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Simulating storm surges and coastal flooding on unstructured grids using a fully-coupled modelling system

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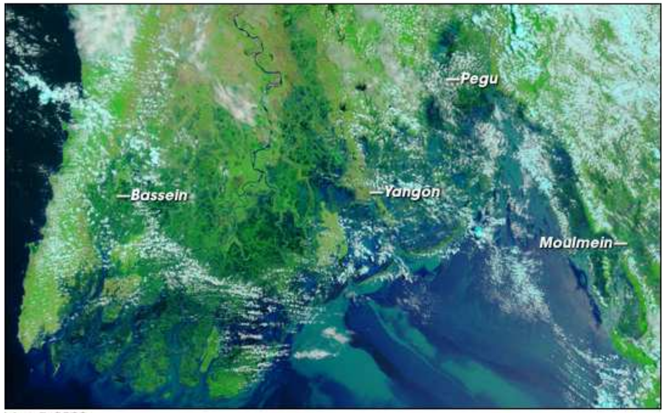
Introduction

Why studying storm-induced coastal flooding?

- Because they are among the most damaging natural disasters:
  - In terms of fatalities



May 5, 2008

Example of Nargis 2008 in Myanmar:

- ~4 m surge flooded the Irriwaddy delta

- Over 140000 fatalities

- In terms material damages Katrina (2005/08):

New Orleans flooded. Credit Jeremy L. Grisham

Example of Katrina 2005 in the USA:

-Locally > 9 m surge in the Mississipi delta

- More than 100 billions $ damage

Modelling storm surges and coastal flooding

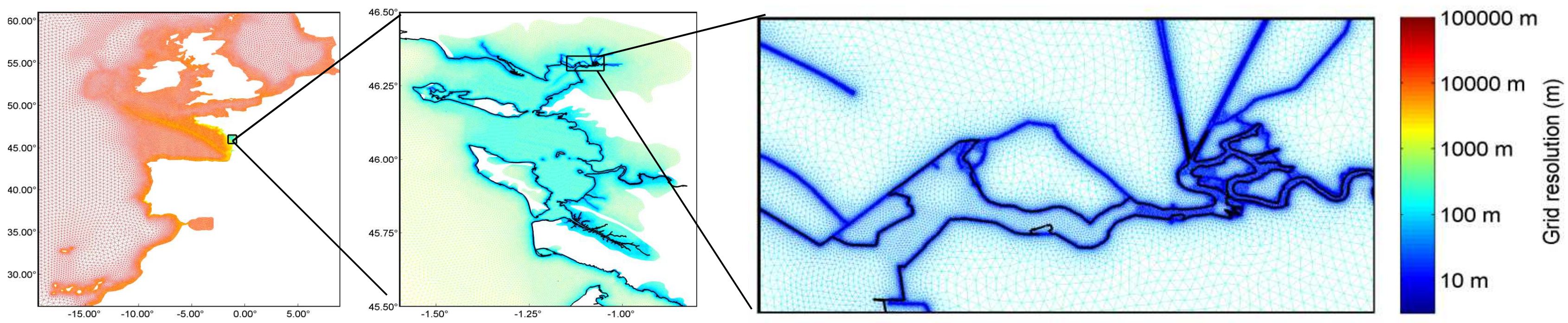
➢Storm surges are nowadays reproduced with a good accuracy (e.g. 10-20 % RMSE), mostly due to:

- Increase computationnal powed, allowing for higher resolutions
- Improved knowledge regarding wave-circulation-atmosphere interactions
- Improved representation of atmospheric forcing

➢On the opposite, modelling of storm-induced flooding is scarce in the literature:

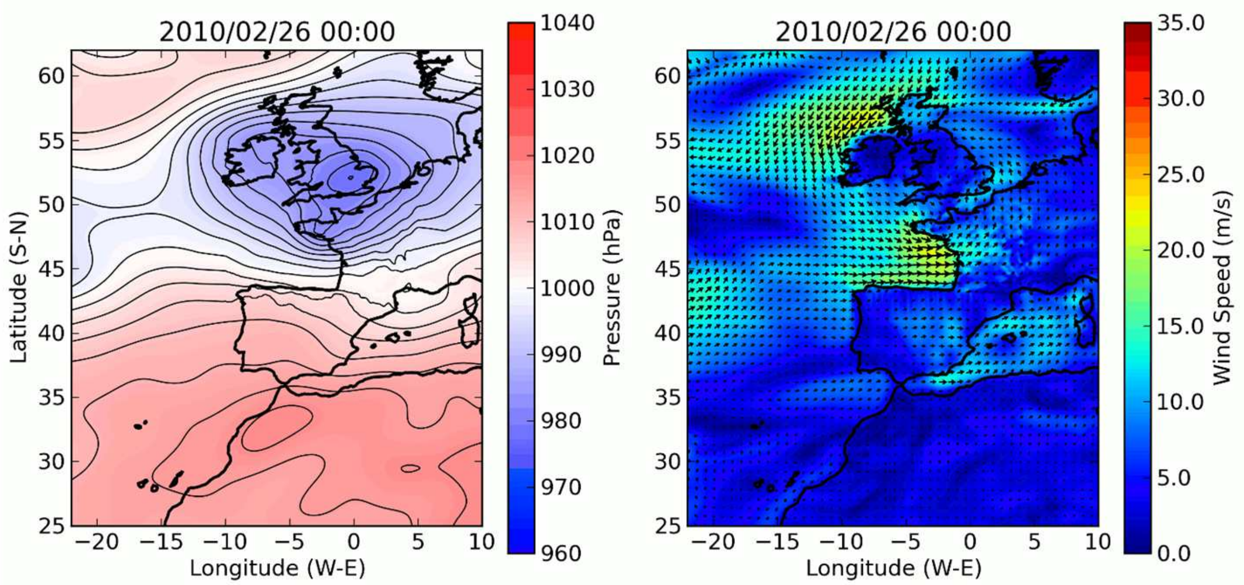
- Challenging multiscale problem, implying large grids with locally very HR
- Steep dikes and barriers cause very strong gradients
- The large variability of CFL conditions implies very robust numerical methods

➢Unstructured grids appear more and more appealing to adress this multi-scale challenging problems



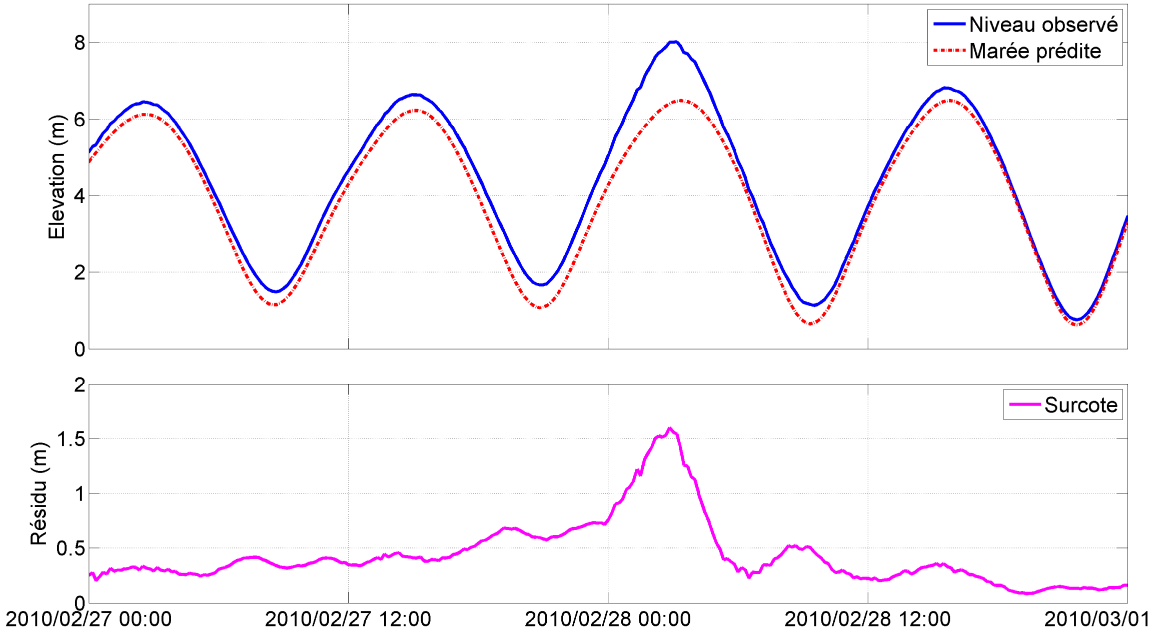
The studied storm

The Xynthia storm



→ Minimum SLP of 970 mbar in the Bay of Biscay

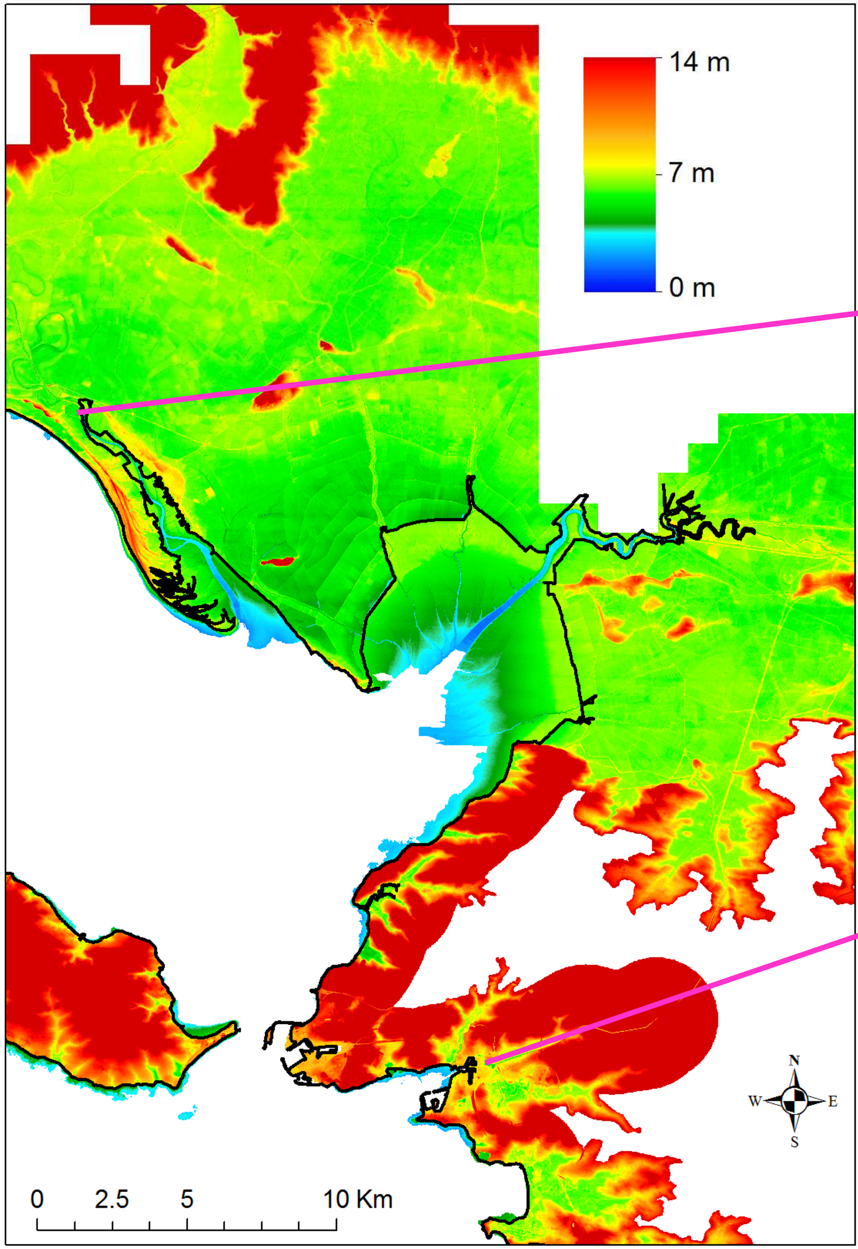
→ Max wind speed of 25-30 m/s in the Bay of Biscay



→ Xynthia induced a surge up to 1.6 m in the Bay of Biscay.

→ This surge peaked at the same time as a high spring tide, causing a massive marine flooding

The flooding associated with Xynthia



→ 47 peoples died
→ More than 2.5 billions € damage

The storm surge modelling system

The spectral wave model WWMII (Roland et al., 2009)

-WWMII solves the Wave Action Equation (WAE) over unstructured grids:

$$\frac{\partial N}{\partial t}+\frac{\partial\left(C_{gx}+U\right)N}{\partial x}+\frac{\partial\left(C_{gy}+V\right)N}{\partial y}+\frac{\partial(C\sigma N)}{\partial\sigma}+\frac{\partial(C\theta N)}{\partial\theta}=\frac{S}{\sigma}$$

With $N(\sigma,\theta)=\frac{Es(\sigma,\theta)}{\sigma}$ and $S(\sigma,\theta) = S_{break} + S_{bfric} + S_{windgrowth} + S_{whitecap}$

- WAE solved by means of a fractional 3-step method (Yanenko, 1971):

1- Advection in geographic space solved first using the N-Scheme of Abgrall (2006).

2- Advection in spectral space is then solved using the finite diference method « Ultimate Quickest » (Leonard, 1991).

3- Integration of source terms (same as WWIII, Tolman 2009).

The hydrocynamic circulation model

- Moded SELFE (Zhang et Batista, OM 2008), developed to simulate baroclinic flows in 3D for a large range of spatio-temporal scales. Here used in 2DH barotropic mode:

$$\frac{\partial \zeta}{\partial t} + \vec{\nabla}.\int_{-h}^{\zeta} \vec{u}\, dz = 0$$

$$\frac{DU}{Dt} = -fU + \alpha g \frac{\partial \hat{\psi}}{\partial x} - \frac{1}{\rho}\frac{\partial P_{Atm}}{\partial x} - g\frac{\partial \zeta}{\partial x} + \frac{\boxed{\vec{\tau}_{Sx}} - \vec{\tau}_{Bx}}{\rho(\zeta + h)} - \frac{1}{\rho(\zeta + h)} \cdot \left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y}\right)$$

$$\frac{DV}{Dt} = fV + \alpha g \frac{\partial \hat{\psi}}{\partial y} - \frac{1}{\rho}\frac{\partial P_{Atm}}{\partial y} - g\frac{\partial \zeta}{\partial y} + \frac{\boxed{\vec{\tau}_{Sy}} - \vec{\tau}_{By}}{\rho(\zeta + h)} - \frac{1}{\rho(\zeta + h)} \cdot \left(\frac{\partial S_{yy}}{\partial y} + \frac{\partial S_{xy}}{\partial x}\right)$$

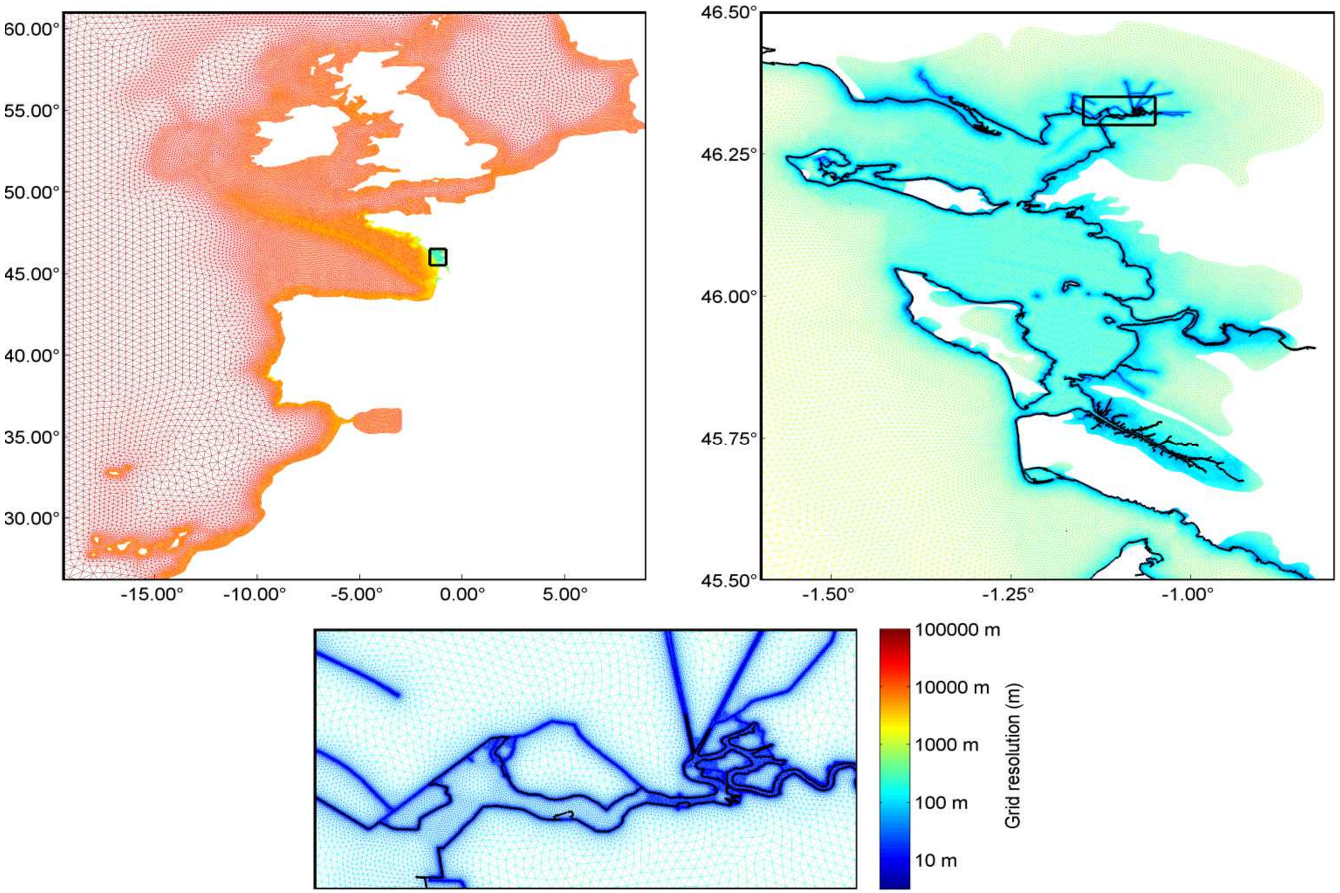
- The surface stress was modified to account for the sea-state through U*

$$\tau_s = \rho_a \cdot U_*^2 - \tau_{ws} \qquad \text{where} \qquad \tau_{ws} = \int_0^{2\pi}\int_{f_{\min}}^{f_{\max}} \frac{k}{\sigma}(\cos\theta, \sin\theta) S_{in}(\theta, \sigma)\partial\theta\partial\sigma$$

- SELFE uses a semi-implicit continuous Galerkin finite element method

-An ELM method for the advection ensures a good stability, even using large time steps

Implementation and forcing



-1,700,000 element unstructured grid

-Resolution ranging from 30000 m to 5 m

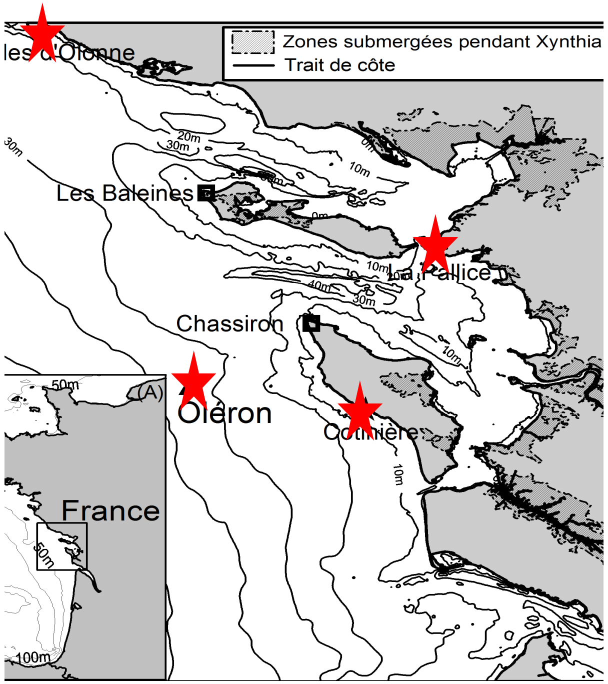
→ SELFE is forced along the boundary by the 18 main harmonic constituents linearly interpolated from TUGO2010 (Pairaud et al., 2006)

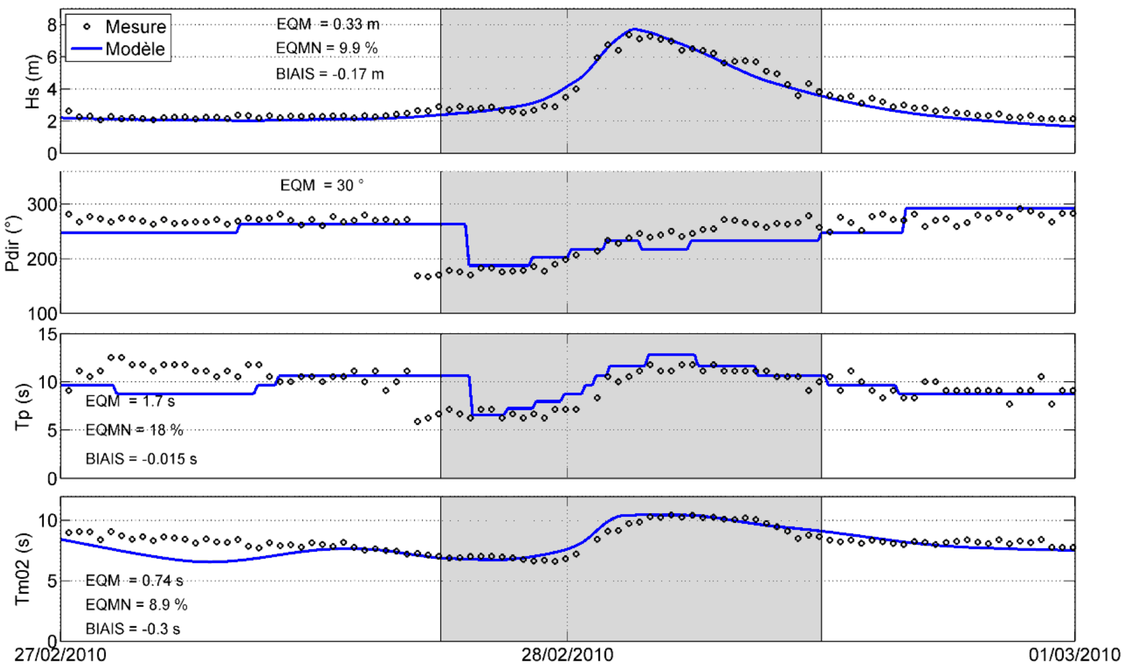
→ The atmospheric forcing originates from ARPEGE (Météo France, 0.1°/1h)

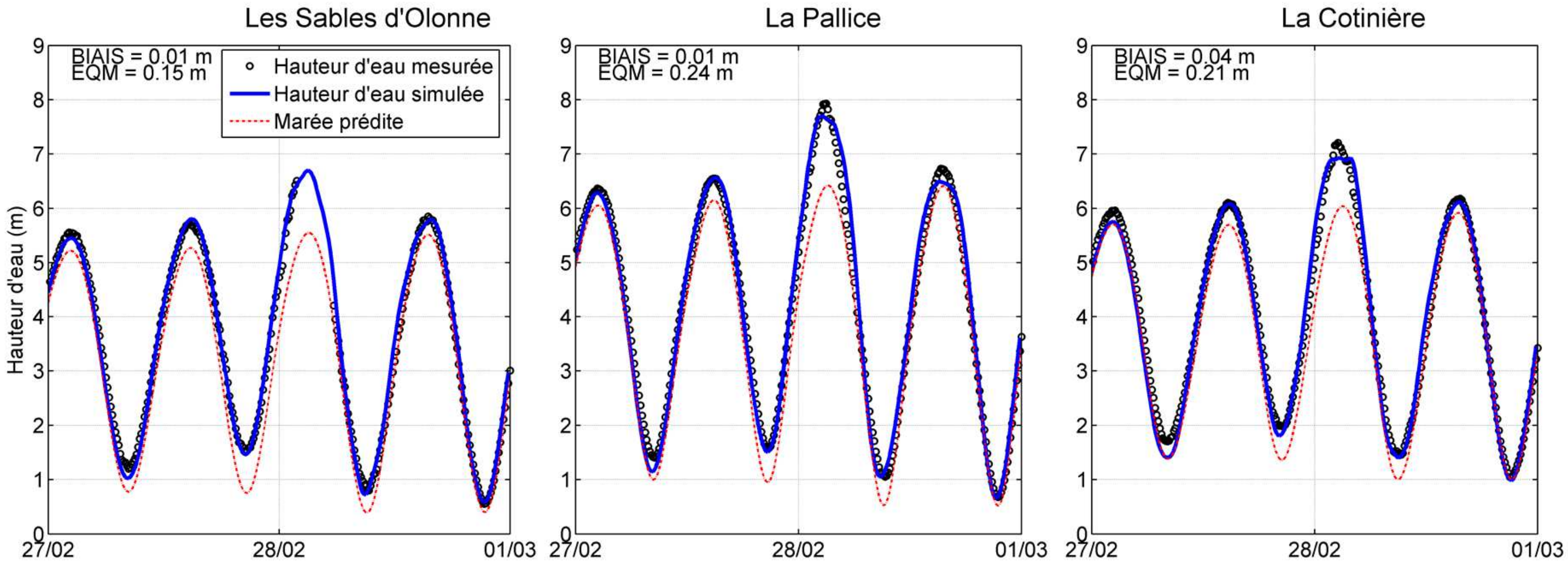
→ WWMII is also forced with wave spectral originating from a WWIII regional model

Modelling results

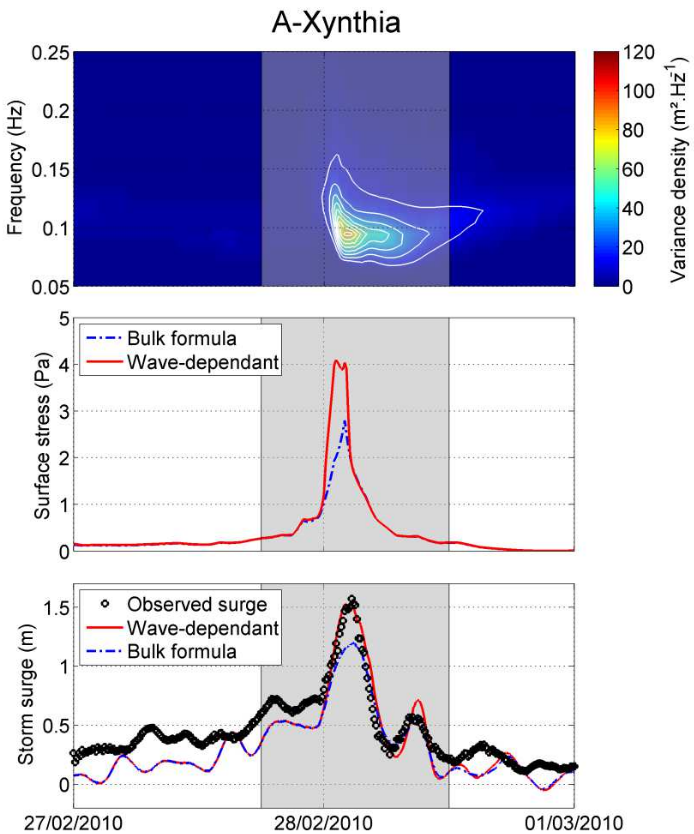
Model validation during Xynthia







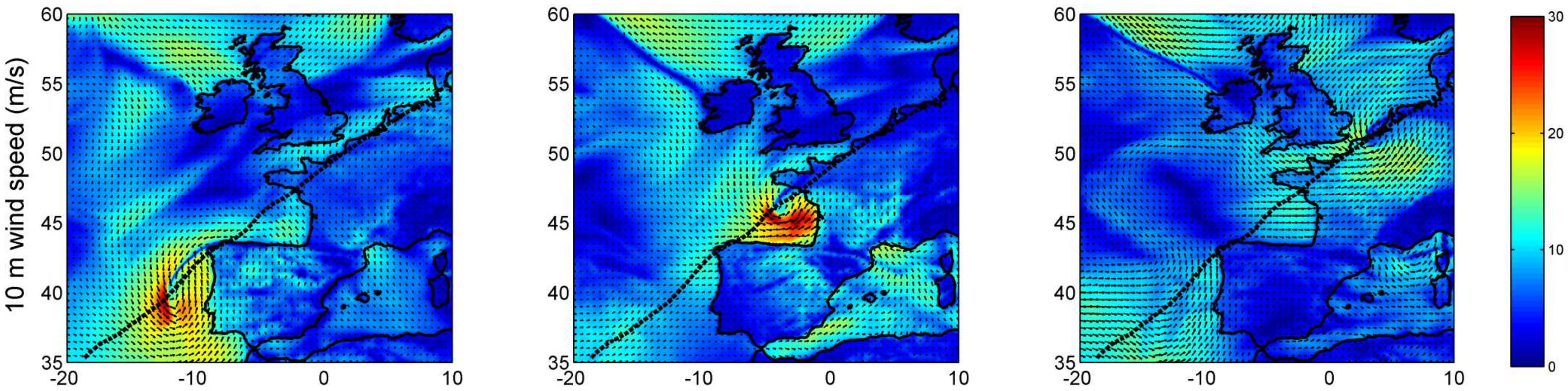
The cause for the abnormally large storm surge



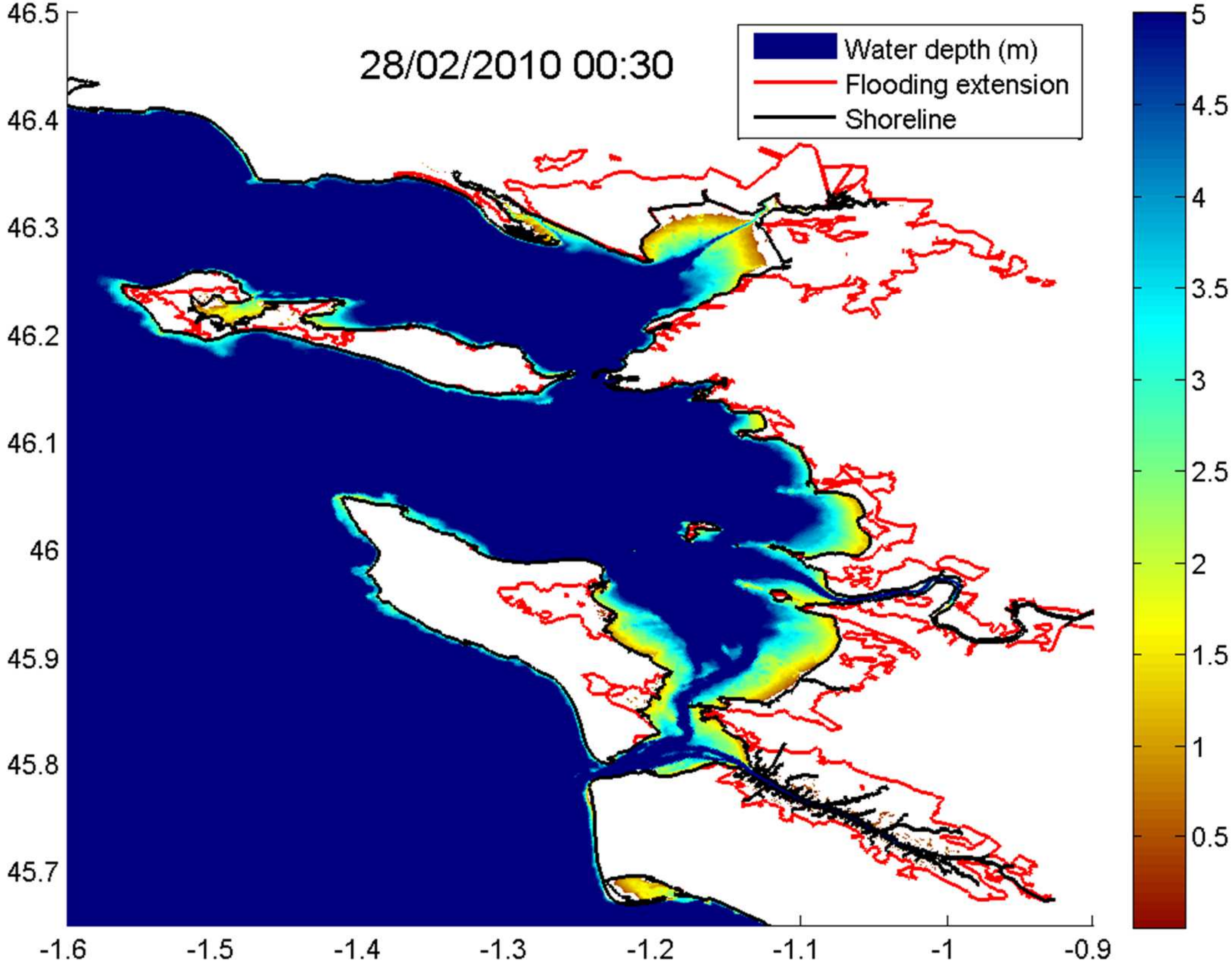
- ➢Several authors have shown that the sea state can impact the surface stress significantly (Mastenbroak et al., 1993; Olabarrieta et al., 2012).

- ➢Here we show that the sea-state during Xynthia was characterized by a very large level of energy in high frequencies, which traduces young waves

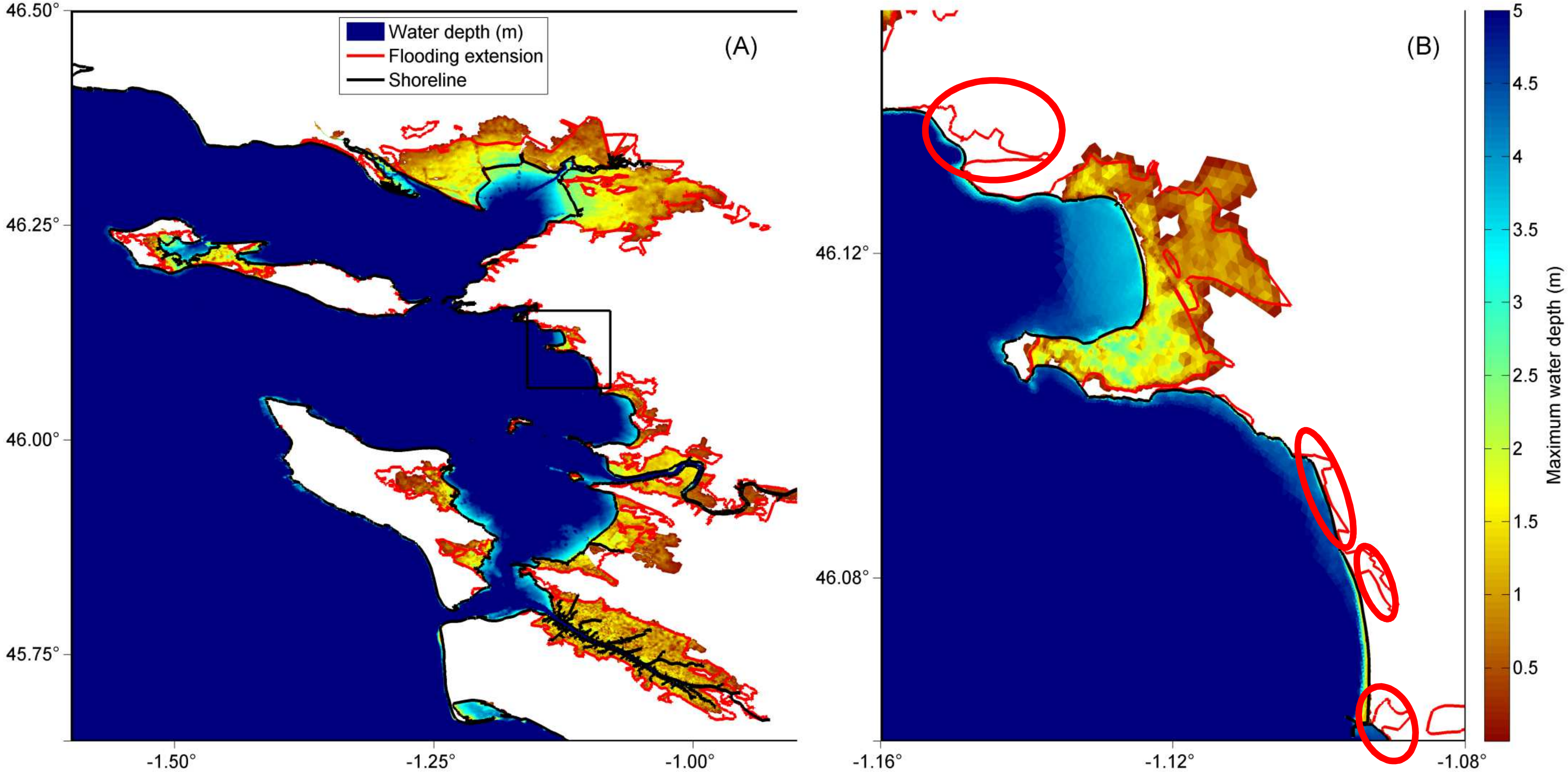
- ➢This particulmar sea-state is explained by the unusual track of Xynthia from SW to NE, which restricted the fetch to a few hundred km



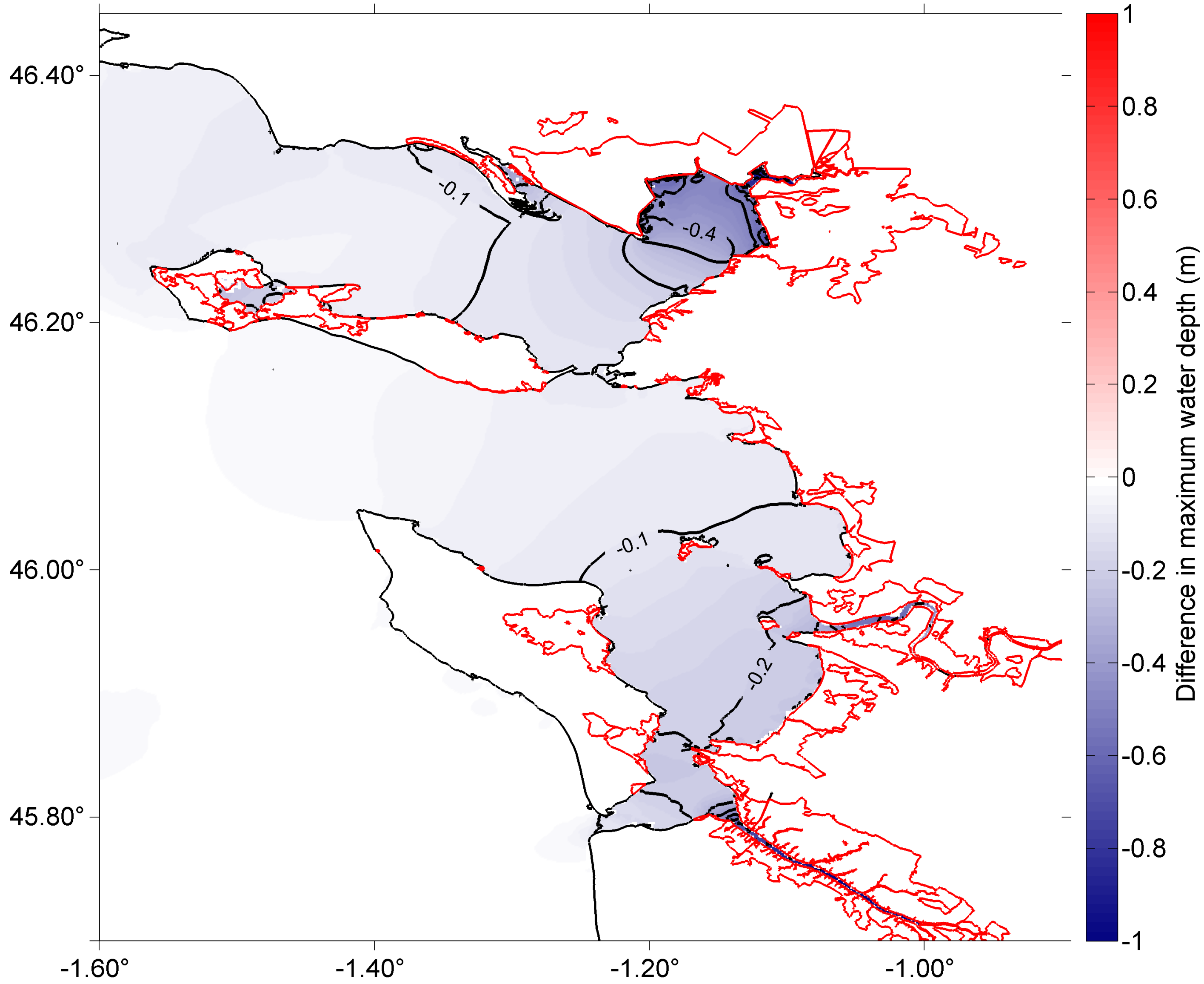
Modelling the flooding associated with Xynthia



Modelling the flooding associated with Xynthia



The impact of marine flooding on coastal water levels



Conclusions

→ We improved and implemented a new storm surge modelling system which yields good predictions for tides, waves, surges and flooding, for Xynthia and for other storms.

→ The analysis of model results revealed that the large storm surge during Xynthia originated from an Ekman transport, strongly enhanced by young waves.

→ Our simulations of flooding are quite relalistic and the analysis of the resultrs suggest that massive flooding can impact coastal water levels significantly.

Thank you for your attention!

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