

Research Article

Comparison between near-inertial oscillations and near-inertial internal waves induced by a cyclone passage in the deep ocean

Shengli Chen¹, Jiuxing Xing¹, Jianyu Hu^{2,3}, and Yunping Song^{1*}

¹ *Shenzhen International Graduate School, Institute for Ocean Engineering, Tsinghua University, Shenzhen 518055, China*

² *State Key Laboratory of Marine Environmental Science, Center for Marine Meteorology and Climate Change, College of Ocean and Earth Sciences, Xiamen University, Xiamen 361102, China*

³ *Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai 519000, China*

Address correspondence to Yunping Song, songyunping@sz.tsinghua.edu.cn

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Abstract

This study investigates near-inertial motions induced by cyclone passage in the deep ocean using three-dimensional numerical simulations, with a primary focus on comparison between near-inertial oscillations (NIOs) and near-inertial internal waves (NIWs). NIOs are initially forced in the surface mixed layer by wind stress, displaying non-baroclinic features. Both the 3D simulations and a linear slab model demonstrate that the energy of NIOs barely penetrates downward into the thermocline. An energy budget analysis reveals that NIWs are primarily generated through inertial pumping, in which vertical pressure work associated with NIOs transfers energy downward into the ocean interior. For NIWs, linear normal-mode theory is valid only in the far field, where the arriving wave packets transition from mode-1 to mode-4. Comparison between the 3D simulation and linear models indicates non-negligible nonlinear effects of both near-inertial motions. A substantial portion of the total energy is stored in a geostrophic current, which induces a pronounced frequency shift in NIOs rather than NIWs. Sensitivity experiments on the beta effect and cyclone translation speed further highlight marked differences in the behavior of NIOs and NIWs.

Keywords: near-inertial oscillations; near-inertial internal waves; cyclone

1 Introduction

Near-inertial motions (NIMs) are pervasive features of the world's oceans [1,2], typically manifesting as a distinct energy peak near the local inertial frequency. These motions play a key role in ocean mixing and energy transfer. They can drive substantial diapycnal mixing within the thermocline [3-5] and propagate into the deep ocean, where they contribute to enhanced turbulent mixing [6,7]. Near-inertial motions also interact with a wide range of dynamical processes, including geostrophic flows [8,9], mesoscale eddies [10-12], and internal tides [13-15]. By modulating smaller-scale motions, they facilitate the energy cascade that ultimately sustains oceanic mixing [16-19]. In addition to sustaining oceanic mixing, they can even suppress intensification of super typhoons in the South China Sea [20]. With increasing observational and numerical evidence, the fundamental role of near-inertial motions in ocean dynamics has become widely recognized.

At the sea surface, near-inertial currents are well captured by the linear slab model driven by wind stress [21], which has been extensively applied to analyze near-inertial motions [22,23] and to estimate wind energy input into the near-inertial band [24,25]. However, this model is inherently local—it neglects horizontal coupling between adjacent points—and yields spatially uniform currents confined to the unstratified mixed layer. Consequently, these wind-driven near-inertial currents do not exhibit internal wave characteristics. To emphasize this distinction, we refer to this non-internal-wave type of motion as near-inertial oscillations (NIOs), although the term ‘oscillation’ also includes the meaning of fluctuating waves. NIOs are dynamically distinct from the near-inertial internal wave (NIW), which is baroclinic and relies on the presence of stratification.

Tropical cyclones and storms can generate exceptionally strong near-inertial motions, with current amplitudes reaching $0.5\text{--}1.0\text{ m s}^{-1}$ and persisting for up to two weeks [23,26-28]. Linear theories, two-layer models, and primitive-equation simulations have been employed to investigate cyclone- and storm-induced near-inertial responses. NIWs can be represented as a superposition of normal modes with distinct phase speeds [29,30], even within nonlinear numerical frameworks where nonlinear effects become pronounced [31,32]. However, the normal-mode theory cannot accurately represent wind-driven NIOs, and the nonlinear processes governing NIOs and NIWs are likely to differ. The characteristics of near-inertial motions are sensitive to the cyclone

translation speed [33,34], the β -effect [29], and the nondimensional parameter U/fL [35]. Given their distinct dynamical origins, these sensitivities are expected to manifest differently in NIOs and NIWs. Moreover, their interactions with other motions of comparable scales, such as internal tides, mesoscale eddies, and background flows, also differ.

In this study, we employ a three-dimensional numerical model to investigate near-inertial motions generated by cyclone passage in the deep ocean, with a particular focus on distinguishing the dynamics of NIOs and NIWs. Section 2 describes the model configuration. Section 3 presents the main results: Section 3.1 analyzes energy fluxes and generation mechanisms of NIOs and NIWs; Section 3.2 examines nonlinear effects through comparisons between three-dimensional simulations and linear models for NIOs, and between simulations and normal-mode predictions for NIWs. Section 3.3 explores their interactions with geostrophic flows, and Section 3.4 discusses their respective contributions to sea surface cooling. Sensitivity experiments examining the β -effect and cyclone translation speed are presented in Section 4, followed by conclusions and discussion in Section 5.

2 Methods

2.1 Three-dimensional Model Settings

Numerical simulations are conducted to examine the near-inertial response to a cyclone passage in the deep ocean. The domain is an idealized rectangular basin, 1,200 km in the x-direction and 900 km in the y-direction, with a uniform depth of 3,000 m. We use the Regional Ocean Modeling System (ROMS), a free-surface primitive-equation model widely adopted [36]. The horizontal grid spacing is 3 km throughout. In the vertical direction, the model employs 30 terrain-following layers, whose thickness decreases from ~ 10 m near the surface to ~ 250 m near the bottom. All boundaries are open: depth-integrated (2-D) momentum uses a Flather condition, while 3-D momentum and density employ radiation (outflow) conditions. A sponge layer with enhanced horizontal viscosity is applied along the northern and southern boundaries.

In the model domain, a cyclone moves westward from the east boundary along the central line (Fig. 1). A total period of 480 hours is simulated, with outputs of basic parameters such as

temperature, salinity, velocities, wind stress, and viscosity. The pressure of the cyclone has the idealized structure of Holland (1980) [37] as below:

$$p = p_c + (p_n - p_c) e^{-A/r^B} \quad (1)$$

$$A = R_m^B \quad (2)$$

where p is the atmospheric pressure at the sea level at a distance (r) away from the cyclone center, p_n and p_c are the ambient and cyclone center pressures, respectively. Two constants (A, B) are related to the radius of maximum wind speed (R_m) (Equation 2). And the wind speed (V) is expressed as [37]:

$$V = \left[\frac{AB(P_n - P_c)e^{-\frac{A}{r^B}}}{\rho_{air} r^B} + \frac{r^2 f^2}{4} \right]^{\frac{1}{2}} - \frac{rf}{2} \quad (3)$$

where ρ_{air} and f are the air density and the Coriolis parameter, respectively. Wind directions are tangential, and such a wind pattern is symmetric along the cyclone path. To compute the wind force from the wind speed, the drag coefficient (C_d) is set as the same as Oey et al. (2006) [38], which combines the situation for both low-moderate wind [39] and high winds [40] (Equation 4). The Mellor-Yamada 2.5 scheme is used for calculating the vertical viscosity and diffusivity [41]. Other parameter values are set as constant (Table 1).

$$C_d \times 10^3 = \begin{cases} 1.2 & V \leq 11 \\ 0.49 + 0.065V & 11 < V \leq 19 \\ 1.364 + 0.0234V - 0.0002V^2 & 19 < V \end{cases} \quad (4)$$

In the control run, the cyclone moves at a constant translation speed of 6 m/s. The parameter B associated with the horizontal distribution of wind is 2.0. The model is in an f -plane situation with a local inertial frequency of $5 \times 10^{-5} \text{ s}^{-1}$, corresponding to an inertial period of 34.9 hours. The initial temperature and salinity profiles come from the World Ocean Atlas (WOA) 2013. A mean profile obtained from the climatological values for summer in the northwestern Pacific Ocean is applied everywhere in the model (Fig. 1).

Table 1. Values of constant parameters

p_n	p_c	R_m	ρ_{air}
1005 hPa	970 hPa	30 km	1.2 kg m ⁻³

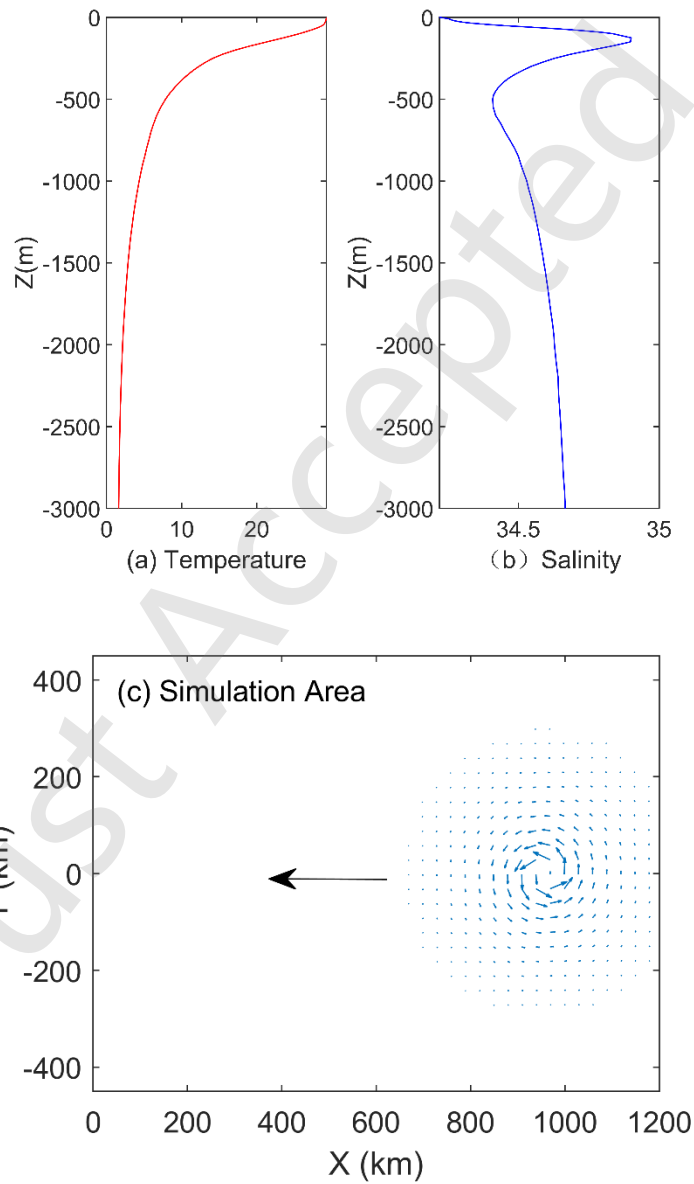


Figure 1. The initial profiles of temperature (a) and salinity (b) obtained from averaged summer values in the northwestern Pacific Ocean (Longitude: 130-150 ° E, Latitude: 5- 20 ° N) of WOA13. (c) The simulation domain with a cyclone moving westward, as shown by the black arrow.

2.2 The Linear Model

The linear slab model [21], calculating the NIO in the mixed layer induced by the sea surface wind, is given as

$$\frac{\partial \mathbf{u}}{\partial t} + i f \mathbf{u} = \frac{1}{\rho} \frac{\boldsymbol{\tau}}{H} - r \mathbf{u} \quad (5)$$

where the current ($\mathbf{u}$, in a complex form) and the wind stress ($\boldsymbol{\tau}$) are assumed uniform in the mixed layer (with a thickness of H). f and ρ are the inertial frequency and the seawater density, respectively. The damping coefficient r is set as an inverse of the e-folding decay time (5 days) [23].

The linear model is similar to a slab model with uniform currents in a single layer. In order to examine the depth dependence of NIOs, the eddy viscosity (A_z) in our 3D model is introduced to the linear model

$$\frac{\partial \mathbf{u}}{\partial t} + i f \mathbf{u} = \frac{\partial}{\partial z} \left(A_z \frac{\partial \mathbf{u}}{\partial z} \right) - r \mathbf{u} \quad (6.1)$$

with the boundary conditions at the surface ($z=0$) and the sea bed ($z=-h_b$):

$$\rho A_z \left. \frac{\partial \mathbf{u}}{\partial z} \right|_{z=0} = \boldsymbol{\tau} \quad (6.2)$$

$$\mathbf{u}|_{z=-h_b} = 0 \quad (6.3)$$

The above equations can be easily solved numerically. They are discretized vertically using an interval of 10 m, with Equations 7.1-7.4 showing the discretized equation for the u component. At each time step, a linear equation with coefficients forms a matrix. The linear equation can then be solved to obtain the velocity profile.

$$\frac{\partial u}{\partial t} - f v = \frac{\partial}{\partial z} \left(A_z \frac{\partial u}{\partial z} \right) - r u \quad (7.1)$$

$$\begin{aligned} & \frac{\Delta t A_z(t_i, z_i) u(t_i, z_{i-1})}{\Delta z^2} - \left(1 + \frac{2 \Delta t A_z(t_i, z_i)}{\Delta z^2} \right) u(t_i, z_i) + \frac{\Delta t A_z(t_i, z_i)}{\Delta z^2} u(t_i, z_{i+1}) \\ & = -u(t_{i-1}, z_i) - \Delta t f v(t_{i-1}, z_i) + \Delta t r u(t_{i-1}, z_i) \end{aligned} \quad (7.2)$$

$$\frac{\rho A_z(t_1, z_1)}{\Delta z} (u(t_i, z_1) - u(t_i, z_2)) = \tau_x(t_i) \quad (7.3)$$

$$u(t_i, z_N) = 0 \quad (7.4)$$

2.3 Other Methods

The perturbation potential energy PPE is calculated using Equation 8, where ρ_o is the initial density profile, and h is the vertical displacement compared to the initial state [42].

$$PPE = \iiint \frac{1}{2} \rho_0 N^2 h^2 dx dy dz \quad (8)$$

Here, we consider how the energy flux in the mixed layer transfers downward. The downward energy flux (F'_z) is attributed to three factors [42]:

$$F'_z = p'w + w \times KE - A_z \frac{\partial KE}{\partial z} \quad (9)$$

$$p'(z, t) = p_{surf}(t) + \int_z^0 (\rho(\hat{z}, t) - \rho(\hat{z}, 0)) g d\hat{z} \quad (10)$$

where the first term at the right-hand side in Equation 9 denotes the vertical pressure work on the kinetic energy (KE), the second term is the vertical advection (w is the vertical velocity), and the third term is the diffusion due to vertical eddy viscosity (A_z). The pressure anomaly p' is calculated from Equation 10, where the P_{surf} is to meet the condition that the depth-averaged pressure perturbation vanishes [43] And g is the gravitational acceleration.

Near-inertial currents are obtained through the band-pass filter using the inverse FFT, with a cutoff frequency of 0.4 cpd and 1.2 cpd, as no tide is included in the simulation. The currents are decomposed into different modes of NIWs by the normal mode decomposition. Under the hydrostatic assumption, the eigenvalue problem for the vertical velocity is given as:

$$\frac{d^2 W}{dz^2} + (k_x^2 + k_y^2) \frac{N^2(z)}{\omega^2 - f^2} W = 0 \quad (11)$$

where W denotes the z -dependent function of the vertical velocity; k_x and k_y are the horizontal wave numbers; N and f are buoyancy and inertial frequencies, respectively. The NIW frequency

(ω) is unknown. The equation can be discretized and solved to obtain the vertical profile of each mode [13].

To explore the nonlinearity of near-inertial motions, our simulation results are compared with the linear superposition of NIWs in different normal modes [29]:

$$u = \sum_{n=0}^{\infty} p_n(z) \omega_n^{-2} \sigma_n (l^2 c_n^2 + f^2 \cos \omega_n t) \sin ly \quad (12)$$

where ω_n and c_n are the wave frequency and wave speed for mode n , respectively. The mode coefficient p_n is calculated by the eigenvalue equation, where the initial stratification of our simulation is used, and σ_n is the coefficient for the expansion of the step function. The horizontal scale, l , is set to 800 km, and the mixed layer depth is set to 50 m.

3 Results

3.1 Energetics

Because the response to a uniformly translating cyclone is approximately invariant in the along-track direction, we focus on analyzing a cross-track section. Near-inertial currents exhibit distinct vertical structures across this section (Fig. 2). Within the mixed layer (~60–100 m), the currents are surface-intensified, dominated by wind-forced near-inertial oscillations (NIOs). Below the mixed layer, the phase propagates upward, consistent with downward energy propagation of near-inertial internal waves (NIWs). At the cyclone center (Fig. 2a), the signal is confined to the upper ~100 m, and the energy is predominantly in NIOs. At two radii of maximum wind ($Y = 60$ km; Fig. 2b), the thermocline shows a clear upward phase propagation, indicative of downward-propagating NIWs. In the mixed layer, NIOs dominate during the first ~3 inertial periods, after which their energy decays rapidly as the underlying NIWs progressively extend upward. Farther from the center ($Y = 120$ km; Fig. 2c), NIOs occupy a shallower ~70 m surface layer, beneath which NIWs propagate downward. In the far field ($Y = 240$ km), NIOs are much weaker and confined to a thin (~30 m) surface layer, consistent with reduced local wind stress. Due to the overlapping frequencies of NIO and NIW, it is challenging to distinguish one from the other. Although the energy of NIWs in the mixed layer does exist, but is much smaller than NIOs due to weak stratification and limited depth range. Under the depth-dependent viscosity, the energy of

NIOs hardly penetrates downward to the thermocline (Fig. 9). Therefore, the energy of near-inertial motions in the mixed layer is approximately calculated as the NIO energy, and that below the mixed layer as NIWs. The mixed-layer base is defined as the shallowest depth at which N^2 reaches $1.5 \times 10^{-4} \text{ s}^{-2}$. This criterion is used as an operational definition to identify the transition from the weakly stratified mixed layer to the strongly stratified upper thermocline in the present idealized stratification. Threshold-based definitions are commonly used in mixed-layer-depth diagnostics, although the exact threshold may depend on the stratification structure and research purpose [44]. The selected value is of the same order as the $N^2 \sim 10^{-4} \text{ s}^{-2}$ threshold commonly used to characterize the transition layer or strongly stratified upper pycnocline [45,46].

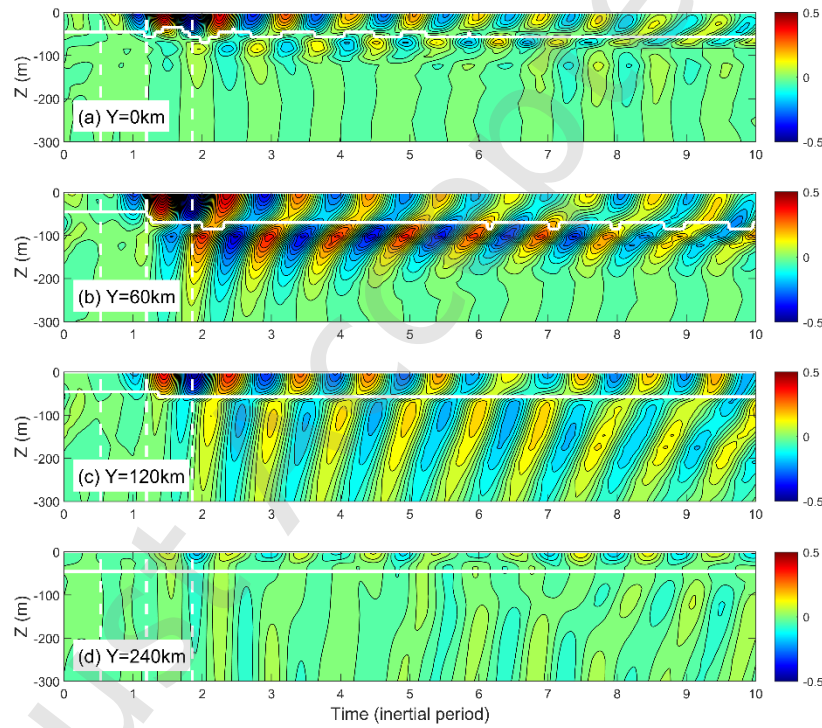


Figure 2. Near-inertial currents (v , north-south component, m s^{-1}) along a specific cross-track section ($X = 600 \text{ km}$). As shown in Fig. 1c, the central line corresponds to $Y = 0$, and the $Y > 0$ is located at the right-hand side of the cyclone path. The contour interval is 0.04 m s^{-1} . Three white dash lines from left to right represent the times of the beginning, the closest position, and the ending of the cyclone influence, respectively. The white line denotes the bottom boundary of the mixed layer, which is set at the shallowest place where N^2 meets the value of $1.5 \times 10^{-4} \text{ s}^{-2}$.

From an energy perspective, near-inertial currents exhibit two energetic cores (Fig. 3): a mixed-layer core associated with wind-forced near-inertial oscillations (NIOs) and a thermocline core ($\approx 100\text{-}200 \text{ m}$) associated with near-inertial internal waves (NIWs). The mixed-layer energy is

surface-intensified and peaks near the radius of maximum wind ($Y \approx 30$ km), where wind stress is both strongest and varies most rapidly. The pronounced right-of-track enhancement at the surface has been widely documented and is attributed to the anticyclonically rotating wind, which continually accelerates near-inertial currents [27,47]. The thermocline core is likewise stronger to the right of the cyclone path ($Y > 0$), but its maximum is displaced farther from the center ($Y \approx 80$ km). The mechanisms underlying this rightward bias in NIWs are examined below.

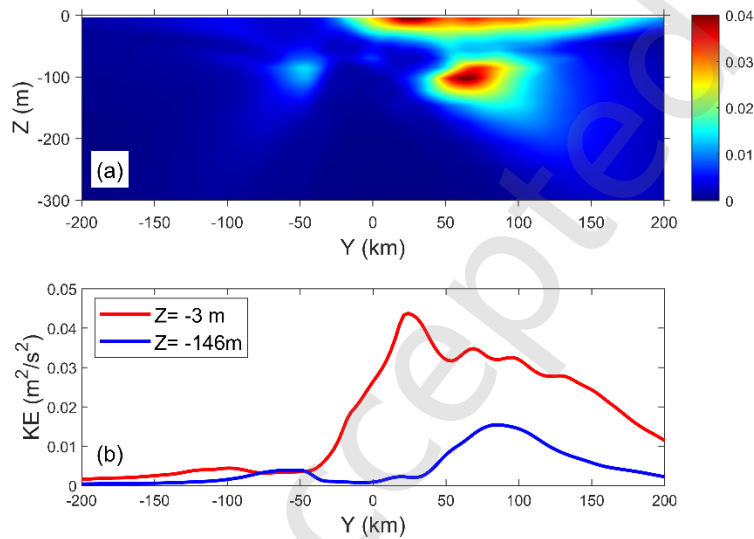


Figure 3. The time-averaged kinetic energy (KE; $(u^2+v^2)/2$, $\text{m}^2 \text{s}^{-2}$) of near-inertial currents along the cross-track section (a) and values at the surface ($Z=-3$ m) and thermocline ($Z=-146$ m) (b).

We analyze the kinetic energy (KE) budget to diagnose the generation of near-inertial oscillations (NIOs) and near-inertial internal waves (NIWs). As the cyclone approaches, intense wind forcing rapidly increases KE in the mixed layer (Fig. 4a). Thereafter, mixed-layer KE declines to $\sim 25\%$ of its peak within two local inertial periods, while KE beneath the mixed layer increases and overtakes it over the same interval. Most KE resides in the near-inertial band (Fig. 4b): NIO energy peaks during the first inertial period and subsequently decays, whereas NIW energy grows steadily. By ~ 1.5 inertial periods, a quasi-steady partition emerges with NIW energy about twice that of NIOs. NIOs are forced directly by surface wind stress; in contrast, the emergence of NIWs appears tightly coupled to the evolving NIO field. Following cyclone passage, the thermocline at the storm center shoals, increasing potential energy (Fig. 4). Geostrophic adjustment likely converts a fraction of this potential energy into NIWs; however, even an upper-bound estimate of the released potential

energy ($\sim 4 \times 10^8$ J) is insufficient to account for the lower-layer NIW energy ($\sim 13 \times 10^8$ J), implying additional energy pathways to the NIWs.

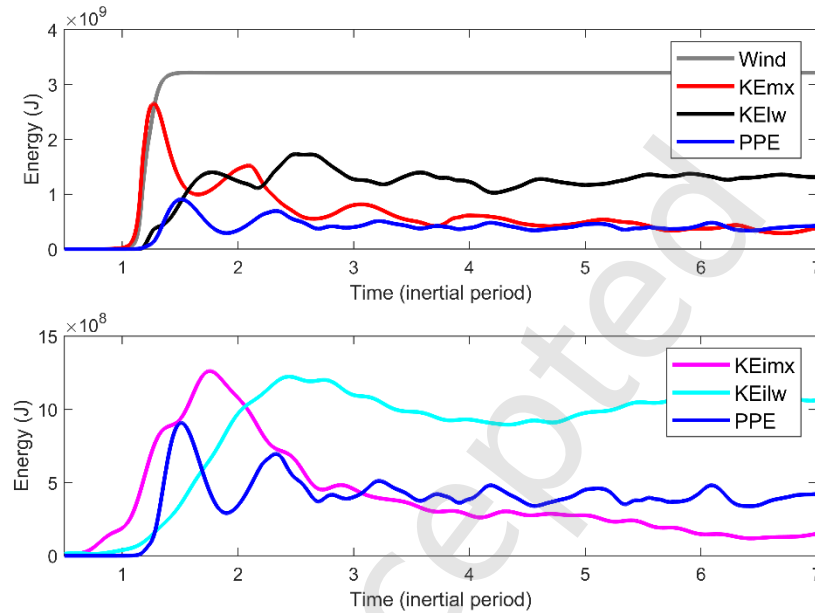


Figure 4. (a) The spatially integrated wind power input (Wind), perturbation potential energy (PPE), kinetic energy in the mixed layer (KEmx), and in the lower layer, which is below the mixed layer (KElw). (b) The spatially integrated perturbation potential energy (PPE), near-inertial kinetic energy in the mixed layer (KEimx), and in the lower layer (KEilw). The bottom boundary of the mixed layer is set at the shallowest point where N^2 equals $1.5 \times 10^{-4} \text{ s}^{-2}$.

The vertical energy flux is composed of the pressure work, the vertical advection, and the diffusion due to vertical eddy viscosity (Equation 9). Fig. 5 summarizes the variability of the energy-budget terms. Vertical advection contributes negligibly. The diffusion term, representing turbulent friction near the base of the mixed layer, is appreciable only briefly as the cyclone approaches. In contrast, vertical pressure work is the dominant contribution, persisting through the first 2–3 local inertial periods and exporting $\sim 1.0 \times 10^9$ J of energy downward. Including the diffusive contribution ($\sim 3 \times 10^8$ J), the total downward transfer amounts to $\sim 1.3 \times 10^9$ J, closely matching the kinetic energy of NIWs in the lower layer. These results indicate that vertical pressure work is the primary pathway for transmitting energy downward to NIWs.

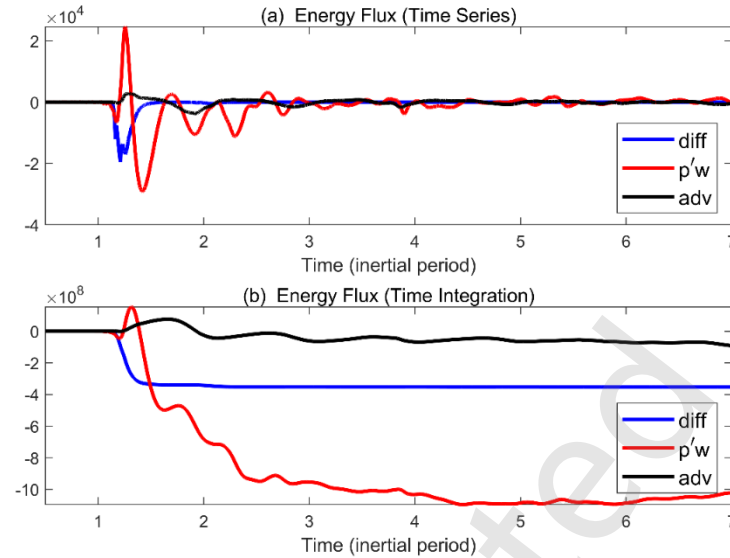


Figure 5. Components of energy flux across the bottom boundary of the mixed layer: (a) time series (in W) and (b) time accumulation (in J). The ‘diff’ denotes the diffusion term, and ‘ $p'w$ ’ the vertical pressure work, and ‘adv’ is the contribution from vertical advection as in Equation 9. The bottom boundary of the mixed layer is set at the shallowest place where the buoyancy frequency meets the value of $1.5 \times 10^{-4} \text{ s}^{-1}$.

The downward transfer of kinetic energy by vertical pressure work is dominated by near-inertial motions: the total vertical pressure work ($p'w$) and the component computed from band-passed near-inertial currents ($p_i'w_i$) are nearly indistinguishable. With the sign convention that negative denotes downward, near-inertial pressure work is predominantly negative within the upper ~ 500 m near the cyclone center and peaks at the base of the mixed layer (Fig. 6), consistent with mixed-layer near-inertial oscillations (NIOs) injecting energy into thermocline near-inertial internal waves (NIWs) via pressure work. The downward flux exhibits a pronounced right-of-track enhancement, with maxima near the radius of maximum wind, aligning with the observed rightward amplification of NIWs. Below the mixed layer, NIW energy flux remains downward (negative) within ~ 200 km of the cyclone center but becomes upward (positive) farther away, implying that NIWs propagate downward near the center and, in the far field, propagate upward—plausibly after reflection from the seafloor.

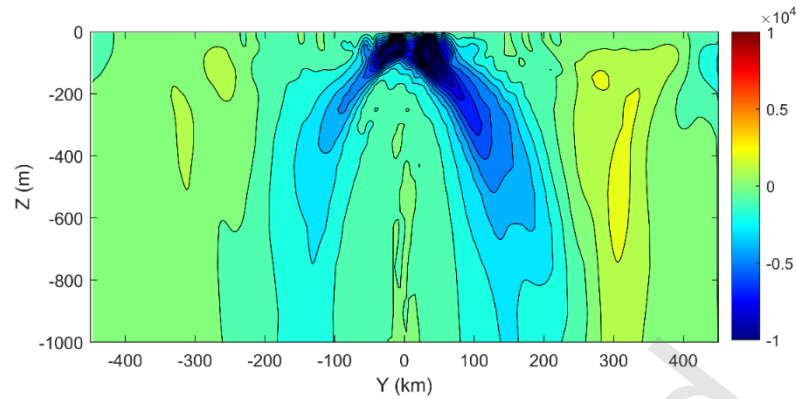


Figure 6. The time-integrated pressure work ($p_i' w_i$) is associated with near-inertial currents, where p_i' and w_i are the pressure perturbation and vertical velocity at the near-inertial frequency band, respectively.

Vertical pressure work arises from the interaction of vertical motion with pressure perturbations. Divergence of surface currents can excite vertical motion at the local inertial frequency, so-called inertial pumping [29,48]. In our experiment, mixed-layer near-inertial oscillations (NIOs) generate pronounced horizontal divergence following cyclone passage, leading to strong, near-inertial vertical velocities (Fig. 7). Through vertical pressure work, this inertial pumping transmits energy from the NIOs downward, thereby generating near-inertial internal waves (NIWs) beneath the mixed layer. Neither divergence nor vertical velocity peaks at the storm center; both are amplified to the right-hand side of the storm track, consistent with the observed right-of-track enhancement of NIWs.

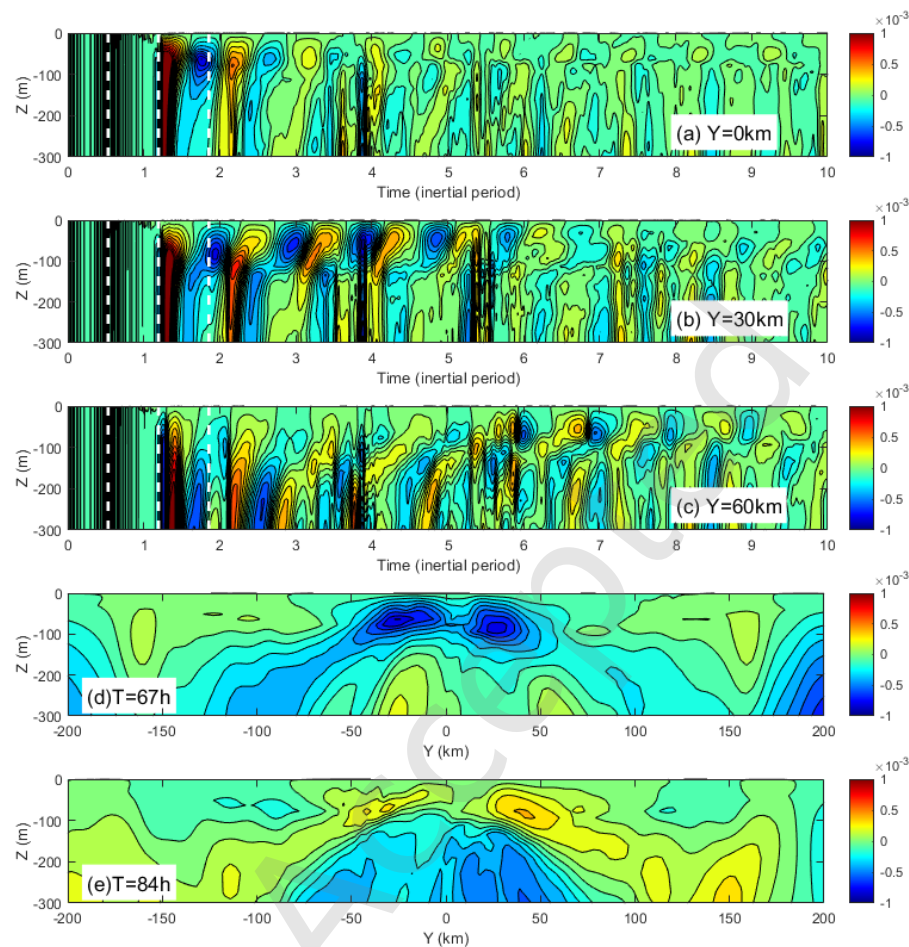


Figure 7. (a-c) Time series of the vertical velocity (m s^{-1}) at different positions; (d-e) the spatial distributions of the vertical velocity (m s^{-1}) at different times.

3.2 Nonlinear Effects

3.2.1 Comparison of NIOs with the linear model

Near-inertial oscillations (NIOs) are forced primarily by surface wind stress. The linear mixed-layer (slab) model of Pollard and Millard (Eq. 5) has been shown to reproduce mixed-layer near-inertial currents [21] and is widely used to estimate wind-driven near-inertial energy [24,25]. We therefore compare NIOs from our 3-D simulation with those from the slab model forced by the same wind stress. The two fields differ substantially (Fig. 8). In the slab solution, inertial currents are out of phase across the track, opposite phase for $Y < 0$ (left-of-track) and $Y > 0$ (right-of-track). Amplitudes peak at the right-of-track radius of maximum wind (RMW), where the wind stress

rotates anticyclonically, and are reduced on the left-of-track side, though a secondary peak remains. In contrast, the 3-D simulation shows negligible NIO intensity on the left-of-track side and a broader, less sharply peaked maximum on the right. Although both models exhibit a right-of-track bias, their horizontal structures differ markedly, indicating that nonlocal and nonlinear processes, such as pressure work and advection, modulate the spatial distribution of NIOs. The phase evolution in the two models generally agrees well, with minor discrepancies near the cyclone center, likely due to the influence of background geostrophic vorticity.

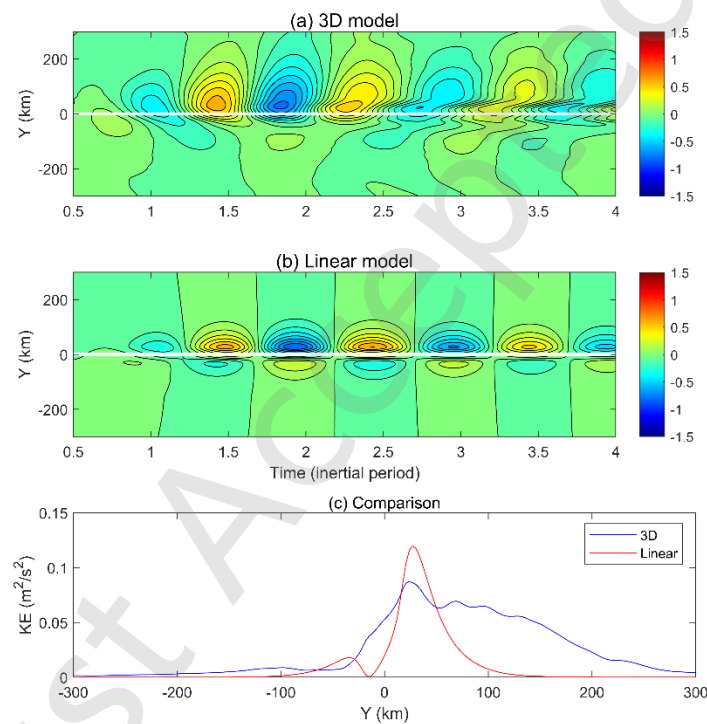


Figure 8. The near-inertial current (v-northward, m s^{-1}) at the surface from the 3D model (a) and from the linear slab model (b). (c) The time-averaged kinetic energy of near-inertial current at the surface from the 3D and the linear models.

Near-inertial currents peak at the sea surface (Fig. 9). At the cyclone center, near-inertial oscillations (NIOs) are confined to the upper ~ 100 m. At the radius of maximum wind (RMW), the penetration depth increases to ~ 120 m, whereas farther from the center, the affected depth decreases progressively (e.g., < 100 m at $Y = 90$ km). These patterns indicate that wind-forced NIOs are largely confined to the mixed layer and rarely penetrate the thermocline; consequently,

motions beneath the mixed layer are dominated by, and can be treated as, near-inertial internal waves (NIWs).

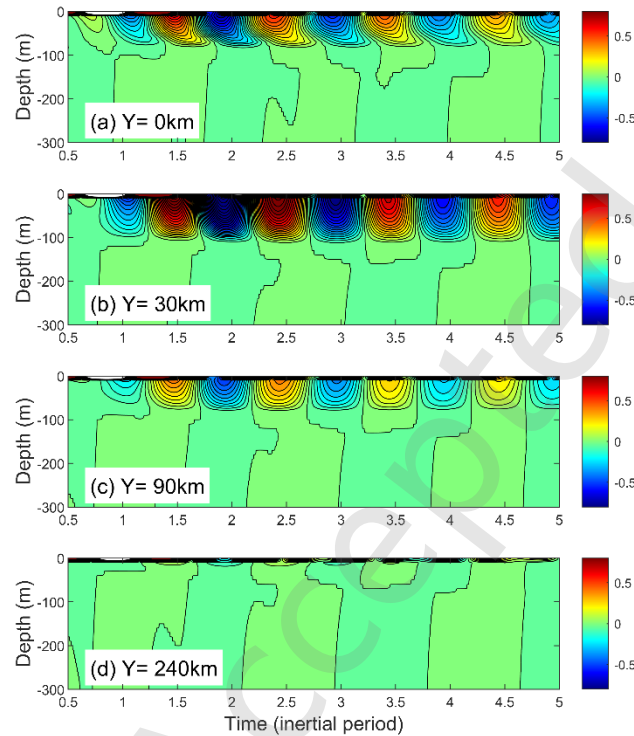


Figure 9. Near-inertial currents of v component (m s^{-1}) obtained from the linear slab model but using the vertical viscosity from the 3D model (Eqs. 6-7).

3.2.2 Mode Decomposition of NIWs

The NIWs described above are generated by NIOs through inertial pumping. After their generation, the NIWs propagate and undergo substantial vertical and horizontal evolution, as examined below. The velocity sections over the full water column (Fig. 10) reveal several new features. Near the cyclone center, the near-inertial energy remains confined to a shallow surface layer. At $Y=120$ km, the near-inertial energy penetrates approximately to the upper 500 m. Farther away, at $Y=240$ km, the energy occupies the entire water column throughout the analysis period, and the vertical structure appears to transition from a dominant mode-1 pattern to higher-order modes over time. A similar evolution is found at $Y=360$ km, although with a noticeable temporal delay. But at $Y=360$ km, the phase propagation of NIWs is downward, indicating an upward energy flux of NIWs,

consistent with the results displayed in Fig. 6, where NIWs are firstly downward near the cyclone center, and are reflected at the sea bed, then going upward in the far field ($Y > 250$ km).

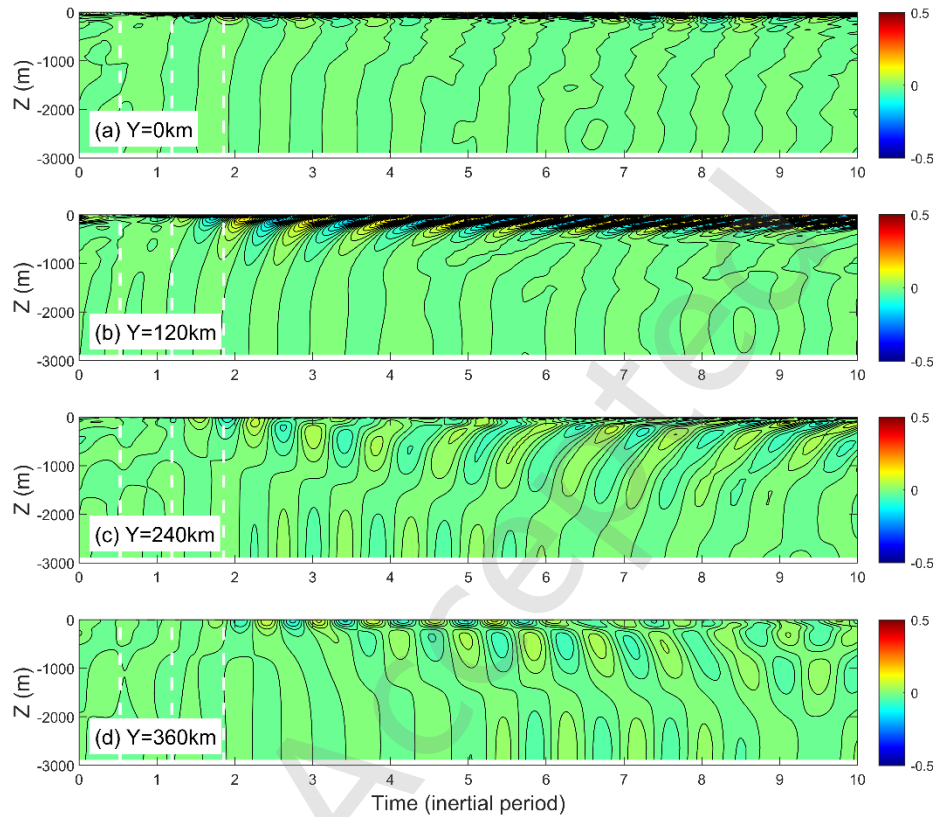


Figure 10. Near-inertial currents (v , north-south component, m s^{-1}) from the 3D simulation at different positions of the cross-track section obtained using band-pass filtering. The contour interval is 0.02 m s^{-1} . Three white dash lines from left to right represent the times of the beginning, the greatest influence, and the ending of the cyclone influence, respectively.

Additional insight is provided by the vertical mode decomposition, of which the first ten modes are displayed in Fig. 11. At $Y = 240$ km, the flow is dominated by mode-1 during the first three inertial periods, accounting for more than 50% of the total energy. During the subsequent two inertial periods, mode-2 becomes the leading contribution at roughly 50%, followed sequentially by mode-3 and mode-4 as the dominant modes. This progression is consistent with analytic NIW theory, which predicts that lower modes propagate at faster phase speeds and therefore arrive earlier [29]. The combined contribution of the first four modes exceeds 90% during the first five

inertial periods, after which it gradually declines. At $Y = 360$ km, the contribution from the first four modes remains around 90% throughout the entire period. However, the clear sequential dominance from mode-1 to mode-4 is not observed, likely due to interference between the downward-propagating NIWs and the upward-propagating waves reflected from the sea bottom (Fig. 6), which can obscure a clean modal evolution. At $Y = 120$ km, the first four modes account for only about 50% of the energy during the first two inertial periods. Thereafter, the largest contribution comes from mode-10, the highest mode included in our decomposition, indicating that most of the NIW energy resides in higher modes. A similar pattern is found at the cyclone center ($Y = 0$ km), where high-mode energy again dominates.

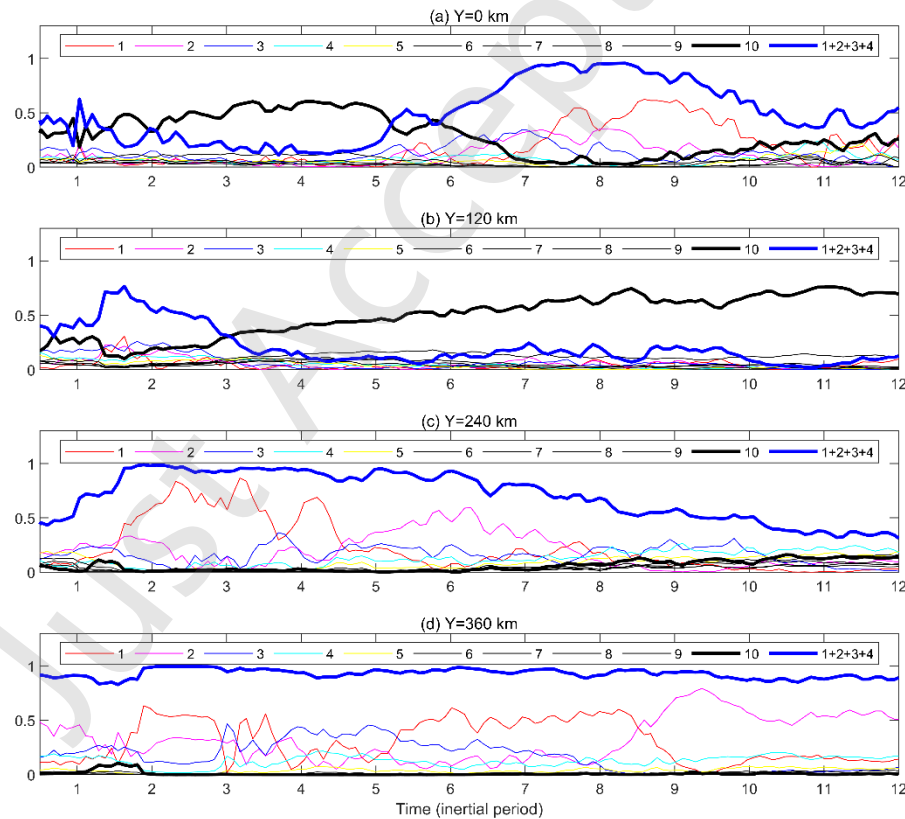


Figure 11. Contributions from the first ten modes, calculated by mode decomposition of near-inertial currents, in terms of percentage in the NIW kinetic energy at different positions of the cross-track section: (a) $Y=0$ km, (b) $Y=120$ km, (c) $Y=240$ km, (d) $Y=360$ km.

The propagation characteristics of NIWs have often been interpreted through vertical normal modes of the linear solution. Assuming the initial field is periodic in the Y direction, the linear analytical solution can be obtained from Equation 12 of Gill (1984) [29] using the stratification taken from our 3-D model. In this framework, the lower modes (Fig. 12), which possess higher phase speeds, arrive earlier. Consequently, the number of turning points of the velocity vectors grows with time, reflecting the increasing influence of higher modes. This behavior is consistent with our simulation results in the far field ($Y = 240$ km; Fig. 11c), but contrasts sharply with the results at other locations. This discrepancy indicates that the applicability of linear theory is limited to a relatively small region in practice.

Moreover, in the linear solution, the downward energy flux arises from modal dispersion, whereby progressively higher modes contribute more significantly through time. Within the mixed layer, the near-inertial energy decreases only gradually. In contrast, in our simulation, the NIOs in the mixed layer decay rapidly within the first two inertial periods as energy is transferred downward to NIWs through inertial pumping. These two mechanisms produce downward energy fluxes of fundamentally different origin.

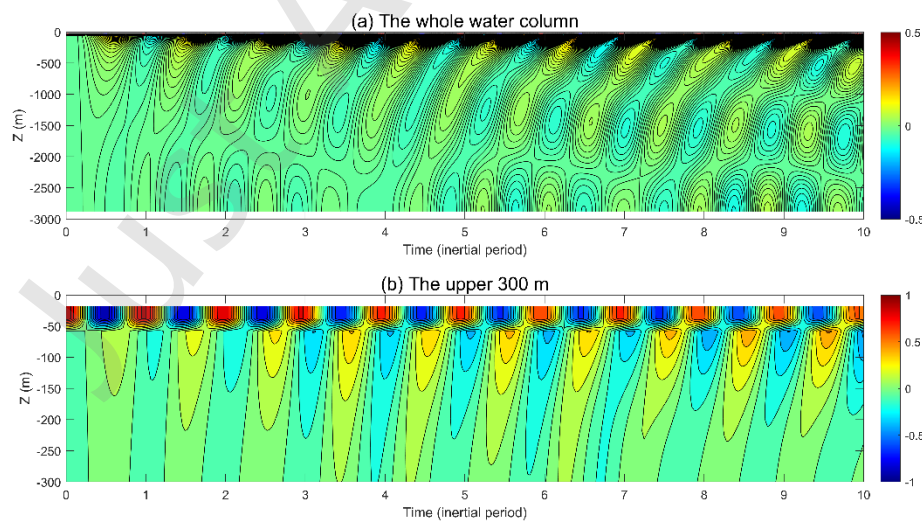


Figure 12. The solution $(u, \text{m s}^{-1})$ in Gill (1984) [29] using the initial profile of N^2 of our simulation. Note the contour line interval is 0.01 for the whole water column (a) and 0.1 for the upper 300 m (b).

3.2.3 The linear 3D simulation

Although linear theories—such as the slab model for NIOs and the vertical normal-mode framework for NIWs—capture many aspects of near-inertial dynamics, they also exhibit substantial discrepancies when compared with our 3-D simulation. The nonlinear terms reach their maximum during the cyclone's passage and oscillate at the near-inertial frequency (Fig. 13). Horizontal advection, which is strongest in the mixed layer, likely contributes to the differences in NIO behavior between the linear model and the full 3-D simulation. Vertical advection is somewhat weaker but remains significant within the thermocline. Overall, the nonlinear terms are concentrated within the upper ~200 m near the cyclone center and display a pronounced right-hand bias (not shown).

When a companion 3-D experiment is performed with advection removed, the resulting fields show noticeable differences (Figs. 14 and 15). The changes are especially large near the cyclone center ($Y = 0$ and 60 km), where the characteristic tilting of the near-inertial contours nearly disappears, indicating that nonlinear processes can substantially modify NIW behavior. In terms of near-inertial energy (Fig. 15), the no-advection case exhibits enhanced energy within the mixed layer but a pronounced reduction in the thermocline. As discussed earlier (Fig. 5), the vertical advection of kinetic energy plays a secondary role compared with the pressure term in mediating the downward energy transfer from NIOs to NIWs. The clear reduction of NIWs energy is probably related to the horizontal advection, which dominates the divergence of currents in the mixed layer. Without the advection terms, the inertial pumping generated diminishes, thus suppressing the energy supplied to NIWs.

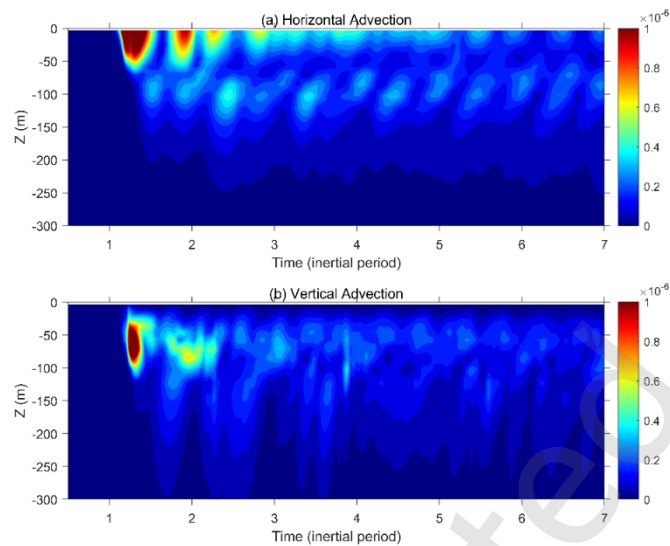


Figure 13. Time-depth variations of the nonlinear terms (a, horizontal advection; b, vertical advection) averaged over the cross-track section ($X=600$ km).

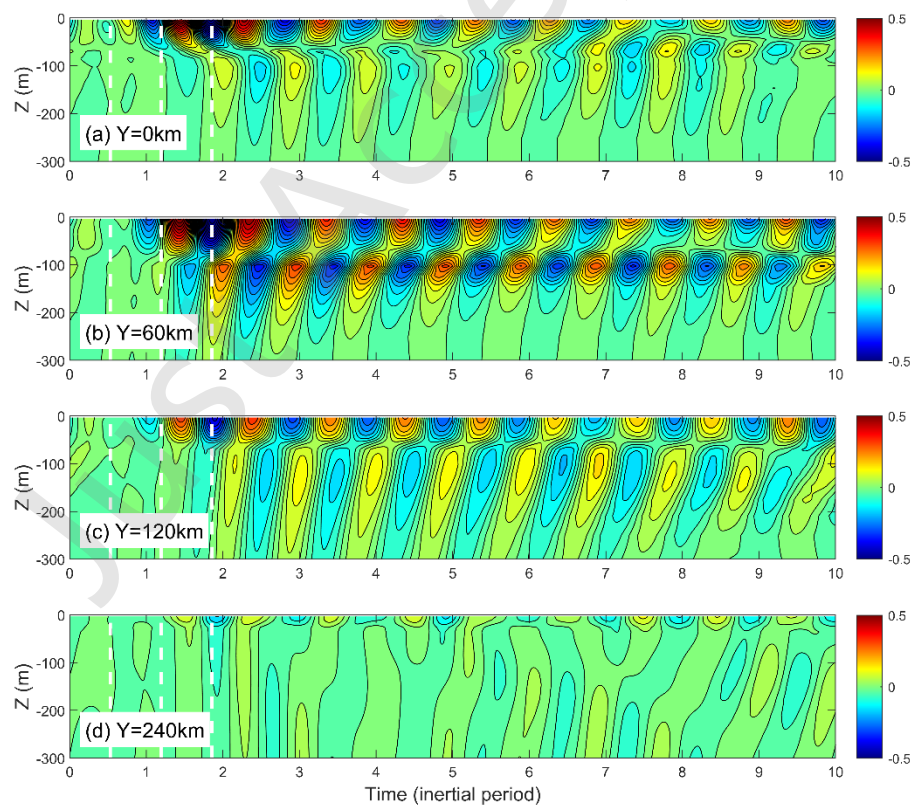


Figure 14. The same as Fig. 2, but the advection terms are turned off in the 3D simulations.

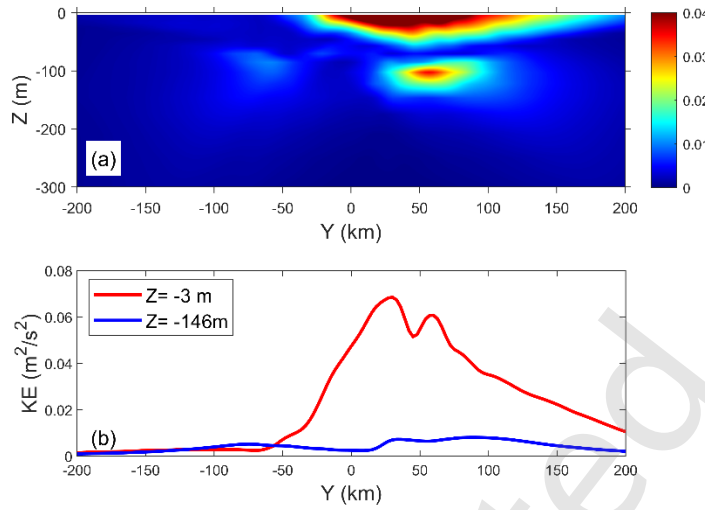


Figure 15. The same as Fig. 3, but the advection terms are turned off in the 3D simulations.

3.3 Influence of the Geostrophic Flow

It is commonly known that the presence of a background vorticity associated with the mean flow can shift the inertial frequency to behave as an effective inertial frequency [8]:

$$f_e \approx f_0 + \frac{\zeta}{2} = f_0 + \frac{1}{2} \left(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y} \right) \quad (13)$$

where U and V are velocities of mean flow, ζ is the relative vorticity, f_0 and f_e are local inertial and effective inertial frequencies, respectively. In our results (Fig. 16), the near-inertial energy below the mixed layer is clearly at a frequency greater than the local inertial frequency ($\sim 10\%$). This is typical for NIWs in which the intrinsic frequency is super-inertial. At the sea surface, where the process is mainly NIOs, both super-inertial and sub-inertial shifts exist. It is super-inertial near the cyclone center, and sub-inertial at $Y > 40$ km. The frequency shift of near-inertial motions may be induced by a background mean flow; however, there is no background mean flow added in the initial or boundary conditions of the simulation.

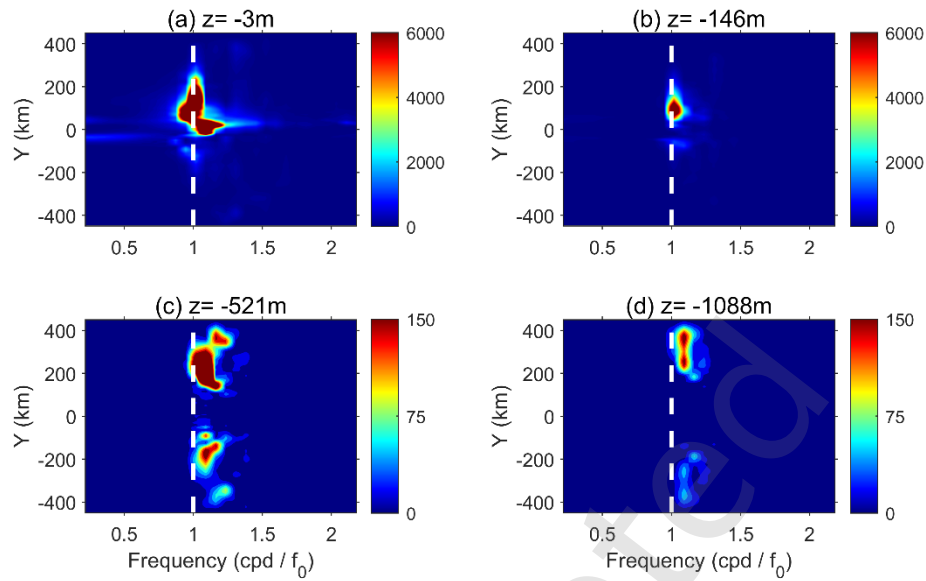


Figure 16. Power spectral density ($\text{m}^2 \text{s}^{-2}/\text{Hz}$) of current (v) at different water depths. Note the different color scales between (a, b) and (c, d). The spectra of u (not shown) are almost the same. The white dashed line represents the local inertial frequency (0.69 cpd). The frequency axis is scaled by the local inertial frequency.

Following the passage of the cyclone, a strong and persistent background mean flow remains (Fig. 17). This current is predominantly oriented in the east–west direction, with magnitudes reaching approximately 0.5 m s^{-1} . It is westward (negative) north of the cyclone track and eastward (positive) to the south, consistent with the elevated sea surface height near the cyclone center. The resulting geostrophic flow is largely confined to the upper $\sim 200 \text{ m}$ and is centered along the cyclone path, spanning roughly 120 km in the cross-track direction. Correspondingly, the induced vorticity is positive near the center ($|Y| < 30 \text{ km}$) and negative in the flanking regions ($30 \text{ km} < |Y| < 120 \text{ km}$). The associated inertial-frequency shift reaches up to $\sim 10\%$. Notably, the spatial pattern of vorticity aligns closely with the observed horizontal distribution of the near-inertial energy frequency shift.

Previous studies have documented the development of geostrophic currents following cyclone passage [32,34]. Price (1983) [48] suggested that the energy contained in these geostrophic flows represents only a small fraction of the total response. In contrast, our simulation indicates that the geostrophic current is of the same order of magnitude as the near-inertial currents. While it is well established that NIWs can be trapped by negative vorticity, the vorticity associated with the geostrophic flow in our case is confined primarily to the upper $\sim 100 \text{ m}$, where NIOs dominate the

near-inertial signal. Consequently, it is the NIOs—rather than the deeper-propagating NIWs—that are most strongly influenced by the geostrophic flow.

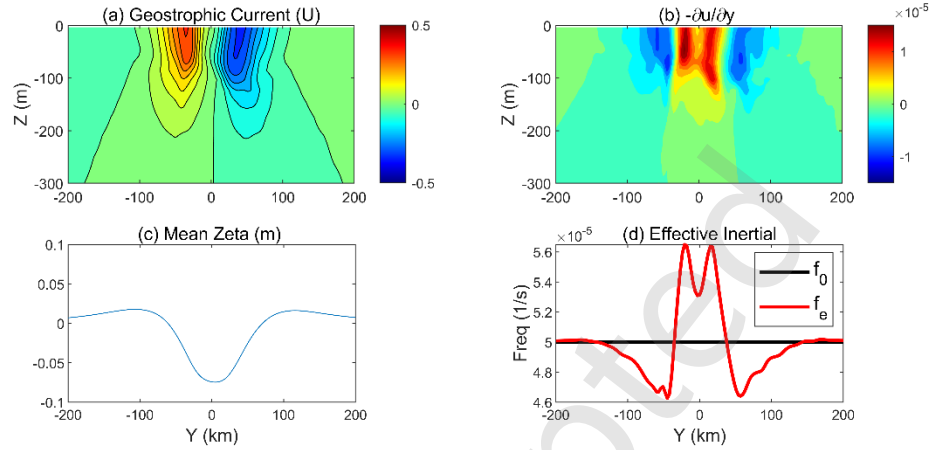


Figure 17. The time-averaged values over 50-480 h along the cross-track section: (a) geostrophic current u (m s^{-1}), (b) relative vorticity (s^{-1}), (c) the average sea level, (d) the effective inertial frequency. The geostrophic current is obtained using low-pass filtering. The local inertial frequency (f_0) and the corresponding effective inertial frequency (f_e) are averaged in the mixed layer, where the contribution of the v component to the relative vorticity is negligible.

4 Sensitivity Studies

4.1 The Beta Effect

The case analyzed above is based on an f -plane approximation. Previous studies have shown that NIWs propagating poleward are reflected equatorward at the critical latitude, where the intrinsic frequency of internal waves equals the local inertial frequency [29,33]. To examine this effect, we conduct an additional experiment that includes the β term, with β set to its value at 16°N ($2.2 \times 10^{-11} \text{ m}^{-1} \text{ s}^{-1}$).

Relative to the f -plane results (Fig. 16), the near-inertial spectra in the β -plane simulation show little difference at the sea surface (Fig. 18). This indicates the dominant NIOs within the mixed layer are largely insensitive to β , because the NIOs are wind-generated, which are hardly affected the beta effect. Below the mixed layer, however, the response is governed by NIWs whose intrinsic frequency is super-inertial in both cases. In the thermocline ($Z = -146 \text{ m}$), the β effect shifts near-inertial energy toward slightly higher frequencies, broadening the spectral band. At $Z = -521 \text{ m}$,

the β -plane case exhibits stronger near-inertial energy within $-100 \text{ km} < Y < 100 \text{ km}$, likely due to partial reflection of NIWs at the critical latitude located near $Y \approx 200 \text{ km}$. At $Z = -1088 \text{ m}$, the NIW energy in the β -plane case diminishes sharply beyond $Y \approx 300 \text{ km}$, whereas in the f -plane case it extends farther poleward to $Y \approx 400 \text{ km}$. Similar behavior is seen in the near-inertial kinetic energy (Fig. 19): the mixed layer remains largely unaffected by β , but substantial differences emerge below it. At depths of -146 m and -521 m , near-inertial energy is significantly enhanced near the cyclone center and reduced farther away.

In summary, the β effect exerts minimal influence on NIOs but produces a clear modification of NIWs. Because the intrinsic frequency of NIWs is approximately 10% higher than the local inertial frequency, the corresponding critical latitude lies roughly 200–300 km poleward of the cyclone center. Reflection of NIWs at this latitude confines a greater portion of the NIW energy to the vicinity of the cyclone track.

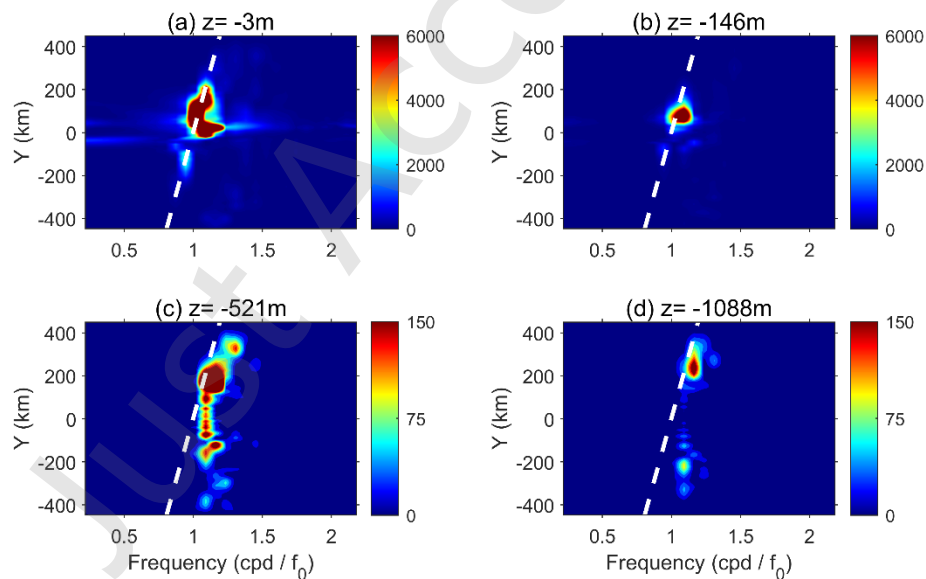


Figure 18. Power spectral density ($\text{m}^2\text{s}^{-2}/\text{Hz}$) of current (v) at different water depths in the simulation, including beta effect. The frequency axis is scaled by the reference frequency f_0 (0.69 cpd). The spectra of u (not shown) are almost the same. The white dashed line represents the local inertial frequency. Note different color scales.

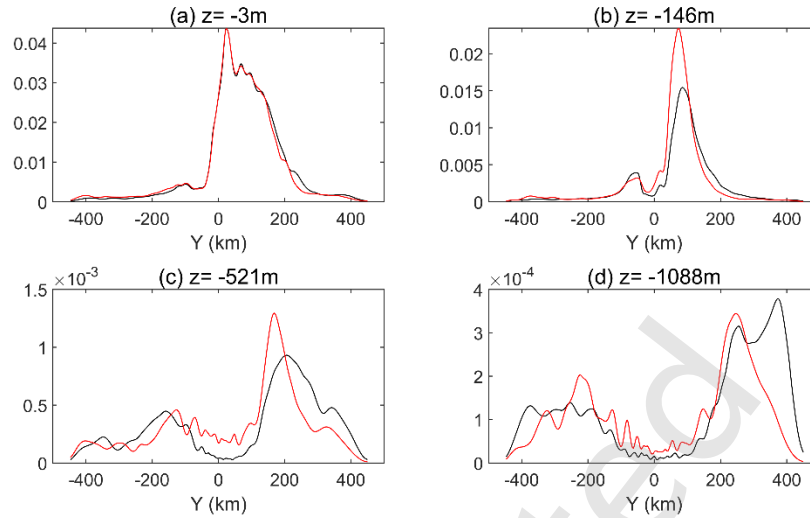


Figure 19. Time-averaged near-inertial kinetic energy ($\text{m}^2 \text{s}^{-2}$) at different depths in cases of the f -plane (black lines) and the β -plane (red lines).

4.2 The Translation Speed of Cyclone

In the control experiment, the cyclone translates at a constant speed of 6 m s^{-1} . Because real cyclones typically propagate at varying speeds, we additionally examine cases with translation speeds of 2, 3, and 9 m s^{-1} . For NIOs in the mixed layer (Fig. 20a), the 6 m s^{-1} case produces the largest near-inertial energy, consistent with Chen et al. [27], who showed that maximum inertial oscillations occur when the cyclone's translation speed optimally balances the forcing intensity and duration. In contrast, when the cyclone moves as slowly as 2 m s^{-1} , the weakest NIOs are generated, and the characteristic right-hand bias disappears. The right-hand asymmetry generally arises from enhanced phase coherence between the near-inertial current and the wind vector on the right-hand side of the track. At a very low translation speed (2 m s^{-1}), the wind vector rotates at a frequency far below the local inertial frequency, reducing the phase coherence and thereby eliminating the right-hand bias.

The NIW response in the thermocline (Fig. 20b) exhibits a different behavior. The strongest NIW energy occurs in the 3 m s^{-1} case, whereas the 9 m s^{-1} case produces the weakest response. In the 2 m s^{-1} case, the energy remains right-hand biased. As previously discussed, NIWs derive their energy primarily from NIOs via inertial pumping, which depends on the divergence of the mixed-layer near-inertial currents. A slower-moving cyclone produces larger divergence, shifting the optimal translation speed for maximizing NIW energy downward to about 3 m s^{-1} .

The geostrophic current response also varies with translation speed (Fig. 20c). Its energy increases as the translation speed decreases, displaying a weak left-hand asymmetry. This suggests that interactions between NIOs and the slowly evolving geostrophic flow become increasingly important for cyclones with slower translation speeds.

In terms of currents, the responses to different translation speeds differ markedly between NIOs and NIWs. Within the mixed layer, the horizontal currents—dominated by NIOs—exhibit a clear periodic pattern trailing the cyclone (Fig. 21). The spacing of these alternating bands is given by $C_t T$ (where C_t is the cyclone translation speed, and T is the inertial period). The corresponding wavelengths are approximately 251 km, 377 km, 754 km, and 1,131 km for translation speeds of 2, 3, 6, and 9 m s⁻¹, respectively. This pattern is consistent with the phase of NIOs lagging behind the translating cyclone.

In the thermocline, the NIWs form a wedge-shaped wake characterized by multiple slopes, resembling the wake generated by a moving ship. The phase speeds associated with these slopes can be diagnosed from the diagram in Fig. 23. For translation speeds of 3, 6, and 9 m s⁻¹, the inferred phase speeds are nearly identical—approximately 2.8 m s⁻¹ and 1.5 m s⁻¹—corresponding to mode-1 and mode-2 NIWs, respectively. In the 2 m s⁻¹ case, however, the mode-1 NIW is absent because its phase speed (2.8 m s⁻¹) exceeds the cyclone's translation speed, preventing its formation. Nevertheless, a wedge-like wake associated with the slower mode-2 NIW (phase speed ~1.5 m s⁻¹) remains. Classical theory [34] suggests that a wake forms only when the translation speed surpasses the wave phase speed. Our results indicate that, although the mode-1 wake is suppressed when $C_t < c_1$, a wake can still occur for higher-mode NIWs whose phase speeds are sufficiently slow. Thus, the presence of the wedge pattern is governed not by a single wave mode, but by the relative relationship between the cyclone translation speed and the phase speeds across the NIW modal spectrum.

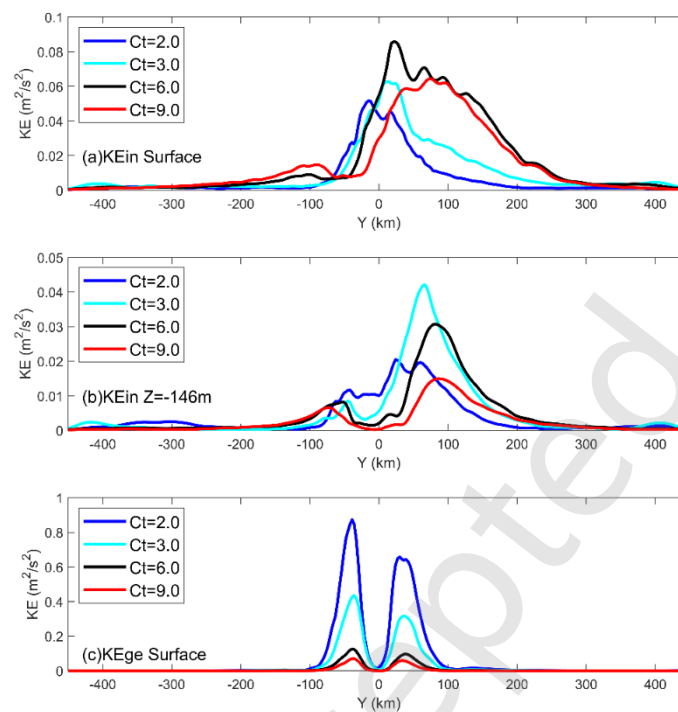


Figure 20. Time-averaged kinetic energy of near-inertial currents at the sea surface (a) and thermocline (b), and that of surface geostrophic currents (c) for the cases with different cyclone translation speeds (C_t).

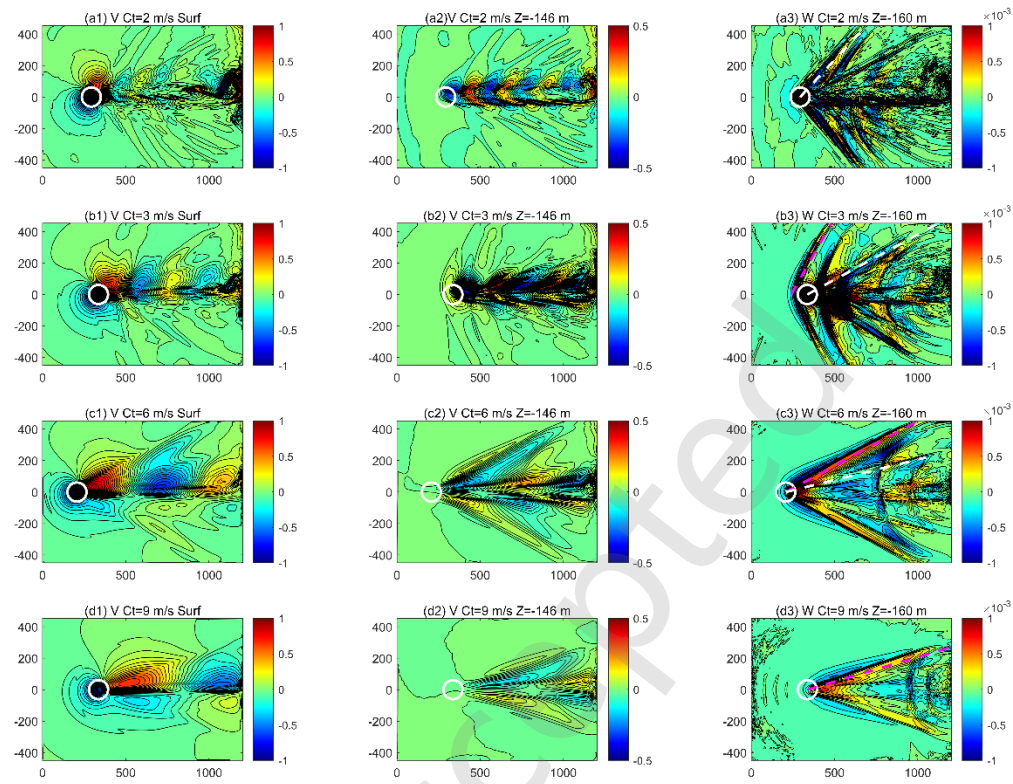


Figure 21. The X(km)-Y(km) distribution of north-south velocities (v) at the sea surface (left panels) and at $Z=-146$ m (middle panels), and vertical velocities (w) at $Z=-160$ m (right panels) for the cases with cyclone translation speeds of 2 m s^{-1} , 3 m s^{-1} , 6 m s^{-1} and 9 m s^{-1} (from upper panels to bottom panels, respectively). The white circle denotes the cyclone center. The dashed lines outline the slope of wedges, which are used for computing the phase speeds of mode-1 (pink) and mode-2 (white).

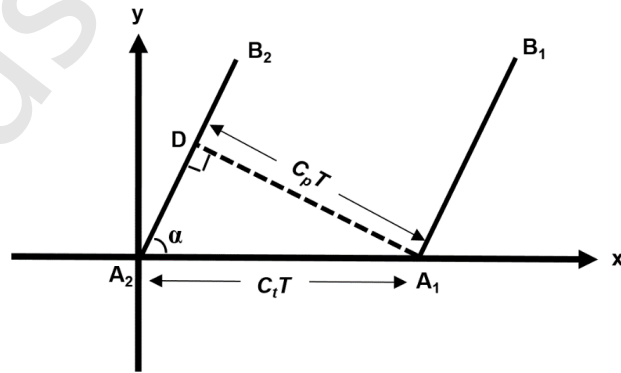


Figure 22. A diagram illustrating the wake after a cyclone. The cyclone moves from point A_1 to A_2 when the wave propagates from A_1 to D . Given the angle of the wedge (α), the wave speed can be obtained by $C_p = C_t \sin \alpha$.

5 Summary and Discussion

To investigate the properties of near-inertial motions, we use a three-dimensional numerical model based on ROMS to simulate idealized cyclone passages over a deep ocean (3000 m). A control experiment is examined in detail, followed by several sensitivity experiments and comparison with linear models. The cyclone generates two distinct types of near-inertial response: near-inertial oscillations (NIOs) in the mixed layer and near-inertial internal waves (NIWs) in the stratified interior.

As the cyclone approaches, NIOs are driven directly by the rapid changes in wind stress within the mixed layer. Owing to the weak stratification there, NIOs are essentially non-baroclinic. Their energy is surface-intensified and strongly right-hand biased, with the maximum located at the radius of maximum wind on the right-hand side, where the wind forcing is strongest and continues to accelerate the near-inertial currents (e.g., Price, 1981 [47]). In the simulation of linear slab model with the vertical viscosity in the 3-D simulation, NIOs hardly go below to the thermocline. And given the short period of intense wind during a cyclone passage, the wind work is mainly on the NIOs, rather than the NIWs that occupy the whole water depth and mainly develop after the cyclone passage.

Within the thermocline, distinct upward phase propagation reveals the presence of NIWs. NIW energy is strongest in the thermocline and is also right-hand biased, but its maximum occurs at approximately twice the radius of maximum wind. Far from the cyclone center, NIWs propagate throughout the full water column, with lower modes traveling ahead of higher modes. An analysis of the near-inertial energy budget shows that the energy released from perturbation potential energy during geostrophic adjustment is insufficient to account for NIW energetics. Instead, the dominant energy source for NIWs is the downward energy flux associated with the vertical pressure work generated by the inertial currents. This vertical pressure work is strongest near the base of the mixed layer, where large vertical velocities arise from the divergent NIO currents—producing strong inertial pumping. Inertial pumping thus acts as the key mechanism transferring kinetic energy from NIOs downward into the stratified interior to generate NIWs. Although this process has been qualitatively described in previous studies [29,48,49], our results provide quantitative evidence for the role of inertial pumping.

Classical linear theories have long been used to describe both NIOs and NIWs. A central motivation of this study is to compare these linear predictions with fully nonlinear 3-D results and to assess the role of nonlinear processes in near-inertial dynamics. For NIOs, we employ the classic linear slab model, using the same wind field as in the 3-D simulation. The linear model also produces a pronounced right-hand bias; however, it yields a much sharper peak and, unlike the 3-D solution, develops a weaker secondary peak on the left-hand side of the cyclone track. Moreover, NIOs remain relatively steady in the linear model, whereas in the 3-D simulation, they decay rapidly as energy is transferred downward to NIWs.

In the stratified interior, NIWs are initially restricted to the thermocline in the near field and subsequently propagate outward and downward. Linear normal-mode decomposition shows that, in the far field, energy arrives sequentially in mode-1 followed by higher modes (2, 3, and 4), consistent with previous findings [29,30,32]. In contrast, within approximately 120 km of the cyclone center, most NIW energy resides in higher modes concentrated within the thermocline—a behavior that is not well captured by linear mode theory. The 3-D simulation reveals that nonlinear terms are substantial during the first 2–3 inertial periods following cyclone passage. Their magnitudes are largest within the upper ~150 m and within ± 100 km of the cyclone track, where NIOs and NIWs are strongest. A companion experiment in which advection terms are removed shows a marked reduction in NIW energy, highlighting the importance of nonlinear processes in facilitating the downward transfer of energy to NIWs—even though Brizuela et al. (2022) [49] argued that coupling between divergence and vorticity during inertial pumping is fundamentally linear. Together, these results demonstrate that nonlinear processes cannot be neglected in near-inertial dynamics, particularly in the generation and evolution of NIWs.

In addition to near-inertial motions, a substantial portion of the cyclone-induced energy remains stored in the geostrophic currents, consistent with earlier findings by Price (1983) [48] and Geisler (1970) [34]. In our simulation, this geostrophic flow is confined to the upper surface layer ($Z > -150$ m) and concentrated within approximately ± 100 km of the cyclone center. Its influence, therefore, acts primarily on the NIOs rather than on the NIWs. Although it is well established that NIWs are trapped by regions of negative vorticity [8], much less is known about how background vorticity affects the essentially non-baroclinic NIOs [12]. Observed frequency shifts in near-inertial motions are typically attributed to pre-existing background flows [28,50], yet the impact

of the geostrophic current generated directly by the cyclone itself has received relatively little attention.

Sensitivity experiments are conducted to assess the β effect and the influence of cyclone translation speed. The β -plane experiment shows little modification to the NIOs within the mixed layer. For NIWs, however, the intrinsic frequency becomes super-inertial, and turning latitudes emerge approximately 200–300 km poleward of the cyclone center. Overall, the β effect is modest, consistent with the results of Chang and Anthes (1978) [33] and Gill (1984) [29]. We also examine cases with translation speeds of 2, 3, 6, and 9 m s⁻¹. At the sea surface, the wake displays a periodic pattern dominated by NIOs. In the thermocline and deeper layers, the wake assumes a wedge-like structure. Geometric estimates yield a phase speed of approximately 2.8 m s⁻¹ for mode-1 NIWs. Classical theory (e.g., Geisler, 1970 [34]) suggests that a wake forms only when the cyclone translation speed exceeds the internal-wave phase speed. However, even in the 2 m s⁻¹ case—slower than the mode-1 phase speed—a clear wedge-like wake persists. This feature arises from the slower mode-2 NIWs rather than from mode-1. Other factors, like the stratification structure and the cyclone intensity and horizontal scale, may also probably affect the quantitative results of NIOs and NIWs, however, the core processes between them would change little. The influence under background flows and the bottom topography will be interesting work worth doing.

In summary, by explicitly distinguishing between near-inertial oscillations (NIOs) and near-inertial internal waves (NIWs) and analyzing their dynamics separately, this study provides a more comprehensive understanding of near-inertial processes and their associated impacts.

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None.

Author contribution statement

Shengli Chen: Conceptualization, formal analysis, writing – original draft, visualization.

Jiuxing Xing: Supervision, writing – review and editing.

Jianyu Hu: Methodology, writing – review and editing.

Yunping Song: Investigation, writing – review and editing.

All the authors have approved the final manuscript.

Data availability

The simulation data used in the study are available at Zenodo via URL: <https://doi.org/10.5281/zenodo.17862073>.

Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

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Use of AI generated contents and AI-assisted technologies statement

None.

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