~~Parameter~~ Sensitivity Study of Energy Transfer Between Mesoscale Eddies and Wind-Induced Near-Inertial Oscillations

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Abstract. Analyses of current observations and numerical simulations at two moorings in the northern South China Sea reveal the transfer of near-inertial energy between the background currents associated with mesoscale eddies and near-inertial currents (NICs). A series of numerical experiments are conducted to determine important parameters affecting the energy transfer between idealized mesoscale eddies and NICs generated by rotating winds. Speeds of NICs transferred by both cyclonic and anticyclonic mesoscale eddies increase linearly with the wind stress and eddy strength. The transferred NICs in anticyclonic eddies have current amplitudes of about six times larger than in cyclonic eddies. The translation speed of the mesoscale eddy and the wind rotation frequency also affect the conversion of NICs. The energy transfer rate is elevated with the increase of the positive Okubo-Weiss parameter. A simple theoretical analysis is conducted to verify our findings based on numerical results. Analytical solutions confirm the evident asymmetry of the energy transfer between anticyclonic and cyclonic eddies, and demonstrate quantitatively the relationship between the wind stress and the near-inertial energy transferred by mesoscale eddies.

1 Introduction

Near-inertial oscillations (NIOs) are very common in the global ocean and they appear as a prominent peak in the spectrum of ocean currents (Garrett, 2001). NIOs contain almost half the total kinetic energy of the internal waves and significantly contribute to the vertical shear in the internal waveband (Ferrari & Wunsch, 2009). When surface winds with high spatiotemporal

29 variations act at the ocean surface, strong NIOs could occur in the ocean surface mixed layer (SML,

30 Chen et al., 2015a; D'Asaro et al. 1995; Pollard & Millard, 1970). At the base of the SML, near-

31 inertial internal waves (NIWs) are generated through the horizontal convergence and divergence

32 of the SML (Gill, 1984). These NIWs are free to radiate to the thermocline and deep waters, and

33 low-mode NIWs with long wavelengths can propagate at least hundreds of kilometers toward the

34 equator from their source regions (Alford, 2003; Jochum et al., 2013; Munk & Wunsch, 1998).

35 NIOs not only affect the energy, momentum, and material transport in the upper ocean, but also

36 play an important role in maintaining diapycnal mixing and global ocean circulation (Chen et al.,

37 2016; Greatbatch, 1984; Price et al., 1986; Wunsch & Ferrari, 2004).

38   Due to the turbulent and inhomogeneous nature of the ocean, the central frequency of NIOs

39 is influenced by the β effect and shows a significant blue or red shift induced by the relative

40 vorticity of mesoscale eddies (Chen et al., 2015b; Elipot et al., 2010; Kunze, 1985; Mooers, 1975;

41 Perkins, 1976; Sun et al., 2011). If the magnitude of the gradient in the relative vorticity is larger

42 than the β effect (Chelton et al. 2011), mesoscale eddies also modulate the energy distribution and

43 propagation of the near-inertial motions (van Meurs, 1998; Wang et al., 2024). Previous studies of

44 current observations in the northwestern South China Sea (nSCS) demonstrated that the near-

45 inertial energy propagates both upwards and downwards under the influence of the anticyclonic

46 eddies (Chen et al., 2013; Zhai et al., 2007). Using the in situ observations and ray-tracing

47 techniques, Jaimes and Shay (2010) demonstrated that anticyclonic eddies trap the near-inertial

48 kinetic energy which rapidly propagates vertically below the thermocline and even to the deep

49 ocean. Young and Jelloul (1997) suggested that the anticyclonic eddies can improve the vertical

50 propagation rate of the near-inertial energy by deepening the thermocline. Zhai et al. (2005)

51 demonstrated that the wind generated near-inertial kinetic energy is also high in the strong

52 mesoscale motion regions. Based on the numerical study, Lelong et al. (2020) reveled that

53 anticyclonic eddies facilitate the energy transfer from wind-driven inertial energy to propagating

54 waves. Fer et al. (2018) found that subinertial waves trapped within the Lofoten Basin eddy can

55 significantly contribute to the observed turbulence in the eddy.

56   Mesoscale eddies and NIOs are energetic in the SML (Bühler & McIntyre, 2005; Vanneste,

57 2013; Xie & Vanneste, 2015). Mesoscale eddies not only change the spatial distribution of NIOs,

58 but also exchange the energy with NIOs through the nonlinear interaction (Muller, 1976; Thomas,

59 2012). Based on the observational studies of specific NIO events, Noh and Nam (2020) found that

mesoscale eddies can effectively enhance the intensity of NIOs. The energy transfer also occurs between NIOs and low-frequency geostrophic currents through the nonlinear interaction (Liu et al., 2023; Thomas, 2012; Whalen et al., 2020). Jing et al. (2018) demonstrated that the large-scale geostrophic currents of the Gulf Stream affect the distribution of near-inertial energy. Whitt and Thomas (2015) suggested that, in a unidirectional laterally sheared geostrophic flow, a continuous energy transfer occurs between mesoscale eddies and NIOs. In the Kuroshio extension, due to the change of the effective Coriolis frequency caused by the relative vorticity of mesoscale eddies, the energy exchange efficiency between the anticyclonic eddies and NIOs is about twice that between the cyclonic eddies and NIOs (Jing et al., 2017). Based on numerical results in the Icelandic Basin, Barkan et al. (2021) found that a significant energy transfer occurs between NIOs and sub-inertial motions, with the energy transfer rate in winter and summer are about half and a quarter of the local near-inertial wind energy input, respectively. The above and other studies suggested that the energy transfer processes between mesoscale eddies and NIOs should play an important role in the ocean energy cascade (Alford et al., 2016; Ford et al., 2000; McWilliams, 2016; Thomas, 2017). Nevertheless, most of previous studies focused on the energy transfer rate and efficiency. There is a knowledge gap in the amplitude of the near-inertial energy transferred by the mesoscale eddy and the sensitivity of the above-mentioned energy transfer to mesoscale eddies and wind parameters. The main objective of this study is to quantity the energy transfer between the mesoscale eddies and wind-induced NIOs.

This paper is structured as follows. Section 2 provides a brief description of observational data and reanalysis used in this study. Section 3 presents the original and modified slab models. Model results for the energy transfer between mesoscale eddies and the NIOs are given in Sect. 4. A series of sensitivity experiments for determining the important factors affecting the energy transfer is presented in Sect. 5. The results of sensitivity experiments are verified through theoretical analysis in Sect. 6. Summary and discussions are given in Sect. 7.
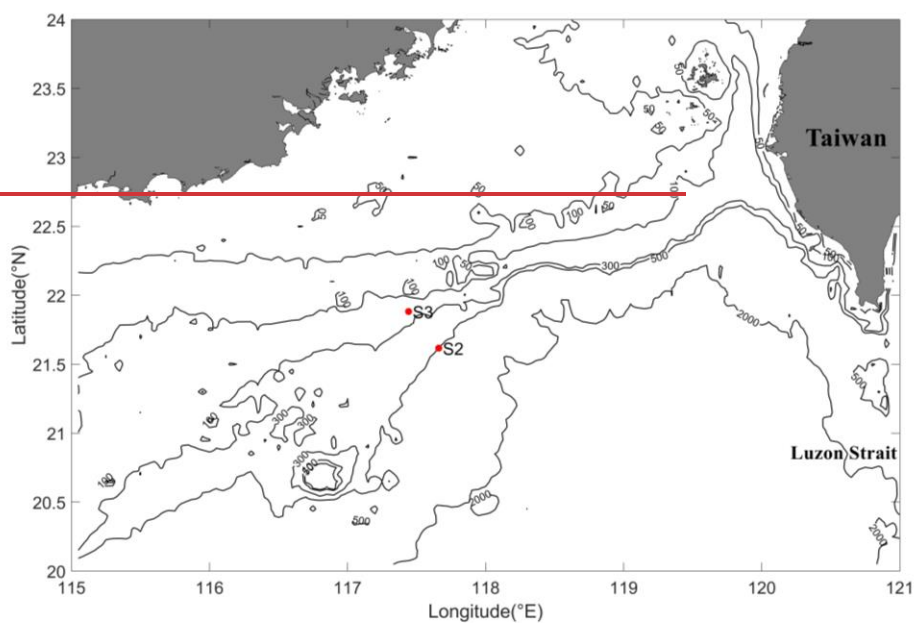
2 Observational and Reanalysis Data

Current observations at two subsurface moorings named S2 and S3 respectively in the nSCS (marked in Fig. 1) are analyzed here. The current observations at these two moorings were made using the Acoustic Doppler Current Profilers (ADCPs). Mooring S2 is located at 117°39.619′ E and 21°37.001′ N, with the water depth of 499 m. Current observations at this location were made

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at depth bins from 58 m to 442 m from 22 August 2016 to 8 May 2017. At ADCP mooring S2, the vertical sampling interval is 16 m and the time internal is 60 minutes. ADCP mooring S3 is located at 117°26.528′ E and 21°52.945′ N, with the water depth of 266 m. Current observations at this mooring were made at depth bins from 37 m to 229 m during the same observational period as at location S2. At mooring S3, the vertical sampling interval is 8 m and the time internal is 30 minutes.
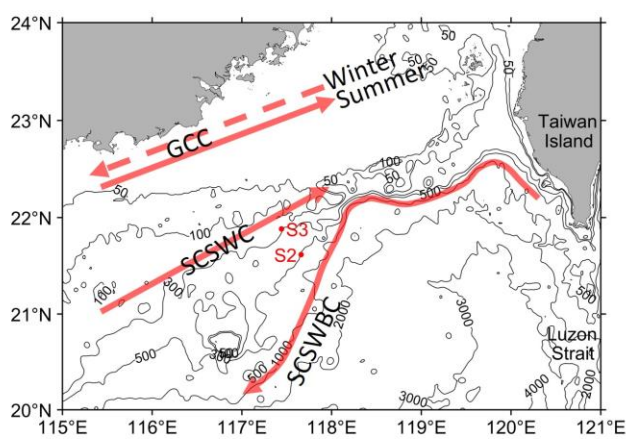
Hourly winds at 10 m above the mean sea level in the nSCS were extracted from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis. The ERA5 winds from July 2016 to June 2017 with an interval of 1 hour and the horizontal resolution of 0.25° are used to calculate the hourly wind stress to be used as the model forcing. The wind speed data obtained from ERA5 is widely used in previous researches on near-inertial motions in the Northwestern Pacific.

The surface geostrophic currents used in this study were derived from ECMWF, using the sea level grid data inferred from the global marine satellite observations provided by the Copernicus Atmosphere Monitoring Service (C3S). The sea surface height anomaly and geostrophic current data in the nSCS from July 2016 to June 2017 are used here, which have a horizontal resolution of 0.25° and a time interval of 24 hours.

The mixed layer depth (MLD) for the nSCS was extracted from the 2018 edition of the World Ocean Atlas (WOA2018) (www.ncei.noaa.gov/products/world-ocean-atlas), with a horizontal resolution of 0.25°. The MLD at each location is defined as the depth at which the vertical change of the potential density from the ocean surface is 0.125 (sigma units).

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Figure 1. Major bathymetric feature <u>and circulation (from Shu et al., 2018)</u> of the northern South China Sea. Two red dots represent locations of two ADCP moorings named S2 and S3. Black contours represent isobaths in meter. <u>GCC refers to the Guangdong Coastal Current, SCSWC refers to the South China Sea Warm Current and SCSWBC refers to the South China Sea Western Boundary Current. The solid (dashed) line in the GCC indicates the current direction in summer (winter).</u>

3 Method

3.1 Strain and Vorticity of a Mesoscale Field

The vertical component of the relative vorticity (ζ) has been used to measure the rate of fluid rotation within a mesoscale eddy, which is defined as

$$\zeta = \frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}, \tag{1}$$

where U and V are zonal (eastward) and meridional (northward) surface geostrophic currents, respectively.

<u>The effective Coriolis frequency (f_{eff}) is defined as</u>

$$f_{eff} = f + \frac{\zeta}{2} \tag{2}$$

<u>where f is the inertial frequency.</u>

The normal and shear components of the rate of strain tensor, S_n and S_s are defined as

$$S_n = \frac{\partial U}{\partial x} - \frac{\partial V}{\partial y}, \tag{3}$$

$$S_s = \frac{\partial V}{\partial x} + \frac{\partial U}{\partial y}. \tag{4}$$

The relative importance of total strain and relative vorticity is diagnosed with the Okubo-Weiss parameter (Okubo 1970):

$$OW = S_n^2 + S_s^2 - \zeta^2. \tag{5}$$

In this study, the dependence of the energy transfer between the mesoscale eddy and NICs on the relative vorticity is considered.

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3.2 Modified Slab Model

A simple linear model known as the slab model (Pollard & Millard 1970) was used in simulating NIOs in the SML. Analysis of observed currents in the nSCS (to be discussed in Sect. 4) demonstrates that NIOs can also occur in the SML under ~~the~~ nearly steady winds. This suggests the importance of the energy transfer between the background currents and near-inertial currents (NICs). To investigate this energy transfer, the background geostrophic currents (U, V) are added to the original slab model as the modified slab model (Jing et al., 2017; Weller, 1982):

$$\begin{cases} \frac{\partial u}{\partial t} + u\frac{\partial U}{\partial x} + v\frac{\partial U}{\partial y} = fv - ru + \frac{\tau_x}{\rho_o H_{mix}} \\ \frac{\partial v}{\partial t} + u\frac{\partial V}{\partial x} + v\frac{\partial V}{\partial y} = -fu - rv + \frac{\tau_y}{\rho_o H_{mix}} \end{cases}, \qquad (6\text{5})$$

where (u, v) are zonal and meridional currents averaged vertically in the SML, and H_{mix} is the MLD. The damping coefficient r is set to 1/8 days^{-1}, which is used to parameterize the loss of near-inertial energy. In Eq. (5̶6), f is the inertial frequency, and ρ_o is the seawater density set to be 1024 kg m^{-3}. Wind stress components (τ_x, τ_y) are calculated using ~~10 m height~~ ERA5's 10-m winds with the drag coefficient suggested by Oey et al. (2006).

The above modified slab model uses two important assumptions: the Rossby number of the geostrophic currents is assumed to be far less than 1, and the horizontal scale of winds to be much larger than that of mesoscale eddies. By ignoring the background geostrophic currents, the above modified slab model becomes the original slab model, which was used in many previous studies of examining the inertial response in the SML (D'Asaro, 1985; Paduan et al. 1989; Pollard & Millard 1970).

The modified slab model in Eq. (5̶6) can be solved numerically using an implicit numerical scheme in time to obtain NICs in the SML:

$$\begin{cases} \frac{u^{n+1}-u^n}{\Delta t} + u^{n+1}U_x^{n+1} + v^{n+1}U_y^{n+1} = fv^{n+1} - ru^{n+1} + \frac{\tau_x^{n+1}}{\rho H_{mix}} \\ \frac{v^{n+1}-v^n}{\Delta t} + u^{n+1}V_x^{n+1} + v^{n+1}V_y^{n+1} = -fu^{n+1} - rv^{n+1} + \frac{\tau_y^{n+1}}{\rho H_{mix}} \end{cases}, \qquad (6\text{7})$$

where Δt is the time step, which is set to 3600 s in this study, and subscripts x and y in U and V represent partial derivatives. The initial value of the NICs is set to 0. In Eq. (6̶7), variables with superscripts n and $n+1$ represent their values at time $n\Delta t$ and $(n+1)\Delta t$, respectively.

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164   After merging some terms, the numerical scheme of the modified slab model can be written

165   as

$$\begin{cases} \frac{u^{n+1}-u^n}{\Delta t} + a_1^{n+1}u^{n+1} + b_1^{n+1}v^{n+1} = c_1^{n+1} \\ \frac{v^{n+1}-v^n}{\Delta t} + a_2^{n+1}u^{n+1} + b_2^{n+1}v^{n+1} = c_2^{n+1} \end{cases},$$

166   (7̶8)

167   where $a_1 = U_x + r$, $a_2 = V_x + f$, $b_1 = U_y - f$, $b_2 = V_y + r$, $c_1 = \tau_x/\rho H_{mix}$, $c_2 = \tau_y/\rho H_{mix}$.

168   Equation (7̶8) can be written in the following tensor form:

$$\begin{bmatrix} a_1^{n+1} + \frac{1}{\Delta t} & b_1^{n+1} \\ a_2^{n+1} & b_2^{n+1} + \frac{1}{\Delta t} \end{bmatrix} \begin{Bmatrix} u^{n+1} \\ v^{n+1} \end{Bmatrix} = \begin{Bmatrix} \frac{u^n}{\Delta t} + c_1^{n+1} \\ \frac{v^n}{\Delta t} + c_2^{n+1} \end{Bmatrix}.$$

169   (8̶9)

170   The numerical update equations for currents are given as

171 $$u^{n+1} = \frac{1+\Delta t b_2^{n+1}}{(1+\Delta t a_1^{n+1})(1+\Delta t b_2^{n+1}) - \Delta t b_1^{n+1} a_2^{n+1}} \left[\frac{u^n}{\Delta t} + c_1^{n+1} - \frac{\Delta t b_1^{n+1}}{1+\Delta t b_2^{n+1}} \left(\frac{v^n}{\Delta t} + c_2^{n+1} \right) \right], \text{(9̶10)}$$

172 $$v^{n+1} = \frac{1+\Delta t a_1^{n+1}}{(1+\Delta t a_1^{n+1})(1+\Delta t b_2^{n+1}) - \Delta t b_1^{n+1} a_2^{n+1}} \left[\frac{u^n}{\Delta t} + c_1^{n+1} - \frac{\Delta t a_2^{n+1}}{1+\Delta t a_1^{n+1}} \left(\frac{v^n}{\Delta t} + c_2^{n+1} \right) \right]. \text{(1̶1̶0)}$$

173 **3.3 Analysis of NICs**

174   The observed zonal and meridional currents at 58.3 m below the sea surface at location S2

175 and at 37.7 m at location S3 (marked in Fig. 1) in the nSCS are analyzed to estimate the near-

176 inertial kinetic energy in the SML. The observed NICs are obtained by using a band-pass filter

177 through Fourier transform with a frequency band of $0.85f$-$1.15f$.

178   The surface geostrophic currents described in Sect. 2 are specified in the modified slab model,

179 based on the assumption that the geostrophic currents are vertically uniform in the SML during

180 the study period. The simulated currents by the original and modified slab models are band-passed

181 through Fourier transform with the frequency band of $0.85f$-$1.15f$ and are further smoothed using

182 a running window of two inertial periods to obtain the simulated amplitude of NICs.

183   To quantitatively assess performances of the original and modified slab models, the

184 correlation analysis and root mean square error (RMSE) analysis between the original slab model,

185 the modified slab model and observations respectively are made.

4 Results

4.1 Observed NICs

Time series of observed NICs at the top depth bins (58.3 m at S2 and 37.7 m at S3) of two subsurface ADCP moorings (known as $\vec{u}_{S2}^{top}$ and $\vec{u}_{S3}^{top}$) are shown in black lines in Fig. 2 during the observational period from day 234 (22 August 2016) to day 492 (7 May 2017) with respect to 1 January 2016. Intense NICs were generated and lasted for about 11 days from day 293 to day 304 under the largest wind forcing (~1.6 N m^{-2}) on day 293 (Fig. 2e and 2f). The largest speed of NICs was ~0.30 m s^{-1} on day 295 at the top depth bin at mooring S2 (Fig. 2a) and ~0.37 m s^{-1} on day 296 at the top depth bin at mooring S3 (Fig. 2b). Some NICs were also excited on other days when the winds were relatively weak and nearly steady.
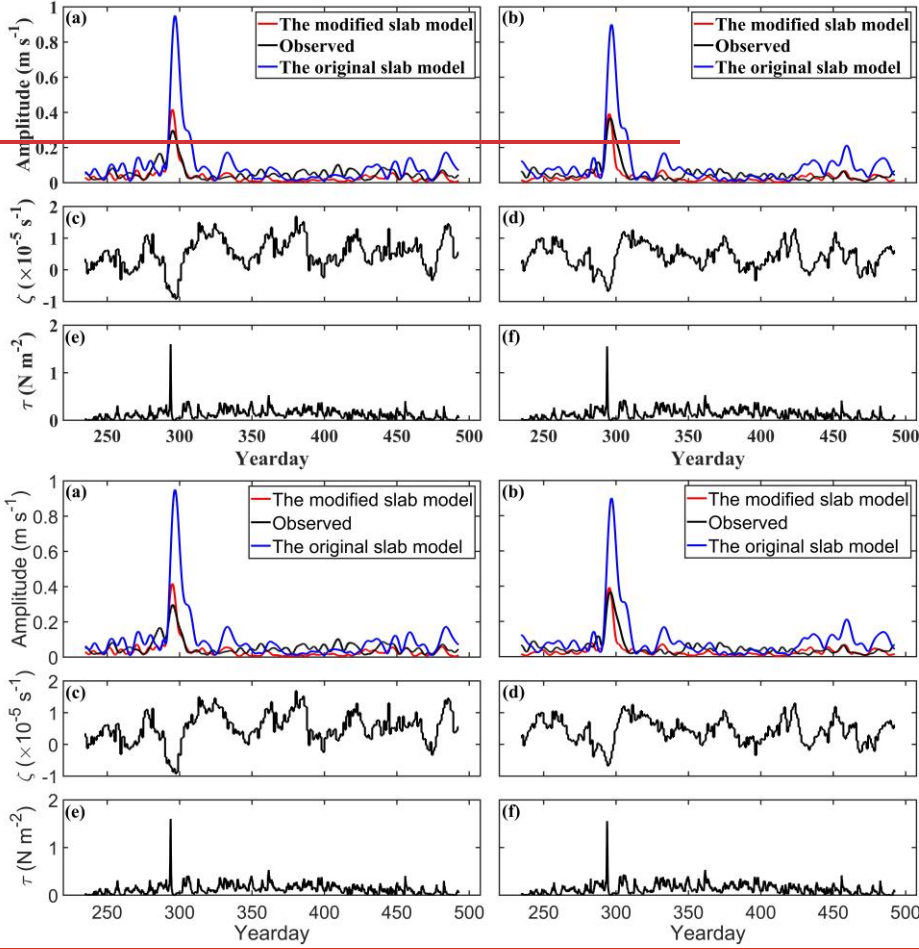
Figure 2. Speeds (m s⁻¹) of observed (black line) and simulated NICs at the top depth bins of ADCP observations at moorings (a) S2 and (b) S3. Red and blue lines denote model results produced by the modified slab and original slab models respectively. Time series of relative vorticity of the surface geostrophic currents at moorings (c) S2 and (d) S3, and time series of wind stress at moorings (e) S2 and (f) S3. The yearday is defined as the number of days elapsed since 00:00:00 (GMT) on 1 January 2016. ~~Yearday is the day relative to 00:00:00 (GMT) on 1 January 2016.~~

Observed NICs at other depth bins of these two ADCP moorings reveal that the intense NICs occurred on days 293-304 at depths between 60 m and 200 m at mooring S2 (not shown) and these

208   NICs were originated from the SML. At mooring S3, similar intense NICs occurred at depths
209   between 40 m and 180 m on days 280-305 (not shown), and these NIC were also originated from
210   the SML. On days 306-318, in comparison, moderate NICs occurred in the lower layer between
211   150 m and 310 m at these two moorings.

212   It should be noted that the current observations ($\vec{u}_{S2}^{top}$ and $\vec{u}_{S3}^{top}$) at the top bins of the two
213   ADCP moorings are in the lower part of the SML or below the SML during the observational
214   period. Based on WOA2018, the climatological monthly mean MLD at the two ADCP moorings
215   is the thinnest and ~20 m in August (days 234-243) and increases to the maximum value of ~90 m
216   in January (days 366-396). The MLD decreases from ~56 m in February (days 397-424) to ~37 m
217   in May (days 486-492) and is about 25 m in June and July. This suggests that the observed NICs
218   at the top depth bin (58.3 m) of S2 were made in the lower part of the SML in December and
219   January (days 335-396), but below the SML on the other days of the observational period (Fig.
220   2a). By comparison, the observed NICs at the top depth bin (37.7 m) of S3 were made in the middle
221   of the SML in December and January (days 335-396), and in the lower part of the SML in October
222   and November (days 274-334) and February-May (days 397-492).

223   The relative vorticity estimated from the surface geostrophic currents was negative at the two
224   moorings on days 290-300 (Fig. 2c and 2d), with the maximum negative values of about -0.92×10^{-5}
225   s^{-1} (-0.17f) at mooring S2 and about -0.68×10^{-5} s^{-1} (-0.13f) at mooring S3. The negative values
226   of the relative vorticity during this period resulted from the westward propagation of an
227   anticyclonic eddy. As shown in Fig. 3a and 3f, moorings S2 and S3 were located over the area
228   between a relatively strong anticyclonic eddy and a weak cyclonic eddy on day 295. The
229   anticyclonic eddy moved westward and passed mooring S2 before day 316 (Fig. 3b and 3g). On
230   day 316, the relative vorticity was low and positive of about 1.23×10^{-5} s^{-1} (0.23f) at mooring S2
231   and 0.83×10^{-5} s^{-1} (0.15f) at mooring S3 respectively.

232   On days 350-450, an anticyclonic eddy moved southwestward and passed through these two
233   moorings S2 and S3 (Fig. 3c, 3d, 3h, and 3i). There was a week cyclonic eddy close to the two
234   moorings on day 435 (Fig. 3d and 3i). The relative vorticity was relatively strong and positive
235   during this period, with the maximum positive values of about 1.68×10^{-5} s^{-1} (0.31f) on day 380 at
236   mooring S2 and 1.29×10^{-5} s^{-1} (0.24f) on day 423 at mooring S3 respectively.

237   Between days 451-492, there is a week anticyclonic eddy close to the moorings S2 and S3 and the
238   two moorings are located at the edge of the anticyclonic eddy on day 452 (Fig. 3e and 3j).

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The relative vorticity estimated from the surface geostrophic currents was negative at the two moorings on days 290-300 (Fig. 2c and 2d), with the maximum negative values of about -0.92×10^{-5}-s^{-1} at mooring S2 and about -0.68×10^{-5}-s^{-1} at mooring S3. The negative values of the relative vorticity during this period resulted from the westward propagation of an anticyclonic eddy. As shown in Fig. 3a and 3f, on day 295, moorings S2 and S3 were located over the area between a relatively strong cyclonic eddy to the southwest and two separate weak cyclonic eddies to the east and south. The anticyclonic eddy moved westward and passed mooring S2 before day 316 (Fig. 3b and 3g). On day 316, the relative vorticity was low and positive of about 1.23×10^{-5}-s^{-1} at mooring S2 and 0.83×10^{-5}-s^{-1} at mooring S3 respectively. On days 350-450, an anticyclonic eddy moved westward and passed through these two moorings S2 and S3, and there was a week cyclonic eddy close to the two moorings on day 435 (Fig. 3c, 3d, 3h, and 3i). The relative vorticity was relatively strong and positive during this period, with the maximum positive values of about 1.68×10^{-5}-s^{-1} on day 380 at mooring S2 and 1.29×10^{-5}-s^{-1} on day 423 at mooring S3 respectively. Between days 451-492, there is a week anticyclonic eddy close to the moorings S2 and S3 and the two moorings are located at the edge of the anticyclonic eddy on day 452 (Fig. 3e and 3j).
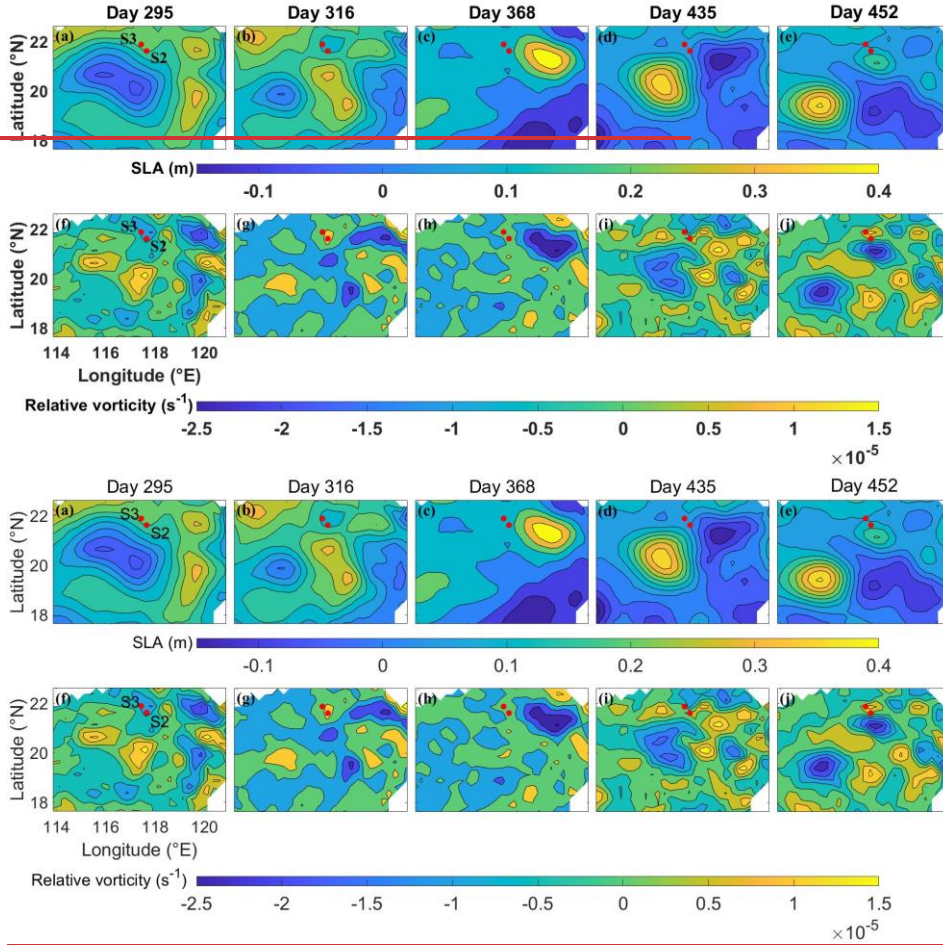
Figure 3. Spatial distributions of sea surface level anomaly (SLA) on day 295 (a), day 316 (b), day 368 (c), day 435 (d) and day 452 (e). Spatial distributions of the relative vorticity on day 295 (f), day 316 (g), day 368 (h), day 435 (i) and day 452 (j). Two red dots mark locations of two ADCP moorings S2 and S3.

4.2 Simulated NICs

Numerical simulations are made using the original and modified slab models to examine whether the energy exchange occurs between the mesoscale eddy and NICs in the SML at moorings S2 and S3. Both the original and modified slab models assume that the NICs in the SML

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266   is vertically uniform and use the damping coefficient r set to a relatively small value of 1/8 day^{-1}.

267   Both the models are forced by time series of wind stress shown in Fig. 2e and 2f.

268   The simulated NICs produced by the original slab model at the top bins of two ADCP

269   moorings are shown by the blue lines in Fig. 2a and 2b. The simulated NICs by the original slab

270   model are large and about 0.95 m s^{-1} (0.90 m s^{-1}) at mooring S2 (S3) on day 296 and relatively

271   weak on days 350-430. In comparison with the observed NICs, the original slab model has large

272   deficiency of overpredicting significantly the observed large NICs on days 285-300 at the two

273   stations and also overpredicting moderately the observed NICs on other days of the observational

274   period. It should be noted that the results of both the original and modified slab models using three

275   different damping coefficients (r = 1/5 day^{-1}, 1/6 day^{-1} and 1/7 day^{-1}) and annual mean MLD at

276   two stations (~45 m) are highly similar with the model results using r = 1/8 day^{-1} and monthly

277   mean MLD shown in Fig. 2a and 2b.

278   In comparison with the original slab model results, the modified slab model generates much

279   smaller NICs than the original slab model on days 280-305 (red lines in Fig. 2a and 2b), with the

280   maximum value of about 0.42 m s^{-1} at mooring S2 and about 0.39 m s^{-1} at mooring S3 on day 295.

281   In comparison with the observed NICs at the two moorings, the modified slab model performs

282   significantly better than the original slab model on days 250-325 and days 451-492, indicating the

283   importance of the energy exchange between the background mesoscale eddies and NICs. On days

284   350-450, the relative vorticity of the background currents is positive, which results in the simulated

285   NICs produced by the modified slab model to be slightly weaker than the observed NICs at these

286   two moorings. As mentioned in Sect. 4.1, the top depth bins of the ADCP observations at the two

287   moorings were in the lower part of the SML or below the SML during the observational period,

288   which explains partially the differences between observed and simulated NICs by the modified

289   slab model shown in Fig. 2a and 2b. Differences between the observed and simulated NICs can

290   also partially be explained by the assumption of vertically uniform geostrophic currents in the

291   SML and exclusion of baroclinic dynamics.

292   The above analysis based on results shown in Fig. 2 suggests that, overall, the simulated NICs

293   produced by the modified slab model agree with the observed NICs significantly better than the

294   original slab model at two moorings S2 and S3. This indicates the occurrence of the near-inertial

295   energy transfer induced by the interaction between mesoscale eddies and NICs in the SML during

296   the observational period.

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297   To quantify the model performance, we use the correlation coefficient (R) and the root mean

298   square error (RMSE) based on the time series of observed and simulated NICs shown in Fig. 2a

299   and 2b. The modified slab model has a higher correlation coefficient (R = ~0.81) and smaller root

300   mean square error (RMSE = ~0.04 m s^{-1}) than the original slab model (R = ~0.70 and RMSE =

301   ~0.12 m s^{-1}) at mooring S2. At mooring S3, the R value between the observed NICs and results of

302   the modified slab model is ~0.84, and RMSE is ~0.03 m s^{-1}. For the original slab model at location

303   S3, the R value is ~0.85, and RMSE is ~0.10 m s^{-1}. These statistical indices suggest that the

304   modified slab model performs better than the original slab model, especially in reproducing the

305   amplitude of the observed NICs. This also suggests the energy transfer between mesoscale eddies

306   and NICs may be a non-negligible process in the energy cascade across different scales in the

307   global ocean.

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309   **Table 1.** Correlation coefficients (*R*) and RMSEs between the simulation results of the modified
310   and original slab models and observations for the observational period, respectively.

Mooring	Correlation coefficient (*R*)		RMSE (m s^{-1})	
	Original slab model	Modified slab model	Original slab model	Modified slab model
S2	0.70	0.81	0.12	0.04
S3	0.85	0.84	0.10	0.03

311   **5 Sensitivity Study**

312   A series of numerical experiments (in total 22~~19~~6) are conducted using the original and

313   modified slab models to examine sensitivity of model results to the wind speed, the wind rotation

314   frequency, the translational speed of the mesoscale eddy, and the strength of the mesoscale eddy.

315   Both the cyclonic and anticyclonic eddies with an idealized eddy structure are used for simplicity.

316   Results of the original and modified slab models are both band-pass (0.60f-1.40f) filtered to get

317   broad NICs signals and then smoothed using a running window of two inertial periods to obtain

318   the near-inertial velocity in the SML.

319   **5.1 Idealized Mesoscale Eddy Structure**

320   Based on the composite analysis of satellite altimetry and Argo float data, Zhang et al. (2013)

321   suggested a universal structure of mesoscale eddies in the global ocean. Their universal structure

322   of mesoscale eddies is used in our experiments.

15

The normalized structure $\tilde{P}(\tilde{r}, z)$ of the pressure anomaly in the universal mesoscale eddy used in this study is decomposed into a radial function $R(\tilde{r})$ and a vertical function $H(z)$:

$$\tilde{P}(\tilde{r}, z) = R(\tilde{r})\,H(z), \tag{12}$$

$$R(\tilde{r}) = \left(1 - \frac{\tilde{r}^2}{2}\right) e^{-\frac{\tilde{r}^2}{2}}, \tag{13}$$

$$H(z_s) = H_0 \sin(kz_s + \theta_0) + H_{ave}, \tag{14}$$

$$\tilde{r} = \frac{r}{R_0}, \tag{15}$$

$$z_s = \int_0^z \left(\frac{N}{f}\right) dz, \tag{16}$$

where r is the radial distance to the eddy center, R_0 is the radius of the mesoscale eddy, N is the buoyancy frequency, H_0, k, θ_0 and H_{ave} are undetermined coefficients, e.g. in this study, $H_0 = 2/3$, $H_{ave} = 2/3$, $N = 10^{-3}$ (1/s), $k = \pi/18000$, $f = 5 \times 10^{-5}$ (rad/s) and $\theta_0 = \pi/6$. The vertical structure function $H(z)$ defined above is similar with the structural diagram in Zhang et al. (2013).

The structure function for the idealized mesoscale eddy in the Cartesian coordinate system can be written as

$$\tilde{P}(x, y, z) = \left(1 - \frac{x^2 + y^2}{2R_0^2}\right) \cdot e^{-\frac{x^2 + y^2}{2R_0^2}} \cdot \left[\frac{2}{3} \cdot \sin\left(\frac{\pi}{900} \cdot z + \frac{\pi}{6}\right) + \frac{2}{3}\right], \tag{17}$$

with the origin of the coordinate to be the eddy center at the sea surface.

Using the pressure anomaly suggested by Wei et al. (2017), the equation for the pressure field based on the different strength of mesoscale eddies can be given as

$$P(x, y, z) = P_0 \cdot \tilde{P}(x, y, z) + \bar{P}(z), \tag{18}$$

$$P_0 = g \cdot \rho_0 \cdot SLA_c, \tag{19}$$

where P_0 is the strength of mesoscale eddies，ρ_0 is the reference density of seawater taken as 1024 kg/m³ , g is the gravitational acceleration set to be 9.8 m/s², SLA_c is the sea surface level anomaly (SLA) of the eddy center where the anticyclone eddies are specified as negative values and the cyclonic eddies are positive values, and the average pressure field is denoted by $\bar{P}$. As only mesoscale eddy signals are added to the ocean in this study, $\bar{P}$ is a function of the vertical direction that is homogeneous in the horizontal direction.
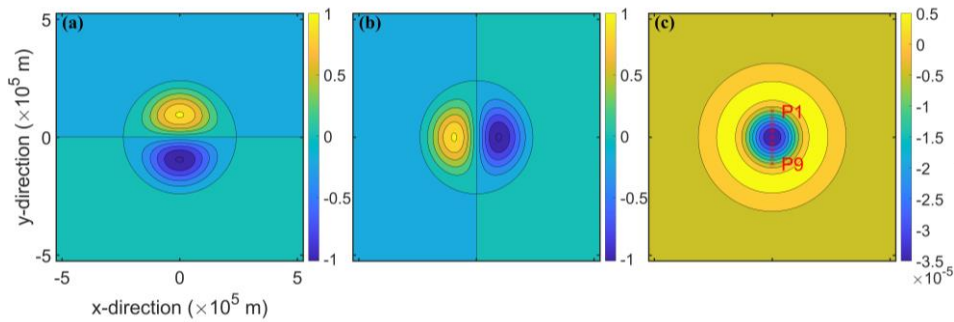
Using the geostrophic balance, the zonal and meridional components of the geostrophic velocity at the ocean surface are given as

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$$u = -\frac{1}{\rho_0 f}\frac{\partial P}{\partial y} = -\frac{P_0}{\rho_0 f}\left[\frac{y^3 + yx^2 - 4yR_0^2}{2R_0^4}\right]e^{-\frac{x^2+y^2}{2R_0^2}}, \qquad (20\text{19})$$

$$v = \frac{1}{\rho_0 f}\frac{\partial P}{\partial x} = \frac{P_0}{\rho_0 f}\left[\frac{x^3 + xy^2 - 4xR_0^2}{2R_0^4}\right]e^{-\frac{x^2+y^2}{2R_0^2}}. \qquad (21\text{0})$$

In this study, the cyclonic and anticyclonic eddies are set to have the same strength with the opposite relative vorticity. Numerical experiments are conducted with the idealized mesoscale eddy moving westward. Figure 4 shows currents and relative vorticity at the sea surface for an idealized anticyclonic eddy with the radius of 120 km, R_0 to be 120 kilometers, and P_0 of 6400 kg/m·s^2 (i.e., SLA_c is equal to 0.64 m), and the core Rossby number of about -0.7. Based on Eq. (18 19), the mesoscale eddy strength P_0 is a positive proportional function of the SLA_c under the constant seawater density and gravitational acceleration. The strength of the mesoscale eddy can be characterized by the absolute values of the SLA_c ($|SLA_c|$).

To examine model results inside the eddy, nine fixed locations in space named P1-P9 along the y-axis (marked in Fig. 4c) are selected. The distance from the eddy center to P1 (P9) is $0.92R_0$, to P2 (P8) is $0.69R_0$, to P3 (P7) is $0.46R_0$, and to P4 (P6) is $0.23R_0$. After the wind-driven currents reach a steady state, the mesoscale eddy propagates westward to reach the area of interest (P1-P9). The zonal and meridional components of currents for an anticyclonic eddy increase from the center to the edge of the eddy, and then gradually decrease outside the anticyclonic eddy (Fig. 4a and 4b). The relative vorticity is largest at the eddy center and then reduces gradually from the center to the edge of the eddy (Fig. 4c). The idealized eddy exhibits has a velocity reversal from the eddy center outward, which forms a circular positive (negative) vorticity around the periphery of the idealized anticyclonic (cyclonic) eddy in the Northern Hemisphere (Zhang et.al 2013).
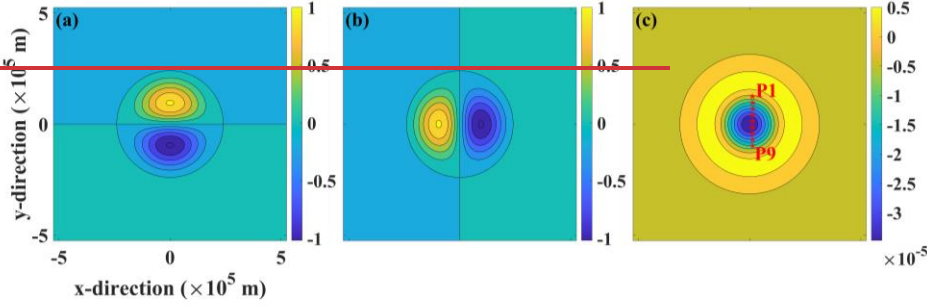
Figure 4. Distributions of (a) zonal (u) and (b) meridional (v) components (m s^{-1}) of currents and (c) relative vorticity (s^{-1}) for an idealized anticyclonic eddy with of radius of 120 km. Model results at nine fixed locations (P1-P9) denoted by red asterisks along the y-axis in (c) are examined.

Jing et al. (2017) proposed a method to calculate the efficiency of energy transfer from background mesoscale eddies to wind-induced NICs. In this study, we use the differences in the average speeds of NICs between the modified and original model (NICs_U_{AE} and NICs_U_{CE}) as the proxies for the near-inertial energy generated in the mesoscale eddies by the interaction between mesoscale eddies and NICs:

$$NICs\_U_{AE} = NICs\_U_{AE}^{Modified} - NICs\_U_{AE}^{Original}, \tag{22}$$

$$NICs\_U_{CE} = NICs\_U_{CE}^{Modified} - NICs\_U_{CE}^{Original}, \tag{23}$$

where $NICs\_U_{AE}^{Modified}$ ($NICs\_U_{AE}^{Original}$) and $NICs\_U_{CE}^{Modified}$ ($NICs\_U_{CE}^{Original}$) are the averaged speeds of NICs based on results produced by the modified (original) slab model in the anticyclonic eddies and cyclonic eddies over the same time period, respectively. It should be noted that the simulated NICs by the original slab model represent the near-inertial energy generated directly by the wind forcing. Therefore, after removing the generation of wind-induced NICs, the differences $NICs\_U_{AE}$ and $NICs\_U_{CE}$ represent the amplitudes of NICs transferred by interactions between mesoscale eddies and NICs in the anticyclonic eddies and the cyclonic eddies respectively.

To quantify differences in the NICs transferred by background currents between the anticyclonic and cyclonic eddies, we introduce a simple parameter α, defined as

$$\alpha = \frac{NICs\_U_{AE}}{NICs\_U_{CE}}. \tag{24}$$

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395 If α is larger than 1, it means that the anticyclonic eddy can transfer more NICs than the cyclonic
396 eddy with the same strength.

5.2 Effect of Wind Speeds

398 The wind speed affects the energy input from the wind to the SML, and therefore influences
399 interaction between mesoscale eddies and NICs. To facilitate theoretical analysis and generate a
400 reasonable magnitude of the NICs speeds, we conduct the numerical experiments using
401 cyclonically rotating winds and anticyclonically rotating and in the Northern Hemisphere with the
402 constant wind speed (A). The wind stress τ used in our sensitivity study takes a form as follows

$$\tau_x(t) + i\,\tau_y(t) = A\,e^{iBt}, \tag{254}$$

404 where $\tau_x(t)$ and $\tau_y(t)$ are time-dependent zonal and meridional components of wind stress, and

405 B is the wind rotation frequency. Positive wind rotation frequencies represent cyclonically
406 rotating winds and negative wind rotation frequencies indicate anticyclonically rotating winds.

407 Five numerical experiments (ExpA1-5) are conducted with the background idealized
408 mesoscale eddy moving westward with a translational speed of 8 cm s^{-1}. The $|SLA_c|$ of both
409 anticyclonic and cyclonic eddies are set to 0.64 m in these five experiments. The speeds (A) of
410 time-varying winds in these five experiments are set to 5 m s^{-1}, 10 m s^{-1}, 13 m s^{-1}, 15 m s^{-1}, and 20
411 m s^{-1} respectively, corresponding to wind stress amplitudes of 0.038 N m^{-2}, 0.150 N m^{-2}, 0.282 N
412 m^{-2}, 0.412 N m^{-2}, and 0.876 N m^{-2} respectively. The wind forcing rotates cyclonically at the inertial
413 frequency f. The conclusions drawn from the average and the sum of nine locations (P1-P9) are
414 consistent. The magnitude of the sum is larger than that of the average, which makes the
415 presentation of the results clearer and more intuitive.

416 For a cyclonic eddy with $|SLA_c|$ = 0.64 m, the sum of averaged speeds of NICs converted
417 from this cyclonic eddy at the above-mentioned nine locations ($\sum$ NICs_U_{CE}) are about 0.009 m s^{-1}
418 and 0.209 m s^{-1} for cyclonic wind speeds of 5 m s^{-1} (i.e. 0.038 N m^{-2}) and 20 m s^{-1} (i.e. 0.876 N
419 m^{-2}) respectively (Fig. 5a). This suggests that, within the cyclonic eddy, the $\sum$ NICs_U_{CE} increases
420 23 times if the cyclonic wind stress increases 23 times, which is consistent with the conclusion
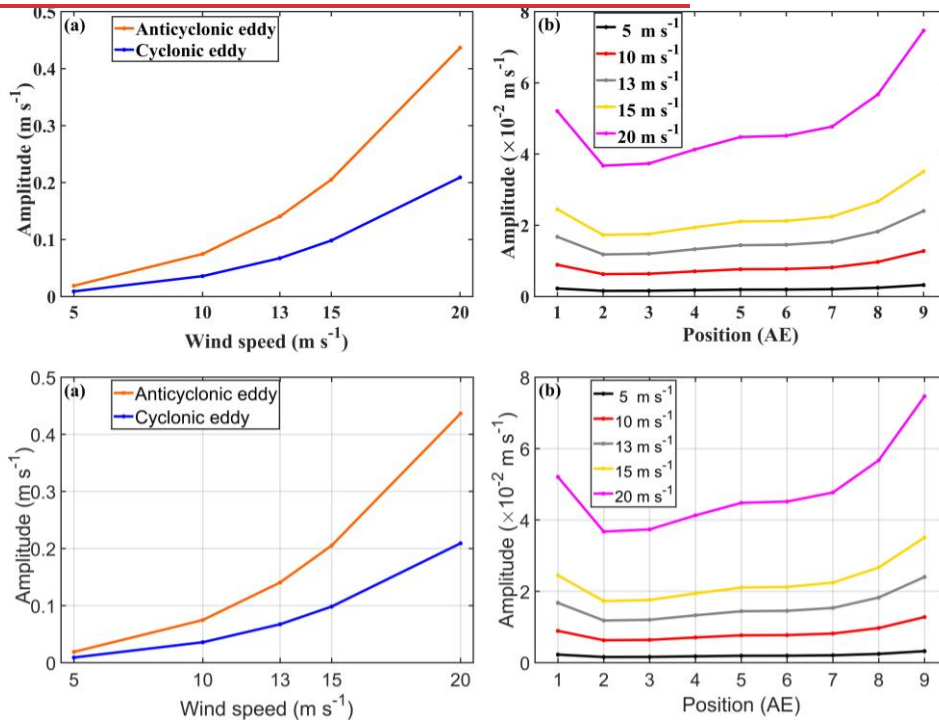421 based on the analytical solution in Sect. 6.

422 In an anticyclonic eddy with the same strength of $|SLA_c|$ = 0.64 m, the sum of averaged
423 speeds of NICs transferred from this anticyclonic eddy at the nine locations ($\sum$ NICs_U_{AE}) also

424 increases with the wind speeds. The $\sum \text{NICs\_U}_{AE}$ values are about 0.019 m s^{-1} and 0.437 m s^{-1} for

425 the cyclonic wind speeds of 5 m s^{-1} (corresponding to 0.038 N m^{-2}) and 20 m s^{-1} (corresponding to

426 0.876 N m^{-2}) respectively (Fig. 5a). This indicates that the averaged speeds of NICs generated in

427 anticyclonic eddies by the interaction between background anticyclonic eddies and NICs also

428 increase <u>linearly with the cyclonic wind stress.</u>~~23 times if the cyclonic wind stress increases 23~~

429 ~~times.~~ But the NICs are stronger in the anticyclonic eddy than in the cyclonic eddy under the same

430 wind conditions.

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434 **Figure 5.** (a) Sum of averaged speeds of transferred NICs at 9 fixed locations P1-P9 as a function
435 of the wind speeds in the anticyclonic eddy (orange line) and cyclonic eddy (blue line), respectively.
436 (b) Averaged speeds of transferred NICs as a function of the wind speeds in the anticyclonic eddy.
437 The black, red, gray, yellow and purple line indicate respectively the wind speed of 5 m s^{-1} (ExpA1),
438 10 m s^{-1} (ExpA2), 13 m s^{-1} (ExpA3), 15 m s^{-1} (ExpA4) and 20 m s^{-1} (ExpA5). Numbers on the
439 horizontal axis in (b) denote nine fixed locations P1 to P9. The wind rotates cyclonically at the

440 inertial frequency. Mesoscale eddies move westward at the translational speed of 8 cm s^{-1} and
441 $|SLA_c| = 0.64$ m.

442

443 It should be noted that, however, the transferred near-inertial energy varies with the actual
444 locations within the mesoscale eddy. We take the example of anticyclonic eddies to illustrate this
445 issue. In anticyclonic eddies, the difference between nine locations P1-P9 is large (Fig. 5b). The
446 amplitude shows a distribution characterized by small values at the eddy center and relatively large
447 values at the eddy edge, and this distribution characteristic is more obvious with the increase of
448 the wind speed. The amplitudes of transferred NICs decrease outward from the eddy edge and are
449 small in the rim of the mesoscale eddy.

450 The Okubo-Weiss parameter increases radially outward from the center of the mesoscale
451 eddy. When the wind speed is relatively small, the difference of the energy generation induced by
452 the Okubo-Weiss parameter is not significant (Fig. 5b). With the increase of the wind energy input,
453 the larger absolute value of the positive Okubo-Weiss parameter gradually has the decisive
454 function in the energy transfer. Therefore, it makes the anticyclonic eddy exhibit superior energy
455 conversion characteristics at the eddy edge, which is consistent with the conclusion based on the
456 energy transfer rate (Fig. 10).

457 The α values (Eq. (~~23~~24)) are about 2.08 based on the sum of averaged speeds of NICs at the
458 nine locations in the five different wind speeds. This indicates that the anticyclonic eddy is more
459 efficient than the cyclonic eddy in transferring the kinetic energy to NICs (Fig. 5a). The difference
460 in the near-inertial energy transfer efficiency between anticyclonic and cyclonic eddies is not
461 affected very much by magnitudes of wind speeds.

462 **5.3 Effect of Wind Rotation Frequencies**

463 The rotation frequency of the winds can affect the generation of the NICs and thus the energy
464 transfer between the mesoscale eddy and NICs, therefore ~~six~~ 28 numerical experiments using
465 different wind rotation frequencies (-$\pm$1.5f, $\pm$-1.25f, $\pm$-1.~~1f~~2f, $\pm$-~~0.9~~1.15f, $\pm$-1.~~1~~0.75f, $\pm$
466 -~~1~~0.05f, $\pm$-0.25f, $\pm$0.9~~25~~f, $\pm$0.9~~0.5~~f, $\pm$0.8~~0.75~~f, $\pm$0.8, $\pm$-0.75f, $\pm$0.5~~1.25~~f and $\pm$
467 0.25~~1.5~~f, where f is the inertial frequency), denoted as ExpB1-~~13~~28, are conducted. Positive wind
468 rotation frequencies correspond to cyclonically rotating winds, and negative wind rotation
469 frequencies are for anticyclonically rotating winds. In these ~~thirteen~~ 28 experiments, the mesoscale

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470   eddy moves westward at the speed of 8 cm s^{-1} and $|SLA_c| = 0.64$ m. The winds rotate at different

471   frequencies and the wind speed is set to 13 m s^{-1}.

472   Figure 6 shows the sum of averaged speeds of the transferred NICs at the nine locations as

473   function of the wind rotation frequency for the cyclonic and anticyclonic eddies. Under

474   cyclonically rotating and anticyclonically rotating wind conditions, there is bidirectional energy

475   transfer between mesoscale eddies and NICs. The closer the absolute value of the wind rotation

476   frequency to f, the stronger the energy transfer between mesoscale eddies and NICs. When the

477   wind rotation frequency is negative, the wind rotation direction is the same as that of the local

478   NICs. Wind rotation frequencies close to the inertial frequency of $-f$ can lead to the resonance and

479   induce large NICs. Therefore, the strong NICs provide a significant energy source for reverse

480   energy conversion, allowing the near-inertial kinetic energy to be reabsorbed into the background

481   mesoscale eddies and contribute to the reconstruction of the geostrophic balance.

482   For cyclonic eddies, the sum of averaged speeds of NICs ($\sum$ NICs_U$_{CE}$) is sensitive to the

483   wind rotation frequency. The $\sum$ NICs_U$_{CE}$ values are less than zero when the winds rotate

484   cyclonically at the frequencies of $0.25f$, $0.75f$ and $1.25f$ (Fig. 6b) and the winds rotate

485   anticyclonically at frequencies ranging from $-1.15f$ to $-0.75f$ (Fig. 6a), indicating that direction

486   of the energy transfer is from the NICs to the cyclonic eddies. The amplitudes of the energy

487   transferred from NICs to cyclonic eddies under anticyclonically rotating wind conditions are larger

488   than those transferred under cyclonically rotating wind conditions. The addition of mesoscale

489   eddies has a damping effect for NICs, leading to the negative energy transfer that aligns with the

490   observed results (Fig. 2). When the direction of the energy transfer is positive, the $\sum$ NICs_U$_{CE}$ has

491   a maximum value of about 0.635 m s^{-1} when the winds rotate anticyclonically at the frequency of

492    $-1.25f$.

493   For anticyclonic eddies, the sum of averaged speeds of NICs ($\sum$ NICs_U$_{AE}$) also varies with

494   the wind rotating frequency. When the winds rotate anticyclonically at frequencies ranging from $-$

495    $1.5f$ to $-0.9f$, the direction of the energy transfer is from NICs to anticyclonic eddies (Fig. 6a).

496   The negative energy transfer is strongest at the resonance frequency of $-f$. The $\sum$ NICs_U$_{AE}$ values

497   are all positive under cyclonically rotating winds, which represent the energy transfer from the

498   anticyclonic eddies to NICs (Fig. 6b). The $\sum$ NICs_U$_{AE}$ values for the anticyclonic eddies increases

499   from the value of ~0.002 m s^{-1} at the wind rotating frequency of $0.25f$ to the maximum value of

500   ~0.213 m s^{-1} at the wind rotating frequency of $0.90f$. The $\sum$ NICs_U$_{AE}$ values are larger than the

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$\sum$ NICs_U_{CE} values under the same positive wind rotation frequency. The closer the rotational frequency of the cyclonic winds is to the inertial frequency, the greater the difference in near-inertial energy conversion induced by anticyclonic eddies and cyclonic eddies.
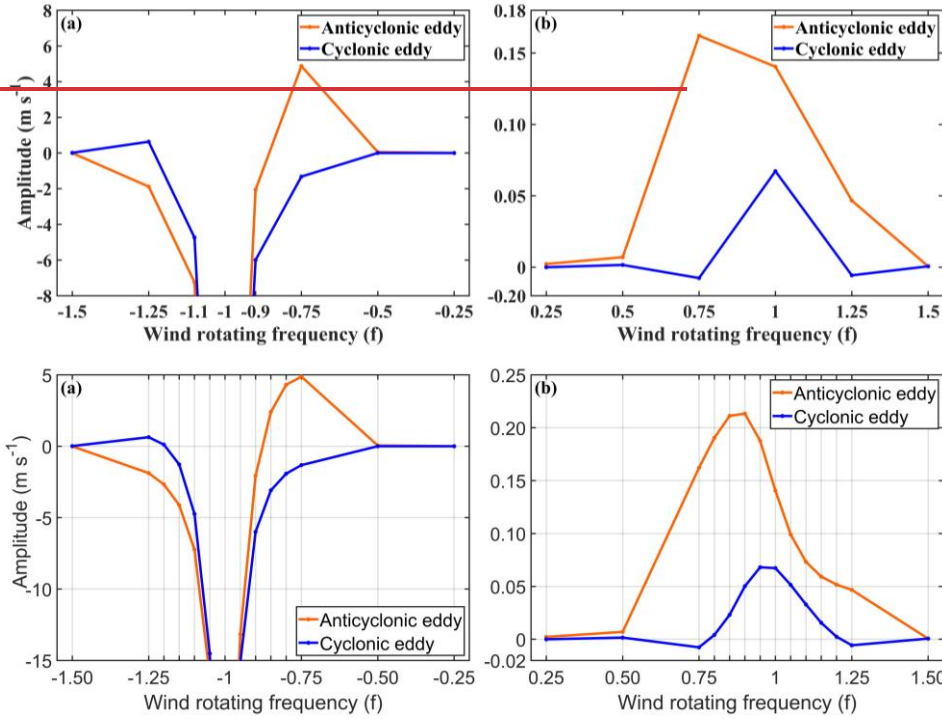
For cyclonic eddies, the sum of averaged speeds of NICs ($\sum$ NICs_U_{CE}) is sensitive to the wind rotation frequency. The $\sum$ NICs_U_{CE} values are less than zero when the winds rotate cyclonically at the frequencies of $0.25f$, $0.75f$ and $1.25f$ (Fig. 6b) and the winds rotate anticyclonically at the frequencies of -1.1f, -0.9f and -0.75f (Fig. 6a), indicating that direction of the energy transfer is from the NICs to the cyclonic eddies. The amplitudes of the energy transferred from NICs to cyclonic eddies under anticyclonically rotating wind conditions are larger than those transferred under cyclonically rotating wind conditions. The addition of mesoscale eddies has a damping effect for NICs, leading to the negative energy transfer that aligns with the observed results (Fig. 2). When the direction of the energy transfer is positive, the $\sum$ NICs_U_{CE} has a maximum value of about 0.635 m s^{-1} when the winds rotate anticyclonically at the frequency of -1.25f.

For anticyclonic eddies, the sum of averaged speeds of NICs ($\sum$ NICs_U_{AE}) also varies with the wind rotating frequency. When the winds rotate anticyclonically at frequencies of -1.5f, -1.25f, -1.1f and -0.9f, the direction of the energy transfer is from NICs to anticyclonic eddies (Fig. 6a). The negative energy transfer is strongest at the frequency of -1.1f. The $\sum$ NICs_U_{AE} values are all positive under cyclonically rotating winds, which represent the energy transfer from the anticyclonic eddies to NICs (Fig. 6b). The $\sum$ NICs_U_{AE} values for the anticyclonic eddies increases from the value of -0.002 m s^{-1} at the wind rotating frequency of 0.25f to the maximum value of -0.162 m s^{-1} at the wind rotating frequency of 0.75f. The $\sum$ NICs_U_{AE} values are larger than the $\sum$ values under the same positive wind rotation frequency. The closer the rotational frequency of the cyclonic winds is to the inertial frequency, the greater the difference in near-inertial energy conversion induced by anticyclonic eddies and cyclonic eddies.

Figure 6. Sum of averaged speeds of transferred NICs at 9 fixed locations P1-P9 as a function of rotation frequencies of (a) anticyclonically rotating winds and (b) cyclonically rotating winds. The orange and blue line indicate respectively the anticyclonic eddy and cyclonic eddy. The wind rotation frequencies are normalized by the inertial frequency f.

5.4 Effect of Eddy Translational Speeds

The translational speed of a background mesoscale eddy defines the forcing duration of winds and thus the energy input to NICs in the ocean SML. Based on the observations of mesoscale eddies in the nSCS, nine numerical experiments (ExpC1-9) using different translational speeds of mesoscale eddies (4 cm s^{-1}, 5 cm s^{-1}, 6 cm s^{-1}, 7 cm s^{-1}, 8 cm s^{-1}, 9 cm s^{-1}, 10 cm s^{-1}, 11 cm s^{-1}, and 12 cm s^{-1}) are conducted. In these nine experiments, the speed of cyclonically rotating winds at the inertial frequency is set to 13 m s^{-1}. The mesoscale eddy moves westward and $|SLA_c| = 0.64$ m.

For the anticyclonic eddy with $|SLA_c| = 0.64$ m, the sum of average speeds of the converted NICs at the nine locations ($\sum \text{NICs\_U}_{AE}$) increases from about 0.133 m s^{-1} to 0.148 m s^{-1} as the

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translational speeds increase from 4 cm s^{-1} to ~~12~~ 11 cm s^{-1} (Fig. 7a). After the translational speed reaches 11 cm/s, the value of $\sum$ NICs_U$_{AE}$ remains almost the same as that at a translational speed of 11 cm/s. The increase of the translational speed enhances the total kinetic energy of mesoscale eddies, which can provide a larger energy source and be more beneficial for the conversion of NICs. The translational speed of the mesoscale eddy is smaller than the maximum rotation speed of the mesoscale eddy. It should be noted that the change in the eddy kinetic energy caused by the different translational speeds is relatively small in comparison with the total eddy energy determined by the mesoscale eddy strength. Therefore, the change in the amplitude of the transferred NICs is relatively small.

For a cyclonic eddy with $|SLA_c|$ = 0.64 m, the sum of average speeds of the transferred NICs at the nine locations ($\sum$ NICs_U$_{CE}$) range from 0.066 m s^{-1} to 0.069 m s^{-1} and are not sensitive to the translational speeds (Fig. 7a). Same as in the anticyclonic eddy case, more total kinetic energy is available for generating NICs within the cyclonic eddy with the same structure but with the faster translational speeds. Different from the anticyclonic eddy case, however, the ~~anti~~cyclonic eddy is not conducive to the energy transfer to NICs naturally. Therefore, the slightly larger energy source caused by the increase of the translational speeds has little influence on the total amount of kinetic energy transferred from the cyclonic eddy to NICs.
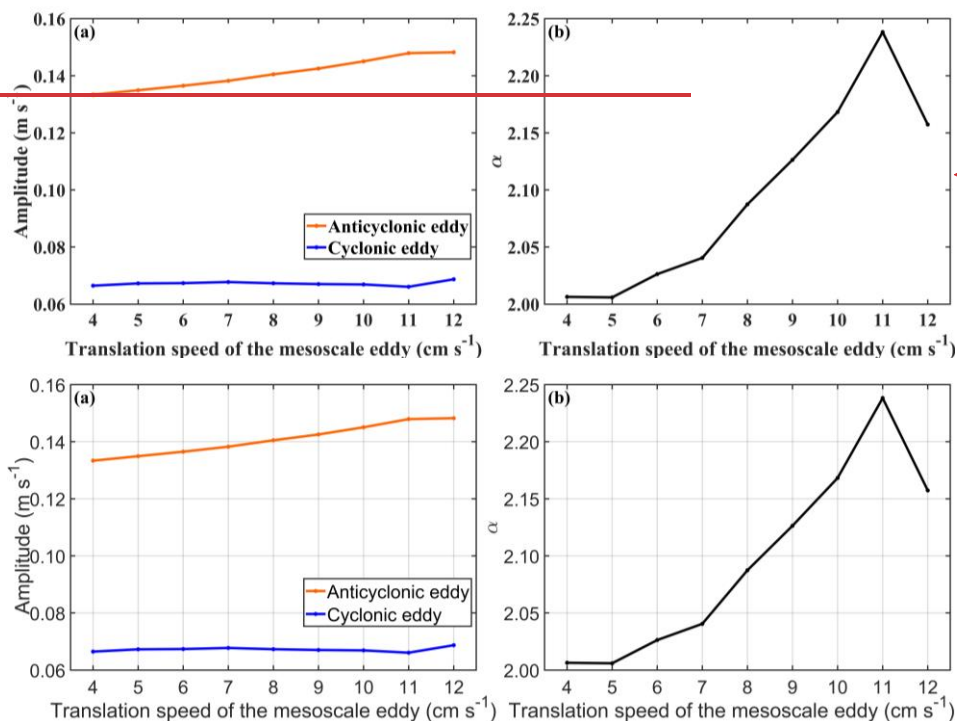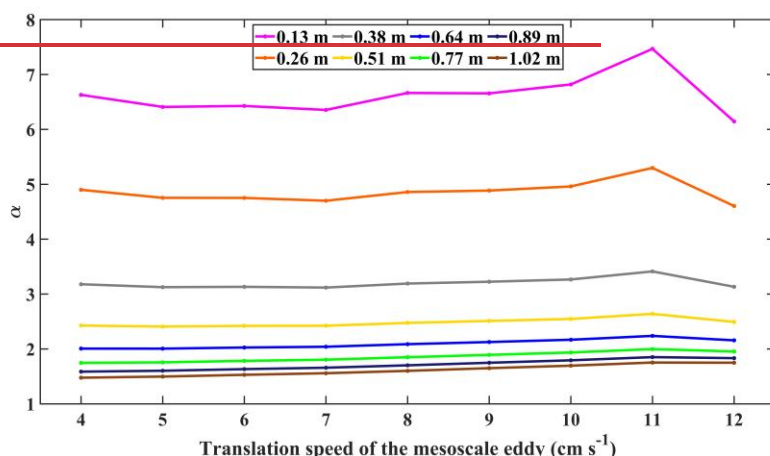
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Figure 7. (a) Sum of averaged speeds of transferred NICs at 9 fixed locations P1-P9 as a function of the eddy translational speed in the anticyclonic eddy (orange line) and cyclonic eddy (blue line), respectively. (b) The α value as a function of the eddy translational speed. The speed of the cyclonic wind is 13 m s^{-1}, and the wind rotates at the inertial frequency. Mesoscale eddies move westward and $|SLA_c| = 0.64$ m.

The α value has a maximum value of ~2.24 occurring at the eddy translational speeds of 11 cm s^{-1} (Fig. 7b). This means that the anticyclonic eddy transfers much more near-inertial energy than the cyclonic eddy does, particular at the translational speed of 11 cm s^{-1}. After exceeding the translational speed of 11 cm s^{-1}, the α values decrease with the increase of the eddy translational speeds. The α value is ~2.16 at the translational speed of 12 cm s^{-1}. The average speeds of the NICs at the mesoscale eddy edge are generally larger than that of at the mesoscale eddy center.

A natural question raises whether the variations of α values within the mesoscale eddy are affected by the strength of anticyclonic eddies. To address this issue, we consider the sum of

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577   averaged speeds of NICs at nine locations for mesoscale eddies and the α values with different
578   strengths and translational speeds (Fig. 8). We consider the case with the cyclonically rotating
579   wind speed of 13 m s^{-1} at the inertial frequency. For mesoscale eddies with larger $|SLA_c|$ values,
580   the α values are relatively less sensitive to the translational speed. For mesoscale eddies with
581   different $|SLA_c|$ values, the α values all have the maximum values with the translational speeds of
582   11 cm s^{-1}. The α value decreases with the elevated translational speed when the eddy translational
583   speed is larger than 11 cm s^{-1}.

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Figure 8. The α values at 9 fixed locations P1-P9 as a function of the strengths and translational speeds of the mesoscale eddies. The speed of the cyclonically rotating winds at the inertial frequency is 13 m s^{-1}. Mesoscale eddies move westward. Different colors of lines represent different mesoscale eddy strengths.

5.5 Effect of Mesoscale Eddy Strengths

In addition to the effect of the eddy translational speed, other characteristics of mesoscale eddies such as the radius and strength of mesoscale eddies can also affect the energy exchange. Sixteen numerical experiments (denoted as ExpD1-16) are conducted in this section using various strengths of mesoscale eddies. In these sixteen experiments, the speed of cyclonically rotating winds at the inertial frequency is set to 13 m s^{-1}, the translational speed of mesoscale eddies is set to 8 cm s^{-1}, and the eddy translational direction to be westward. The $|SLA_c|$ values are set to 0.13 m, 0.26 m, 0.38 m, 0.51 m, 0.64 m, 0.77 m, 0.89 m, and 1.02 m for cyclonic and anticyclonic eddies, respectively.

Figure 9a shows that the sum of averaged speeds of the transferred NICs at nine locations as a function of the mesoscale eddy strengths for the cyclonic ($\sum \text{NICs\_U}_{CE}$) and anticyclonic eddies ($\sum \text{NICs\_U}_{CE}$). Both values of $\sum \text{NICs\_U}_{AE}$ and $\sum \text{NICs\_U}_{CE}$ are larger for higher eddy strengths, particularly for the anticyclonic eddies. For the $|SLA_c|$ values equal to 0.13 m, values of $\sum \text{NICs\_U}_{AE}$ and $\sum \text{NICs\_U}_{CE}$ are about 0.019 m s^{-1} and about 0.003 m s^{-1}. The averaged speeds of the converted NICs increase with the $|SLA_c|$ value, particularly for the anticyclonic eddies. For $|SLA_c| = 1.02$ m, the averaged speeds of the transferred NICs are ~0.280 m s^{-1} and ~0.175 m s^{-1} for the anticyclonic and cyclonic eddies respectively, which are ~14.74 times and ~58.33 times larger than the counterparts at $|SLA_c| = 0.13$ m. As the geostrophic strain field is relatively stronger at the eddy edge, the average speeds of the converted NICs at the mesoscale eddy edge are larger than that at the mesoscale eddy center.
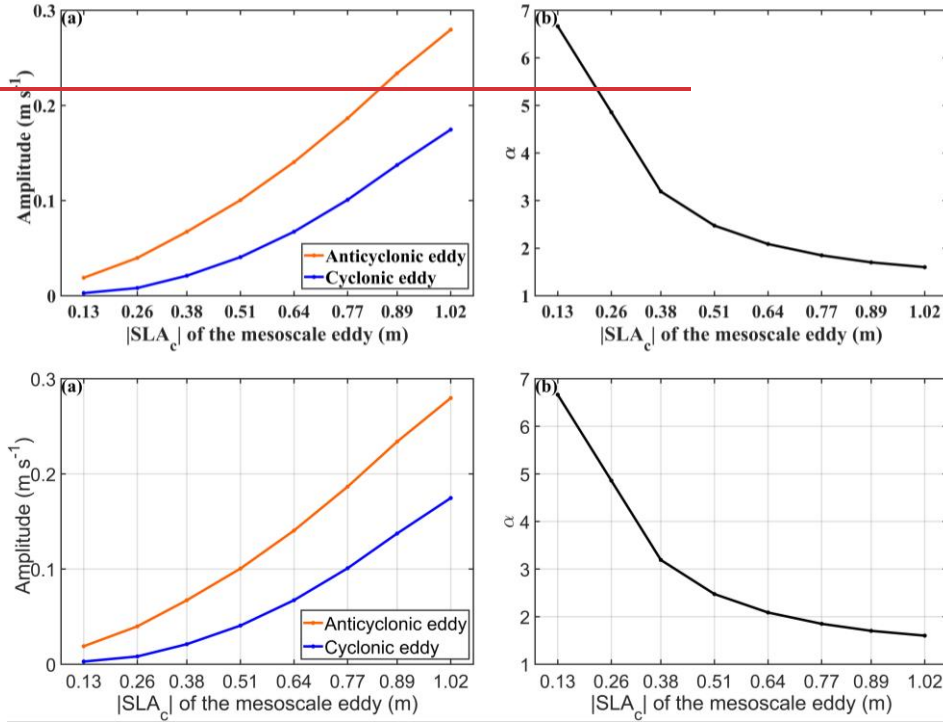
Figure 9. (a) Sum of averaged speeds of transferred NICs at 9 fixed locations P1-P9 as a function of the strengths ($|SLA_c|$ of the mesoscale eddy) of the anticyclonic eddy (orange line) and cyclonic eddy (blue line). (b) The α value as a function of the eddy strengths ($|SLA_c|$ of the mesoscale eddy). The mesoscale eddy moves westward at the speed of 8 cm s^{-1}. The speed of the cyclonically rotating wind speed at the inertial frequency is set to 13 m s^{-1}.

The α value also varies with the mesoscale eddy strength (Fig. 9b). The α value decreases significantly from about 6.66 to 1.60 for the $|SLA_c|$ values in the range of 0.13 and 1.02 m. As mentioned above, cyclonic eddies have limited ability in transferring their kinetic energy to NICs, which differs significantly from anticyclonic eddies. However, stronger cyclonic eddies with more eddy energy provide the more favorable condition for the energy transfer, which can narrow the difference in the near-inertial energy transfer induced by anticyclonic eddies and cyclonic eddies. Furthermore, stronger geostrophic currents lead to stronger geostrophic strain field which can generate stronger NICs.

29

5.6 Relative Vorticity and Strain

As mentioned above, the anticyclonic eddies in the SML are more efficient than cyclonic eddies for transferring kinetic energy to NICs, which can be explained by the relative vorticity of the background flow (ζ) defined in Eq. (1). In numerical experiments, the direction of the energy transfer is bidirectional, but primarily positive, that is, from mesoscale eddies to NICs. For cyclonic eddies, the direction of the energy transfer is from the NICs to the cyclonic eddy under cyclonically rotating winds at frequencies of $0.25f$, $0.75f$ and $1.25f$ and anticyclonically rotating winds at ~~frequencies~~ frequency range of -1.1$5f$ to, ~~-0.9f and~~ –$0.75f$. When the frequencies of anticyclonically rotating winds are range from -1.5f to -0.9f, the energy transfer is also negative in the anticyclonic eddy. The α value is more than 1.0 for about 87~~8~~% of these experiments, which indicates that the transferred near-inertial energy is larger in anticyclonic eddies than cyclonic eddies.

In addition to the relative vorticity and translational speed of a mesoscale eddy, the normal strain and shear strain of the background flow can also affect the energy transfer between the mesoscale eddy and NICs in the SML. Jing et al. (2017) proposed a method to calculate the rate of energy transfer from background mesoscale eddies to wind-induced NICs. Following Jing et al. (2017), the energy transfer rate (ε) between the NICs and the mesoscale eddy in the SML is given as

$$\varepsilon = -\rho H_{mix}\left(uuU_x + uvU_y + uvU_x + vvV_y\right), \tag{2\underline{6}\sout{5}}$$

where u and v are respectively the zonal and meridional components of the near-inertial current velocity reproduced by the modified slab model, and subscripts x and y in U and V represent partial derivatives. The positive ε mean the energy transfer from the mesoscale eddy to the NICs, and the negative ε indicates the backward energy cascade. In the numerical experiments, the NICs can be generated directly by the cyclonic winds, and the wind-induced NICs can further interact with the mesoscale eddy and transfer the near-inertial energy from the mesoscale eddy to the NICs when the mesoscale eddy passed by the nine locations P1-P9. Therefore, we also calculate the energy transfer rate and Okubo-Weiss parameter at the nine fixed locations P1-P9 in the sensitivity experiments ExpA3, ExpC1-C9 and ExpD1-D16, which are under the same wind conditions.
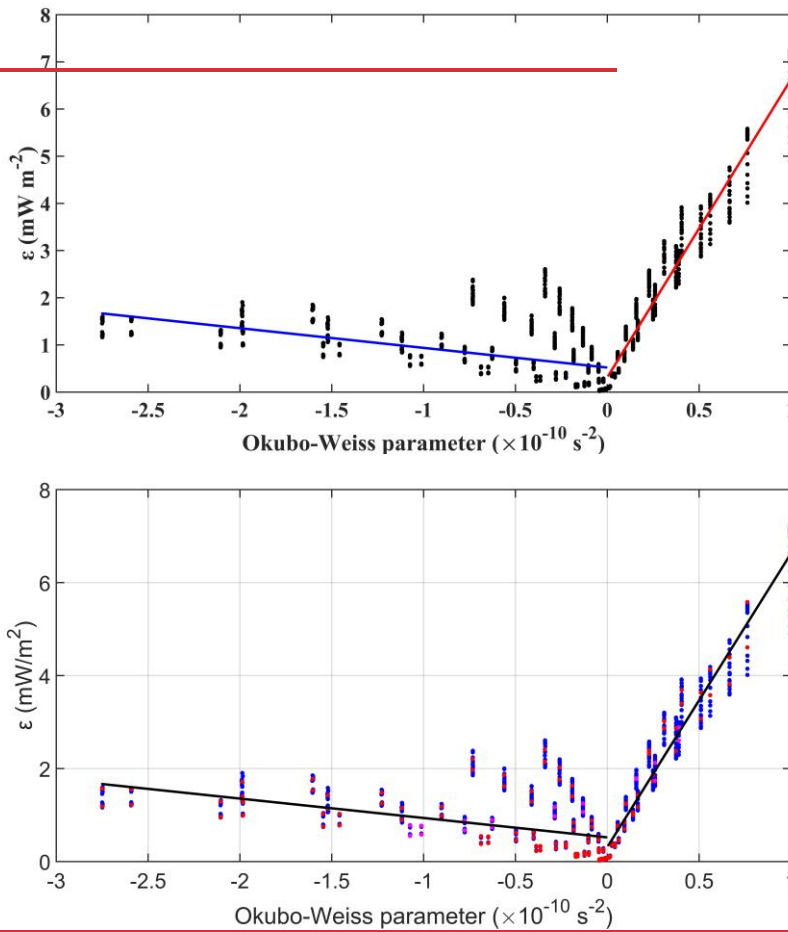
When the Okubo-Weiss parameters (strains) are negative, the energy transfer rate decreases as the Okubo-Weiss parameter (strain) increases (Fig. 10). However, when the Okubo-Weiss

30

659   parameters (strains) are positive, the energy transfer rate shows an elevated trend with the increase

660   of the Okubo-Weiss parameter (strain) (Fig. 10). Based on limited sensitivity studies, we found

661   the relative vorticity and the strain of the mesoscale eddy both have an influence on the near-

662   inertial energy transferred by interactions between mesoscale eddies and NICs.

663

665

Figure 10. Scatterplot between the energy transfer rate and the Okubo-Weiss parameter. Purple, blue and red dots respectively represent ExpA3, ExpC1-9 and ExpD1-16. The left (right) blue (red) lineblack line isis the linear fitting line when when thethe Okubo-Weiss parameters are negative ((positivee)e)..

31

6 Theoretical Analyses

6.1 Solutions in the Frequency Domain

To gain better understanding of the role of the relative vorticity in the background flow for anticyclonic eddies to be significantly more efficient than the cyclonic eddies in transferring their kinetic energy to NICs, we examine analytically the effect of the relative vorticity in the frequency domain solution of the modified slab model.

The modified slab model can be written in the tensor form:

$$\frac{\partial}{\partial t}\begin{Bmatrix} u \\ v \end{Bmatrix} + \begin{bmatrix} a_1 & b_1 \\ a_2 & b_2 \end{bmatrix} \begin{Bmatrix} u \\ v \end{Bmatrix} = \begin{Bmatrix} c_1 \\ c_2 \end{Bmatrix}, \tag{27}$$

where, $a_1 = U_x + r$, $a_2 = V_x + f$, $b_1 = U_y - f$, $b_2 = V_y + r$, $c_1 = \tau_x/\rho H_{mix}$ and $c_2 = \tau_y/\rho H_{mix}$. ~~For simplicity, we consider the steady wind forcing to eliminate the wind-induced NICs here.~~ Under the steady winds, the NICs produced by the original slab model are zero, therefore the NICs produced by the modified slab model directly represent the near-inertial energy converted between mesoscale eddies and NICs. For simplicity, we consider the steady wind forcing to directly ~~eliminate the wind-induced NICs here.~~ In the case of steady winds, we use the Fourier transform to translate the modified slab model from the time domain into the frequency domain:

$$\begin{bmatrix} a_1 + i\omega & b_1 \\ a_2 & b_2 + i\omega \end{bmatrix} \begin{Bmatrix} \tilde{u} \\ \tilde{v} \end{Bmatrix} = \begin{Bmatrix} \widetilde{c_1} \\ \widetilde{c_2} \end{Bmatrix}, \tag{28}$$

where ω is the frequency and variables with a tilde represent the values after Fourier transform.

Assuming the mesoscale eddy is in an almost steady state during an inertial period (Jing et al. 2017), the analytical solution for the zonal and meridional components of NICs in the frequency domain can be written as

$$\tilde{u} = \frac{(b_2 + i\omega) \cdot 2 \cdot \pi \cdot c_1 \cdot \delta(\omega) - b_1 \cdot 2 \cdot \pi \cdot c_2 \cdot \delta(\omega)}{(a_1 + i\omega)(b_2 + i\omega) - a_2 b_1}, \tag{29}$$

$$\tilde{v} = \frac{(a_1 + i\omega) \cdot 2 \cdot \pi \cdot c_2 \cdot \delta(\omega) - a_2 \cdot 2 \cdot \pi \cdot c_1 \cdot \delta(\omega)}{(a_1 + i\omega)(b_2 + i\omega) - a_2 b_1}, \tag{30}$$

where $\delta(\omega)$ is the Dirac Delta function.

Based on Perceval's theorem, the energy of NICs is the same in both the time and frequency domains:

$$\frac{1}{T}\int |U(t)|^2 dt = \int |U(\omega)|^2 d\omega, \tag{31}$$

32

696   where T is the total period.

697   The time-mean near-inertial kinetic energy $\overline{U_{NIW_s}}^2$ in the time domain can be written as

$$\overline{U_{NIW_s}}^2 = \overline{u^2} + \overline{v^2}, \tag{3$\underline{2}$$\cancel{1}$}$$

$$\overline{u^2} = \int \frac{\left((b_2 c_1 - b_1 c_2)^2 + \omega^2 c_1{}^2\right) \cdot \left((2 \cdot \pi \cdot \delta(\omega))^2\right)}{(a_2 b_1 - a_1 b_2 + \omega^2)^2 + \omega^2 (a_1 + b_2)^2} \cdot d\omega, \tag{3$\underline{3}$$\cancel{2}$}$$

$$\overline{v^2} = \int \frac{\left((a_1 c_2 - a_2 c_1)^2 + \omega^2 c_2{}^2\right) \cdot \left((2 \cdot \pi \cdot \delta(\omega))^2\right)}{(a_2 b_1 - a_1 b_2 + \omega^2)^2 + \omega^2 (a_1 + b_2)^2} \cdot d\omega. \tag{3$\underline{4}$$\cancel{3}$}$$

701   For a unidirectional laterally sheared geostrophic flow and the southwestward wind, U=0,
702 V=V(x), $c_1 < 0$ and $c_2 < 0$. Substitution of $a_1 = r$, $a_2 = \zeta + f$, $b_1 = -f$ and $b_2 = r$ into Eq.
703 ($\cancel{32}$$\underline{33}$) and Eq. ($\cancel{33}$$\underline{34}$) yields

$$\overline{u^2} = \int \frac{\left((rc_1 + fc_2)^2 + \omega^2 c_1{}^2\right) \left((2 \cdot \pi \cdot \delta(\omega))^2\right)}{\left(r^2 - \omega^2 + f(\zeta + f)\right)^2 + 4\omega^2 r^2} d\omega, \tag{3$\underline{5}$$\cancel{4}$}$$

$$\overline{v^2} = \int \frac{\left((rc_2 - (\zeta + f)c_1)^2 + \omega^2 c_2{}^2\right) \left((2 \cdot \pi \cdot \delta(\omega))^2\right)}{\left(r^2 - \omega^2 + f(\zeta + f)\right)^2 + 4\omega^2 r^2} d\omega. \tag{3$\underline{6}$$\cancel{5}$}$$

706   Since the relative vorticity is negative in anticyclonic eddies, the denominator term for $\overline{u^2}$ in
707 Eq. ($\cancel{34}$$\underline{35}$) is less than the value with $\underline{\text{positive}}$ $\cancel{\text{the}}$ relative vorticity $\cancel{\text{to be positive}}$. Therefore, the
708 value of $\overline{u^2}$ is greater in anticyclonic eddies than in cyclonic eddies. For the positive relative
709 vorticity, the numerator term of $\overline{v^2}$ is smaller and the denominator term in Eq. ($\cancel{35}$$\underline{36}$) becomes
710 larger than the case of negative vorticity. This indicates that $\overline{v^2}$ is more elevated in the anticyclonic
711 eddies. Since both $\overline{u^2}$ and $\overline{v^2}$ are elevated when the relative vorticity is negative than counterparts
712 with the positive relative vorticity, anticyclonic eddies can transfer more near-inertial energy than
713 cyclonic eddies.

714 **6.2 Analytical Solution**

715   An analytical solution based on the modified slab model is considered here to demonstrate
716 that mesoscale eddies can transfer more near-inertial energy for stronger winds. The modified
717 slab model cane be written as

$$\frac{\partial u}{\partial t} + a_1 u + b_1 v = c_1, \tag{3$\underline{7}$$\cancel{6}$}$$

$$\frac{\partial v}{\partial t} + a_2 u + b_2 v = c_2, \tag{3$\underline{8}$$\cancel{7}$}$$

720 where, $a_1 = U_x + r$, $a_2 = V_x + f$, $b_1 = U_y - f$, $b_2 = V_y + r$, $c_1 = \tau_x / \rho H_{mix}$, $c_2 = \tau_y / \rho H_{mix}$,
721 $\tau_x = A\cos ft$ and $\tau_y = A\sin ft$.

33

For the cyclonic wind, substitution of Eq. (36̶37) into Eq. (37̶38) yields

$$\frac{\partial^2 u}{\partial t^2} + (a_1 + b_2)\frac{\partial u}{\partial t} + (a_1 b_2 - a_2 b_1)u = b_2 c_1 - (f + b_1)c_2 \tag{39̶8}$$

$$\Delta = (a_1 + b_2)^2 - 4(a_1 b_2 - a_2 b_1). \tag{40̶39}$$

The analytical solutions of the current to the modified slab model are

$$u_{Modified} = e^{\gamma t}(Q_1 \cos\beta t + Q_2 \sin\beta t) + Q_3 \cos ft + Q_4 \sin ft, \tag{41̶0}$$

$$v_{Modified} = \frac{1}{b_1}(c_1 - e^{\gamma t}(a_1 + \gamma)(Q_1 \cos\beta t + Q_2 \sin\beta t)$$

$$-e^{\gamma t}\beta(Q_2 \cos\beta t - Q_1 \sin\beta t) + (fQ_3 - a_1 Q_4)\sin ft - (fQ_4 + a_1 Q_3)\cos ft), \tag{42̶1}$$

where

$$\gamma = -\frac{a_1 + b_2}{2}, \tag{43̶2}$$

$$\beta = \frac{\sqrt{-\Delta}}{2}, \tag{44̶3}$$

$$Q_1 = -Q_3, \tag{45̶4}$$

$$Q_2 = \frac{c_1 + \gamma Q_3 - fQ_4}{\beta}, \tag{46̶5}$$

$$Q_3 = \frac{Ab_2(a_1 b_2 - a_2 b_1 - f^2) + A(f + b_1)(fa_1 + fb_2)}{\rho H_{mix}((a_1 b_2 - a_2 b_1 - f^2)^2 + (fa_1 + fb_2)^2)}, \tag{47̶6}$$

$$Q_4 = \frac{\rho H_{mix} Q_3(fa_1 + fb_2) - A(f + b_1)}{\rho H_{mix}(a_1 b_2 - a_2 b_1 - f^2)}. \tag{48̶7}$$

Increasing the wind stress c_1 and c_2 by a factor of n named c_1' and c_2' yields

$$c_1' = nc_1 = \frac{n\tau_x}{\rho H_{mix}} = \frac{nA\cos ft}{\rho H_{mix}}, \tag{49̶8}$$

$$c_2' = nc_2 = \frac{n\tau_y}{\rho H_{mix}} = \frac{nA\sin ft}{\rho H_{mix}}. \tag{50̶49}$$

Substitution of c_1' and c_2' into Q_3 and Q_4 yields

$$Q_3' = \frac{nAb_2(a_1 b_2 - a_2 b_1 - f^2) + nA(f + b_1)(fa_1 + fb_2)}{\rho H_{mix}((a_1 b_2 - a_2 b_1 - f^2)^2 + (fa_1 + fb_2)^2)} = nQ_3, \tag{51̶0}$$

$$Q_4' = \frac{\rho H_{mix} nQ_3(fa_1 + fb_2) - nA(f + b_1)}{\rho H_{mix}(a_1 b_2 - a_2 b_1 - f^2)} = nQ_4. \tag{52̶1}$$

Substitution of Q_3 and Q_4 into Q_1 and Q_2 yields

$$Q_1' = -nQ_3 = nQ_1, \tag{53̶2}$$

$$Q_2' = \frac{nc_1 + \gamma nQ_3 - fnQ_4}{\beta} = nQ_2. \tag{54̶3}$$

Therefore, the current with the increased wind stress to the modified slab model is given as

$$u_{Modified}' = nu_{Modified}, \tag{55̶4}$$

$$v_{Modified}' = nv_{Modified}. \tag{56̶5}$$

748   The analytical solution of the current to the original slab model is

749
$$U_{Original} = \frac{Ae^{ift}}{\rho H_{mix}(if+r)} + \left(\left(\frac{Ae^{-(if+r)t}}{\rho H_{mix}(if+r)}\right)\left(\frac{if}{2if+r}\right)\left(1 - e^{(2if+r)t}\right)\right) - \frac{Ae^{-(if+r)t}}{\rho H_{mix}(if+r)}. \quad (5\cancel{7}6)$$

750   Therefore, the current with the increased wind stress to the original slab model is given as

751
$$U_{Original}' = nU_{Original}. \quad\quad\quad (5\underline{8}\cancel{7})$$

752   The above analytical solutions demonstrate that when the wind stress increases by n times,

753 the current speeds simulated by the modified and original slab models both increase by n times.

754 The differences in the average speeds of NICs between the modified and original model represent

755 the transferred near-inertial energy by the interaction between mesoscale eddies and near-inertial

756 motions (Eq. (2$\cancel{1}$22) and (2$\cancel{2}$23)). As the NICs are the component of the total currents in the near-

757 inertial frequency band, the transferred near-inertial energy in the mesoscale eddies also increases

758 by a factor of n times when the wind stress is multiplied by n times. This feature is consistent with

759 our sensitivity experiments in Sect. 5.

7 Summary and Discussion

761   Analysis of in situ current observations at two offshore ADCP mooring sites in the northern

762 South China Sea (nSCS) demonstrated that relatively strong near-inertial currents (NICs) occurred

763 during certain periods of nearly steady winds in the lower part of the ocean surface mixed layer

764 (SML). The NICs produced by the original slab model are significantly larger than the observations,

765 indicating other important processes operating over the area. We followed Welle (1982) and Jing

766 et al. (2017) and used a modified slab model in this study by including contributions from the

767 background geostrophic currents. Using the surface geostrophic currents inferred from the satellite

768 sea level data and assuming the geostrophic currents in the SML is vertically uniform, we found

769 that the modified slab model performs significantly better than the original slab model in

770 reproducing the observed NICs at two ADCP mooring sites in the nSCS. Examinations of

771 observations and numerical results produced by the modified and original slab models revealed

772 the occurrence of the energy exchange between the mesoscale eddies and the NICs. Based on the

773 energy budget analysis for NICs during the observational period, the difference of the near-inertial

774 wind power input between the original slab model and the modified slab model is the same order

775 as the energy transfer rate (Eq. $\cancel{25}$26). This also indicates the importance of the near-inertial energy

35

776 transfer induced by the interaction between mesoscale eddies and NICs in the SML during the
777 observational period.

778   The modified slab model and original slab model were then used to examine sensitivity to
779 winds and eddy parameters with idealized mesoscale eddies under cyclonic winds. Both cyclonic
780 and anticyclonic mesoscale eddies were considered, using the universal eddy structure suggested
781 by Zhang et al. (2013). One of our major findings is that anticyclone eddies can transfer more
782 kinetic energy to NICs than cyclonic eddies. Idealized experiments show that induced NICs speed
783 in anticyclonic eddies can reach over 6 times the speed in cyclonic eddies. We also found that the
784 energy transfer rate is related to the Okubo-Weiss parameter. When the Okubo-Weiss parameter
785 is positive, the energy transfer rate is elevated with the larger Okubo-Weiss parameter.

786   Analyses of model results in 196 numerical experiments using the modified slab model
787 demonstrated that there exists bidirectional energy transfer between mesoscale eddies and NICs.
788 The direction of the energy transfer is primarily from mesoscale eddies to NICs. When the cyclonic
789 winds rotate at frequencies of $0.25f$, $0.75f$ and $1.25f$ and the anticyclonic winds rotate at
790 frequencies ~~of~~ ranging from -1.1$5f$~~, 0.9f and~~ to -0.75f, the direction of the energy transfer is
791 negative in the cyclonic eddy, that is, from NICs to cyclonic eddies. Under anticyclonically
792 rotating winds at the frequency range~~ies~~ of -1.5f to ~~, 1.25f, 1.1f and~~ -0.9$9f$, the negative energy
793 transfer also occurs in the anticyclonic eddy. The NICs transferred from mesoscale eddies are
794 stronger for higher wind speeds, faster translational speeds and stronger strengths of mesoscale
795 eddies. When the wind stress increases by a factor of n times, the amplitudes of the converted
796 NICs are also multiplied by n times. The NICs transferred in mesoscale eddies by the interactions
797 between mesoscale eddies and NICs are stronger for higher translational speeds of anticyclonic
798 eddies. At the translational speeds of 11 cm s^{-1}, the ratios of the amplitudes of the converted NICs
799 by anticyclonic eddies to that transferred by cyclonic eddies reach maximum values.

800   For analytical considerations, the modified slab model was transferred from the time domain
801 to the frequency domain using the Fourier transform. Using Parseval's theorem, we derived the
802 time-mean value of the induced NICs. The analytical expression was used to demonstrate that, for
803 the negative relative vorticity, i.e., such as within an anticyclonic eddy, the transferred NICs are
804 larger in an anticyclonic eddy than a cyclonic eddy. The analytical solution under the cyclonic
805 winds also demonstrated that the NICs transferred by mesoscale eddies increase linearly with the

806 wind stress. These analytical results are consistent with the results produced by the modified and
807 original slab models.

808 We also conducted the same set of numerical experiments using steady winds in both constant
809 speeds and direction and model results in the steady winds are not presented here due to the page
810 limit. Our main findings on the energy transfer between mesoscale eddies and NICs in these
811 experiments with the steady winds are the same as the results using the rotating winds.

812 This study suggests that there is bidirectional energy transfer between mesoscale eddies and
813 NICs in the SML, of which the mechanism and influence factors are further explored by idealized
814 simulations. Our findings can further contribute to the understanding of the energy budget in the
815 global ocean and the ocean response to the climate change. In order to examine major physical
816 processes affecting the NICs generated by the mesoscale eddies and quantify their influence on
817 turbulent mixing in the deeper ocean, further studies are needed using a three-dimensional ocean
818 circulation model.

819 **Data availability**

820 All the data can be obtained by contacting the authors.

821 **Competing interests**

822 The authors declare that they have no conflict of interest.

823 **Acknowledgments**

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