EPIRUS: An Integrated "Clouds-to-Coast" Ensemble Modelling Framework Of Coastal Flood Risk

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NATURAL ENVIRONMENT RESEARCH COUNCIL

Capital Value of Assets at Flood Risk (£ billions)

		Region							
		Anglian	**Midland**	**North East**	**North West**	**South West**	**Southern**	**Thames**	**Total**
Fluvial	***Property***	10.7	14.1	7.8	2.9	3.9	4.6	28.6	72.5
	Agriculture	2.9	0.6	0.4	0.2	0.4	0.1	0.3	4.9
	Total	13.6	14.7	8.2	3.1	4.3	4.7	28.9	**77.4**
Sea/ Tidal	***Property***	9.7	1.8	10.4	7.8	2.9	13.8	81.3	127.8
	Agriculture	0.7	0.3	0.3	0.2	0.1	0.3	0.0	1.9
	Total	10.4	2.1	10.7	8.0	3.0	14.1	81.3	**129.7**
Total	***Property***	20.4	15.9	18.2	10.7	6.9	18.4	109.8	200.3
	Agriculture	3.6	0.9	0.7	0.4	0.5	0.4	0.3	6.8
	Grand Total	24.0	16.8	18.9	11.1	7.4	19.8	110.1	**207.1**

After MAFF (2001)

Coastal Flood and Erosion

- £132 billion assets at coastal flood risk
- £7.8 billion assets at coastal erosion risk
- 4 million people and properties in England and Wales at coastal flooding and erosion risk

Coastal Flood at Brighton (Jan 2007)


Coastal Erosion at Happisburgh (July 2006)

Coastal Flood Defence Failure

- **Functional failure:**
  Conditions exceed what the defence was designed for
- **Structural failure:**
  Element or components of defence fail to perform as expected

  - **Wave overtopping**
    - Erosion of the back and crest of defence
    - Damage to armour layers
  - **Toe scour**

    Leads to beach lowering

    ↓

    increase water depth

    ↓

    larger waves

    ↓

    more beach lowering

    ↓

    Undermining defence

Objectives

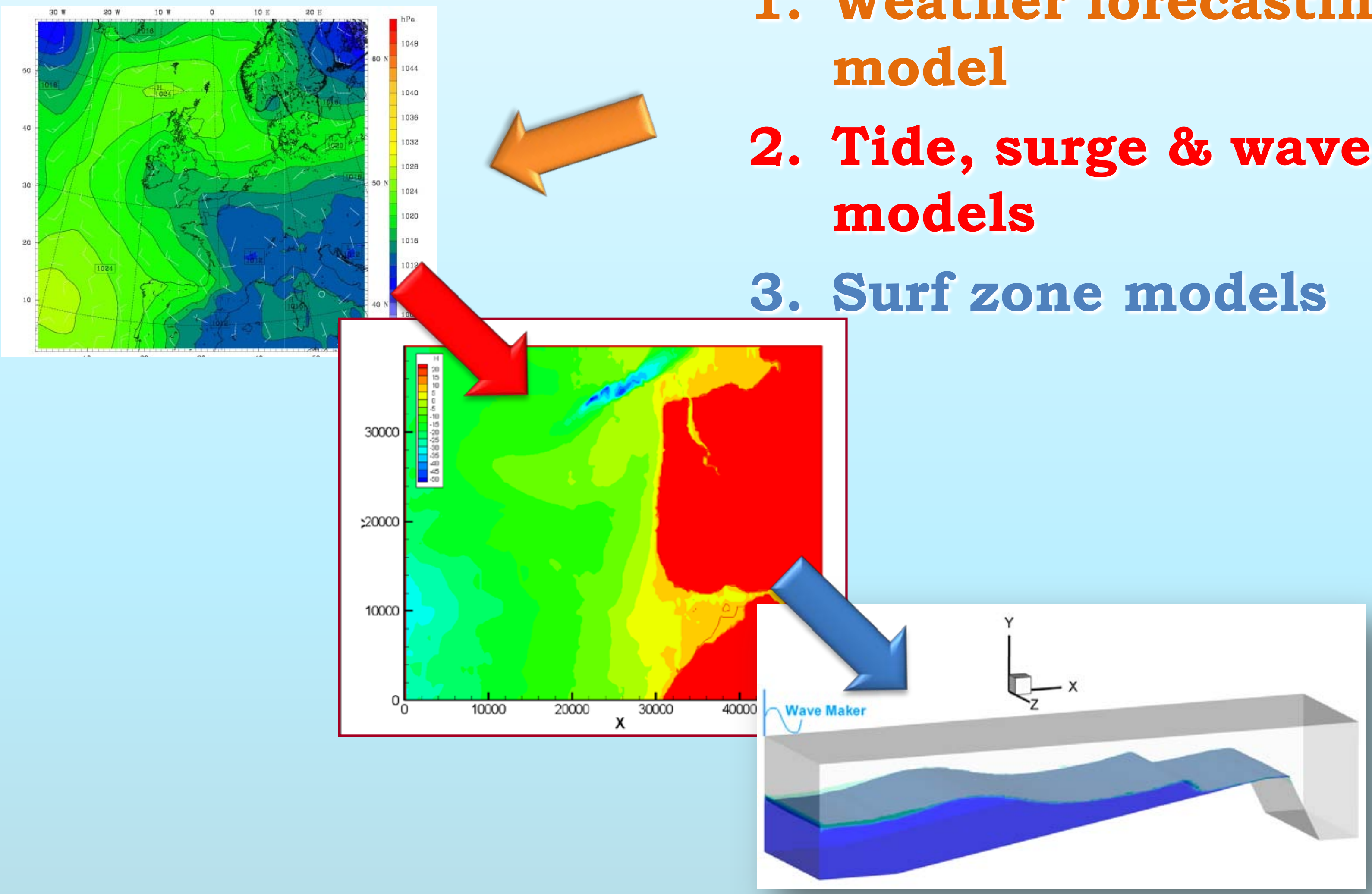
- To improve the capacity for predicting *coastal flood risk* due to *extreme events* and estimate the associated *uncertainty*
- To assess the propagation of uncertainty from meteorological forecasts to coastal flood risk predictions

Approach

a "clouds-to-coast", integrated modelling framework for ensemble prediction of coastal flood risk arising from overtopping and scour

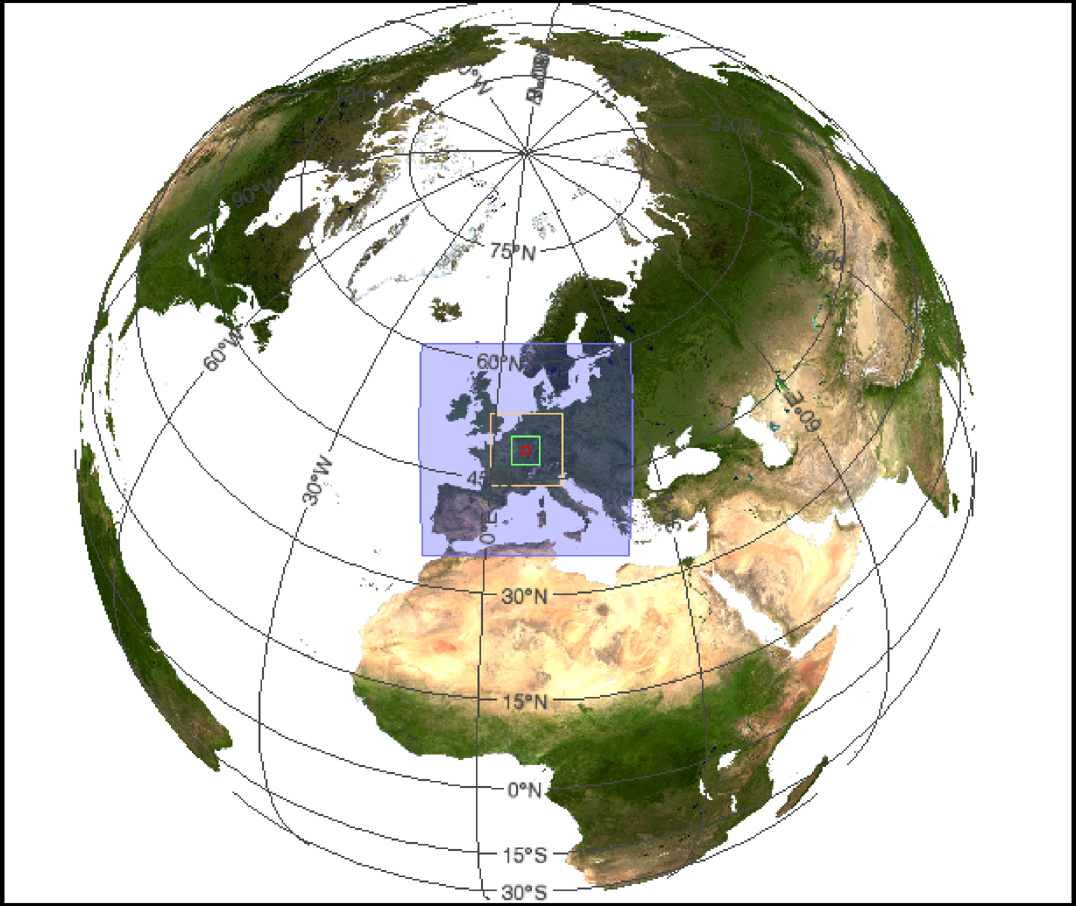
"Clouds-to-coast" Ensemble Modelling Framework of Coastal Flood Risk

1. **Weather forecasting model**
2. **Tide, surge & wave models**
3. **Surf zone models**

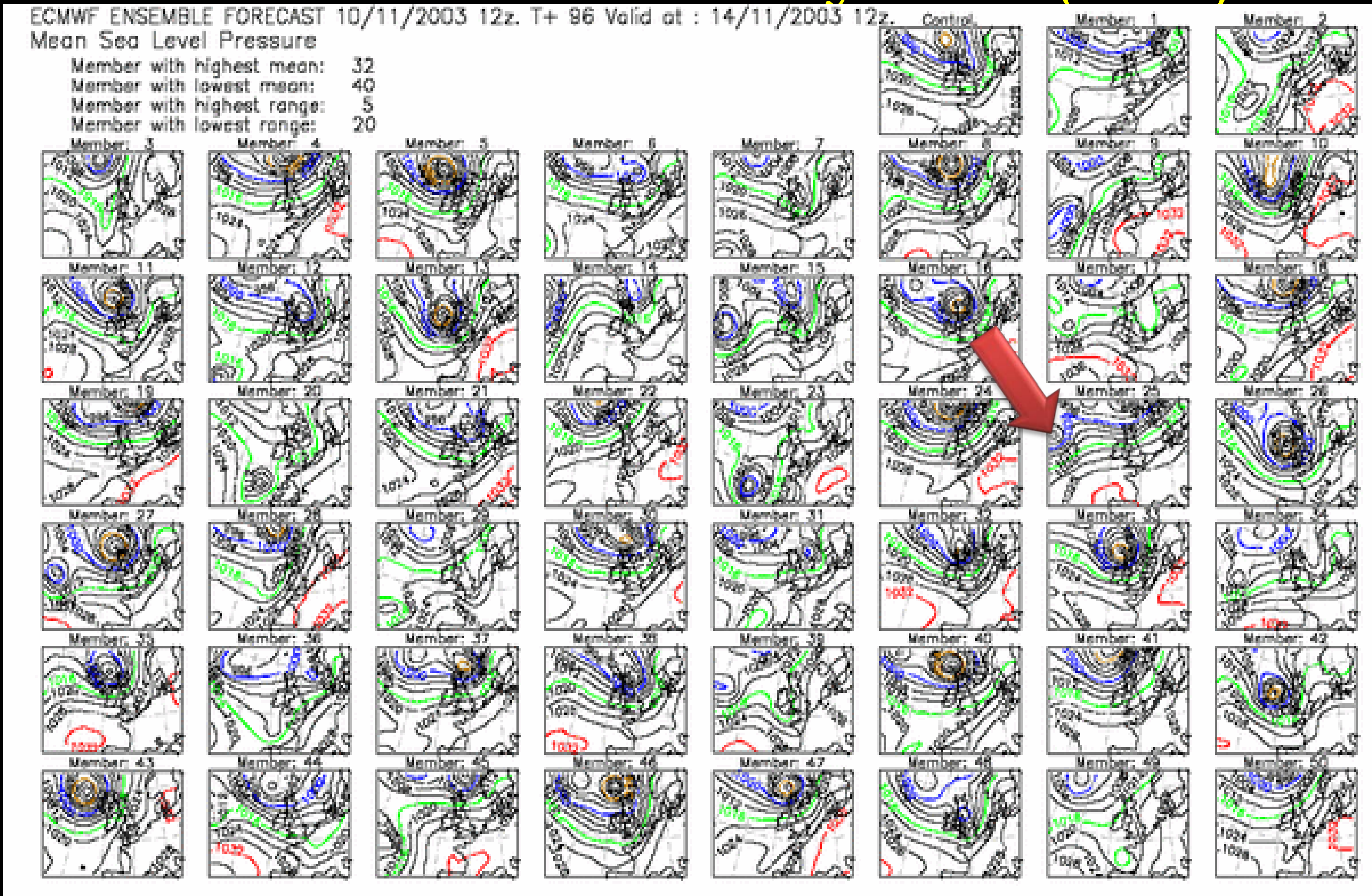


Ensemble Weather Forecasting Model

- Dynamical-downscaling approach from global to regional to local scale
- Compromise between domain size and resolution
- Hi-res wind and pressure forecast using WRF



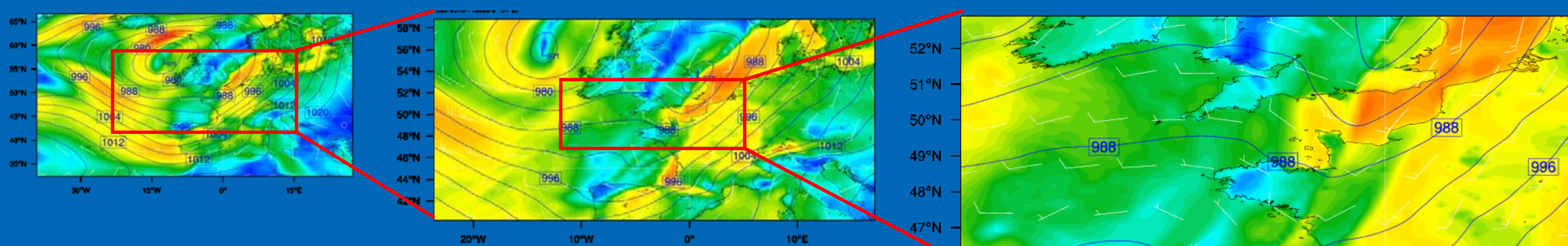
Ensemble Prediction System (EPS)



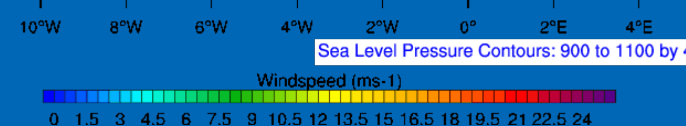
EPIRUS – Meteorological component

Example:

- The “Great Storm” – 16th October 1987
  - ERA40 boundary conditions
  - Downscaling → high temporal (hourly) and spatial (~1km) wind and pressure fields for input in oceanographic models.



Wind and pressure fields at 03:00 on 16th Oct 1987, in three domains with increasing spatial resolution



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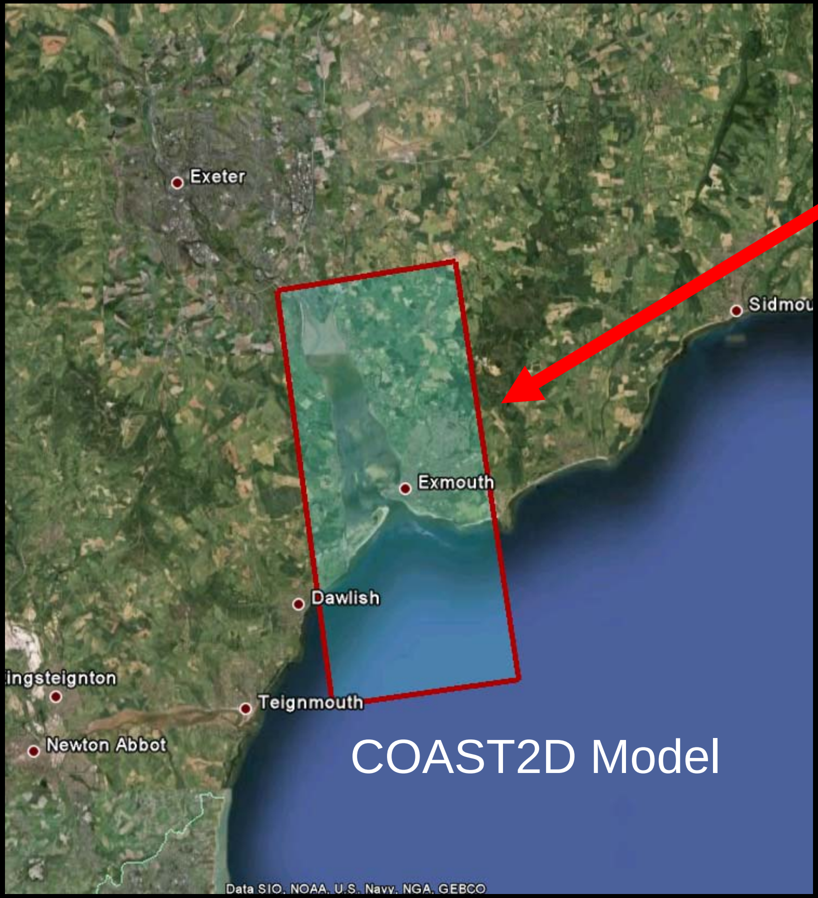
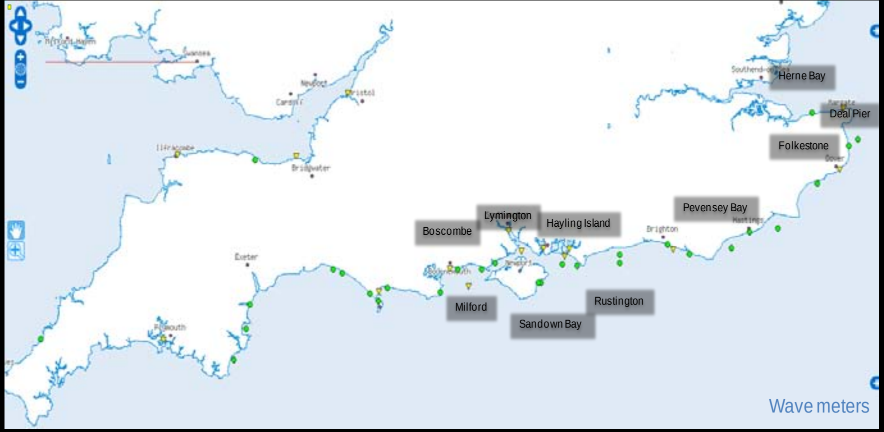
Tide, Surge & Wave Modelling

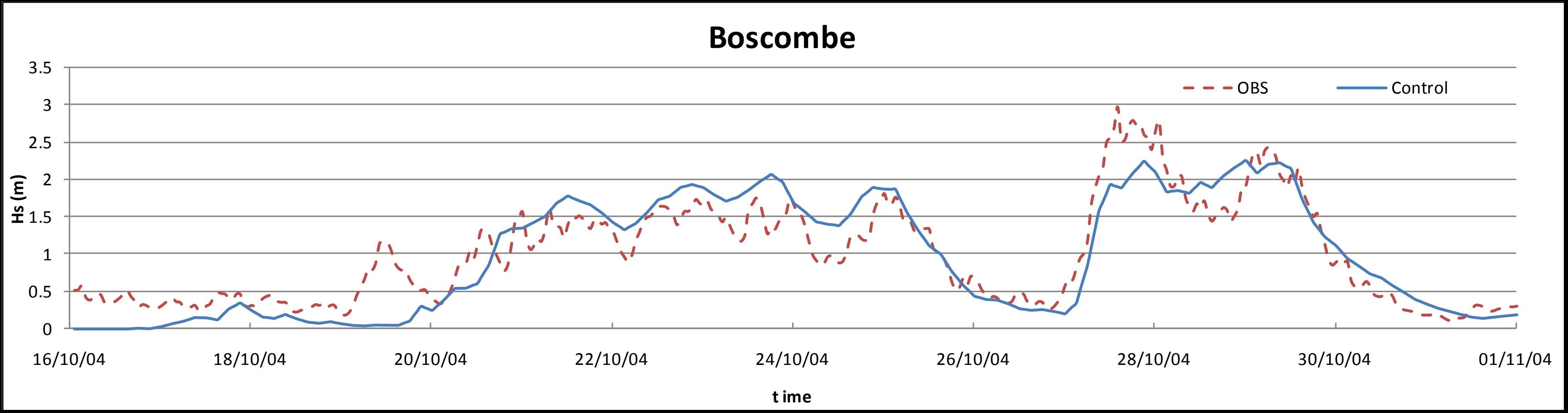


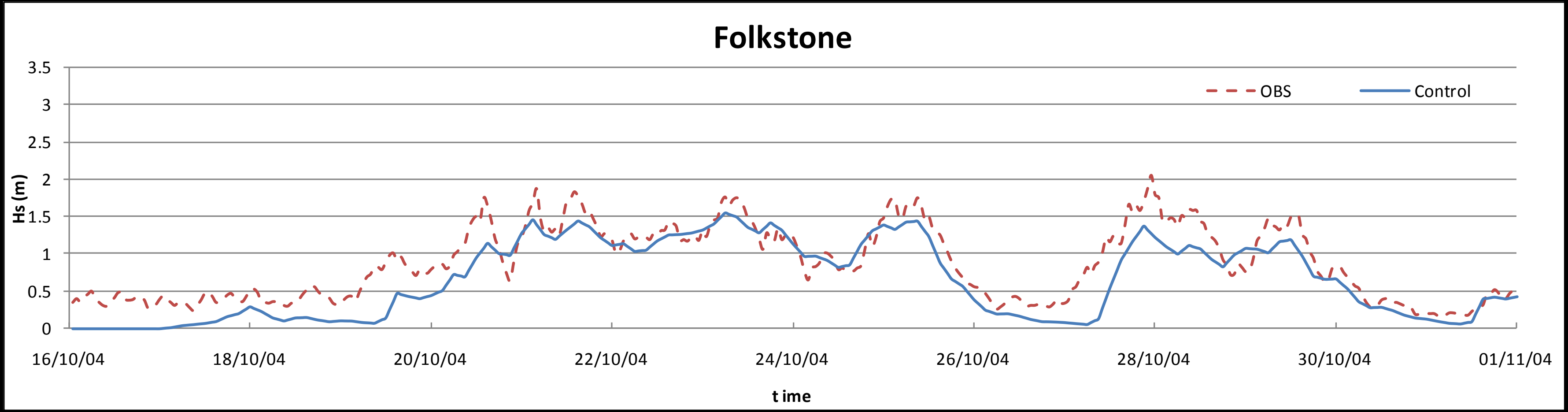
POLCOMS & ProWAM Models

WAM Model

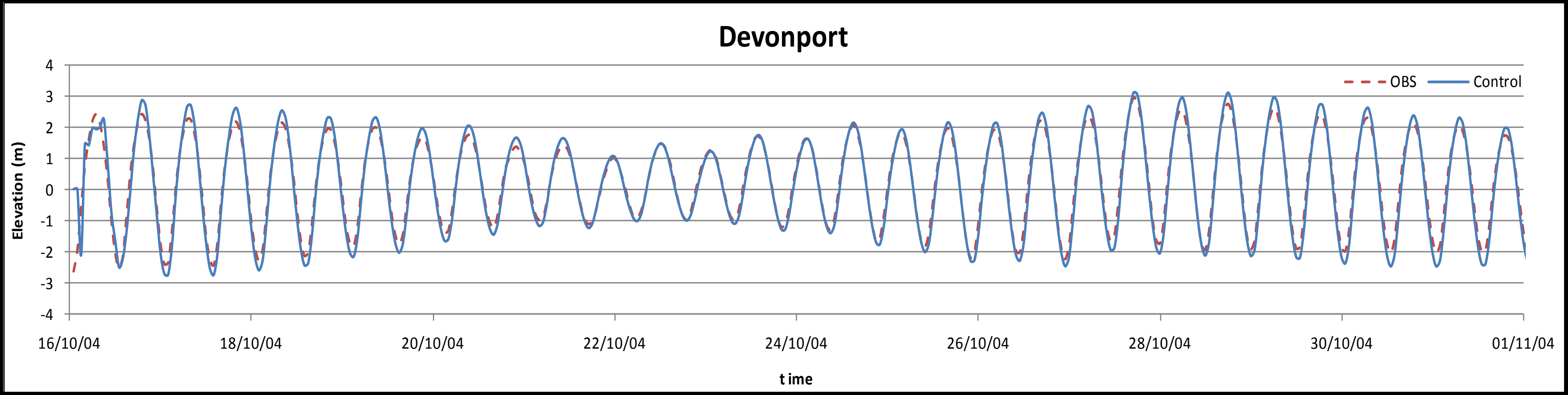
Model Validations - Waves

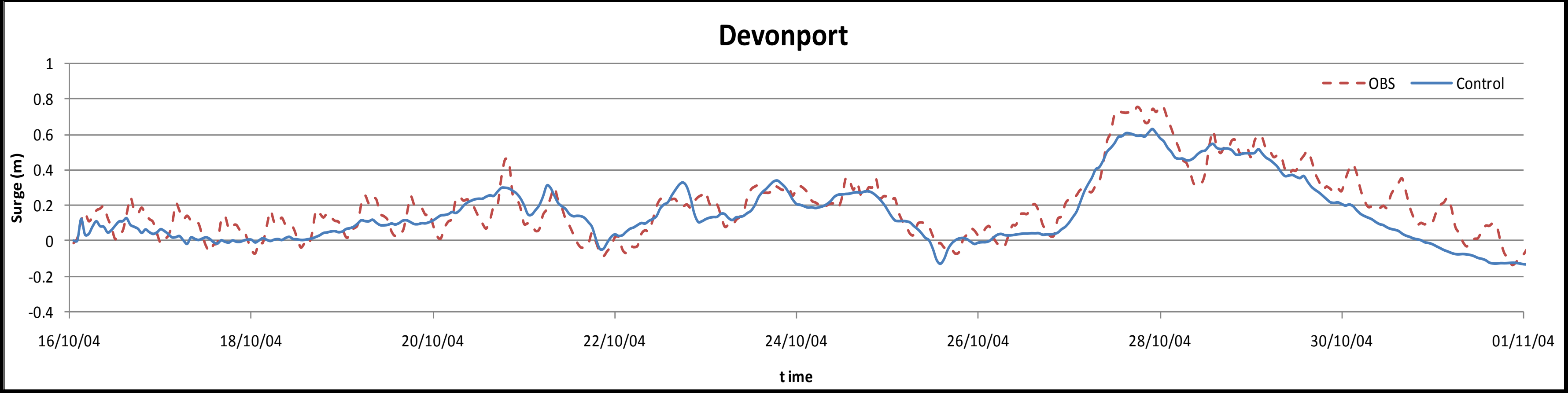




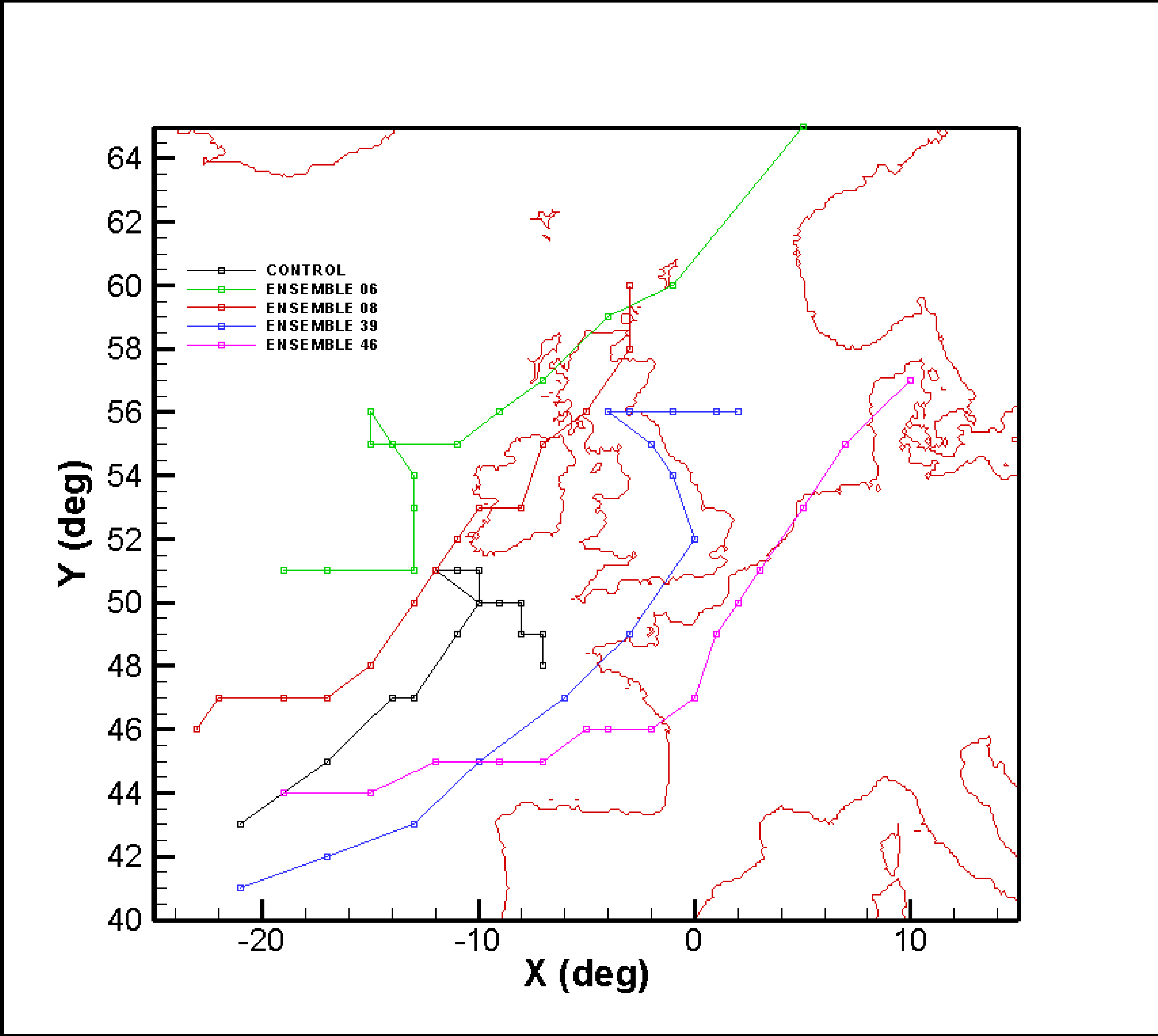


Model Validations – Tides & Surge

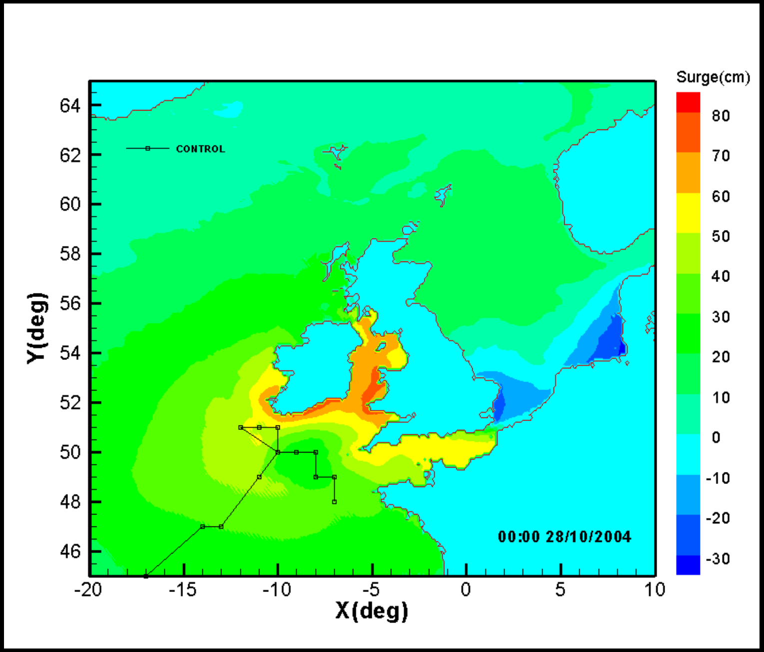




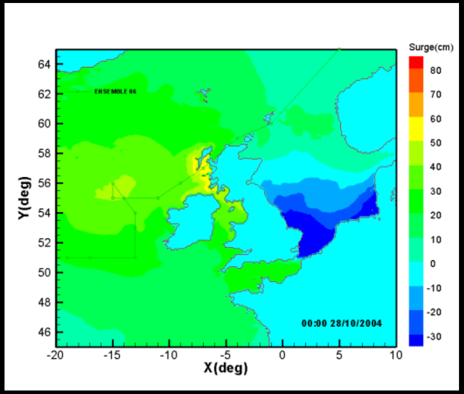
Ensemble Modelling – Storm Tracks



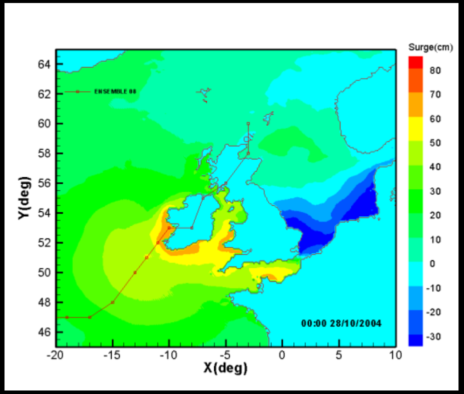
Ensemble Modelling - Surges



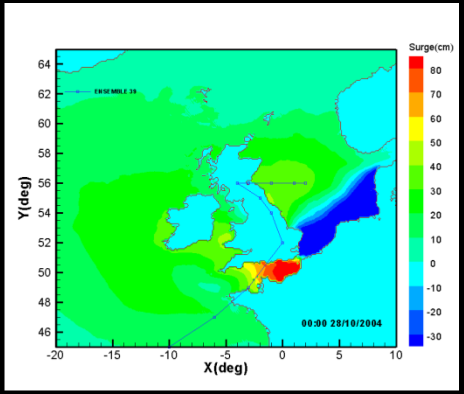
Control



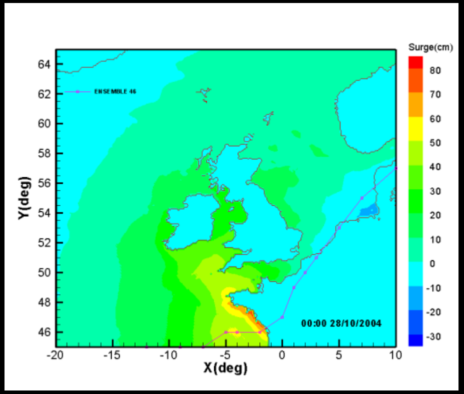
Ensemble 06



Ensemble 08

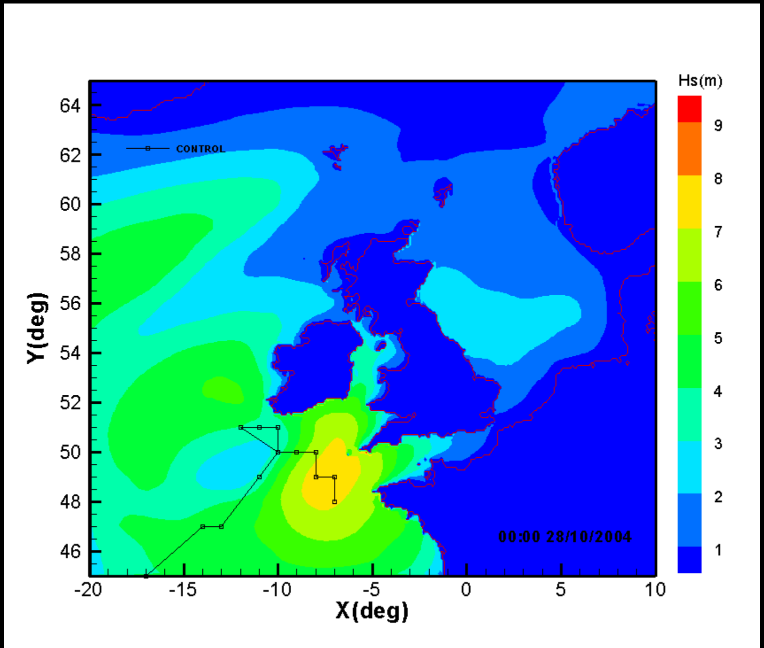


Ensemble 39



Ensemble 46

Ensemble Modelling - Waves



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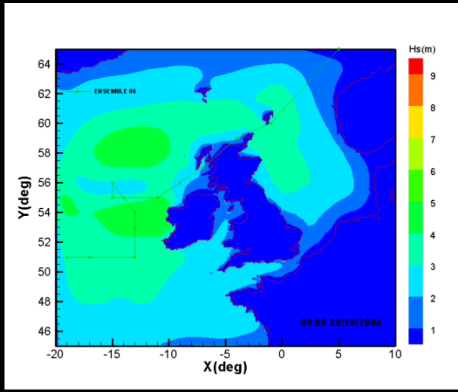
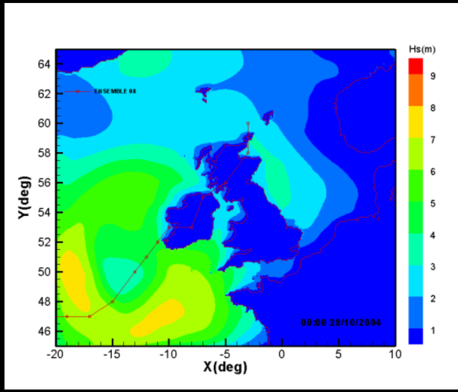
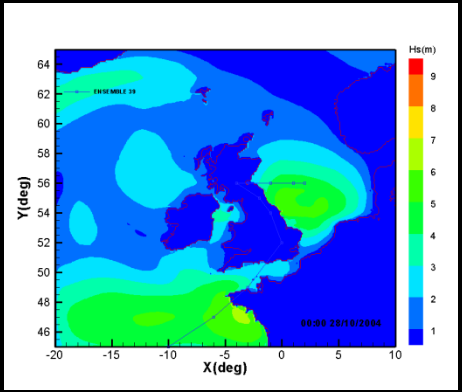


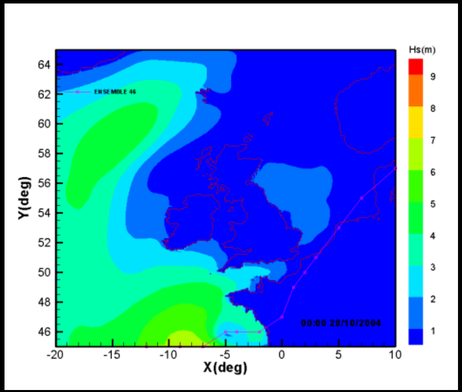
Ensemble 06



Ensemble 08



Ensemble 39



Ensemble 46

Surf Zone Model

1. Fluids:

- 3-D LES-VOF model-unstructure grid
- 2-D RANS-VOF model-structure grid
  - Overtopping of coastal structures

2. Sediments:

- Advection-diffusion equation
- Bedload transport model

3. Morphology:

- Sediment conservation equation over the whole water column

  - Scour

Numerical Model (2D RANS-VOF)

- Governing equations:
  Reynolds-Averaged Navier-Stokes equations (RANS)
- Turbulence:
  Algebraic nonlinear k–ε turbulence model
- Surface capture scheme:
  Volume of Fluid (VOF)
  VOF function, f :

$$f = \frac{\rho}{\rho_f}$$

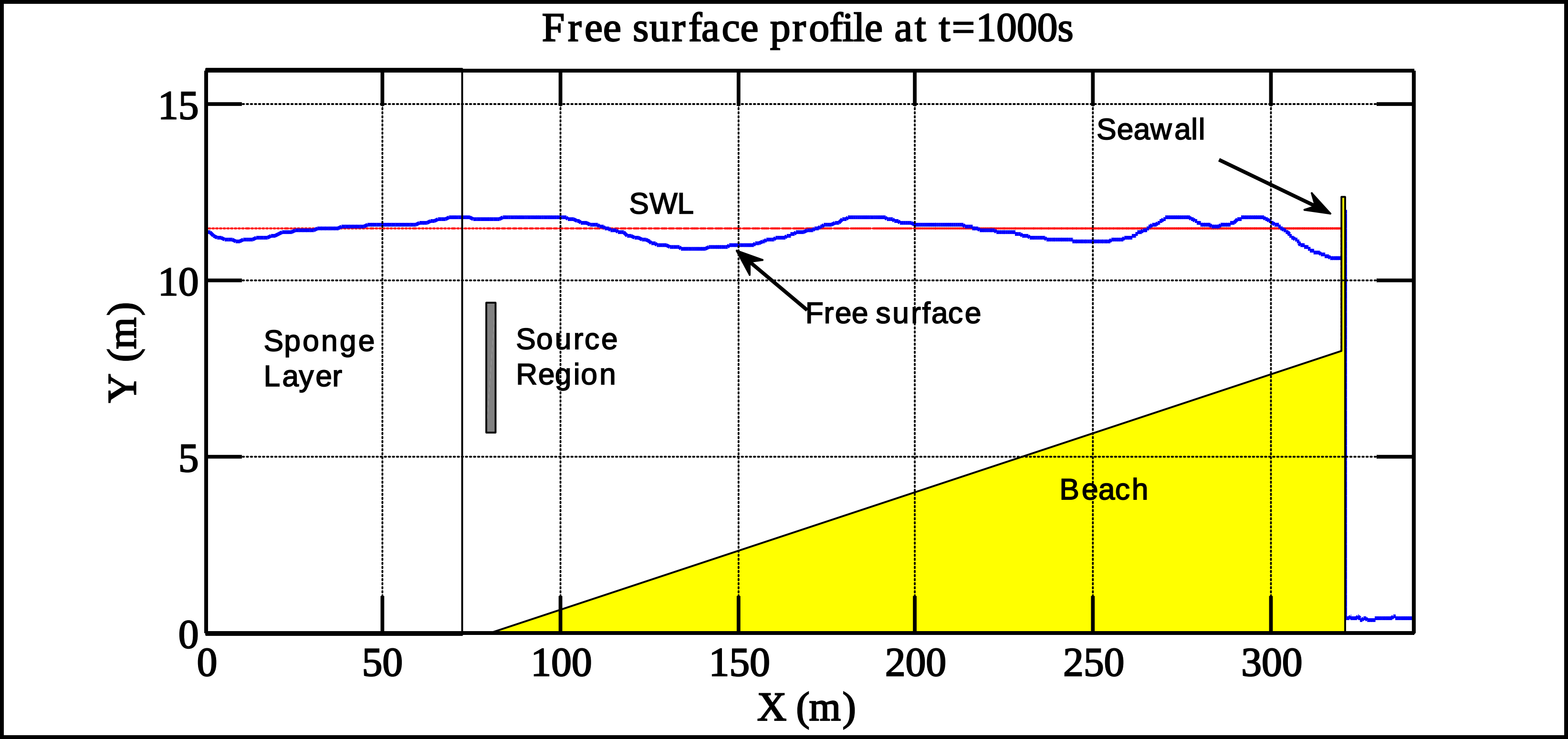
ρ_f : fluid density, ρ: averaged density

$$f = \begin{cases} 0 & \text{empty cell} \\ 1 & \text{full cell} \\ \text{other} & \text{surface cell} \end{cases}$$

The transport equation for f:

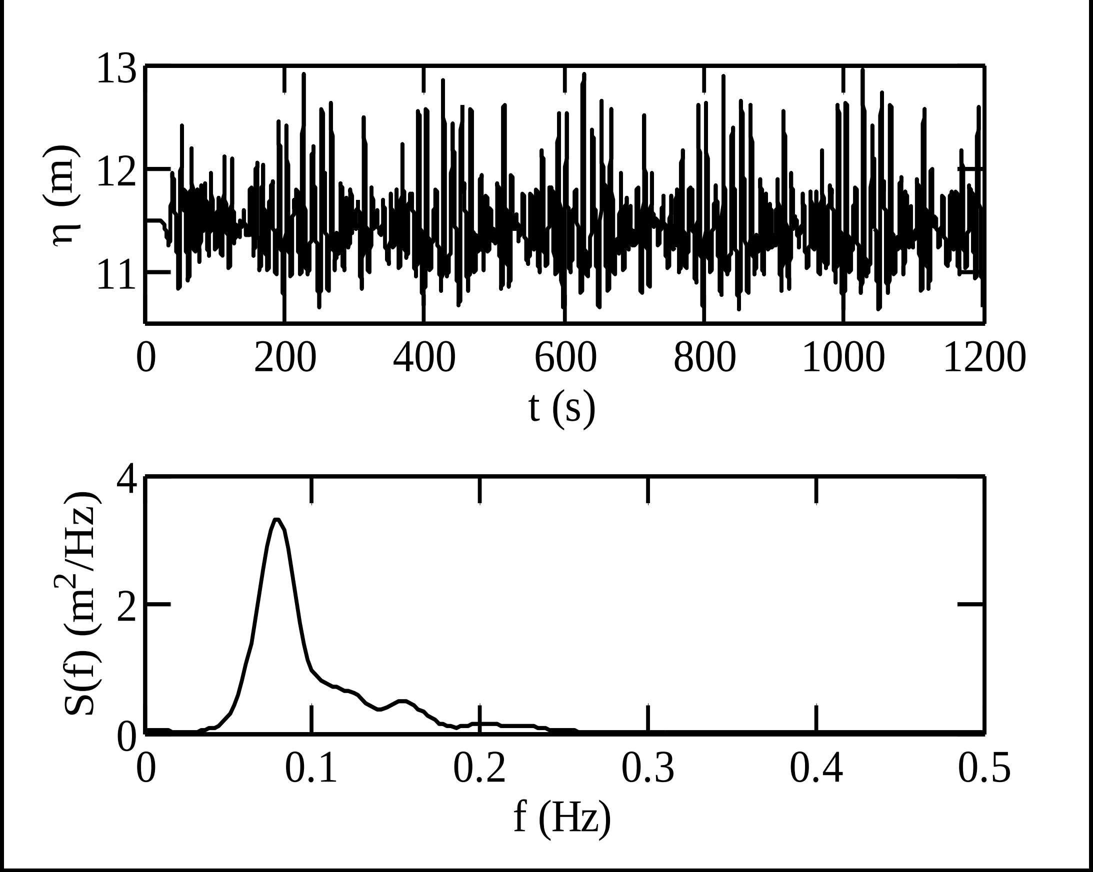
$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial x}(uf) + \frac{\partial}{\partial y}(vf) = 0$$

Numerical simulation setup



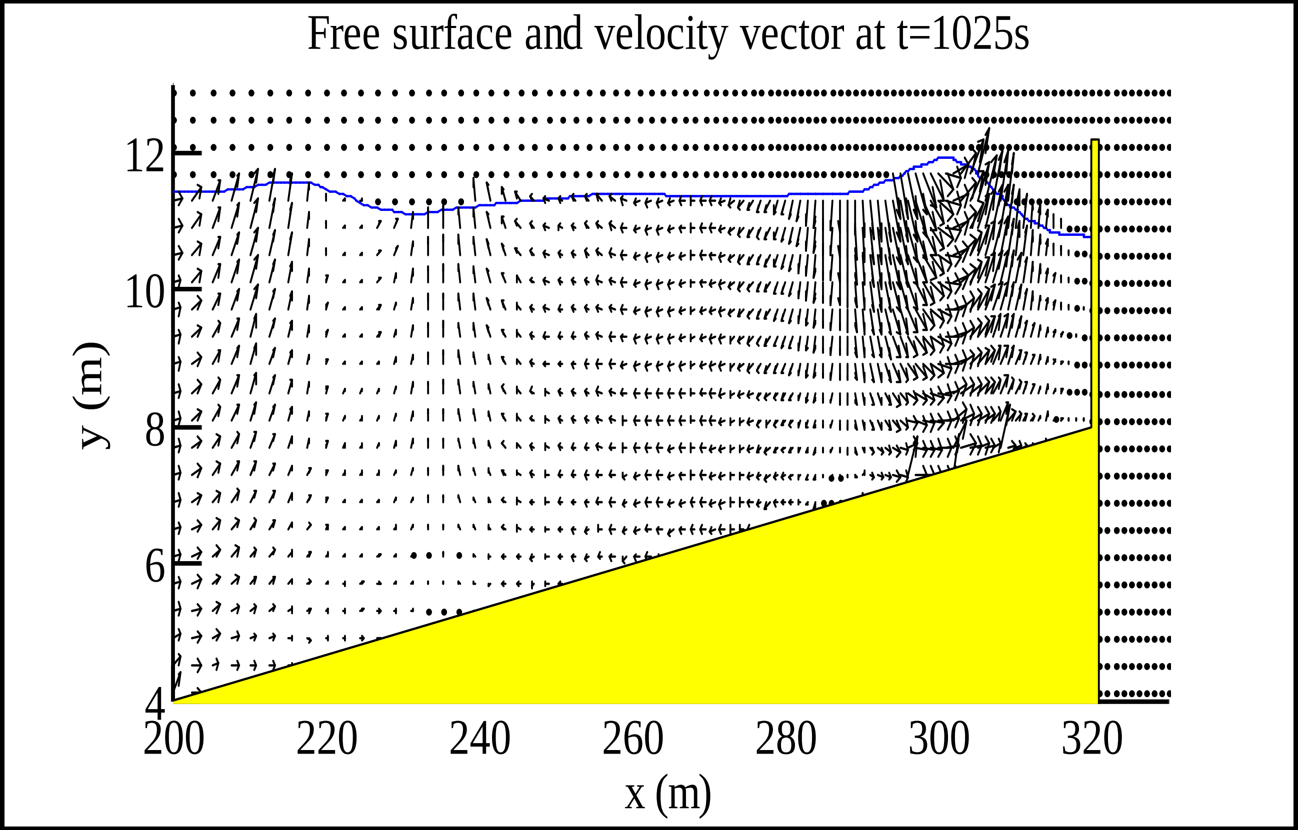
Free surface profile at *t*=1000 s and setup of numerical simulation.

Waves at the toe of seawall



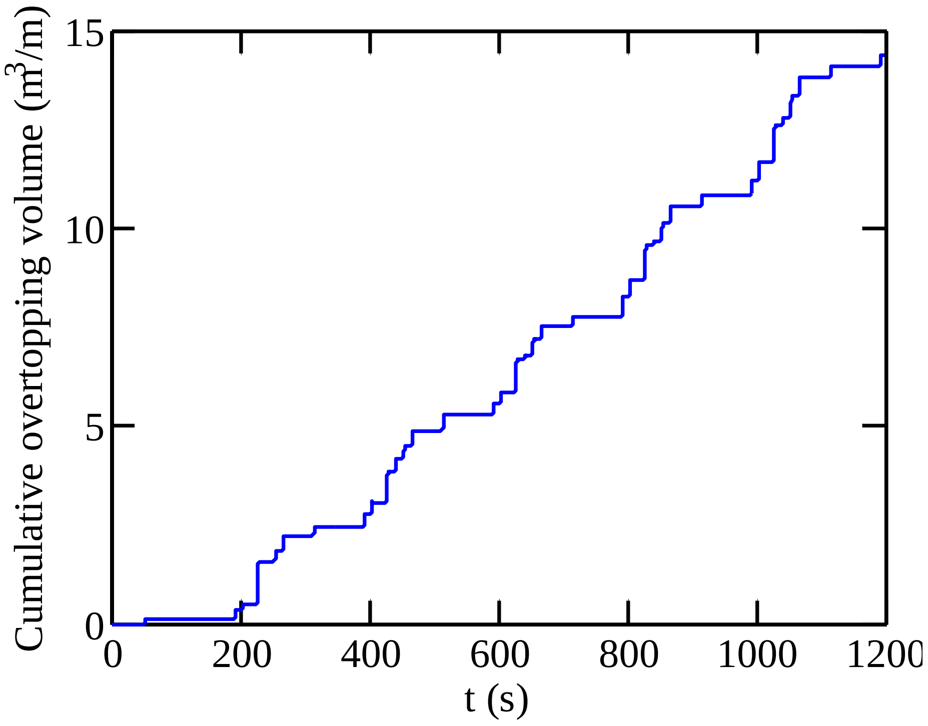
Wave conditions at the toe of seawall (x=320 m): $H_{1/3}$ =1.68 m; T_m = 9.9747 s; T_p = 12.8 s.

Velocity vector at t=1025s

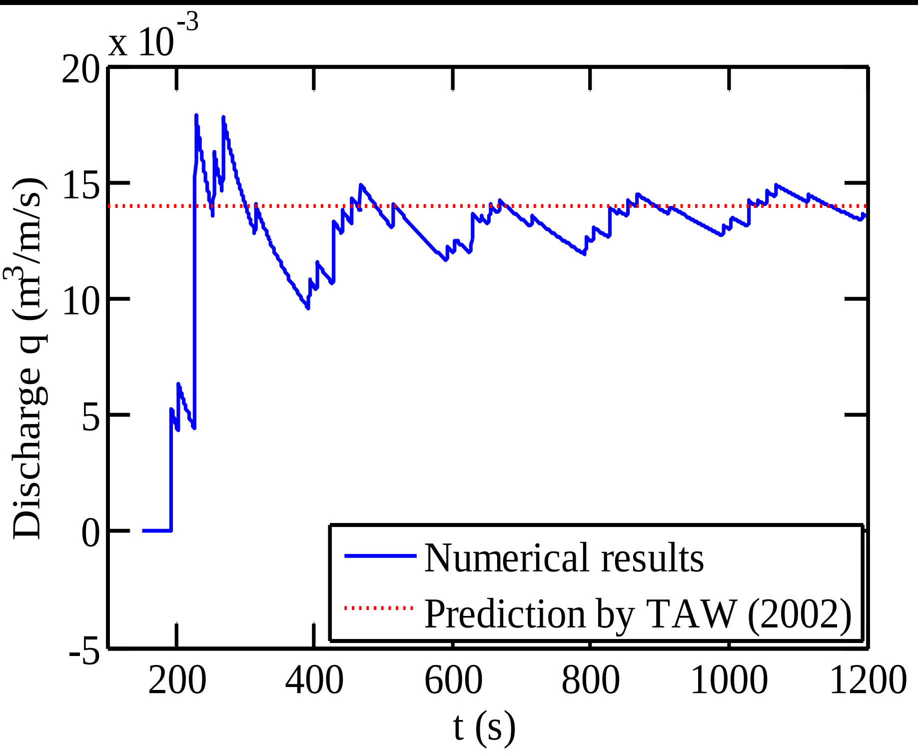


Velocity vector distribution at t=1025s around the seawall. Blue line is the free surface and yellow layer represents the seawall and foreshore with slope of 1:30

Results of wave overtopping

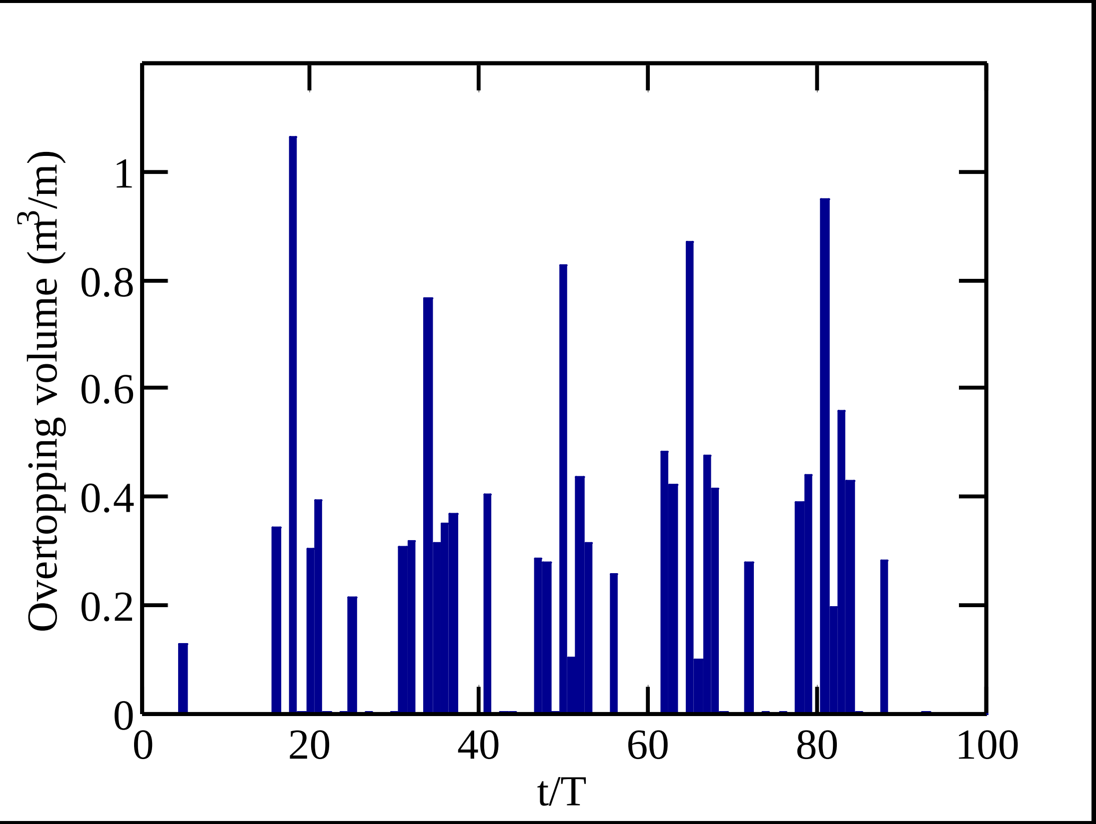


Predicted time series of accumulative overtopping volume



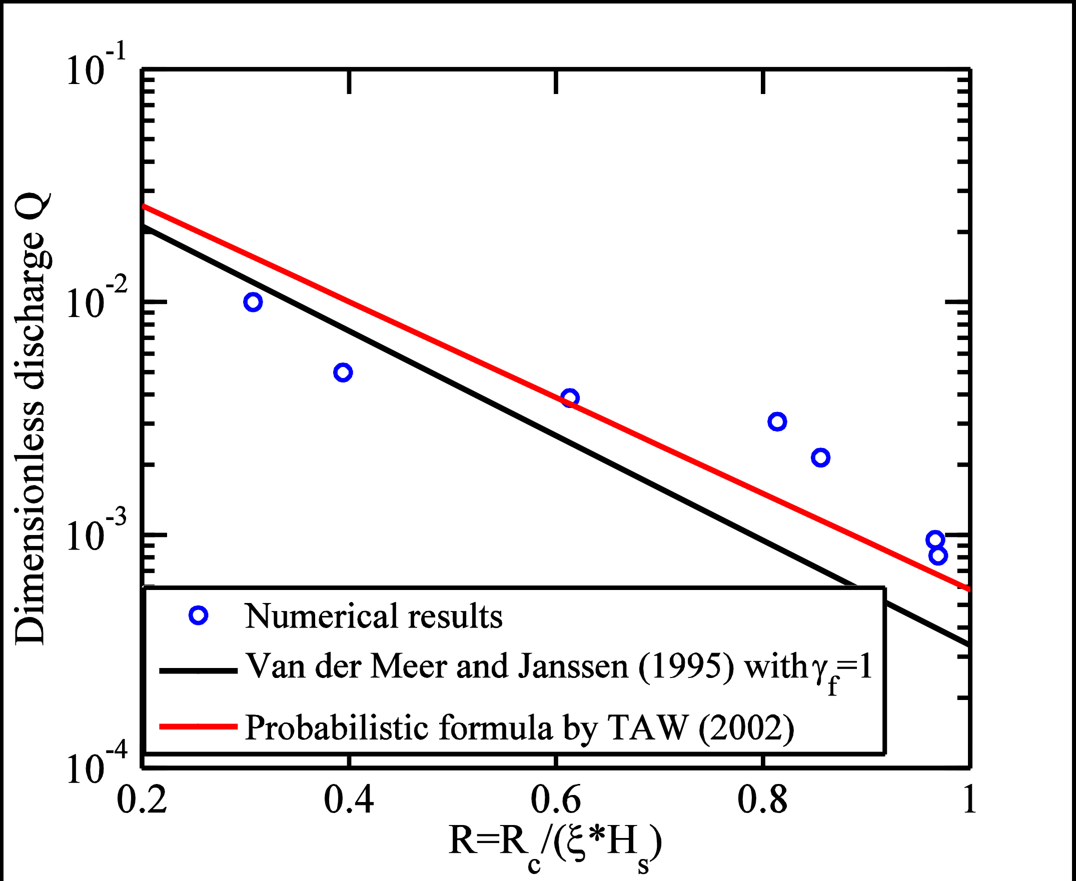
Overtopping discharge q calculated roughly after 12 waves. Red dotted line is the prediction by the empirical formula of TAW (2002) and blue solid line is simulation results

Overtopping volume per wave



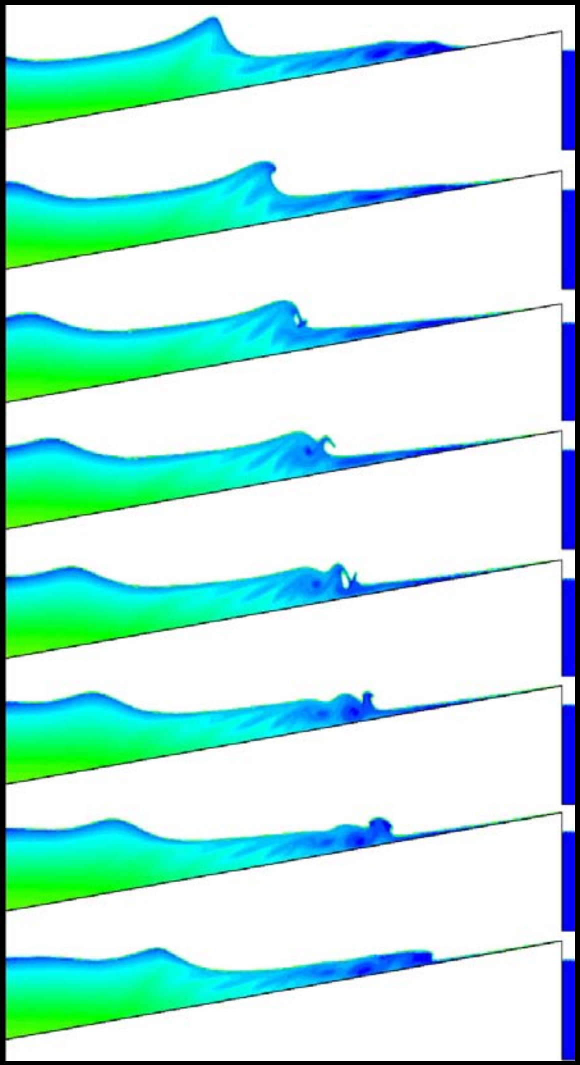
Wave overtopping volume per wave cycle. t is the simulation time and T equals the peak period here.

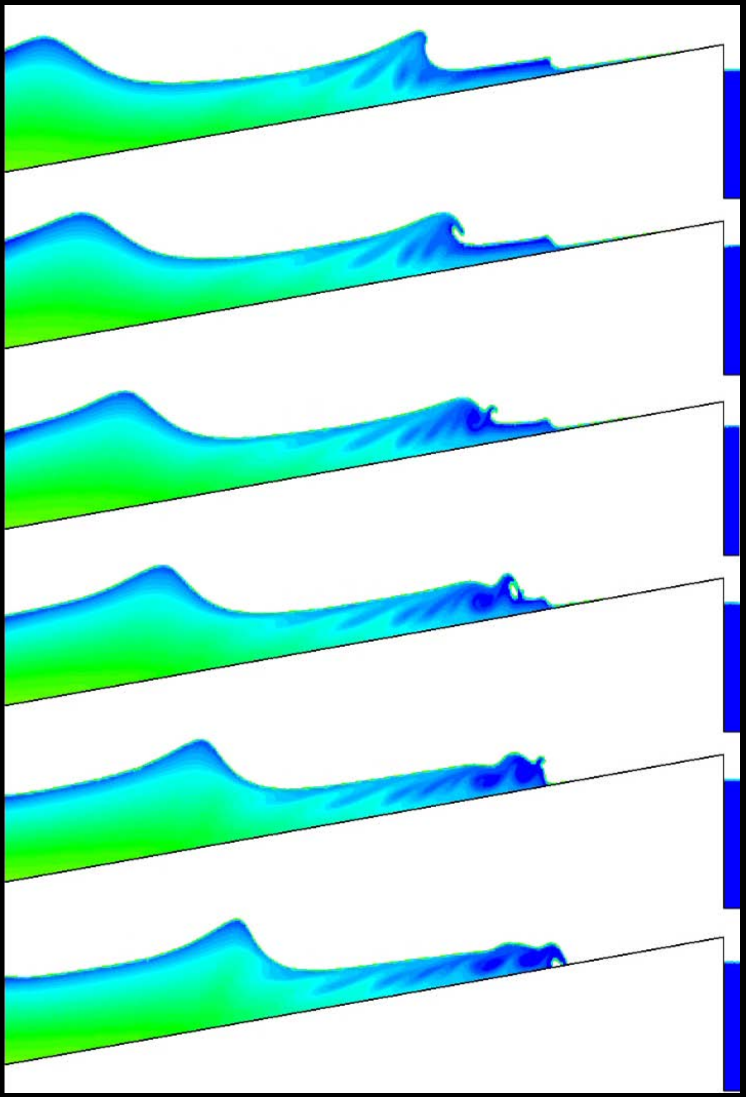
Comparisons of discharge Q



Comparison of dimensionless overtopping discharge, Q, between numerical results and predictions of design formulae by Van der Meer and Janssen (1995) and TAW (2002)

3-D Simulation of Suspended Sediment Under breaking waves

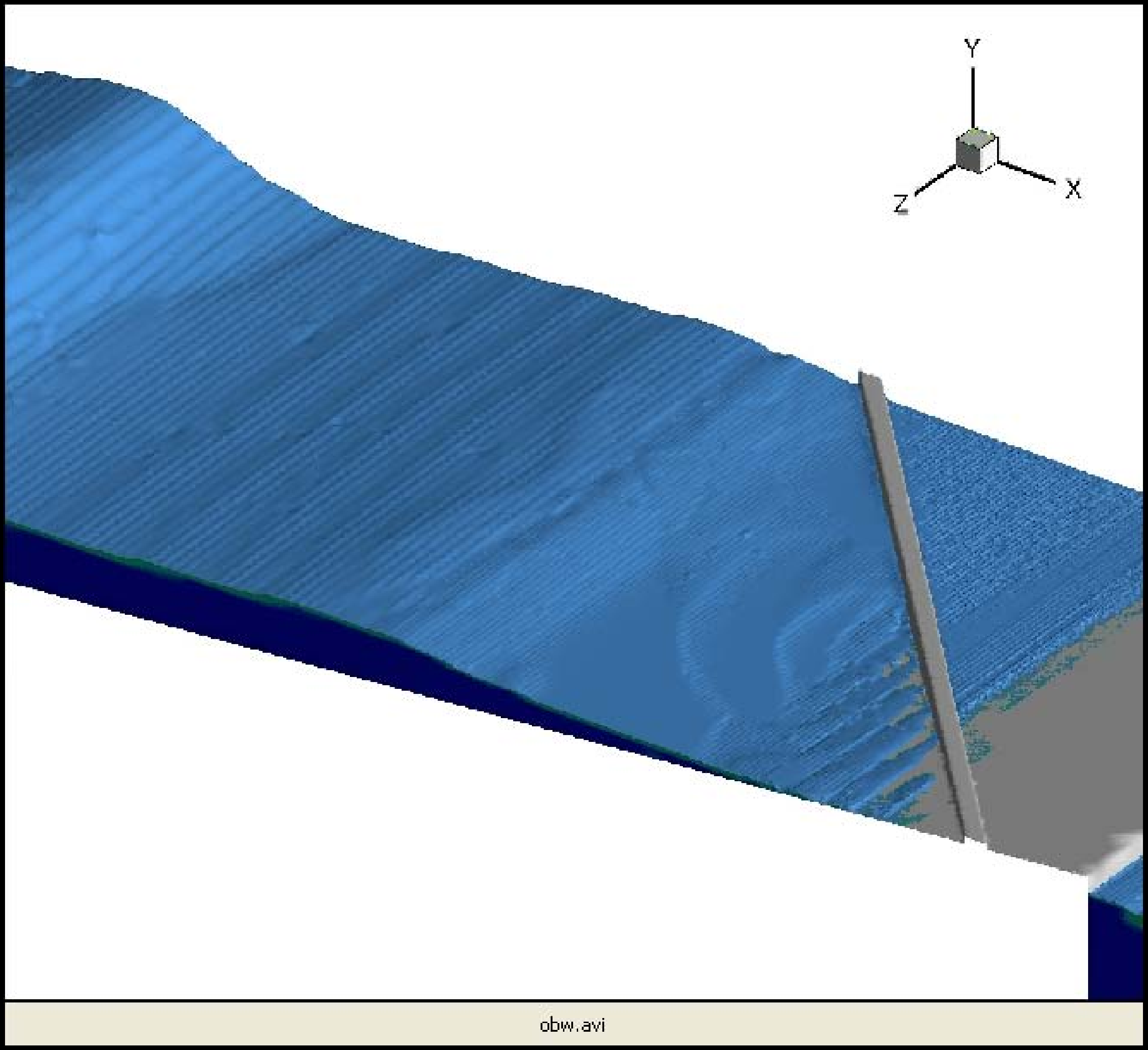




3-D Wave Overtopping and run up over a steep Seawall

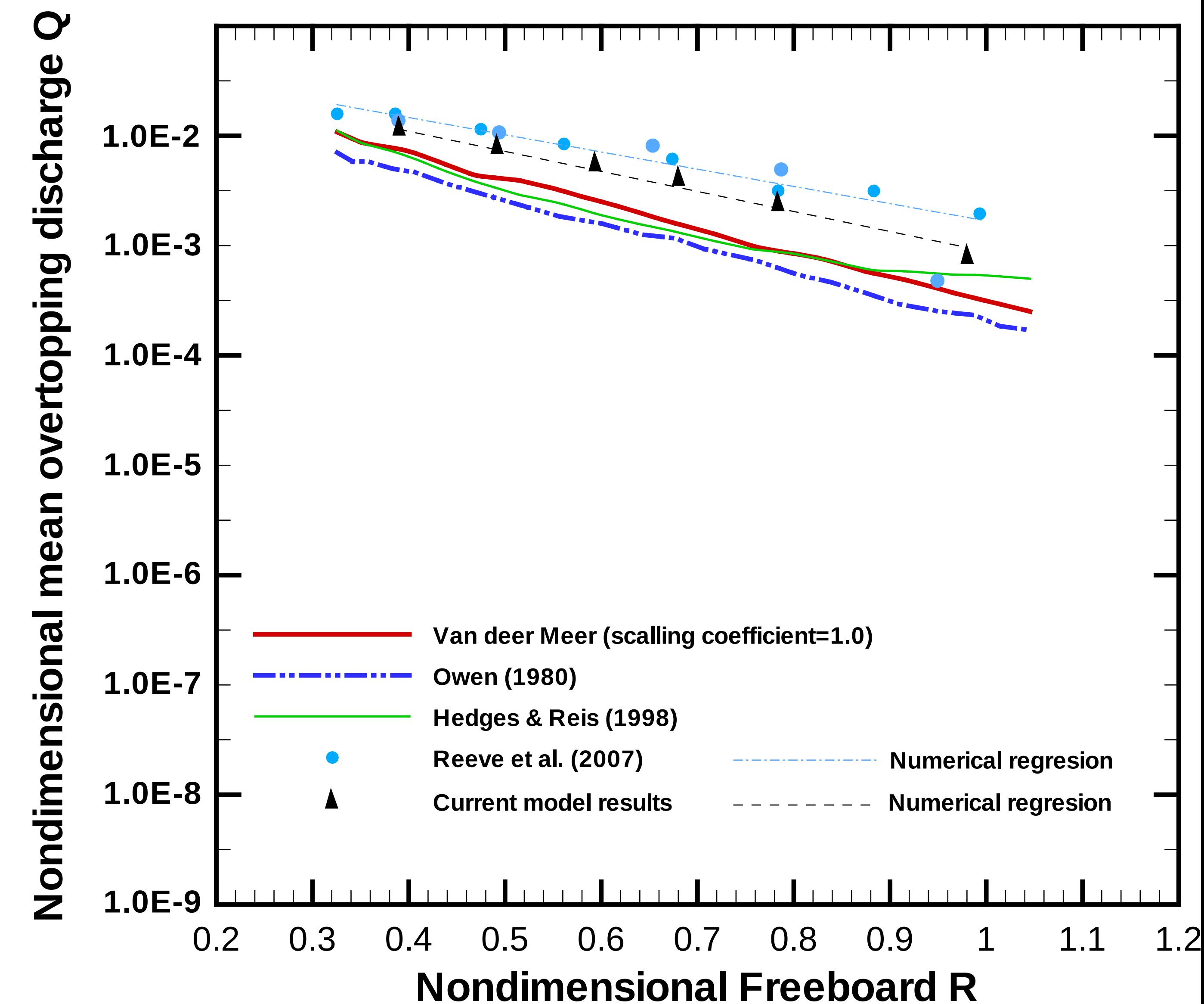
wave3D1.avi

3-D Wave Overtopping over a Seawall



Random Wave Overtopping a Seawall

---Overtopping Discharge



Conclusions/Summary

- Weather forecasting, wave/surge and surf zone models have been identified and tested individually
- Good agreement between wave, tidel and surge prediction with observations
- Large uncertaity in ensemble predictions of surge and wave for 2004 storm
- Overtopping predictions in good agreement with published data
- Test sites and events have been selected
- Morphological model at testing stage

Future Work

- Ensemble run of surf zone model to create ensemble forecasts of overtopping and scour
- Big question: how best to use ensembles – is mean necessarily the most useful?
- How Uncertainty propagate from meteorological forecasts to overtopping and coastal flooding risk predictions?

EPIRUS – Meteorological component

Aim: Dynamically downscale coarse climate data for severe storms → high resolution wind and pressure fields

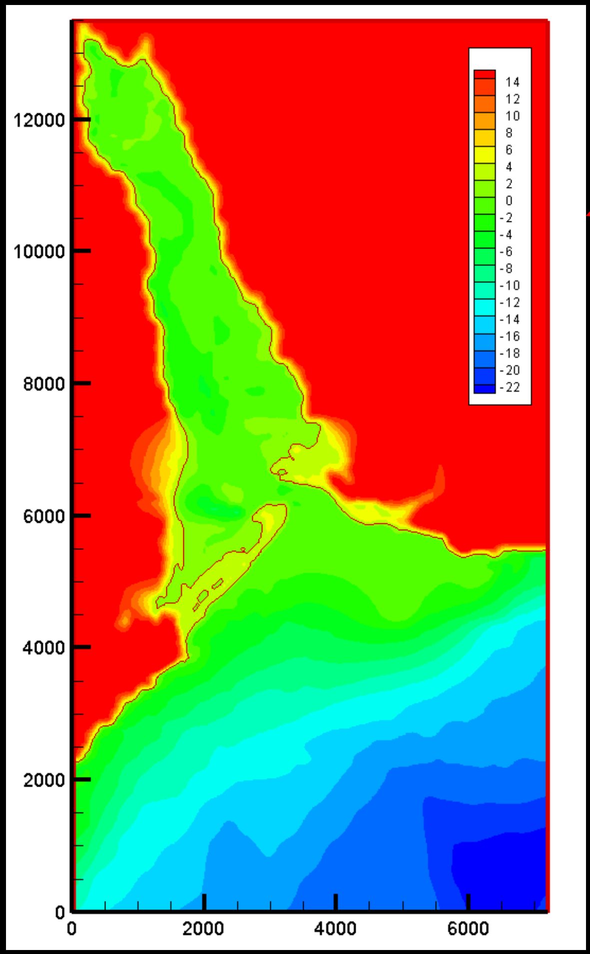
Methodology:

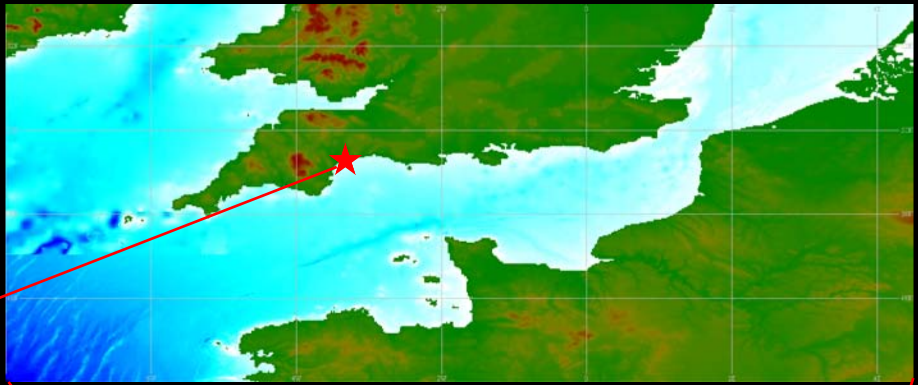
- **W**eather **R**esearch and **F**orecasting model (WRF)
  - Next-generation NWP and data assimilation system
  - WRF run in parallel across several nodes on high performance computer "Blue Ice"
- Initial focus on historic severe storms, before exploring impact of climate change
- Generating ensembles will allow estimate of uncertainty

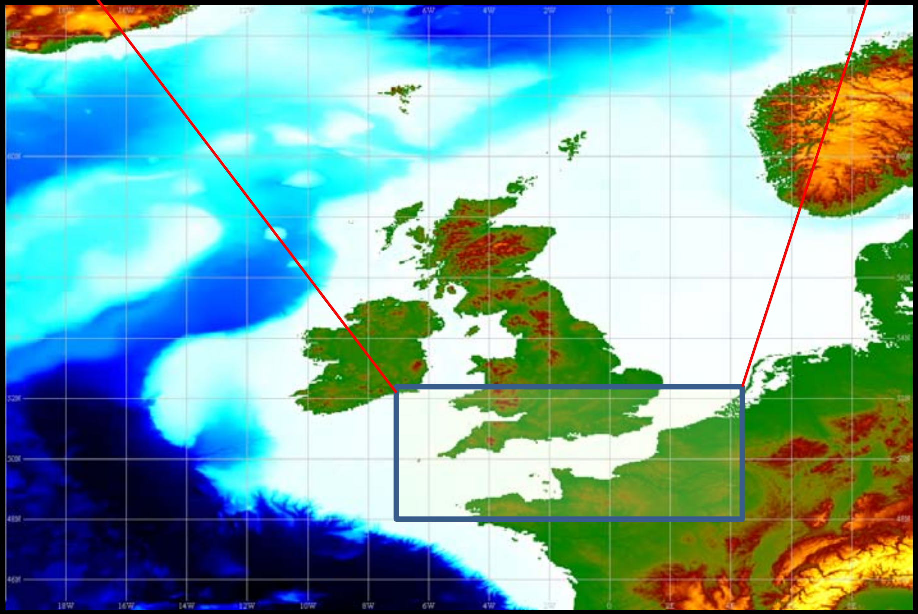
Ref: Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, M.G. Duda, X-Y. Huang, W. Wang, and J. G. Powers, 2005: A description of the advanced research WRF version 2. NCAR Tech. Note NCAR/TN-475+STR. 125pp

Thank you for your attention!

Model Scales







Numerical Model (3D LES Coupled LS & VOF)

- Governing equations:

  Filtered Navier-Stokes equations (LES)

$$\mathbf{C}\frac{\partial \mathbf{W}}{\partial \tau}+\mathbf{K}\frac{\partial \mathbf{W}}{\partial \mathrm{t}}+\nabla\cdot\vec{\mathbf{F}}_{\mathbf{c}}=\nabla\cdot\vec{\mathbf{F}}_{\mathbf{v}}+\vec{\mathrm{S}}$$

- Turbulence:

  Dynamic Smagorinsky-Lilly SGS model. Only large turbulent eddies (equal to or larger than grid size) are simulated, the rest are modelled.

- Surface capture scheme:

  Coupled Level Set (LS) and Volume of Fluid (VOF)

  VOF function, *F* :

$$\frac{\partial F}{\partial t}+u\cdot\nabla F=0$$

  LS function, φ :

$$\frac{\partial \varphi}{\partial t}+u\cdot\nabla \varphi=0$$

3D Navier Stokes solver

Basic features:

- Unstructured grid based, higher-order Finite-Volume scheme (FV)
- Parallel computations (MPI)
- Multigrid, Dual-time stepping & implicit residual smoothing
- Fully implicit schemes available

Turbulence:

- Large-Eddy Simulation
- Novel Dynamic SGS model for free-surface simulations

Fluid-Structure Interaction:

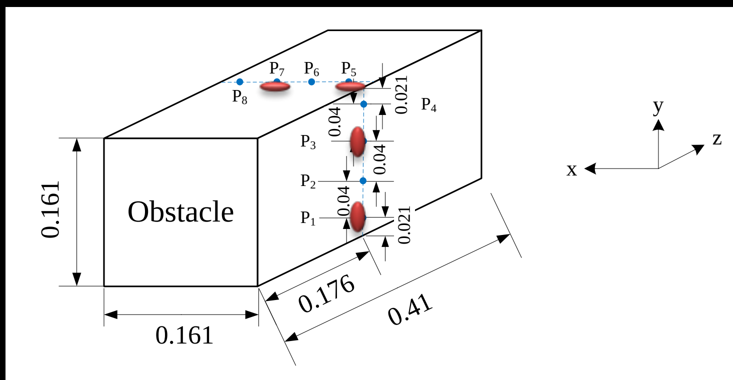
- Structural dynamics solver integrated
- Parallel Immersed Boundary Method (IBM)

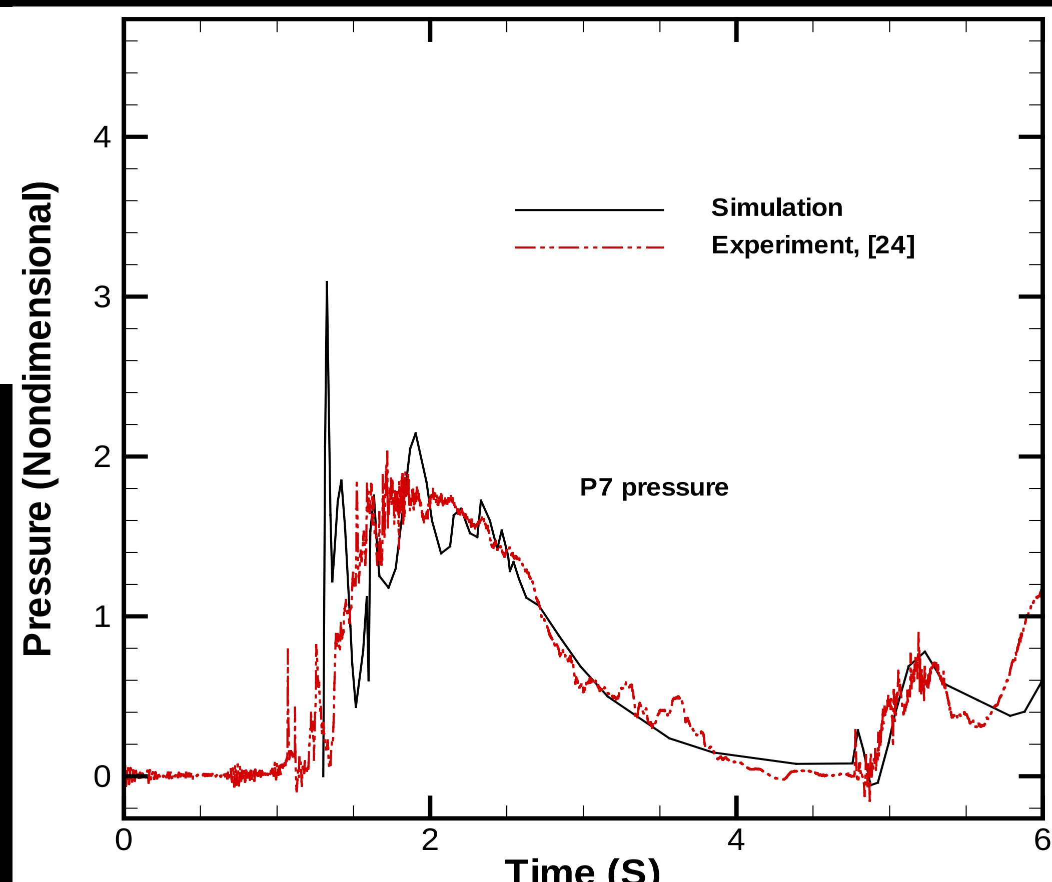
Free Surface capturing Model

- Newly developed interface capturing scheme for flows with violent free-surface motion
- Coupling of VOF and Level Set method renders its capabilities that:
  - ➢ Can capture the interface in a very sharp manner
  - ➢ Can simulate the surface tension effects
  - ➢ Can conserve the liquid mass very accurately
- Both single-phase and two-phase flow can be simulated
- Using Unstructured Meshes, surf zone simulations with complex geometry can now be considered without any difficulty
- Benefited from IBM, sea water interacting with offshore structures and the morphologic change of sea bed can be predicted

3D Dam Breaking Wave over an Obstacle

--- Wave Impact





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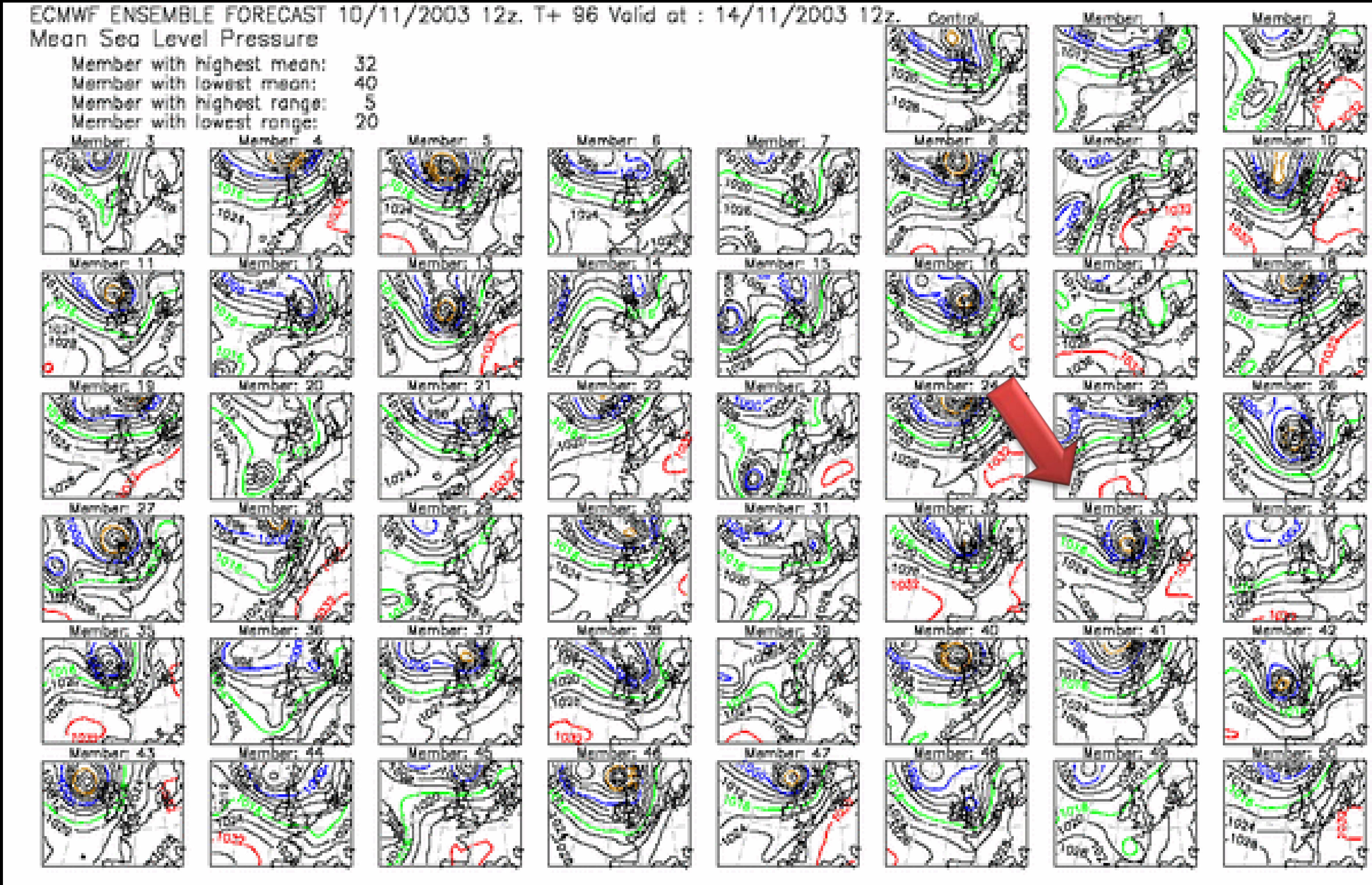

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