

Article

Stokes Drift Drives the Intensification of Nearshore Submesoscale Fronts in the Northern South China Sea

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Abstract

Submesoscale processes in marginal seas are central to the ocean's energy cascade, mixed-layer dynamics, and biogeochemical exchanges and are typically driven by complex mechanisms influenced by local background currents as well as external forcings such as winds, tides, and topography. Among these drivers, however, the role of surface gravity waves has received comparatively little attention. In this study, we investigate the influence of surface waves on nearshore submesoscale processes in the northern South China Sea using high-resolution nested simulations with the Coastal and Regional Ocean COmmunity model (CROCO). The model implements the Eulerian wave-averaged current equations based on the vortex-force formalism, accounting for wave-induced effects. Our results reveal that onshore Stokes drift induces an onshore transport of water masses, thereby raising the nearshore sea level and intensifying nearshore currents. The strengthened currents, in turn, enhance convergence- and strain-induced frontogenesis, leading to the intensification of nearshore submesoscale fronts. These findings elucidate a specific mechanistic link between wave-induced sea-level changes and submesoscale dynamics, contributing to a better understanding of the role of surface waves in shaping coastal circulation.

Keywords: submesoscale fronts; Stokes drift; wave–current interaction; turbulent thermal wind

1. Introduction

Ocean submesoscale processes refer to a class of dynamical phenomena with spatial scales ranging from several hundred meters to tens of kilometers [1–3] and temporal scales spanning from several hours to a few days [3–5]. These processes include fronts, filaments, and small eddies. Situated between mesoscale eddies and small-scale turbulence, submesoscale dynamics play a central role in bridging the energy pathways across scales. On the one hand, they facilitate a forward energy cascade from balanced geostrophic flows to smaller dissipative scales, predominantly through secondary instabilities [1,2,6,7]. On the other hand, instabilities associated with submesoscale processes can also trigger a reverse energy cascade, returning energy toward mesoscale motions and thereby reshaping the larger-scale circulation [4,8,9].

A defining characteristic of submesoscale dynamics is the presence of strong horizontal gradients and intense vertical motions. These features substantially enhance vertical exchange and mixing in the upper ocean, thereby exerting a first-order influence on air–sea interactions. Specifically, submesoscale processes mediate the transfer of heat and materials



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between surface and subsurface layers, accelerating heat loss from the ocean surface and modifying local weather and climate variability [10–12]. At the same time, by transporting and redistributing nutrients, they directly regulate marine primary productivity and phytoplankton distributions, leading to rapid ecological responses with important implications for ecosystem stability and fishery resources [13–16]. Collectively, these processes represent a vital link between physical circulation and marine biogeochemistry.

In recent years, an emerging body of research has highlighted the significant role of surface waves in shaping submesoscale variability, recognizing that surface gravity waves and internal waves share fundamental physical principles in how they modulate eddies and balanced flows [17]. Theoretically, the coupling between Stokes drift and vertical shear generates secondary circulations—known as the Craik–Leibovich mechanism [18]—which is fundamental to the formation of Langmuir cells and the sharpening of upper-ocean gradients. Advancements in wave–current interaction theory have further demonstrated that wave forcing can act as an impulsive body force to generate circulation [19] and that a sheared mean drift is dynamically mandated by the intrinsic momentum, vorticity, and energy balances within irrotational wave fields [20]. For instance, Suzuki et al. (2016) and McWilliams (2018) demonstrated that surface gravity waves strongly modulate the dynamics of submesoscale fronts and filaments by altering ageostrophic secondary circulations [21,22]. In particular, the Stokes drift induced by surface waves enhances vertical mixing and secondary currents, thereby intensifying or reshaping frontal structures. Building on this, Hypolite et al. (2021) [23] emphasized that wave–current interactions amplify near-surface velocity and density gradients, with the effects being especially pronounced during energetic wave events. Both remotely generated swells and locally forced wind waves act to sharpen surface gradients; notably, wind-driven waves induce distinctive roll-cell patterns that disrupt conventional submesoscale dynamics and give rise to new modes of variability. Despite these theoretical insights into wave–eddy interactions, waves can act as either a source or a sink for balanced flow energy depending on the specific dynamical regime [24].

In nearshore regions, the presence of a coastal boundary allows onshore-directed Stokes drift to markedly alter sea level and modify the pressure gradient force, potentially influencing nearshore currents and associated frontal processes. However, these effects remain insufficiently explored. To address this gap, the present study investigates the role of surface waves in shaping submesoscale fronts, with a focus on shallow nearshore waters in the northern South China Sea.

The remainder of this paper is organized as follows: Section 2 introduces the numerical experiment design. Section 3 presents and analyzes the simulation results, revealing how surface waves modulate nearshore submesoscale fronts. Section 4 summarizes the main findings and discusses their broader implications.

2. Model Setup and Data

To examine the modulation of nearshore submesoscale dynamics by surface waves in the northern South China Sea, we utilize the Coastal and Regional Ocean COmmunity model (CROCO) to perform high-resolution nested simulations. The integration of wave-induced impacts in the model follows the theoretical frameworks of McWilliams et al. (2004) and Uchiyama et al. (2010), which utilize the vortex force formalism [25,26]. This approach represents a modern, depth-dependent reformulation of the classical wave radiation stress theory established by Longuet-Higgins and Stewart (1964) [27]. The wave-induced momentum flux, traditionally represented by the wave radiation stress gradients, is integrated through partitioned components, specifically incorporating the Stokes Coriolis force, the Stokes vortex force, and wave-driven pressure variations (Bernoulli head). This partitioning

allows the model to resolve the vertical structure of the wave forcing. Additionally, the model accounts for non-conservative phenomena related to the dissipation of current and wave energy, including wave streaming and breaking [26,28]. The robustness of CROCO in resolving wave–current coupling has been demonstrated in various prior studies, including research on nearshore rip currents [29–31], wave-driven streaming [28,32,33], and coastal upwelling or downwelling events [34,35]. These successful applications confirm the model’s reliability for the present investigation. The model integrates the hydrostatic wave-averaged primitive equations. The primitive equations for momentum, continuity and tracers are given by:

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}_L \cdot \nabla) \mathbf{u} + f \mathbf{k} \times \mathbf{u}_L = -\nabla \phi + \mathcal{F} + \mathcal{D}, \quad (1)$$

$$\frac{\partial \phi}{\partial z} = -\frac{g\rho}{\rho_0}, \quad (2)$$

$$\nabla \cdot \mathbf{u}_L = \frac{\partial u_L}{\partial x} + \frac{\partial v_L}{\partial y} + \frac{\partial w_L}{\partial z} = 0, \quad (3)$$

$$\frac{\partial C}{\partial t} + \nabla \cdot (\mathbf{u}_L C) = \mathcal{F}_C + \mathcal{D}_C, \quad (4)$$

where $\mathbf{u}$ represents the Eulerian velocity vector, while $\mathbf{u}_L$ denotes the Lagrangian velocity vector, defined as the sum of the Eulerian velocity and the Stokes drift velocity $\mathbf{u}_{st}$. f is the Coriolis parameter, $\mathbf{k}$ is the vertical unit vector, g is the acceleration due to gravity, ρ is the in situ density, and ϕ represents the dynamic pressure. C represents a scalar property such as potential temperature or salinity. $\mathcal{F}$ and $\mathcal{D}$ denote the forcing and dissipation terms of momentum, while $\mathcal{F}_C$ and $\mathcal{D}_C$ account for the forcing and diffusive dissipation terms of tracers.

The numerical experiments utilize a curvilinear horizontal grid (latitude–longitude) and terrain-following (sigma-type) vertical layers. We define 31 vertical levels in the system, applying grid refinement near both the surface and seabed boundaries (Figure 1). The model configuration uses a one-way, offline nesting scheme, whereby boundary data from a coarse parent domain (L1, horizontal resolution ~3 km) is transmitted to a refined child domain (L2, horizontal resolution ~1 km). As specified by Penven et al. (2006) [36], no interactive feedback from the child to the parent grid is incorporated. By adopting this hierarchical nesting setup, the model effectively resolves submesoscale structures while optimizing computational resources.

To resolve vertical turbulent processes, K-profile parameterization (KPP) is applied to both tracers and momentum [37], while a Laplacian operator is utilized for horizontal mixing [38]. The advection of momentum and tracers is managed by a fifth-order weighted essentially non-oscillatory (WENO5) scheme. This algorithm, characterized by its quasi-monotone features, is chosen to suppress artificial diffusion and improve computational stability across all spatial dimensions [39]. Regarding the domain edges, open boundary conditions (OBCs) are implemented using a suite of algorithms tailored to different physical variables. For the barotropic mode, we employ characteristic-based condition to regulate sea surface height and depth-averaged currents, respectively. For the baroclinic mode (3D velocity) and tracers (temperature and salinity), radiation-type condition is applied in conjunction with adaptive nudging [40].

Atmospheric forcing at the sea surface, encompassing wind stress as well as heat and freshwater fluxes, is derived from the hourly ERA5 reanalysis at a grid resolution of $0.25^\circ \times 0.25^\circ$, provided by the ECMWF [41]. The three-dimensional initial and boundary states for salinity, temperature, and currents are based on the Global Ocean Physics Analysis and Forecast (GOPAF) data, which is sampled every six hours at a spatial scale of

$0.083^\circ \times 0.083^\circ$. Furthermore, wave-driven inputs—including wave period, direction, and significant height—are supplied by the three-hourly Global Ocean Waves Analysis and Forecast (GOWAF) dataset, featuring a horizontal resolution of $0.125^\circ \times 0.125^\circ$ [42].

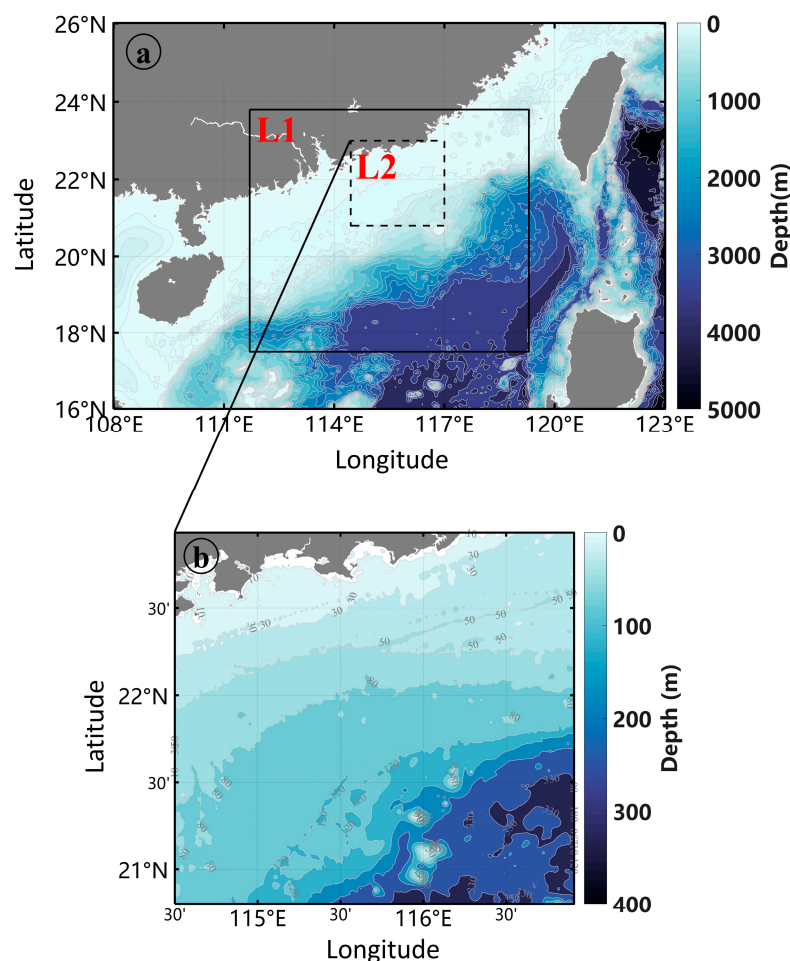


Figure 1. (a) Seafloor topography of the northern South China Sea. The extent of the parent grid (L1) is delineated by a solid black outline, while the nested child grid (L2) is represented by a dashed black rectangle. (b) Detailed bathymetric map specifically for the L2 domain.

The model is integrated from 1 October to 22 November 2021, covering a strong cold-air outbreak that generates high wave conditions and pronounced wave–current interactions. To allow for dynamical adjustment and to minimize spin-up effects, the final 20 days are used for analysis, which strikes a balance between capturing energetic wave-driven events and focusing on the mature and dynamically adjusted model state.

3. Results

3.1. Sea Surface Height

As shown in Figure 2, the cold air outbreak on 8 November 2021 triggered a sharp increase in wind stress and markedly enhanced surface wave activity. Following this event, the sea surface temperature (SST) exhibited a steady decline of nearly 1°C over the next ten days. Meanwhile, horizontal SST gradients intensified and reached a quasi-equilibrium state around 13 November, as indicated by the shaded areas in Figure 2.

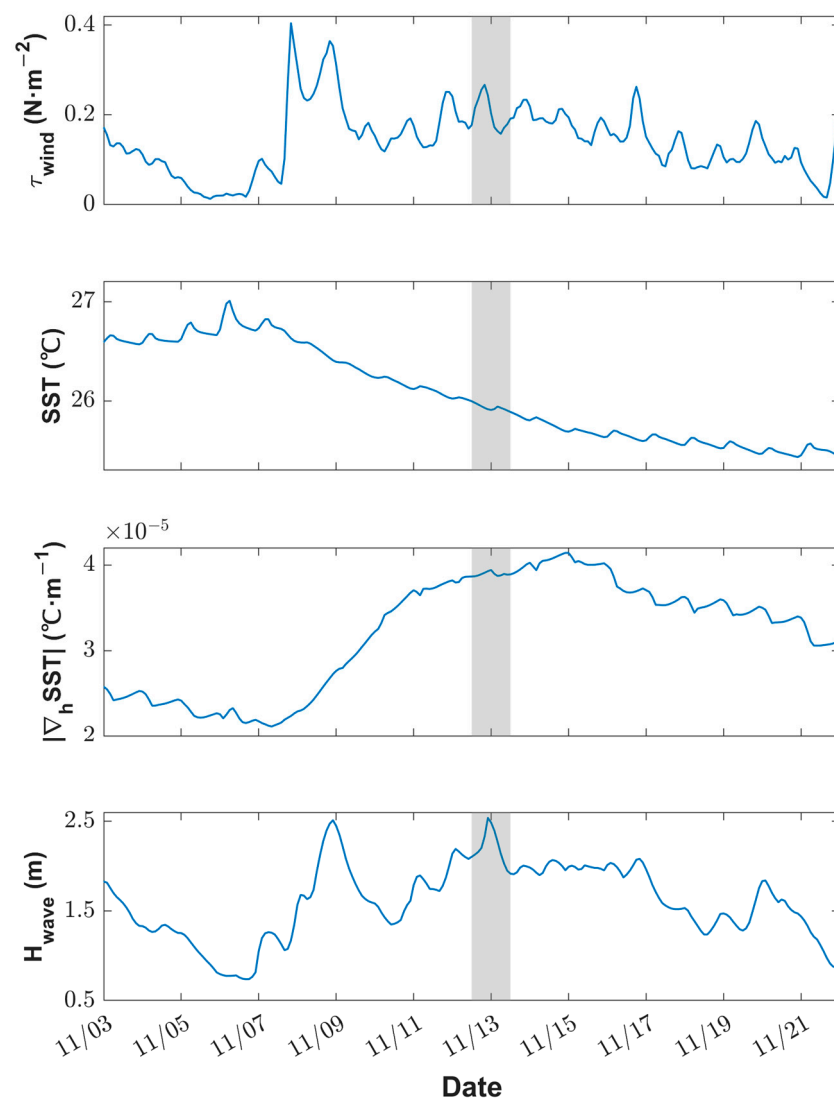


Figure 2. Panels from top to bottom show time series of wind stress (τ_{wind}), SST, horizontal SST gradients, and significant wave height (H_s). All variables are averaged horizontally over the L2 region. The shaded gray areas mark the period with significant wave heights exceeding 2 m and strong SST gradients.

In shallow waters, the reduced wave phase speed caused refraction that directed wave propagation toward the shore (Figure 3a), thereby strengthening the onshore Stokes drift. To capture this effect, the analysis focused on the dashed-box region in Figure 3a, where sea surface height (SSH) differences between the wave and no-wave cases were most pronounced (Figure 3e). Within this area, the onshore Stokes transport intensified progressively toward the coast (Figure 3b), reflecting the cumulative effect of wave-induced mass flux. As a result, the convergence of this transport near the shoreline led to water accumulation and a distinct rise in SSH relative to the no-wave case (Figure 3c–f). This phenomenon represents a wave-induced ‘set-up’, which is driven by two complementary mechanisms. First, the energetic wave conditions during the cold-air outbreak induce distributed dissipation via bottom friction and white-capping across the inner shelf. This leads to a sustained decrease in wave radiation stress and a consequent rise in mean water level, as conceptualized by the momentum balance framework of Bowen et al. (1968) [43]. Second, the continuous landward mass transport via Stokes drift results in mass convergence against the coastal boundary, further elevating the nearshore sea surface.

Hereafter, unless otherwise specified, the analysis is conducted within the dashed-box region in Figure 3a, where wave effects on nearshore processes are pronounced.

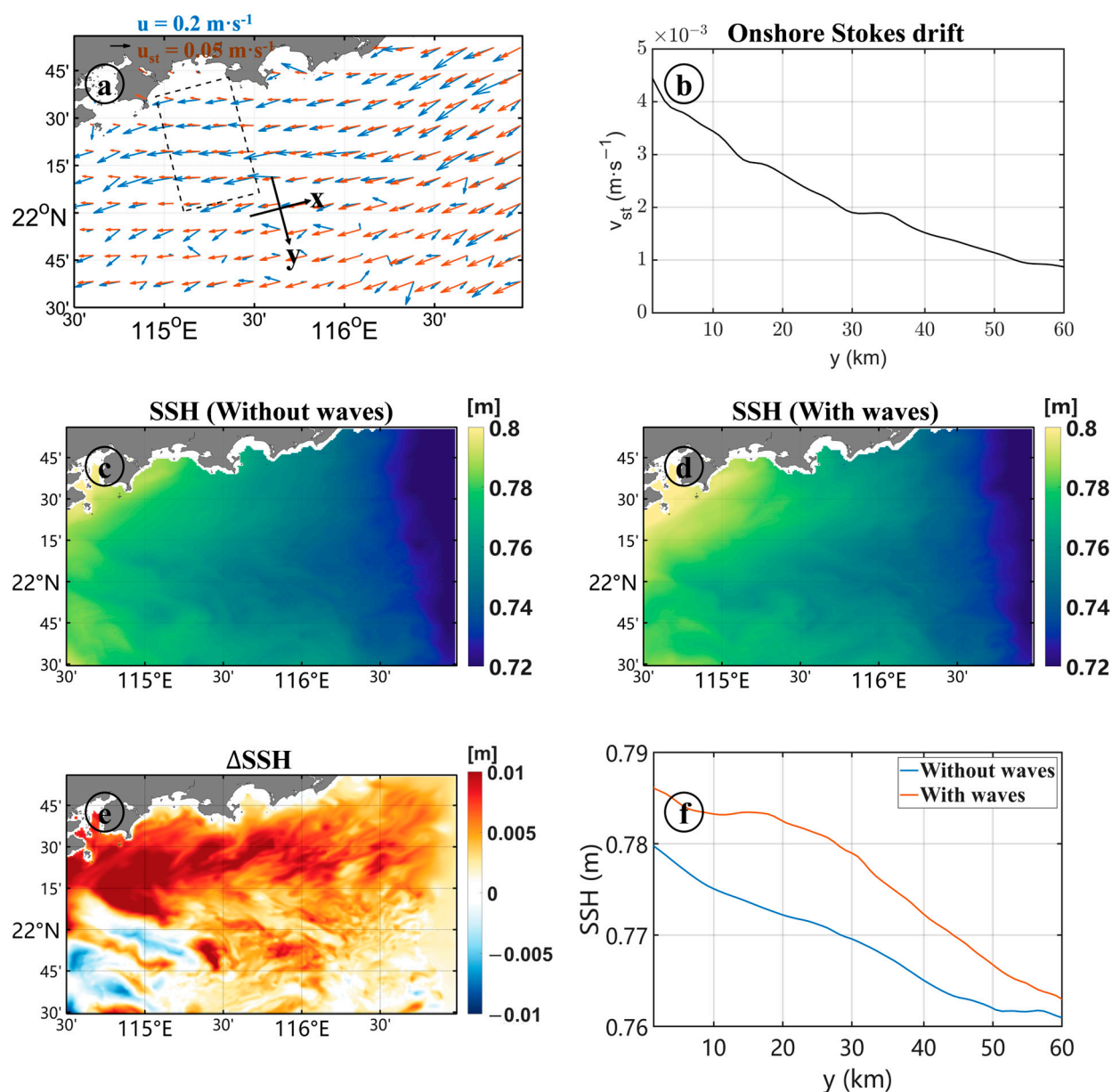


Figure 3. (a) Surface ocean currents (blue arrows) and Stokes drift (orange arrows). (b) Alongshore-averaged onshore Stokes drift velocity in the cross-shore direction. Sea surface height (SSH) fields: (c) without waves, (d) with waves, and (e) their difference ($\text{SSH}_{\text{wave}} - \text{SSH}_{\text{nowave}}$). (f) Alongshore-averaged SSH in the cross-shore direction. All results are averaged over 13 November. The cross-shore direction is denoted as y (increasing from nearshore to offshore) and the alongshore direction as x (increasing from southwest to northeast).

3.2. Flow Field and Momentum Analysis

The cold-air outbreak generated strong northeasterly winds that drove alongshore currents and onshore Ekman transport (Figure 4a,c), producing coastal downwelling and an associated frontal structure (Figure 4e). The event also induced intense vertical mixing, which homogenized the nearshore water column.

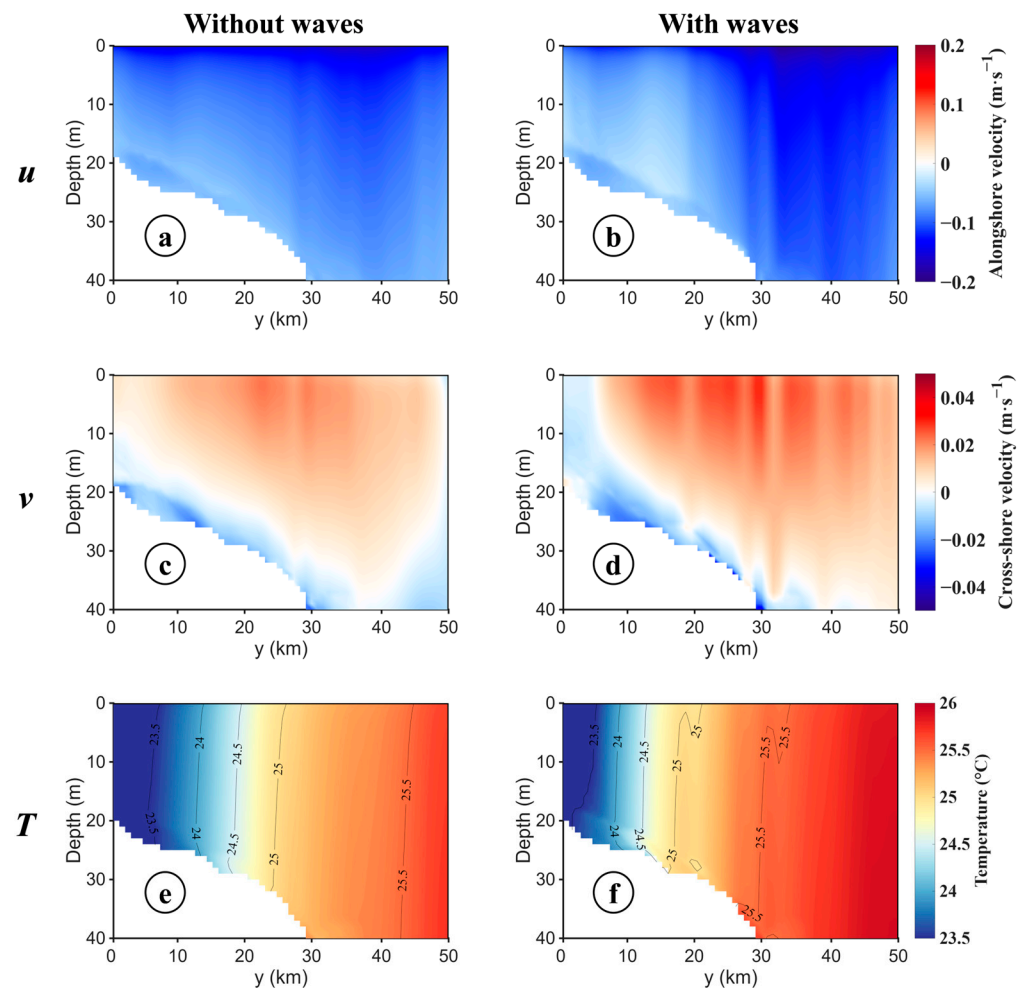


Figure 4. (a,b) Alongshore velocity (u), (c,d) cross-shore velocity (v) and (e,f) temperature (T) under conditions without waves (left column) and with waves (right column). All results are averaged alongshore over the dashed-box region in Figure 3a and temporally averaged over 13 November.

Surface waves exerted a substantial influence on the nearshore circulation (Figure 4). When wave effects were included, both the alongshore velocity (u) and cross-shore velocity (v) increased markedly relative to the no-wave case (Figure 4a–d). In particular, the wave-induced enhancement of onshore flow strengthened the coastal downwelling, as reflected by an intensified offshore flow along the bottom (Figure 4d).

The elevated nearshore sea level resulting from onshore Stokes transport (Figure 3) increased the cross-shore sea surface height gradient, thereby amplifying the offshore-directed pressure gradient force in the wave case compared with the no-wave case (Figure 5a,b). This stronger pressure gradient, in turn, helped sustain the intensified alongshore velocity (u) under wave conditions (Figure 4a,b), partly through geostrophic adjustment.

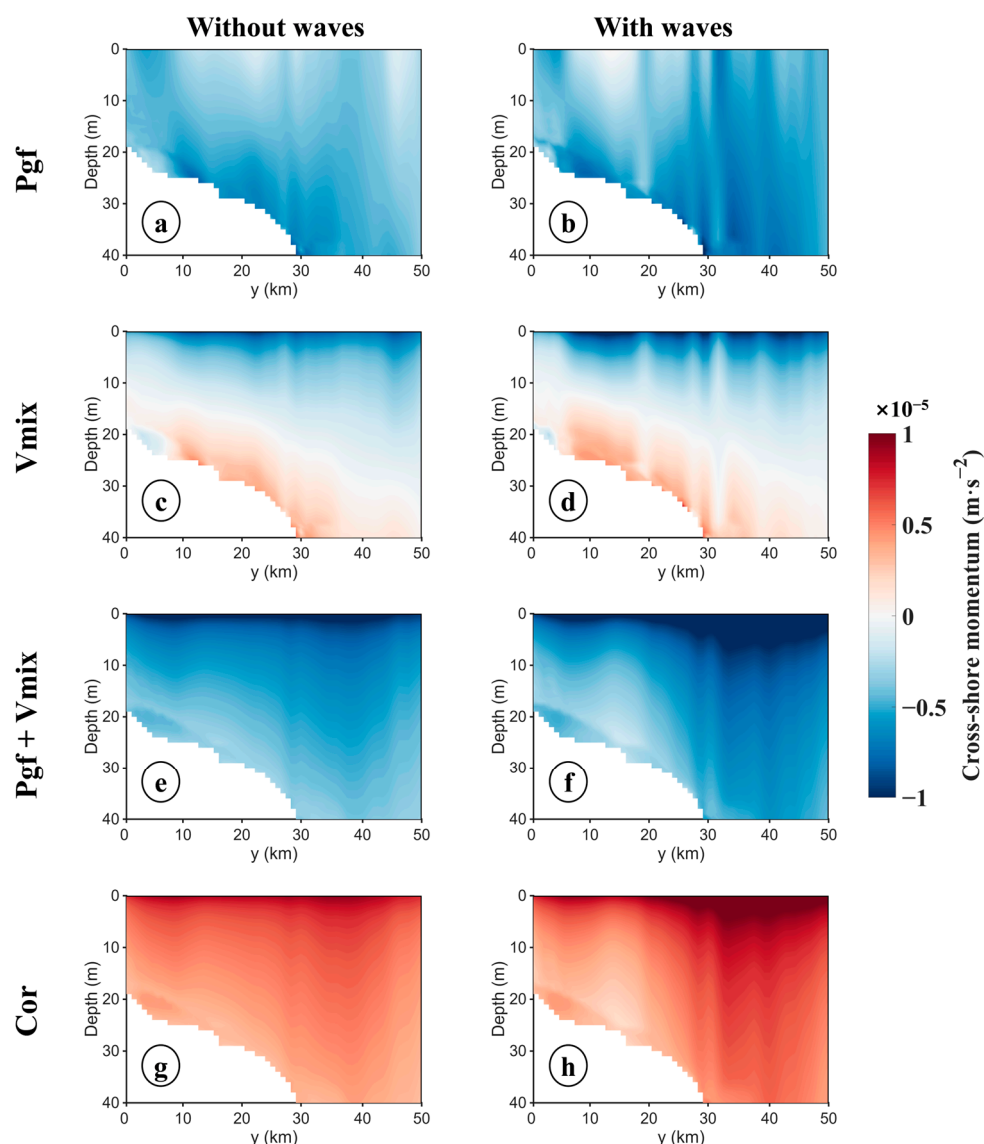


Figure 5. Alongshore-averaged cross-shore momentum budget terms: (a,b) pressure gradient force (Pgf), (c,d) vertical mixing (Vmix), (e,f) the sum of pressure gradient force and vertical mixing, and (g,h) Coriolis force (Cor), shown for conditions without waves (left column) and with waves (right column). All results are averaged over 13 November.

The inclusion of waves also strengthened vertical mixing by increasing vertical shear associated with the enhanced alongshore current (Figure 5c,d). The momentum balance in this region is dominated by the turbulent thermal wind (TTW) regime: the pressure gradient force, together with vertical mixing, is approximately balanced by the Coriolis force (Figure 5e–h). Through TTW adjustment, the enhanced mixing reinforces the secondary circulation linked to the downwelling front, leading to a stronger cross-shore velocity under wave conditions (Figure 4d).

Additionally, in the shallow nearshore zone, the wave-enhanced offshore bottom flow increases vertical shear and mixing, resulting in elevated kinetic energy dissipation. This phenomenon of enhanced dissipation is analogous to the flow behavior observed in corrugated pipes, where the wavy geometry of the walls similarly intensifies vertical shear and mixing [44,45]. As a consequence, the alongshore current is weakened in this region under wave conditions (Figure 4b).

3.3. Frontogenesis

In the presence of surface waves, the isothermals are more compact than in the no-wave case, indicating the front is intensified with waves (Figure 4e,f). To further quantify this intensification, we analyze the frontogenesis using the frontogenetic tendency equation that incorporates surface wave effects. Following Wang et al. (2023) [34], the rate of change in the lateral buoyancy gradients can be expressed as:

$$\frac{D^L}{Dt} \left(\frac{1}{2} b_{,i} b_{,i} \right) = \underbrace{-u_{j,i} b_{,j} b_{,i}}_{F_{\text{cur}}} - \underbrace{u^s_{j,i} b_{,j} b_{,i}}_{F_{\text{stk}}} + \underbrace{(\kappa b_{,j})_{,ji} b_{,i}}_{F_{\text{mix}}} \quad (5)$$

where $\frac{D^L}{Dt} = \frac{\partial}{\partial t} + u^L \cdot \nabla$ is the Lagrangian derivative; $b = -\frac{g}{\rho_0} \frac{\partial \rho}{\partial z}$ is the buoyancy; κ is the buoyancy diffusivity; $i = (1, 2)$ represents horizontal coordinates (x, y), while $j = (1, 2, 3)$ represents all three coordinates (x, y, z); and commas denote derivative. The terms on the right-hand side of the equation represent forcing associated with current gradients F_{cur} , Stokes drift gradients F_{stk} , and buoyancy mixing F_{mix} . Here, the gradient of Stokes drift is relatively small, making the corresponding F_{stk} much smaller than the other two terms.

Furthermore, the frontogenetic forcing associated with current gradients, F_{cur} , can be decomposed into two components: the convergence-induced term and the strain-induced term, denoted as F_{conv} and F_{strn} , respectively. That is,

$$F_{\text{cur}} = \underbrace{-\frac{1}{2}(u_{,x} + v_{,y})[(b_{,x})^2 + (b_{,y})^2]}_{F_{\text{conv}}} - \underbrace{\{(v_{,x} + u_{,y})b_{,x}b_{,y} + \frac{1}{2}(u_{,x} - v_{,y})[(b_{,x})^2 - (b_{,y})^2]\}}_{F_{\text{strn}}} \quad (6)$$

where (u, v) are the (x, y) components of horizontal ocean currents, and commas denote derivative. Strain in the background flow stretches surface density fronts and filaments, thereby sharpening horizontal density gradients [2,46]. At the same time, convergence associated with frontal secondary circulation compresses water masses of differing densities in the cross-front direction, further intensifying the front [47].

The spatial patterns of large F_{conv} , F_{strn} , and F_{mix} generally align with regions of strong horizontal density gradients (Figure 6). In the presence of waves, all three contributions, namely convergence-induced forcing, strain-induced forcing, and mixing-induced forcing, are markedly enhanced relative to the no-wave case. Among them, the strain-induced term F_{strn} emerges as the dominant driver of frontogenesis, while convergence F_{conv} also plays an important role in specific localized areas. Quantitatively, the value of the domain-averaged F_{conv} , F_{strn} , and F_{mix} increased by approximately 18%, 62% and 68%. These changes collectively illustrate the intensified frontogenesis resulting from the strengthened flow field under wave conditions.

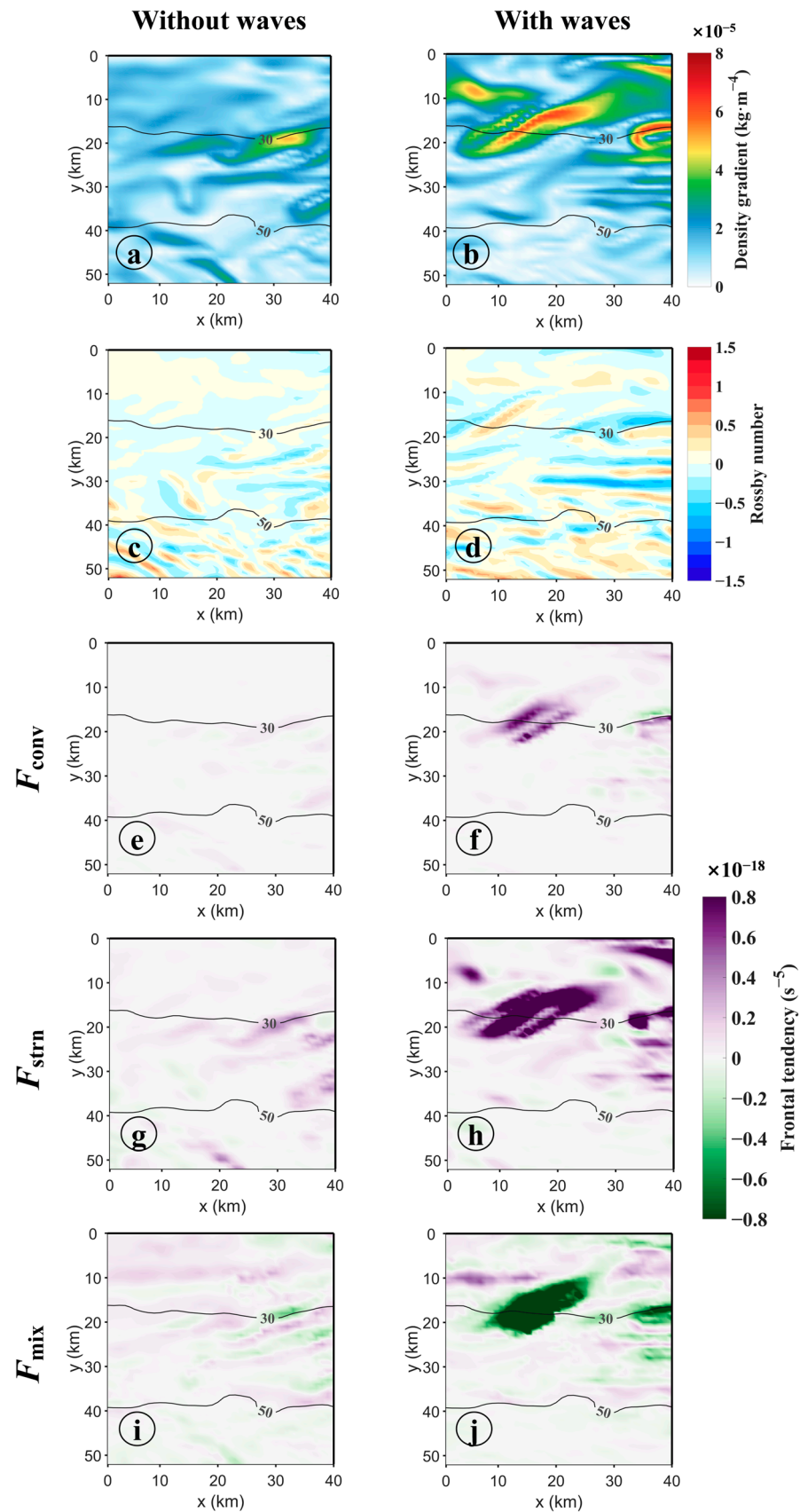


Figure 6. Depth-averaged (a,b) density gradients and (c,d) Rossby numbers under conditions without waves (left column) and with waves (right column). Depth-averaged frontogenetic forcing induced by (e,f) flow convergence (F_{conv}), (g,h) flow strain (F_{strn}), and (i,j) mixing (F_{mix}) under conditions without waves (left column) and with waves (right column). Gray contours indicate isobaths (m). All results are temporally averaged on 13 November.

4. Discussion and Conclusions

In this study, we employ a nested realistic simulation of a cold-air outbreak in the northern South China Sea to examine how surface waves influence nearshore submesoscale fronts by comparing scenarios with and without wave effects.

Our results show that onshore Stokes drift drives shoreward water transport, leading to water accumulation along the coast and an associated rise in sea surface height. This sea level increase strengthens the cross-shore pressure gradient force and, through geostrophic adjustment, enhances the alongshore current. The intensified alongshore flow increases vertical shear, which promotes vertical mixing. Because the momentum balance in this region is largely governed by the turbulent thermal wind (TTW) associated with the downwelling front, the enhanced vertical mixing further amplifies the secondary circulation via TTW adjustment. This process ultimately strengthens both the cross-shore current and the downwelling. Additionally, the strengthened flow field promotes frontogenesis by enhancing strain and convergence, thereby intensifying nearshore submesoscale fronts.

The spatial heterogeneity of the observed intensification is further modulated by the region's bathymetric gradients and bottom roughness. In our realistic setup, the sloping topography drives localized wave refraction and pressure non-uniformities [26], which explains why the sea-level setup and resulting pressure gradients are concentrated near specific isobaths (Figure 3). Furthermore, wave-induced turbulence can significantly enhance effective bottom drag [48], acting as a primary control on the stability of the pressure-driven currents and the associated cross-front shear (Figure 5). These bathymetric features effectively steer localized flow convergence and strain [49], resulting in the patchy frontogenesis patterns quantified in Figure 6. Consequently, the nearshore submesoscale response we identify is not merely a uniform product of Stokes drift but is dynamically shaped by the active interplay between waves and the underlying topography.

These findings are consistent with previous studies of wave impacts on coastal circulation. For example, Wang et al. (2023) [34] demonstrated in an idealized coupled wave–circulation model that onshore Stokes drift elevates nearshore sea level and strengthens downwelling, whereas Lin and Gan (2025) [50] showed in a realistic wave–current simulation that onshore Stokes drift similarly increases sea level and modifies coastal circulation east of Hainan. Our results not only corroborate these conclusions but also extend them by illustrating how wave forcing modulates the strength and evolution of nearshore submesoscale fronts.

The finding of frontal intensification in this study complements our previous work [51], which reported a wave-induced suppression of submesoscale fronts in the NSCS. The difference lies in the dominant dynamical regime: while Peng et al. (2026) [51] highlighted the role of the Stokes Coriolis force in driving an anti-Stokes flow that weakens currents on the open shelf, the current study focuses on the nearshore zone. In shallow waters near the coastal boundary, the onshore Stokes drift leads to a significant sea-level rise. Through geostrophic adjustment, the stronger pressure gradient force strengthens the flow field, thereby leading to a frontal intensification.

While this study focuses on Stokes drift, other wave-driven processes can also significantly reshape submesoscale circulation and frontal dynamics. Wave breaking injects turbulence and vorticity into the upper ocean, altering vertical fluxes and modifying nearshore flows [52]. Langmuir mixing, generated by the interaction between surface waves and wind, organizes turbulence into coherent roll structures that penetrate deeply into the mixed layer, redistributing momentum and tracers more effectively than shear-driven turbulence alone [53,54]. These processes are not included in our simulations; however, they may substantially influence nearshore circulation and frontogenesis at submesoscales, affecting the exchange of heat, gases, and nutrients across the mixed layer. Furthermore,

it is important to acknowledge that our simulations employ a one-way coupling framework. However, submesoscale currents are known to actively modulate waves through refraction and focusing [55]. Such interactions can lead to localized ‘wave-trapping’ at frontal zones, which might further concentrate Stokes transport and enhance the nearshore sea-level setup. Consequently, the omission of this two-way feedback suggests that our results may provide a conservative estimate of frontal intensification. Despite this limitation, our analysis robustly identifies the primary dynamical mechanism driving the nearshore submesoscale frontal intensification. Future studies integrating two-way feedback loops will be essential to provide a more comprehensive understanding of wave–turbulence interactions.

Author Contributions: C.P.: Writing—original draft, Visualization, Formal analysis, Data curation. J.W.: Writing—original draft, Visualization, Formal analysis, Data curation. P.W.: Writing—review and editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. D.W.: Writing—review and editing, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The Coastal and Regional Ocean Community model (CROCO; Inria, Paris, France) used in this study is openly available at <https://www.croco-ocean.org/> (accessed on 30 April 2023), and this model documentation can be accessed at https://croco-ocean.gitlabpages.inria.fr/croco_doc/model.html (accessed on 30 April 2023). The model outputs are available from the authors upon request. All figures in this manuscript were produced using MATLAB R2023a (The MathWorks Inc., Natick, MA, USA; <http://www.mathworks.com/>; accessed on 15 April 2023). This study makes use of GOPAF (<https://doi.org/10.48670/moi-00016>) and GOWAF (<https://doi.org/10.48670/moi-00017>) from the E.U. Copernicus Marine Service; ERA5 (<https://doi.org/10.24381/cds.e2161bac>) from the Climate Data Store.

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Conflicts of Interest: Author Cheng Peng has employed by the company Fujian Yongfu Power Engineering Co., Ltd. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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