

# Next Generation Multiscale Adaptive Mesh Atmospheric Modelling, Rapid Response and Data Assimilation

Fangxin Fang, Jeff Gomes



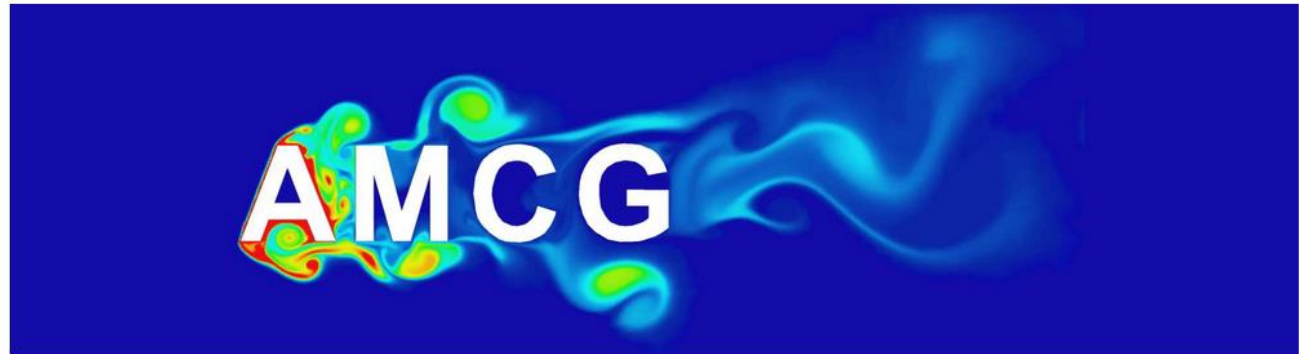
# AMCG website

(<http://www.imperial.ac.uk/earth-science/research/research-groups/amcg/>)

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- Petroleum Geoscience & Engineering
- Energy, Environment, Modelling & Minerals
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  - 3D@IC - 3D Seismic Interpretation Research
  - AMCG - Applied Modelling & Computation Group**
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- BRG - Basins Research Group
- Carbonate Research
- Centre for Petroleum Studies
- CRG - Centre for Reservoir Geophysics
- Diagenesis Linked Research
- Flow, Transport, Reaction
- Geodynamics: Core to Surface
- IARC - Impacts and Astromaterials Research Centre
- ICOG - Imperial College Organic Geochemistry
- LODF - London Centre for Ore

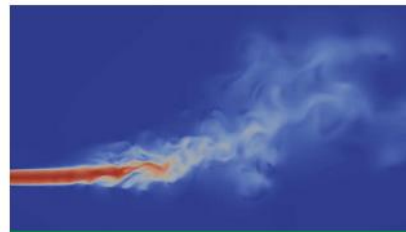
## AMCG - Applied Modelling & Computation Group



AMCG is committed to both the development and application of innovative modelling techniques in earth, nuclear, engineering and biomedical sciences.

AMCG Internal

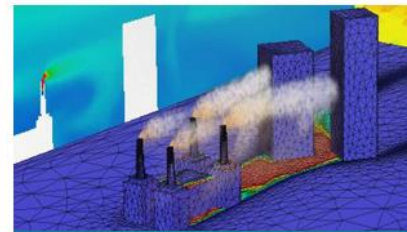
The group has core research interests in the development and application of numerical methods for fluids including ocean, atmosphere, and industrial multi-phase flows, for neutral particle radiation transport, for optimisation mathematics and its applications, and for the solution of inverse (imaging/tomographic) problems.



### Software

[Read more about the software we develop](#)

- [Fluidity](#)



### Publications

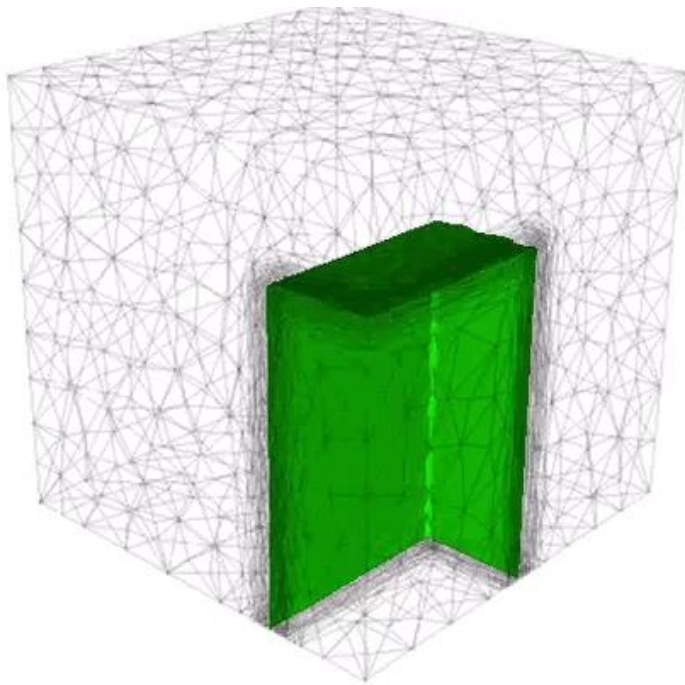
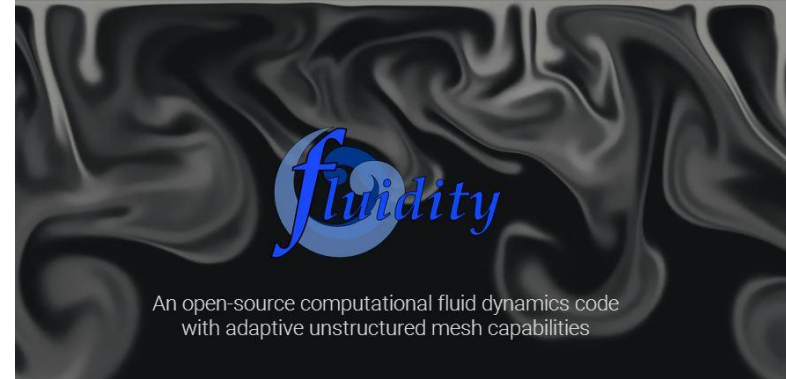
[See a list of our most recent publications on a broad range of topics](#)

### People

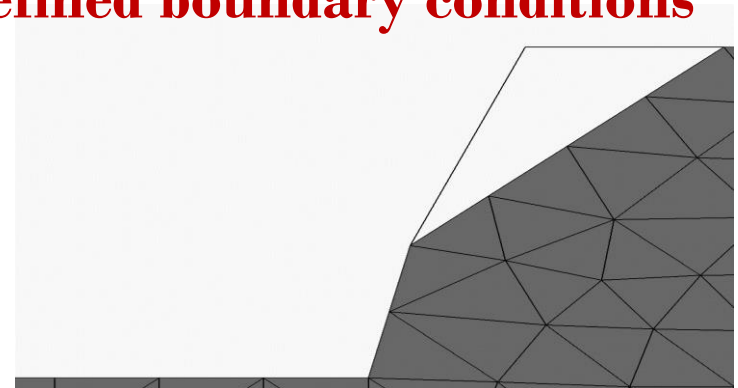
[The team at AMCG](#)

# Fluidity

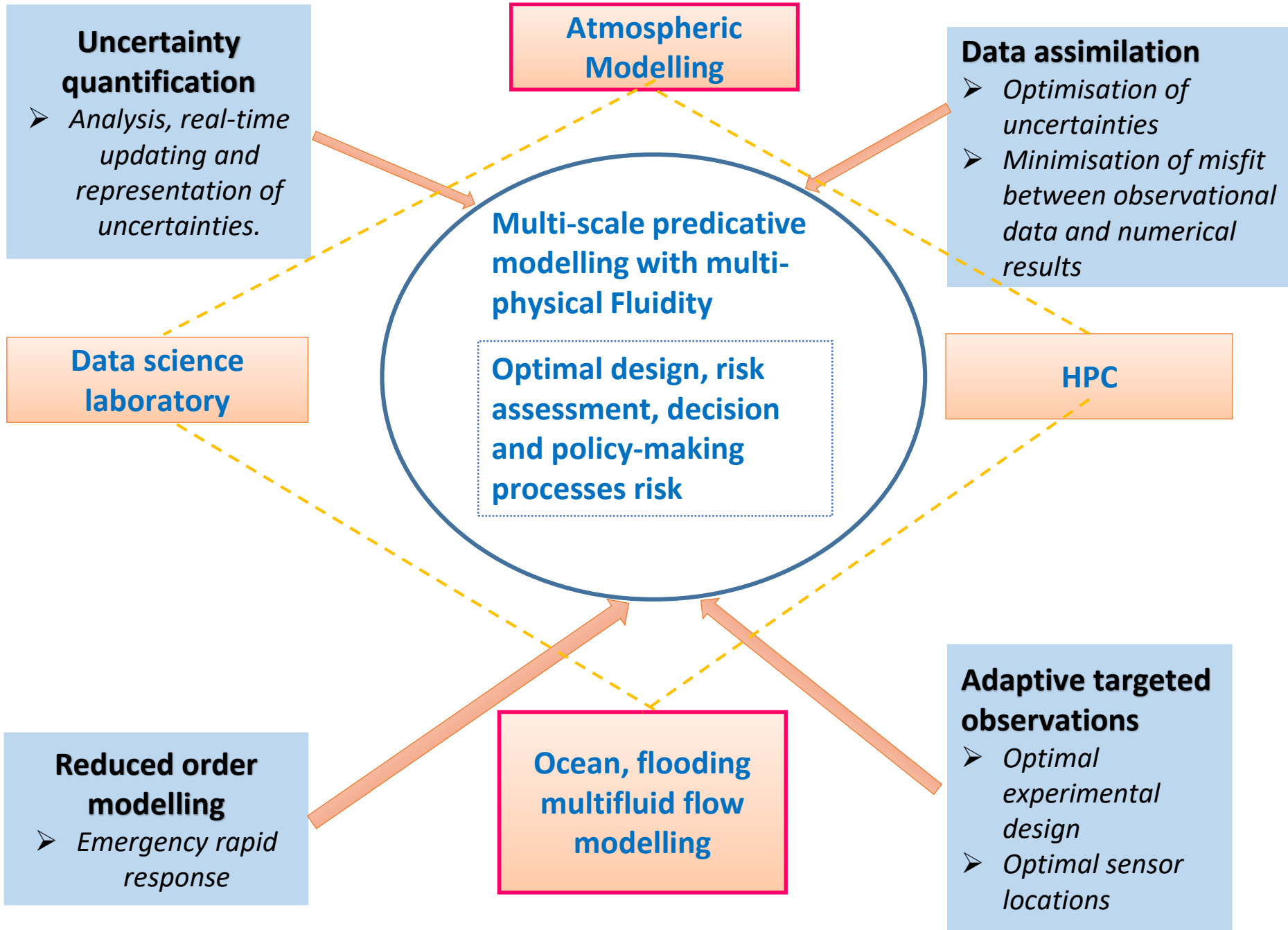
- ❖ **Open Source Model Software for Multiphysics Problems**
- ❖ **Unstructured FEM Meshes**
- ❖ **Anisotropic Adaptive Mesh technology**



- ❖ **User-friendly GUI**
- ❖ **Python interface to calculate diagnostic fields, to set prescribed fields and user-defined boundary conditions**

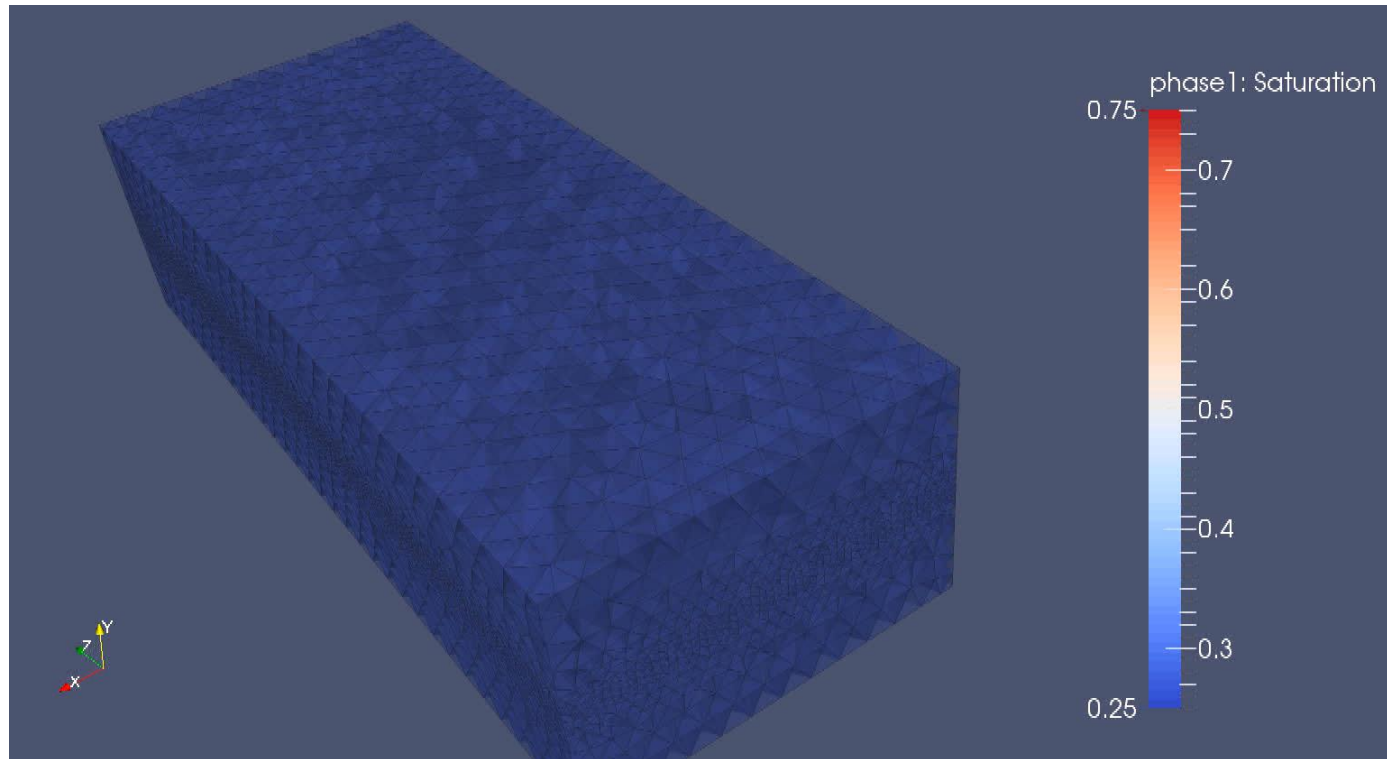


# Predictive and Uncertainty Model Framework



# Computational Multi-Fluid Flow Dynamic Model

- ❖ Porous media model embedded in Fluidity are based on:
  - new family of FE element-pairs ( $P_n$ DG- $P_m$  and  $P_n$ DG- $P_m$ DG) and
  - numerical formulation (overlapping CVFEM) that ensures high-order accuracy on the solution fields (i.e., pressure, velocity, saturation, temperature etc)
- ❖ The model has been used on transport of contaminant in subsurface media (mining spillage), oil and gas production, nuclear waste repository etc;



# Atmospheric Environmental Model: Critical bridge between human activities and environmental change (IAP)

Severely Polluted Day

$PM_{2.5} \sim 470 \mu g m^{-3}$

奥运区俯瞰实时图

中国科学院大气物理研究所

Polluted Day

$PM_{2.5} \sim 200 \mu g m^{-3}$

奥运区俯瞰实时图

中国科学院大气物理研究所

Beijing, Olympic site

Clean Day

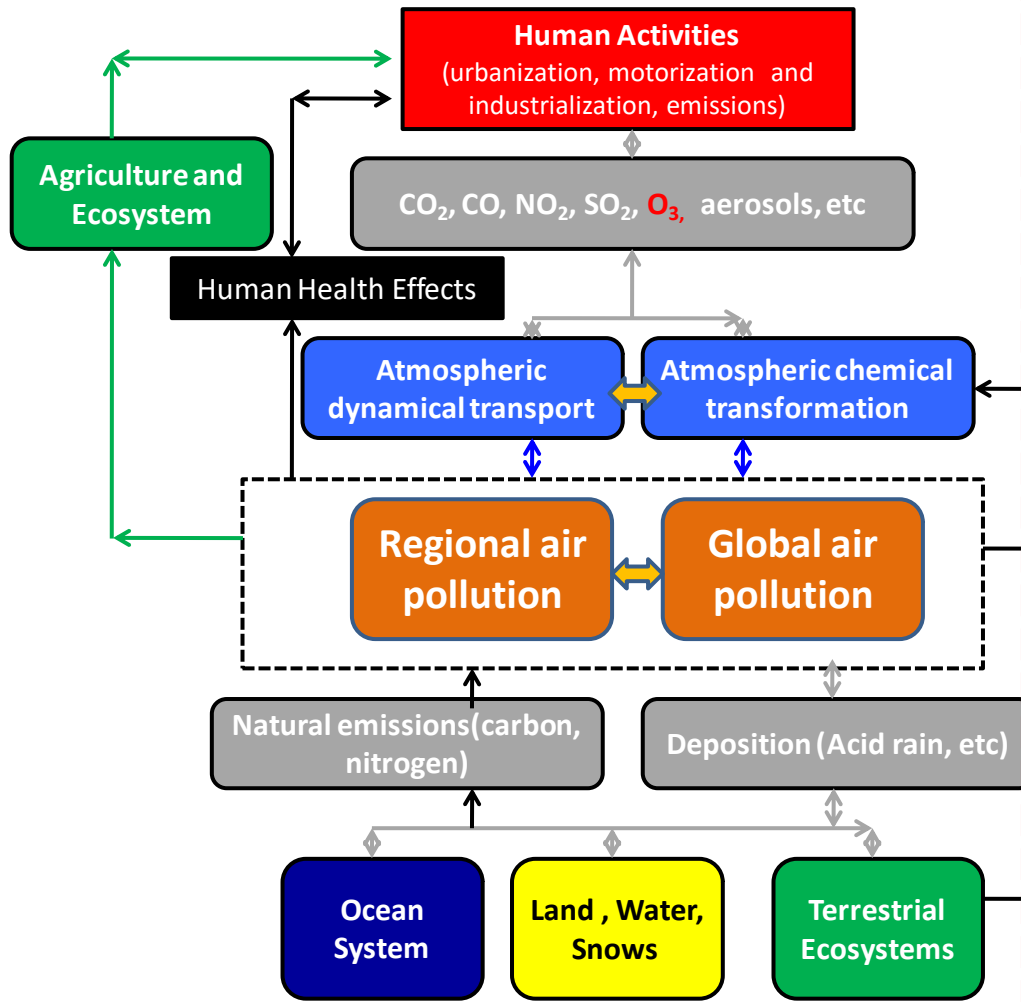
$PM_{2.5} \sim 15 \mu g m^{-3}$

奥运区俯瞰实时图

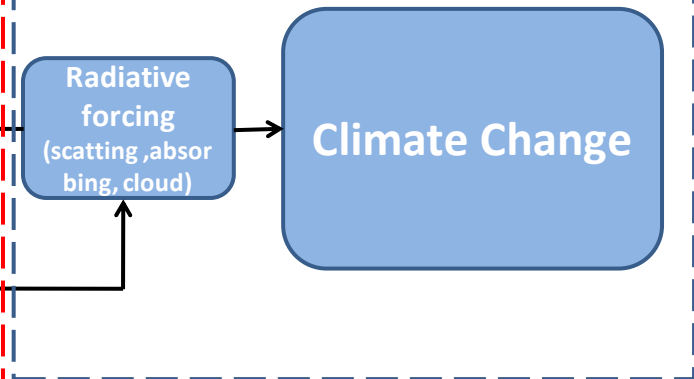
中国科学院大气物理研究所

# Atmospheric Environmental Model: Critical bridge between human activities and environmental change (IAP)

## Environmental issues



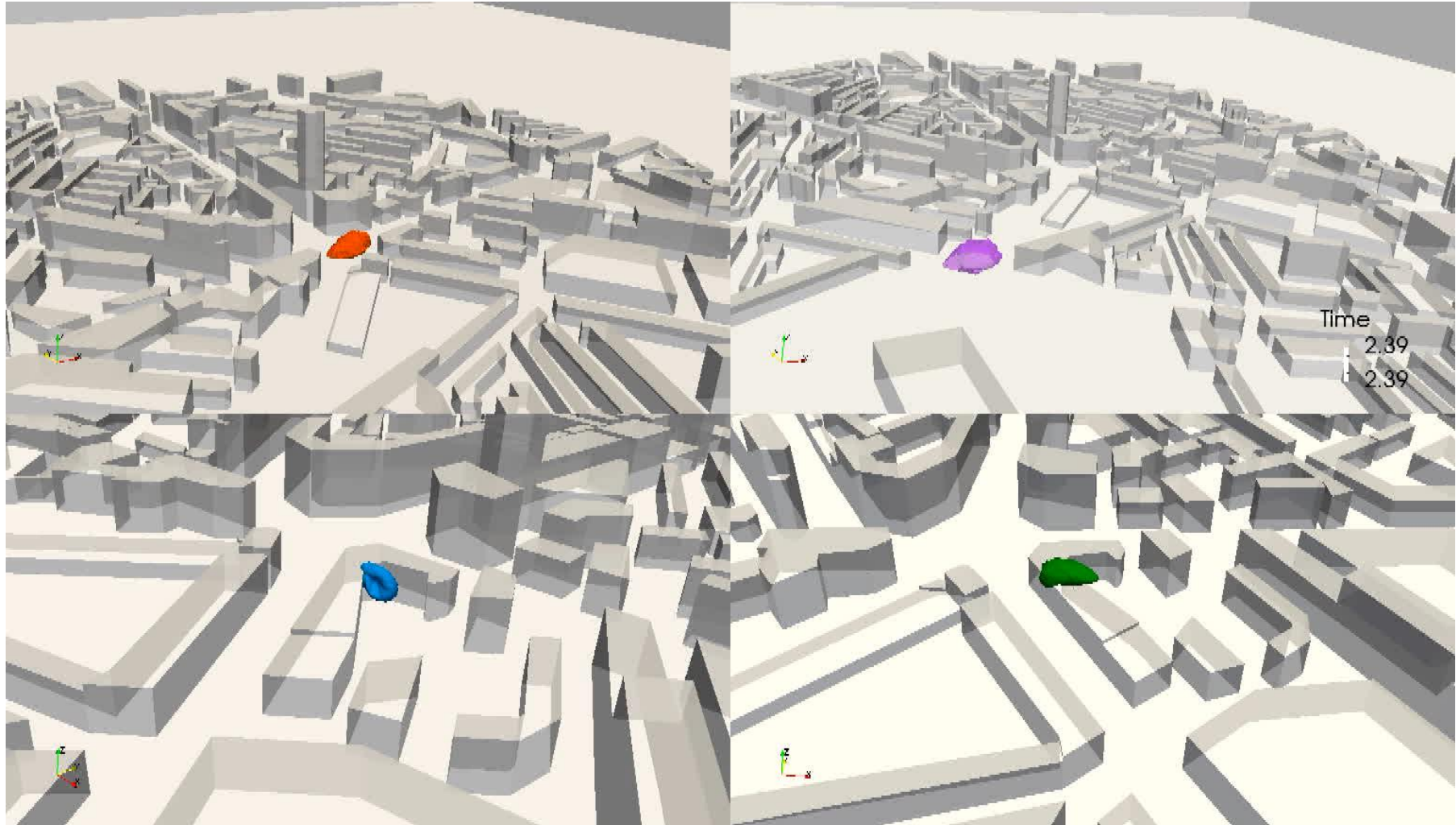
## Climate issues



**Air pollution is largely influenced by human activities, and can be reduced by human.**

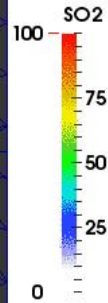
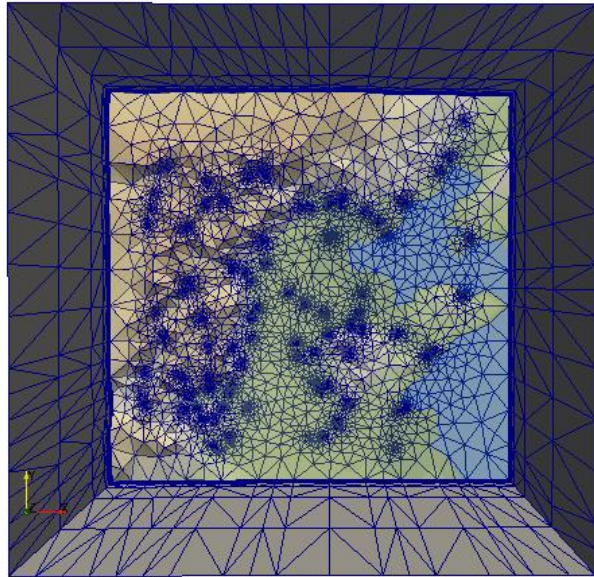
# Urban Air Pollution Modelling

(MAGIC, supported by EPSRC) @Elephant Castle, London

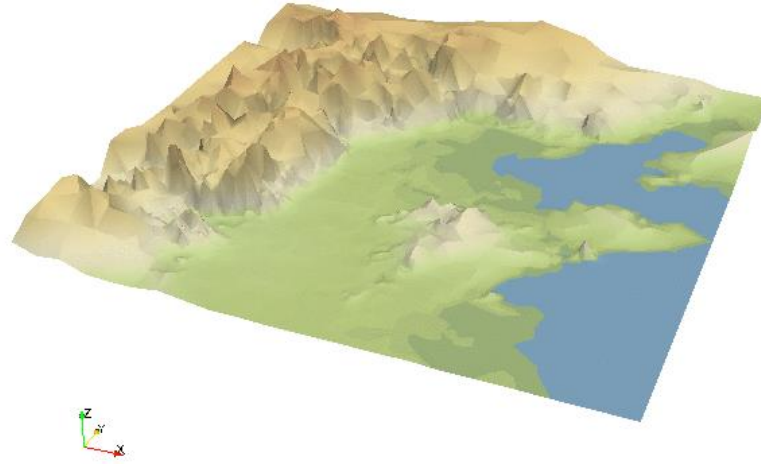




# Air Pollutant Modelling (IAP-ICL, supported by NSFC/ EPSRC)

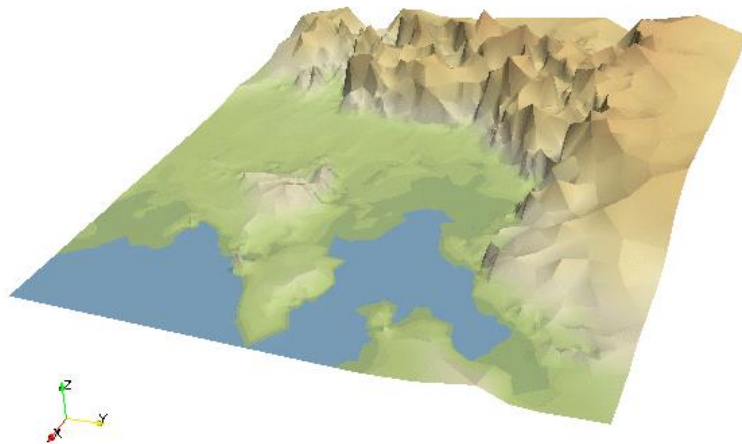


View1: SE-NW

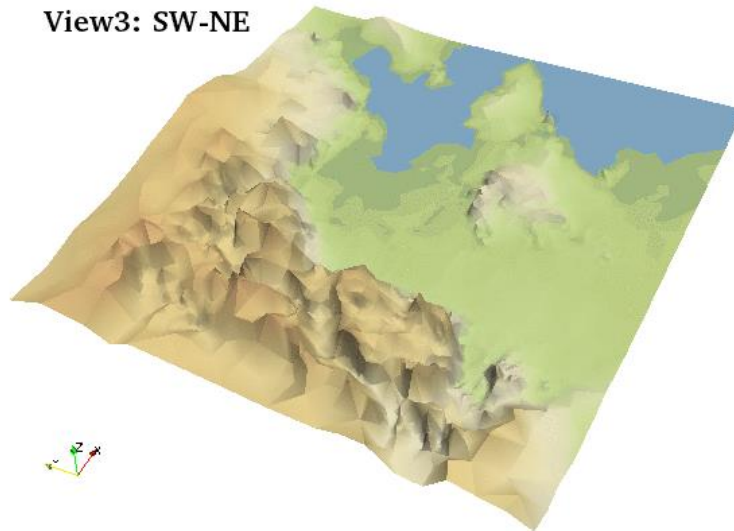


SO<sub>2</sub> released  
from over 100  
power plants  
(over Beijing  
and 55 cities)

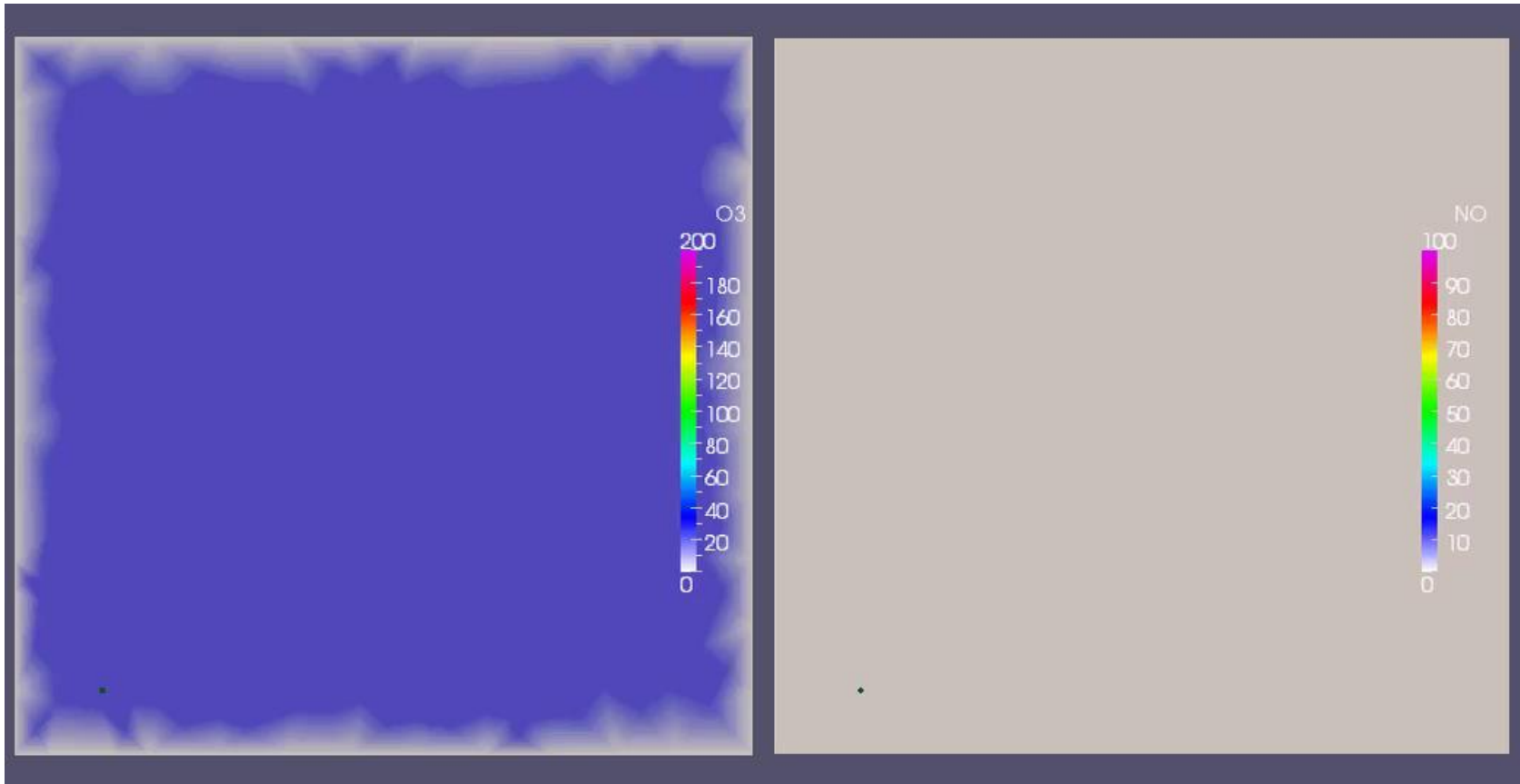
View2: NE-SW



View3: SW-NE

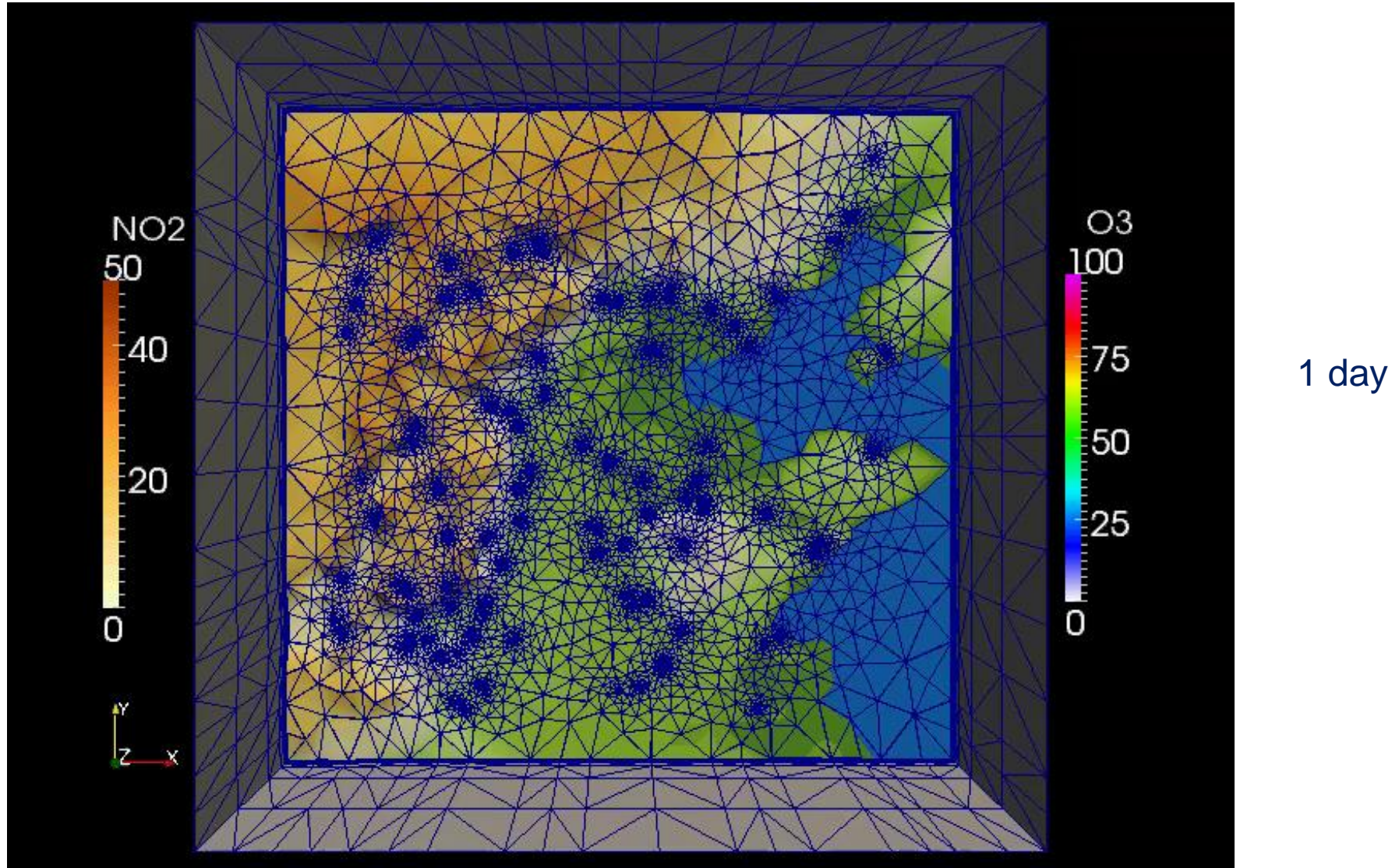


# Chemical modelling (IAP-ICL, Zheng etc.) (NO and NO<sub>2</sub> released from over 100 power plants)

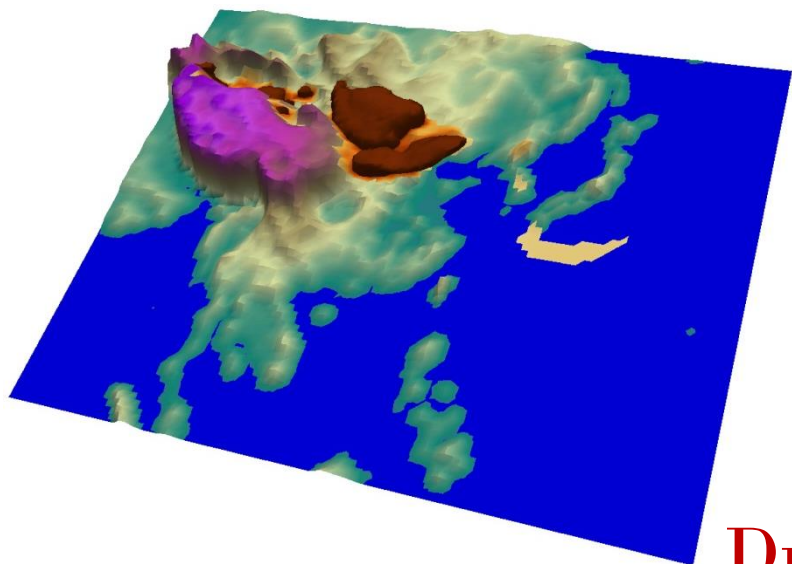


Continuous formation/consumption of NO<sub>x</sub> and Ozone over 5 days.

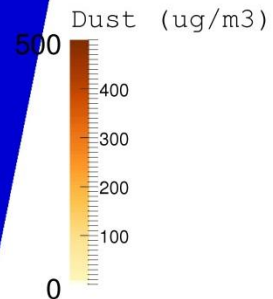
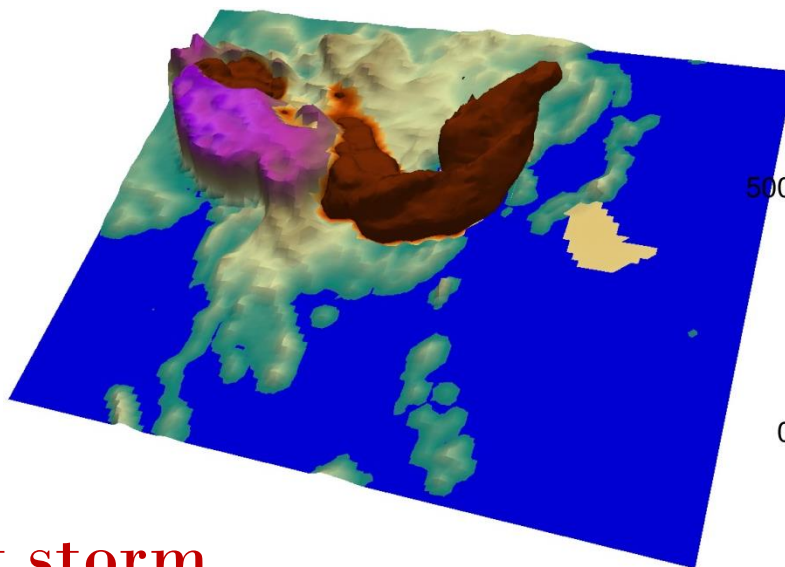
# 3D chemical modelling (IAP-ICL, Zheng etc.) (NO and NO2 released from over 100 power plants)



2010-03-19\_04

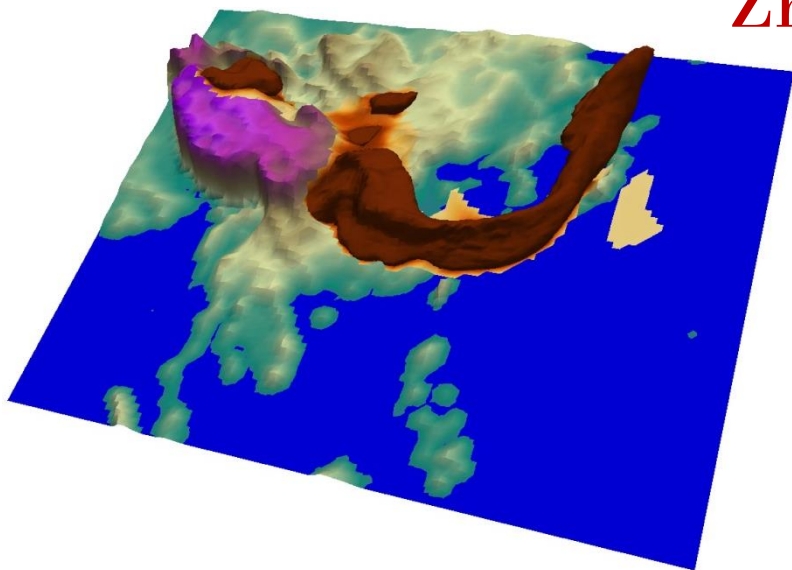


2010-03-20\_04

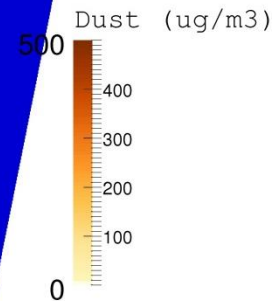
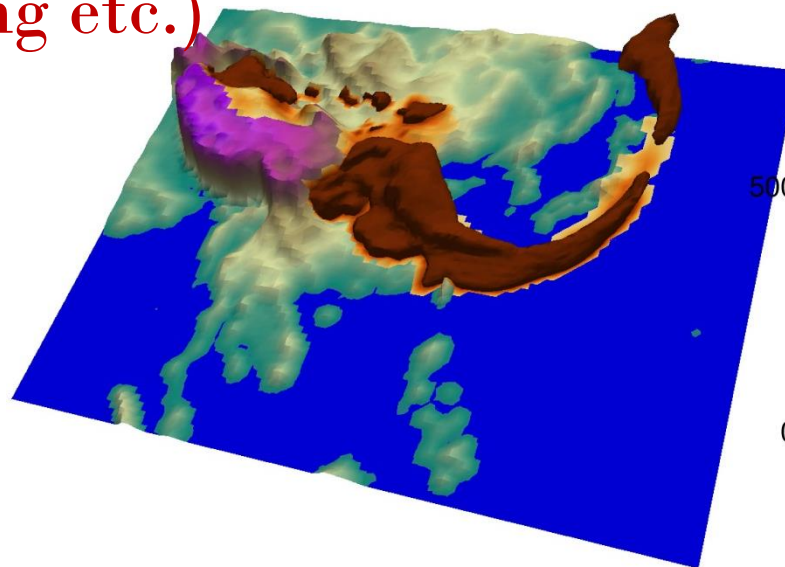


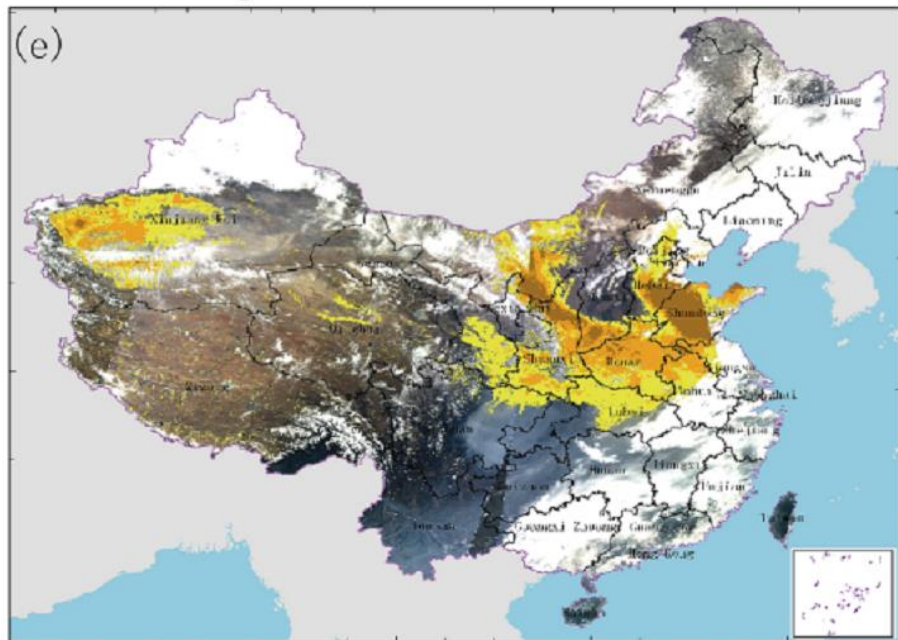
Dust storm  
(IAP-ICL,  
Zheng etc.)

2010-03-20\_18

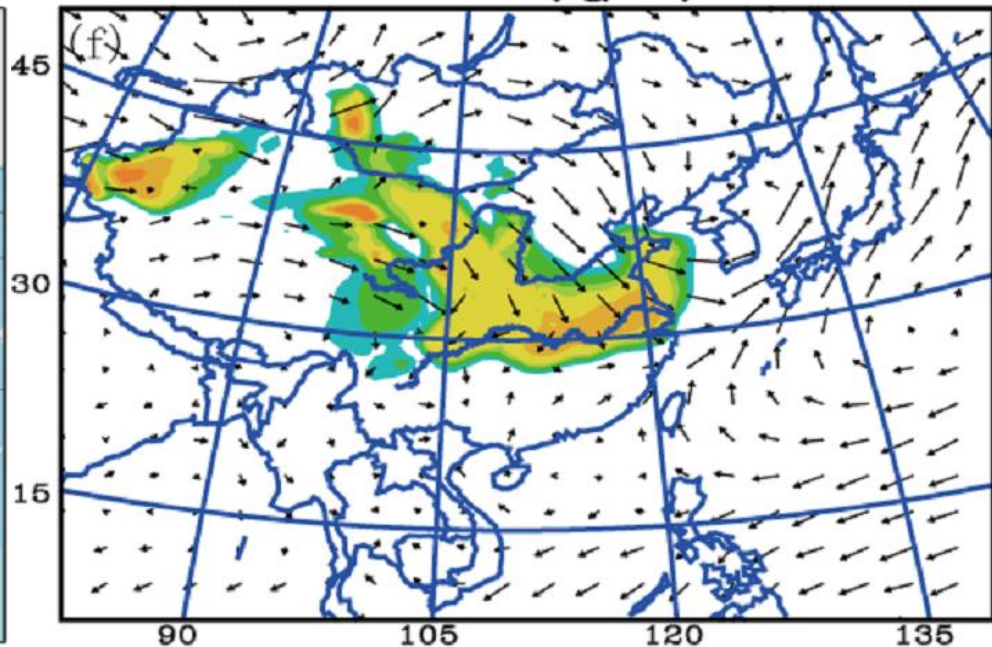


2010-03-21\_04

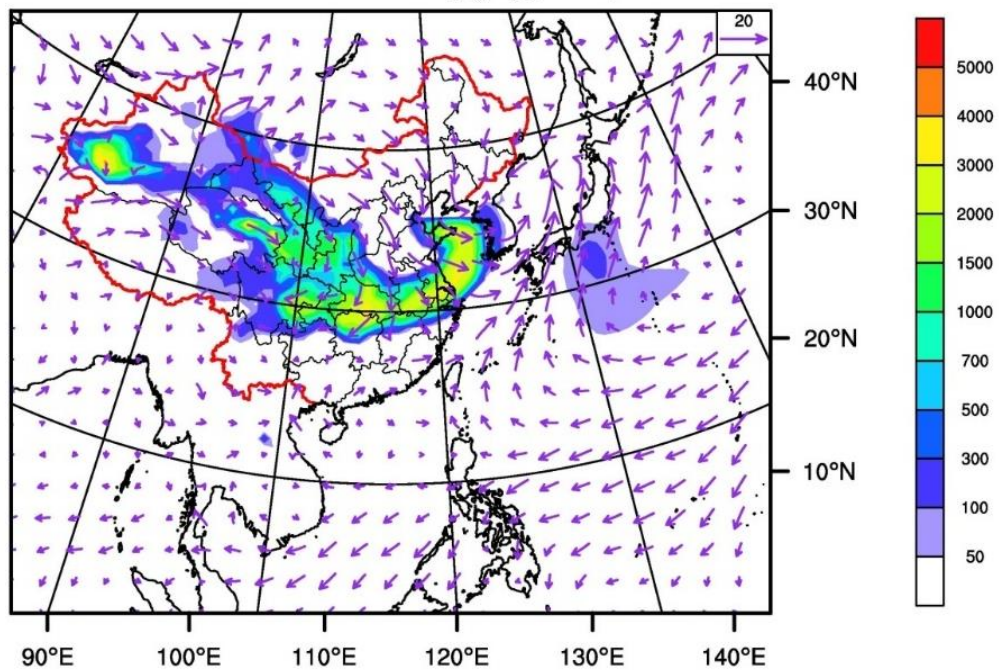
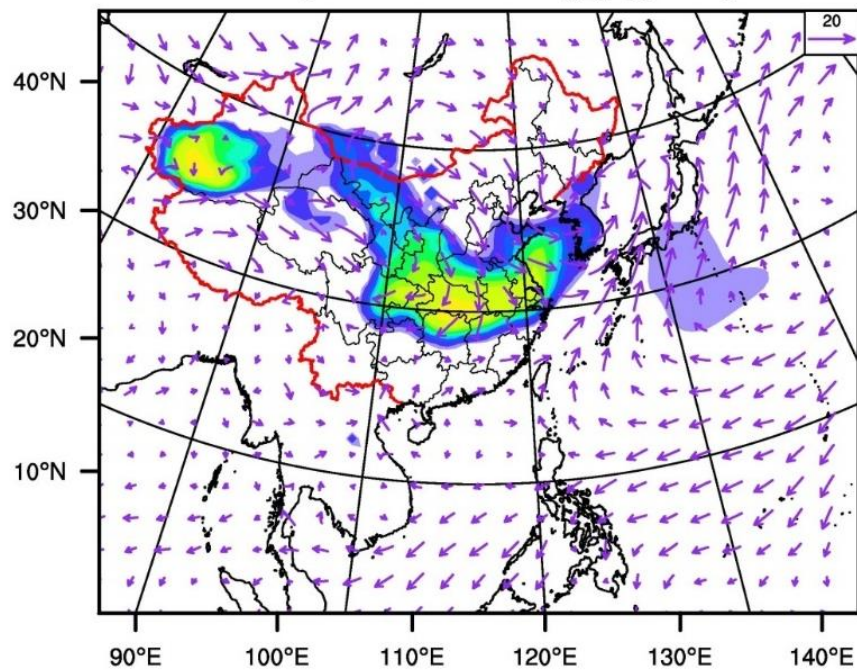




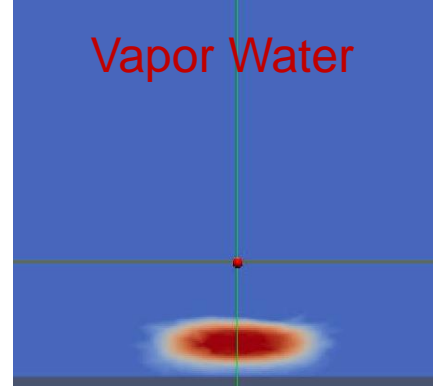
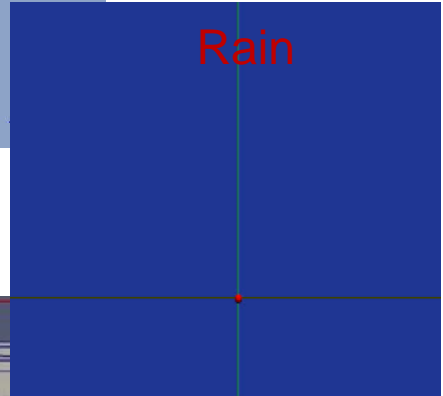
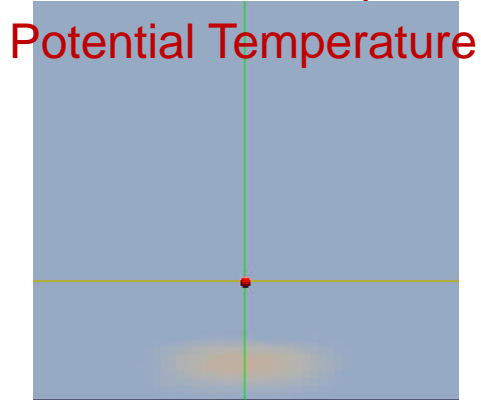
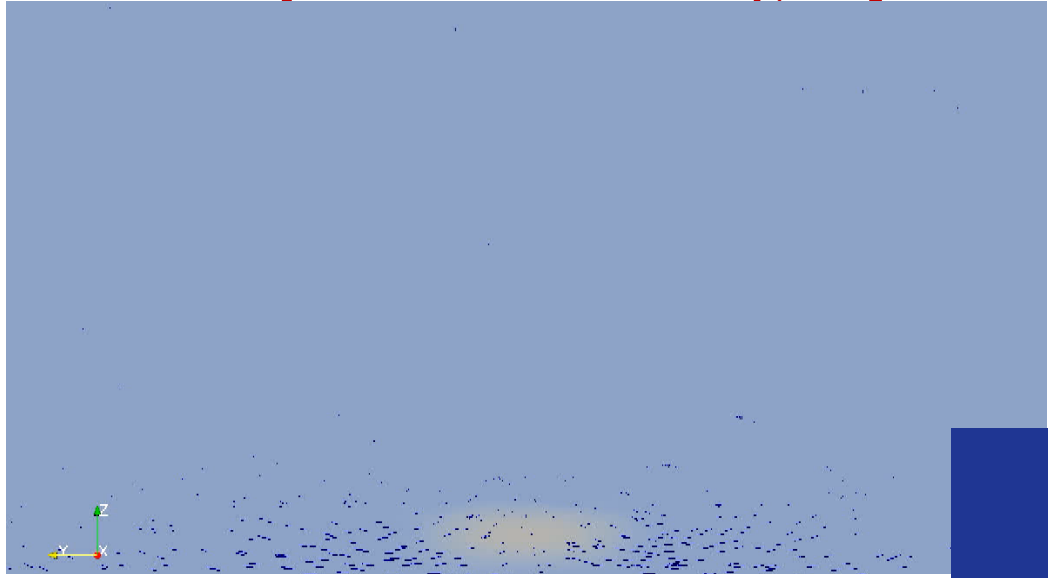
Fluidity-Dust surface  $\text{PM}_{10}$  ( $\mu\text{g}/\text{m}^3$ )



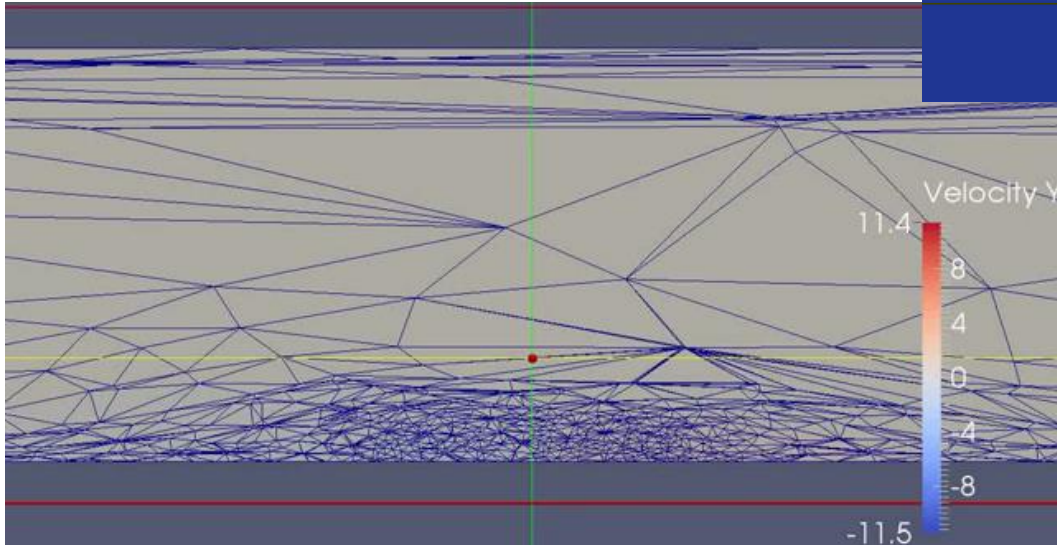
NAQPMS surface  $\text{PM}_{10}$  ( $\mu\text{g}/\text{m}^3$ ) on 20100320 06:00



# 3D Atmospheric Modelling: Cyclone 3D Simulation (IAP-ICL)



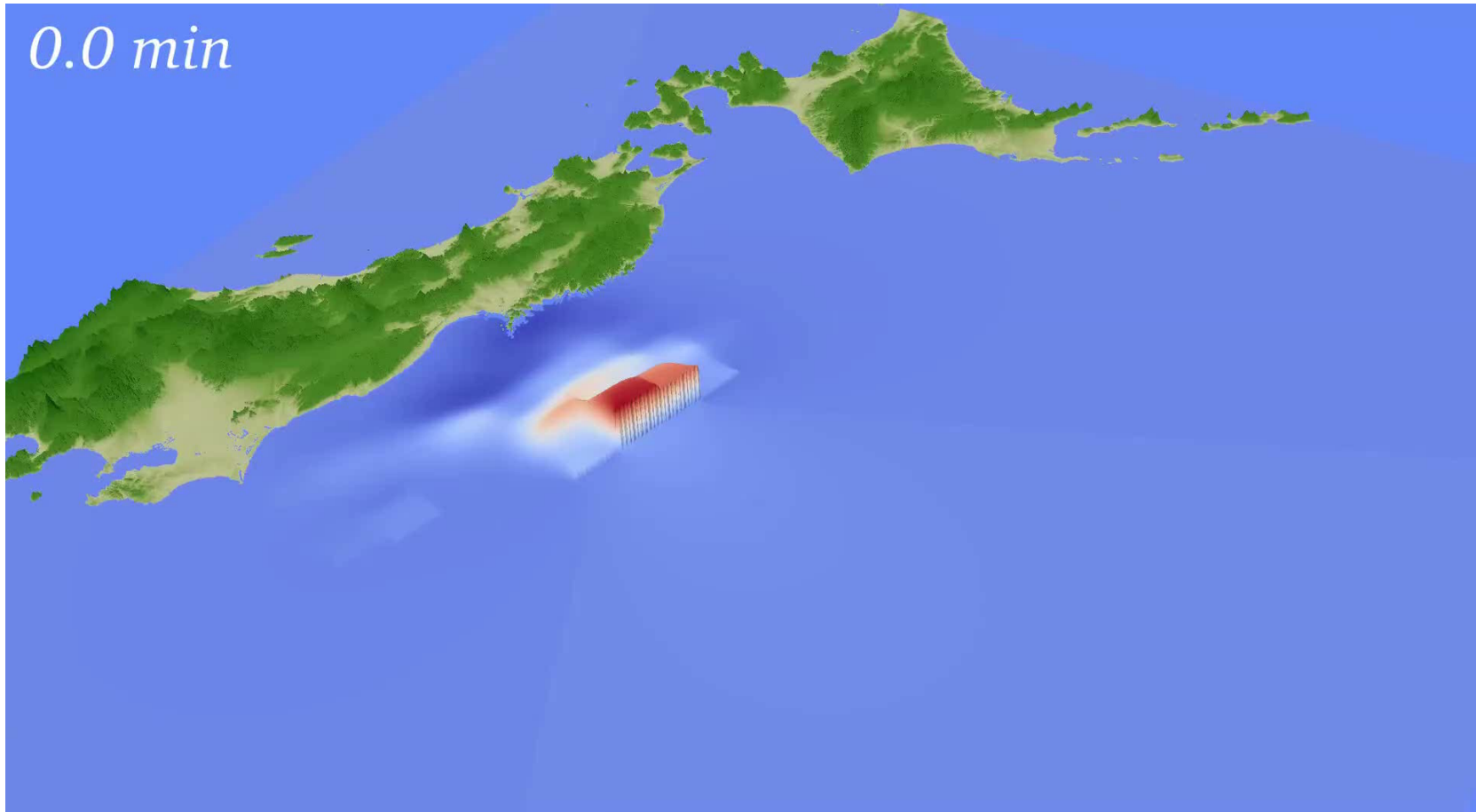
Velocity Vector



Adaptive mesh

Cloud

# Tohoku event from 2011 (Visiting PhD student from Japan)



# Natural Disaster: Simulating Flooding – Denmark (R. Hu etc. supported by the EU PEARL project)

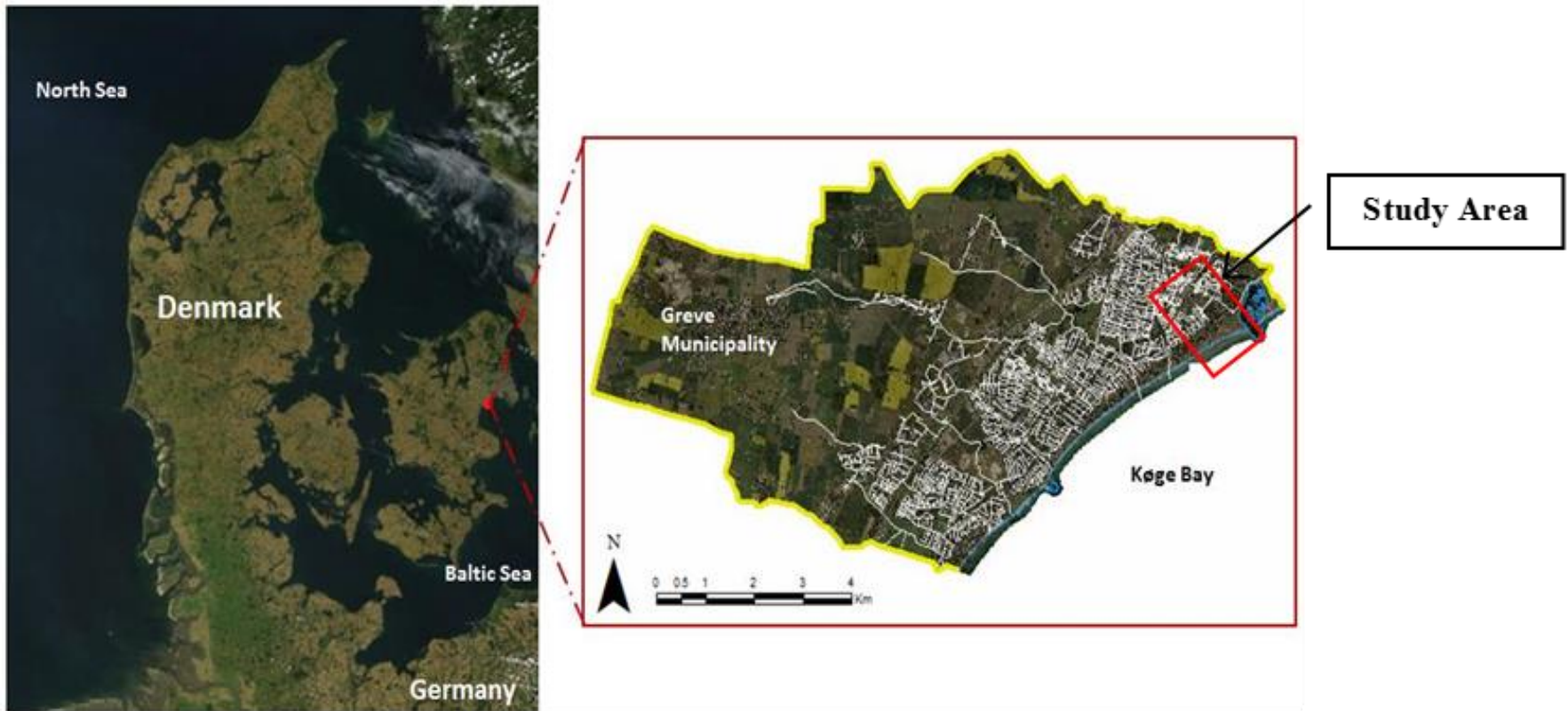
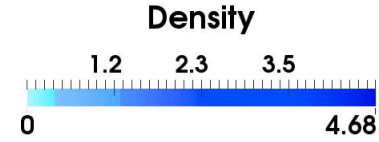
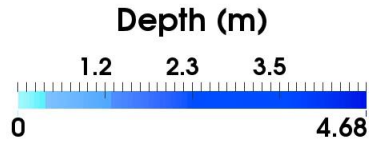


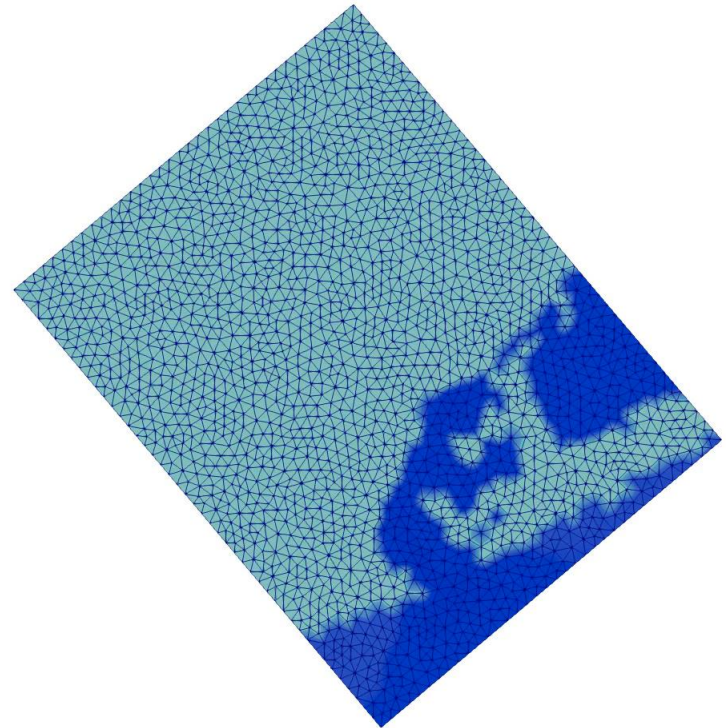
Fig. 11. Situation of Study Area in Greve, Municipality of Denmark, see [Soledad \(2014\)](#)



# Natural Disaster: Simulating Flooding – Denmark (R. Hu etc. supported by the EU PEARL project)

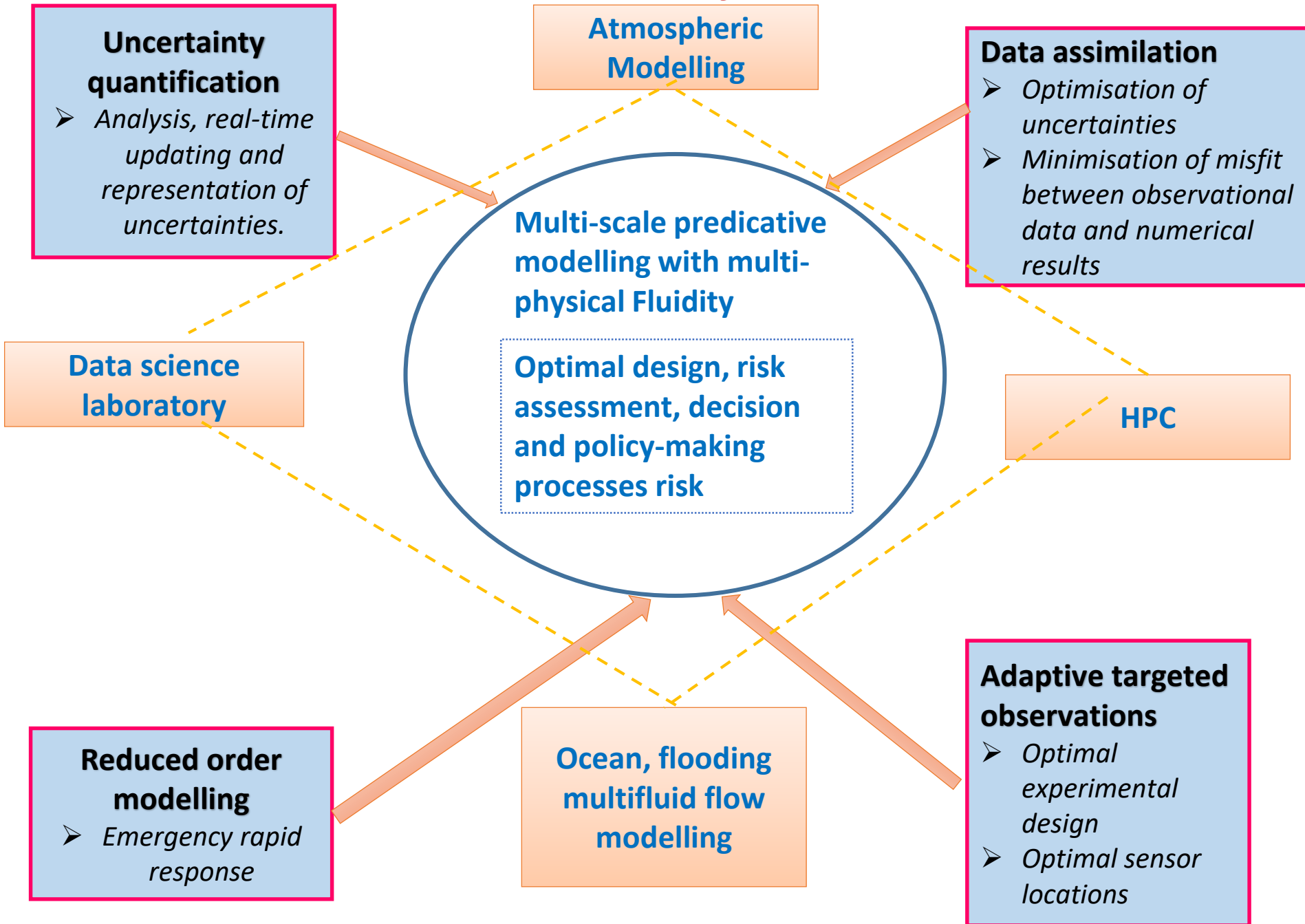


**Surface**



**Surface with mesh**

# Predictive and Uncertainty Model Framework



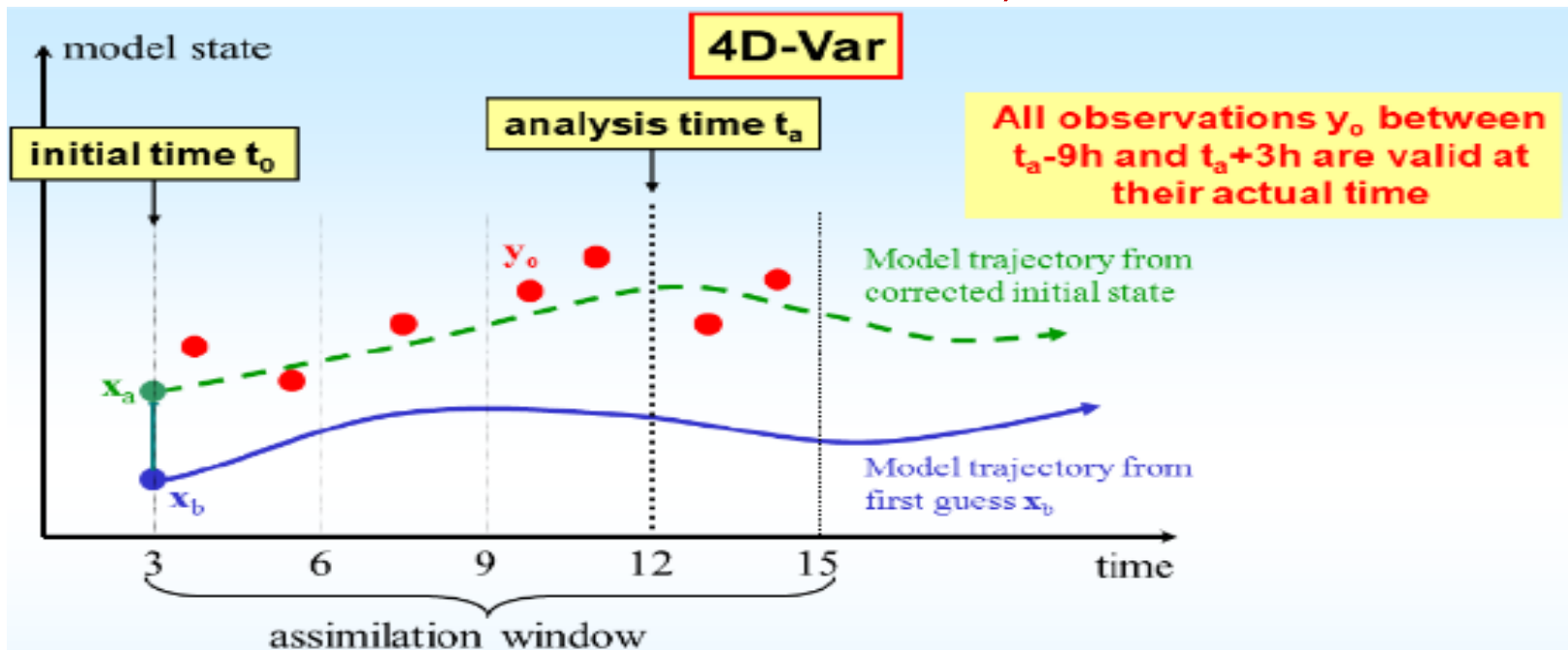
# Data Assimilation (DA)

## DA methods:

- ❖ Optimal interpolation;
- ❖ Nudging;
- ❖ 3D-Var;
- ❖ 4D-Var (Adjoint);
- ❖ Ensemble KF

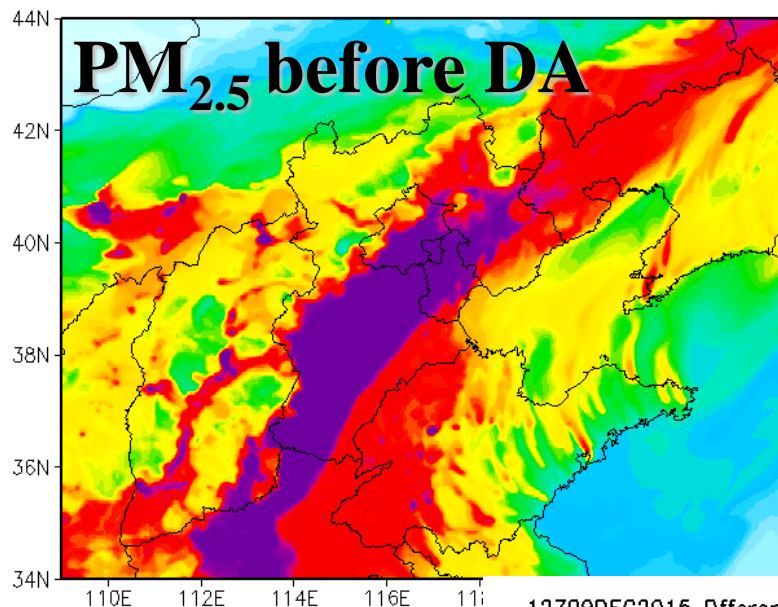
## Motivation for DA:

- ❖ To improve the predictability of numerical models;
- ❖ Uncertainty sensitivity analysis;
- ❖ Optimisation of uncertainties in models;
- ❖ Goal-based error measure and mesh adaptivity;
- ❖ Design optimisation;
- ❖ Adaptive observation (Optimisation of sensors locations).

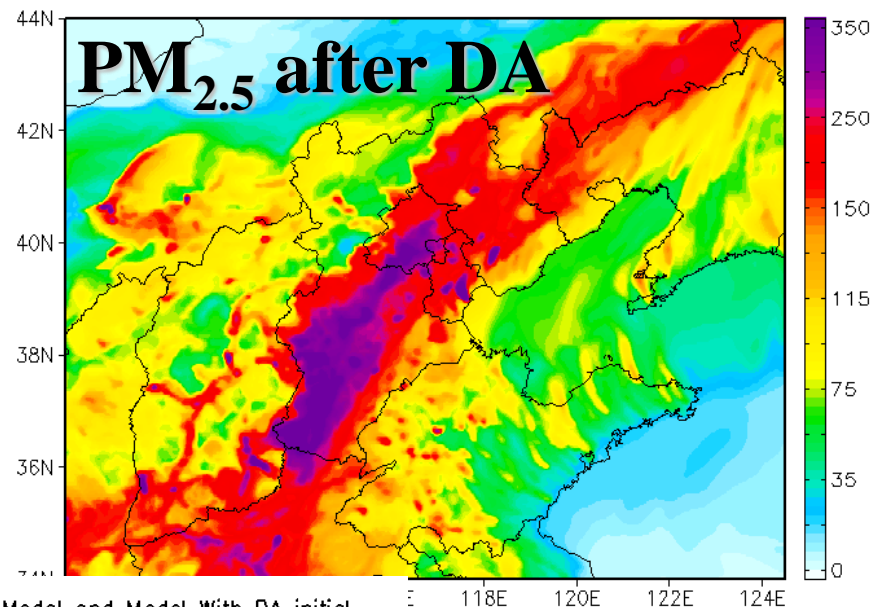


# Work from Institute of Atmospheric and Physics, China

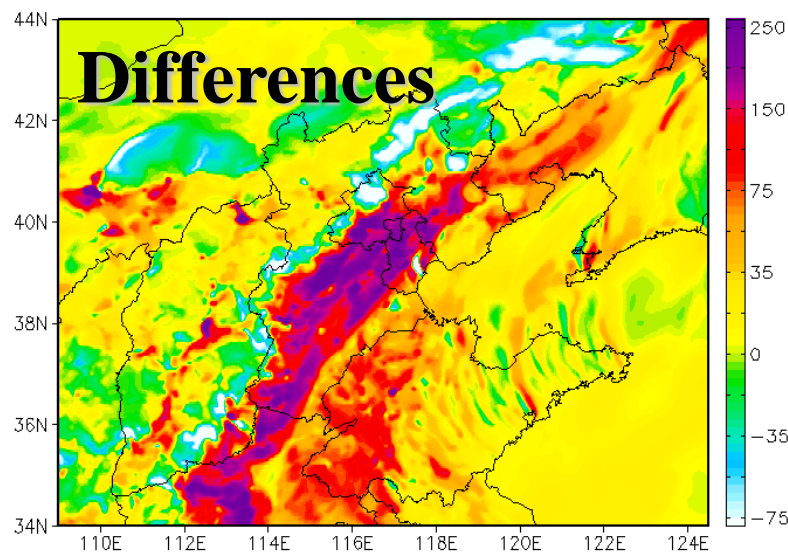
12Z09DEC2015 Model initial (UTC)  
Hourly Surface  $PM_{2.5}$   $\mu g \cdot m^{-3}$  / Wind ( $m \cdot s^{-1}$ )



12Z09DEC2015 Model With DA initial (UTC)  
Hourly Surface  $PM_{2.5}$   $\mu g \cdot m^{-3}$  / Wind ( $m \cdot s^{-1}$ )

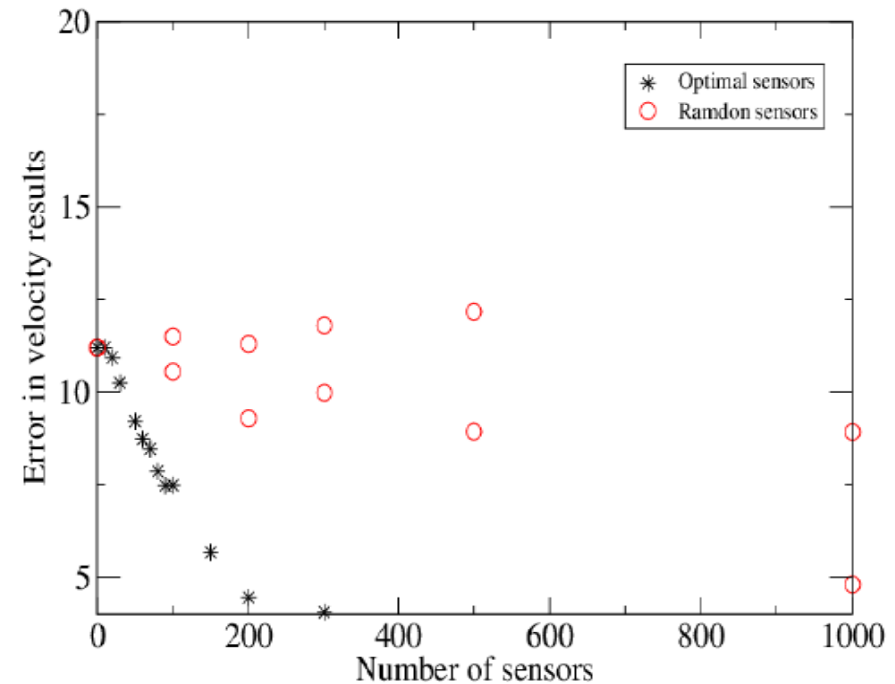
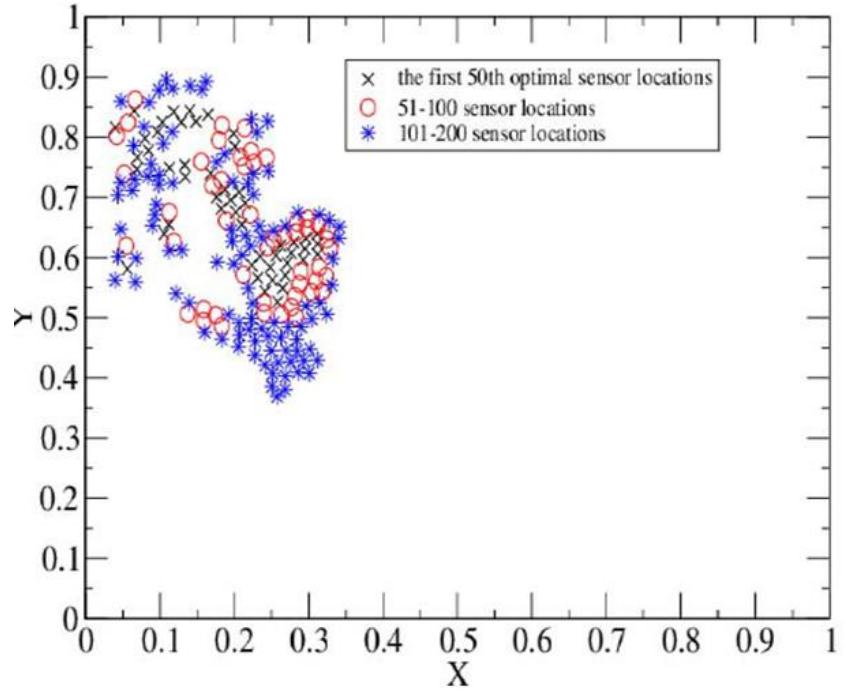
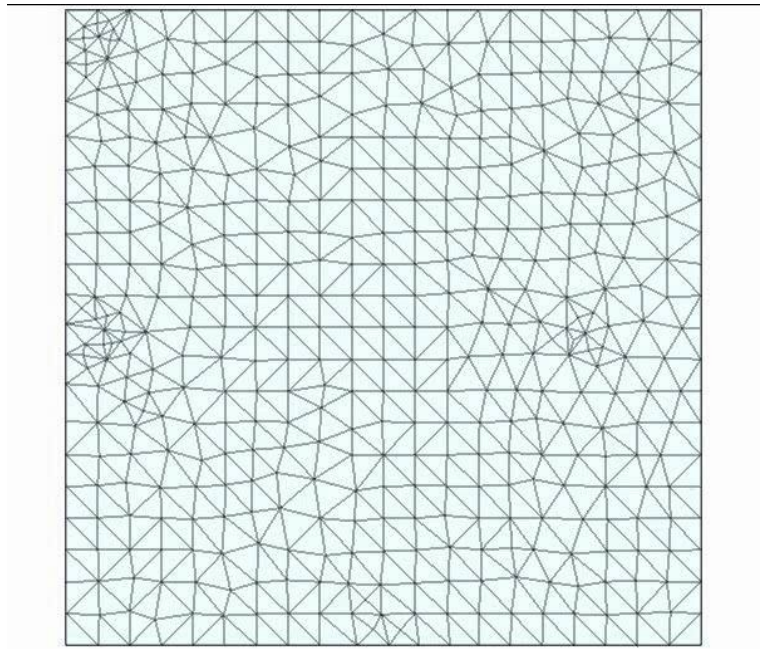


12Z09DEC2015 Difference between Model and Model With DA initial  
Hourly Surface  $PM_{2.5}$   $\mu g \cdot m^{-3}$  / Wind ( $m \cdot s^{-1}$ )



**Sources: CNEMC  
IAP**

# DA: Optimal sensor location



# Reduced Order Modelling

Navier-Stokes Equations:

$$\rho_0 \left( \frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) - \nabla \cdot \mu \nabla \vec{u} + \nabla \bar{p} = -(\rho' + \rho_0) g \vec{n}_g, \quad (1)$$

$$\nabla \cdot \vec{u} = 0, \quad (2)$$

Discretising equations (1) and (2)

Full discretised system (high dimensional):

$$\begin{bmatrix} B & C \\ C^T & 0 \end{bmatrix} \begin{bmatrix} \mathbf{u}^{n+1} \\ p^{n+1} \end{bmatrix} = \begin{bmatrix} B' & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \mathbf{u}^n \\ p^n \end{bmatrix} + \begin{bmatrix} s \\ 0 \end{bmatrix}$$

Projecting onto the reduced space using SVD/POD

$$\begin{bmatrix} B^{POD} & C^{POD} \\ (C^{POD})^T & 0 \end{bmatrix} \begin{bmatrix} \alpha^{u,n+1} \\ \alpha^{p,n+1} \end{bmatrix} = \begin{bmatrix} B'^{POD} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \alpha^{u,n} \\ \alpha^{p,t} \end{bmatrix} + \begin{bmatrix} s^{POD} \\ 0 \end{bmatrix}$$

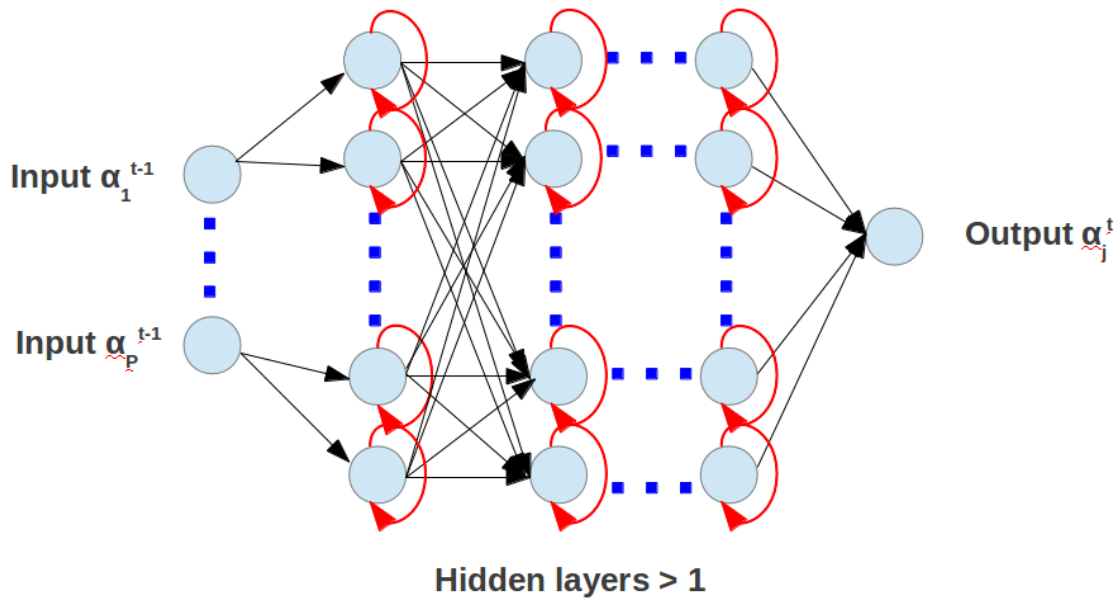
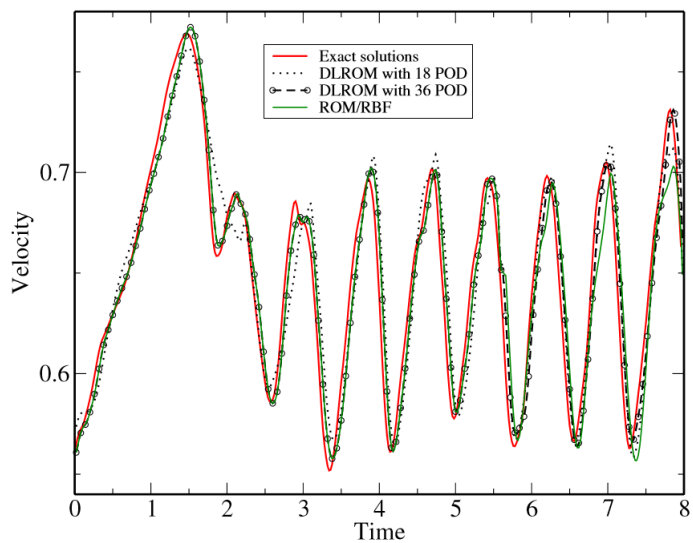
Wring the reduced order model in a general form

$$\alpha_i^n = f_i(\boldsymbol{\alpha}^{n-1}), \quad n \in \{1, 2, \dots, N_t\},$$

The function  $f$  is represented by deep learning

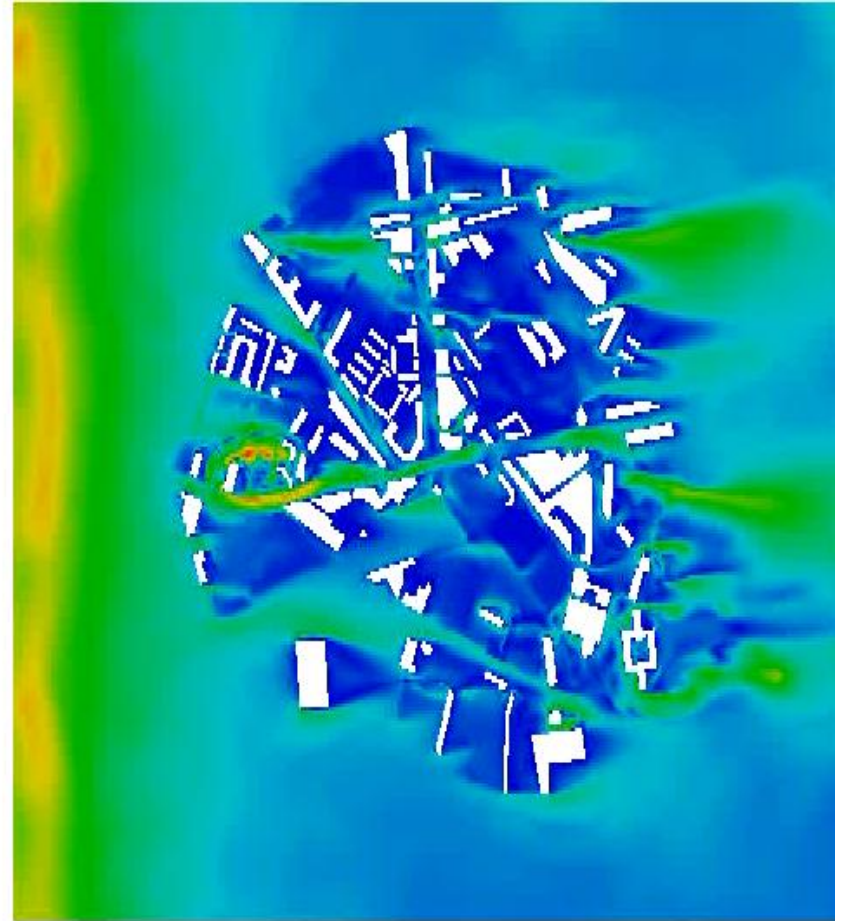
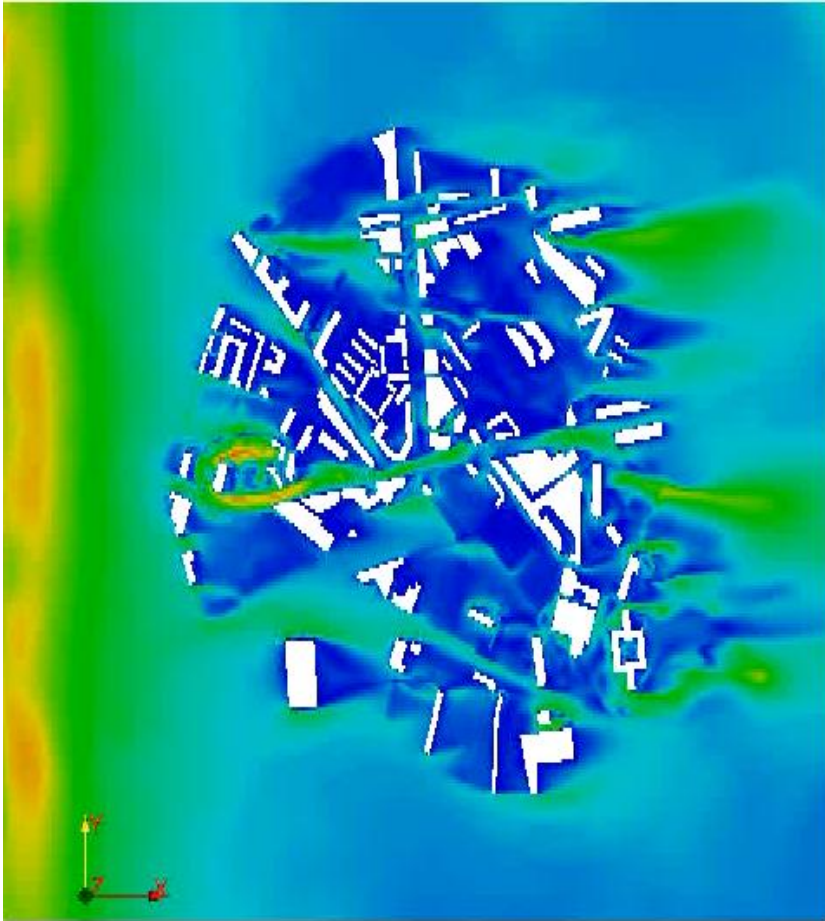
# Reduced Order Modelling (POD) and Deep Learning (Xiao etc)

## Top panel: Full modelling



**Rapid modelling: Air flow (Elephant Castle London)  
(Xiao etc. supported by MAGIC –EPSRC)**

**Left: reduced order modelling; right: high fidelity modelling**



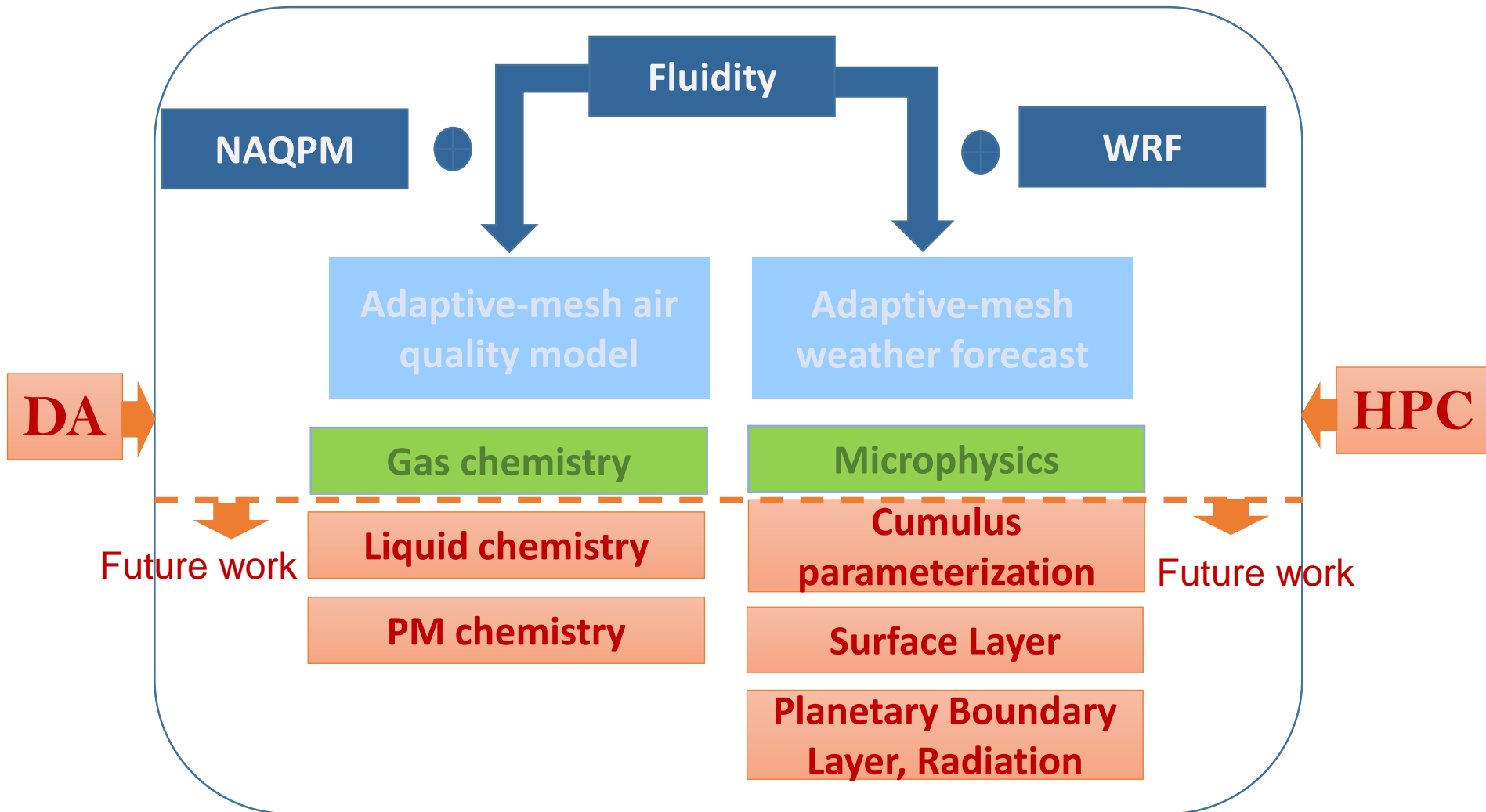
CPU time: seconds (Reduced order model); 3 hours (10 cores, Full fidelity model)



# Future work

Reginal Model

Global Model



**Thanks**

# Rapid modelling: Flow past two buildings

Top: reduced order modelling; bottom: high fidelity modelling

