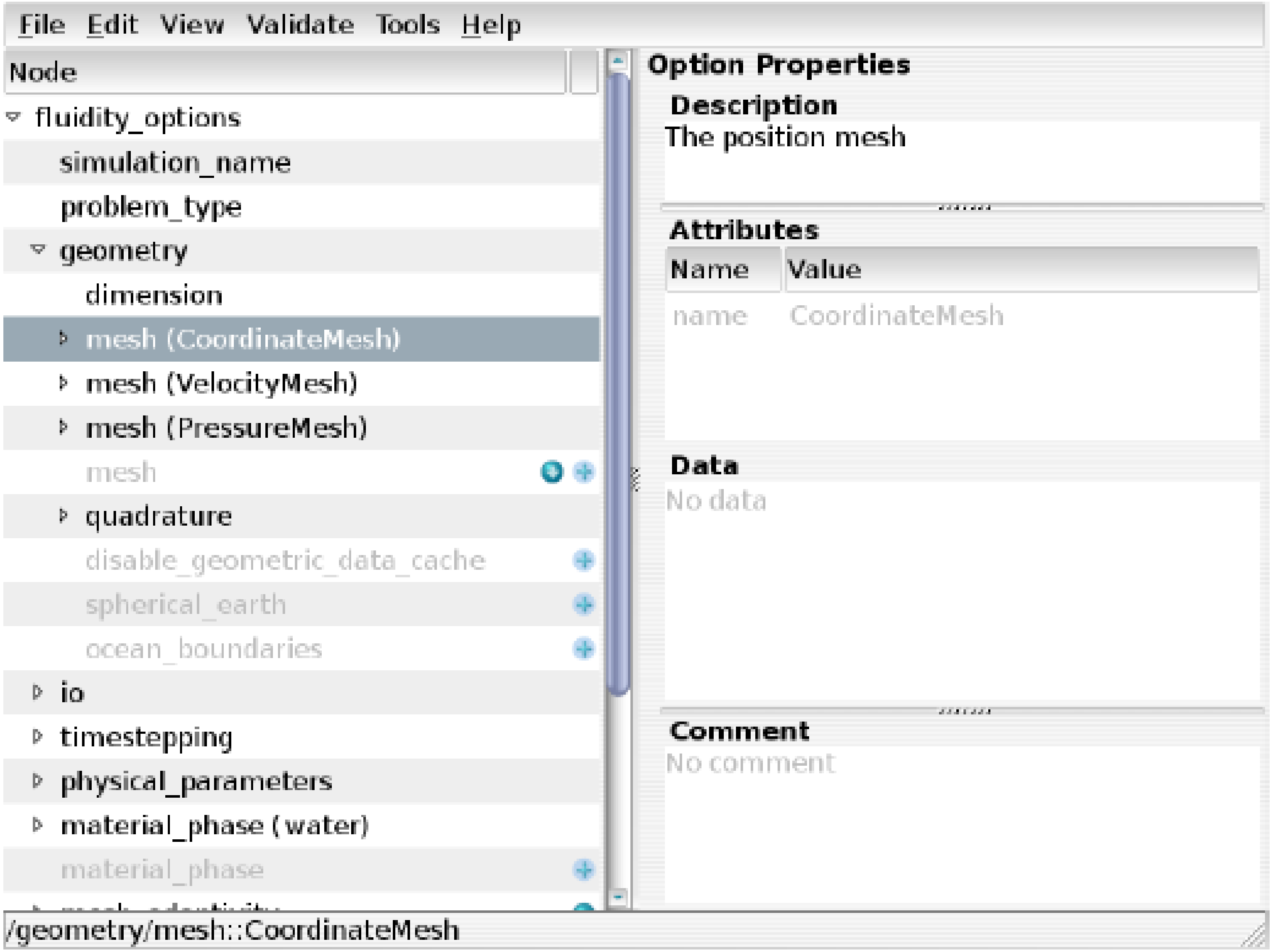
(Farrell et al. 2011)

- All models require rigorous validation / verification. A continuous automated approach is required as the codebase changes.
- A central copy of the source is kept in a version control repository. When developers commit changes this must result in a pass of the code test suite.
- Buildbot checks out and builds on various platforms with several different compilers. Any errors are relayed back to developers.



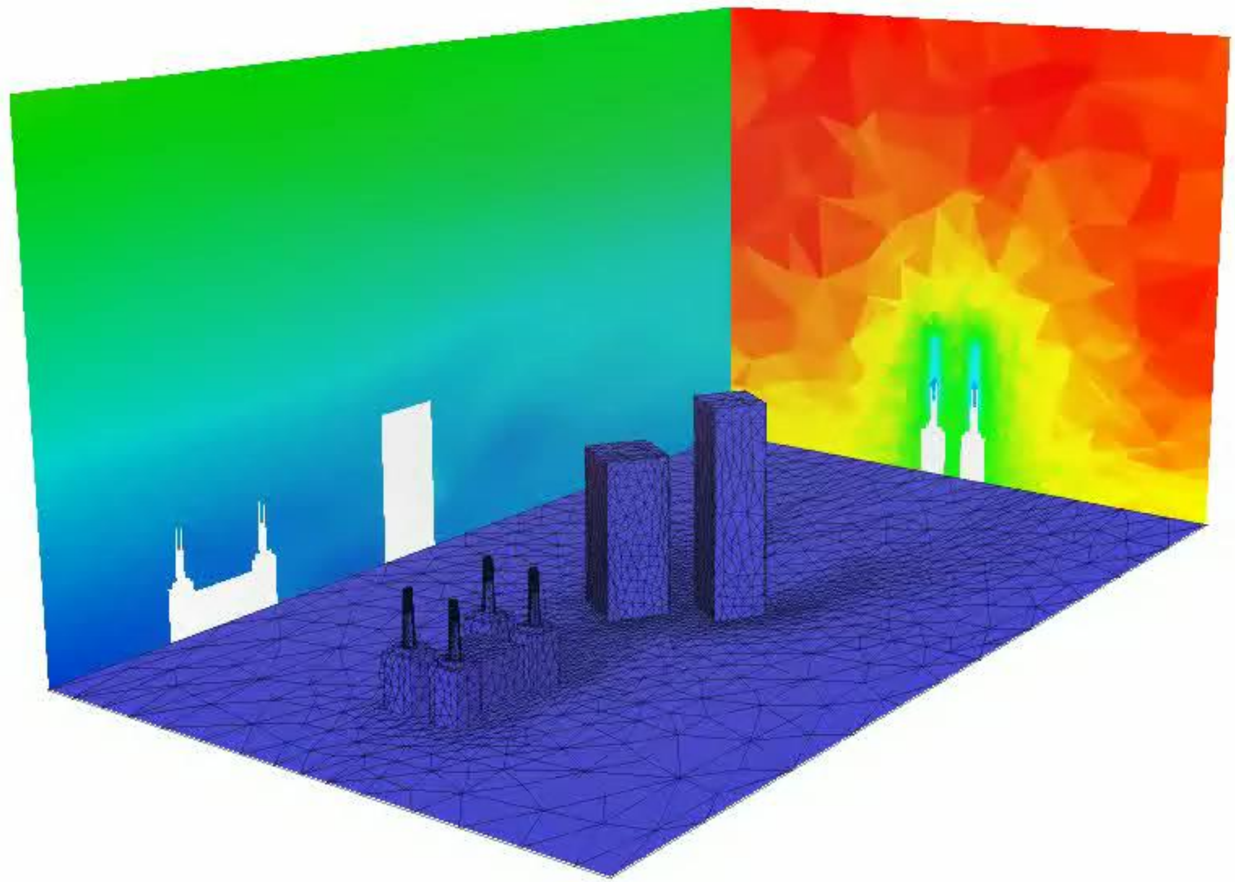
- If a failure is detected in a test problem, the developers are notified details via email.
- Statistical information about code quality is automatically collected from the newly validated code. This allows for the monitoring of performance. Results available via a web interface.
- This modern approach to software engineering has yielded dramatic improvements in code quality and programmer efficiency.

Configuring Fluidity –Diamond (Graphical user interface)



Fluidity-ICOM:Flexibility

- Nuclear engineering and radiation transport
- Mantle flow and geodynamics (Stokes flow)
- Multiphase flows (applied to gas and oil reservoir engineering)
- Small scale atmospheric modelling. Idealized Battersea Power Station (from James Percival).
- Ocean modelling (with biology, sediments etc)

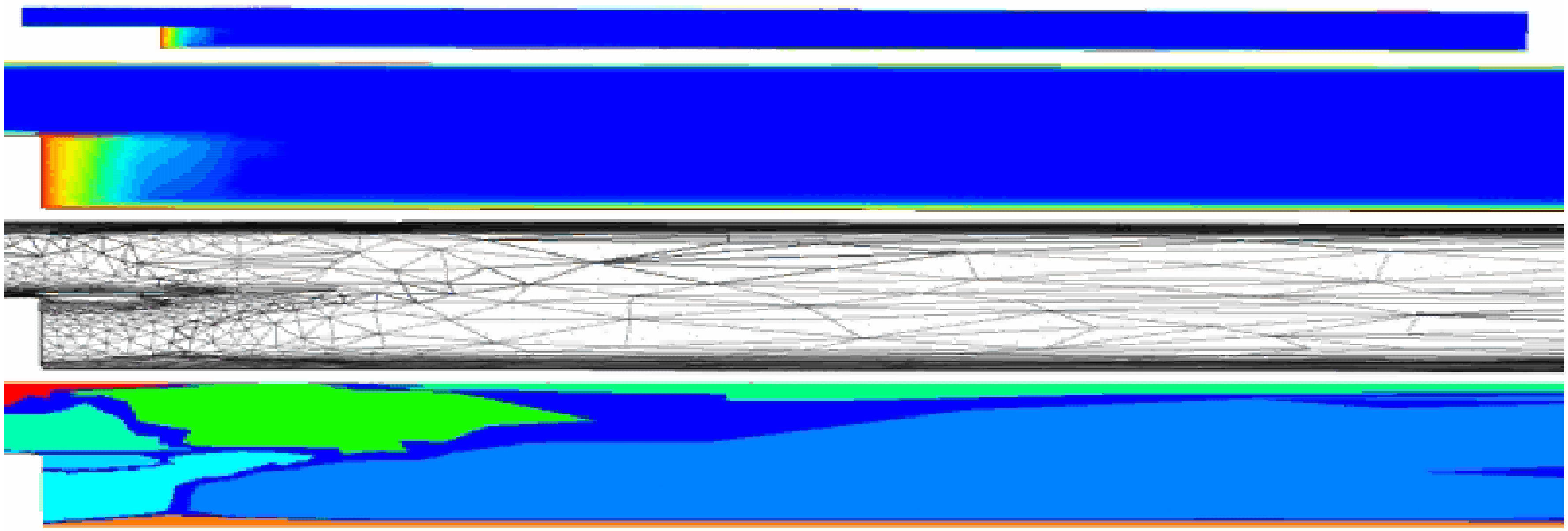


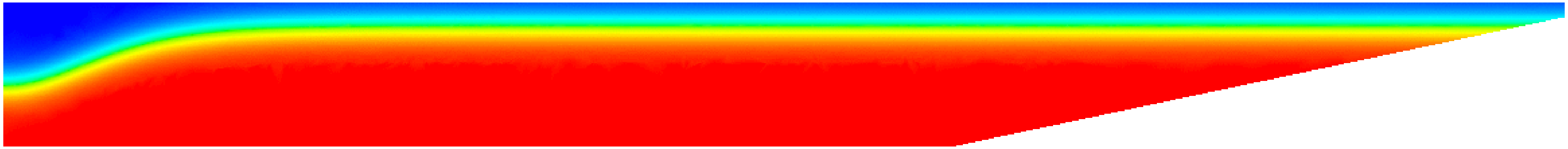
CFD Modelling

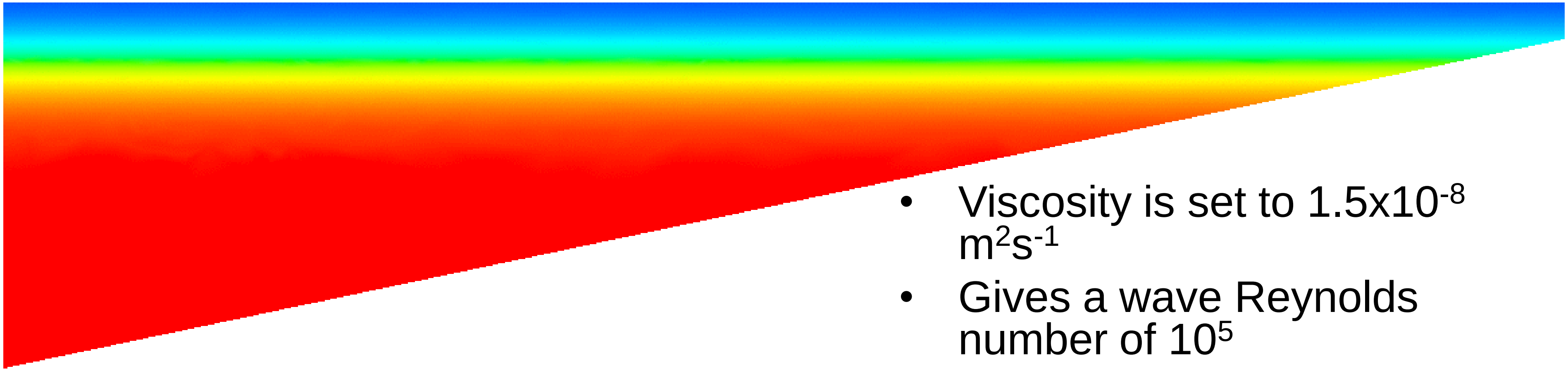
Mesh Adaptivity and Domain Decomposition

Flow past a backward facing step – a classical CFD problem for motivation and validation

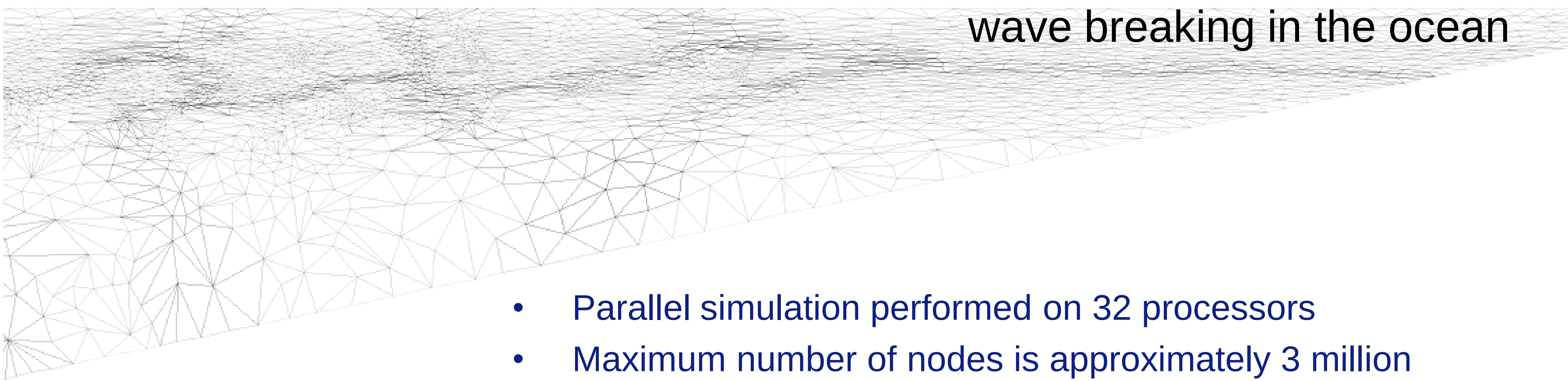
Movie below shows the entire domain, and then zooms of a tracer field, the adapting mesh, and the adapting load-balanced domain decomposition





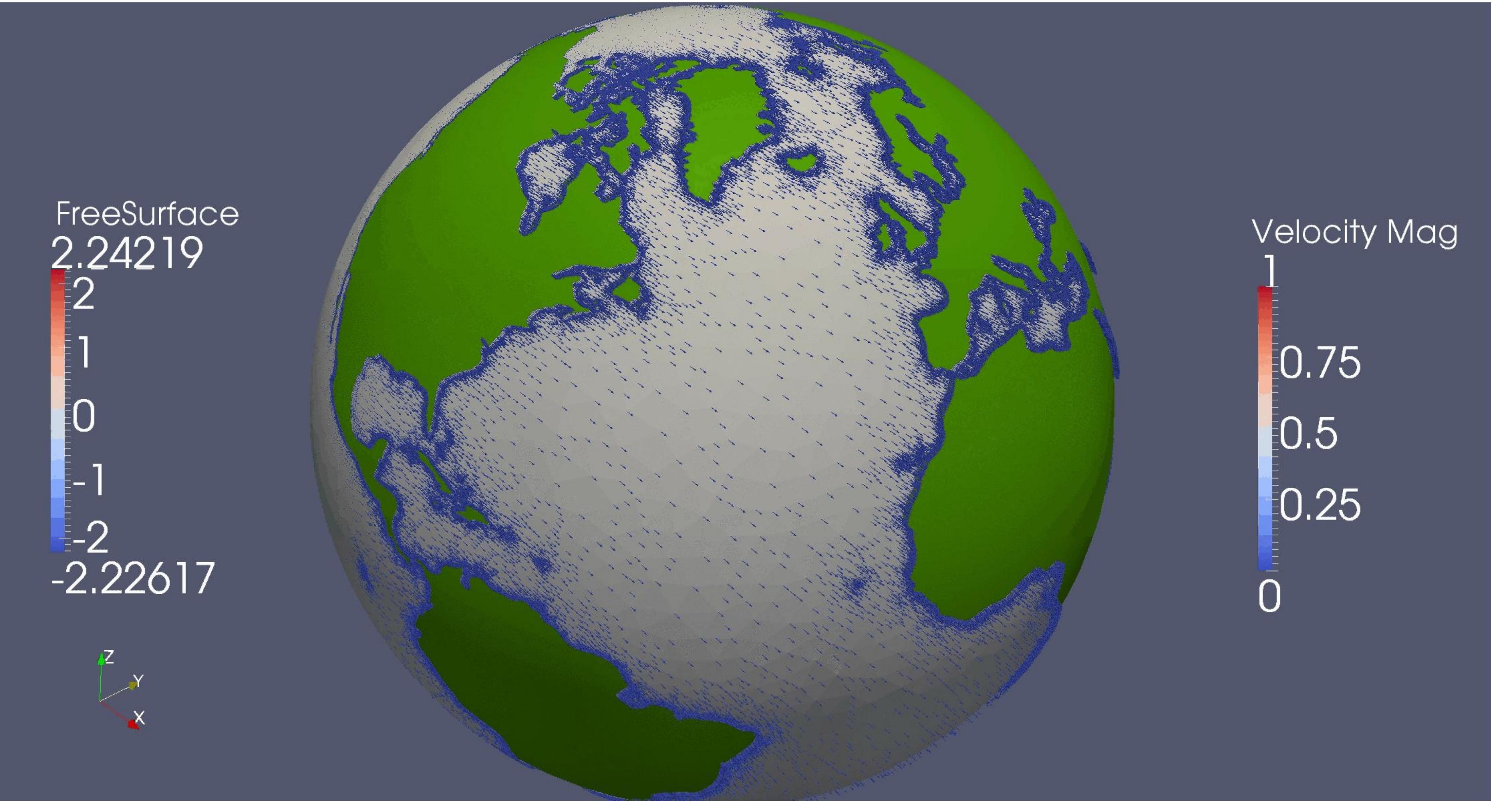


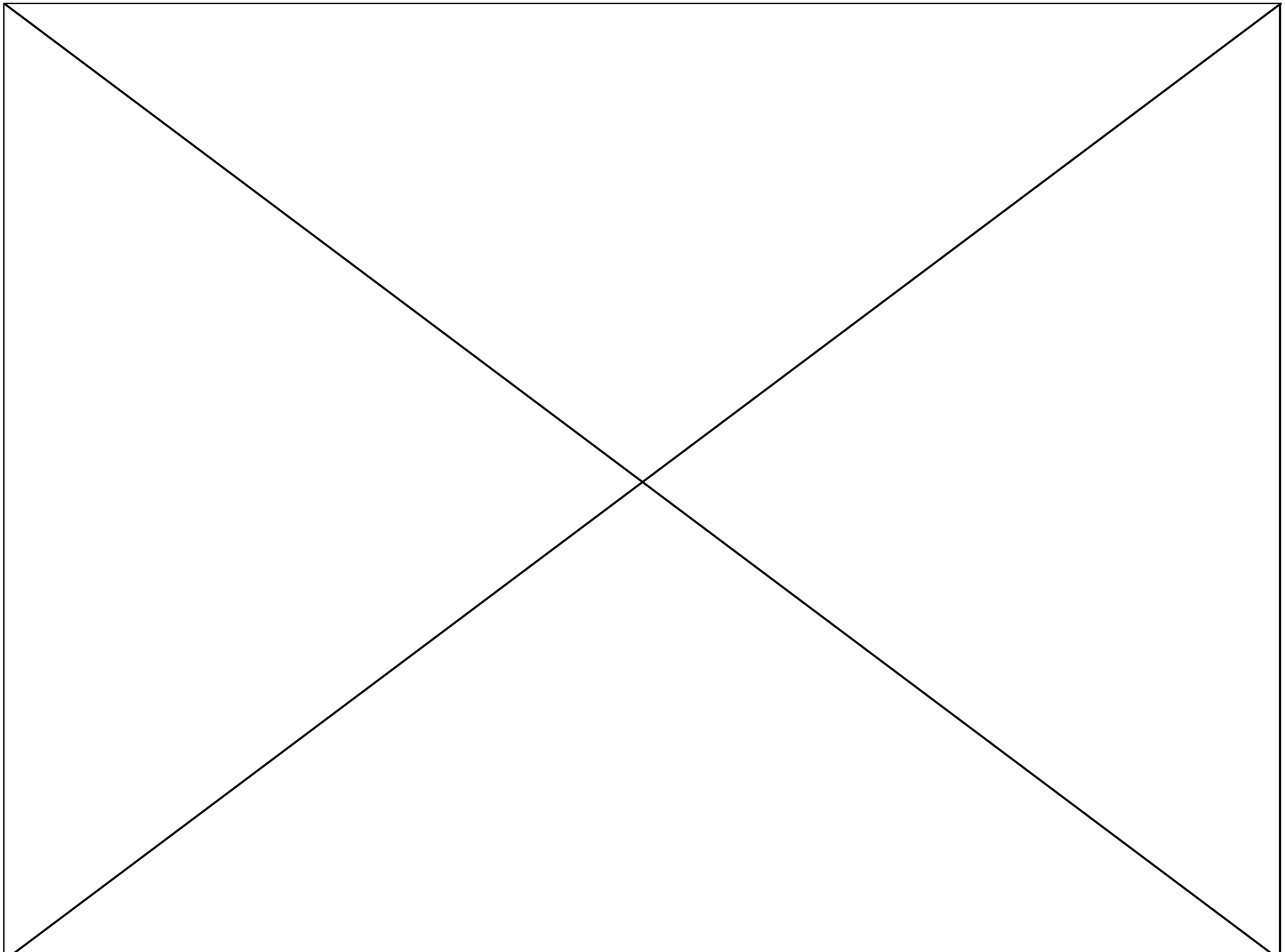
- Viscosity is set to $1.5x10^{-8}$ m^2s^{-1}
- Gives a wave Reynolds number of 10^5
- More indicative of an internal wave breaking in the ocean



- Parallel simulation performed on 32 processors
- Maximum number of nodes is approximately 3 million
- Smallest element has edge lengths of 10^{-5} m
- Would require more than 1 billion nodes if run on a uniform mesh with those edge lengths everywhere

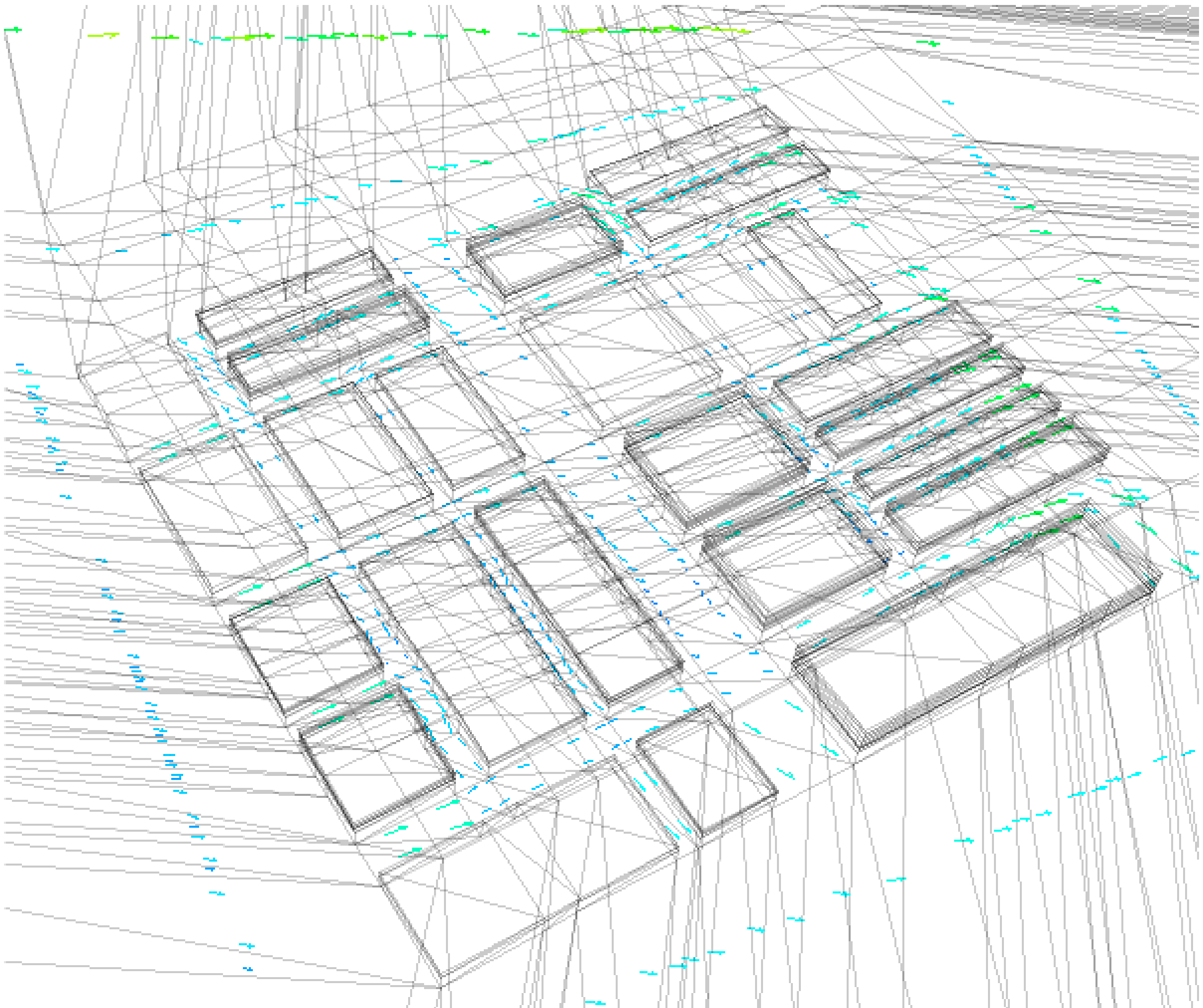
Global Ocean Case (work has been done by Jon hill)





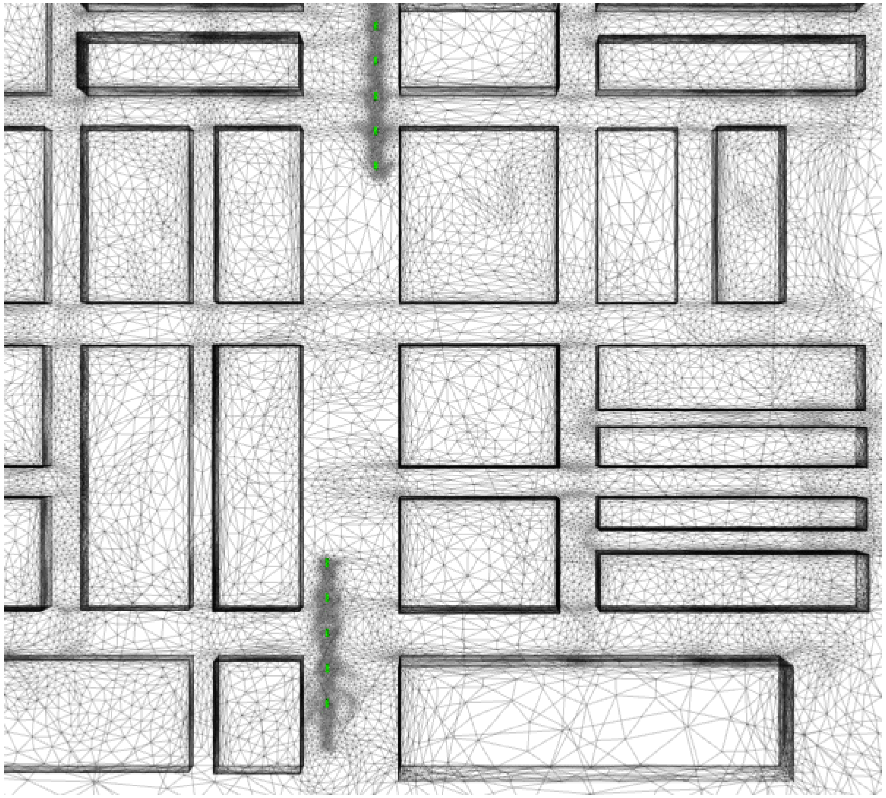
Environmental Modelling

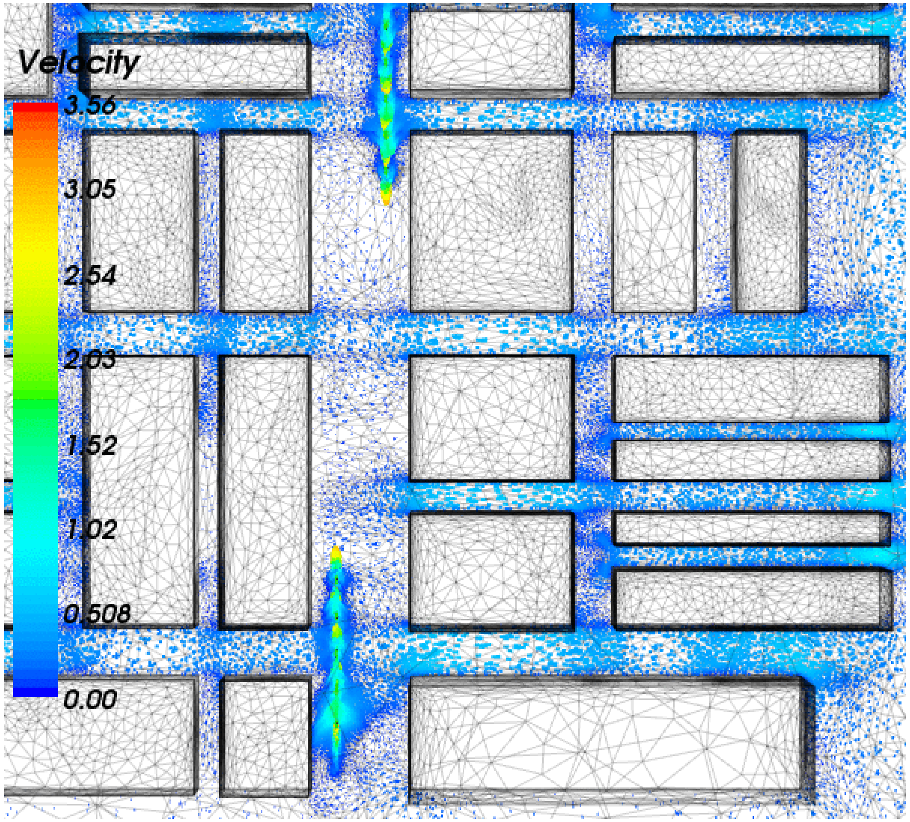
24 Building Case (Fine Mesh – 600000 Nodes): 20 Processors



Environmental Modelling

Moving Vehicles and Scalar Dispersions in Street Canyons





Mesh generated by GMSH using GSHHS coastline database (J. DU, IAP)

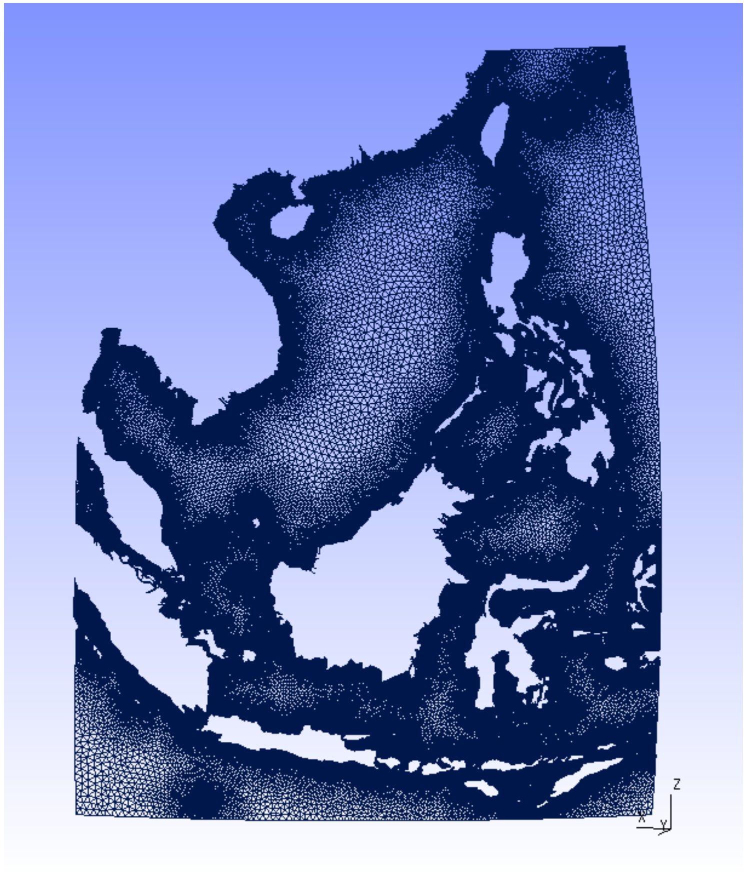
The P1dg-P2 element pair

- This has polynomial order one discontinuous Galerkin velocity (DG) and polynomial order two pressure (P2).
- Temperature/Salinity are usually of order one, but can be continuous or discontinuous Galerkin.

Static mesh

Adaptivity

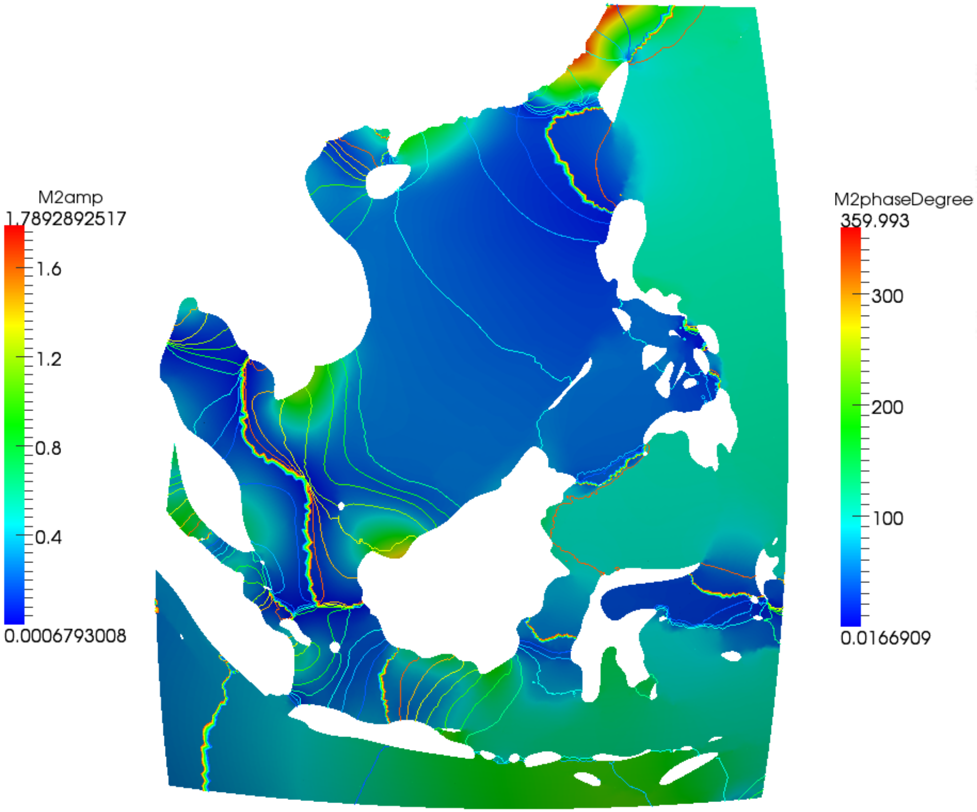
to resolve islands and complex coastline



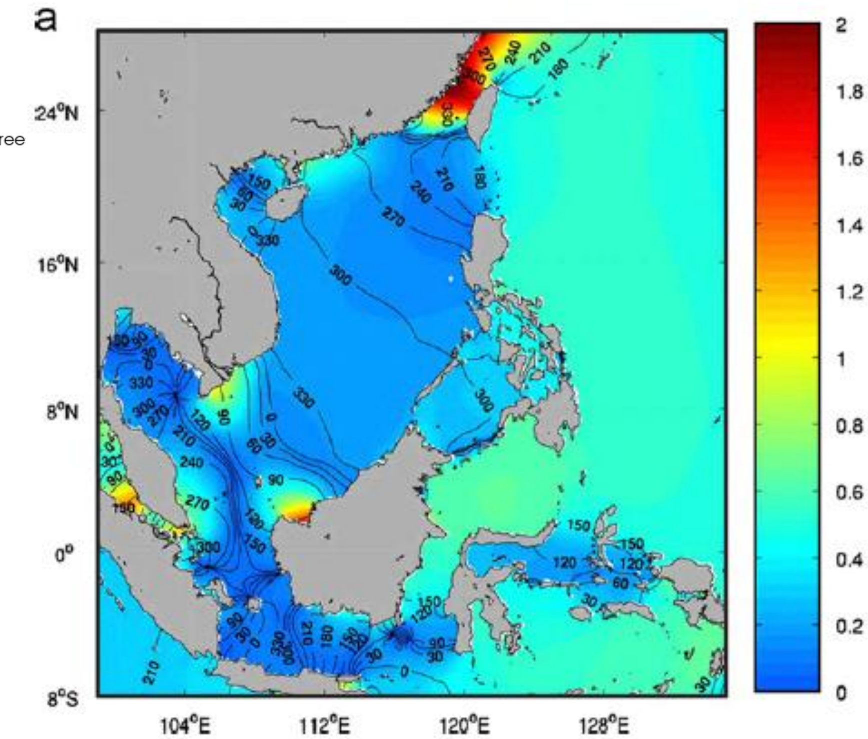
Coarse coastline

5km-40km

Intermediate coastline



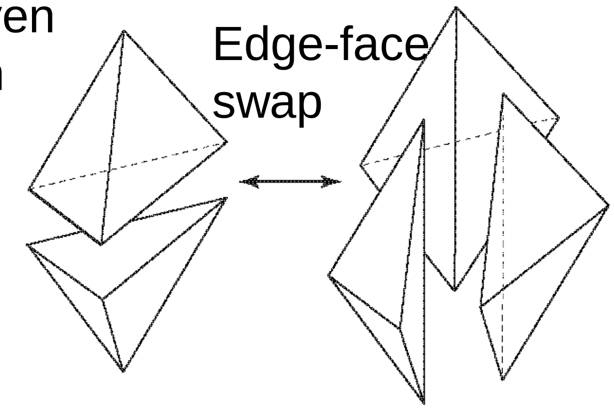
M2 amplitude and co-phase lines of FLUIDITY simulation using FES2004 data as B.C.

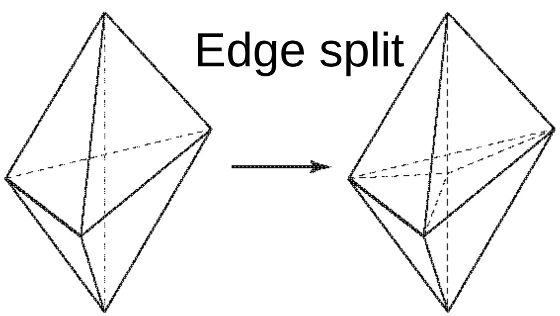


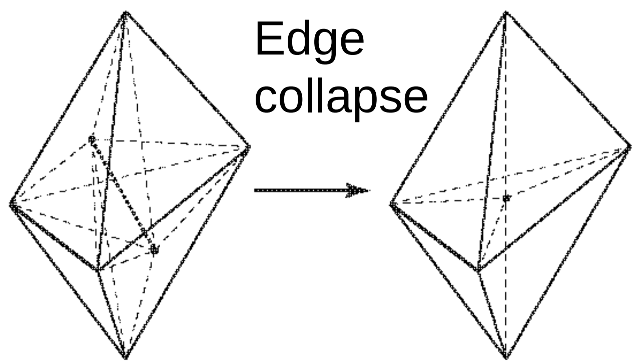
M2 amplitude and co-phase lines of SCS (zu. 2007)

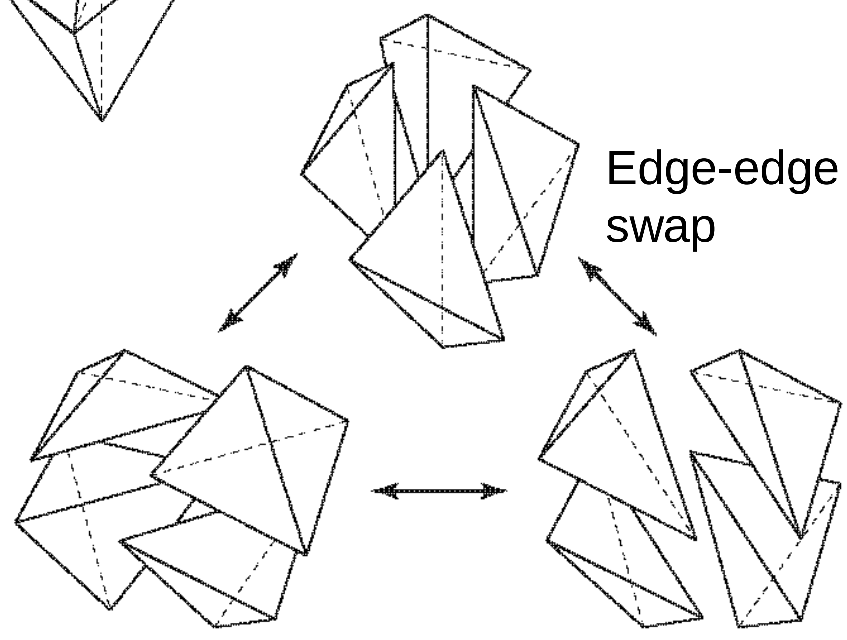
Mesh optimisation

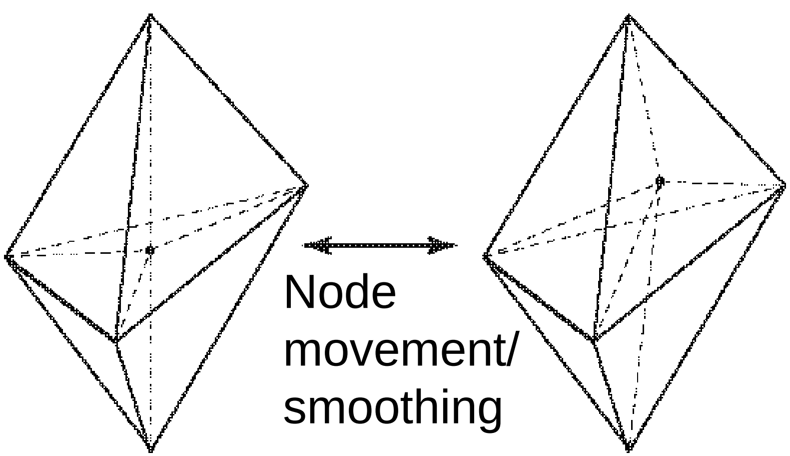
Operations used by the *mesh optimisation* algorithm, driven by an inhomogeneous & anisotropic metric obtained from error analysis (library described in Pain et al., 2001)











References on adaptive mesh techniques

Pain CC, Umpleby AP, de Oliveira CRE and Goddard AJH. Tetrahedral mesh optimisation and adaptivity for steady-state and transient finite element calculations. Comput. Methods Appl. Mech. Engrg., 190:3771-3796, 2001.

Power PW, Piggott MD, Fang F, et al, Adjoint goal-based error norms for adaptive mesh Ocean modelling, *Ocean Modelling, 2006, Vol. 15, Pages: 3-38, doi:10.1016/j.ocemod.2006.05.001.*

Data assimilation with unstructured adaptive mesh ocean model

Advantages:

- Use high resolution mesh at the regions of large flow gradients or non-smooth coastlines to better approximate the continuous flow;
- Use high resolution around the observation points in order to reduce the representative errors of observations

EnKF algorithm in use

- The EnKF algorithms used here are based on the work of Evensen (2003) and the analysis scheme from Burgers et al. (1998).

$$A^a = A + P_e H^T (H P_e H^T + R_e)^{-1} (D - HA)$$

$$A = (\psi_1, \psi_2, \ldots, \psi_N) \in R^{n \times N}$$

$$P_e = \frac{A' A'^T}{N-1}$$

$$A' = A - \overline{A}$$

$$R_e = \frac{r' r'^T}{N-1}$$

$$K_e = P_e H^T (H P_e H^T + R)^{-1}$$

$$HA' \gamma^T = 0$$

$$HA' + r = U \Sigma V^T \qquad A^a = A + A' (HA')^T U \Lambda U^T (D - HA)$$

Wind driven ocean circulation (J.DU – IAP, China)

Computational domain: 1500km x 1500km with 1km depth

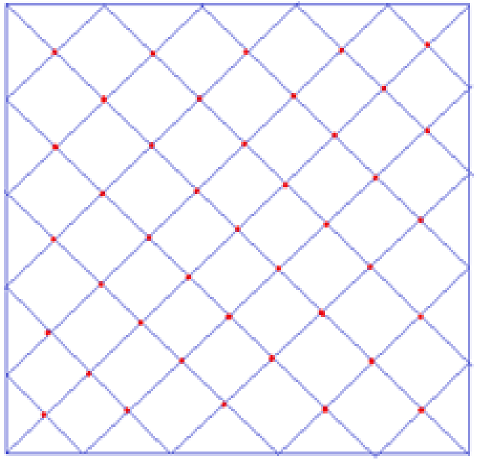
Barotropic: free surface, velocity, pressure,
one layer in the vertical direction

Wind stress on surface: $\tau_y = \tau_0 \cos(\pi y / L), \quad \tau_x = 0$

Lateral boundary condition: no-slip

The Coriolis terms: the beta-plane approximation

Pseudo-observations: 5km resolution fixed mesh solution
41 locations, per 210km



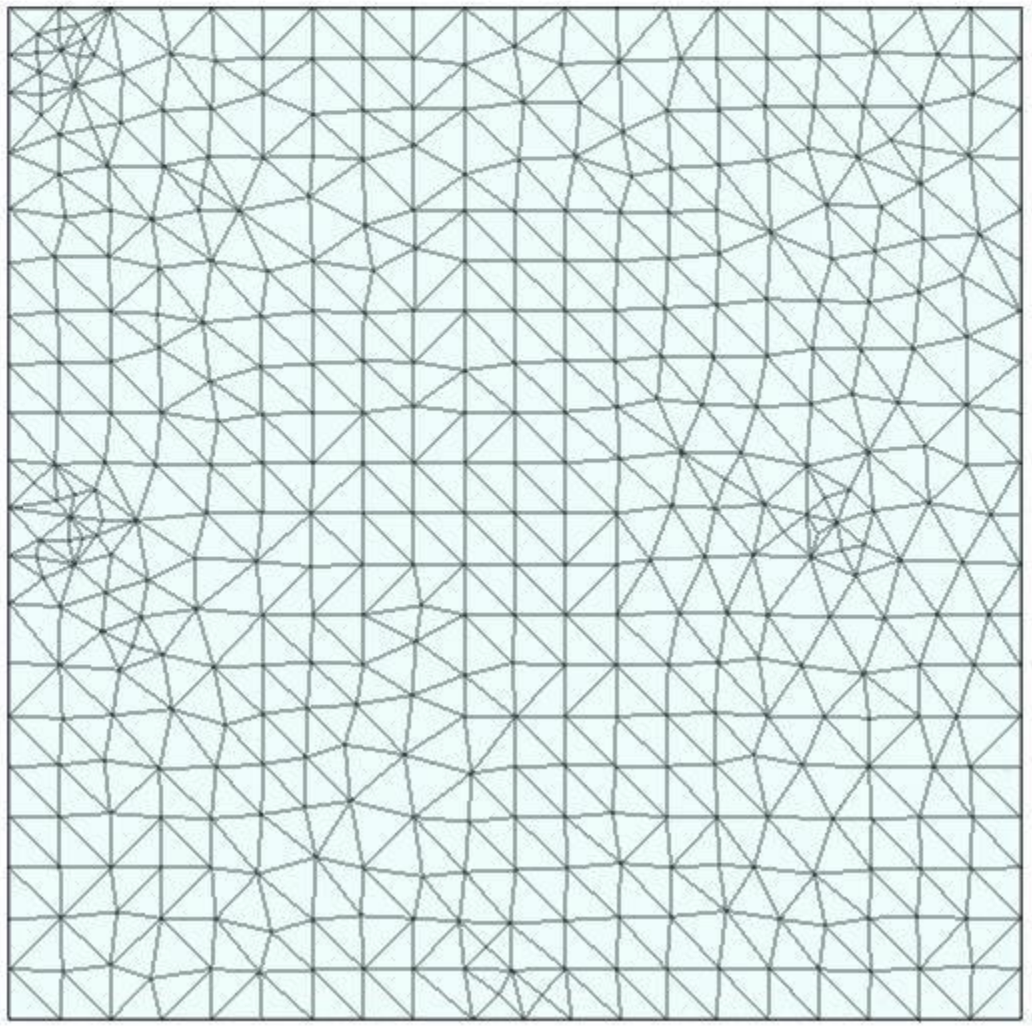
Initial ensemble: 20km uniform resolution mesh,
biased wind forcing， perturbation

From 600 day to 730 day

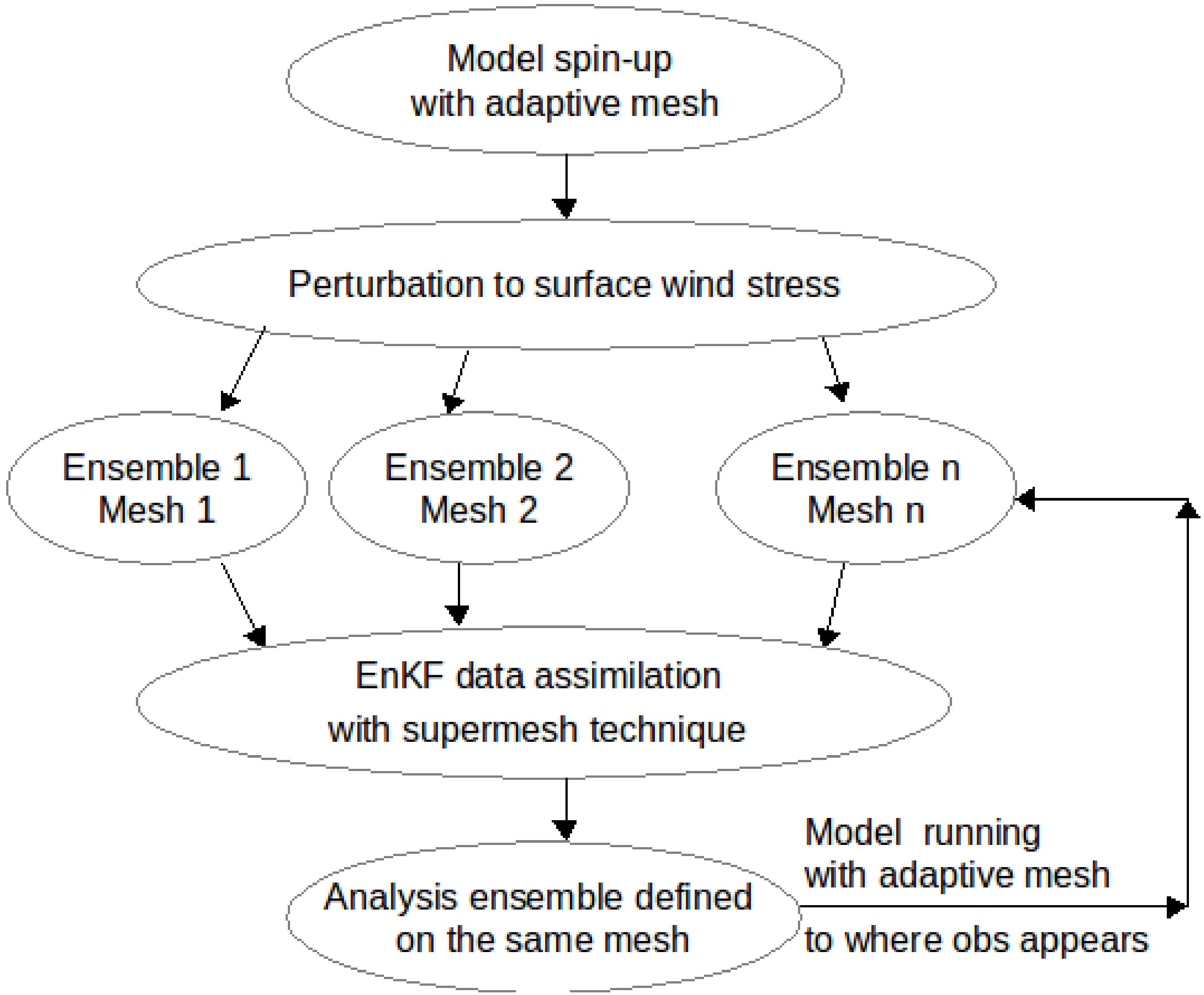
First EnKF DA: the 740th day

DA period: per 10 days, to 1100th day

Case 1: -- Gyre



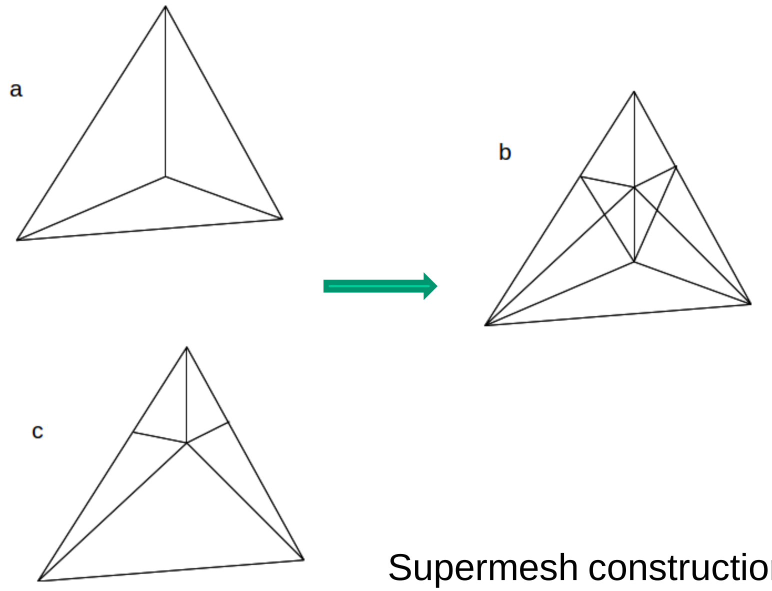
EnKF with adaptive mesh



Mesh interpolation techniques

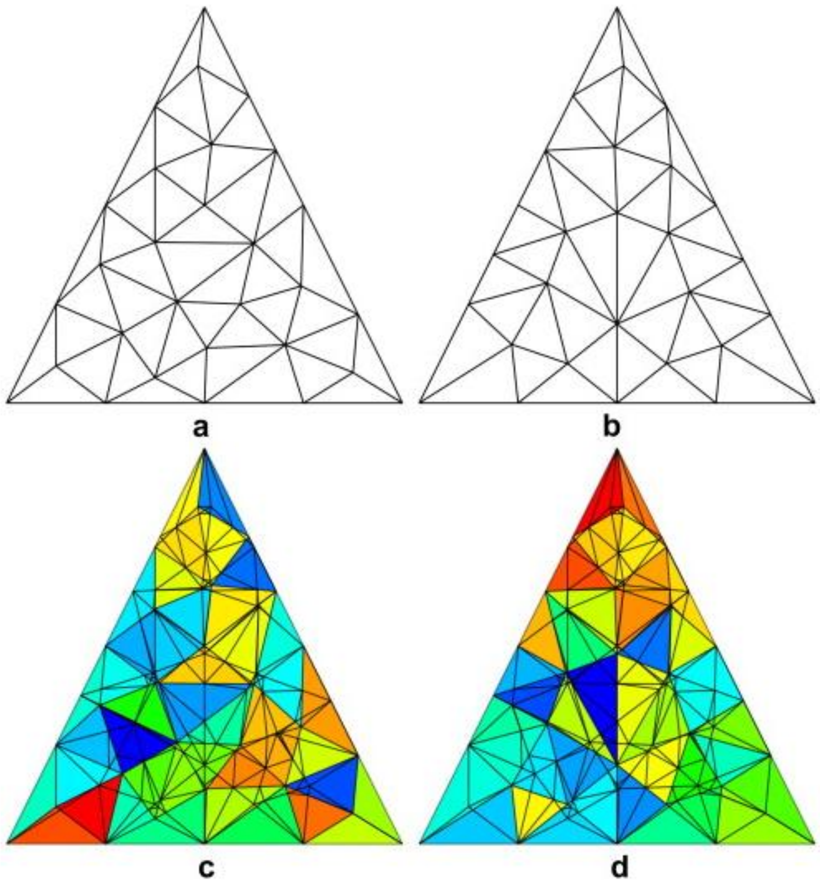
Mesh interpolation of the ensembles

- Consistent interpolation: interpolation by basis function evaluation, unsuitable for discontinuous fields, lack of conservation
- Galerkin projection: optimally accurate projection in the L2 norm, conservative, difficult to implement
- Supermesh: a bounded variant of Galerkin projection
  Farrell and Maddison [2011]



Supermesh construction

The ‘supermesh’ technique-- Conservative Interpolation



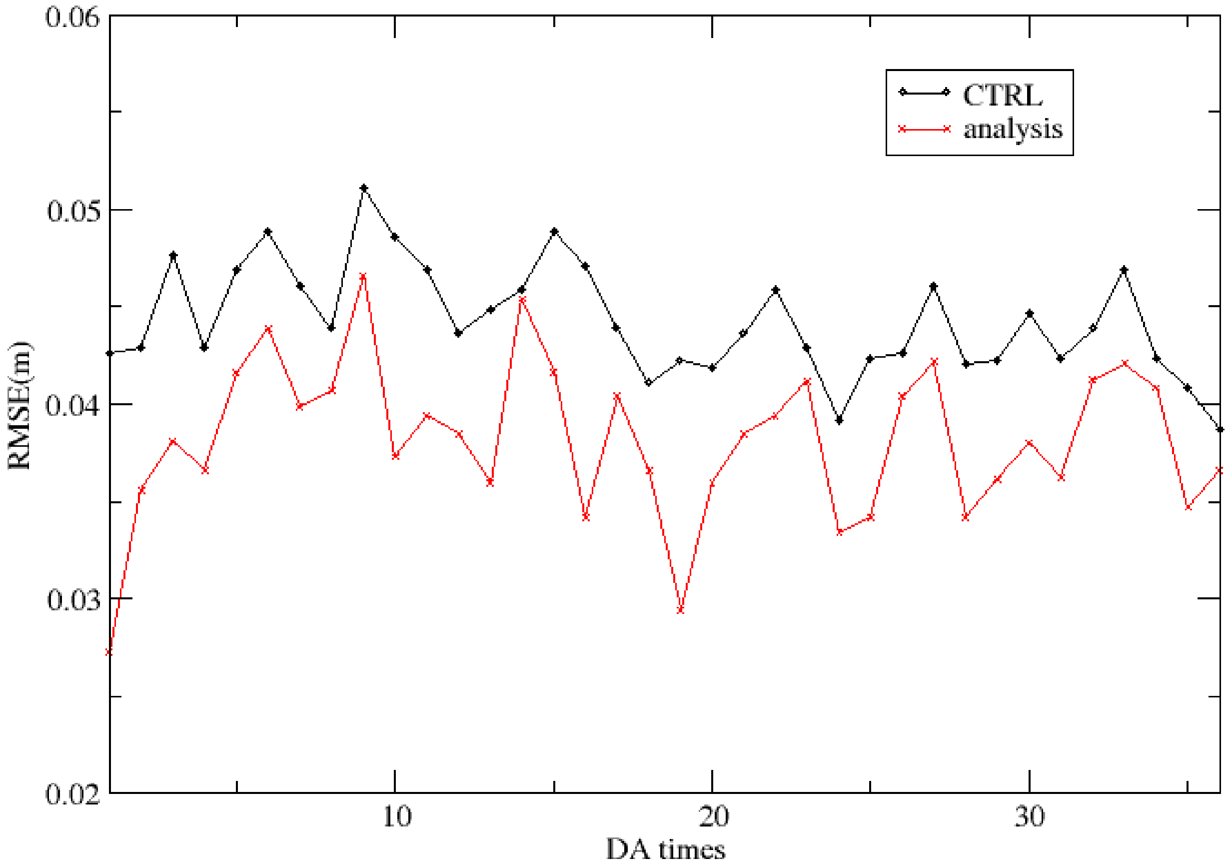
Two meshes and their supermesh
(P.E.Farrell et.al.2009)

Key problem:

conservation of quantities important to the physical accuracy of the simulation

Solver:

globally conservative interpolation operators between general unstructured meshes via the construction of an intermediate supermesh.



0.06
0.05
0.04
0.03
0.02
RMSE(m)
10
20
30
DA times
CTRL
analysis

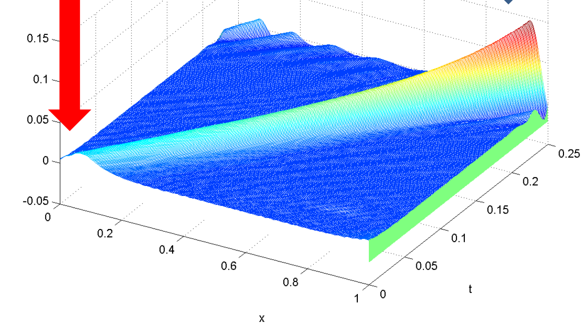
Adaptive Observation

- **Goal-based adaptive observation** technique can be used to optimise the distributed data (e.g. velocity/pollution monitoring) networks with respective to a goal (*e.g.* energy norm, heat transport, people health impacts), *i.e.* determine where to best collect data. This optimises the use of expensive data collecting devices.
- **Provide importance map** of error covariance over time and space;
- **Optimal observation network** by re-allocating observation data and adding extra data in the existing network.

Place the sensor at the target region

A target functional is defined at the verification region

What is adaptive (targeted) observation



Data assimilation approaches are used to improve accuracy of numerical modelling. It will provide a best estin model solution by fitting a numerical simulation observational data over both space and time.

Adaptive (targeted) observations methods aim to identify optimal locations where a modest number of additional observations deployed-improve a specific forecast aspect.

Verification time and region where results are most important. We define a functional (goal), e.g. Energy norm, error, vorticity, pollutant concentration at the verification time and region

A target region where the initial condition error is expected to cause significant forecast error or uncertainty at the forecast verification time

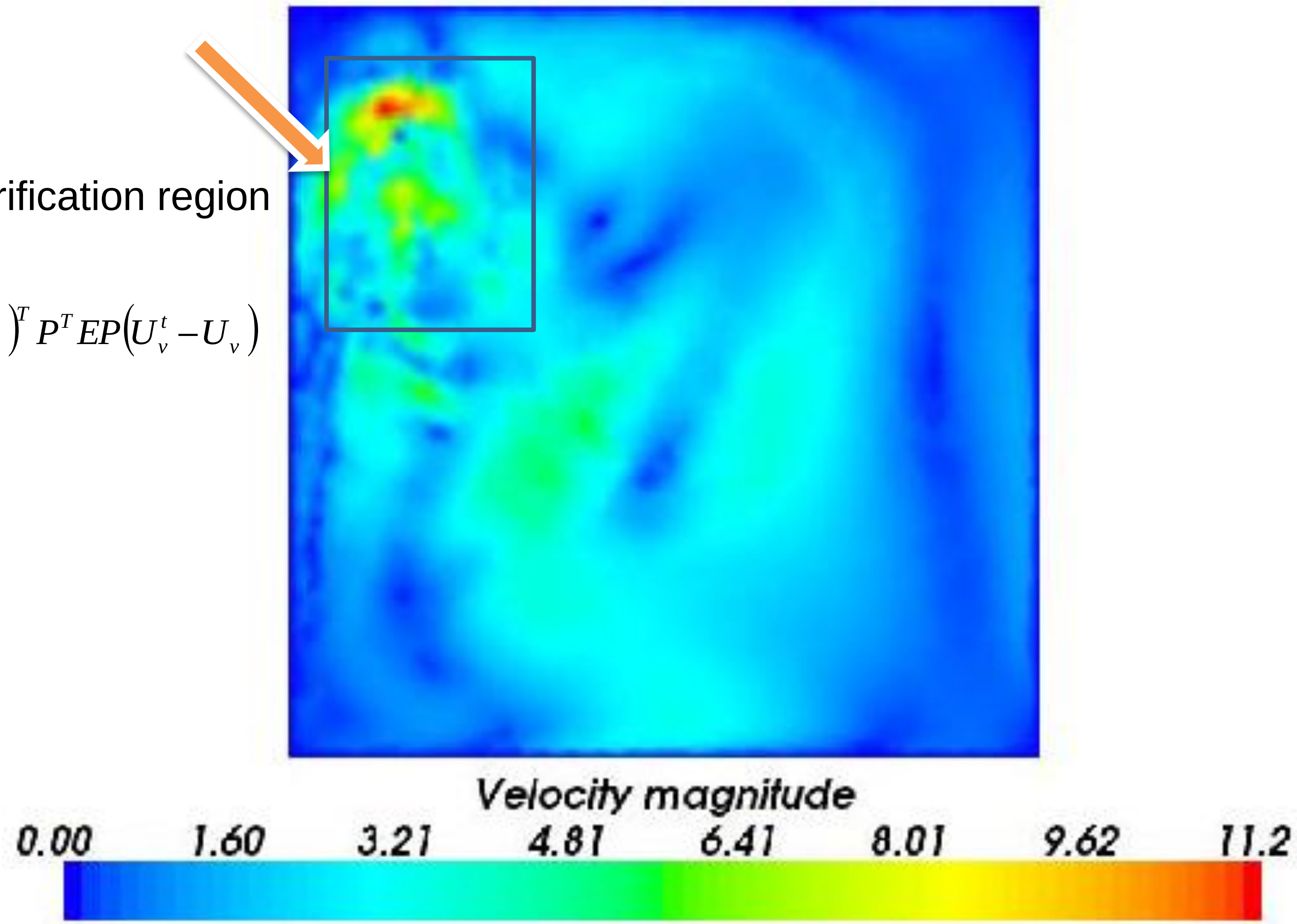
An overall goal (target functional) will be defined as a measure of what is deemed important in a simulation at the verification time over the verification region

Adaptive (targeted) observation *methods can be used to* identify the area (targeted) where the errors are rapidly growing and will mostly influence the forecast over the verification region and time, we are able to design an optimal observational network.

Results -- Error in velocity field at the verification time level (t = 66 days)

Verification region

$$\Im^{v} = \frac{1}{2}\left(U_v^t - U_v\right)^T P^T E P\left(U_v^t - U_v\right)$$

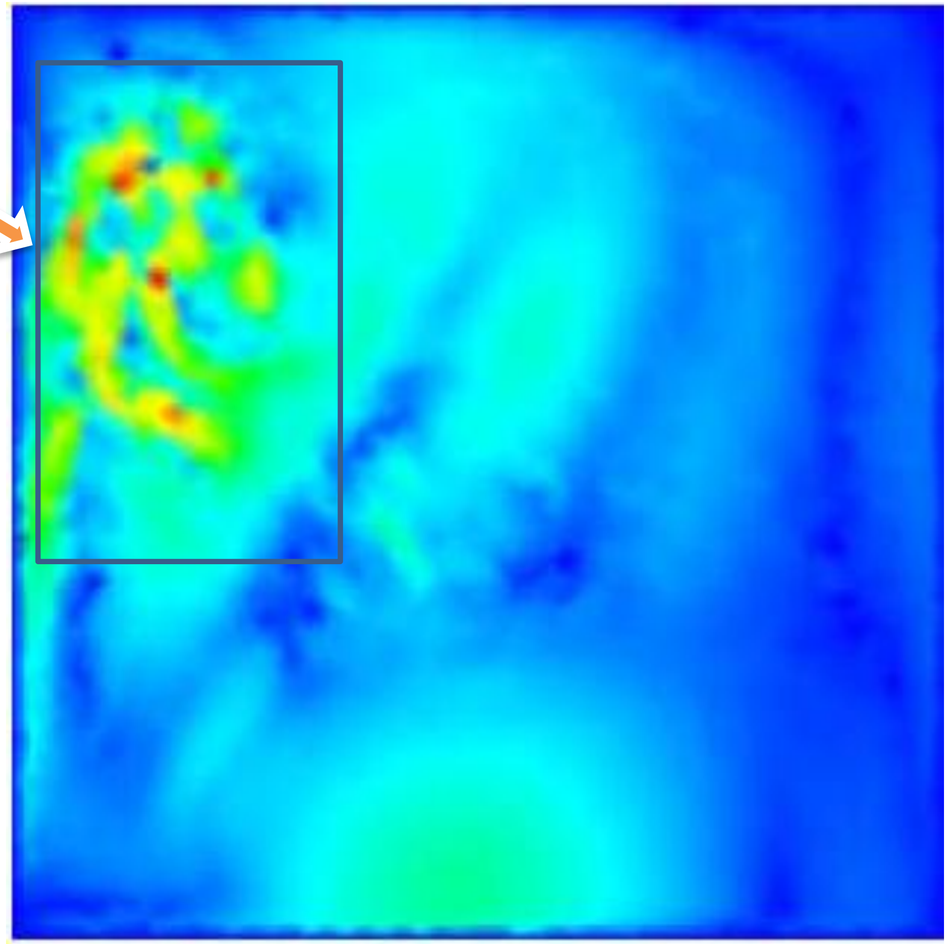


Imperial College London

The observation/forecast sensitivity at the target time
Adjoint sensitivity analysis

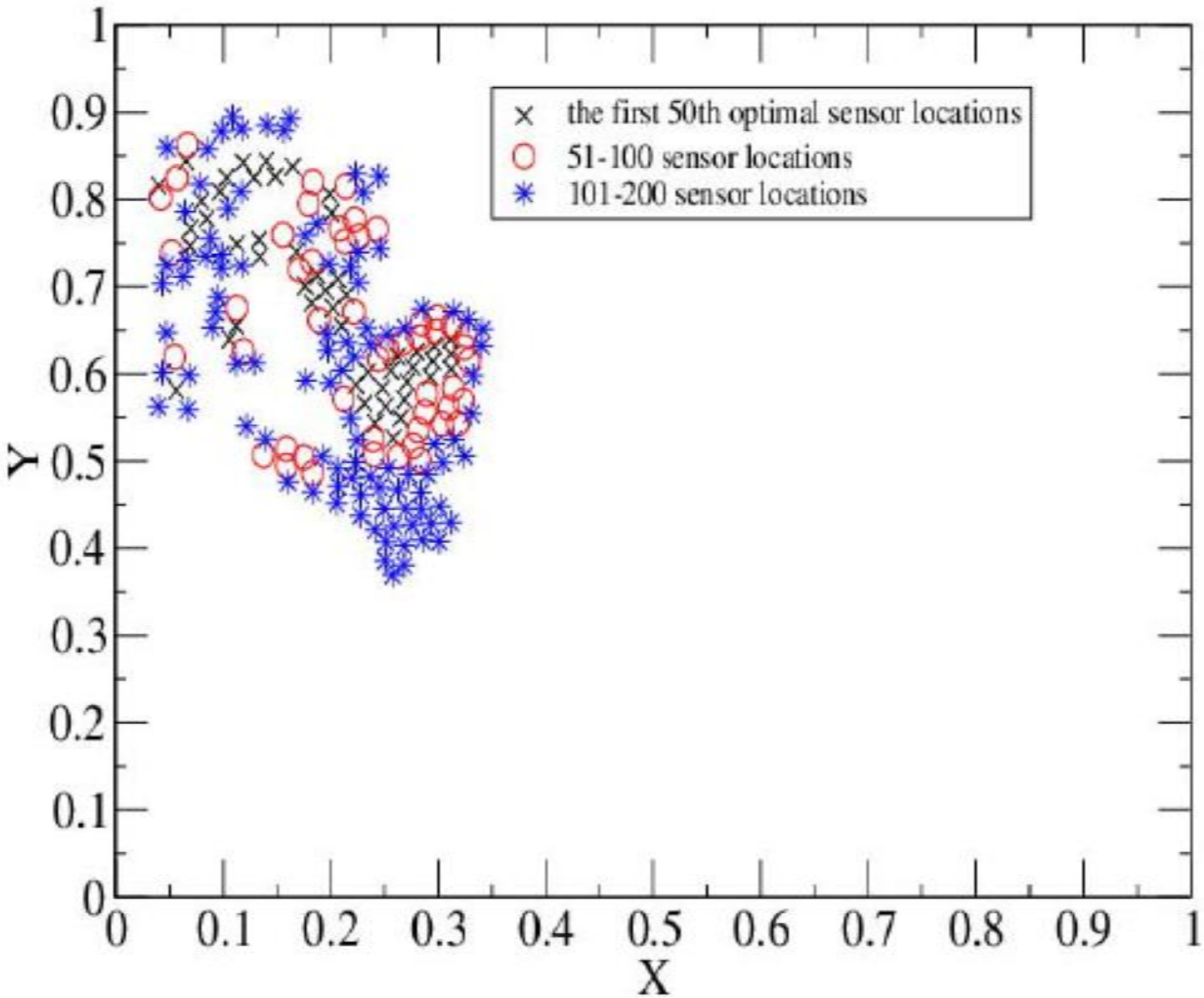
Target region

$$\nabla \mathfrak{I}^{v}(U_i) = M_{i,v}^{T} P^{T} E P \left(U_v^{t} - U_v \right)$$

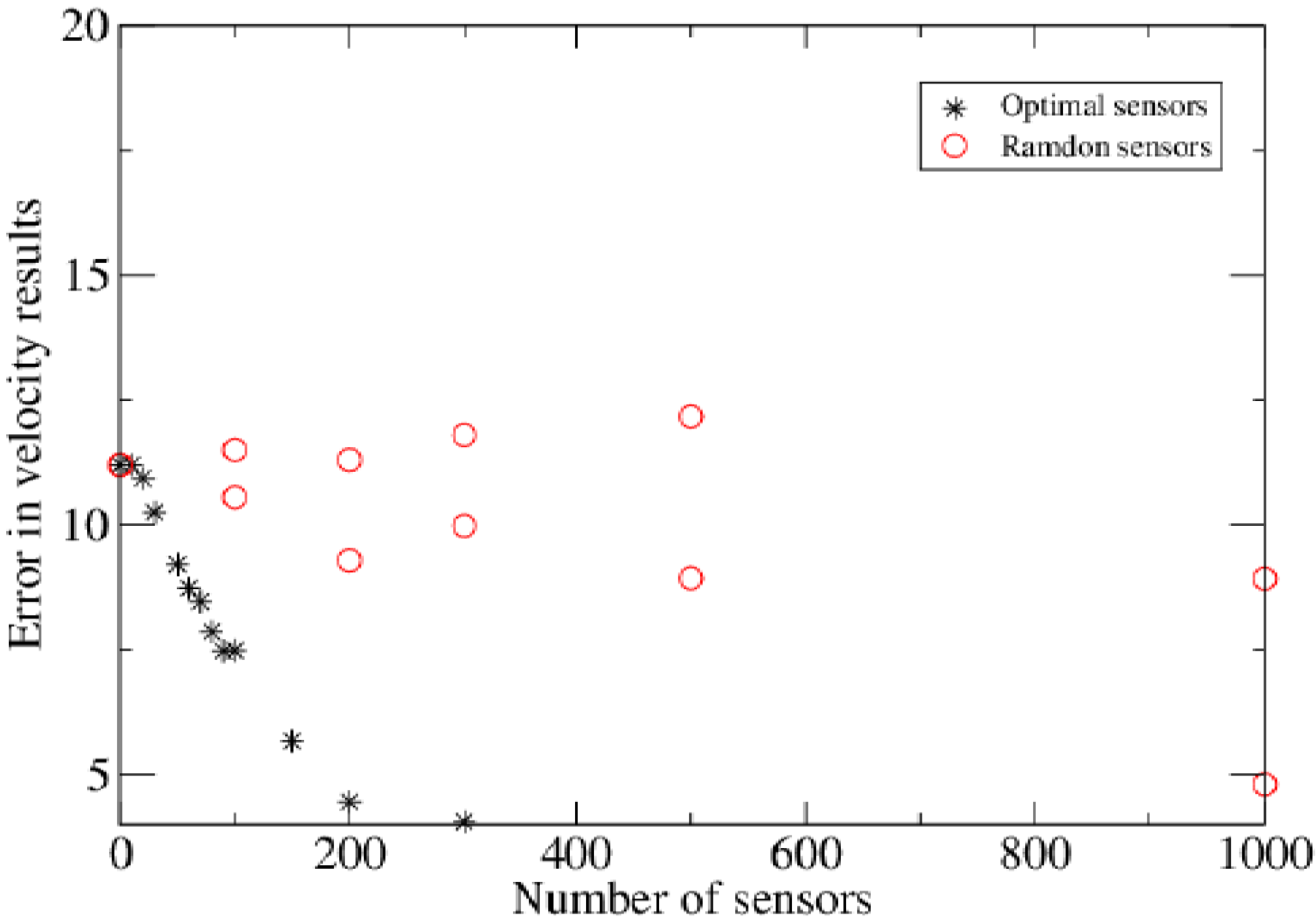


The locations of the observations and error variances of the largest forecast sensitivity are displayed

Optimal sensor location



Results -- Error in velocity field at the verification time and region



Conclusions

- Unstructured adaptive mesh will be able to conform accurately to coastlines and to ocean floor topography.
- Use mesh adaptivity to focus computational resource where it is most required, and to resolve wide range of critical spatial and temporal scales present in oceanographic dynamics.
- Conservative interpolation between different unstructured meshes with the construction of superrmesh.

Future Work

- The representative error of observations with adaptive mesh and its impact on the data assimilation process will be studied.
- EnKF data assimilation with adaptive mesh will be further implemented in the realistic ocean model with complex topography and boundary conditions, such as the South China Sea.

Thanks for your attention