

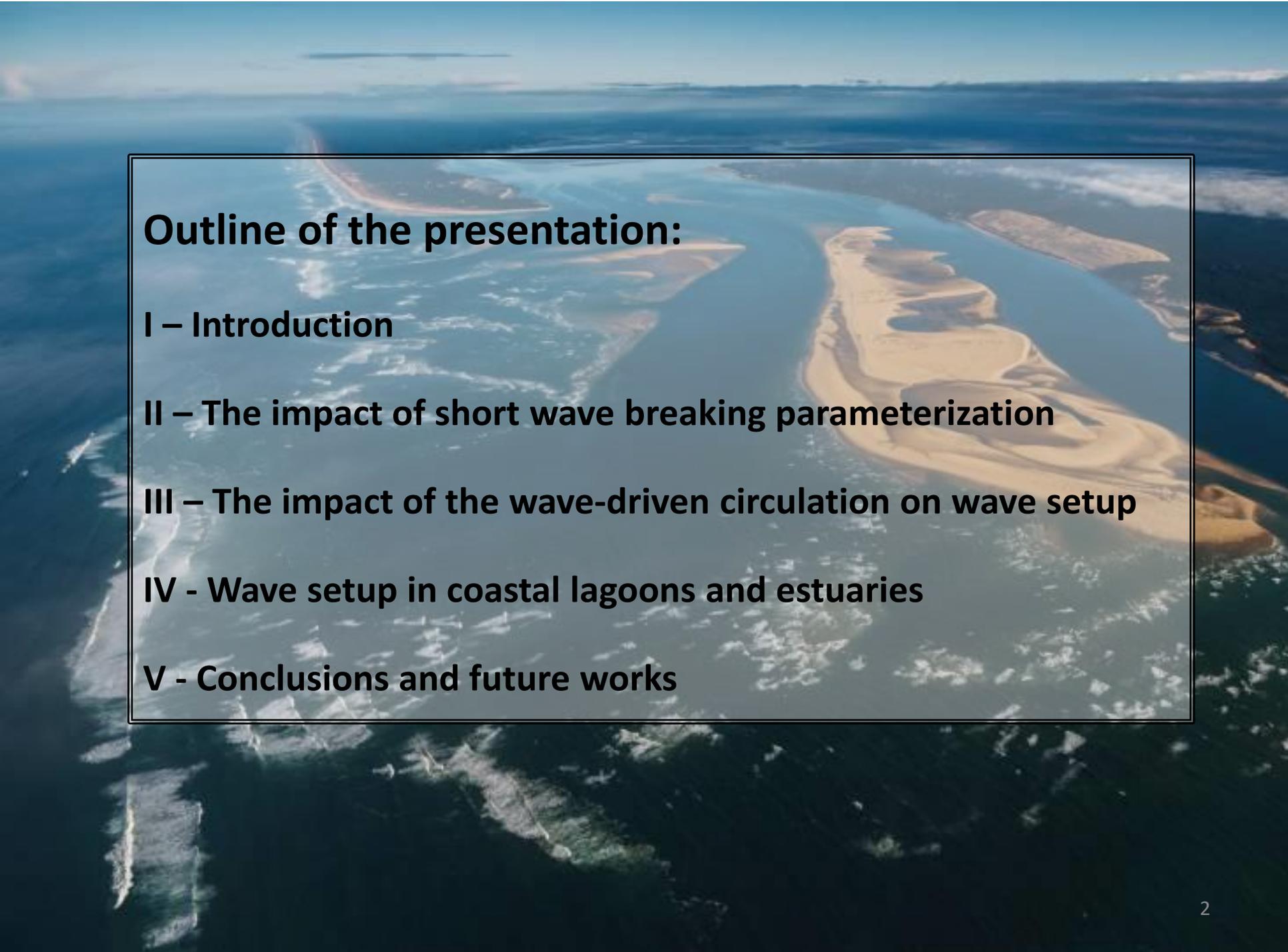
# ***Modelling wave setup with SCHISM: from the surfzone to large estuaries***



***Xavier Bertin, Laura Lavaud, Marc Pezerat and Kévin Martins***

***UMR LIENSs, CNRS-University of La Rochelle, France***

***E-mail: [xbertin@univ-lr.fr](mailto:xbertin@univ-lr.fr)***



## **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**



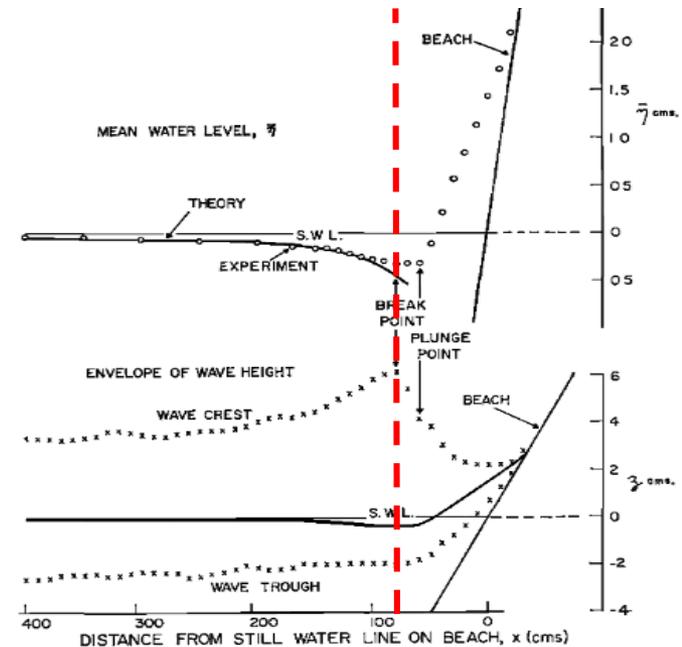
# I - Introduction

# 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:

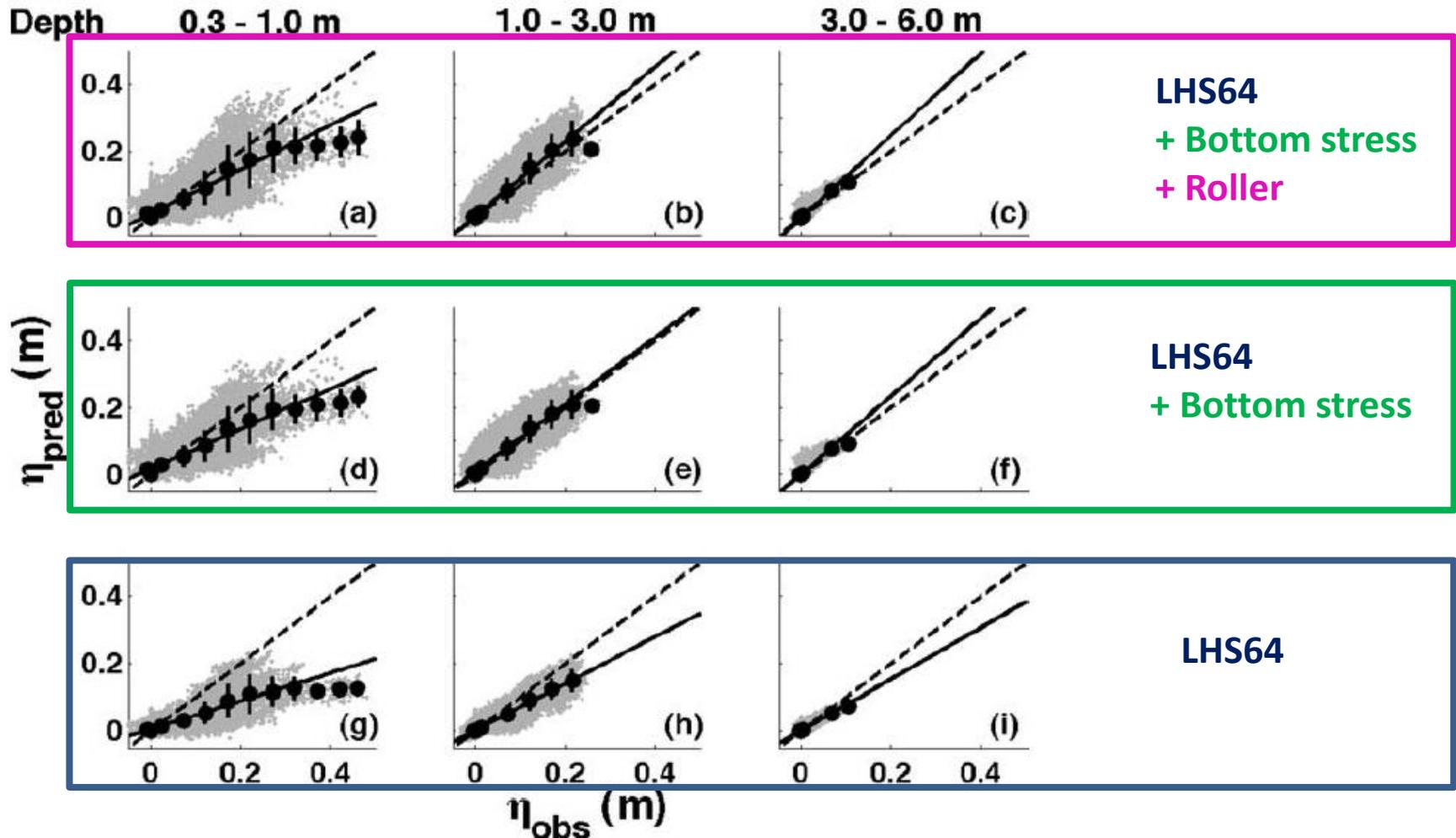
$$\frac{1}{\rho(h+\xi)} \frac{\partial S_{xx}}{\partial x} = -g \frac{\partial \xi}{\partial x} \quad \text{where} \quad S_{xx} = \frac{E}{2} \left( 2 \frac{C_g}{C} (\cos^2 \alpha + 1) - 1 \right) \quad \sim \frac{3E}{2}$$

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



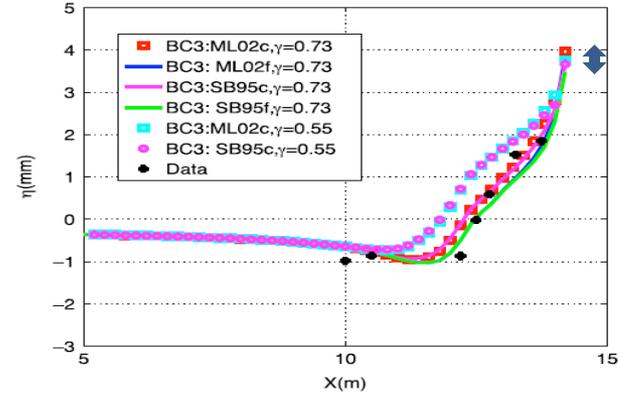
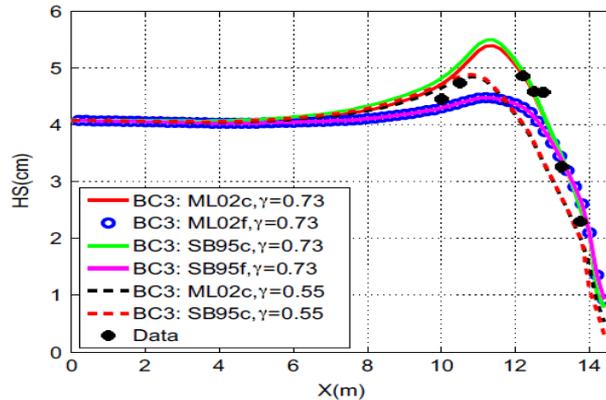
# The “setup enigma”

- ✓ 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:



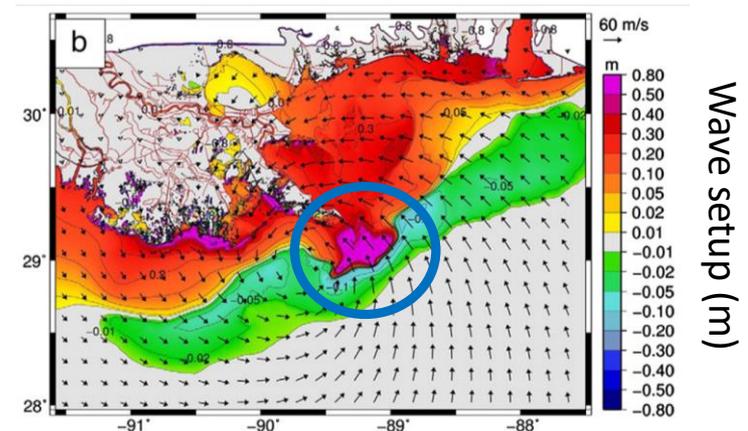
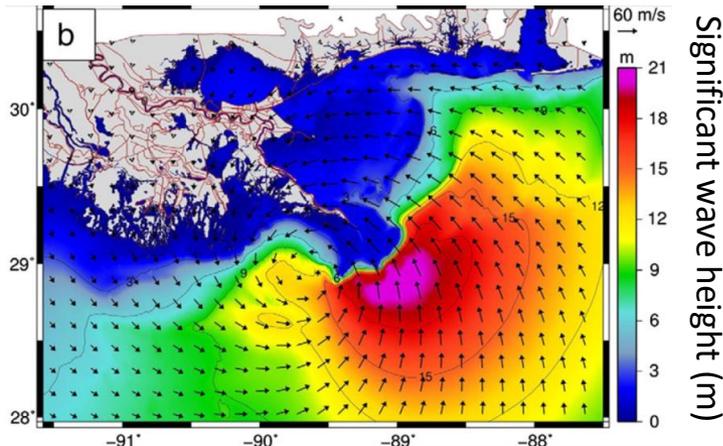
# The “setup enigma”

- ✓ 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):

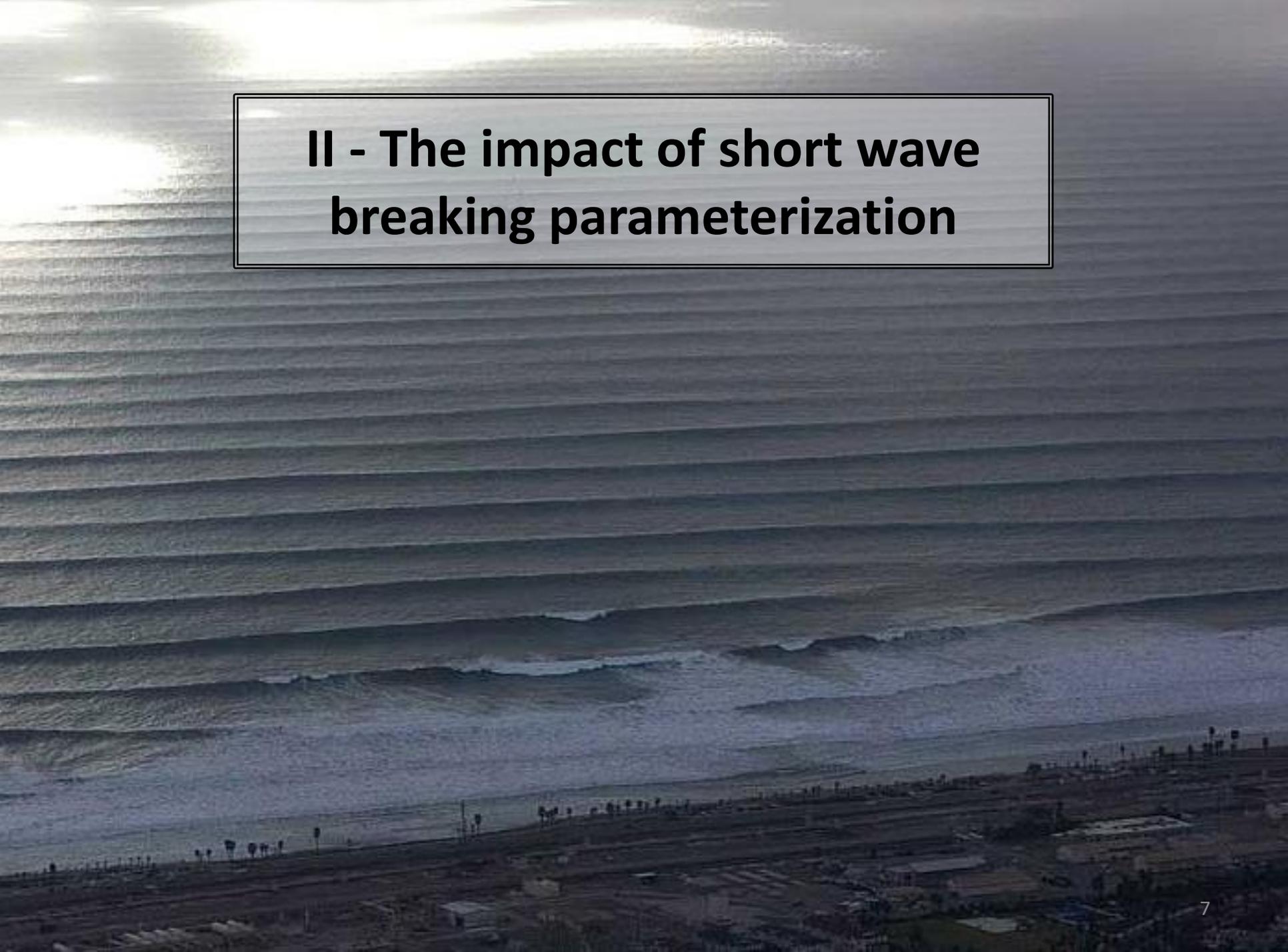


- Parameterizations for mixing and bottom stress can impact wave setup by  $O(10\%)$

- ✓ 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

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

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

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

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

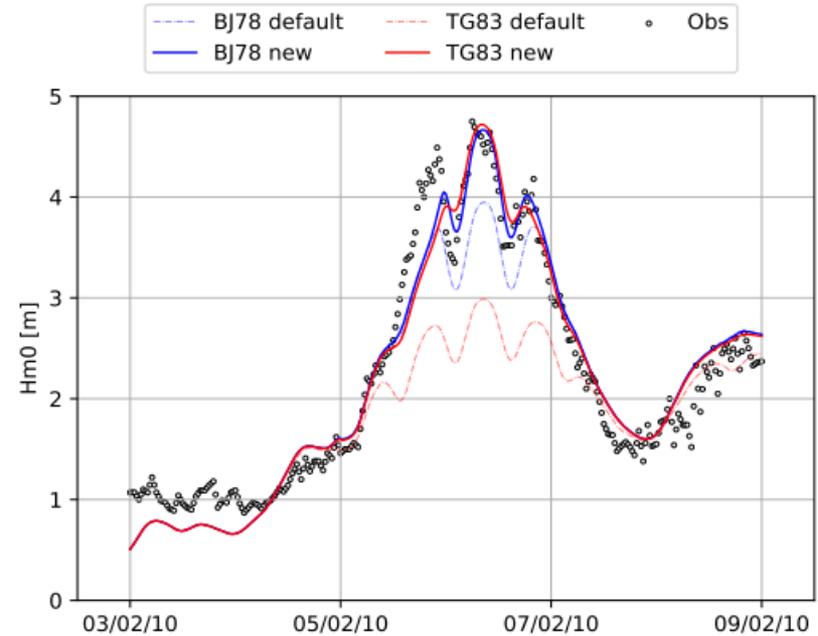
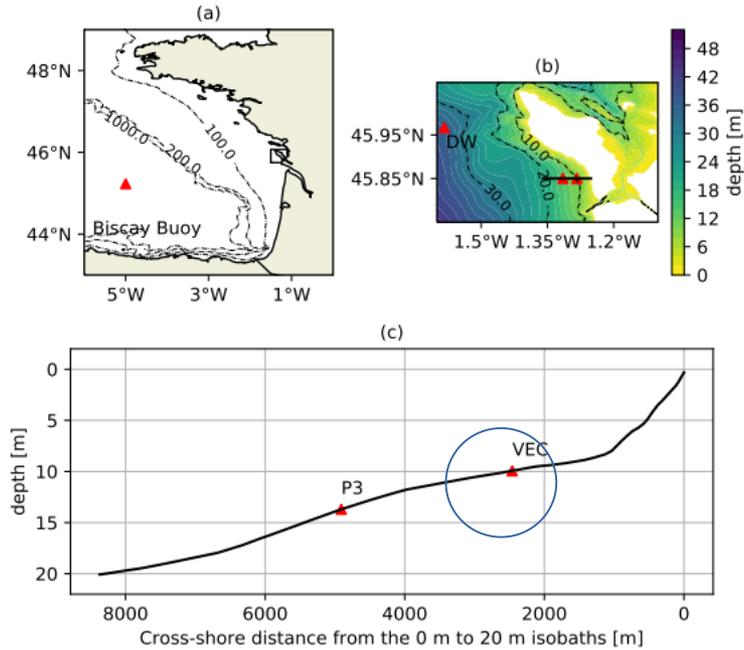
$$\alpha_{\text{default}} \approx 1 \quad (\text{tuning parameter})$$

$$\alpha_{\text{new}} \approx 40 \cdot \tan \beta$$

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



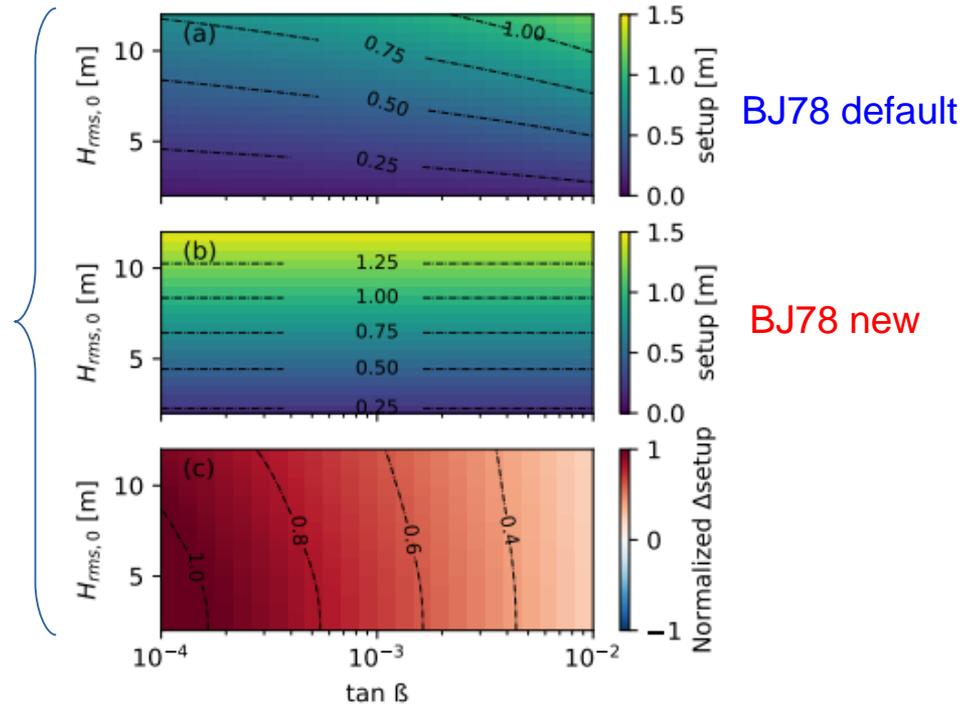
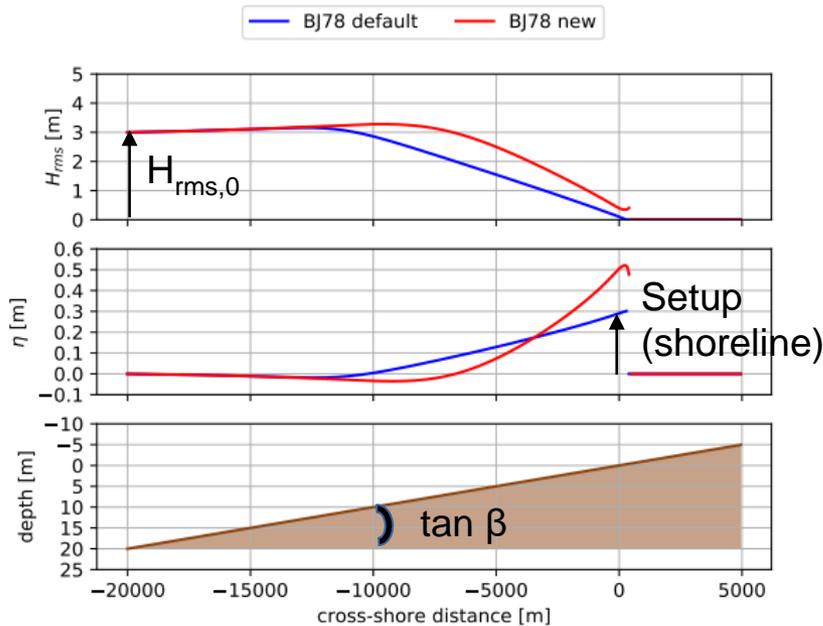
Over-dissipation of wave energy in intermediate depth

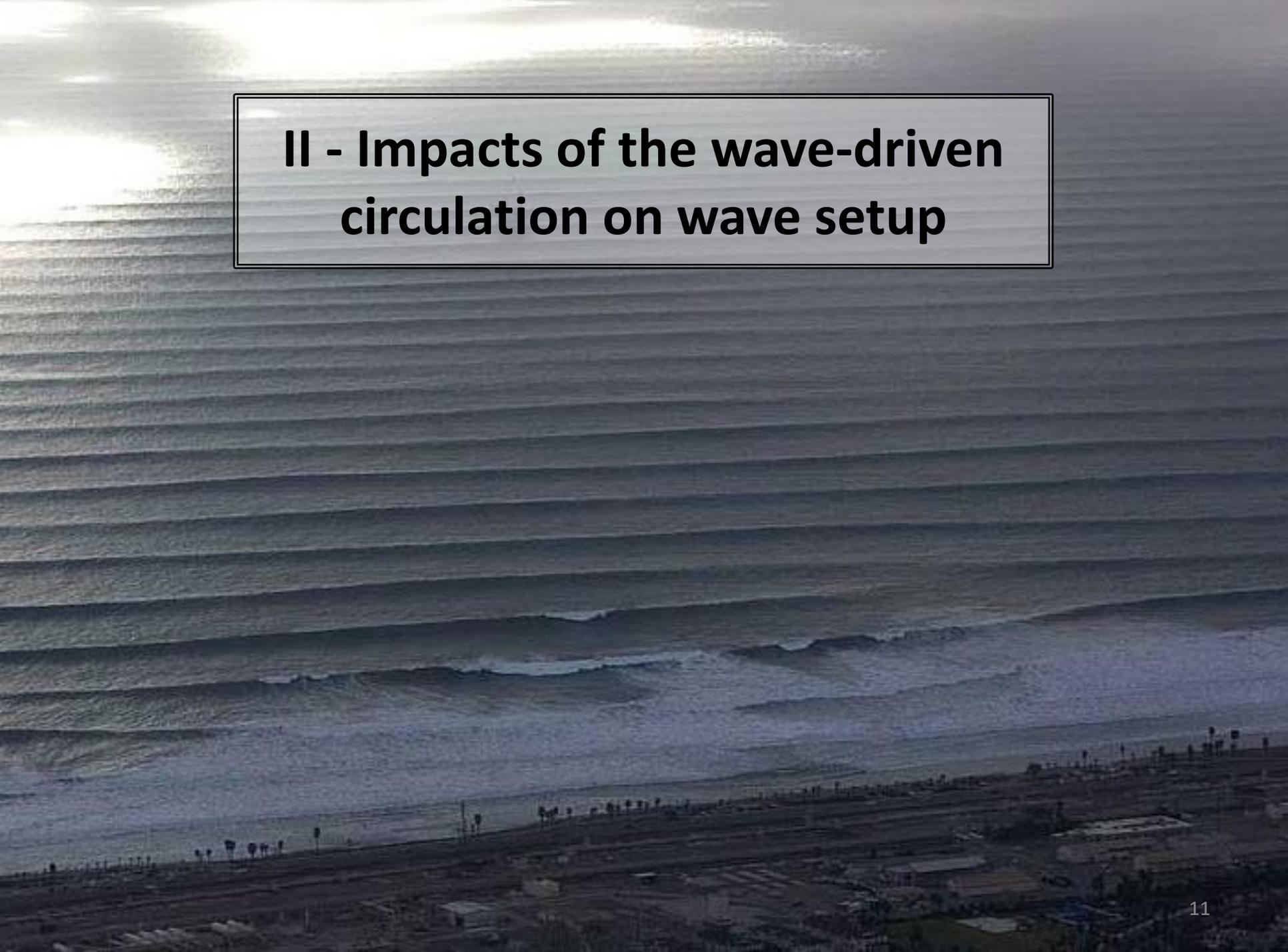


Underestimation of  $H_{m0}$  in the nearshore area

# What implications on the wave setup ?

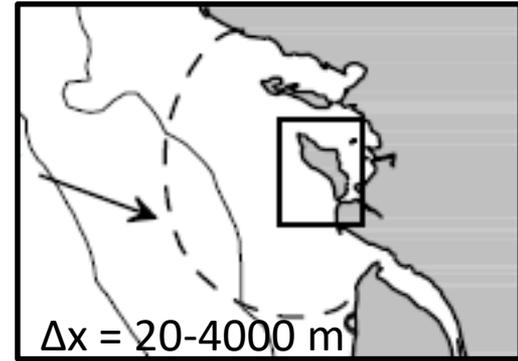
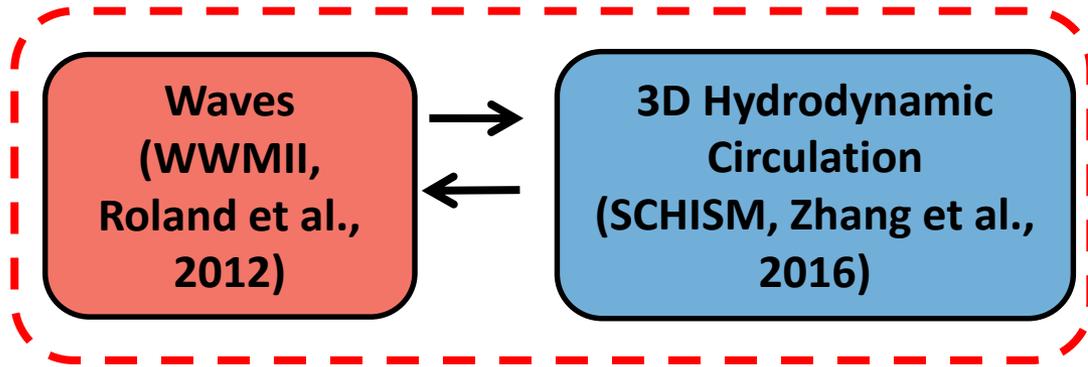
➡ An early wave energy dissipation in intermediate depth should result in weaker wave forces, yielding an underestimation of wave setup near the shoreline



An aerial photograph of a coastline. The top half of the image shows the ocean with waves breaking onto a sandy beach. The bottom half shows a coastal town with buildings, roads, and palm trees. The sky is overcast with grey clouds. A white rectangular box with a black border is centered in the upper portion of the image, containing the title text.

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

# The modelling system SCHISM



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

$$\frac{\partial \eta}{\partial t} + \nabla \int_{-h}^{\eta} (\hat{U} + U_s) dz = 0 \quad \nabla \cdot \hat{U} = 0$$

$$\frac{D\hat{u}}{Dt} = f\hat{v} - g\frac{\partial \eta}{\partial x} + \underbrace{\frac{\partial}{\partial z} \left( \nu \frac{\partial \hat{u}}{\partial z} \right)}_{\text{Vertical mixing accounting for waves}} + \underbrace{\left( f_c + \frac{\partial \hat{v}}{\partial x} + \frac{\partial \hat{u}}{\partial y} \right) v_s + w_s \frac{\partial \hat{u}}{\partial z}}_{\text{Vortex force}} - \underbrace{\frac{\partial J}{\partial x}}_{\text{Mean wave pressure}} + \underbrace{\hat{F}_{dx} + \hat{F}_{bx}}_{\text{Wave dissipation terms}}$$

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

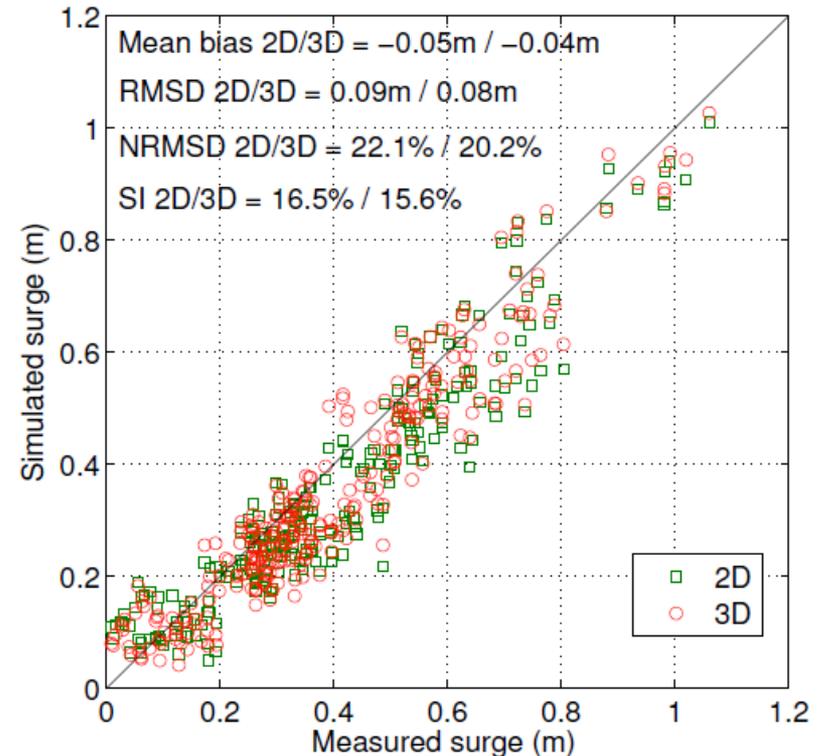
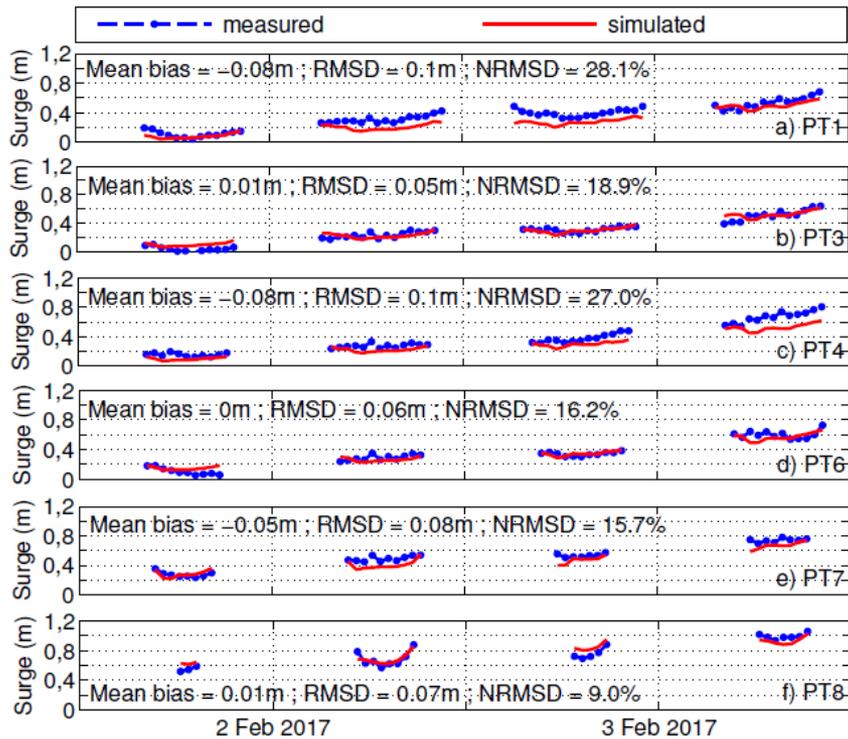
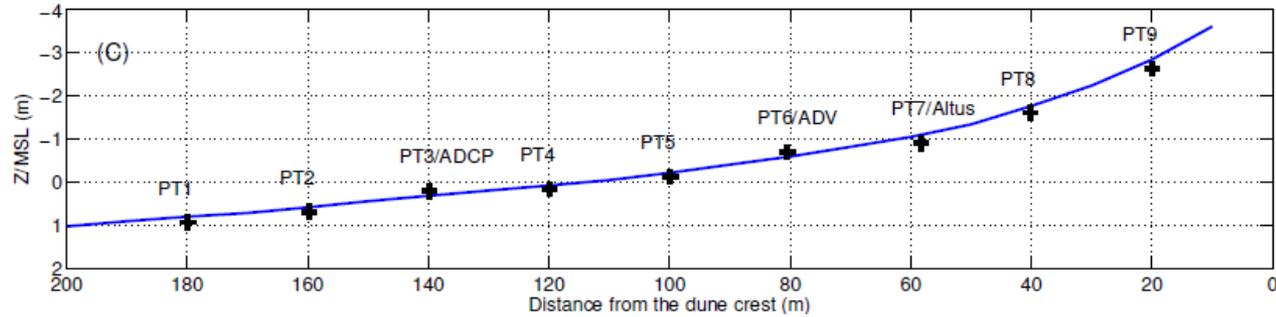
Vertical mixing  
accounting for waves

Vortex force

Mean wave  
pressure

Wave dissipation  
terms

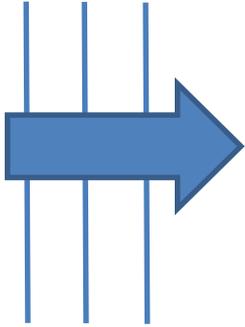
# Wave setup predictions (Guérin et al., OM2018)



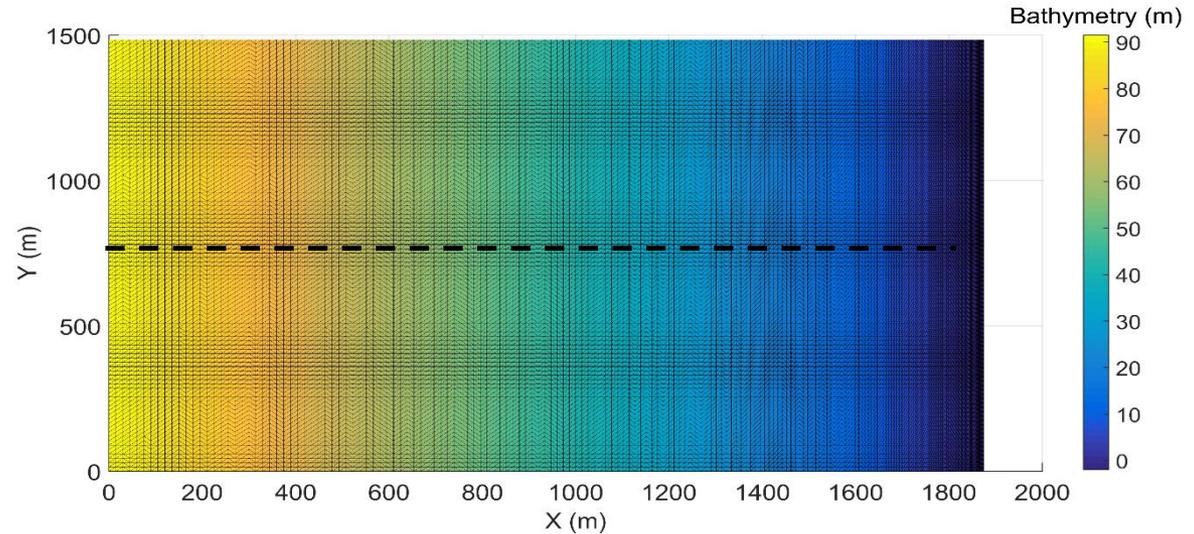
➤ Improvements with the 3D model are very limited: bottom slope too mild?

# Extention of this study to idealized beaches

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



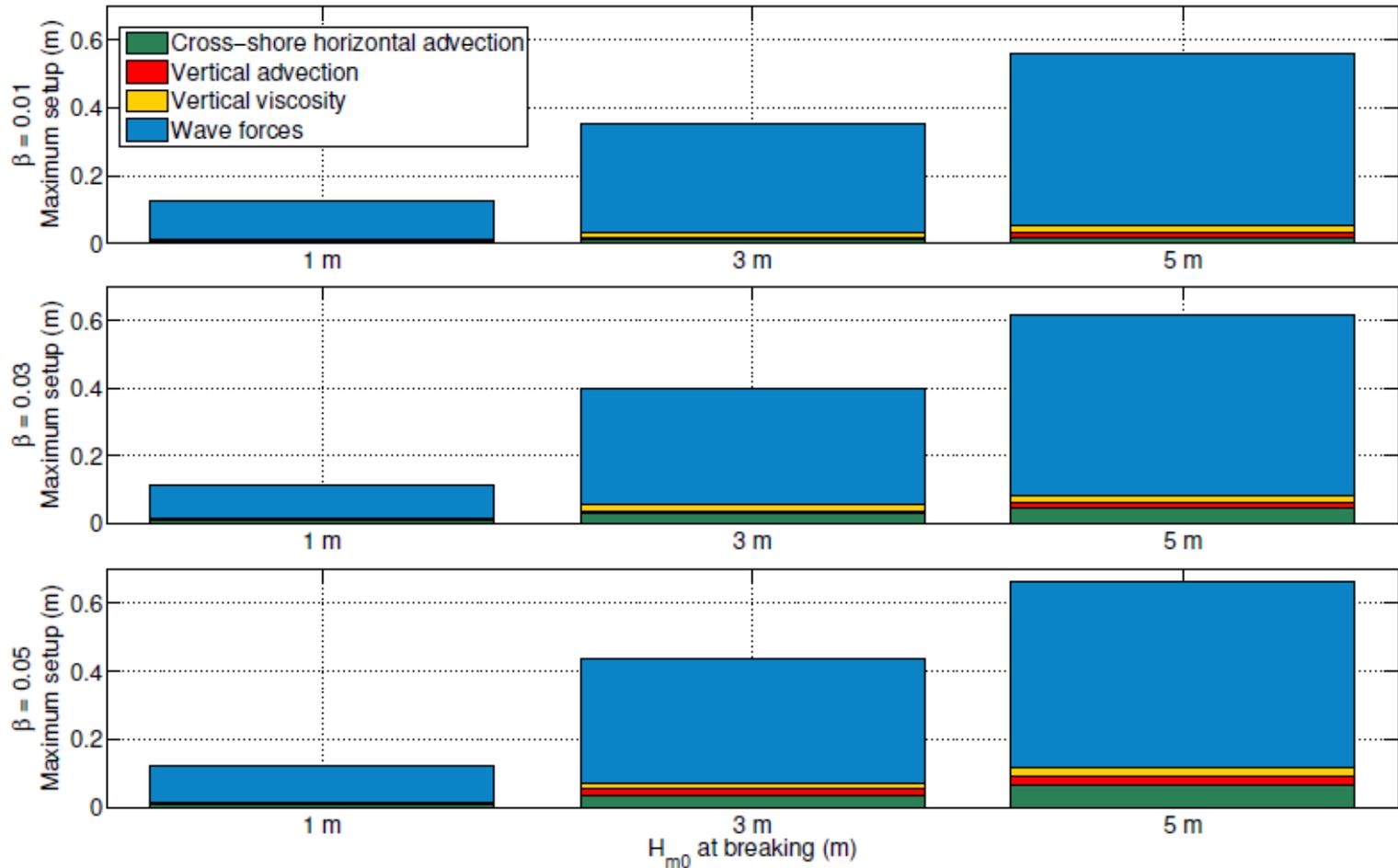
Uniform beach of constant slope = 0.01, 0.03 and 0.05



- ✓ 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



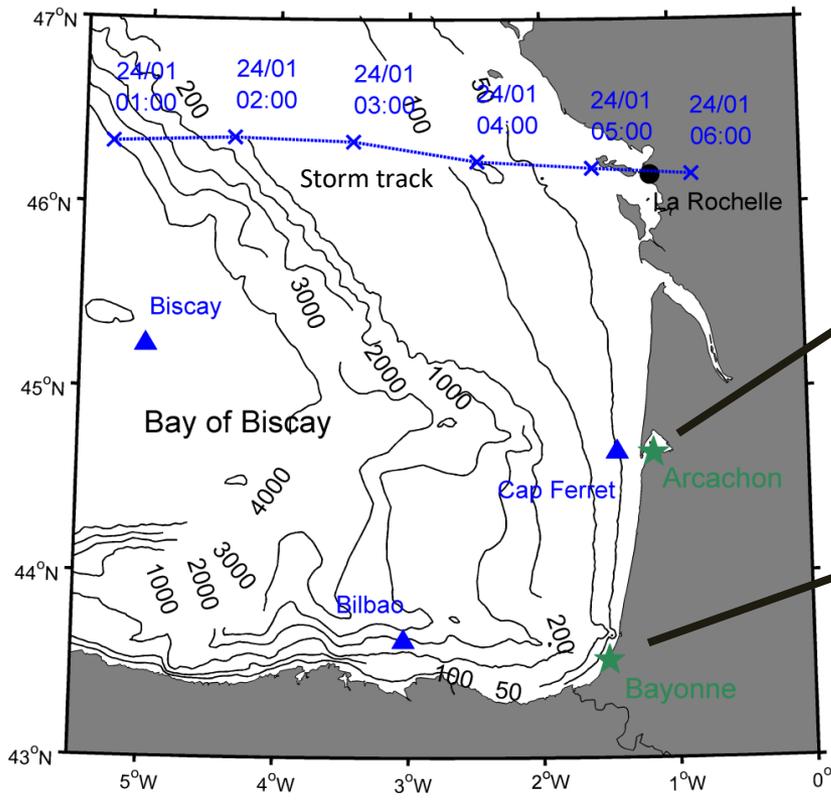
- For a given  $H_s$ , wave setup increases with the beach slope due to a more important contribution of the depth-varying wave-induced circulation.
- For a slope of 0.1, wave setup is increased by 30 %: could this explain the « setup enigma »?
- We are verifying this hypothesis using the data of Apotsos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

An aerial photograph of a coastal lagoon and estuary system. A prominent, elongated sandbar runs diagonally across the center of the image, separating the lagoon from the open ocean. The water in the lagoon is a light, milky blue, while the ocean water is a deeper, darker blue. The sandbar shows intricate patterns of sand dunes and channels. The sky is clear and blue, and the horizon is visible in the distance.

### **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., OM2020)

➔ 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).



## Arcachon Lagoon

- Max. sustained wind speed: 35 m.s<sup>-1</sup>
- Peak storm surge: **1.70 m**



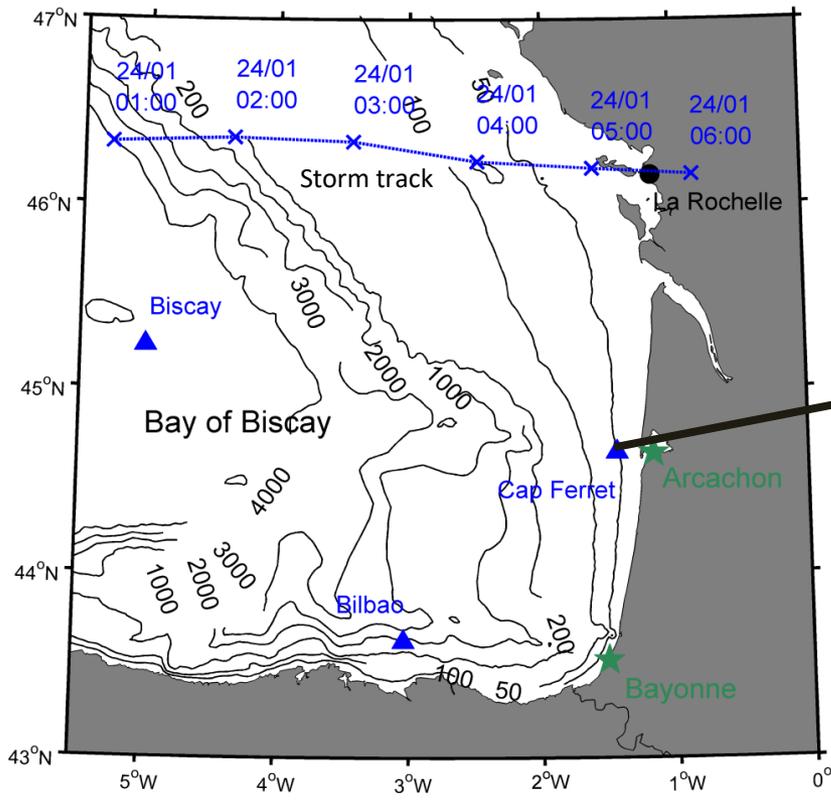
## Adour Estuary (Bayonne)

- Max. sustained wind speed: 21 m.s<sup>-1</sup>
- Peak storm surge: **1.10 m**

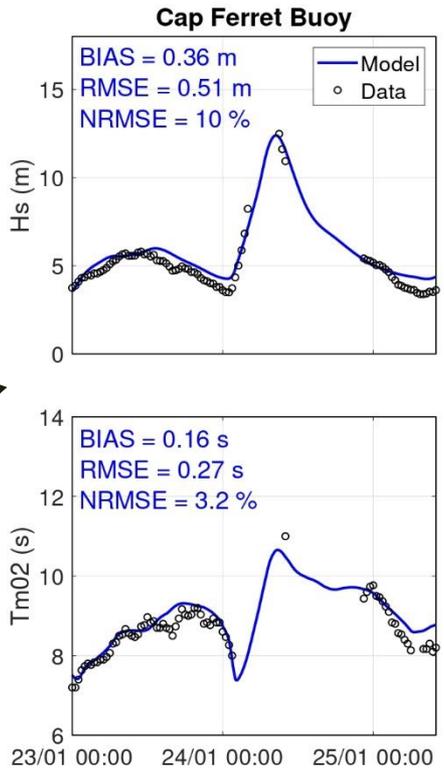
Study area: wave buoys (blue triangles), tide gauges (green stars)

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

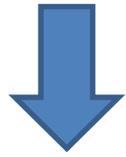
➔ The extra-tropical storm Klaus made landfall in the southern part of the Bay of Biscay on the 24/01/2009 (min. atm. pressure of 965 hPa).



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



- 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.

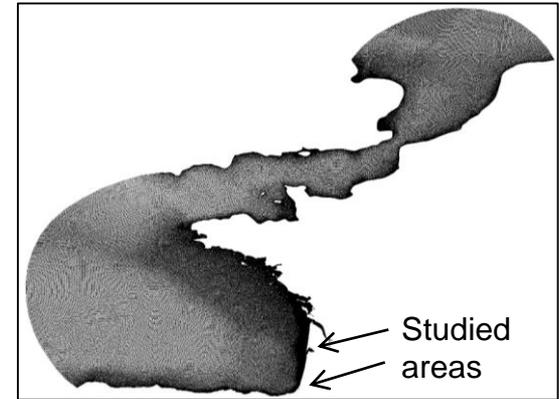


Relevant case study to investigate the contribution of short-wave breaking to storm surges.

# The contribution of short-wave breaking to storm surges

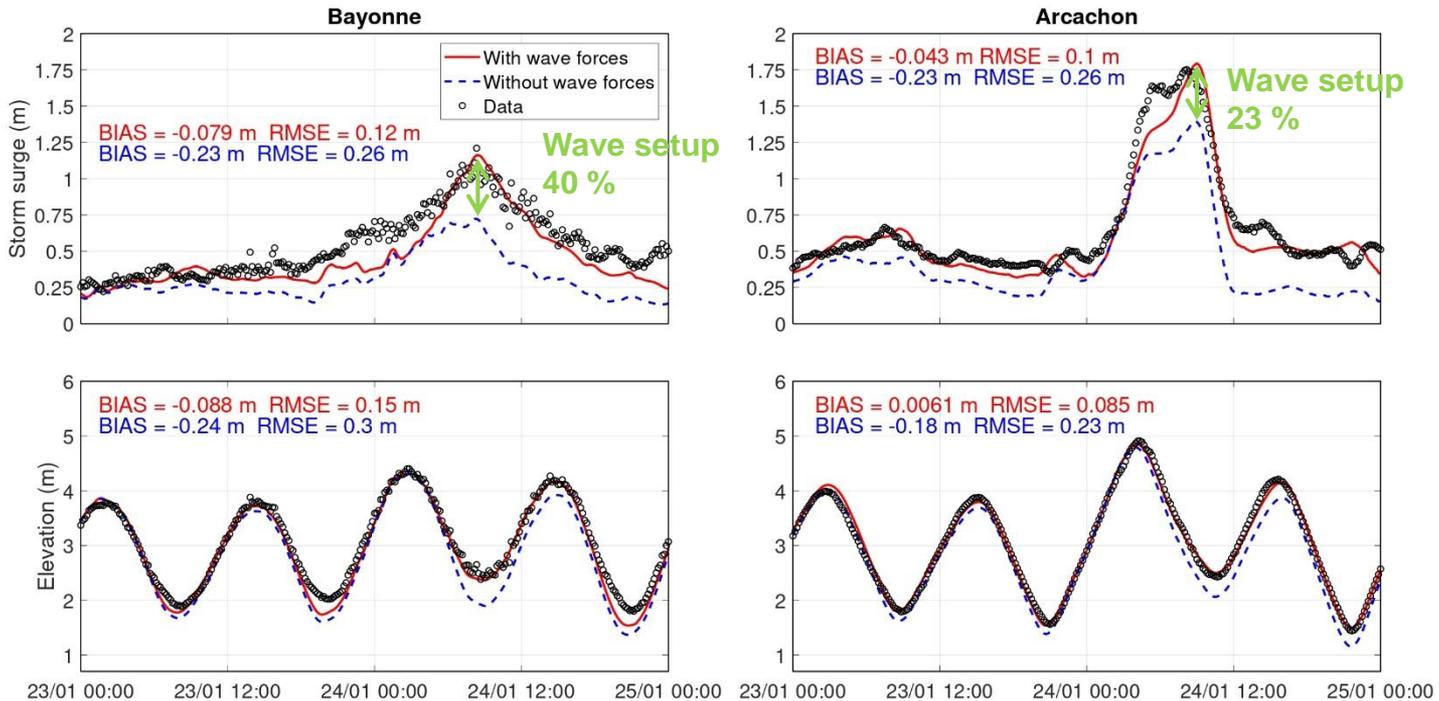
## Modelling system SCHISM:

- 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

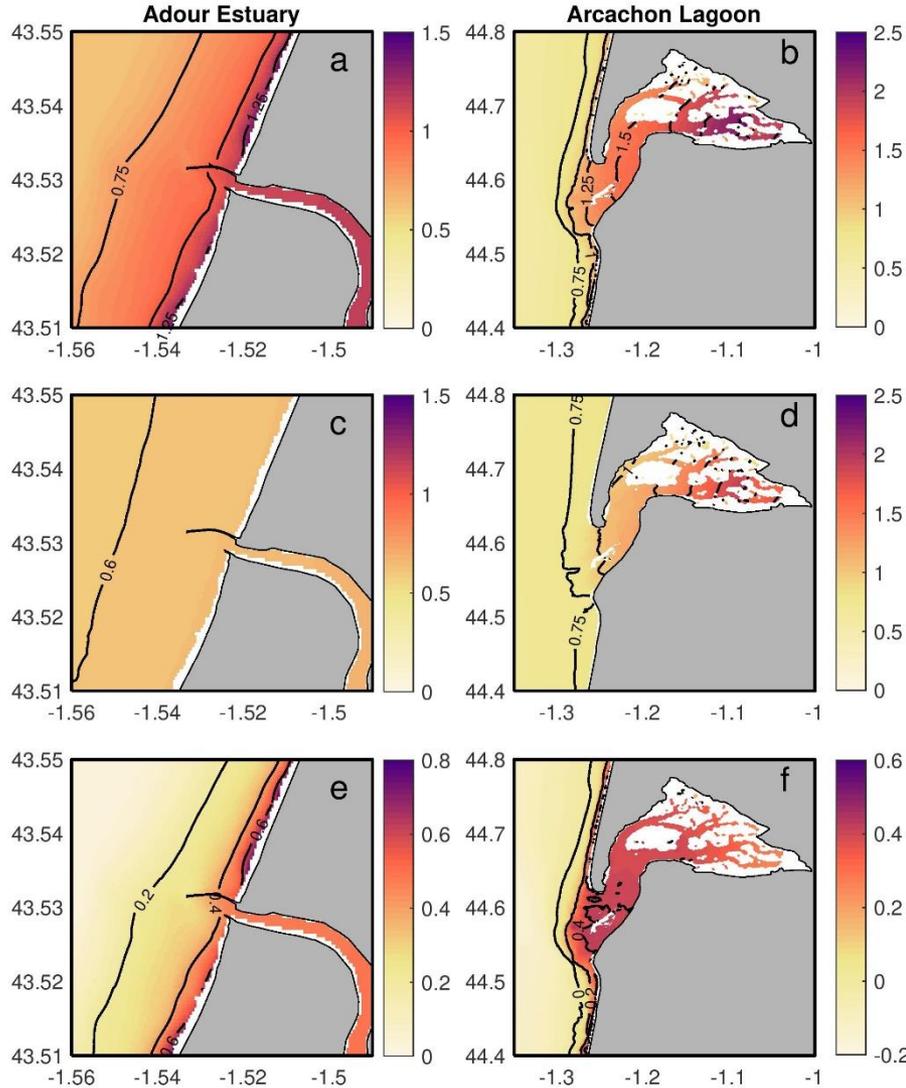
## Storm surge predictions:



Storm surge predictions improved by **50 to 60 %** when **accounted for wave forces**.

# The contribution of short-wave breaking to storm surges

Storm surge predictions:



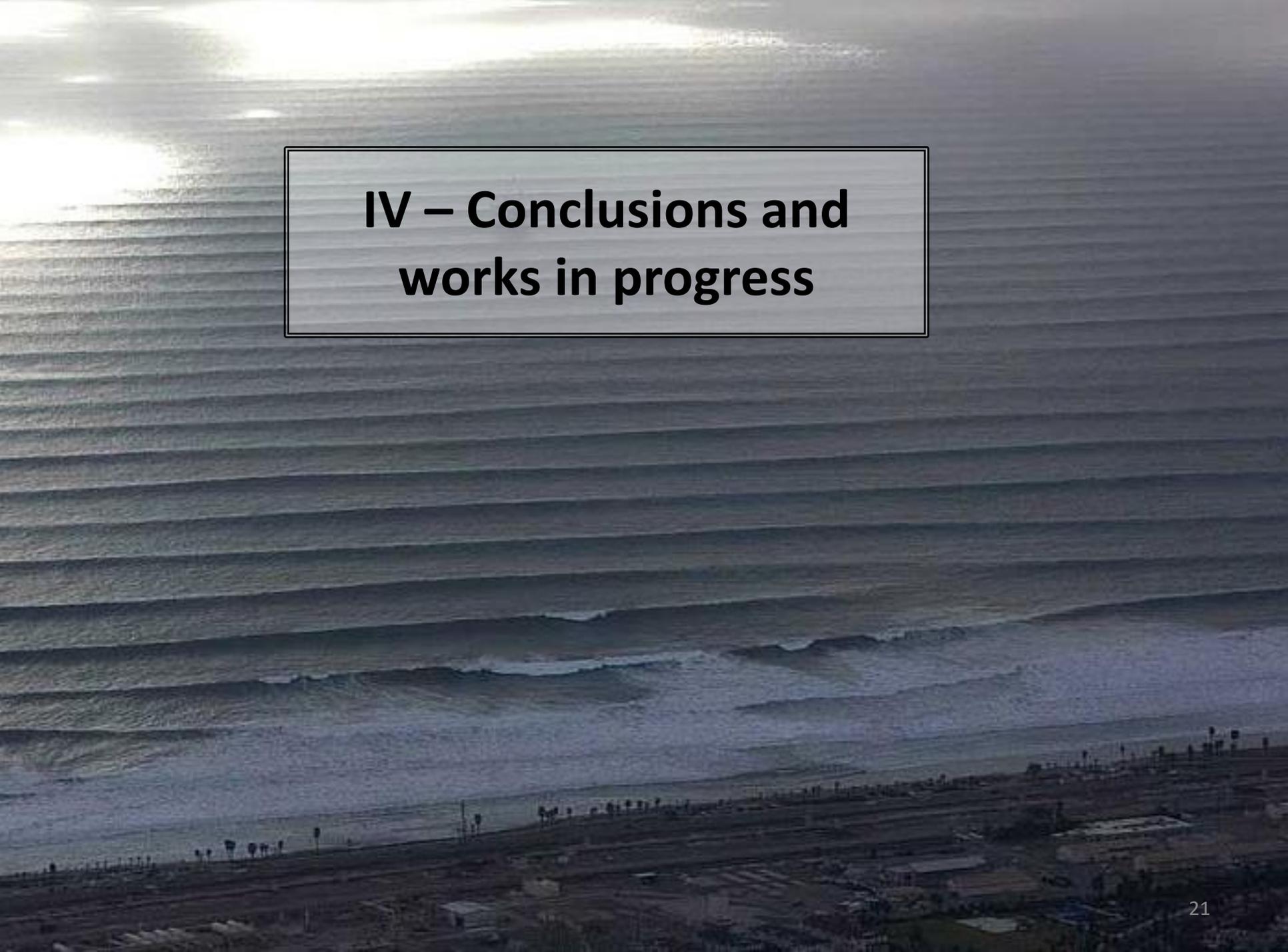
With wave forces

Without wave forces

Difference



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

An aerial photograph of a coastline. The top half of the image shows the ocean with waves breaking onto a sandy beach. The bottom half shows a coastal town with buildings, roads, and palm trees. The sky is overcast with grey clouds. A white rectangular box with a black border is centered in the upper half of the image, containing the text 'IV – Conclusions and works in progress'.

## **IV – Conclusions and works in progress**

## IV – Conclusions and works in progress

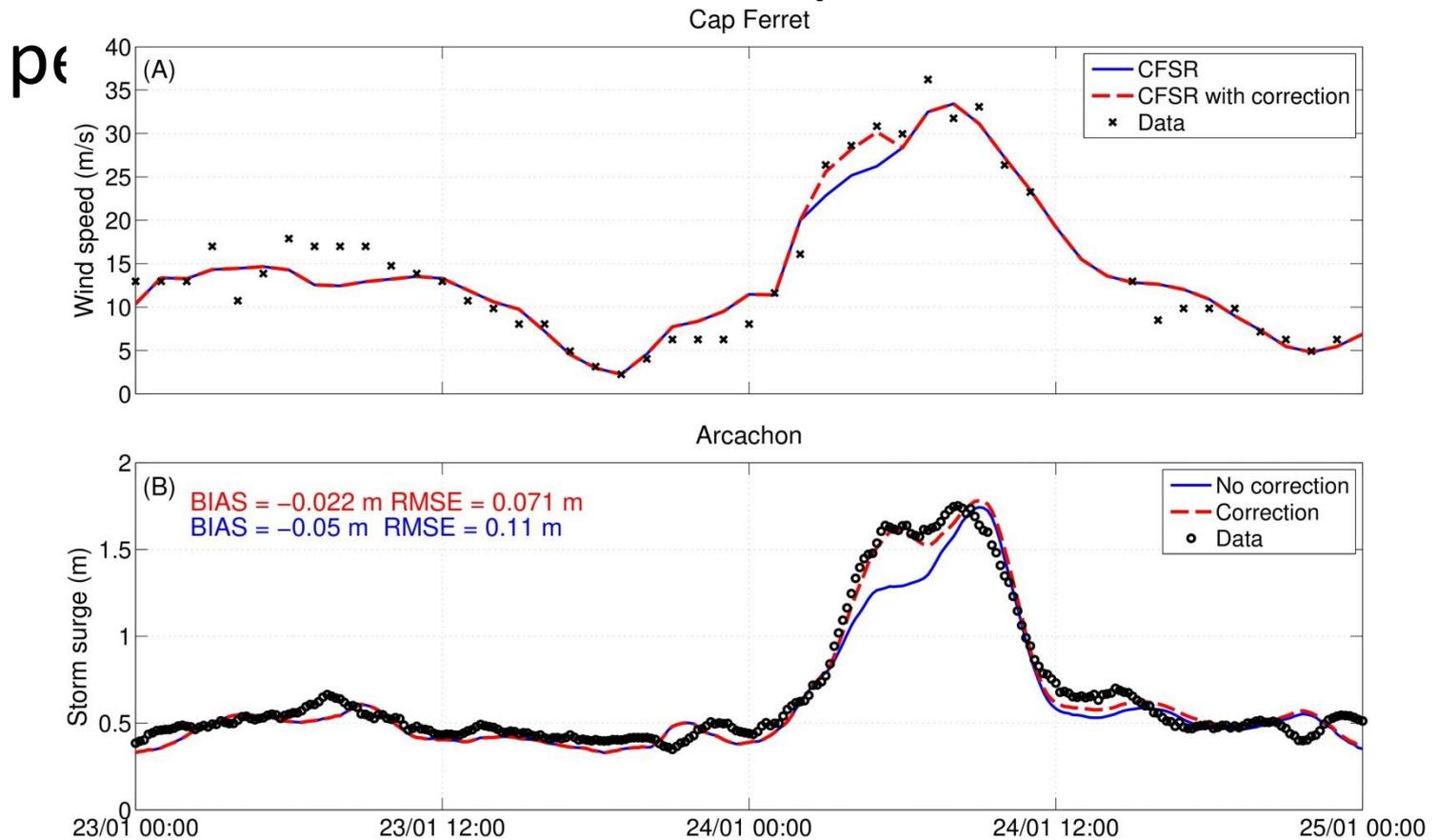
- Several studies reported a severe underestimation of wave setup along the shoreline using LHS64, we propose that this problem is mostly due to: (1) inadequate wave breaking parameterizations and (2) neglecting the wave-driven circulation.
- We are verifying this hypothesis using the data of Apotsos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

An aerial photograph of a coastline. The top half of the image shows the ocean with waves breaking onto a sandy beach. The bottom half shows a coastal town with buildings, roads, and palm trees. The sky is overcast with soft light.

**Thank you for your attention!**

# Supplementary material

## Correction of the wind speed before the storm



# Supplementary material

## ☐ Sensitivity of the wave setup to the grid resolution

