1. Introduction

Numerous in situ and remote sensing observations reveal that internal solitary waves (ISWs) are ubiquitous in density-stratified oceans and commonly exist in coastal seas, fjords, and straits (Apel et al. 1985; Helfrich and Melville 2006; Alford et al. 2015). These waves are mostly generated through energetic tide–topography interactions under favorable oceanic conditions (Alford et al. 2015; Li and Farmer 2011; Lien et al. 2005; Zhao et al. 2004; Klymak et al. 2006; Chang et al. 2006). The fronts of these waves can extend for hundreds of kilometers and may propagate hundreds of kilometers from their source, carrying momentum and mass toward the coastline, which has been demonstrated to carry a large amount of energy (Klymak et al. 2006; Huang et al. 2014, 2017). The energy dissipation of ISWs represents a step in the energy cascade from internal wave (IW) motions down to small-scale turbulent mixing (Lien et al. 2005; Chang et al. 2006, 2021a,b; Moum et al. 2007; St. Laurent et al. 2011; Bai et al. 2019; Rivera-Rosario et al. 2020; Liu et al. 2022), which plays an important role in controlling the stratification and vertical distribution of biogeochemical material in marine ecosystems (Wang et al. 2007; Alford et al. 2015; Dong et al. 2015).

Based on field observations, many previous studies have been performed on the properties of the mixing process of ISWs (Sandstrom et al. 1989; Moum et al. 2003, 2007; Zhao et al. 2004; Klymak et al. 2006; Chang et al. 2006, 2021a,b; St. Laurent et al. 2011; Lamb 2014; Zhang and Alford 2015; Rivera-Rosario et al. 2020). On the Oregon shelf, Moum et al. (2003) observed high acoustic backscatter in the leading solitary wave of a wave packet starting near the wave trough, behind which the estimated maximum turbulent diffusivity values exceeded 0.1 m² s⁻¹. They inferred that the Richardson number (Ri) at the high acoustic backscatter interface was less than 0.25 based on a velocity field from fine-scale density measurements, indicating a site of enhanced mixing. Subsequently, Moum et al. (2007) captured an ISW exhibiting shear instabilities over a distance of 32.5 km as it shoaled between depths of approximately 180 and 70 m on the same shelf associated with an average rate of energy loss of approximately 14 W m⁻¹. Lien et al. (2012) reported that a large-amplitude (100–200 m) ISW propagating up the slope near Dongsha Island reached its breaking limit and formed a subsurface trapped core as its propagation speed decreased from 2 to 1.3 m s⁻¹, while the maximum along-wave current speed (Umax) remained constant at 2 m s⁻¹. The local turbulent dissipation rate at the center of the trapped core was as high as O(10⁻⁴) W kg⁻¹. Additionally, some observations revealed that shoaling ISWs after polarity conversion will break more easily in the bottom boundary layer on the continental shelf and thus enhance turbulent mixing due to bottom stress (Klymak and Moum 2003; Bourgault et al. 2007). Martini et al. (2013) pointed out that on a slope parallel to the reflected wave beam, both generated and incident waves...
are prone to breaking through energy transfer to high wave-numbers and the formation of strong along-slope currents and density overturns.

In summary, Lamb (2014) concluded that the mixing process of shoaling ISWs occurs under four certain conditions: 1) shear instabilities triggered by ISW-induced vertically sheared currents under the condition of $\text{Ri} < 1/4$ (Sandstrom et al. 1989; Moum et al. 2003; St. Laurent et al. 2011), 2) convectively unstable wave cores as the propagation speed of ISWs decreases to less than the maximum along-wave current speed (Lamb 2002, 2003; Lamb and Farmer 2011; Lien et al. 2012, 2014), 3) instabilities in the bottom boundary layer induced by the no-slip bottom boundary condition (Bourgault et al. 2008; Carter et al. 2005; Orr and Mignerey 2003; Richards et al. 2013; Scotti and Pineda 2004), and 4) wave breaking while shoaling at an abrupt change in topography. As these conditions are relatively easy to satisfy, previous observations have shown that the first two processes are dominant for midcolumn mixing in areas without abrupt bathymetric changes on the continental slope/shelf (Moum et al. 2003, 2007; Shroyer et al. 2010; Zhang and Alford 2015; St. Laurent et al. 2011; Lien et al. 2012).

Previous studies have demonstrated that the typically enhanced mixing processes of ISWs can appear in a variety of ways; however, they have largely focused on shoaling ISWs or fission ISWs over the continental shelf. The energy dissipation route of ISWs as they propagate in deep waters before shoaling or fission is still largely unclear at present. Investigating the dissipation process of ISWs in deep waters can help us clarify the energy budget and deep-ocean ecological environment changes associated with ISWs. In this study, we provide observational evidence of the energy cascade process from ISWs to mixing via near-$N$ waves in the deep water of the northern South China Sea (SCS), and we then show the properties, instabilities, and mechanism of

![Fig. 1. Bathymetry of the northern South China Sea. The location of the high-temporal-resolution mooring PU is indicated by the red star.](image1)

![Fig. 2. (a) Depth-time distribution of the observed temperature. The lines represent the isothermal displacements at every 1°C between 12°C and 20°C. The white arrows indicate the occurrences of the ISW1–ISW8 ISWs. (b) The observed 20°C isotherm obtained from (a).](image2)
the enhanced near-N waves in detail. The remainder of this paper is organized as follows. We introduce the data, methods, and theory in section 2. We show the detailed results of the new method of assessing ISW energy mixing in deep water in section 3. Then, the mechanism of the cascade process is discussed based on theoretical analysis in section 4. Finally, a summary is provided in section 5.

### 2. Data, methods, and theory

#### a. Data and methods

A high temporal resolution mooring named PU, as a part of the South China Sea Mooring Array (SCSMA) (Huang et al. 2017, 2018; Zhang et al. 2017, 2016), was deployed near Dongsha Island in the northern SCS (the red pentagram in

### Table 1. Information of mooring and detailed settings of instruments used to monitor ISWs and near-N waves.

<table>
<thead>
<tr>
<th>Mooring</th>
<th>Longitude, latitude</th>
<th>Water depth (m)</th>
<th>Observation period</th>
<th>Instruments (facing direction)</th>
<th>Instrument depth (m)</th>
<th>Working time</th>
<th>Record length (days)</th>
<th>Sample interval (s)</th>
</tr>
</thead>
</table>

#### 2.1 Instruments

- Thermistor chain
- 75-kHz ADCP: an upward-looking and a downward-looking

At 450 m beneath the sea surface

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![Fig. 3. Wavelet analysis of the observed 20°C isotherm fluctuations at PU. (a) The color-filled contours are the log₁₀-scaled variance (m²) of the wavelet transform of the normalized isotherm for the whole observational time. The black solid line is the 95% confidence level. (b) The wave power of the 20°C isotherm fluctuations with periods less than 5 min for the whole observational time (red line); the blue solid lines are the observed tide-out 20°C isotherm for the whole observational time. (c),(d) As in (a) and (b), respectively, but for the period of the occurrence of the ISW7 around 2030 LT 27 Jul. The correlation coefficient between the wave power of the 20°C isotherm fluctuations with periods less than 5 min and the time series of the observed tide-out 20°C isotherm fluctuations reaches 0.81 and 0.70 for the whole observational time and the period of the occurrence of ISW7 around 2030 LT 27 Jul, respectively.](image-url)
Fig. 1), where ISWs are concentrated (Zhao et al. 2004). This mooring was deployed at a water depth of 1000 m from 24 to 28 July 2014. It was equipped with an upward-looking and a downward-looking 75-kHz acoustic Doppler current profiler (ADCP) (both at 450 m beneath the sea surface) to measure current velocities with vertical bins of 8 m, bin number of 70, and sampling intervals of 20 s. A thermistor chain consisting of six conductivity–temperature–depth (CTD) sensors and 53 thermometers mounted at different depths throughout most of the water column was also established (Table 1) and collected data with vertical interval of 10 or 20 m and sampling intervals of 6 s. Since the maximum Brunt–Väisälä frequency (the Brunt–Väisälä frequency $N = \sqrt{g/\rho \partial \rho / \partial z}$, here the density profiles $\rho$ are computed from the temperature and salinity profiles measured by mooring PU) around the thermocline was approximately $2 \times 10^{-2}$ s$^{-1}$, the instruments on the moorings with high sampling rates were capable of recognizing high-frequency IWs near the maximum local buoyancy frequency.

The energy density per unit volume of IWs is defined as

\[ E = KE + APE, \] (1)

where the kinetic energy (KE) is defined as

\[ KE = \frac{\rho_0}{2} (u_a^2 + w^2) \] (2)

and the available potential energy (APE) is defined as

\[ APE = \int_{\alpha - \zeta}^{\alpha} g(\rho(z) - \rho_r(z'))dz'. \] (3)

Here, $\rho_0 = 1024$ kg m$^{-3}$ is the constant density, and $u_a$ and $w$ are the along-wave velocity and vertical velocity, respectively. The term $g$ is the gravity constant, $\zeta$ is the isothermal displacement, $\rho(z)$ is the in situ density, and $\rho_r$ is the reference density; here the density profiles $\rho_r$ are computed from the temperature and salinity profiles 30 min before the ISW measured by

![Fig. 4. Spectrum analysis for the wave energy of the period less than 5 min. The red solid line indicates over the 30-min periods before the observed eight ISWs. The green solid line indicates at the time of the occurrence of the observed eight ISWs. The black solid line indicates over the 30-min periods after the observed ISWs. The red dotted lines indicate the period of 200 min.](image-url)
The definition of APE used here has been proven to be optimal for ISWs by Kang and Fringer (2010).

b. KdV–Burgers equation

The traditional Korteweg–de Vries (KdV) equation that contains dispersion and nonlinear terms has restoring forces, making solitons keep constant waveforms (Holloway et al. 1997; Michallet and Barthélemy 1998; Helfrich and Melville 2006; Grimshaw 2001; Grimshaw et al. 2004; Grimshaw 2015). Through analyzing the dissipation mechanism of turbulence in strong nonlinear wave systems, Burgers (1948) proposed the KdV–Burgers equation, and Liu and Liu (1991) demonstrated that the KdV–Burgers equation can be used to explain the detailed damped oscillation cascade process from soliton to turbulence in nonlinear mathematical physics:

$$\frac{\partial \eta}{\partial t} + c \frac{\partial \eta}{\partial x} + \alpha \eta \frac{\partial \eta}{\partial x} + \beta \frac{\partial^3 \eta}{\partial x^3} - \mu \frac{\partial^2 \eta}{\partial x^2} = 0,$$

where $\eta(x, t)$ is the vertical interface displacement; $c$ is the linear long wave speed; and $\alpha$, $\beta$, and $\mu$ are the coefficients of quadratic nonlinear, dispersion, and dissipation, respectively. The nonlinear and dispersion coefficients can be calculated following the method in our earlier papers (Huang et al. 2017; Zhang et al. 2018) and are computed using continuous stratification (Grimshaw 2001; Grimshaw et al. 2004; Grimshaw 2015),

$$\alpha = \frac{3}{2} \frac{\int_{-h}^{0} (c - U)^2 \Phi^2 dz}{\int_{-h}^{0} (c - U) \Phi^2 dz},$$

$$\beta = \frac{1}{2} \frac{\int_{-h}^{0} (c - U)^2 \Phi^2 dz}{\int_{-h}^{0} (c - U) \Phi^2 dz}.$$
\[ ((c - U)^2 \Phi_x) + N^2 \Phi = 0, \quad (7) \]

where \( U(z) \) is the background shear current and \( N(z) \) is the buoyancy frequency. The term \( T(z) \) is the nonlinear correction to the modal structure, which is obtained by solving the inhomogeneous eigenvalue problem

\[
\frac{d}{dz}[(c - U)^2 T_z] + N^2 T = -\alpha \frac{d}{dz}[(c - U) \Phi_x] + \frac{3}{2} \frac{d^2}{dz^2}[(c - U)^2 \Phi_x^2]. \quad (8)
\]

As pointed out by Liu and Liu (1991) and Liu and Liu (1992), the dissipation coefficient \( \mu \) is the actual kinematic viscosity \( \nu \). In this paper, the value of \( \nu \) is \( 5 \times 10^{-4} \text{ m}^2 \text{ s}^{-1} \), which was chosen following Helfrich and Melville (1986).

3. Observational results

a. Occurrence of ISWs and near-\( N \) waves

Using the measurements from the mooring PU, the occurrence of ISWs and high-frequency IWs were examined. The time series of temperature at PU during the whole observational period are shown in Fig. 2. Notable solitary signals characterized by depressed isotherms in the mode-1 category are visible in the temperature measurements (Figs. 2a,b). The 4-day observations recorded 8 ISWs, which are named as ISW1–ISW8 following the sequence of them (Fig. 2a). The isotherm fluctuation showed that the amplitudes of the observed ISWs were up to around 100 m.

Wavelet analysis of the displacements of the 20°C isotherm demonstrated a corresponding relationship between the occurrence of high-frequency IWs (period < 5 min) and ISWs (Fig. 3). The wave power of high-frequency IWs during the occurrence of ISWs was obviously stronger than that in the absence of ISWs (black dotted box in Figs. 3a,c). To examine such correspondence in detail, we focused on the variations in wave power related to the high-frequency IWs accompanied by the largest ISW (the ISW named ISW7 captured around 2030 local time (LT) 27 July as shown in Fig. 2a) captured during the observational period. The wave power of high-frequency IWs was enhanced remarkably during the passage of the ISW7 (Fig. 3b). The correlation coefficient between the wave power of the 20°C isotherm fluctuations with periods less than 5 min and the time series of the observed tide-out (a bandpass filter is used on each isotherm to eliminate the fluctuations signals of diurnal internal tides and semidiurnal internal tides) 20°C isotherm fluctuations reaches 0.81 and 0.70 for the whole observational time and the period of the occurrence of ISW7 around 2030 LT 27 July, respectively. Moreover, we make the spectrum analysis over all the observed ISW events available. The spectrum analysis results revealed that a remarkable peak emerged near the buoyancy frequency of approximately 200 s\(^{-1}\) during the occurrence of the eight ISWs (green lines in Fig. 4). Combined with the calculated correlation coefficient between the wave power time series of the period less than 5 min and the time series of the observed 20°C isotherm fluctuations, we can infer that the peaks near the buoyancy frequency \( N \) were induced by the occurrence
Thus, the above results indicate that the enhanced near-N waves are closely associated with the occurrence of ISWs.

b. Properties of the enhanced near-N waves

A Butterworth high-pass filter ($T < 5$ min) is used to extract the isotherm fluctuations signals associated with the high-frequency near-N waves. High-frequency signals ($T < 5$ min) are extremely weak in the lower layer deeper than 300 m (not shown), one possible reason is that the isotherm and current anomalies induced by ISWs are much weaker in the deep layer than in the upper layer and thus, the structure of the enhanced high-frequency near-N waves along with ISWs in the upper layer is the focus of this work. From Fig. 5a, each isotherm from which is high-pass filtered with a cutoff period of 5 min, it can be seen that the occurrence of intensified near-N waves correlated well with the eight large-amplitude ISWs during the entire observational period, suggesting a relatively steady coexisting relationship between them. To show the subtle structure of near-N waves more clearly, isotherm fluctuations of near-N waves during the occurrence of ISW7 were investigated. As shown in Fig. 5b, the thermocline depth fluctuated rapidly during the passage of the ISW7, characterized by remarkable high-frequency near-N waves extending from the ISW trough to the rear face with increasing amplitudes. The amplitude of near-N waves was also calculated to investigate their structural features (Fig. 6), and the high-frequency isothermal displacement enhancement was shown to be significant in the upper 200 m, with a maximum amplitude of 12 m.

With respect to the current velocity of the near-N waves, the modified beam-to-Earth transformation is used to measure short-wavelength internal waves with an ADCP following the method of Scotti et al. (2005). Measurements from the four spatially diverging beams and the backscatter intensity signal are used to calculate the propagation direction and celerity of the near-N waves. Then, a beam-to-Earth transformation that combines appropriately lagged beam measurements is used to obtain current estimates in Earth coordinates. As shown in
Fig. 7a, the high-pass signals associated with near-N waves are shown to fluctuate between $-0.2$ and $0.2$ m s$^{-1}$ during the passage of the ISW observed on 27 July (Fig. 7a). Similar oscillations can also be seen in the high-passed vertical velocity with peak-to-peak fluctuating magnitudes of up to $0.1$ m s$^{-1}$ (Fig. 7b). The high-pass time series of both the zonal and vertical currents are shown to be significantly enhanced in the upper layer around the thermocline. Although they varied rapidly at high frequency, the vertical currents associated with the near-N waves were generally in phase through the full water column.

Figure 8 presents the plan view of the horizontal velocity vector fields of the near-N waves over the 30-min periods before and after the ISWs as well as during the passage of the ISW. The horizontal velocity vectors were isotropic before and after the ISW, suggesting the random nature of the background high-frequency waves. As the ISW approached, the current velocities of the near-N waves accompanying the ISW were spatially anisotropic, which is significantly different from those of the high-frequency waves before and after the ISW. The magnitude of the high-frequency horizontal velocity increased largely along the propagation direction of the ISW (the red arrow in Fig. 8), which was much stronger than that in the direction perpendicular to the ISW propagation direction.

c. Energetics of the near-N waves

The time series of energetics for the near-N waves on 27 July are shown in Fig. 9. The KE of the near-N waves is much weaker during the period without an ISW but is enhanced remarkably at the trough of the ISW and extends to the rear face of the ISW, with a maximum of up to over $10$ J m$^{-3}$. The KE structure of the near-N waves is consistent with the occurrence of the ISWs, indicating that the enhanced KE of the near-N waves is significantly modulated by the accompanying ISW. The APE is intense around the thermocline and tends toward zero near the bottom. The enhancement of the APE begins at the trough of the ISW and extends to the rear face of the ISW, similar to that of the KE. The maximum APE is approximately $10$ J m$^{-3}$.

The energetics of the near-N waves observed at the occurrence period of ISW7 between 1900 and 2200 LT 27 Jul showed that the KE component was stronger than the APE component, indicating that more turbulent KE existed (Figs. 9 and 10). The depth-integrated energy $\left\langle E_{\text{HIW}} \right\rangle_z = \int E_{\text{HIW}} dz$ of the near-N waves is enhanced at the trough of the ISW and gradually extends to the rear face of the ISW (Fig. 10b). It increases from approximately 100 to approximately 1000 J m$^{-2}$ by a factor of 10 at the center of the accompanying ISW. After the ISW, the energetics of near-N waves return to their normal situations.

d. Instabilities of the near-N waves

It is generally accepted that an $\text{Ri} < 0.25$ [Ri = $N^2/S^2$, where stratification $N^2 = -(g/p)(dp/dz)$, $\rho$ is the potential density, shear $S^2 = \langle u u \rangle z^2$, and $u$ is the horizontal velocity including the zonal and meridional velocity] indicates the potential for shear instabilities. Here, the criterion of $\text{Ri} < 1/4$ is used to identify the instability of near-N waves. Figures 11a–c show the Richardson number calculated with the current shear
of ISW7 and near-\(N\) waves, near-\(N\) waves alone and ISW7 alone, respectively. If the observed current shear (both ISW and near-\(N\) waves) is included in the calculation, the occurrence of potential instabilities is notable between 110 and 150 m in the regions full of strong near-\(N\) waves (Fig. 11a). If only the \(S^2\) value of the near-\(N\) waves is used in the analysis, the depth between 110 and 160 m around the ISW trough is kept in a state of instability, where the Ri is lower than 1/4 (Fig. 11b) with
a minimum of 0.063. However, if only the $S^2$ value of the ISW is used when calculating the $\text{Ri}$, the occurrence of potential instabilities is largely confined, especially around the thermocline (Fig. 11c). As can be seen, the strong current shear of near-$N$ waves can result in notable instabilities, which may lead to strong mixing and rapid dissipation of near-$N$ waves.

4. Theoretical analyses

The breaking of ISWs may occur during the shoaling process, which generate high-frequency motions like the overturning billows in Moum et al. (2003). Previous studies have shown that the occurrence of ISW breaking largely depended on the wave amplitude, water depth, and bottom slope:

1) Vlasenko and Hutter (2002) and Lien et al. (2014) concluded that ISWs reached a conjugate flow limit when their maximum vertical displacement $\eta_{\text{max}}$ reached half the water depth.

2) Helfrich (1992) demonstrated that ISW breaking might occur when the normalized maximal vertical displacement $\eta = \eta_{\text{max}}/(H - H_m)$ [$H$ is the water depth, $H_m$ is the depth of the maximum vertical displacement (Lien et al. 2014)] exceeded 0.4 and could be identified as shear instability waves when $\eta_{\text{max}}$ was between 0.3 and 0.4.

3) Vlasenko and Hutter (2002) also demonstrated that ISW breaking might happen as propagating over a relatively steep bottom slope with a relatively large amplitude.

In this study, the high-frequency near-$N$ waves riding on ISWs were captured at a water depth of 1000 m. With amplitudes of 50–100 m, the $\eta_{\text{max}}$ of the observed ISWs ranged between $\sim 0.06$ and $\sim 0.08$ (Fig. 12), much less than the values indicating ISWs at states of convective and shear instabilities. Therefore, the high-frequency near-$N$ waves presented in this study were probably unrelated to the breaking of ISWs during the shoaling process.

Using the KdV–Burgers equation, we simulated the process of the enhanced near-$N$ waves acting as cascades from an ISW to turbulence with the initial conditions involving a depression solitary wave. Here, the dissipation parameter $\mu$ is expressed as the kinematic viscosity $\nu$, as pointed out by Liu and Liu (1991) and Liu and Liu (1992). The value of $\nu$ is $5 \times 10^{-4}$ m$^2$ s$^{-1}$, which was following Table 1 in Helfrich and Melville (1986). The numerical scheme is a second-order finite difference scheme in space and leapfrog in time (Li et al. 2015; Zhang et al. 2018).

As shown in Fig. 13, when the wave propagates forward (left) at the propagation speed $c$, the waveform is a balance of the nonlinear term and the dispersion term at first, as the dissipation term has not yet begun to make a contribution (Liu and Liu 1991). Hence, the wave front presents typical soliton characteristics under both the KdV equation (black dotted curves) and KdV–Burgers equation (red solid curves). As the wave continues to propagate, the dissipative term (in the condition of the KdV–Burgers equation) begins to play an important role in the rear face of the wave. The attenuation oscillation caused by it controls the IW field (with the maximum amplitude as the boundary line), resulting in a train of trailing attenuation oscillation waves following the wave trough. Liu and Liu (1991) pointed out that the dissipative term produces continuous attenuation oscillation in the rear face of an ISW. Meanwhile, the waveform in the condition of the KdV equation continues to present typical soliton characteristics. The wavelength of the attenuation oscillation based on the solution of the KdV–Burgers equation is $\Delta x = 4\beta n^2 \sqrt{\max(\eta_1 - \eta_2)} - \mu^2$. Here, $\eta_1 - \eta_2 = a$, where $a$ is the amplitude of the soliton (Liu and Liu 1991). Based on the observed data, the coefficients of dispersion $\beta$ was computed as 4000 m$^3$ s$^{-1}$ following the method in our earlier paper (Zhang et al. 2018). Hence, we can estimate the period of the trailing attenuation oscillation wave: $T = \Delta x/c$. The estimated $T$ is between 160 and 260 s, which corresponds to the period of the observed enhanced near-$N$ waves (the blue solid line in Fig. 4). Furthermore, the waveform simulated based on the KdV–Burgers equation is in better agreement with the observed waveforms than that simulated by the KdV equation (Fig. 14). Thus, the cascade process of ISWs simulated by the KdV–Burgers equation is consistent with the observational results, indicating that the observed enhanced near-$N$ waves represented the energy cascade from ISWs to turbulence in the ocean.

5. Discussion and summary

The spatially integrated energy along the wave direction and depth $\langle E \rangle_{xz} = \int \int E \, dx \, dz$ of the near-$N$ waves is
approximately 5% of the parent ISW observed on 27 July (Fig. 15). Although the energy of near-N waves is relatively small, the simulation result of the KdV–Burgers equation revealed that the near-N waves are generated continuously during the propagation of ISWs in the northern SCS, and our observational results suggest that they may dissipate rapidly due to instabilities. Thus, the total energy of near-N waves along with the propagation path of ISW over the continental shelf of the northern SCS is expected to be greater than 5% of the ISW’s energy. Therefore, the near-N waves likely play an essential role in the energy budget of ISWs, and their instable features further illustrate their potential contributions to the enhanced mixing in the northern SCS.

Over the past several decades, the energy dissipation process of shoaling ISWs on the continental slope/shelf has been extensively studied. However, this issue remains largely unexplored in deep water due to the difficulty in fine-scale observations, resulting in a major knowledge gap in the study of the energy cascade associated with the fate of IWs in the ocean. In this study, the new cascade process of ISW energy to mixing is investigated based on high-resolution mooring observations in the deep water of the northern SCS. Enhanced near-N waves with a period of approximately 200 s are induced along with the propagation of the ISW in the upper layer, and enhanced waves occur beginning at the trough of the ISW and extending to the rear face of the ISW. Their isothermal displacements are shown to be significant in the upper 200 m, with a maximum amplitude of 12 m. Instability investigations showed that due to the strong current shear, the regions full of near-N waves are characterized by $R_i < 0.25$, suggesting that the near-N waves are instable and may lead to enhanced mixing. The cascade process of ISWs simulated by the KdV–Burgers equation is consistent with the observed intense near-N waves. These results illustrate a route for energy cascading from ISWs to turbulent mixing via enhanced near-N waves during the passage of ISWs. In the coming days, systematic observations involving microstructure processes are planned to examine the detailed relationship of near-N waves and ISWs and to reveal their important roles in energy cascade routes from IWs to turbulence.

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Data availability statement. Bathymetric data are from GEBCO Gridded Bathymetry Data (https://download.gebco.net/). The processed mooring data used to construct figures in this work are also available, and anyone who wants to get access to these data could contact the corresponding author, Wei Zhao.

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