The contribution of wave setup to sea-level variations: from the surfzone to lagoons and estuaries

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Outline of the presentation:

I – Introduction

II – The impact of short wave breaking parameterization

III – The impact of the wave-driven circulation on wave setup

IV - Wave setup in coastal lagoons and estuaries

V - Conclusions and future works

I - Introduction

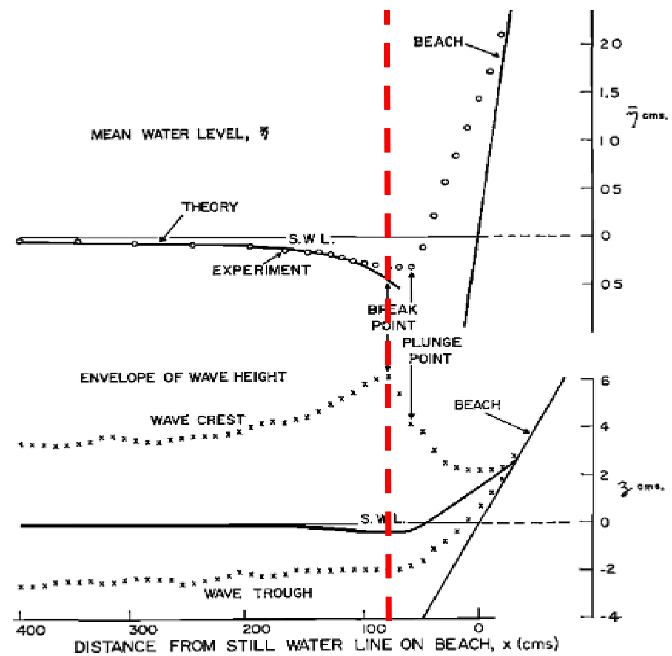
Definition and first descriptions of wave setup

- ✓ **Wave setup corresponds to the rise in mean water level that accompanies wave dissipation in the nearshore and was first reported by Saville (1961).**

- ✓ **The first physical explanation is due to Longuet-Higgins and Stewart (1964), who introduced the concept of radiation stress:**

$$\frac{1}{\rho(h+\xi)}\frac{\partial S_{xx}}{\partial x} = -g\frac{\partial \xi}{\delta x} \qquad \text{where} \qquad S_{xx} = \frac{E}{2}\left(2\frac{C_g}{C}\left(\cos^2\alpha+1\right)-1\right) \qquad \sim\frac{3E}{2}$$

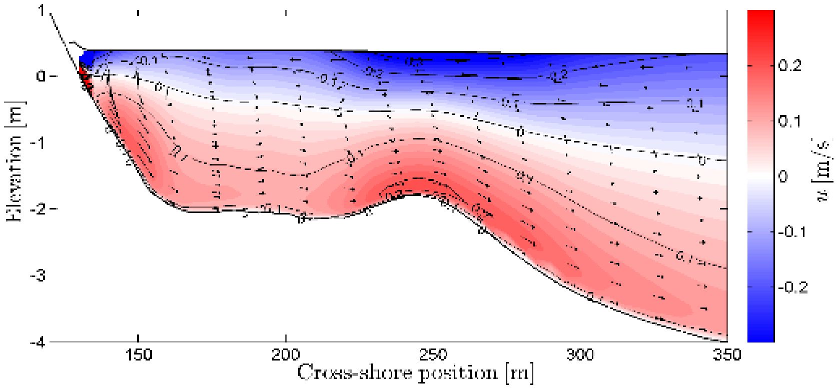
- ✓ **Wave setup and setdown was then investigated in the Lab, as for instance in the pioneer study of Bowen et al. (1969).**



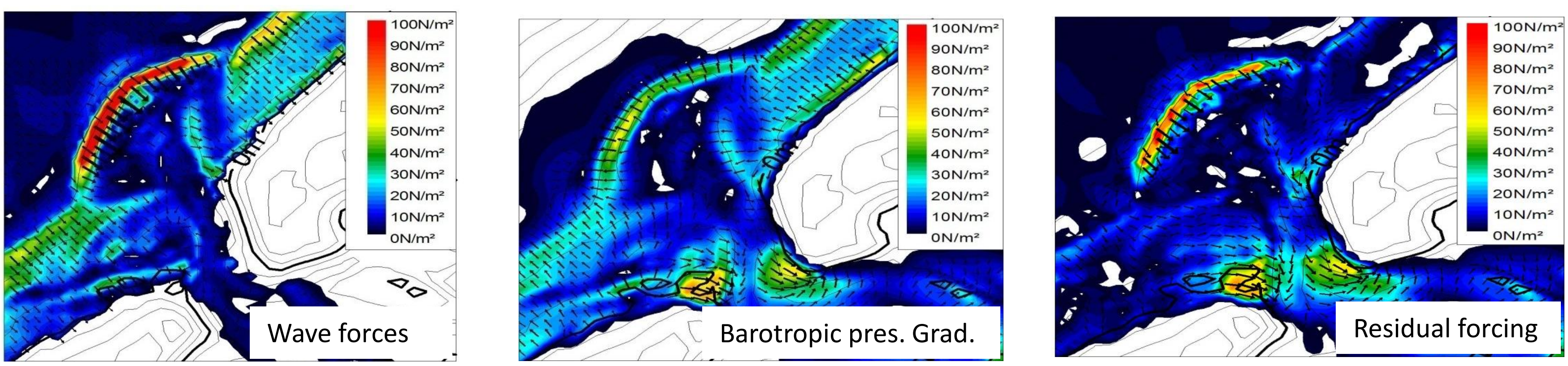
Why wave setup matters

✓ **Under storm waves, wave setup can reach or exceed 1 m (e.g. Lerma et al. 2017; Guérin et al., 2018) and therefore can have a key contribution to storm surges and subsequent flooding.**

✓ **In the surfzone, the local imbalance between the depth-uniform barotropic pressure gradient and depth varying wave forces and Stokes drift drives a bed return flow, which contributes to coastal erosion.**

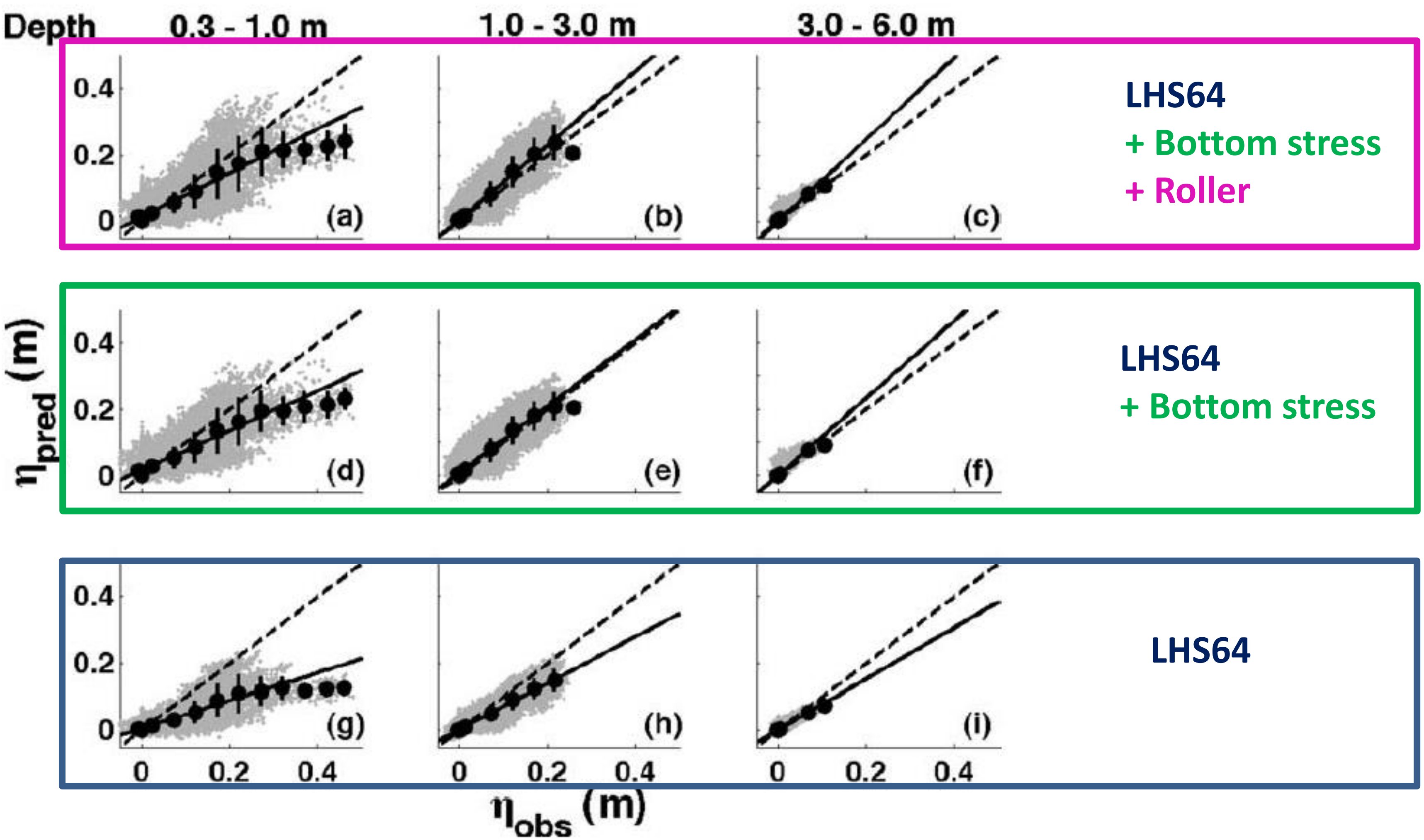


✓ **In tidal inlets, wave setup drives a lateral barotropic pressure gradient, which forces strong flows towards the lagoon (Bertin et al., CSR2009).**



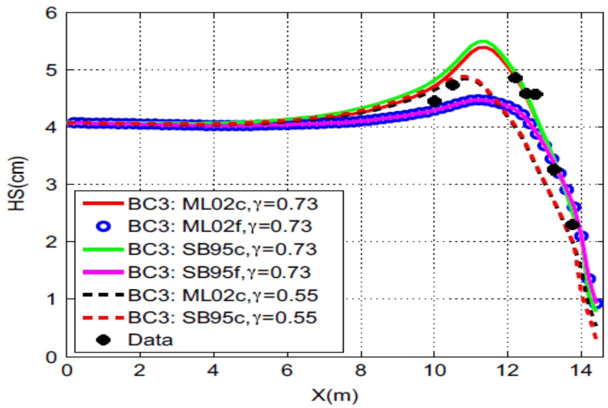
The "setup enigma"

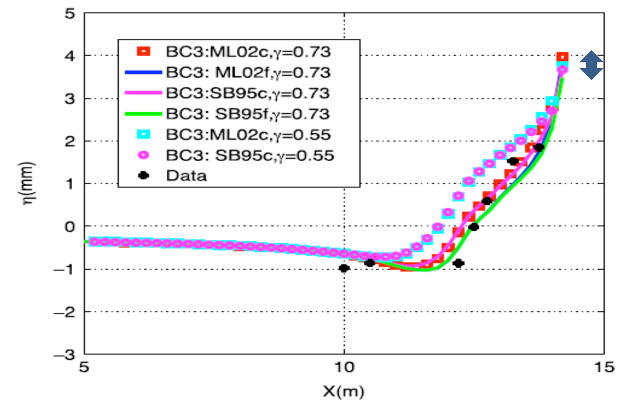
✓ **Based on comprehensive field experiments, Raubenheimer et al. (JGR2001) and Apotsos et al. (JGR2007) reported a severe underestimation of wave setup along the shoreline when using the model of LHS64:**



The "setup enigma"

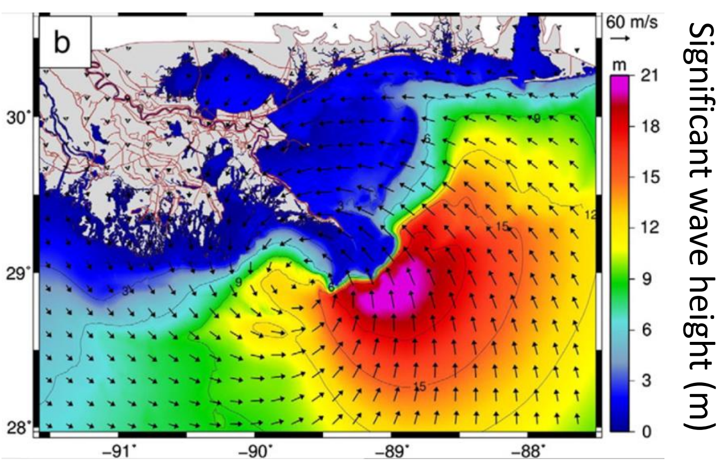
✓ **The study of Apotsos et al. (2007) fostered some research on wave setup, namely using 3D models capable to simulate the wave driven circulation (e.g. Bennis et al., 2014):**

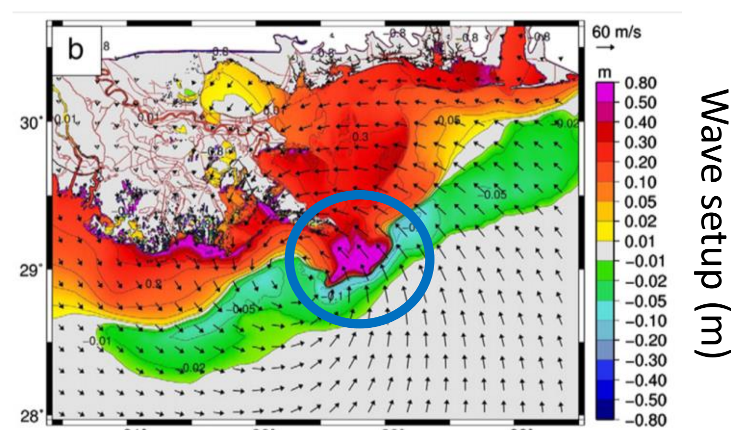




➢ Parameterizations for mixing and bottom stress can impact wave setup by O(10%)

✓ **However, storm surge studies keep using LHS64 with default breaking parameterizations, which questions the validity of wave setup predictions (e.g. Dietrich et al., 2010):**





➢ Are these values also underestimated by a factor of two?

II - The impact of short wave breaking parameterization

Parameterization of wave breaking in spectral models

- The Wave Action Equation

$$\frac{\partial N}{\partial t}+\nabla_x(\dot{x}\cdot N)+\frac{\partial \dot{\sigma} N}{\partial \sigma}+\frac{\partial \dot{\theta} N}{\partial \theta}=S_{atm}+S_{ds}+S_{nl4}+S_{nl3}+S_{bf}+S_{db}$$

$$\text{With} \quad N(x,t,\sigma,\theta)=\frac{E(x,t,\sigma,\theta)}{\sigma}$$

- The depth-induced breaking source term S_{db}

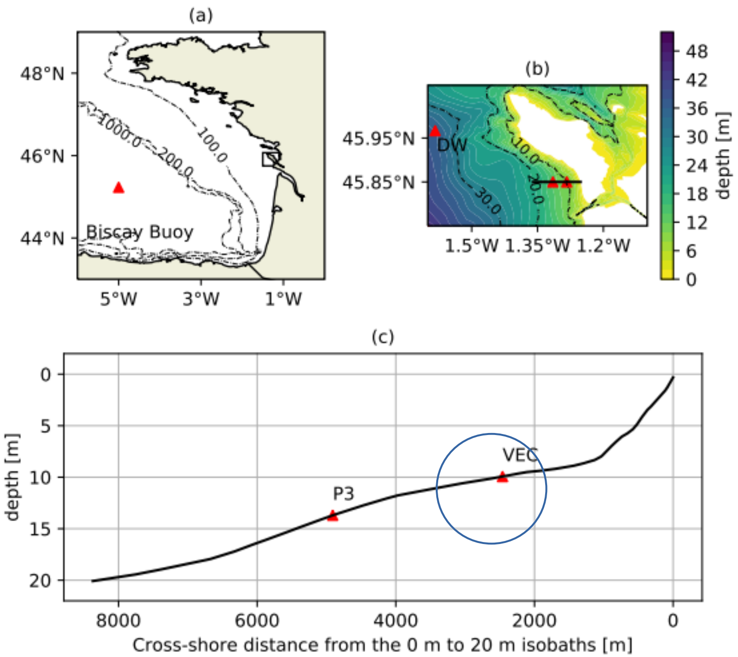
$\alpha_{default} \approx 1$ (tuning parameter)
$\alpha_{new} \approx 40 \cdot \tan\beta$

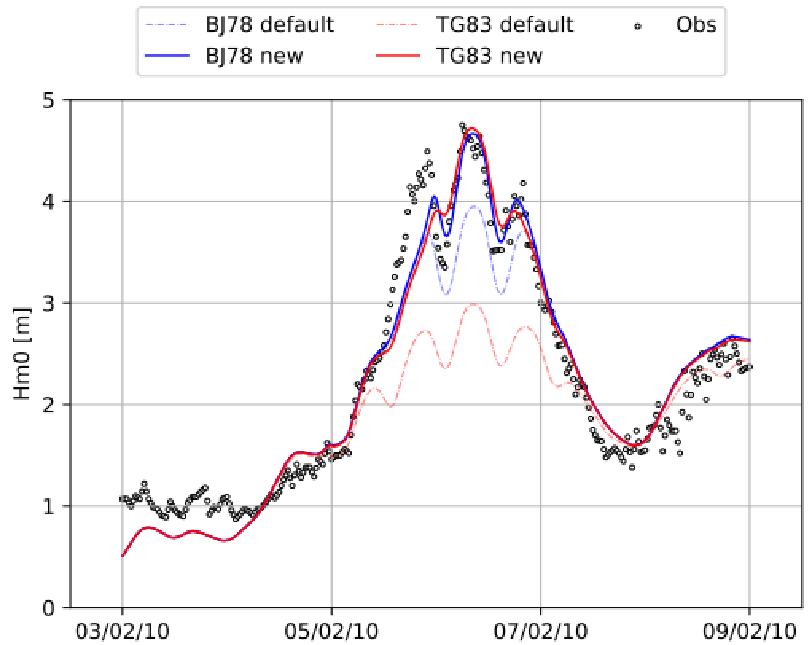
$$S_{db}=\frac{D}{E_{tot}}N \quad \text{with} \quad D \approx f(Q_b, D_{breaker}) \quad \text{e.g.} \quad D_{BJ78}=\frac{\alpha}{4}\rho g f_{mean} H_m{}^2 Q_b$$

Fraction of breaking waves. Profusely studied, numerous formulations and parameterizations

Energy dissipation rate of a breaker.
New analytical parameterization of the **breaking coefficient** proposed by Pezerat et al. (OM2021)

Improved predictions of storm waves in the shoreface

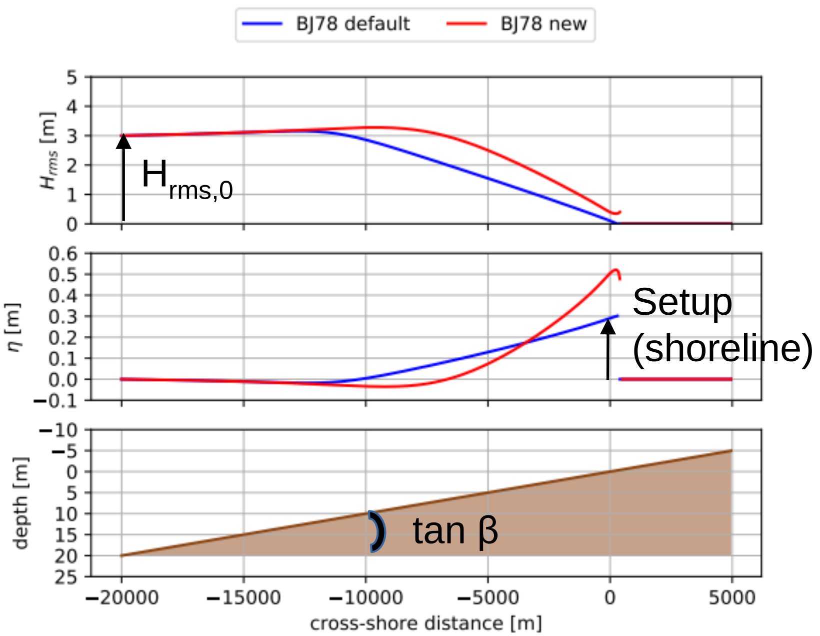


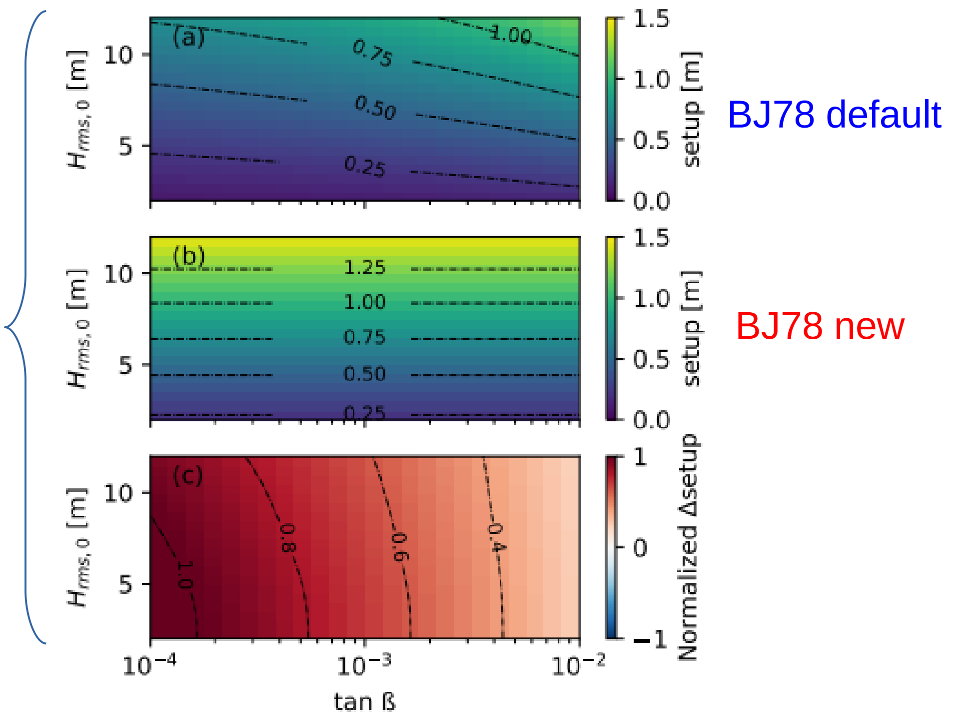


Inadequate parameterization of the breaking coefficient → Over-dissipation of wave energy in intermediate depth → Underestimation of H_{m0} in the nearshore area

What implications on the wave setup ?

An early wave energy dissipation in intermediate depth should result in weaker wave forces, yielding an undererstimation of wave setup near the shoreline

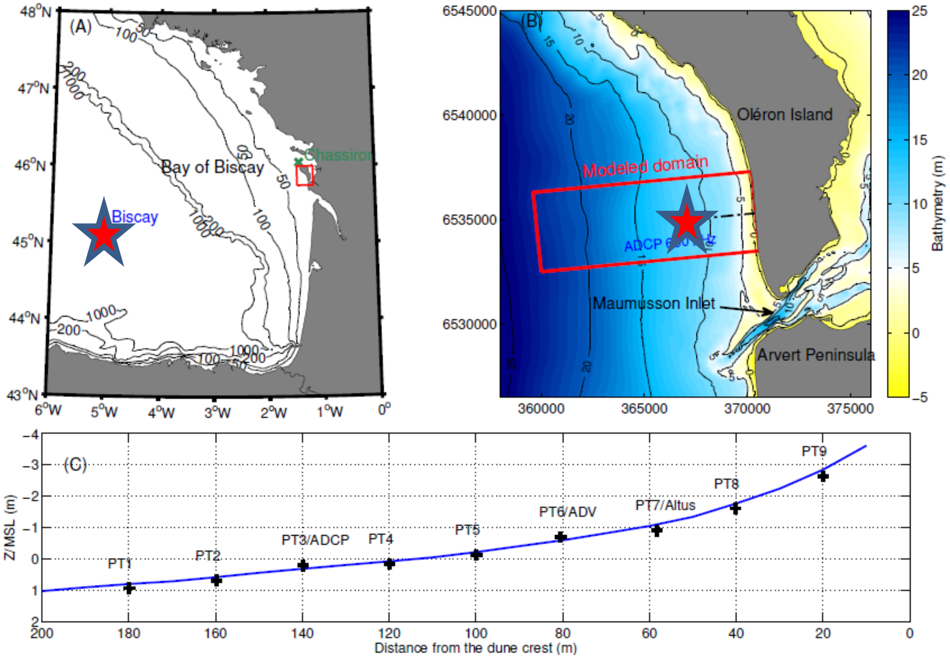


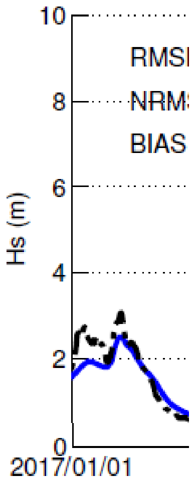


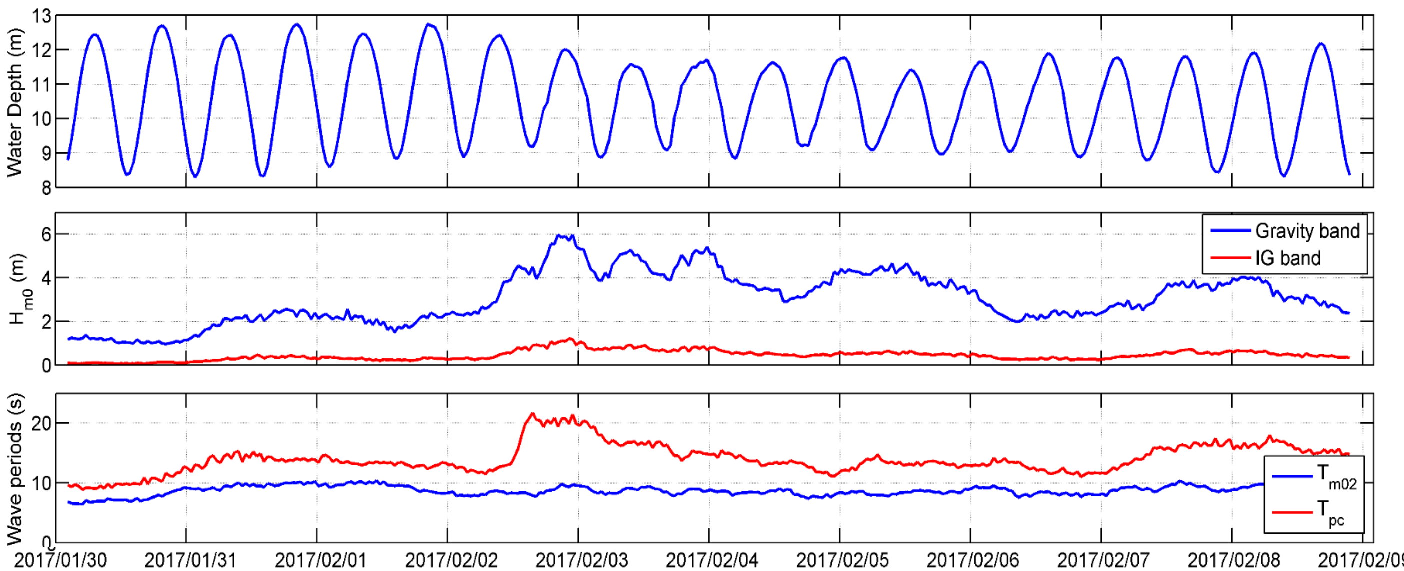
II - Impacts of the wave-driven circulation on wave setup

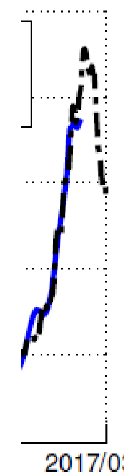
The field campaign of February 2017

(Guérin et al., OM2018)





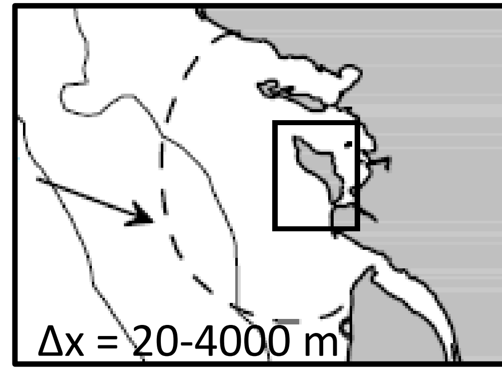




➢ Wave setup 0(0.1*$H_{s,break}$) but estimated with errors O(0.05-0.1 m)

The modelling system SCHISM

Waves (WWMII, Roland et al., 2012) ⇄ **3D Hydrodynamic Circulation (SCHISM, Zhang et al., 2016)**



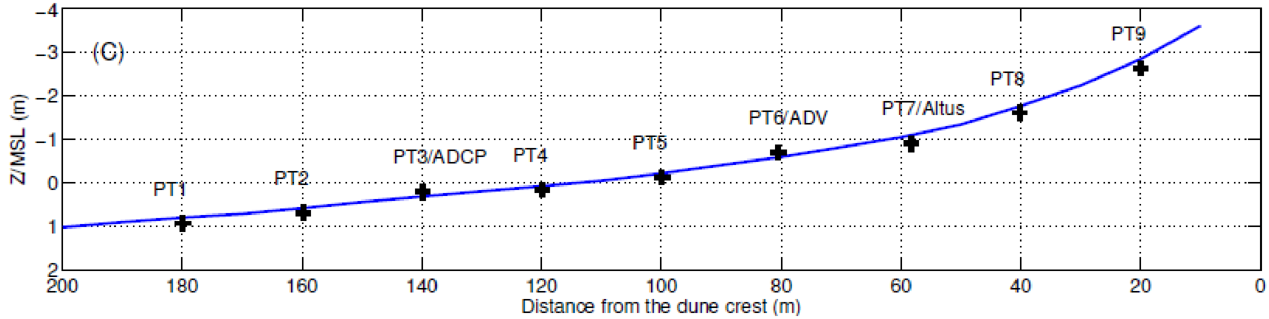
The coupling through a vortex force formalism (e.g. Bennis et al., 2012)

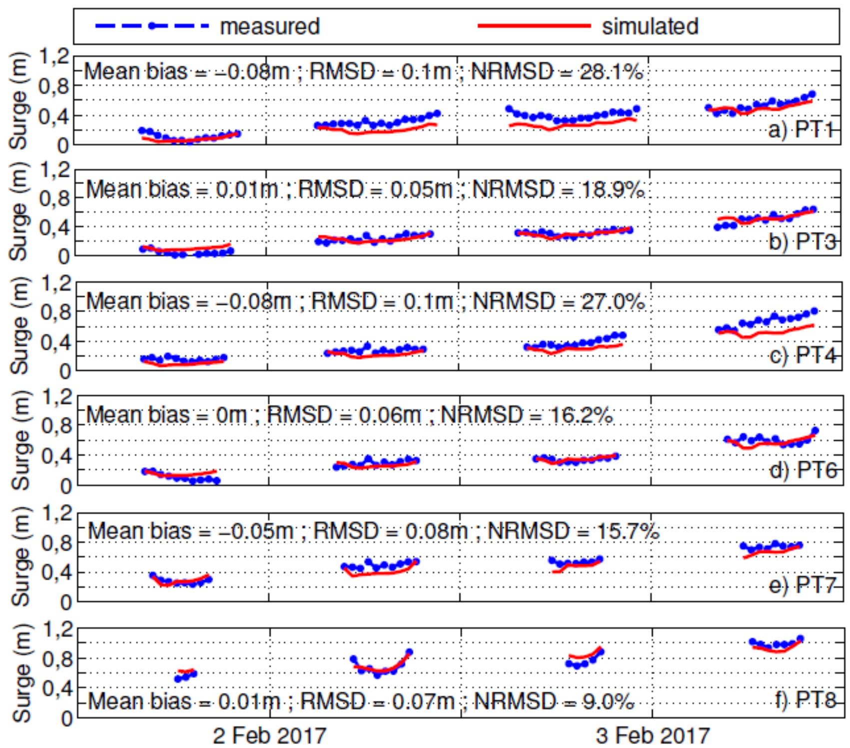
$$\frac{\partial \eta}{\partial t} + \nabla \int_{-h}^{\eta} \left(\hat{U} + U_s \right) dz = 0 \qquad \nabla . \hat{U} = 0$$

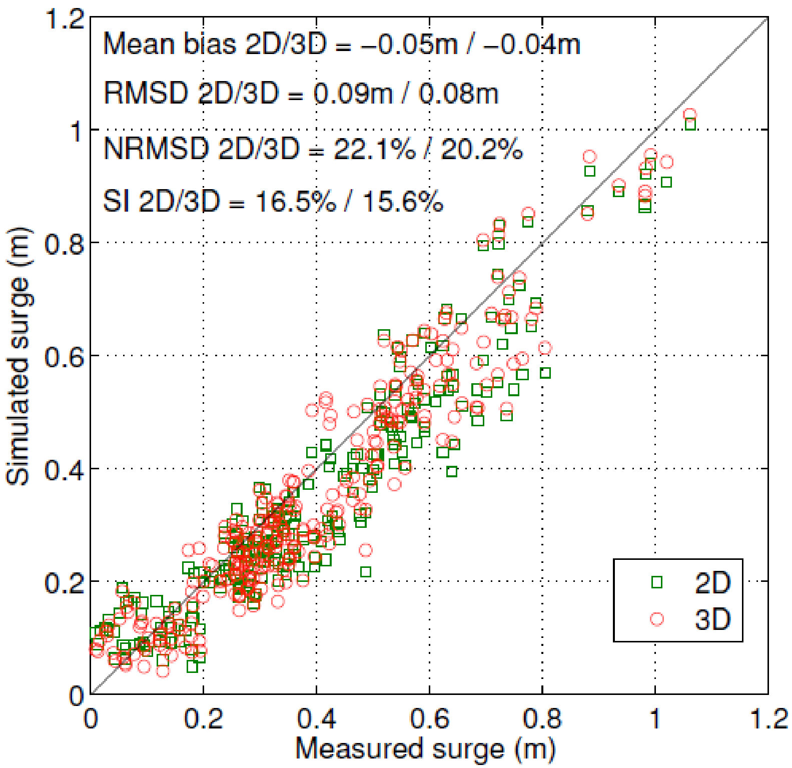
$$\frac{D_{\hat{u}}}{D_t} = f\hat{v} - g\frac{\partial \eta}{\partial x} + \underbrace{\frac{\partial}{\partial z}\left(\nu \frac{\partial \hat{u}}{\partial z}\right)} + \underbrace{\left(f_c + \frac{\partial \hat{v}}{\partial x} + \frac{\partial \hat{u}}{\partial y}\right) v_s + w_s \frac{\partial \hat{u}}{\partial z}} \underbrace{- \frac{\partial J}{\partial x}} + \underbrace{\hat{F_{dx}} + \hat{F_{bx}}}$$

$$\frac{D_{\hat{v}}}{D_t} = -f\hat{u} - g\frac{\partial \eta}{\partial y} + \underbrace{\frac{\partial}{\partial z}\left(\nu \frac{\partial \hat{v}}{\partial z}\right)}_{\text{Vertical mixing accounting for waves}} \underbrace{- \left(f_c + \frac{\partial \hat{v}}{\partial x} + \frac{\partial \hat{u}}{\partial y}\right) u_s + w_s \frac{\partial \hat{v}}{\partial z}}_{\text{Vortex force}} \underbrace{- \frac{\partial J}{\partial y}}_{\text{Mean wave pressure}} + \underbrace{\hat{F_{dy}} + \hat{F_{by}}}_{\text{Wave dissipation terms}}$$

Wave setup predictions (Guérin et al., OM2018)



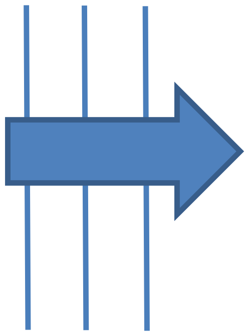




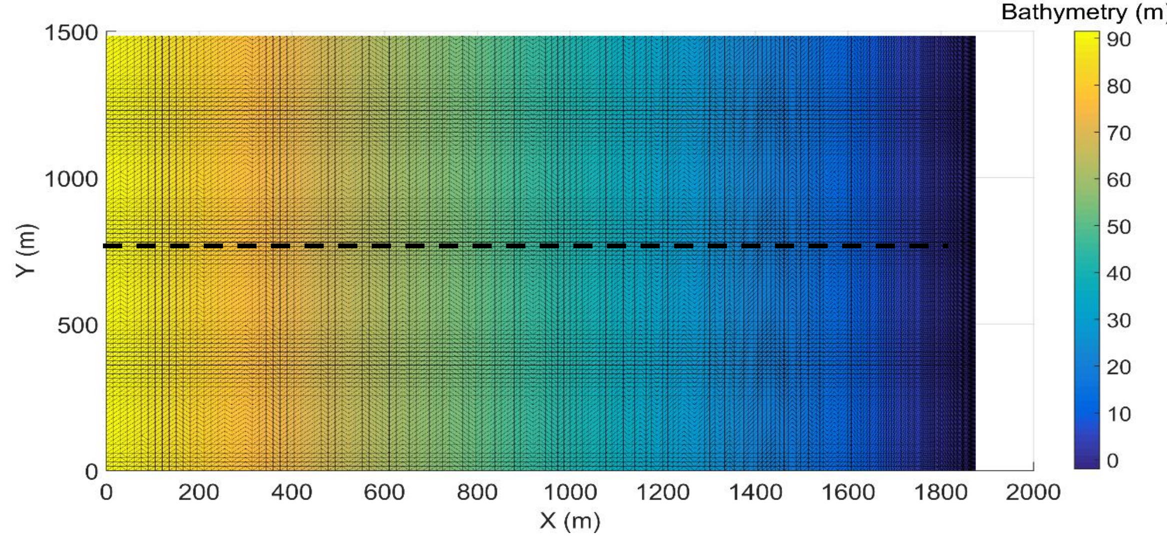
- Improvements with the 3D model are very limited: bottom slope too mild?

Extention of this study to idealized beaches

Shore-normal waves
of Hs = 1,3 and 5 m



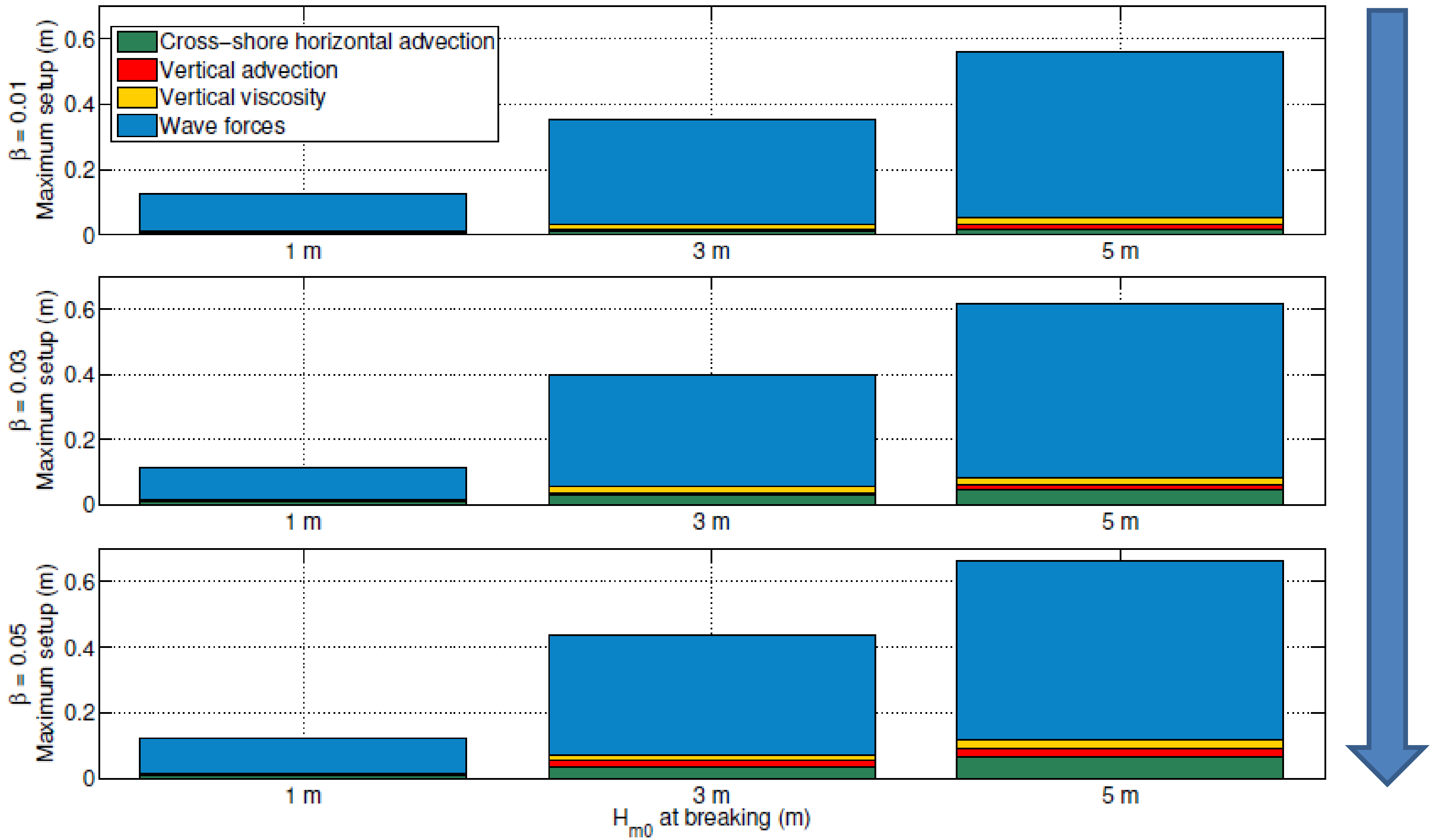
Uniform beach of constant slope = 0.01, 0.03 and 0.05



✓ Under steady state, the wave setup is balanced by the following depth-integrated terms in the momentum equation along x:

$$g\frac{\partial \eta}{\partial x} = \frac{1}{h}\int_{-d}^{\eta}\left(\underbrace{-\hat{u}\frac{\partial \hat{u}}{\partial x} - \hat{v}\frac{\partial \hat{u}}{\partial y}}_{\text{Horizontal advection}} \underbrace{- \hat{w}\frac{\partial \hat{u}}{\partial z}}_{\text{Vertical advection}} + \underbrace{\frac{\partial}{\partial z}\left(\nu\frac{\partial \hat{u}}{\partial z}\right)}_{\text{Vertical mixing}} + \underbrace{F_{wave,x}}_{\text{Wave forces}}\right) dz$$

Extention of this study to idealized beaches

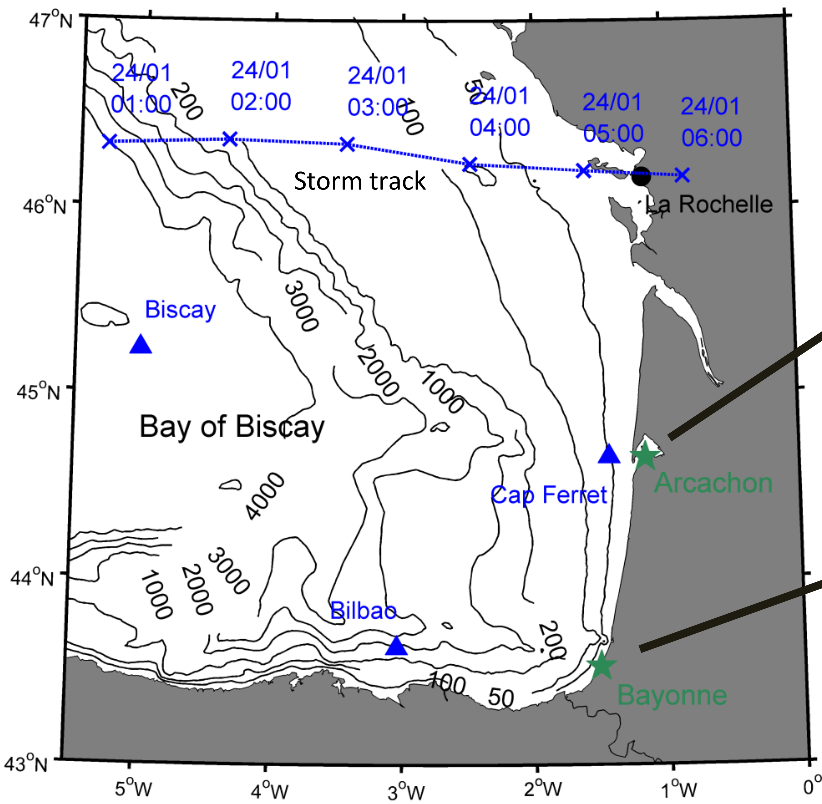


- For a given Hs, wave setup increases with the beach slope due to a more important contribution of the depth-varying wave-induced circulation.
- For a slope of 0.1, wave setup is increased by 30 %: could this explain the « setup enigma »?
- We are verifying this hypothesis using the data of Apotsos (2007) and a more complete model.

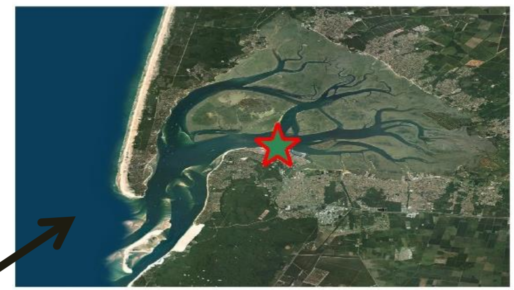
III - Wave setup in coastal lagoons and estuaries

The contribution of wave setup to the storm surge associated with Klaus in the Bay of Biscay (Lavaud et al., 0M2020)

The extra-tropical storm Klaus made landfall in the southern part of the Bay of Biscay on the 24/01/2009 (min. atm. pressure of 965 hPa).

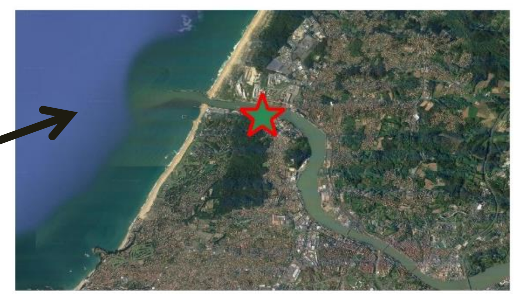


Study area: wave buoys (blue triangles), tide gauges (green stars)



Arcachon Lagoon

- Max. sustained wind speed: 35 m.s^{-1}
- Peak storm surge: **1.70 m**



Adour Estuary (Bayonne)

- Max. sustained wind speed: 21 m.s^{-1}
- Peak storm surge: **1.10 m**

The contribution of wave setup to the storm surge associated with Klaus in the Bay of Biscay (Lavaud et al., 0M2020)

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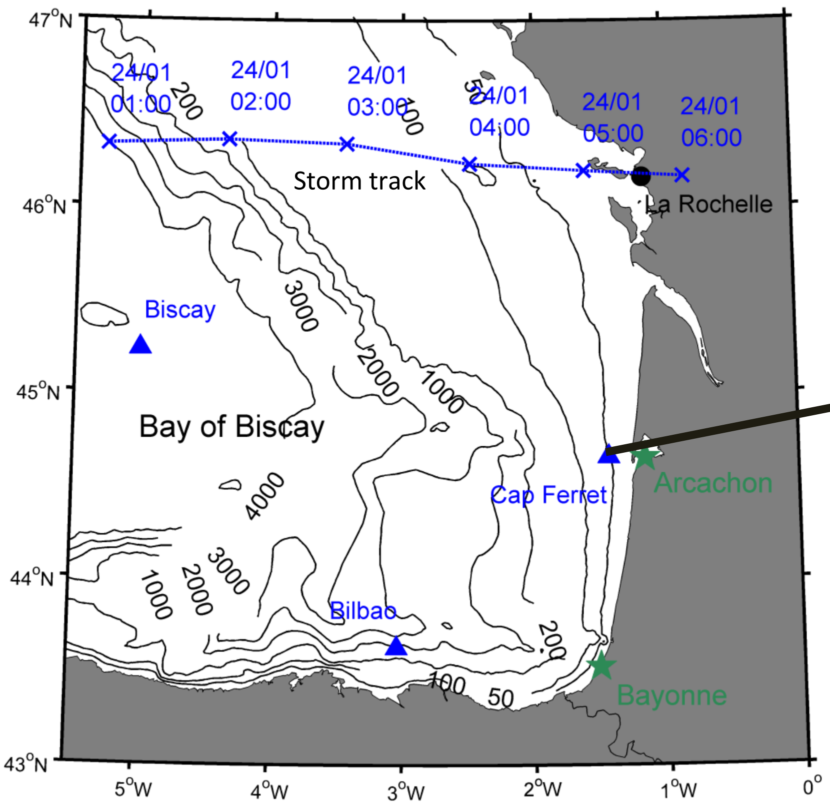

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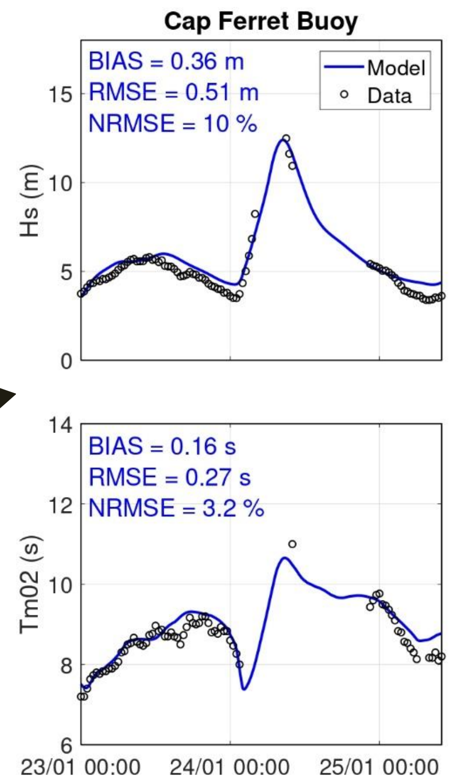


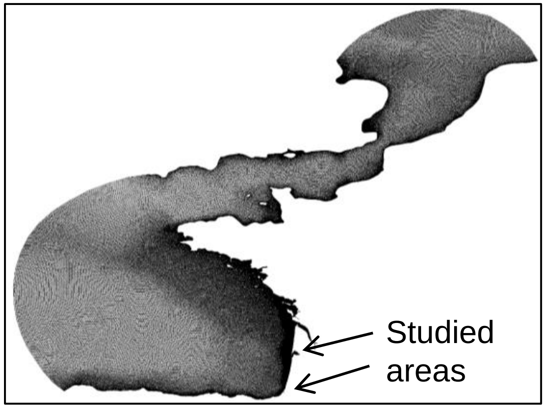
- Significant wave height (Hs) of 13 m with a peak period (Tp) of 16 s recorded at Bilbao and Cap Ferret buoys.
- Largest waves recorded over the last 20 years along the coasts of this region.

Relevant case study to investigate the contribution of short-wave breaking to storm surges.

The contribution of short-wave breaking to storm surges

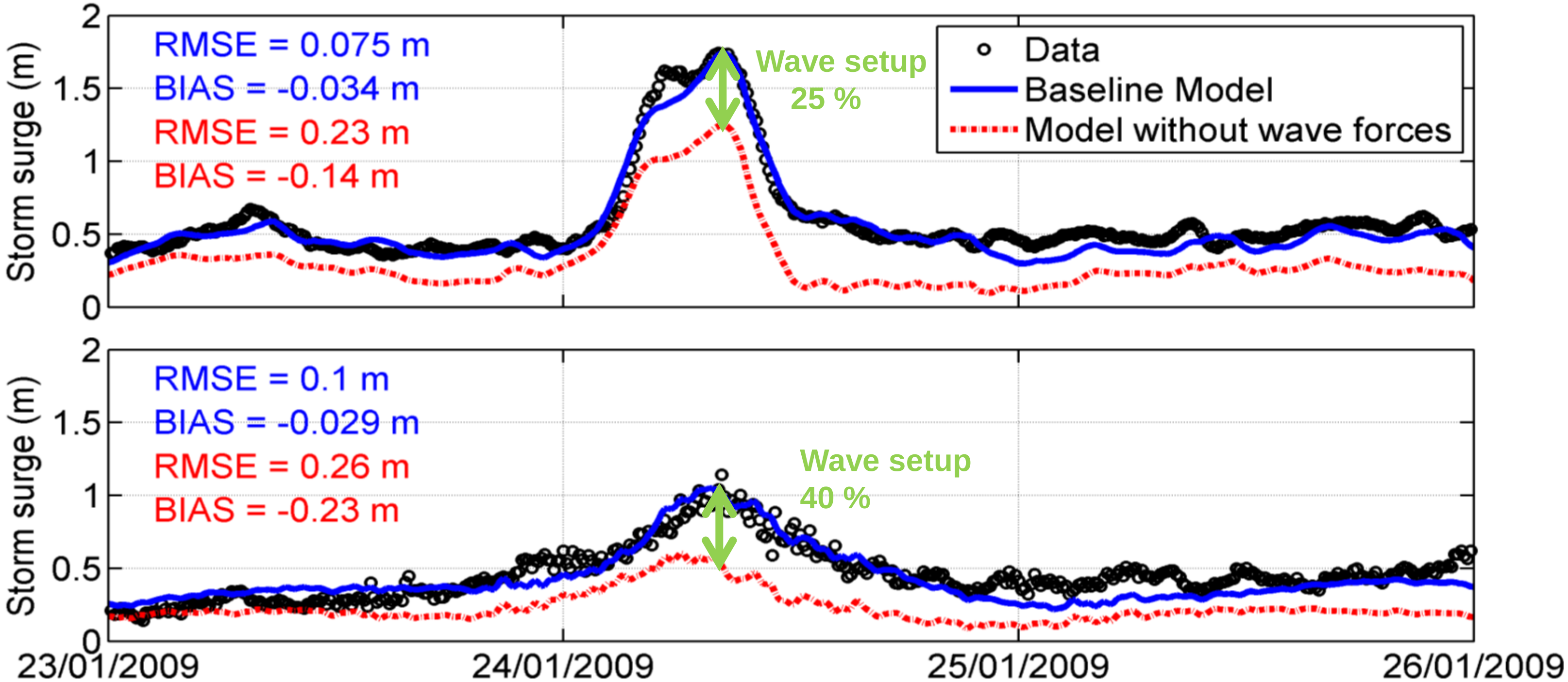
Modelling system SCHISM:

- Fully-coupled (wave-current) 3D simulations (SCHISM-WWM)
- Vortex force formalism
- Spatial resolution down to 35 m in the surf zones of the studied areas



Unstructured grid

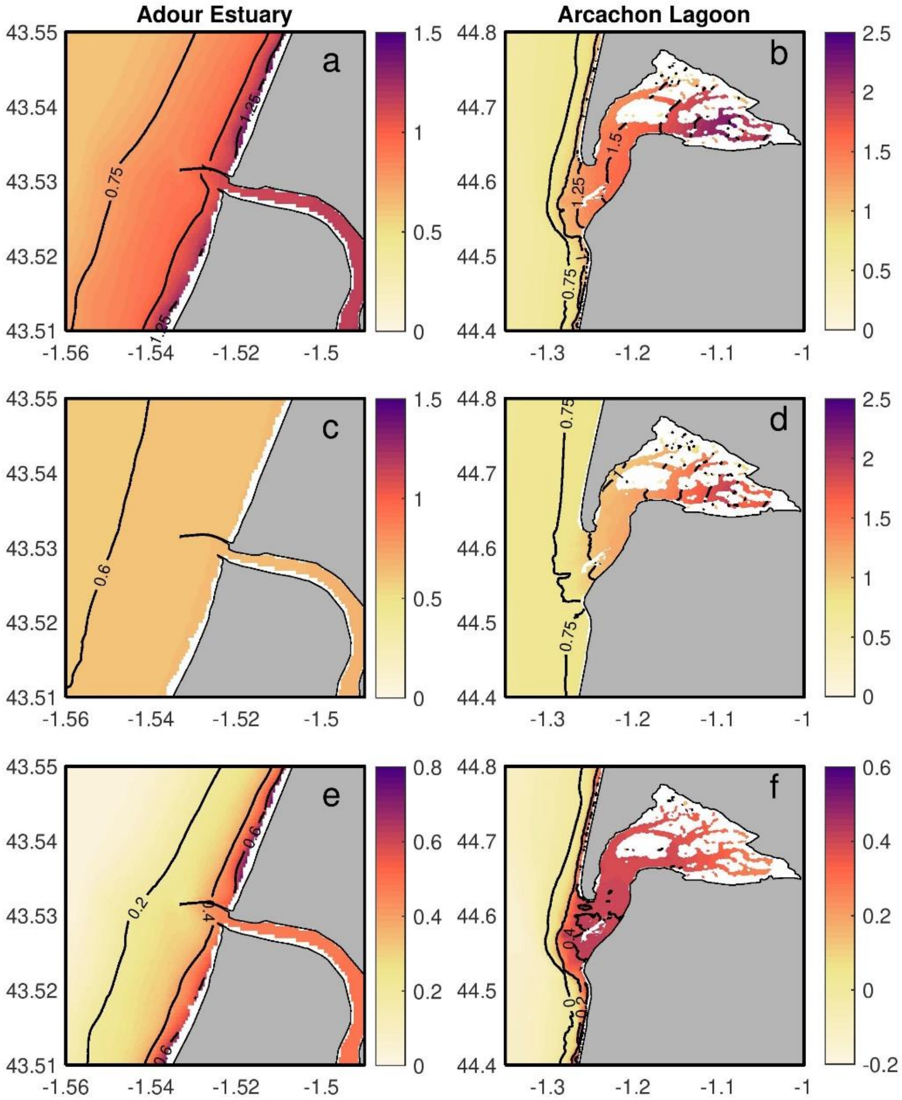
Storm surge predictions:



Storm surge predictions strongly improved when **accounted for wave forces**.

The contribution of short-wave breaking to storm surges

Storm surge predictions:



With wave forces

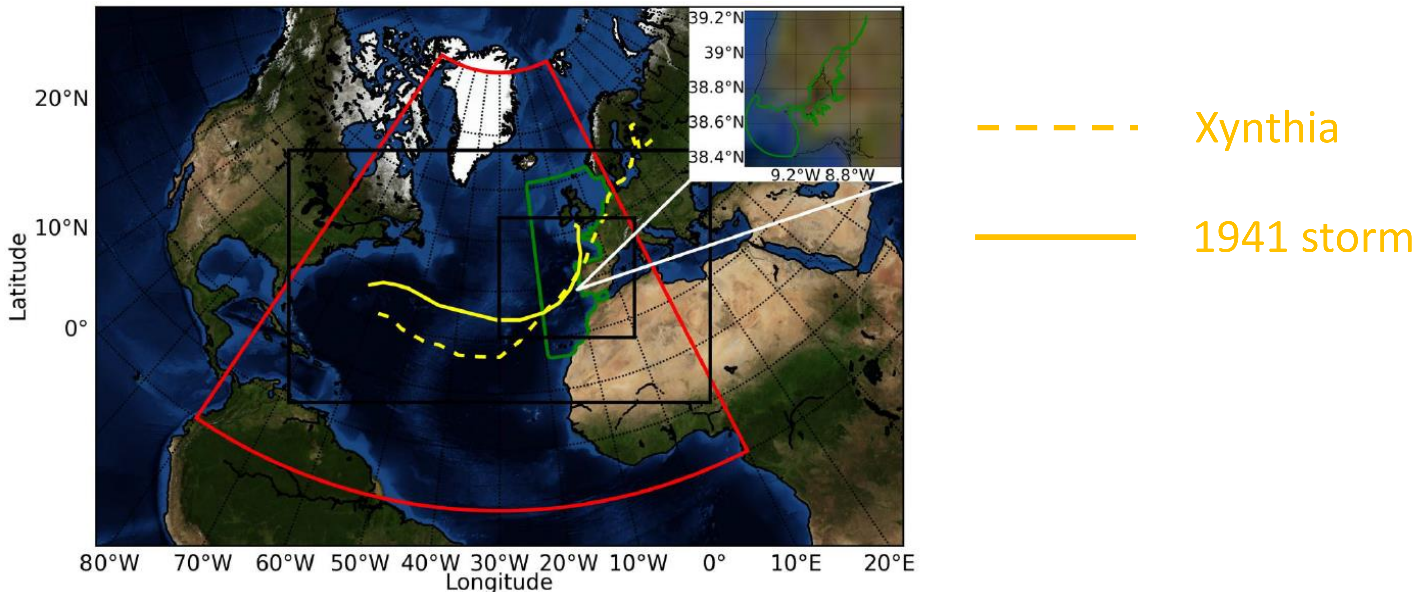
Without wave forces

Difference

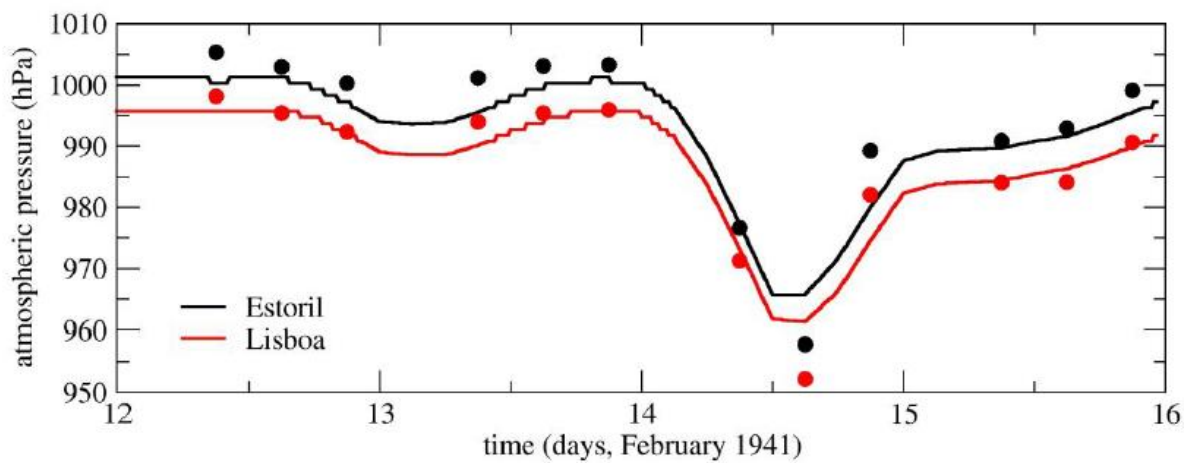
Storm wave breaking can greatly contribute to storm surge, **even in areas sheltered from this process**.

Surge associated with the 1941 storm in the Tagus Estuary

(Fortunato et al., CSR 2017)

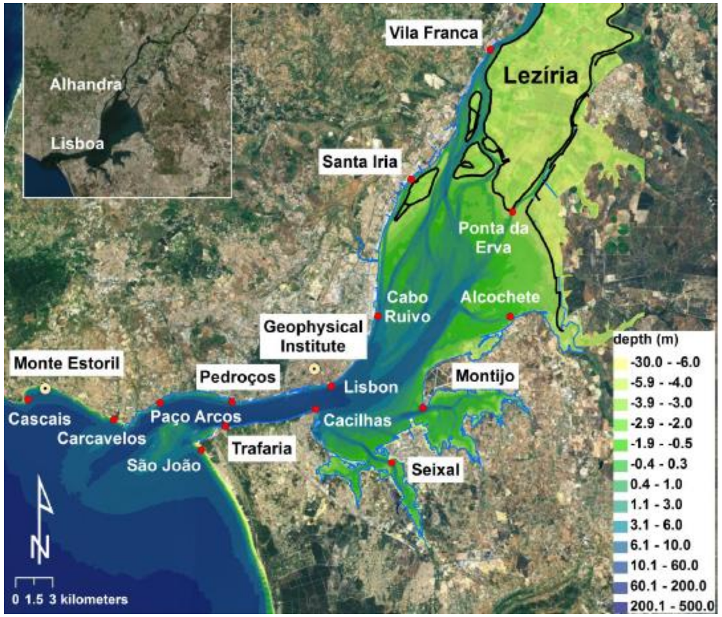


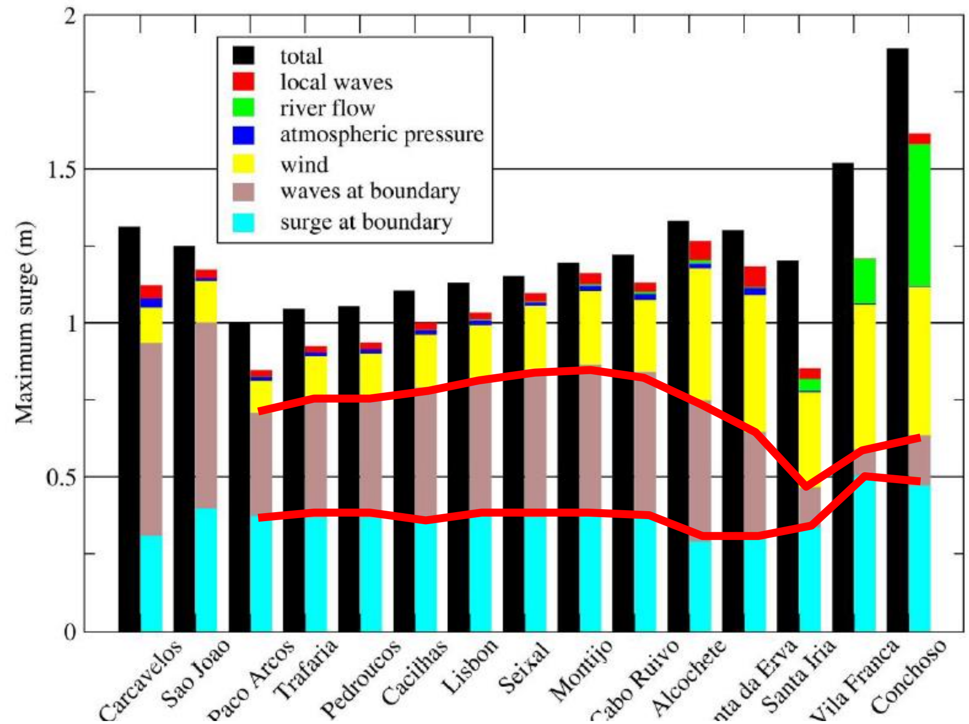
- Dynamical hindcast of the storm using WRF forced with the 20CR reanalysis (Compo et al., 2011)



- According to the model, incident waves reached Hs ~13 m

Surge associated with the 1941 storm in the Tagus Estuary

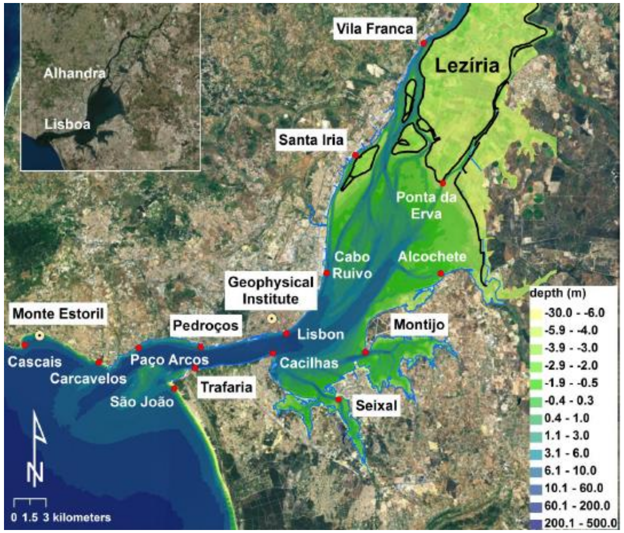


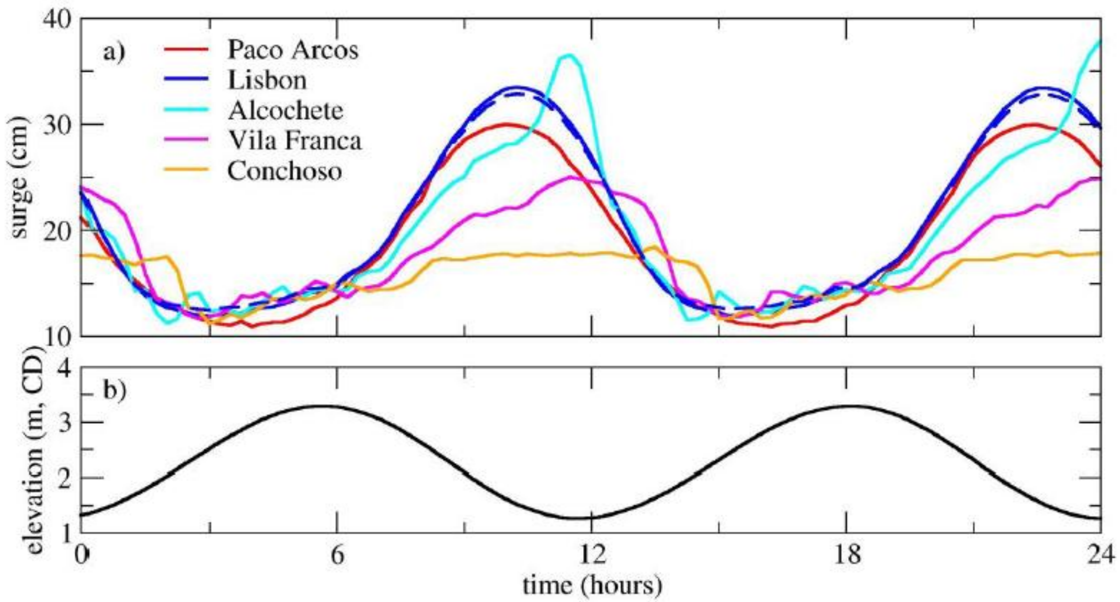


- Inside the Tagus Estuary, wave setup locally dominates the total surge (~0.5 m/ 1.0 m)

- Wave setup locally grows inside the Tagus Estuary by up to 20 % compared to the entrance.

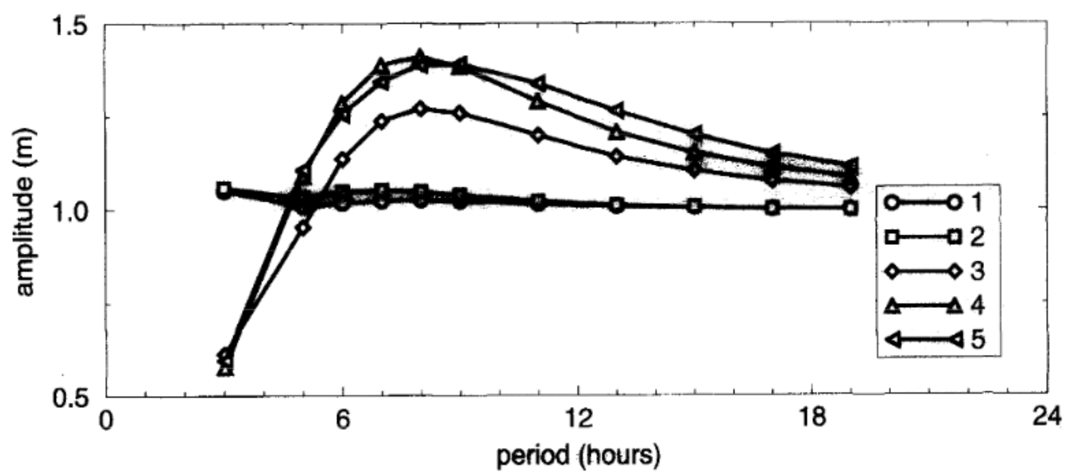
Surge associated with the 1941 storm in the Tagus Estuary



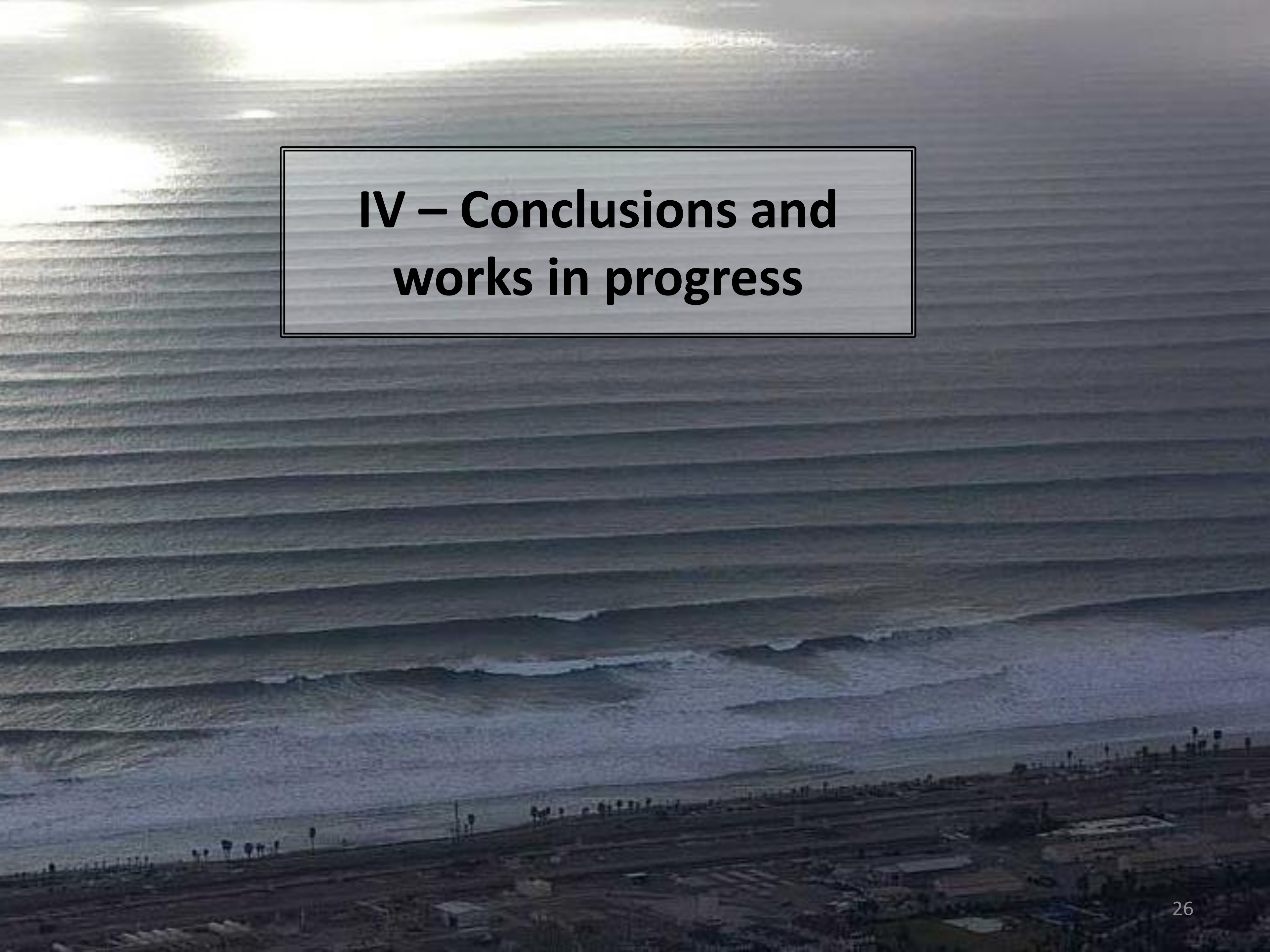


➢ Wave setup is tidally-modulated, with a maximum ~1-2 hour before low tide.

➢ According to Fortunato et al. (1999), semi-diurnal waves are amplified by 25% inside the estuary by resonance.



➢ All these findings are based on the model, we need observations under storm waves!



IV – Conclusions and works in progress

IV – Conclusions and works in progress

- Several studies reported a severe underestimation of wave setup along the shoreline using LHS64, we propose that this problem is mostly due to: (1) inadequate wave breaking parameterizations and (2) neglecting the wave-driven circulation.

- We are verifying this hypothesis using the data of Apotsos (Duck Beach) with a more complete model, including a representation of the roller.

- Wave setup can extend outside surfzones and develop at the scale of large estuaries and lagoons.

Thank you for your attention!