



ORCTM v2.0: implementation and evaluation of wave effects on currents based on the vortex-force formalism

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Abstract. The Ocean Regional Circulation and Tide Model version 2.0 (ORCTM v2.0), which represents wave effects on currents (WEC) through online field exchange with SWAN via OASIS3-MCT, is presented. The configuration evaluated here is restricted to one-way wave-to-current forcing. The established vortex-force formulation is incorporated into ORCTM's orthogonal curvilinear Arakawa C-grid, z-coordinate, partial-cell, and barotropic–baroclinic framework. It represents Stokes transport in the mass and free-surface equations; the Stokes–Coriolis force, vortex force, Bernoulli head, and wave-induced pressure contributions; and non-conservative momentum input associated with wave breaking, rollers, whitecapping, and surface and near-bottom streaming. SWAN bulk-wave and dissipation diagnostics are used to reconstruct the three-dimensional Stokes field and term-resolved WEC tendencies in ORCTM. The implementation is evaluated using an idealized plane-beach experiment with obliquely incident waves and the DUCK94 barred-beach experiment. These benchmarks examine wave-induced water-level adjustment, Stokes–Eulerian transport compensation, three-dimensional nearshore circulation, and momentum balances. The experiments demonstrate that ORCTM v2.0 can reproduce the principal nearshore WEC processes and provide process-resolved diagnostics of wave-induced mass and momentum pathways.

1 Introduction

Interactions between surface gravity waves and ocean currents occur throughout coastal, shelf, and open-ocean environments and are a fundamental component of ocean dynamics. As waves propagate, transform, and dissipate, they modify mean circulation, sea surface height, and water transport. These changes arise from Stokes transport, wave-induced pressure adjustments, and momentum transfer to the water column and boundary layers (McWilliams et al., 2004; Ardhuin et al., 2008; Lentz and Fewings, 2012; Breivik et al., 2015). These wave effects on currents (WEC) are strongest where wave shoaling, breaking, and



30 dissipation are substantial, particularly in coastal and shelf seas. However, their dynamical influence is not confined to these regions. Their quantitative representation therefore requires a wave-averaged framework that treats wave-induced mass transport, pressure adjustment, and momentum exchange consistently.

Early descriptions of WEC were based primarily on the radiation stress (RS) framework. Longuet-Higgins
35 and Stewart (1960, 1962, 1964) established radiation stress theory by relating the divergence of the wave-induced, depth-integrated excess horizontal momentum flux to changes in mean water level and circulation. The framework directly represents wave set-down, set-up, and depth-averaged circulation driven by wave shoaling and dissipation. Classical RS therefore provides a depth-integrated constraint on wave-induced momentum. Extending it to a three-dimensional water column requires the vertical
40 structures of the wave-induced momentum flux and pressure contributions to be specified. Subsequent studies developed several vertically resolved or depth-dependent wave-current equations (Mellor, 2003, 2008, 2011, 2015; Xia et al., 2004).

For three-dimensional applications, the vortex-force (VF) formulation provides another wave-averaged framework that is convenient for model implementation. It developed from the theory of Langmuir
45 circulation (Craik and Leibovich, 1976) through applications to wave-driven ocean circulation (McWilliams and Restrepo, 1999) and finite-depth coastal wave–current interaction (McWilliams et al., 2004). Within this VF formulation, the Stokes-Coriolis force, the vortex force, and the Bernoulli-head gradient enter the momentum equations explicitly. The vortex force represents coupling between Stokes drift and mean-flow vorticity, while Stokes transport enters the mass and free-surface budgets. Suzuki
50 and Fox-Kemper (2016) further clarified the associated momentum effects and energy conversions by decomposing them into Stokes advection, the Stokes-Coriolis force, and the Stokes shear force. Because the individual processes appear explicitly in the governing equations, the VF formulation is well suited to modular implementation and term-by-term dynamical diagnosis (Zheng et al. 2017).

Building on these developments, three-dimensional WEC has been incorporated into many coastal,
55 regional, and global ocean models. In coastal and shelf seas, frameworks such as POM/NearCoM, ROMS/COAWST, and FVCOM-UnSWAN have progressively represented wave-driven circulation and



its vertical structure, together with momentum input from wave dissipation. Relevant processes include depth-induced breaking, rollers, near-bottom streaming, wave-current bottom stress, and wave-related mixing (Newberger and Allen, 2007a, b; Warner et al., 2008; Uchiyama et al., 2010; Kumar et al., 2011, 60 2012; Zheng et al., 2017, 2023). In regional and global ocean models, WEC has also been implemented through prescribed wave forcing, one-way wave-to-current forcing, or more general two-way wave-ocean coupling configurations. These implementations must coordinate Stokes transport, sea-state-dependent stress, upper-ocean mixing, and field exchanges with spectral wave models at the target scale (Breivik et al., 2015; Wu et al., 2019; Couvelard et al., 2020; Sun et al., 2023; Porcile et al., 2024). Together, these 65 studies have established the principal theoretical and technical foundations for three-dimensional WEC simulations. They also show that implementation details depend on prognostic variables, vertical coordinates, free-surface treatment, pressure decomposition, and discretisation of momentum fluxes. Existing WEC schemes therefore cannot be transferred unchanged between different numerical frameworks.

70 This dependence on numerical framework is the central challenge in extending WEC to the Ocean Regional Circulation and Tide Model (ORCTM). ORCTM is derived from MPI-OM and uses an orthogonal curvilinear Arakawa C-grid, z-level, and a partial-cell representation of topography. It also supports open-boundary relaxation, pressure decomposition, and optional non-hydrostatic dynamics (Huang et al., 2023). ORCTM provides the core capabilities needed to simulate regional circulation and 75 multiscale ocean dynamics. It has been applied to studies of coastal upwelling and cold-water patches (Zhang et al., 2025), internal tide and internal solitary wave generation and propagation (Huang et al., 2025; Wang et al., 2026; Chen et al., 2025), and Kuroshio intrusion (Zhang et al., 2026). However, ORCTM v1.0 lacks a wave-to-current pathway for WEC. It therefore cannot systematically represent Stokes transport, wave-induced pressure adjustment, vortex forces, or momentum inputs associated with 80 wave dissipation and boundary-layer processes. The key challenge is not simply to add wave forcing, but to establish a consistent and testable dynamical pathway within ORCTM's existing discretisations of mass, pressure, and momentum.



To address this gap, we develop ORCTM v2.0 and use OASIS3-MCT to organize field exchanges between SWAN and ORCTM. The configuration evaluated here focuses on a one-way wave-to-current
85 pathway, in which SWAN provides wave information to ORCTM. Specifically, we (1) incorporate corrections related to Stokes transport, the Stokes–Coriolis force, the vortex force, and the Bernoulli head. We further integrate wave-induced pressure and free-surface contributions into ORCTM’s mass, pressure, and momentum framework. (2) Using SWAN-derived wave parameters, dissipation rates, and near-bottom orbital velocities, we construct three-dimensional wave forcing for ORCTM’s z-level water
90 column and partial bottom cells. This forcing represents momentum inputs from depth-induced breaking, rollers, whitecapping, and surface and near-bottom streaming. (3) We establish diagnostics for Eulerian and Stokes transports, three-dimensional velocity, and component-wise momentum budgets. These diagnostics track the input, vertical redistribution, and ultimate balance of wave momentum. In this way, established VF/WEC dynamics are implemented in ORCTM in a form that supports process-level
95 diagnosis and evaluation.

The remainder of this paper is organised into four main sections. Section 2 describes the ORCTM-SWAN component framework, exchanged variables, VF/WEC governing equations, and parameterisations of non-conservative wave terms. Section 3 uses an idealised plane-beach test with obliquely incident waves to examine free-surface response, transport compensation, and dominant momentum balances. Section 4
100 uses the DUCK94 barred-beach case to evaluate wave fields, three-dimensional currents, momentum budgets, and sensitivity to the roller parameterisation. Section 5 discusses the capabilities and limitations of the current implementation, and summarises the main conclusions and priorities for future development.

2 Model development and implementation

2.1 ORCTM-SWAN configuration and coupling strategy

105 In this study, the third-generation spectral wave model SWAN v41.51 (Simulating Waves Nearshore), developed at Delft University of Technology, was incorporated into ORCTM as a new model component. SWAN was used to provide the wave-field variables required by the wave-effects-on-currents (WEC) momentum module in ORCTM. ORCTM is a three-dimensional regional ocean dynamical model that



employs an orthogonal curvilinear Arakawa C-grid in the horizontal, while retaining its existing
110 framework for vertical discretization and bathymetric representation (Huang et al., 2023). The nearshore
wave-induced mean-circulation processes considered here are simulated under a hydrostatic configuration
in the present benchmark. OASIS3-MCT (Craig et al., 2017) was used to manage inter-component
communication and to support future extensions of the coupled system.

In regional ocean-model simulations, the treatment of open boundaries is essential for minimizing
115 spurious reflections of outgoing wave- and current-induced disturbances. We retained the mature open-
boundary framework of ORCTM v1.0, in which an exponential sponge-layer relaxation condition is
applied at the offshore open boundary (Huang et al., 2023). This treatment gradually relaxes model
variables towards prescribed boundary values, thereby damping outward-propagating disturbances while
smoothly introducing external forcing.

120 The architecture of the coupled model is illustrated in Fig. 1. In the configuration evaluated in this study,
SWAN transfers a set of wave-field variables to ORCTM, including (1) bulk wave parameters, namely
significant wave height, mean and spectral-peak wave directions, mean wavelength, and wave periods at
the sea surface and seabed; (2) wave-dissipation source terms, including whitecapping, depth-induced
breaking, and bottom-friction dissipation; (3) wave-breaking statistics; and (4) near-bottom kinematic
125 parameters, such as wave orbital velocity at the seabed. After receiving these wave variables, ORCTM
reconstructs the representative-wave quantities k , σ , c , together with the three-dimensional Stokes-drift
field, and calculates the wave-effects-on-currents (WEC) momentum terms, including the vortex force,
wave-induced pressure contribution, and breaking- and roller-induced forcing. The three ocean fields
associated with the ORCTM-to-SWAN direction are retained only as reserved interfaces and were neither
130 activated nor evaluated in the benchmarks presented here. The field and unit contract is provided in
Appendix A.

To interface ORCTM with OASIS3-MCT, we implemented data-exchange calls in the ORCTM main
program for the initialization, execution, and finalization phases. During initialization, ORCTM passes
its grid information to the coupler. During model execution, ORCTM receives the SWAN-provided wave
135 variables at the prescribed communication interval and uses them to drive the WEC momentum terms.
Corresponding OASIS3-MCT interfaces for initialization, execution, and finalization were also added on



the SWAN side. Although this interface design retains the capacity for future extensions towards two-way coupling, the benchmark evaluation presented here is strictly limited to the SWAN-to-ORCTM wave-to-ocean forcing configuration.

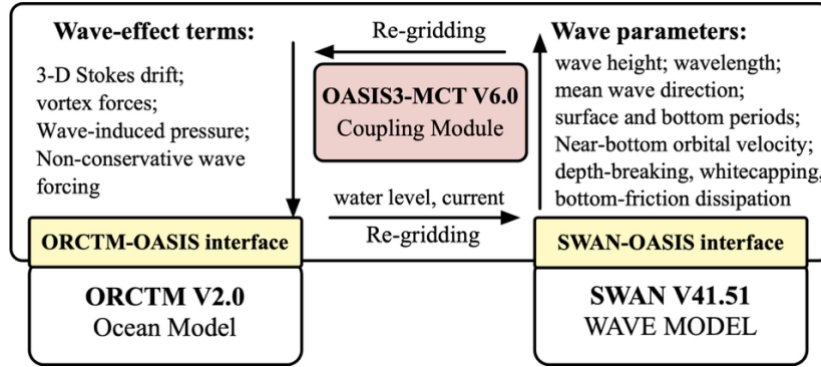


Figure 1. Schematic of the ORCTM–SWAN wave-to-ocean coupled system, illustrating the one-way coupling of SWAN v41.51 and ORCTM v2.0 through OASIS3-MCT v6.0.

2.2 Governing equations for wave effects on currents in ORCTM

ORCTM v2.0 incorporates wave effects on the phase-averaged flow within the incompressible, Boussinesq, free-surface equation framework of ORCTM v1. Its vortex-force (VF) implementation follows the fundamental conventions of McWilliams et al. (2004) and adopts the wave-averaged equation formulation of Zheng et al. (2017), with the modifications required for the ORCTM discretization:

$$\frac{\partial \mathbf{V}_H}{\partial t} + (\mathbf{V}_H \cdot \nabla_H) \mathbf{V}_H + w \frac{\partial \mathbf{V}_H}{\partial z} + f \hat{\mathbf{z}} \times \mathbf{V}_H \quad (1)$$

$$= -\frac{1}{\rho_0} \nabla_H \mathbf{P}_h - g \nabla_H \zeta + \mathbf{F}_{Hor} + \mathbf{F}_{Ver} + \mathbf{F}^{ext} - \nabla_H \mathcal{K} + \mathbf{J}_H + \mathbf{F}^{wave}$$

$$\frac{\partial \phi}{\partial z} + \frac{g\rho}{\rho_0} = -\frac{\partial \mathcal{K}}{\partial z} + \mathbf{J}_z \quad (2)$$

$$\nabla_H \cdot \mathbf{V}_H + \frac{\partial w}{\partial z} = 0 \quad (3)$$

Where, the governing equations are formulated in a right-handed local Cartesian coordinate system; t is time; $\partial/\partial t$ time partial derivative; x - y - z axes are directed eastward, northward, and upward, respectively; $\nabla_H = (\partial/\partial x, \partial/\partial y)$, is the horizontal gradient operator; $\hat{\mathbf{z}}$ is the vertical unit vector, $f\hat{\mathbf{z}}$ is Coriolis parameter.



$\mathbf{V}_H=(u,v)$ and w are the Eulerian horizontal and vertical velocities, respectively, $\mathbf{V}_H^{st}=(u^{st}, v^{st})$ 和 w^{st} are the corresponding horizontal and vertical Stokes velocities; ρ seawater density, ρ_0 is reference seawater density, g is gravitational acceleration, $\mathbf{P}_h$ is hydrostatic pressure; ζ is the change in the free surface elevation; The horizontal eddy viscosity vector $\mathbf{F}_{Hor}$ described with the scale-dependent biharmonic formulation(Wolff et al., 1997; Marsland et al., 2003); In addition, the vertical eddy viscosity vector is $\mathbf{F}_{Ver}$. $\mathbf{F}^{ext}$ is external forcing, this includes tidal forcing, while surface wind stress and bottom drag are imposed through the surface and bottom boundary conditions; $\mathcal{K}$ is Bernoulli head; $\mathbf{J}_H, \mathbf{J}_Z$ denote the horizontal and vertical vortex-force terms, respectively; and $\mathbf{F}^{wave}$ denotes non-conservative wave forcing.

2.2.1 Bulk reconstruction of the Stokes drift

Using the received bulk wave parameters, ORCTM reconstructs the three-dimensional Stokes velocity $(\mathbf{V}_H^{st}, w^{st})$ with a single finite-depth representative wave:

$$\mathbf{V}_H^{st}(z) = \frac{2E}{\rho_0 c} \frac{\cosh[2Z]}{\sinh[2\mathcal{H}]} \mathbf{k} \quad (4)$$

$$w^{st}(z) = -\nabla_{\perp} \cdot \int_{-h}^z \mathbf{V}^{st} dz' \quad (5)$$

Here, E is the wave energy and c is the wave phase speed. The wavenumber vector is $\mathbf{k} = k(\cos\theta, \sin\theta)$, where $k = |\mathbf{k}|$, and $h(x)$ is the still-water depth. The wave direction θ is defined in the model's eastward–northward physical coordinate system; The normalized vertical coordinates $\mathcal{H}$ and Z are defined as:

$$Z = k(z + h); \mathcal{H} = k(h + \zeta + \zeta^w) = kD \quad (6)$$

where the seabed is located at $z=-h$ and $D = h + \zeta + \zeta^w$ is the wave-averaged water-column thickness.

Finally, the wave energy E , phase speed c , and intrinsic frequency σ are given by

$$E = \frac{1}{16} \rho_0 g H_s^2 \quad (7)$$

$$c = \frac{\sigma}{k} \quad (8)$$

$$\sigma = \sqrt{gk \tanh[\mathcal{H}]} \quad (9)$$

Where, H_s is the significant wave height.



2.2.2 Horizontal and vertical vortex-force terms

The vortex-force terms ($\mathbf{J}_H, J_z$) and the Bernoulli-head term $\mathcal{K}$ in Eq. (1) are expressed as follows:

$$\mathbf{J}_H = -\hat{\mathbf{z}} \times \mathbf{V}^{st} (f + (\hat{\mathbf{z}} \cdot \nabla_{\perp} \times \mathbf{V})) - w^{st} \frac{\partial \mathbf{V}}{\partial z} \quad (10)$$

$$J_z = \mathbf{V}^{st} \cdot \frac{\partial \mathbf{V}}{\partial z} \quad (11)$$

$$\mathcal{K} = \frac{1}{32} \frac{\sigma H_s^2}{k \sinh^2[kD]} \int_{-h}^z \frac{\partial^2 r}{\partial z'^2} \sinh[2k(z - z')] dz' \quad (12)$$

Where, $r = \mathbf{k} \cdot \mathbf{V}$.

175 2.2.3 Wave-induced pressure potential

The quasi-static sea level component is expressed as:

$$\zeta^w = -\frac{P_{atm}}{g\rho_0} - \frac{H_s^2 k}{16 \sinh[2\mathcal{H}]} \quad (13)$$

The first term represents the inverse-barometer response to spatial variations in atmospheric pressure. The second term is the phase-averaged, wave-induced quasi-static sea-level correction relative to the still-water level.

180 2.3 Boundary conditions

The kinematic and dynamic pressure boundary conditions in the presence of wave effects on currents are written as follows:

$$\begin{aligned} w|_{-h} + \mathbf{V}|_{-h} \cdot \nabla_{\perp} h &= 0 \\ \frac{\partial \zeta^c}{\partial t} &= -\nabla_H \cdot \left[\int_{-h}^{\zeta^c} \mathbf{V}_H dz + \int_{-h}^{\zeta^c} \mathbf{V}_H^{st} dz \right] + Q_{\zeta} \\ g\zeta - \phi|_{\zeta+\hat{\zeta}} &= \mathcal{P} \end{aligned} \quad (14)$$

Where, $\zeta^c = \zeta + \zeta^w$ denotes the total wave-averaged composite free-surface elevation. Accounting for Stokes transport, the free-surface equation is obtained by combining the linearized kinematic boundary condition with the freshwater forcing term Q_{ζ} associated with evaporation and precipitation (Marsland et al., 2003); $\mathcal{P}$ is the wave-averaged forcing surface boundary condition:



$$\mathcal{P} = \frac{gH_s^2}{16\sigma} \left\{ \frac{\tanh[kD]}{\sinh[2kD]} \left(-\frac{\partial Y}{\partial z} \Big|_{\zeta+\hat{\zeta}} + \cosh[2kD] \frac{\partial Y}{\partial z} \Big|_{-h} + \int_{-h}^{\zeta+\hat{\zeta}} \frac{\partial^2 Y}{\partial z'^2} \cosh[2kz'] dz' \right) - 2k \tanh[kD] Y \Big|_{\zeta+\hat{\zeta}} \right\} \quad (15)$$

2.4 Non-conservative wave terms

190 As surface gravity waves propagate shoreward, they lose energy through multiple dissipation processes. Within the vortex-force framework, the conservative vortex-force and wave-induced pressure terms do not represent the irreversible transfer of dissipating wave energy into mean-flow momentum. This transfer is introduced explicitly into the mean-current momentum balance as non-conservative wave forcing, expressed as an acceleration. Following parameterizations used in three-dimensional wave–current
 195 modelling systems (Kumar et al., 2012; Zheng et al., 2017), the total non-conservative wave forcing term $\mathbf{F}^{wave}$ on the right-hand side of the horizontal momentum equation (Eq. 1) is represented as the additive sum of its component processes:

$$\mathbf{F}^{wave} = \mathbf{B}^{wb} + \mathbf{B}^{bf} + \mathbf{B}^{sf} = \mathbf{B}^b + \mathbf{B}^r + \mathbf{B}^{wcap} + \mathbf{B}^{bf} + \mathbf{B}^{sf} \quad (16)$$

Where, $\mathbf{B}^{wb} = \mathbf{B}^b + \mathbf{B}^r + \mathbf{B}^{wcap}$ denotes the wave-breaking-related acceleration, including the depth-induced breaking acceleration $\mathbf{B}^b$ and the wave-roller-induced acceleration $\mathbf{B}^r$. $\mathbf{B}^{wcap}$ denotes the
 200 whitecapping-induced acceleration, whereas $\mathbf{B}^{bf}$ and $\mathbf{B}^{sf}$ denote the accelerations associated with bottom and surface streaming, respectively.

2.4.1 Wave breaking term

Nonconservative momentum input from wave breaking is generally available only after depth averaging (Longuet-Higgins and Stewart, 1964; Smith, 2006). In three dimensional models, this forcing can be
 205 applied either as a surface stress or as a body force distributed within the upper water column (Newberger and Allen, 2007a; Kumar et al., 2011a). Following Zheng et al. (2017), ORCTM applies $\mathbf{B}^{wcap}$ $\mathbf{B}^b$, and $\mathbf{B}^r$ using a prescribed vertical distribution concentrated near the surface.

(a) Whitecapping-induced acceleration term



Unlike depth-induced breaking, whitecapping is controlled primarily by wave steepness and can occur
210 over a wide range of water depths (van der Westhuysen et al., 2007). ORCTM converts the whitecapping
dissipation rate ϵ^{wcap} provided by SWAN into a momentum tendency. Following Kumar et al. (2012)
and Zheng et al. (2017), this tendency can be applied either as a three dimensional body force.

$$\mathbf{B}^{wcap} = \frac{\epsilon^{wcap}}{\rho_0 \sigma} k f^b(z) \quad (17)$$

As an equivalent surface stress. The vertical structure of the body force is prescribed as

$$f^b(z) = \frac{\cosh[k_b(h+z)]}{\int_{-h}^{\zeta^c} \cosh[k_b(h+z)] dz} \quad (18)$$

Here, $k_b^{-1} = a_b H^*$ determines the penetration depth, where H^* is the representative wave height and a_b
215 is an empirical coefficient. Following Uchiyama et al. (2010), a_b is set to 0.2. The normalization of $f^b(z)$
ensures that its vertical integral equals unity and therefore preserves the total momentum input.

When the thin surface layer cannot be resolved by the vertical grid, the same momentum input is applied
as an equivalent surface stress:

$$\tau_{sur}^{wcap} = \rho_0 D \overline{\mathbf{B}^{wcap}} = \frac{\epsilon^{wcap}}{\sigma} \quad (19)$$

where D is the total water column thickness and $\overline{\mathbf{B}^{wcap}}$ is the depth averaged whitecapping acceleration.

220 (b) Depth-induced breaking dissipation and acceleration term

As surface waves propagate into shallow coastal waters, decreasing water depth causes strong
deformation and eventually depth-induced breaking. Within the surf zone, this process provides a major
momentum input driving nearshore circulation and wave setup (Uchiyama et al., 2010; Kumar et al.,
2012). The associated wave energy dissipation rate, ϵ^b , is calculated by SWAN using the formulation of
225 Battjes and Janssen (1978). It is passed to the ocean component at each coupling exchange (Zheng et
al., 2017):

$$\epsilon^b = -\frac{\rho g}{4} \alpha_{BJ} Q_b \tilde{f} H_{max}^2 \quad (20)$$

Where, α_{BJ} is a tunable empirical coefficient of order unity, Q_b is the fraction of breaking waves, and $\tilde{f}$
is the mean wave frequency. H_{max} is the maximum wave height permitted by the local water depth. Only
part of the dissipated wave energy is transferred directly to the mean flow. A fraction α_r is transferred to



230 surface wave rollers and released gradually as they propagate shoreward, delaying the momentum transfer.
 The remaining fraction, $1 - \alpha_r$, directly produces the depth-induced breaking acceleration B^{db} .
 As for whitecapping, ORCTM provides both a three dimensional body force and an equivalent surface
 stress representation. The choice depends on whether the vertical grid can resolve the thin forcing layer
 near the surface. In the body force representation, the acceleration is given by (Uchiyama et al., 2010;
 235 Kumar et al., 2012):

$$B^b = \frac{(1 - \alpha_r)\epsilon^b}{\rho_0 \sigma} k \cdot f^b(z) \quad (21)$$

Here, f^b is the normalized hyperbolic cosine distribution defined in Eq. (18).

When the surface forcing layer cannot be resolved, the body force is replaced by an equivalent surface
 stress (Kumar et al., 2012):

$$\tau_{sur}^b = \rho_0 D \overline{B^{db}} = \frac{(1 - \alpha_r)\epsilon^b}{\sigma} k \quad (22)$$

(c) Wave Roller dissipation and acceleration term

240 Within the surf zone, depth-induced breaking dissipates ϵ^b primary wave energy and supplies part of this
 energy to surface wave rollers. Rollers are aerated turbulent bores carried by broken waves. As they
 propagate shoreward, they gradually transfer their stored energy and momentum to the water column.
 This delayed transfer can modify the undertow and longshore currents within the surf zone (Svendsen,
 1984; Deigaard et al., 1991; Stive and de Vriend, 1995).
 245 To represent this spatial lag, ORCTM follows Reniers et al. (2004a) and Zheng et al. (2017) and solves
 the roller energy equation

$$\frac{\partial E^r}{\partial t} + \frac{\partial}{\partial x}(C_x E^r) + \frac{\partial}{\partial y}(C_y E^r) = \alpha_r \epsilon^b - \epsilon^r \quad (23)$$

with

$$\epsilon^r = \frac{g \sin \beta E^r}{c} \quad (24)$$



Where, E^r is the roller energy per unit horizontal area, and $\mathbf{C} = (C_x, C_y)$ is the horizontal roller
250 propagation velocity. The corresponding phase speed is denoted by c . The coefficient α_r specifies the
fraction of breaking dissipation transferred to the rollers, and ε^r is the roller energy dissipation rate.
Following Reniers et al. (2004a), $\sin\beta$ is the empirical constant controlling roller dissipation and set to
0.1 here.

The roller acceleration $\mathbf{B}^r$ uses the same vertical distribution f^b as the depth-induced breaking
255 acceleration. Combining whitecapping, depth-induced breaking, and roller dissipation gives the total body
force associated with surface wave breaking:

$$\mathbf{B}^{wb} = \frac{(1 - \alpha_r)\varepsilon^b + \varepsilon^r + \varepsilon^{wcap}}{\rho_0 \sigma} \mathbf{k} \cdot f^b(z) \quad (25)$$

When represented as a surface stress, the same depth integrated momentum input becomes:

$$\tau_{sur}^{swb} = \rho_0 D \overline{B^{wb}} = \frac{\varepsilon^{wcap} + (1 - \alpha_r)\varepsilon^b + \varepsilon^r}{\sigma} \mathbf{k} \quad (26)$$

Rollers also contribute to the shoreward Stokes transport (Svendsen, 1984; Kumar et al., 2012). Assuming
that roller transport follows the same vertical profile as the primary wave Stokes drift, the total Stokes
260 velocity is written as:

$$\mathbf{V}^{st} = \frac{\cosh[2Z]}{\sinh[2\mathcal{H}]} \frac{2(E + E^r)}{\rho_0 c} \mathbf{k} \quad (27)$$

The wave parameters and breaking dissipation supplied by SWAN are held fixed between coupling
exchanges, whereas the roller equation is advanced internally by ORCTM at every ocean time step. Roller
advection is discretized using a first-order upwind scheme, while roller dissipation is treated semi-
implicitly.



265 2.4.2 Bottom-friction dissipation and bottom streaming term

In addition to depth-induced breaking, viscous interaction between waves and the wave bottom boundary layer (WBBL) produces non-conservative momentum forcing. In shallow water, wave orbital motion reaches the seabed, and frictional dissipation shifts the horizontal and vertical orbital velocities from exact quadrature. The resulting net momentum flux is directed along wave propagation and is referred to as
 270 bottom streaming (Longuet-Higgins, 1953; Kranenburg et al., 2012). This boundary-layer pathway can provide an additional contribution to the momentum budget (Wang et al., 2021).

Bottom friction is an important wave-energy sink over continental shelves and in shallow coastal water. ORCTM evaluates the positive bottom-friction energy-loss magnitude ϵ^{bf} following Reniers et al. (2004b) and Zheng et al. (2017):

$$\epsilon^{bf} = \frac{1}{2\sqrt{\pi}} \rho_0 f_w |\mathbf{u}_{orb}^w|^3 \quad (28)$$

275 The near-bed wave-orbital velocity amplitude and wave friction factor (Soulsby, 1995) are:

$$|\mathbf{u}_{orb}^w| = \frac{\sigma H_s}{2\sqrt{2} \sinh k d}; f_w = 1.39 \left(\frac{\sigma z_b}{|\mathbf{u}_{orb}^w|} \right)^{0.52} \quad (29)$$

Here, σ is the intrinsic radian frequency, H_s is significant wave height, D is the total wave-averaged depth, k is the wavenumber magnitude, z_b is the physical bottom-roughness length, $|\mathbf{u}_{orb}^w|$ is the near-bed orbital-velocity amplitude, and f_w is the wave friction factor.

ORCTM represents the bottom-streaming contribution either as a three-dimensional body force or as an
 280 equivalent bottom stress (Uchiyama et al., 2010; Kumar et al., 2012). When the vertical grid can represent the structure above the WBBL, the body-force acceleration B^{bf} is

$$B^{bf} = \frac{\epsilon^{bf}}{\rho_0 \sigma} \mathbf{k} \cdot f^{bf}(z) \quad (30)$$

Here, $f^{bf}(z)$ is a normalized empirical profile that decays upward from the seabed:



$$f^{\text{bf}}(z) = \frac{\cosh[k_{\text{bf}}(\zeta^c - z)]}{\int_{-h}^{\zeta^c} \cosh[k_{\text{bf}}(\zeta^c - z)] dz} \quad (31)$$

The decay scale $k_{\text{bf}}^{-1} = a_{\text{bf}}\delta_w$ depends on the empirical coefficient a_{bf} and WBBL thickness δ_w . Following Reniers et al. (2004b), $a_{\text{bf}}=3$ for random waves (a value of 1 is commonly used for monochromatic waves). The boundary-layer thickness is expressed in terms of the half-orbital excursion $A_{\text{orb}}^w = \frac{|u_{\text{orb}}^w|}{\sigma}$ and the Nikuradse roughness $k_N = 30z_b$ (Fredsøe and Deigaard, 1992):

$$\delta_w = 0.09k_N \left(\frac{A_{\text{orb}}^w}{k_N} \right)^{0.82} \quad (32)$$

If the WBBL is unresolved, the depth-integrated body force is instead applied as the equivalent bottom stress $\tau_{\text{bot}}^{\text{bf}}$:

$$\tau_{\text{bot}}^{\text{bf}} = \rho_0 D \overline{\mathbf{B}^{\text{bf}}} = \frac{\varepsilon^{\text{bf}}}{\sigma} \mathbf{k} \quad (33)$$

2.4.3 Surface streaming

By analogy with bottom streaming, a thin viscous wave boundary layer also develops at the free surface and produces surface streaming in the direction of wave propagation (Longuet-Higgins, 1953; Xu and Bowen, 1994; Lentz et al., 2008). ORCTM v2.0 parameterizes the resulting kinematic surface stress following Xu and Bowen (1994):

$$\mathbf{B}^{\text{sf}} = \frac{K_m H_s^2 \sigma}{4} \mathbf{k} \cdot \mathbf{k} \cdot \coth(kh) \quad (34)$$

Here, K_m is the near-surface eddy viscosity and H is the root-mean-square wave height (distinct from the normalized coordinate $\mathcal{H}$). Because the surface viscous layer is only millimetres thick, it cannot be resolved by the vertical grid of a three-dimensional ocean model. ORCTM therefore applies $\mathbf{B}^{\text{sf}}$ directly through the surface momentum boundary condition rather than as an interior body force. Its dynamical role is analogous to a surface stress acting on the upper ocean (Weber et al., 2006).



300 Although surface streaming is generally small compared with breaking-induced forcing in the inner surf zone, it can affect cross-shore circulation and upper-ocean shear outside the main breaking region and over the inner shelf (Lentz et al., 2008).

2.5 Vertical momentum boundary conditions

305 In addition to the kinematic and pressure conditions in Sect. 2.2.4, wind stress τ_w and hydrodynamic bottom stress τ_b are imposed as vertical boundary conditions on turbulent momentum flux:

$$\begin{aligned}\tau^{wind}/\rho_c &= A_v \frac{\partial u_h}{\partial z} \Big|_{z=\zeta} \\ \tau_b/\rho_c &= A_v \frac{\partial V_H}{\partial z} \Big|_{z=-H} = (\gamma + C_d^* |\mathbf{V}_b|) \mathbf{V}_b\end{aligned}\tag{35}$$

Here, τ^{wind} is the surface wind stress, τ_b is the hydrodynamic bottom stress, and A_v is the vertical eddy viscosity. The vector $\mathbf{V}_b$ denotes the Eulerian horizontal current in the lowest wet velocity cell. The parameters γ and C_d^* are the applied linear and quadratic bottom-drag coefficients, respectively. The standard ORCTM formulation uses $C_d^* = C_{d0}$. When the wave-enhanced bottom-drag option is active, C_d^* is replaced by the effective coefficient C_{deff} defined in Sect. 2.3.5.

Several non-conservative wave processes described above can be represented either as interior body forces or as equivalent boundary stresses. When the boundary-stress representation is selected, the corresponding previously defined stress is added to the left-hand side of Eq. (35). Breaking, roller, whitecapping, and surface-streaming stresses are applied at the free surface, whereas the bottom-streaming stress is applied at the seabed. When the body-force representation is selected, the corresponding stress is omitted from the boundary condition.

2.6 Wave-enhanced bottom drag

Wave orbital motion enhances the turbulent shear experienced by the mean current within the bottom boundary layer. ORCTM v2.0 optionally represents this effect using the Soulsby (1995) parameterization, following Zheng et al. (2017). When activated, the current-only quadratic drag coefficient is replaced by the wave-enhanced effective coefficient



$$C_{d,eff} = C_{d,log} \left[1 + 1.2 \left(\frac{\tilde{\tau}_w^b}{\tilde{\tau}_w^b + \tilde{\tau}_c} \right)^{3.2} \right] \quad (36)$$

The current and wave kinematic stress magnitudes in Eq. (36) are defined as:

$$\tilde{\tau}_c = \frac{\tau_c}{\rho_c} = C_{d,log} |\mathbf{V}_b|^2, \quad \tilde{\tau}_w^b = \frac{\tau_w^b}{\rho_c} = \frac{1}{2} f_w (\mathbf{u}_{orb}^w)^2 \quad (37)$$

Here, V_b is the Eulerian velocity in the lowest wet velocity cell. The current-only logarithmic drag

325 coefficient is

$$C_{d,log} = \left[\frac{\kappa}{\ln(z_m/z_b)} \right]^2, \quad z_m = \max \left(\frac{\Delta z_b}{2}, z_{m,min}, 1.05 z_b \right) \quad (38)$$

Here, $\kappa = 0.4$ is the von Kármán constant, z_b is the bottom roughness length, and Δz_b is the local thickness of the lowest wet velocity cell. The minimum reference height is $z_m = 0.001$ m. The lower bounds on z_m prevent invalid values of the logarithmic drag coefficient in very thin bottom cells.

$$A_b = \frac{\mathbf{u}_{orb}^w \mathbf{T}_b^w}{2\pi}, \quad f_w = \min \left[0.3, 1.39 \left(\frac{A_b}{z_b} \right)^{-0.52} \right] \quad (39)$$

330

$$\tau_b^{cw} = \tau_c \left[1 + 1.2 \left(\frac{\tau_w^b}{\tau_w^b + \tau_c} \right)^{3.2} \right] \quad (40)$$

Equation (36) is algebraically equivalent to the stress formulation of Equation (40), but it is more convenient for the ORCTM implementation because $C_{d,eff}$ directly replaces C_d^* in Eq. (35).

3 Obliquely incident waves over an idealized plane beach

3.1 Experiment design

335 This idealized plane-beach experiment assesses the ability of the coupled ORCTM–SWAN system to reproduce key nearshore circulation responses to oblique wave forcing. The evaluated responses include wave setup and setdown, cross-shore Stokes–Eulerian transport compensation, and the structures of the longshore current and undertow. The simulated water-level and depth-mean current responses were compared with established analytical balance relations. Plane-beach configurations have been widely



340 used as benchmarks for coupled nearshore wave–current models (Haas and Warner, 2009; Uchiyama et al., 2010; Kumar et al., 2012; Zheng et al., 2017).

The experiment used an alongshore-uniform plane beach with an open offshore boundary, a closed shoreline, and periodic alongshore boundaries. A z-level grid with bottom partial cells was used to represent the sloping seabed. The Coriolis acceleration and atmospheric forcing were omitted. Bottom
 345 stress was represented using a quadratic drag law. The domain, grid, bathymetry, and physical parameters are summarized in Table 1.

Obliquely incident waves were prescribed at the offshore boundary using a JONSWAP spectrum. The relatively fine directional discretization was selected to minimize numerical underestimation of significant wave height during shoreward propagation. Wave fields supplied by SWAN were held fixed
 350 between coupling exchanges, and the WEC tendencies were applied with a one-ocean-step lag. Reverse ocean-to-wave feedback was disabled, so this experiment evaluated the wave-to-current pathway. The coupling parameters and activated WEC processes are listed in Table 1.

Table 1. Main configuration of the idealized plane beach case.

Component	Configuration
Domain and Depth	1900 m × 300 m; offshore depth approximately 12 m; slope 1:80 from x=880 m
Grid	$\Delta x = \Delta y = 20$ m; 40 levels: $\Delta z = 0.3$ m;
Boundaries	Western open boundary; eastern shoreline; periodic northern and southern boundaries
Wave forcing	JONSWAP; $H_s = 2$ m; $T_p = 10$ s; incident angle (10°); 90 directional bins; 30 frequency bins over 0.04–0.5 Hz
Time and coupling	ORCTM/SWAN time steps: 10 s; exchange interval: 120 s
Activated processes	Stokes transport; vortex forces; quasi-static wave pressure; depth-induced breaking acceleration
Disabled processes	Roller effects; surface and bottom streaming;
Ocean physics	Quadratic bottom drag, $C_d = 0.0015$; PP81 mixing; homogeneous water
External forcing	No Coriolis acceleration, wind, heat, or freshwater forcing

355 Under steady, alongshore-uniform conditions ($\partial/\partial y = 0$), cross-shore integration of the barotropic continuity equation gives zero net depth-mean transport. The depth-mean Eulerian velocity, $\bar{u}$, and wave-induced Stokes velocity, $\overline{u^{St}}$, therefore satisfy (Uchiyama et al., 2010):



$$\bar{u} + \overline{u^{st}} = 0 \quad (41)$$

The shoreward Stokes transport is therefore compensated by an offshore Eulerian return flow,
 360 commonly referred to as undertow. In the cross-shore direction, the leading quasi-steady barotropic
 momentum balance is between the pressure gradient and forcing due to depth-induced wave breaking:

$$\rho \sigma g \frac{\partial(\zeta^c - \zeta^w)}{\partial x} - \frac{\varepsilon^b k_x}{D \sigma} = 0 \quad (42)$$

The alongshore momentum balance is between wave-breaking acceleration and quadratic bottom
 drag:

$$\rho_0 c_d \bar{v} \sqrt{u^2 + v^2} = \frac{\varepsilon^b k_y}{D \sigma} \quad (43)$$

Equation (43) therefore yields the classical local steady-state analytical solution used to evaluate the
 365 simulated cross-shore distribution of the depth-mean longshore current, $\bar{v}$.

3.2 Wave parameters and wave–current response fields

The model was first integrated for 8 h as a spin-up, after which the circulation and sea-surface elevation
 reached a quasi-steady state. All results presented in this section are based on temporal averages over
 370 the subsequent quasi-steady period.

Fig.2a shows the cross-shore distributions of significant wave height, breaking dissipation, and
 bathymetry. As the incident waves propagated shoreward, shoaling gradually increased the significant
 wave height from 2.0 m at the offshore boundary to a maximum of 2.2 m at a location 380 m seaward of
 the shoreline, where the local water depth was 5.28 m. After peaking, H_s decreased rapidly across the
 375 main breaking zone $x=1360$ - 1820 m. The breaking dissipation rate per unit density, ε^{bf}/ρ_0 , peaked at
 $7.374e-2 \text{ m}^3/\text{s}^3$ at $x=1600$ m. This concentrated dissipation drove the free-surface response shown in
 Fig. 2b. The mean water level decreased slightly as the waves approached the surf zone, reaching -

0.024 m near the onset of breaking, and then increased rapidly towards the shoreline. The modeled and analytical setdown minima were -0.024 and -0.023 m, while the corresponding maximum setups were 0.267 and 0.255 m, respectively. The water-level RMSE was 0.0077 m, with a bias of 0.001 m. These results show that the model reproduced the magnitude and cross-shore structure of the analytical water-level response.

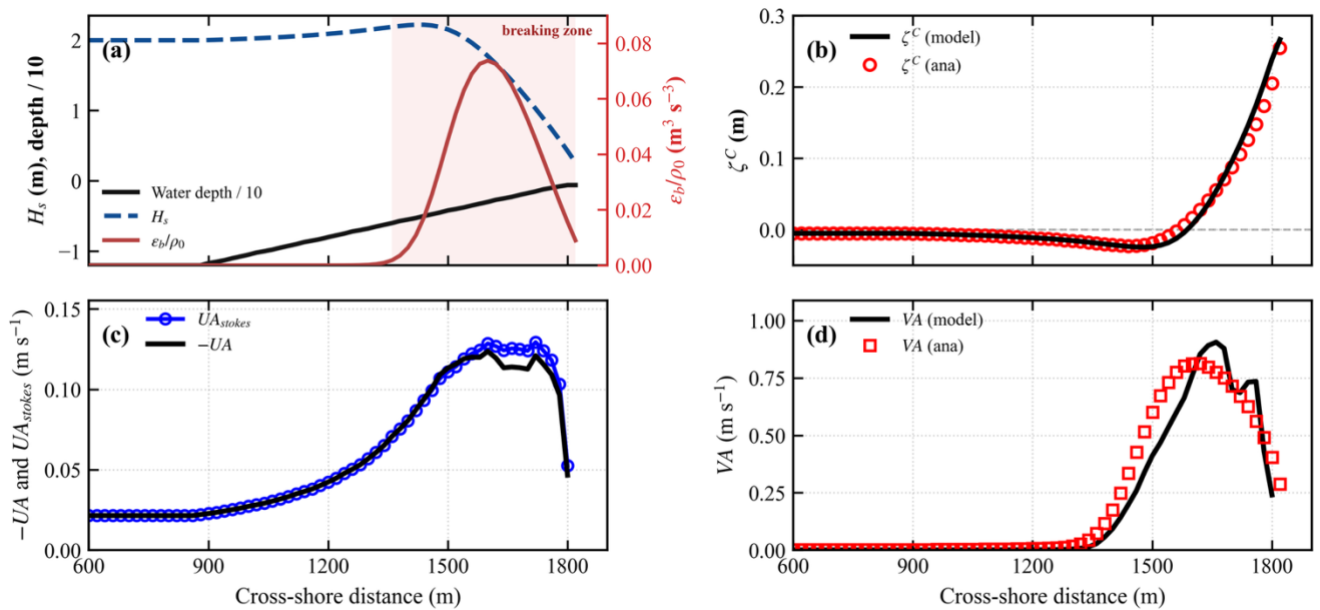


Figure 2. Cross-shore response of the idealized plane-beach case and comparison with analytical solutions. (a) Significant wave height H_s , water depth divided by 10, and breaking dissipation rate ϵ_b/ρ_0 ; shading marks the diagnosed breaking region. (b) Wave-induced mean sea-surface elevation ζ^C ; the black line shows the coupled-model result, and open red circles show the analytical cross-shore balance. (c) Depth-mean Stokes drift U_A^{St} and compensating Eulerian return flow $-U_A$, both in m s^{-1} . (d) Depth-mean longshore velocity V_A in m s^{-1} ; the black line shows the model result, and red squares show the analytical solution.

Figures 2c and 2d show the depth-mean cross-shore and longshore current responses, respectively. Within the surf zone, the shoreward Stokes velocity, U_A^{St} , was closely balanced by the offshore Eulerian return flow, U_A . Their peak magnitudes were 0.130 and 0.124 ms^{-1} , respectively. The normalized RMS



395 residual of $UA + U_A^{St}$ was 5.23 %, indicating near closure of the cross-shore transport balance. The modeled longshore current captured the leading magnitude and overall cross-shore structure of the analytical solution. Its peak was 0.906 m s^{-1} at $x=1680 \text{ m}$, compared with 0.813 m s^{-1} at $x=1620 \text{ m}$ in the analytical solution. This 60 m shoreward displacement may reflect differences between the local analytical balance and the three-dimensional model response. The latter also includes advection, vertical
400 mixing, vortex-force redistribution, bottom-stress feedback, and variations in local water depth. Overall, the model reproduced the dominant cross-shore compensation and longshore-current response within the surf zone.

3.3 Three-dimensional structure of wave-driven currents

Fig.3 extends the depth-mean diagnostics by showing the cross-shore–vertical structures of the Eulerian
405 velocity and Stokes drift. Within the surf zone, the cross-shore Eulerian velocity exhibited a distinct return-flow structure, with localized shoreward flow near the surface and offshore undertow dominating the middle and lower water column. The strongest offshore velocity was -0.4 m s^{-1} at $x=1620 \text{ m}$, whereas the maximum near-surface shoreward velocity was 0.321 m s^{-1} at $x=1600 \text{ m}$. The alongshore Eulerian velocity intensified markedly within the surf zone, forming a longshore current that reached
410 0.958 m s^{-1} at $x=1700 \text{ m}$. Meanwhile, the cross-shore Stokes drift remained shoreward throughout the wet water column and peaked at 0.147 m s^{-1} at $x=1620 \text{ m}$. Its largest values occurred near the surface and within the shallow breaking region, indicating sustained shoreward wave-induced transport. Offshore, the Stokes drift was strongly surface intensified, whereas its vertical variation weakened within the shallower surf zone.

415 The depth-mean diagnostics demonstrate cross-shore transport compensation and the principal magnitude of the longshore current, while the three-dimensional sections reveal their vertical organization. Together, these results support a dynamically consistent three-dimensional response under the activated WEC configuration. The contributions of individual momentum terms are examined further through the momentum budgets shown in Fig. 4.

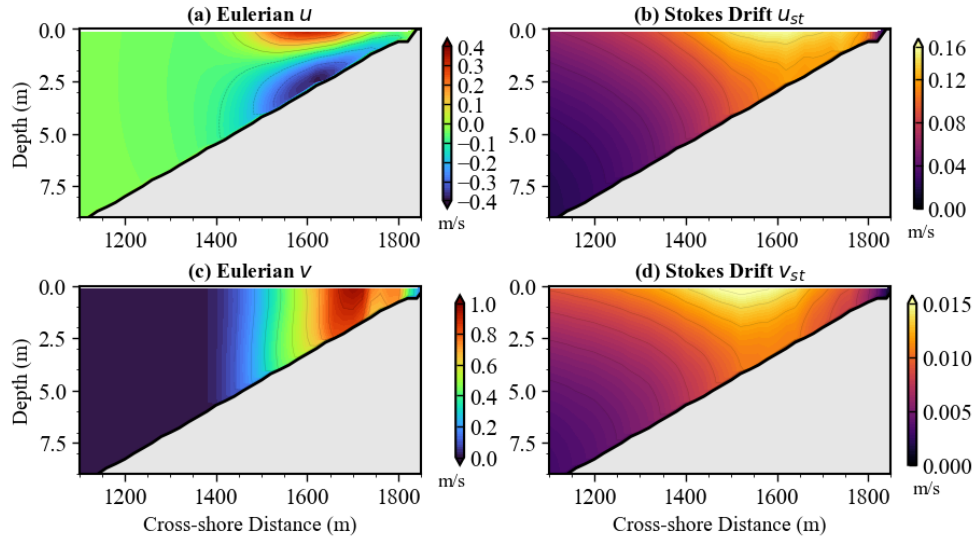


Figure 3. Cross-shore and vertical velocity structure driven by obliquely incident waves. The left column shows the cross-shore component u and alongshore component v of Eulerian velocity. The right column shows the corresponding Stokes drift. The panels display undertow, the longshore current, and their vertical structure within the surf zone. The horizontal and vertical axes show cross-shore distance (m) and depth (m), respectively.

3.4 Depth-integrated momentum budgets

Fig.4a shows that the depth-averaged cross-shore momentum budget was dominated by a near balance between pressure-gradient acceleration and breaking acceleration. As wave breaking intensified, the shoreward breaking acceleration reached $O(10^{-2}) \text{ m s}^{-2}$. The pressure-gradient acceleration closely counterbalanced this forcing, with an approximately equal magnitude and opposite direction across the main breaking zone. Bottom stress, horizontal vortex force, and horizontal advection were substantially weaker and provided only local corrections within the inner surf zone.

Fig.4 relates the free-surface and current responses shown in Figs. 2 and 3 to their time-mean momentum balances. In the cross-shore direction, breaking acceleration was closely counterbalanced by pressure-gradient acceleration, consistent with the setup and setdown pattern in Fig. 2b. The pressure-

gradient decomposition showed that the Eulerian non-WEC component, P_c dominated the total cross-shore pressure-gradient acceleration, while the quasi-static wave component, P_{qs} , provided a smaller correction. In the alongshore direction, the leading balance between breaking acceleration and bottom stress was consistent with the intensified longshore current in Figs. 2d and 3c. Within the inner surf zone, horizontal vortex force and horizontal advection were comparable in magnitude and largely offset one another. This secondary momentum redistribution may contribute to the modeled peak displacement and nearshore structure relative to the local analytical balance.

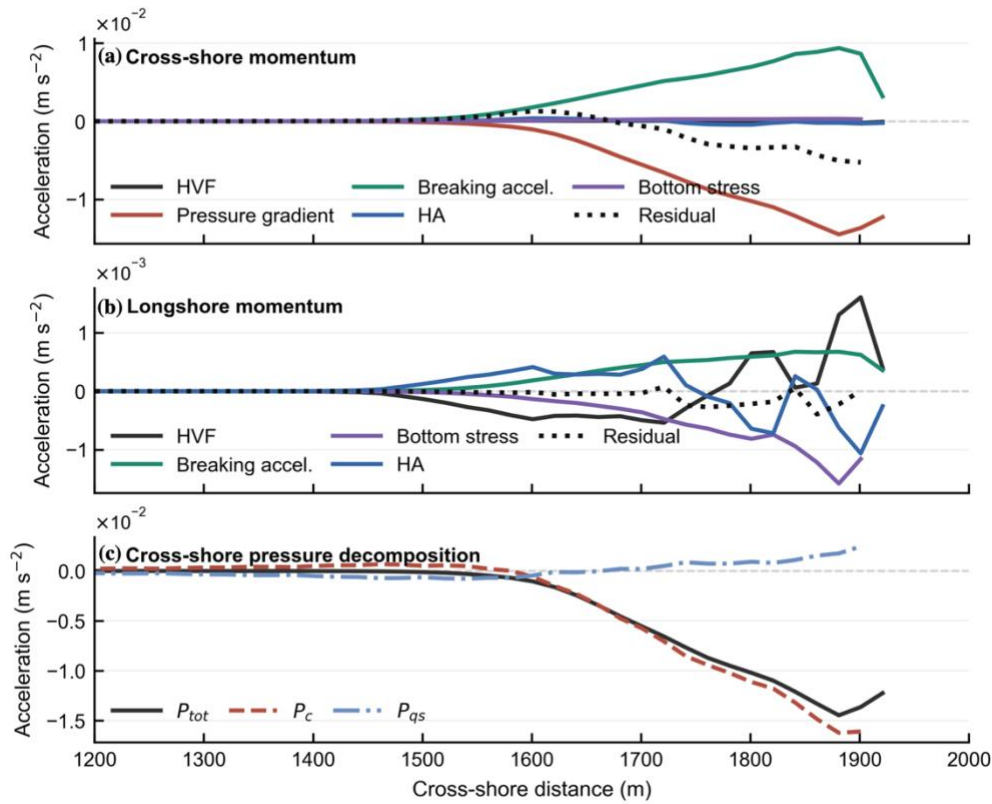


Figure 4. Cross-shore distributions of the depth-averaged momentum-budget terms and wave-induced force components under oblique wave incidence. (a) Cross-shore momentum budget, dominated by the balance between pressure-gradient acceleration (PG, red) and breaking-wave acceleration (BA, green), which governs wave setup and setdown. (b) Alongshore momentum budget, whose terms are smaller in



magnitude than their cross-shore counterparts. The leading balance between BA and bottom stress
450 drives the longshore-current response. (c) Decomposition of the total cross-shore wave-induced force
into the cross-shore wave-forcing and quasi-static components. The horizontal axis denotes the cross-
shore distance (m), increasing from the offshore boundary towards the shoreline.

4 DUCK94 barred-beach experiment

455 4.1 Experimental configuration

Following the plane-beach test in Sect. 3, the DUCK94 barred-beach case examines the performance of
ORCTM–SWAN v2.0 over a measured sandbar profile. The simulation represents conditions during the
storm on 12 October 1994, when obliquely incident waves generated strong longshore currents and
cross-shore undertow. This case has been widely used in three-dimensional wave–current modelling
460 studies (Garcez Faria et al., 2000; Newberger and Allen, 2007b; Uchiyama et al., 2010; Kumar et al.,
2012; Zheng et al., 2017).

The measured cross-shore profile was extended uniformly in the alongshore direction to form an 800 m
domain extending from a closed shoreline at $x = 0$ m to an offshore water depth of 7.26 m, with the
sandbar crest located near $x = 240$ m, as shown in Fig.5. A constant tidal elevation of 0.70 m was
465 superimposed on the mean sea level throughout the simulation. Periodic boundary conditions were
applied in the alongshore direction, while Coriolis acceleration was neglected. SWAN was forced by an
offshore JONSWAP spectrum, while ORCTM applied the roller-induced momentum transfer and the
Soulsby wave–current bottom-stress formulation. The roller parameters were adopted from previous
sensitivity experiments. The main forcing and numerical parameters are shown in Table 2.

470



Table 2. Model parameters used in the Duck94 simulation

Component	Configuration
Domain and Depth	800 m × 300 m; barred-beach bathymetry; constant still-water-level offset of 0.70 m
Grid	$\Delta x = \Delta y = 5$ m; 70 vertical levels with $\Delta z = 0.1$ m;
Boundaries	Western shoreline; eastern open boundary; periodic northern and southern boundaries
Wave forcing	SWAN-derived offshore JONSWAP spectrum; $H_s = 2.23$ m; $T_p = 6.0$ s; incident angle of 13°
Time and coupling	Simulation duration: 6 h; ORCTM time step: 2.0 s
Activated processes	Stokes transport; vortex forces; quasi-static wave pressure; depth-induced breaking acceleration; roller effects($\sin \beta = 0.1$; $\alpha_r = 1.0$)
Disabled processes	surface and bottom streaming;
Ocean physics	Soulsby wave–current bottom-stress formulation with $z_s = 0.001$ m; PP81 vertical mixing; biharmonic horizontal momentum diffusion with $A_4 = 0.25$ m ⁴ s ^{−1} ; homogeneous water
External forcing	Wind stresses $\tau_x = -0.253$ N m ^{−2} and $\tau_y = -0.146$ N m ^{−2} ; no Coriolis acceleration, heat flux, or freshwater forcing

4.2 Wave parameters

475 The wave field in the DUCK94 experiment is evaluated first. As the waves propagated shoreward, H_{rms} began to decrease on the seaward flank of the sandbar, with the main breaking-dissipation region extending across the bar crest and its shoreward flank (Fig. 5). The simulated H_{rms} agreed well with the observations, with a root-mean-square error of 0.079 m and a mean bias of -0.012 m, indicating that the model captured the observed cross-shore variation in wave height. Breaking and roller dissipation

480 exhibited distinct spatial distributions. The depth-induced breaking dissipation rate, ϵ^b/ρ_0 , was concentrated near the bar crest, whereas the roller dissipation rate, ϵ^r/ρ_0 diagnosed from the roller energy balance peaked farther shoreward and extended over a broader cross-shore region. This spatial offset indicates that part of the energy extracted from the organized wave motion during breaking was not dissipated locally, but was temporarily stored and transported shoreward within the roller before

485 being progressively dissipated. Having established the cross-shore structures of wave transformation and breaking–roller dissipation, the following analysis examines how the associated wave forcing shapes the mean circulation and redistributes momentum

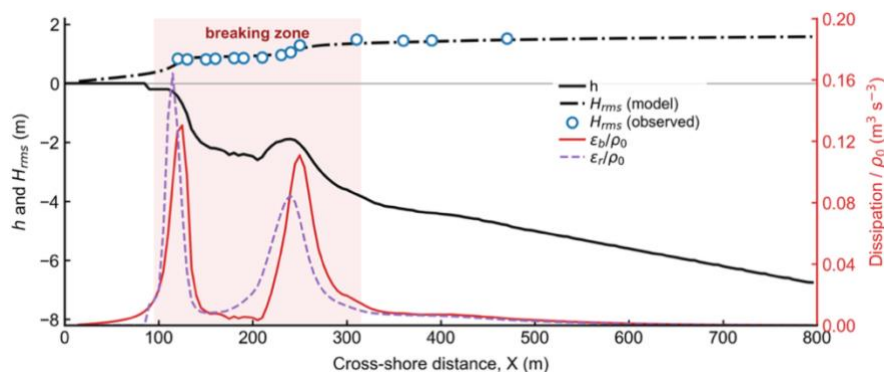


Figure 5. Cross-shore wave transformation in the DUCK94 simulation. The solid curve shows simulated H_{rms} , and blue circles show observations from Elgar et al. (1997). The black curve denotes water depth h . The red and purple dashed curves show depth-induced breaking dissipation ε^b/ρ_c and roller dissipation ε^r/ρ_c , respectively. Shading marks the principal breaking region.

4.3 Three-dimensional velocity profiles

Fig.6 shows the simulated three-dimensional Eulerian velocity and Stokes drift in the DUCK94 experiment. The cross-shore Eulerian velocity exhibits a typical undertow structure, with offshore flow occupying the middle and lower water column and strengthening near the sandbar (Fig. 6a). The enhanced vertical shear near the bar spatially coincides with the pronounced bathymetric variation and the concentrated wave breaking and momentum input. By contrast, the cross-shore Stokes drift is directed shoreward, reaches its maximum near the surface, and decreases rapidly with depth (Fig. 6b). The opposing directions of the Eulerian velocity and Stokes drift are consistent with an offshore Eulerian return flow that compensates the shoreward Stokes transport.

In the alongshore direction, the Eulerian flow forms a bar-controlled surf-zone jet (Fig. 6c). The current reaches approximately 0.9 m s^{-1} near $x=230 \text{ m}$, at the transition between the shoreward flank of the sandbar and the inner surf zone. The jet is strongest in the upper water column and weakens toward the bed, producing pronounced vertical shear. This vertical structure is consistent with the redistribution of alongshore momentum supplied by obliquely breaking waves through vertical mixing and bottom

friction. By comparison, the alongshore Stokes drift is substantially weaker than the Eulerian current and is more strongly confined to the upper water column (Fig. 6d), providing a smaller but surface-intensified contribution to the alongshore transport.

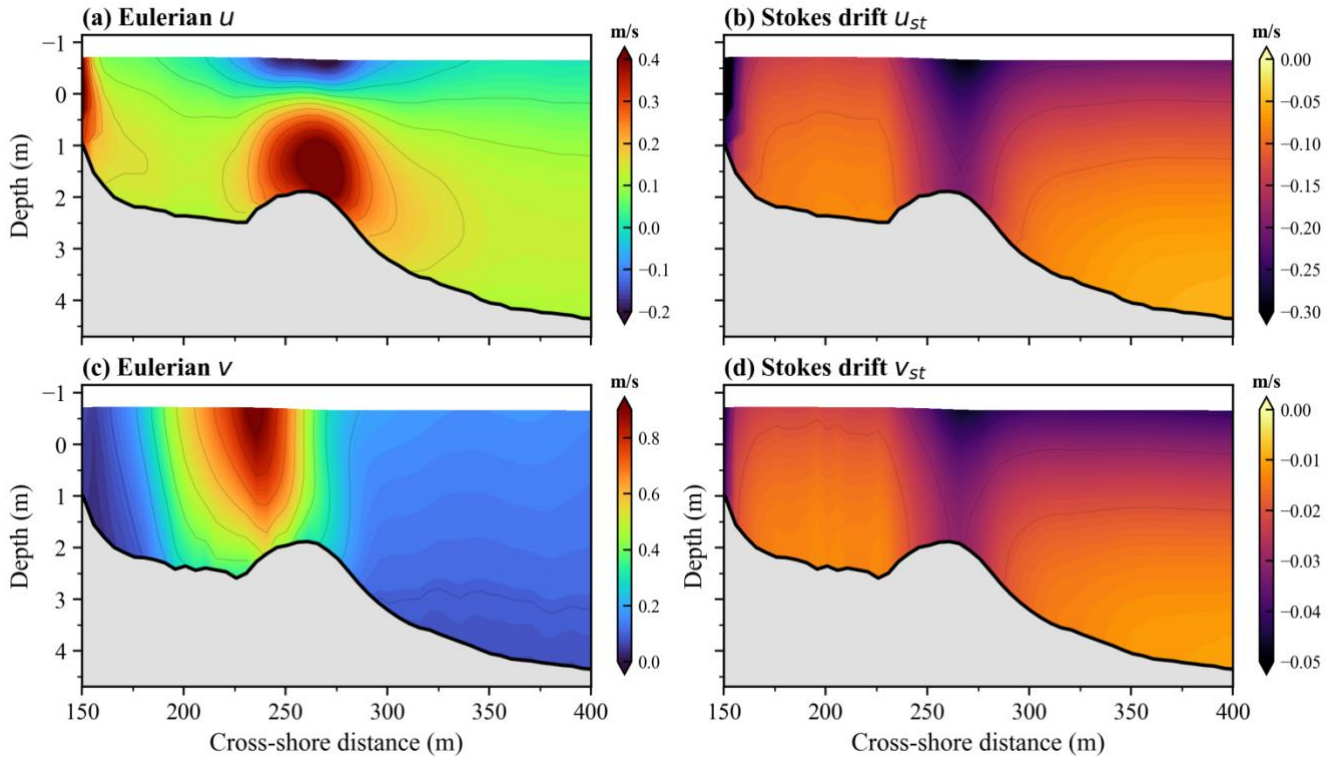


Figure 6. Simulated nearshore circulation with roller effects included. Panels (a–d) show vertical cross-shore sections of (a) the cross-shore Eulerian velocity u (m s^{-1}), (b) the cross-shore Stokes drift u^{st} (m s^{-1}) (c) the alongshore Eulerian velocity V (m s^{-1}), and (d) the alongshore Stokes drift v^{st} (m s^{-1}). The sections illustrate the enhanced undertow and alongshore current associated with the sandbar.

Fig.7 compares the simulated velocity profiles with the DUCK94 observations. Overall, the model reproduces the principal cross-shore undertow and alongshore jet over the barred beach. In particular, the simulated and observed profiles at locations 3–5 show broadly consistent velocity magnitudes and vertical variations. Across all valid comparison points, the cross-shore velocity U has an RMSE of 0.136 m s^{-1} , and a correlation coefficient of 0.64. The corresponding values for the alongshore velocity V are 0.178 m s^{-1} , and 0.83, respectively. The cross-shore comparison captures the leading undertow

structure but exhibits larger pointwise discrepancies. The following momentum-budget analyses examine the internal dynamical consistency of the simulated circulation.

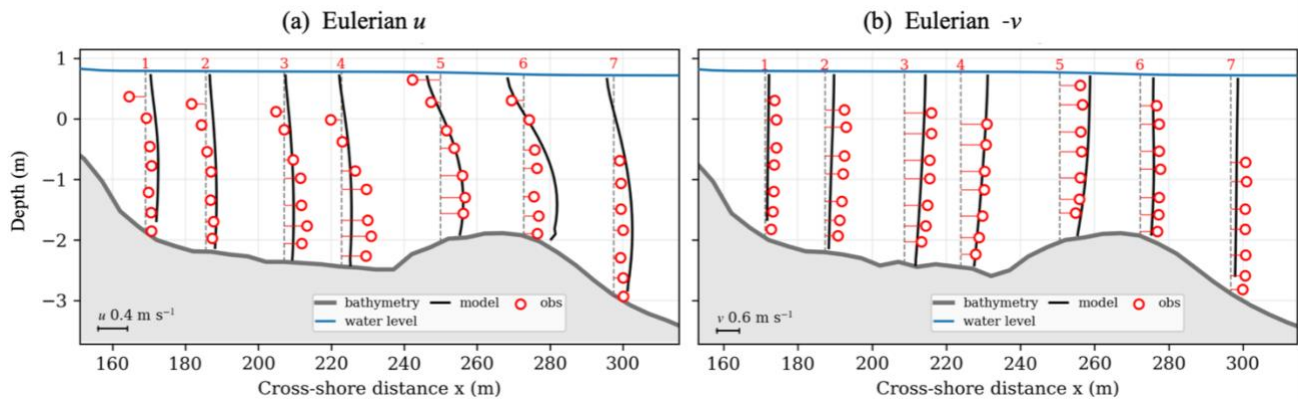


Figure 7. Comparison of simulated and observed vertical profiles of (a) cross-shore and (b) alongshore velocity. Black curves denote the model results, and red circles denote the observations. Vertical dashed lines indicate the profile locations and the zero-velocity reference for each profile; red numbers identify the profile numbers. Gray shading denotes the bathymetry, and the blue line indicates the water surface. Observations are from Garcez Faria et al. (1998, 2000).

4.4 Momentum analysis

Figures 8 and 9 present the depth-averaged and three-dimensional momentum budgets for the DUCK94 experiment, respectively. All terms are averaged over the quasi-steady period of the simulation. In the depth-averaged cross-shore budget (Fig. 8a), the leading balance over the sandbar and its shoreward slope $x \approx 210\text{--}270$ m is between the pressure-gradient and breaking accelerations. These terms have opposite signs and comparable magnitudes, with the pressure-gradient acceleration reaching a local maximum near $x = 240$ m. In the alongshore direction (Fig. 8b), the breaking/roller acceleration provides the principal momentum input, while bottom stress, horizontal advection (HA), and the horizontal vortex force (HVF) contribute to the balance. HA and HVF exhibit comparable but oppositely signed or spatially offset extrema between $x \approx 210\text{--}260$ m, indicating that the alongshore-current maximum does not necessarily coincide with the maximum wave forcing. Fig. 8c shows that the total cross-shore pressure-gradient acceleration, P_{tot} comprises both the current-related contribution, P_c and the quasi-static wave-pressure



contribution, P_{qs} . The marked variation and sign reversal of P across the bar–trough region indicate that the cross-shore pressure response is not determined by mean surface setup alone.

545 Fig.9 further resolves the vertical structure of the momentum-budget terms. In the cross-shore direction, x -BA and x -PG are concentrated primarily in the upper part of the breaking region and its surroundings, whereas x -VM extends more continuously over the shoreward flank of the sandbar and into the middle and lower water column. This distribution indicates that wave-induced momentum applied near the surface is transferred into the water column and toward the seabed through vertical mixing. In the
550 alongshore direction, y -BA is concentrated in the near-surface breaking region, while y -HVF and y -HA form adjacent positive and negative structures around the sandbar. The vertically layered distribution of y -VM coincides with regions of strong shear in the alongshore current. Together, these patterns are consistent with the cross-shore and vertical redistribution of breaking-wave momentum by horizontal advection, Stokes–vorticity interaction, and vertical mixing, with bottom friction contributing to the
555 limitation of the mean alongshore current.

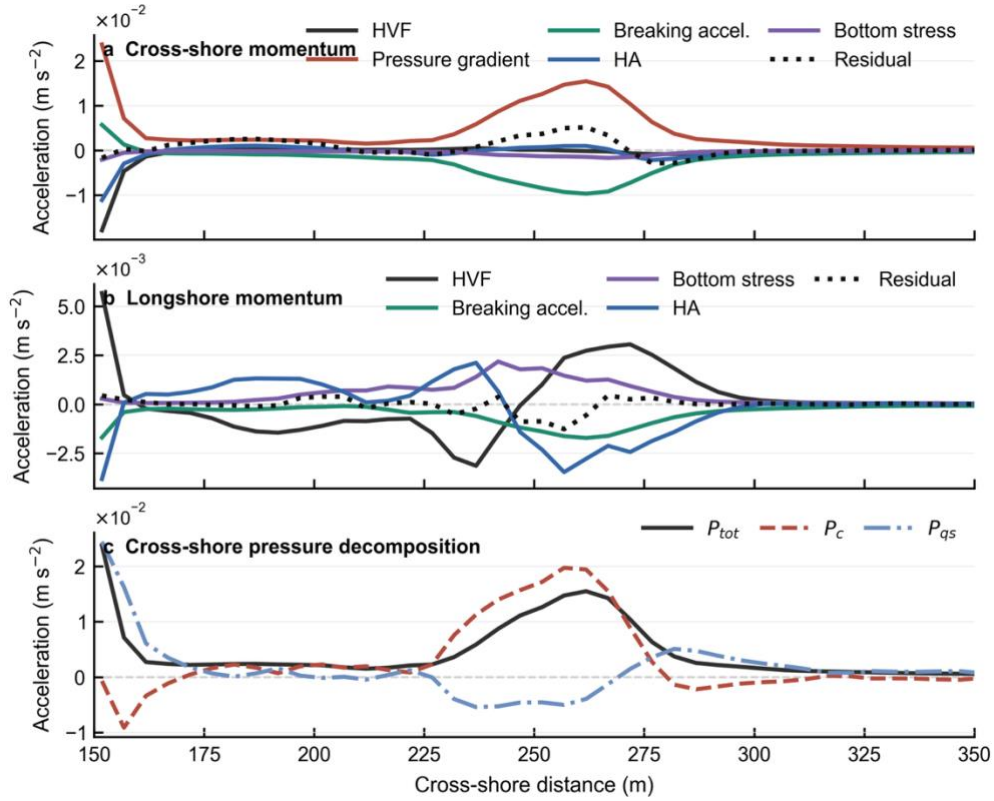


Figure 8. Depth-averaged momentum budgets and decomposition of the cross-shore pressure-gradient acceleration for the DUCK94 case. (a) Cross-shore momentum budget, including the horizontal vortex force (HVF), pressure-gradient acceleration, breaking acceleration, horizontal advection (HA), bottom stress, and residual. (b) Alongshore momentum budget, including HVF, breaking/roller acceleration, bottom stress, HA, and the residual. (c) Decomposition of the cross-shore pressure-gradient acceleration into the total pressure-gradient term (P_{tot}), the Eulerian non-WEC pressure contribution (P_c), and the quasi-static wave-pressure contribution (P_{qs})

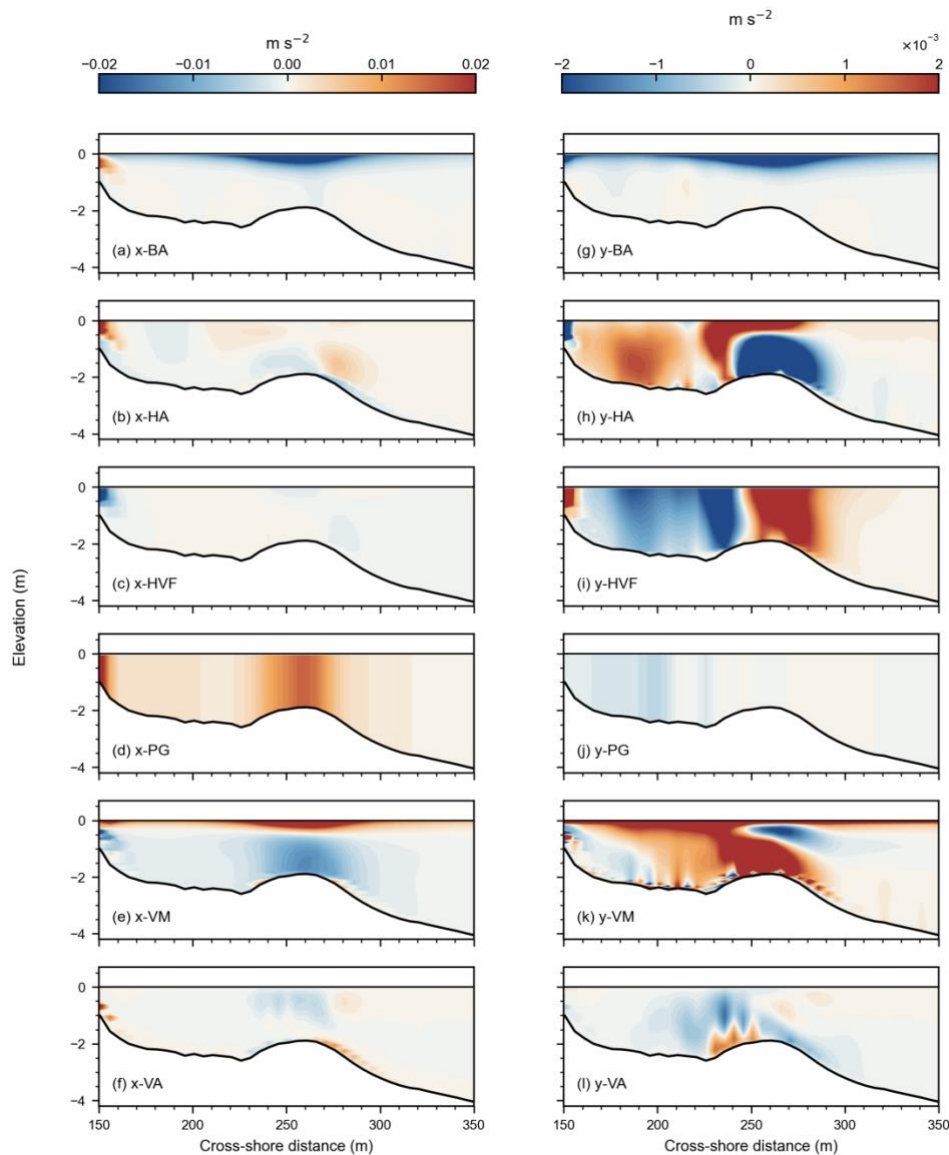


Figure 9. Cross-shore and vertical distributions of the time-averaged three-dimensional momentum-budget terms for the DUCK94 case. Cross-shore components: (a) breaking acceleration x-BA, (b) horizontal advection x-HA, (c) horizontal vortex force x-HVF, (d) pressure-gradient acceleration x-PG, (e) vertical mixing x-VM, and (f) vertical advection x-VA. Alongshore components: (g) breaking/roller acceleration y-BA, (h) horizontal advection y-HA, (i) horizontal vortex force y-HVF, (j) pressure-gradient acceleration y-PG, (k) vertical mixing y-VM, and (l) vertical advection y-VA.

4.5 Roller activation comparison

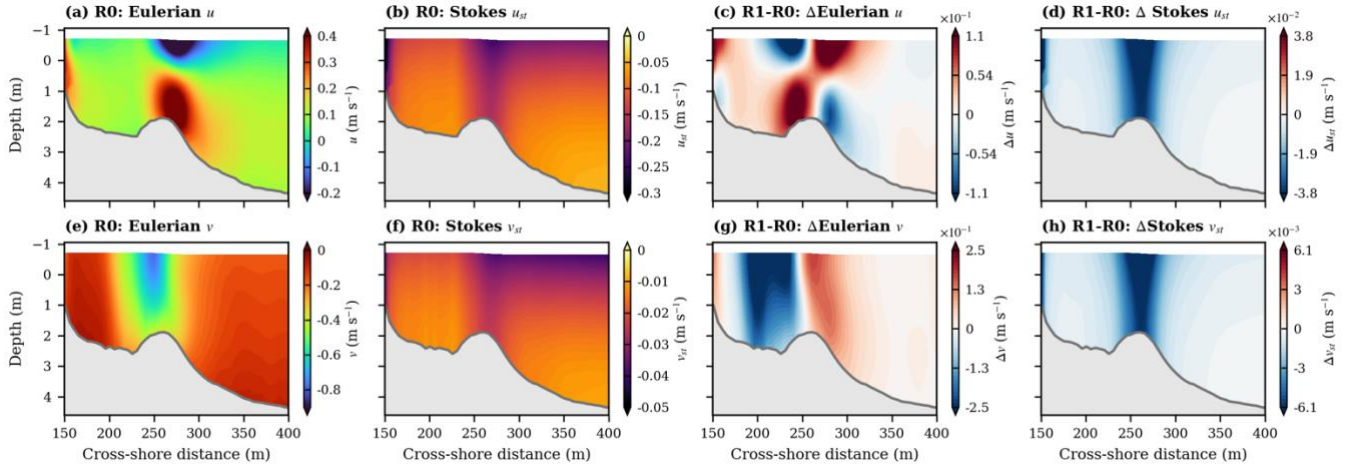


Figure 10. Sensitivity of Eulerian and Stokes velocity components to roller activation in the DUCK94 benchmark. R0 denotes the roller-off case ($\alpha_r = 0$), and R1 denotes the roller-on case ($\alpha_r = 1$). Difference panels show $\Delta = R1 - R0$. Panels (a, c, e, g) show Eulerian velocity components, while panels (b, d, f, h) show Stokes drift components. Roller activation mainly modifies the Eulerian circulation near the bar and surf-zone transition, whereas the associated changes in Stokes drift are much smaller.

Fig.10 compares the DUCK94 simulations with the roller parameterization disabled and enabled. R0 denotes the roller-off case $\alpha_r=0$ whereas in R1 $\alpha_r=1$, the full depth-induced breaking dissipation is transferred through the roller energy balance. The corresponding dissipation distributions are shown by the purple (ϵ^r/ρ_c) and red lines ϵ^b/ρ_c in Fig.5. Previous sensitivity studies of the DUCK94 and other barred-beach cases have shown that the roller parameter controls the shoreward displacement and broadening of breaking-related energy dissipation and momentum input, thereby affecting both the undertow and the alongshore current (Garcez Faria et al., 2000; Newberger and Allen, 2007b; Uchiyama et al., 2010; Kumar et al., 2012; Zheng et al., 2017). The reference value $\alpha_r=1$, adopted here follows these previous studies.



The R1–R0 difference fields show that activating the roller parameterization primarily modifies the Eulerian circulation over the sandbar and near the transition to the inner surf zone. The largest differences occur above the sandbar and on its shoreward slope, corresponding to the region of strongest breaking- and roller-related momentum input. The maximum absolute differences are approximately 0.1 m s⁻¹ for the cross-shore Eulerian velocity and 0.25 m s⁻¹ for the alongshore Eulerian velocity. By contrast, the changes in Stokes drift are substantially smaller, reaching approximately 4×10^{-2} m s⁻¹ for U_{st} and 6×10^{-3} m s⁻¹ for V_{st} . The circulation sensitivity therefore arises mainly from the roller-mediated redistribution of breaking-wave momentum within the Eulerian flow, rather than from changes in Stokes transport. This behaviour is consistent with previous VF-WEC and nearshore modelling studies, in which roller dynamics primarily modify the spatial distribution of breaking-related momentum input and the resulting wave-driven circulation (Kumar et al., 2012; Zheng et al., 2017).

5 Discussion and summary

ORCTM v2.0 extends ORCTM v1.0 with an online, one-way SWAN-to-ORCTM capability to represent wave effects on currents within the established vortex-force formalism. The contribution is the realization of this formalism in the native C-grid, z-level, partial-cell, and barotropic–baroclinic architecture of ORCTM (Huang et al., 2023). Through OASIS3-MCT, bulk SWAN diagnostics are mapped to ORCTM and used to reconstruct the three-dimensional fields required by the mass, free-surface, pressure, and momentum pathways. Term-resolved diagnostics distinguish the conservative Stokes transport and Stokes–vorticity pathways from parameterized non-conservative momentum transfer associated with wave losses (McWilliams et al., 2004; Lane et al., 2007; Uchiyama et al., 2010; Kumar et al., 2012).

The two benchmarks constitute a staged evaluation of the same implementation rather than two independent application exercises. The plane-beach case first isolates equation-level consistency under controlled forcing and monotonically varying bathymetry. The water-level RMSE of 0.0077 m supports the consistency of the implemented pressure and free-surface pathways, while the 5.23 % residual between the Eulerian return transport and the opposing Stokes transport provides a complementary test of the modified continuity response. DUCK94 then examines whether these pathways remain coherent when transferred to measured barred bathymetry, spatially varying wave dissipation, and observation-



constrained forcing. The significant-wave-height RMSE of 0.079 m indicates reasonable agreement in
 620 the simulated wave transformation before the circulation response is assessed., while the velocity
 correlations indicate more coherent agreement for the longshore current than for the station-dependent
 undertow profiles. Across the two cases, the model reproduces the leading surf-zone circulation response,
 but the current maxima do not necessarily coincide with either the analytical prediction or the local
 maximum in wave forcing. The 60 m displacement of the plane-beach longshore-current maximum and
 625 the bathymetrically controlled displacement of the DUCK94 jet therefore mark the transition from an
 idealized local balance to the spatially integrated response of the three-dimensional model.

The momentum budgets explain these spatial displacements and connect the responses in the two
 benchmarks. In the cross-shore direction, wave-loss-related momentum input is largely opposed by
 pressure-gradient adjustment. In the alongshore direction, non-conservative wave-momentum input and
 630 bottom stress form the leading source and sink, whereas horizontal advection (HA) and the horizontal
 vortex force (HVF) reshape their spatial balance. The HVF represents the interaction of Stokes drift with
 current vorticity and belongs to the conservative Stokes–vorticity pathway rather than to the
 parameterized wave-loss source (Uchiyama et al., 2009, 2010; Kumar et al., 2012). Its locally comparable
 magnitude and spatially offset structure relative to HA indicate that these terms can redistribute the forced
 635 circulation without constituting the dissipative momentum input itself. This distinction between
 momentum input and subsequent redistribution explains why the longshore-current maximum can be
 separated from the maximum wave-dissipation forcing and illustrates the diagnostic advantage of
 retaining the individual VF terms.

To isolate and evaluate the implemented WEC momentum pathways, the experiments retain the original
 640 Richardson-number-dependent PP81 closure as a common vertical-mixing baseline. In this configuration,
 SWAN breaking dissipation is not coupled as a surface TKE flux, and Langmuir turbulence is not
 parameterized. Nevertheless, WEC forcing can modify vertical velocity shear and thereby adjust the PP81
 eddy viscosity through its Richardson-number dependence. The resulting current profiles therefore
 characterize the response to the implemented WEC momentum forcing within the PP81 mixing
 645 framework, rather than quantify the additional mixing associated with breaking-wave TKE input or
 Langmuir turbulence. This controlled configuration provides a baseline for distinguishing momentum-



driven changes in circulation from additional changes produced by breaking-induced and Langmuir-enhanced turbulence. Extending ORCTM with prognostic and wave-aware turbulence closures will enable these contributions to be evaluated separately in future coupled applications.

650 Together, these results establish ORCTM v2.0 as a numerically consistent and diagnostically traceable for representing wave effects on currents within a regional z-level ocean model. Its main contribution is not limited to reproducing the circulation patterns of the two benchmarks, but lies in integrating the vortex-force formulation into the C-grid, partial-cell of ORCTM, while reconstructing the required three-dimensional wave quantities from online SWAN bulk diagnostics. The resulting implementation provides
655 internally consistent mass, free-surface, pressure, conservative Stokes–vorticity, and non-conservative wave-momentum pathways, together with term-resolved diagnostics that allow wave forcing, pressure adjustment, advection, vertical mixing, and bottom stress to be distinguished in the simulated response. The present one-way benchmarks therefore provide a controlled foundation rather than an exhaustive demonstration of the applicability of model. ORCTM v2.0 can now support regional investigations of
660 wave-modified circulation and transport, while further developments should evaluate current-to-wave feedback, wave-aware turbulence closures, and the behavior of the coupled system under realistic stratification, complex bathymetry, and regional forcing.

Appendix A: Coupling variables and interface status

Table A1 documents the SWAN-to-ORCTM variables communicated by the evaluated interface and
665 distinguishes direct model inputs from fields retained for optional parameterizations. The reported SWAN runs used INRHOG=1; consequently, DISB, DISSU, and DISW were communicated as energy-dissipation rates per unit horizontal area in $W\ m^{-2}$.

Table A1. SWAN-to-ORCTM field and unit contract.

Interface field	Interface unit	ORCTM processing and downstream use
SWH (H_s)	m	Significant wave height; used to calculate the representative wave energy $E/\rho_0 = gH_s^2/16$ and reconstruct the Stokes drift (Sect. 2.2.1; Eq. (4) and (7)).
MDIR (θ)	degree	Mean wave direction; converted from the SWAN nautical convention as $\theta = 3\pi/2 - \theta_{SWAN}$ and used to obtain $k_x = k \cos \theta$ and $k_y = k \sin \theta$.
PDIR (θ_p)	degree	Spectral-peak direction;



Interface field	Interface unit	ORCTM processing and downstream use
AWL (L)	m	Average wavelength; used to calculate $k = 2\pi/L$ and the representative intrinsic frequency σ and phase speed c (Sect. 2.2.1; Eq. (8-9)).
SWP (T_p)	s	Relative peak period at the surface
BWP (T_b)	s	Near-bottom wave period; used with uorbw in the Soulsby wave–current bottom-stress formulation applied in DUCK94 (Sect. 2.6; Eq. (36-40)).
PBW (Q_b)	%	Fraction of breaking waves; retained for the optional Svendsen and monochromatic roller formulations
DISB (ϵ^{bf})	W m^{-2}	SWAN bottom-friction wave-energy dissipation;
DISSU (ϵ^b)	W m^{-2}	Depth-induced breaking dissipation; used in the breaking-related momentum input and as the energy source for the Reniers roller model (Sect. 2.4.1b–c).
DISW (ϵ^{wcap})	W m^{-2}	Whitcapping dissipation; used in the whitcapping-induced momentum input (Sect. 2.4.1a).
WBOV (u_{orbw})	m s^{-1}	RMS near-bottom orbital velocity; used in the Soulsby wave–current bottom-stress formulation applied in DUCK94 (Sect. 2.6; Eq. (36-40)).

670 The coupling interface transfers the SWAN bulk variables required by the WEC and wave–current bottom-stress formulations. To evaluate wave effects on currents, the benchmarks employed one-way SWAN-to-ORCTM coupling. The framework also provides an ORCTM-to-SWAN pathway for transferring WSL, UX2, and VY2, enabling future two-way coupling.

675 **Table A2. Reserved ORCTM-to-SWAN interface fields.**

Interface field	Interface unit	Intended ORCTM-to-SWAN quantity and status
WSL (ζ)	m	ORCTM sea-surface elevation;
UX2 (u)	m s^{-1}	ORCTM surface current in the model x direction;
VY2 (v)	m s^{-1}	ORCTM surface current in the model y direction;

Code and data availability

The source code developed for ORCTM–SWAN v2.0 is archived on Zenodo (<https://zenodo.org/records/23068534>), and the archive includes the coupling modules, the model grids, bathymetry, forcing data, and boundary conditions, and configuration files for the planar-beach and DUCK94 benchmark experiments. The SWAN model v41.51 can be get : <https://swanmodel.sourceforge.io/download/zip/swan4151.tar.gz>. The OASIS3-MCT v6.0 coupler is



maintained by CERFACS code is available at <https://oasis.cerfacs.fr/en/download-oasis3-mct-sources/> or <https://zenodo.org/records/18020824>. The fixed-array pressure and current-meter observations from the DUCK94 experiment are available from Elgar and Raubenheimer (doi:10.5281/zenodo.8286252).

685 **Author contributions**

CY worked on the coding tasks for coupling SWAN with ORCTM using OASIS3-MCT, and performed the simulations for the numerical experiments. CY, PZ and XC developed the wave–current coupling framework and worked on the technical details for debugging the model. JZ and SW contributed to the analysis and interpretation of the results. HH and JG contributed to the technical details. All authors
690 discussed the results, and contributed to revising the manuscript.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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