CROCO for wave-resolving nearshore dynamics

CROCO dev, 2023

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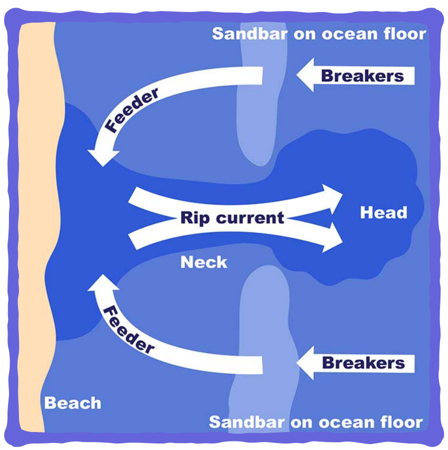
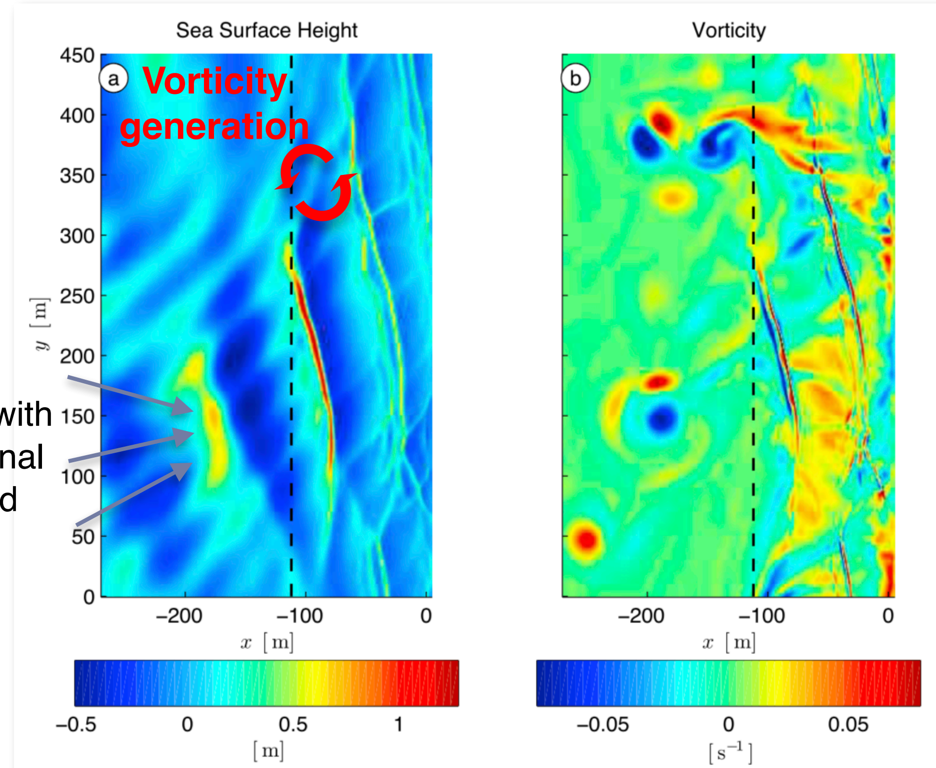
Surfzone eddies are largely due to individual short-crested waves (Peregrine, 1998)

Swimmers caught in a rip current at Haeundae Beach,



Waves with directional spread



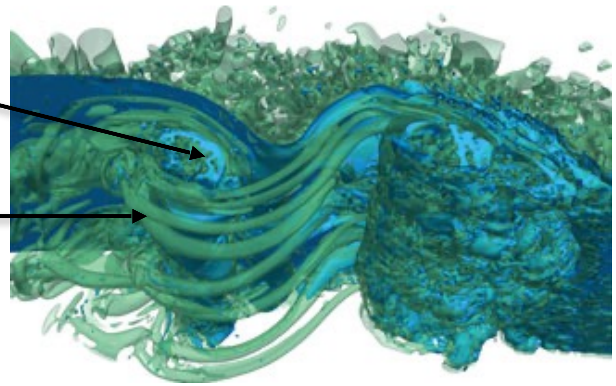
2D wave-resolving Boussinesq model (Feddersen et al., 2011)

3D wave-resolving models

- VOF/SPH LES models: “Direct” turbulence

Roller vortices

Rib vortices

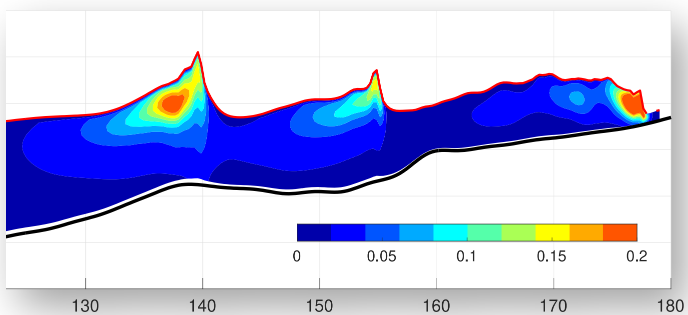


Time scale < wave period

(Lubin & Glockner, 2015)

- Free-surface RANS models: “Instabilities of the undertow”

CROCO
NHWAVE
SWASH

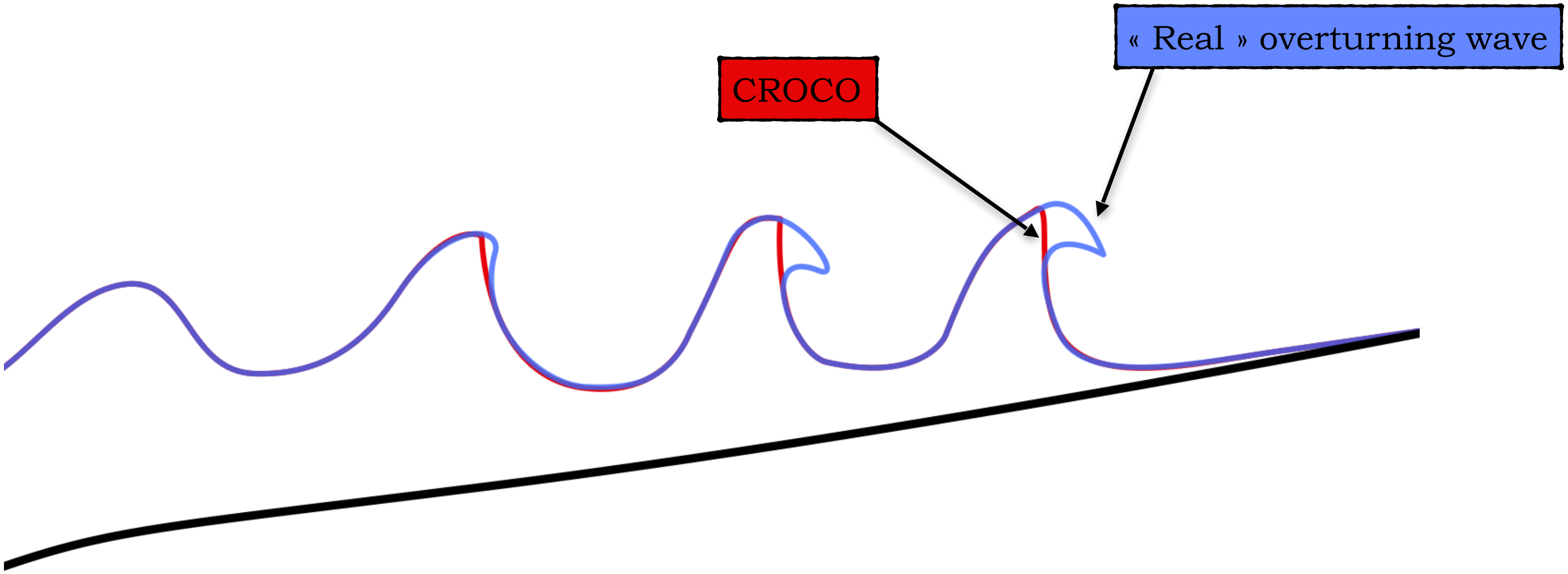


(Marchesiello et al., 2021)

Time scale > wave period

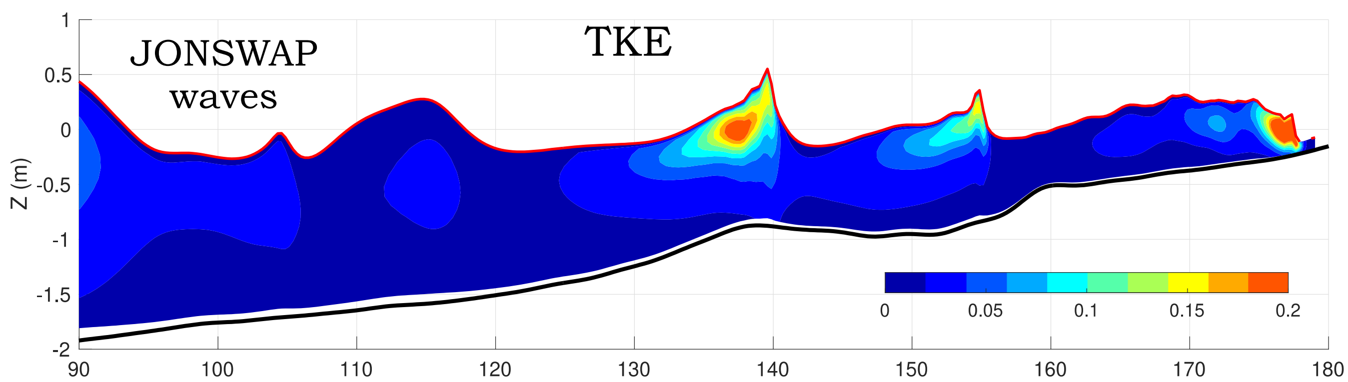
Breaking waves are treated as shocks

How are breaking waves treated in CROCO



- ✓ Breaking waves are treated as **bores** or shocks with a **shock-capturing scheme** (WENO5)… see Bonneton JFM 2023
- ✓ When the wave is too steep, the model naturally transfers energy to the **mean currents** (about 90%) and to the **sub-grid turbulence** (via turbulence closure).

GLS subgrid scale turbulence



$$\nu_t \sim k^{\frac{1}{2}} l \sim kT \sim \frac{k}{\omega} \sim \frac{k^2}{\epsilon}$$

[m²/s]

k turbulent kinetic energy
l mixing length
T correlation time scale
ω frequency of turbulence decay (dissipation rate)
ϵ turbulence dissipation

Delta Flume (Deltares)

Validation with flume experiments

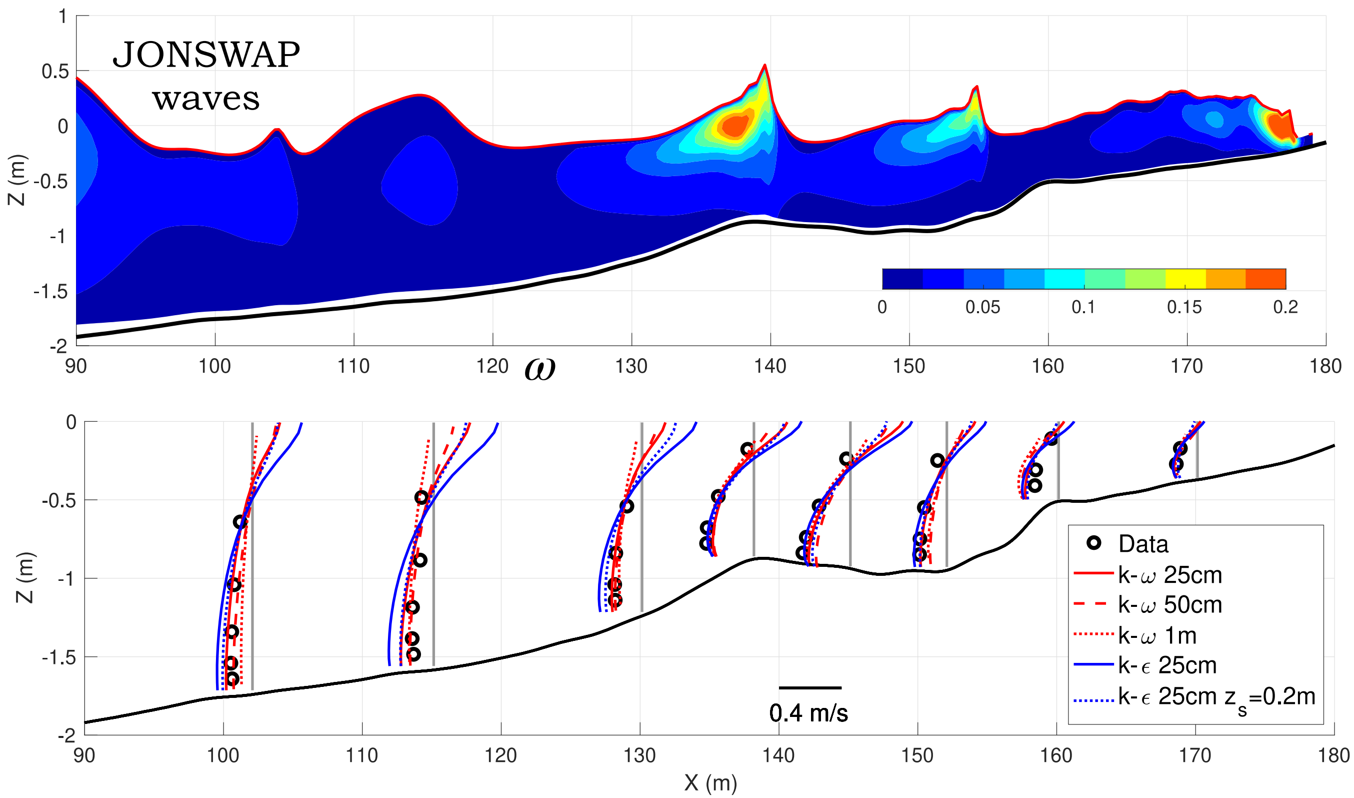
LIP-11D (1B) - Roelvink & Reniers (1995)

- Marchesiello et al. (2021, 2022)

TKE

Mean U

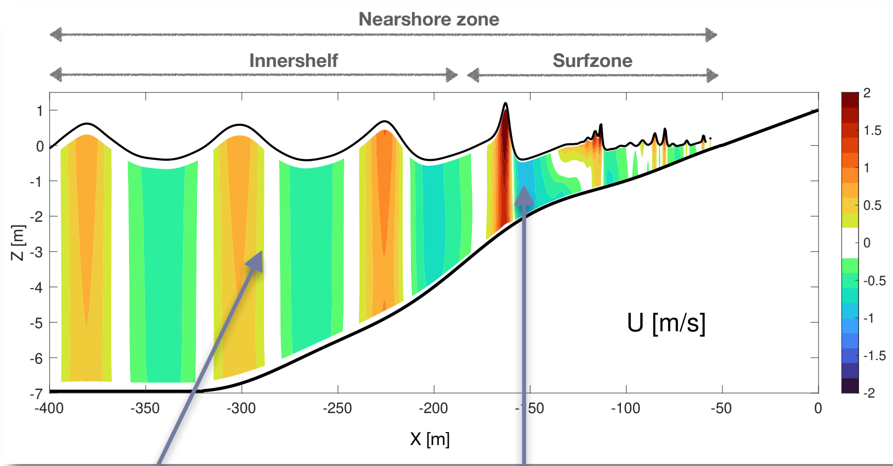
Test of resolution and turbulence model



Good performances of GLS two-equation turbulence models, especially k-ω

Stabilized GLS turbulence closure

(Marchesiello & Treillou 2023, Larsen & Fuhrman 2018, Mayer & Madsen 2000)



Near-potential flow (irrotational) region of non-breaking waves

$\frac{\Omega}{S}$ small

Breaking waves

$\frac{\Omega}{S}$ large

Linearized k-ω model

Shear production

Dissipation

Dissipation rate $\sim \frac{\epsilon}{k}$

$$
\begin{cases}
\dfrac{\partial k}{\partial t} = P - \epsilon \\[2ex]
\dfrac{\partial \omega}{\partial t} = \dfrac{\omega}{k}(c_{\omega 1} P - c_{\omega 2}\epsilon)
\end{cases}
$$

Shear Production $P = 2\nu_t S^2$

Eddy $\nu_t = \frac{\omega}{k} = c_\mu \frac{k^2}{\epsilon}$

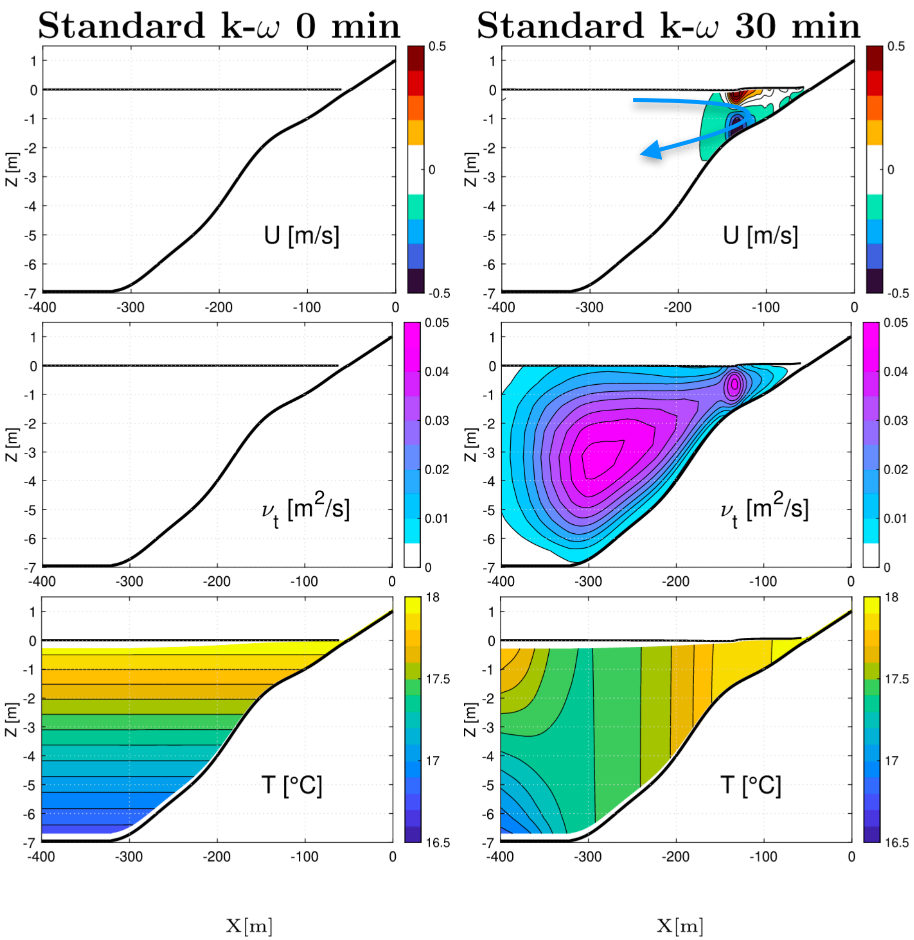
3D

Strain $S^2 = S_{ij}S_{ij} \quad S_{ij} = \frac{1}{2}(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i})$

Rotation rate (vorticity) $\Omega^2 = \Omega_{ij}\Omega_{ij} \quad \Omega_{ij} = \frac{1}{2}(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i})$

Stabilized GLS turbulence closure

(Marchesiello & Treillou 2023, Larsen & Fuhrman 2018)



Shear production

Dissipation

Dissipation rate

$$\begin{cases} \dfrac{\partial k}{\partial t} = P - \epsilon \\ \dfrac{\partial \omega}{\partial t} = \dfrac{\omega}{k}(c_{\omega 1} P - c_{\omega 2}\epsilon) \end{cases}$$

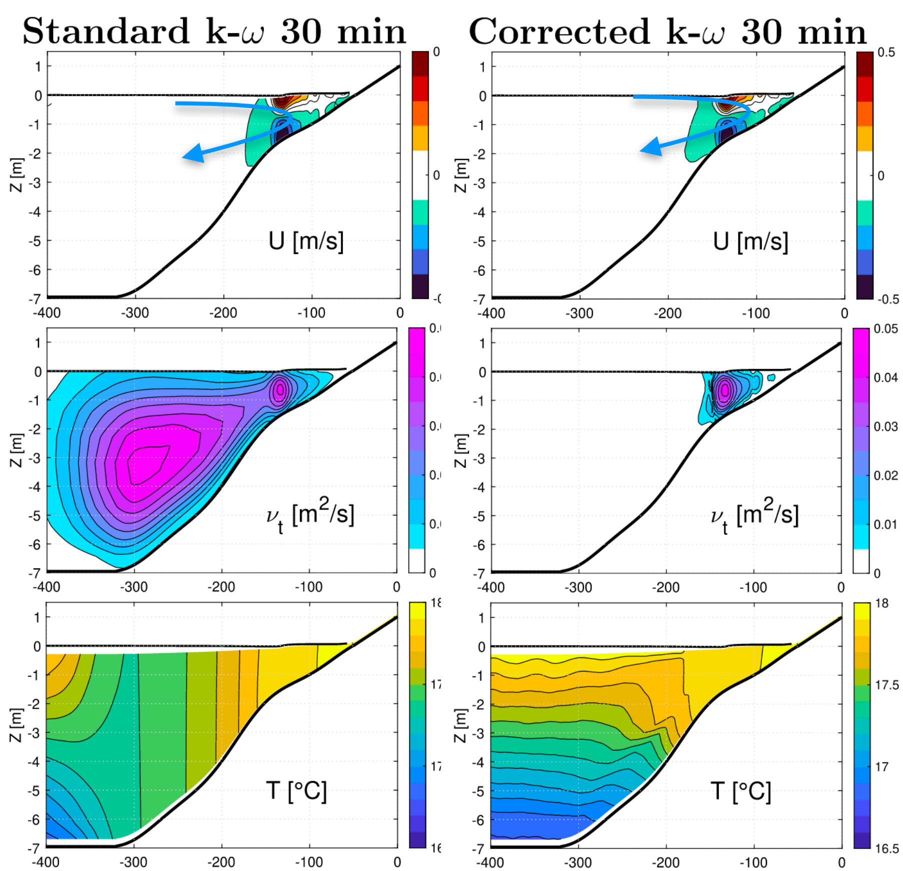
$$P = 2\nu_t S^2 \qquad \nu_t = c_\mu \frac{k^2}{\epsilon}$$

Instability of the 2-equation turbulence closure equations :

- ✓ **Overmixing** under non-breaking waves
- ✓ Destruction of innershelf stratification

Stabilized GLS turbulence closure

(Marchesiello & Treillou 2023, Larsen & Fuhrman 2018)



Shear production

Dissipation

Dissipation rate

$$\begin{cases} \dfrac{\partial k}{\partial t} = P - \epsilon \\[2ex] \dfrac{\partial \omega}{\partial t} = \dfrac{\omega}{k}(c_{\omega 1} P - c_{\omega 2}\epsilon) \end{cases}$$

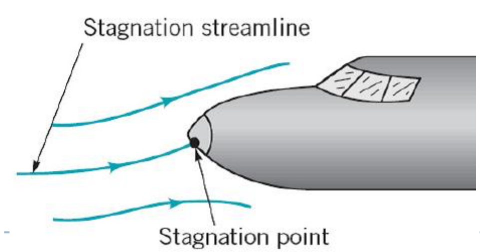
$$P = 2\nu_t S^2 \qquad \nu_t = c_\mu \frac{k^2}{\epsilon *}$$

$$\boxed{\epsilon * = \max\left(1, \lambda \frac{S^4}{\Omega^4}\right)\epsilon}$$

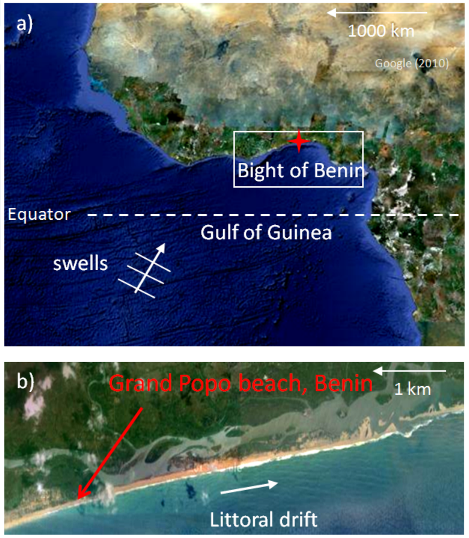
same for all GLS models

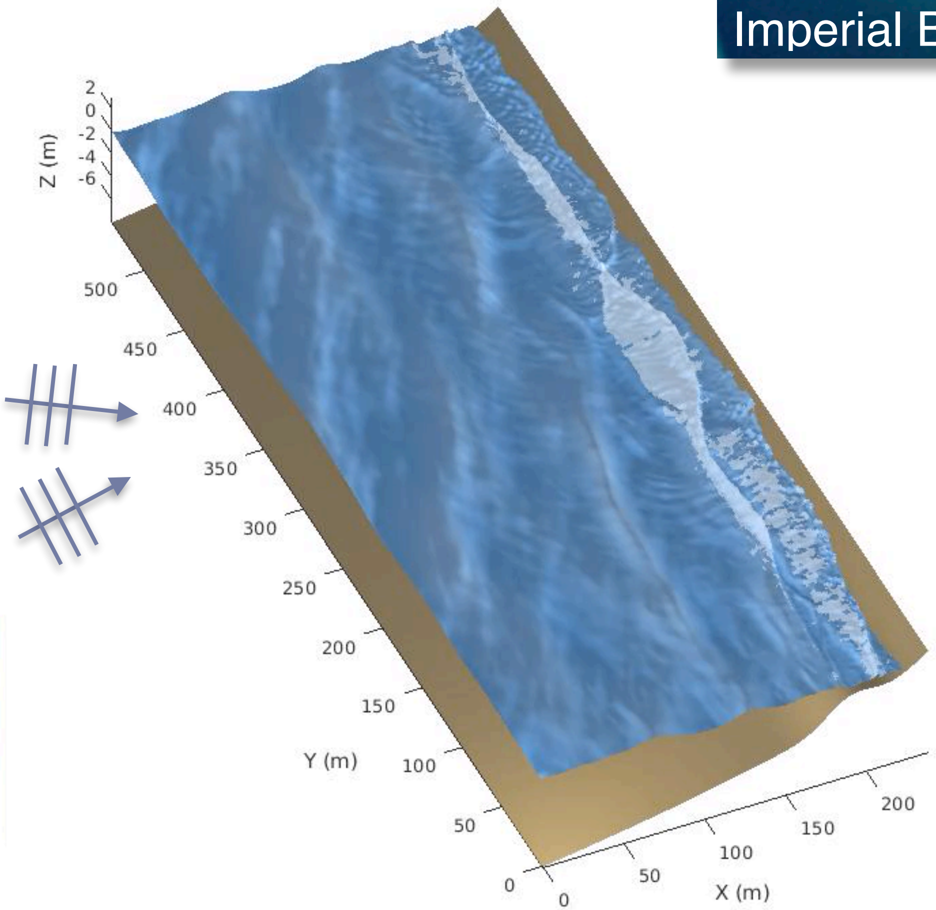
☑ **Turbulence production is limited when strain rate is much greater than vorticity**

Akin to realizability constraints for stagnation point anomalie (Durbin 2009):

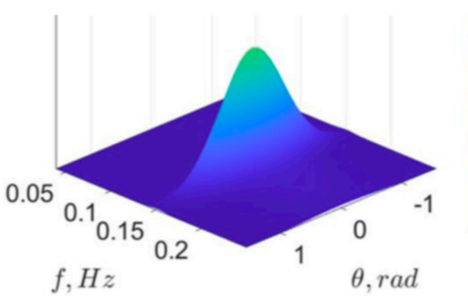


3D Wavemaker
Application to a natural Beach





JONSWAP wave spectrum
with directional spread



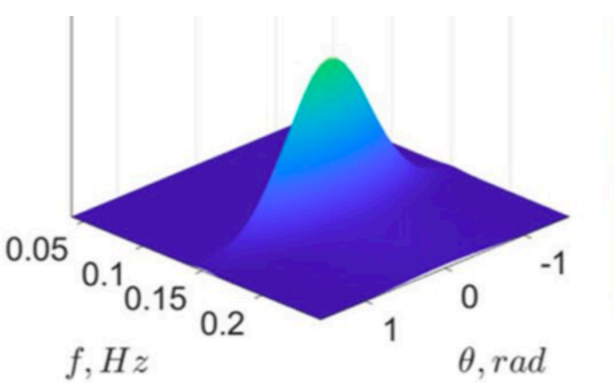
Wavemaker correction for the standing wave problem

Salatin et al., 2021

Wave-resolving models generally use a classical double summation wave-maker:

$$\eta_{bc}(y,t) = \sum_i \underbrace{a_i}_{\text{Amplitude depending on a frequency spectrum}} \sum_j \underbrace{d_j}_{\text{Directional spread}} cos(k_{y,i,j}y - \omega_i t - \phi_{ij})$$

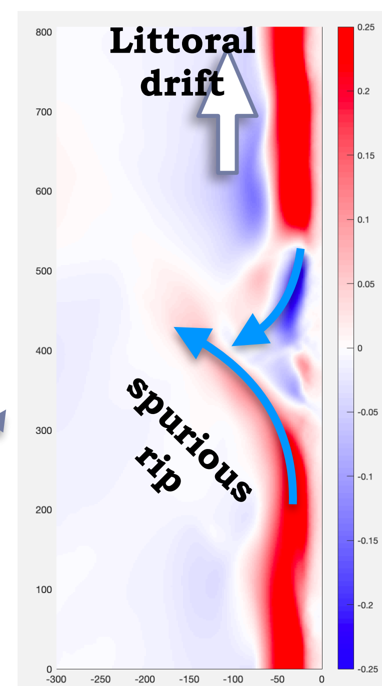
… leading to interferences between waves of different directions with same frequencies (phase-locking)

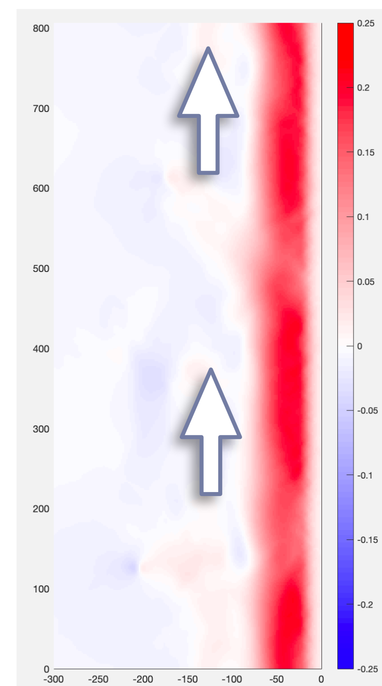


Waves directional spread

Wave-maker modification such that all wave components have distinct frequencies and directions:

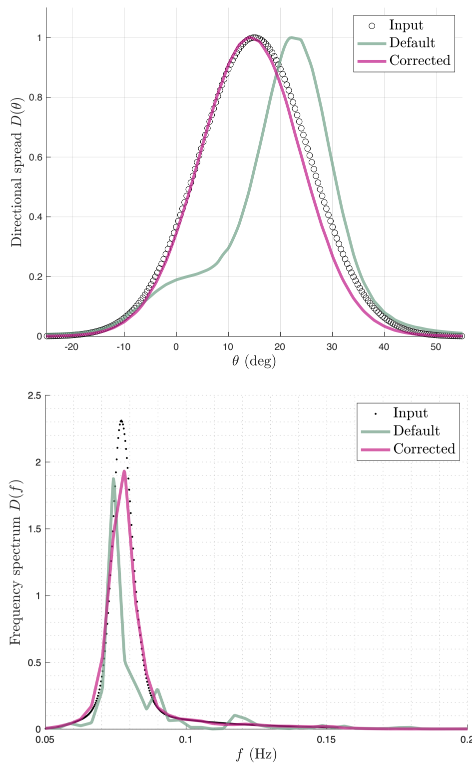
$$\eta_{bc}(y,t) = \sum_i a_i d_i cos(k_{y,i}y - \omega_i t - \phi_i)$$

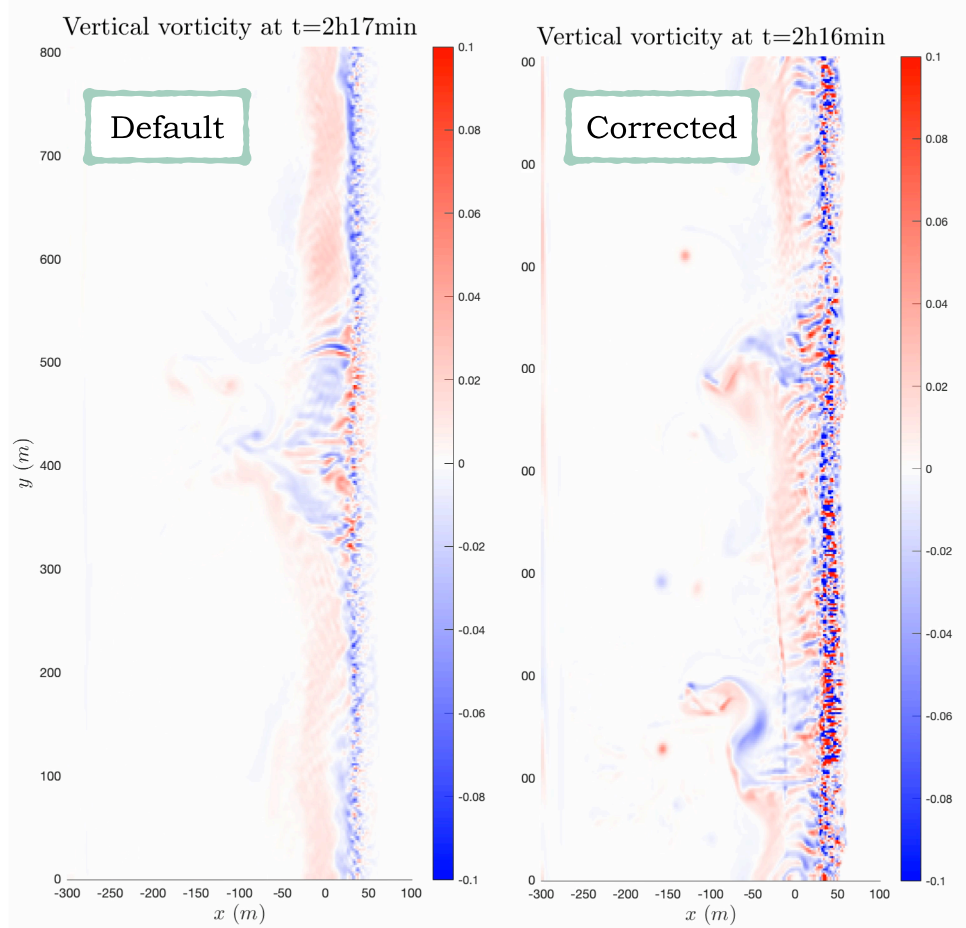




Wavemaker correction for the standing wave problem

Modification of the wave-maker such that all wave components have distinct frequencies and directions





☑ **Avoid negative impact on rip currents, cross-shore exchanges, wave streaming…**