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

Xavier Bertin, Laura Lavaud, Marc Pezerat and Kévin Martins

UMR LIENSs, CNRS-University of La Rochelle, France

E-mail: 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:

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

✓ 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:

- Depth: 0.3 - 1.0 m
- 1.0 - 3.0 m
- 3.0 - 6.0 m

![Graphs showing comparison between observed and predicted wave setup for different depth ranges.](image)
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

\[ \frac{\partial N}{\partial t} + \nabla_x (x \cdot N) + \frac{\partial \sigma N}{\partial \sigma} + \frac{\partial \theta N}{\partial \theta} = S_{\text{atm}} + S_{Ss} + S_{nl4} + S_{nl3} + S_{bf} + S_{db} \]

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

- The depth-induced breaking source term \( S_{db} \)

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

\( \alpha_{\text{default}} \approx 1 \) (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.
II - Impacts of the wave-driven circulation on wave setup
The field campaign of February 2017

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

(Guérin et al., OM2018)
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)

\[
\frac{\partial \eta}{\partial t} + \nabla \int_{-h}^{\eta} \left( \hat{U} + U_s \right) \, dz = 0 \quad \nabla \cdot \hat{U} = 0
\]

\[
\frac{D_{\hat{u}}}{D_t} = f \hat{u} - g \frac{\partial \eta}{\partial x} + \frac{\partial}{\partial z} \left( \nu \frac{\partial \hat{u}}{\partial z} \right) + \left( f_c + \frac{\partial \hat{v}}{\partial x} + \frac{\partial \hat{u}}{\partial y} \right) u_s + w_s \frac{\partial \hat{u}}{\partial z} - \frac{\partial J}{\partial x} + \hat{F}_{dx} + \hat{F}_{bx}
\]

\[
\frac{D_{\hat{v}}}{D_t} = -f \hat{v} - g \frac{\partial \eta}{\partial y} + \frac{\partial}{\partial z} \left( \nu \frac{\partial \hat{v}}{\partial z} \right) - \left( f_c + \frac{\partial \hat{v}}{\partial x} + \frac{\partial \hat{u}}{\partial y} \right) u_s + w_s \frac{\partial \hat{v}}{\partial z} - \frac{\partial J}{\partial y} + \hat{F}_{dy} + \hat{F}_{by}
\]

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 Hs = 1, 3 and 5 m

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

\[
\frac{g}{h} \frac{\partial \eta}{\partial x} = \frac{1}{h} \int_{-d}^{\eta} \left( -\hat{u} \frac{\partial \hat{u}}{\partial x} - \hat{v} \frac{\partial \hat{u}}{\partial y} - \hat{w} \frac{\partial \hat{u}}{\partial z} + \frac{\partial}{\partial z} \left( \nu \frac{\partial \hat{u}}{\partial z} \right) + F_{wave,x} \right) dz
\]

- Horizontal advection
- Vertical advection
- Vertical mixing
- Wave forces
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.
III - Wave setup in coastal lagoons and estuaries
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\(^{-1}\)
- Peak storm surge: 1.70 m

**Adour Estuary (Bayonne)**
- Max. sustained wind speed: 21 m.s\(^{-1}\)
- Peak storm surge: 1.10 m

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

Significant wave height ($H_s$) of 13 m with a peak period ($T_p$) 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

Storm surge predictions:

Storm surge predictions strongly improved when accounted for wave forces.
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 $H_s \sim 13$ 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
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➢ 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!