# Kinematic characteristics and water mass transports of submesoscale coherent vortices in the northeastern South China Sea

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March 21, 2024

#### Abstract

As a unique phenomenon occurring in the subsurface ocean, submesoscale coherent vortices (SCVs) are believed to have a pivotal role in the long-distance ocean tracer transports. SCVs have been widely observed in the global oceans, however, most of them are captured accidentally and their kinematic characteristics and water mass transports have only been studied in a limited number of regions. Here, we use 4-year observations of velocity, temperature, and salinity from five moorings in the northeastern South China Sea (NESCS) to examine dozens of newly discovered SCVs. A total of 34 SCVs were identified during the observational period, including 25 convex lens-like anticyclones and 9 concave lens-like cyclones. The maximum swirl velocity, mean radius, and vertical length scale of the anticyclones (cyclones) are  $0.19\pm0.07$  m s<sup>-1</sup> ( $0.19\pm0.07$  m s<sup>-1</sup>),  $26.4\pm13.9$  km ( $17.0\pm5.4$  km), and  $204\pm62$  m ( $188\pm53$  m), respectively. Vertically, the velocity structure of the observed SCVs conforms to a Gaussian function when the effect of stratification is removed. Water mass analyses suggest that 88% (30/34) of the SCVs carried Kuroshio water, which demonstrates the mechanism proposed by Zhang et al. (2022) that they are formed by Kuroshio-islands interactions within the Luzon Strait. This category of SCVs is therefore named Luzon Strait island wake eddies (Liddies). We further estimate that Liddies can result in an equivalent annual-mean volume transport of 0.20 Sv westward across the Luzon Strait, which suggests that they play a nonnegligible role in the subsurface water transports between the NESCS and the northwestern Pacific.

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14	Key points
15	1. Dozens of submesoscale coherent vortices (SCVs) are observed at moorings in the
16	northeastern South China Sea based on a mooring array
17	2. The kinematic characteristics of the SCVs are statistically analyzed
18	3. Water mass transports induced by the SCVs are quantified
19	

20 Abstract

As a unique phenomenon occurring in the subsurface ocean, submesoscale 21 22 coherent vortices (SCVs) are believed to have a pivotal role in the long-distance ocean tracer transports. SCVs have been widely observed in the global oceans, 23 24 however, most of them are captured accidentally and their kinematic characteristics and water mass transports have only been studied in a limited number of regions. 25 Here, we use 4-year observations of velocity, temperature, and salinity from five 26 27 moorings in the northeastern South China Sea (NESCS) to examine dozens of newly 28 discovered SCVs. A total of 34 SCVs were identified during the observational period, including 25 convex lens-like anticyclones and 9 concave lens-like cyclones. The 29 30 maximum swirl velocity, mean radius, and vertical length scale of the anticyclones (cyclones) are  $0.19\pm0.07 \text{ m s}^{-1}$  (0.19±0.07 m s<sup>-1</sup>), 26.4±13.9 km (17.0±5.4 km), and 31 204±62 m (188±53 m), respectively. Vertically, the velocity structure of the observed 32 SCVs conforms to a Gaussian function when the effect of stratification is removed. 33 34 Water mass analyses suggest that 88% (30/34) of the SCVs carried Kuroshio water, 35 which demonstrates the mechanism proposed by Zhang et al. (2022) that they are formed by Kuroshio-islands interactions within the Luzon Strait. This category of 36 SCVs is therefore named Luzon Strait island wake eddies (Liddies). We further 37 estimate that Liddies can result in an equivalent annual-mean volume transport of 38 0.20 Sv westward across the Luzon Strait, which suggests that they play a 39 40 nonnegligible role in the subsurface water transports between the NESCS and the northwestern Pacific. 41

#### 43 Plain Language Summary

Submesoscale coherent vortices (SCVs) are unique anticyclonic or cyclonic 44 eddies which occur in subsurface oceans. SCVs have the capability to transport water 45 for long distances, and therefore, they may play a significant part in tracer transports 46 47 of the subsurface ocean. Nevertheless, because of the paucity of long-term in situ SCV observations, their statistical kinematic characteristics and water mass transports 48 are still poorly quantified. Here, based on 4-year velocity and temperature/salinity 49 measurements of five moorings in the northeastern South China Sea (NESCS), 34 50 51 SCVs are identified, 9 of which are cyclones, and the rest are anticyclones, and their statistical kinematic characteristics (e.g., maximum swirl velocity, radius, and vertical 52 length scale, etc.) are revealed. The swirl velocity structures of SCVs in vertical share 53 54 a uniform Gaussian. We also find that ~90% of the observed SCVs contained water from the Kuroshio current, demonstrating the mechanism of Kuroshio-islands 55 interactions in the Luzon Strait which generate SCVs. These SCVs can lead to 56 significant westward volume transport through the Luzon Strait into the NESCS, 57 suggesting that SCVs play a nonnegligible role in NESCS-northwestern Pacific 58 59 subsurface water exchange and thus have potential impacts on marine ecosystems and biogeochemical cycles. 60

#### 62 1. Introduction

The upper mixed layer of the ocean is abundant with submesoscale processes 63 64 that have spatial scales of O(1-10) km and temporal scales of O(1-10) days with O(1)Rossby and Burger numbers (McWilliams, 2016; Taylor and Thompson, 2023). In 65 addition to those in the upper mixed layer, a unique submesoscale phenomenon called 66 submesoscale coherent vortices (SCVs) can occur within or beneath the thermocline 67 (McWilliams, 1985). SCVs typically have much longer lifespans (sometimes up to 68 years) than the upper-layer submesoscale processes due to the absence of external 69 70 forcing and thus weak dissipation in the ocean interior. As a result, SCVs can transport source water hundreds to thousands of kilometers away from their origins, 71 which is likely to have a significant impact on subsurface tracer transports (Bosse et 72 73 al., 2017; Bower et al., 2013; Collins et al., 2013; Frenger et al., 2018; Li et al., 2017; Pelland et al., 2013; Richardson et al., 1989; Zhang et al., 2015). 74

In order to provide readers with a more intuitive understanding of SCVs, we 75 76 show the composite three-dimensional structures of SCVs identified in the northeastern South China Sea (NESCS) in Figure 1. As we can see, SCVs have weak 77 78 expressions at the sea surface and their horizontal scales are smaller than the first baroclinic Rossby deformation radius. This makes them difficult to be investigated by 79 traditional satellite and in situ observations as applied to surface-intensified mesoscale 80 eddies (Adams et al., 2017; Zhang et al., 2016, 2021). Till to now, most of the 81 reported SCVs were discovered by accident from shipboard profiles of 82 Conductivity-Temperature-Depth (CTD) and Acoustic Doppler Current Profiler 83

84 (ADCP), moorings, and subsurface floats. In addition, SCVs have only been systematically studied in a few certain regions, for instance, the Mediterranean Water 85 86 eddies (Meddies) of North Atlantic (Bashmachnikov et al., 2015; Bower et al., 1997; McDowell & Rossby, 1978; Richardson et al., 1991), the California Undercurrent 87 eddies (Cuddies) of northeastern Pacific (Collins et al., 2013; Garfield et al., 1999: 88 Pelland et al., 2013; Steinberg et al., 2019; Torres et al., 2017), and the Kuroshio 89 Extension region intermediate-layer eddies (Kiddies) of northwestern Pacific (NWP; 90 Li et al., 2017; Zhang et al., 2015; Zhu et al., 2021). The ever-increasing utilization of 91 92 Argo float profiles has further revealed that SCVs widely exist in the world ocean (McCoy et al., 2020). However, statistically robust kinematic characteristics and 93 water mass transports of SCVs on the global scope remain unknown (Gula et al., 94 95 2021).

The South China Sea (SCS) is abundant with energetic multiscale dynamic 96 processes due to complex forcing factors such as a strong Asian monsoon, 97 98 complicated topography, and Kuroshio intrusions (see Sun et al., 2022 and references therein). Basin-scale circulation, mesoscale eddies, small-scale internal waves, and 99 100 microscale turbulent mixing in the SCS have all been extensively studied, but it is 101 only recently that submesoscale processes have been explored thanks to improved resolution of in situ observations and numerical simulations (e.g., Cao et al., 2019; 102 Dong et al., 2022; Dong and Zhong, 2018; Lin et al., 2020; Song et al., 2022; Zhang 103 et al., 2016, 2020; Zhong et al., 2017). However, most previous efforts only 104 considered submesoscale processes in the upper mixed layer, and the knowledge of 105

106 SCVs in the SCS is still lacking.

Based on observations of concurrent velocity, temperature, and salinity data from 107 108 a high-resolution mooring array in the NESCS, the recent research in Zhang et al. (2022) discovered a pair of opposite-polarity SCVs for the first time. One of these 109 SCVs had trapped Kuroshio water, and it was proposed that it was formed by 110 111 Kuroshio-islands interactions within the Luzon Strait. In addition, it was also suggested that when a SCV migrates across a mooring site, it can be properly 112 identified using time series data from moored velocity and temperature/salinity (T/S) 113 114 profiles. We here further expand on Zhang et al. (2022) by conducting broader investigations of the kinematic characteristics and water mass transports of SCVs in 115 the NESCS, with the help of 4-year-long observations from a mesoscale-resolving 116 117 mooring array west of the Luzon Strait (Sun et al., 2020, 2022). The remaining part of this paper proceeds as follows. Section 2 introduces the data and methods. Section 3 118 presents the kinematic characteristics of SCVs containing a description of two SCV 119 cases, the SCVs' vertical structure, and statistical characteristics of SCVs' kinematic 120 parameters. Section 4 shows the SCVs' water mass properties, origin, generation 121 122 mechanism and volume transports. At last, Section 5 gives the summary and discussions. 123

- 124 **2. Data and Methods**
- 125 **2.1. Moored data**

We use five moorings from a mooring array (denoted by NS1–NS5) west of
Luzon Strait to investigate SCVs (Figure 2). These five moorings were deployed

between June 2014 and June 2018 to study multiscale dynamic processes in the 128 NESCS and associated water exchange with the NWP (Sun et al., 2020, 2022), and 129 130 they are an important part of SCS mooring array system (Zhang et al., 2013). The moorings are located along 119.9 °E between latitude 19.45° to 21.96 °N with a mean 131 132 spacing of ~76 km. To measure the velocity and T/S profiles continuously in nearly 133 the full water column, each mooring is typically equipped with one upward- and one or two downward-looking 75 kHz ADCPs, several recording current meters with 134 135 CTDs below, and temperature chains (composed of dozens of temperature loggers and 136 several CTDs). Given that SCVs primarily occur in the upper 500 m, only moored data above 500 m are used here (Zhang et al., 2022). All of these instruments had a 137 time sampling interval of 3 min. The vertical sampling interval of the ADCPs was 16 138 139 m, and the vertical resolutions of temperature chains was generally 10 or 20 m and 50 m above and below ~450 m, respectively. Most moorings and their instruments 140 functioned well except for several occasional issues, including a malfunction of the 141 uppermost ADCP of NS2 in the first year and a loss of the temperature chain of NS4 142 in the third year. As to more detailed information about these moorings, see Tables 143 144 S1–S4 in the supporting material and Sun et al. (2020, 2022).

Data processing is similar to that of previous mooring-based researches (Sun et al., 2020, 2022). At first, the original velocity and temperature measurements with a temporal resolution of 3 min were averaged on an hourly basis. Then, the hourly data were linearly vertically interpolated onto a uniform grid with 5 m intervals. After that, all the moored time series were lowpass filtered (a fourth-order Butterworth filter)

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with a cut-off period of 2.5 days so that tidal and near-inertial signals were effectively removed. Finally, these sub-inertial data were further daily averaged.

In the upper 500 m, there are 3-4 CTDs mounted on the temperature chain of 152 each mooring, so the vertical resolution of salinity measurement is much coarser than 153 154 the temperature. For the SCVs' water mass analysis, the CTDs-derived T/S data were 155 processed using a different procedure, rather than the above method of the relatively sufficient temperature data. The NESCS has energetic tidal currents (especially 156 157 internal tides), so that the mooring instruments typically swing and thus one or two 158 T/S profiles per day within specific depth ranges can be obtained from each CTD. Under the assumption that T-S properties do not change within one day, we then 159 obtained daily T/S profiles at the potential density coordinate by interpolating the 160 161 original T/S data from all the CTDs at each mooring onto isopycnals from 22.0 to  $27.0\sigma_0$  at an interval of  $0.02\sigma_0$  (Sun et al., 2022). It should be noted that the 162 temperature and salinity used in the following are all referred as potential temperature 163 164 and practical salinity, respectively.

#### 165 **2.2. Other data**

We also employ concurrent 1/4° daily gridded altimeter data including sea surface height (SSH) and surface absolute geostrophic velocity to help study the generation and migration processes of SCVs (http://marine.copernicus.eu/). For the NESCS, previous studies have demonstrated that the altimeter data can well capture the Kuroshio intrusion (Nan et al., 2011; Sun et al., 2020; Zhang et al., 2017). In order to calculate the volume transport through Luzon Strait, the HYCOM reanalysis data is

also used here (http://www.hycom.org/dataserver/glb-analysis). The 1/12° daily 172 HYCOM reanalysis data contains 33 levels vertically from surface to 5500 m, 14 of 173 which are in the upper 500 m with a resolution of 10–100 m. In addition, the  $1/4^{\circ}$ 174 monthly and annual climatology of T/S data from the World Ocean Atlas 2018 175 (WOA18; Locarnini et al., 2019; Zweng et al., 2019) are analyzed in this study to 176 compare water mass properties of SCVs with those of Kuroshio water and NESCS 177 water and thus trace the origins of SCVs (https://www.nodc.noaa.gov/OC5/woa18/). 178

179

#### 2.3. SCVs identification criteria

180 Here, we introduce the criteria to help identify SCVs in the upper 500 m from the moored data. First, the stratification or vertical temperature gradient should be 181 enhanced for cyclones and decreased for anticyclones in the subsurface ocean. The 182 183 enhanced (decreased) stratification corresponds to convex (concave) lens-shaped thermal structures, which can be directly identified from depth-time distributions of 184 temperature. Second, vertical vortex core, defined as the location where the maximum 185 186 swirl velocity occurs vertically, should be beneath the main thermocline where the maximum stratification occurs. 187

188 Third, SCVs should have a significant isopycnic salinity anomaly  $(S_a)$  relative to the local water mass. For each specific SCV, its T/S profile is obtained by averaging 189 190 the T/S profiles on the isopycnals during the period when it went across the mooring. The T/S profiles of the local water mass are calculated using the WOA18 monthly 191 climatology at mooring site. Here, the  $|S_a|$  at the SCV's core should be greater than 192 0.03 psu, and the vertical thickness of  $|S_a| > 0.02$  psu should be larger than 100 m. The 193

194 criteria adopted here are similar to those of Zhu et al. (2021) which investigated SCVs 195 using moorings in the Kuroshio Extension region. In the following analysis, we 196 primarily focus on the 34 SCVs that simultaneously satisfy the above three criteria 197 unless otherwise specified.

#### 198 2.4. Methods to estimate kinematic parameters of SCVs

For each SCV, we assume that the swirl (azimuthal) velocity V within the vortex 199 maximum velocity circle obeys the theoretical distribution of a Rankine vortex (i.e., 200  $v(r) = V_0 \frac{r}{R}$  for  $r \le R$ ), and the migration speed  $U_m$  and direction  $\alpha$  are constant 201 when a SCV passes a certain mooring (i.e., its center moves straightly over the short 202 term). The SCV-induced velocity anomalies u' and v' (i.e., zonal and meridional 203 components) are derived through removing background current velocity defined as 204 205 the time average within 5 days before and after the observed SCV. Its maximum absolute velocity anomaly is taken as the maximum swirl velocity  $V_0$ , 206

207 
$$V_0 = \left(\sqrt{{u'}^2 + {v'}^2}\right)_{\max}$$
(1)

and *R* is defined as the radius where the maximum velocity occurs. The background current velocity and direction are approximately used to describe the migration speed  $U_m$  and direction angle  $\alpha$  (in relation to the due east direction corresponding to  $\alpha$  $= 0^\circ$ ) of SCV (Dewar and Meng, 1995; McWilliams, 1985). According to the Rankine vortex model, the nearest distance *d* from mooring to SCV's center is associated with the minimum swirl velocity, i.e.,  $d = \frac{V_{\min}}{V_0}R$ . Thus, the radius of SCV can be

214 calculated based on the daily swirl velocity ( $\Delta t = 1$  day) through

215 
$$R = \frac{U_m \Delta t V_0}{\sqrt{V^2 - V_{\min}^2}}$$
(2)

Then, the theoretical value of the Rankine vortex-derived azimuthal velocity can be further deduced using

218 
$$V = \frac{V_0 \sqrt{(U_m \Delta)^2 + {^2}d}}{R}$$
(3)

The core depth of SCV is defined as the depth that the maximum of  $V_0$  occurs, and the vertical length scale  $H_e$  of the SCV is defined as the depth range where the maximum of  $V_0$  is e-folded. More details of the methods can be found in Zhang et al. (2022).

# 222 **2.5.** Methods to estimate Rossby and Burger numbers of SCVs

After obtaining the above-mentioned kinematic parameters of SCVs, we can further estimate the Rossby number (*Ro*) of the SCVs using

$$Ro = \frac{2V_0}{fR} \tag{4}$$

where  $V_0$  and R are the maximum swirl velocity and radius of SCVs, respectively, and *f* is the local Coriolis parameter (e.g., Bosse et al., 2015). In addition, we can also estimate the Burger number (*Bu*) using

229 
$$Bu = \frac{N^2 H_e^2}{f^2 R^2}$$
(5)

where  $H_e$  is the vertical length scale of SCVs (see the method in Section 2.4) and *N* is the average buoyancy frequency within the SCVs (e.g., Dewar and Meng, 1995; Zhang et al., 2022).

# 233 **3. Kinematic Characteristics**

234 **3.1. Two cases of SCVs** 

235	Based on the methods in Section 2, we have identified a total of 34 SCVs
236	including 25 anticyclonic SCVs and 9 cyclonic SCVs from the moored data between
237	June 2014 and June 2018. The occurrence time and depth range of these SCVs are
238	shown schematically in Figure 3. In order to describe the characteristics of SCVs
239	more clearly, we first illustrate a respective example of anticyclonic and cyclonic
240	SCVs in Figure 4 and Figure 5. These two SCVs were captured by moorings NS4 and
241	NS2, respectively. The anticyclone (cyclone) is named A7 (C9) for short because it is
242	the 7th (9th) anticyclonic (cyclonic) SCV captured by the moorings in chronological
243	order. This naming method is also applied to all of the other SCVs.
244	It shows that A7 and C9 have convex and concave lens-shaped structures in the
245	depth-time plots of temperature, respectively. Corresponding to their lens-shaped
246	structures, both A7 and C9 have subsurface-intensified velocity anomalies. For the
247	anticyclone A7, the upper- and lower-boundary isotherms of the convex lens are 10
248	and 17 °C, and its stratification (denoted by vertical temperature gradient) is
249	significantly reduced. Concerning cyclone C9, the concave lens-like structure is
250	approximately located between 10 and 22 °C isotherms and the stratification is
251	markedly enhanced. From the depth-time plots of velocity anomalies, we see that both
252	u' and $v'$ of A7 change from positive to negative when it passes through the
253	mooring NS4 (Figures 4a and 4b), while the opposite is true when C9 passes through
254	the mooring NS2 (Figures 5a and 5b). According to the polarities of A7 and C9, we
255	can infer that both SCVs migrated northwestward when they were observed by the
256	moorings. The above migration direction is consistent with the direction $\alpha$ of the

background currents (i.e., 158° for A7 and 152° for C9). This consistency can be
found for all of the identified SCVs which further demonstrates that migration of
SCVs is mainly caused by the advection of background currents (Dewar and Meng,
1995; McWilliams, 1985).

For A7 (C9), the maximum velocity anomaly  $V_0$  reaches 0.27 m s<sup>-1</sup> (0.25 m s<sup>-1</sup>) 261 at 260 m (235 m) beneath the main thermocline, whose depth is roughly 100 m. At the 262 core depths of A7 and C9, their observed swirl velocities are in good agreement with 263 those calculated based on the Rankine vortex model (Figures 4d and 5d), 264 265 demonstrating the assumption of Rankine vortex applied to our parameter estimation methods. It is estimated that the radius R of A7 (C9) is  $48\pm6$  km (27 $\pm6$  km), and both 266 of them are less than radius of O(100) km for typical mesoscale eddies observed in 267 268 the NESCS (Chen et al., 2011). The vertical length scale  $H_e$  and averaged buoyancy frequency N of A7 (C9) reaches 235 m and  $7.6 \times 10^{-3}$  s<sup>-1</sup> (275 m and  $1.2 \times 10^{-2}$  s<sup>-1</sup>), 269 respectively. On the basis of above parameters, for A7 (C9), the Rossby number Ro is 270 estimated to be -0.22 (0.35), while the Burger number Bu is estimated to be 0.55 271 (5.16). All the above parameters of A7 and C9 are generally within the scope of 272 previous descriptions of SCVs (e.g., Li et al., 2017; McWilliams, 1985). Noted that 273 the basic characteristics of A7 and C9 described here are common to all of the other 274 identified SCVs and two other examines can be found in supplementary Figures S1 275 and S2. 276

277 **3.2. Vertical structure of SCVs** 

In Figure 6a, we show vertical profiles of swirl velocity for all the 34 SCVs as a

function of relative vertical distance to the vortex core (i.e.,  $z' = z - z_0$ , where  $z_0$  is 279 the depth of the vortex core). For each SCV, the profile of its maximum daily swirl 280 velocity is analyzed here. It shows that SCVs' maximum swirl velocities are generally 281 between 0.1–0.3 m s<sup>-1</sup> and their vertical length scales are between 130–280 m. At first 282 283 glance, the vertical structure of swirl velocity varies substantially for different SCVs. Under the influence of depth-dependent stratification, the swirl velocity above the 284 core depth generally decreases more rapidly with distance than that below the core 285 depth. 286

287 In order to investigate whether the SCVs share a uniform vertical structure in terms of swirl velocity, for each SCV, we normalize the swirl velocity profile by 288 dividing its maximum (i.e.,  $V_0$ ) and project it onto the stretched coordinate 289  $z_s = \int_0^{z'} \overline{N}(z') / f dz'$  according to Flierl (1987) and Z.-G. Zhang et al. (2017). Here, 290  $\overline{N}$  is the time-mean stratification during the period of each SCV. Given that SCVs 291 have different vertical length scales, the stretched coordinate of each SCV is further 292 293 normalized by dividing the corresponding e-folding vertical scale H (i.e.,  $H_e/2$  in the stretched coordinate). In Figure 6b, we show all profiles of the normalized swirl 294 velocity  $V_n$  in the normalized stretched coordinate  $z_n$ . The results clearly show that 295  $V_n(z_s)$  of the SCVs have a uniform vertical structure that shapes like a Gaussian 296 function. This is further verified by the very close distribution between the average 297 profile of  $V_n(z_s)$  and the Gaussian function  $\exp(-z_n^2)$ . 298

#### 299 3.3. Statistical characteristics of SCVs

300 Latitudinal and seasonal distributions of the number of SCVs are shown in

Figures 7a and 7b, respectively. It shows that SCVs are more likely to go across the 301 central and northern parts of the mooring section. For example, eleven SCVs are 302 303 being captured at NS1 (i.e., the northernmost mooring) while the number is only one at NS5 (i.e., the southernmost mooring). In addition, both anticyclonic and cyclonic 304 305 SCVs have notable seasonal variations. Specifically, the number of cyclonic SCVs is largest in autumn but smallest in winter, while for anticyclonic SCVs the minimum 306 occurs in summer. If we consider the sum of anticyclonic and cyclonic SCVs, they 307 have the lowest occurrence possibility in summer. As will be discussed in Section 4, 308 309 the above latitudinal and seasonal variations of SCVs are closely associated with their generation and migration processes, which significantly depend on the state of 310 background currents. 311

312 The statistical distributions of SCVs' other kinematic parameters including their core depth, vertical length scale (i.e.,  $H_e$ ), radius (i.e., R), maximum swirl velocity 313 (i.e.,  $V_0$ ), Rossby number (i.e.,  $R_0$ ), and Burger number (i.e.,  $B_u$ ) are shown in Figures 314 8a-8f, respectively. The detailed information of each SCV including its location, 315 observation data, and different parameters of anticyclones and cyclones can be found 316 in Tables S5 and S6, respectively. The majority of SCVs' core depths are located at 317 150-300 m, especially concentrated between 200-250 m. The core depths of 318 anticyclonic SCVs are distributed over a relatively wide range than cyclonic SCVs. 319 For the anticyclonic SCVs, ~80% of the estimated  $H_e$  and R values are between 320 321 130-280 m and 9-38 km, respectively, and their respective mean (median) values are 204±62 m and 26.4±13.9 km (220 m and 19.6 km). Concerning cyclonic SCVs, their 322

mean (median) values of  $H_e$  and R are estimated to be  $188\pm53$  m and  $17.0\pm5.4$  km (230 m and 16.4 km), respectively. These estimations suggest that in general the anticyclones are larger than cyclones; both anticyclones and cyclones are much smaller than the first baroclinic Rossby deformation radius and typical mesoscale eddies in the NESCS (Chelton et al., 1998; Chen et al., 2011; Zhang et al., 2016).

The maximum swirl velocities (i.e.,  $V_0$ ) of ~80% anticyclonic and all cyclonic 328 SCVs are distributed between 0.1–0.3 m s<sup>-1</sup> (Figure 8d). The mean and median value 329 of  $V_0$  for anticyclones (cyclones) are 0.19±0.07 and 0.18 m s<sup>-1</sup> (0.19±0.07 and 0.16 m 330  $s^{-1}$ ), respectively. The statistical results also reveal that cyclones have larger Ro and 331 Bu than anticyclones. Specifically, all the Ro (Bu) values for cyclones exceed 0.25 332 (1.8), while the percentage is only 60% for anticyclones. The mean (median) Ro 333 334 values for cyclones and anticyclones are  $0.45\pm0.18$  and  $-0.39\pm0.27$  (0.42 and -0.28), respectively. With respect to the mean (median) Bu values, they are  $4.25\pm2.12$  and 335 3.62±3.31 (4.21 and 2.21) for cyclones and anticyclones, respectively. The finite to 336 337 order one Ro and Bu of SCVs further demonstrate that they are indeed classified as submesoscale processes in dynamics. 338

Based on the kinematic parameters of SCVs, we further estimate the water volume trapped in the SCVs with the assumption that a SCV can trap the whole water mass within its vortex core (i.e., maximum velocity radius within its vertical length scale) during the migration. Given that the SCV's vertical structure exhibits a Gaussian function distribution, the volume of SCV can be obtained by:

344 
$$Vol = \pi R^2 \int_{-H_e/2}^{H_e/2} \exp\left[-\frac{2z^2}{\left(H_e/2\right)^2}\right] dz = \left(\frac{\pi}{2}\right)^{\frac{3}{2}} H_e R^2 erf\left(\sqrt{2}\right) \approx 1.96 H_e R^2 \tag{6}$$

where *erf* is the error function. The results show that the water volumes trapped by anticyclones  $(Vol_{AE})$  and cyclones  $(Vol_{CE})$  are on average  $3.4\pm3.3\times10^{11}$  m<sup>3</sup> and  $1.3\pm1.1\times10^{11}$  m<sup>3</sup>, respectively. The above estimations are overall in order of magnitude agreement with those of Meddies (Bashmachnikov et al., 2015) and Kiddies (Li et al., 2017). Note that the  $Vol_{AE}$  is 180% larger than the  $Vol_{CE}$ , which is due to the much larger radii of anticyclones than cyclones.

#### 351 **4. Water Mass Transports by SCVs**

#### 352 **4.1. Water mass properties of SCVs**

Because SCVs can conserve the original water properties over a long transport 353 distance, properties of the water mass trapped in SCVs are theoretically different from 354 355 the surrounding water if they originated from nonlocal regions. To help investigate the origins of SCVs and then quantify their water mass transport, we first characterize 356 their T-S properties here. According to Zhang et al. (2022), the SCVs observed by the 357 moorings can be generated both in the NESCS and in the Luzon Strait. Therefore, we 358 compare the T-S diagrams of SCVs with those of the NESCS water, the Kuroshio 359 water, and the local water at the mooring sites. Here, T-S diagrams of SCVs are 360 obtained from mooring CTDs derived T/S profiles within the SCVs (Zhang et al., 361 2022); Based on WOA18 monthly climatology, T-S diagram of Kuroshio (NESCS) is 362 computed within the eastern (western) red squares of Figure 2, while that of local 363 364 waters is computed at mooring sites.

365

As shown in Figure 9, the Kuroshio water is much saltier and warmer than the

NESCS water in the upper layer above ~350 m. For the Kuroshio water, its maximum 366 salinity reaches 34.85, while it is only 34.65 for the NESCS water. Because the 367 368 moorings are just west of Luzon Strait, the local water's T-S properties are between Kuroshio and NESCS waters. Through comparisons of T-S diagrams, we find that the 369 370 identified 34 SCVs can be divided into two major categories according to their T-S properties (Figure 9). One category is that T-S properties of SCVs are closer to 371 Kuroshio water and warmer and saltier than local water. The other category is the 372 opposite, i.e., the T-S properties of SCVs are closer to NESCS water and lower and 373 374 fresher than local water. For all of the 34 SCVs, 84% of the anticyclones (i.e., 21/25) and 100% of the cyclones (i.e., 9/9) trap water mass close to the Kuroshio water. This 375 result suggests that 88% (i.e., 30/34) of these SCVs trap Kuroshio water and their 376 377 generations must be closely associated with the Kuroshio. Given that only the SCVs trapping Kuroshio water can contribute to NESCS-NWP subsurface water mass 378 transports, we will primarily focus on this major category of SCVs (i.e., the first 379 category) in the following analysis. 380

381

#### 4.2. Origin and generation of SCVs

After SCVs are generated, they migrate under the advection of background currents with their water properties being to a large degree conserved (McWilliams, 1985). Based on this truth, we can roughly infer the origin of each SCV by tracing the salinity within its core along isopycnal surface by combing the WOA18 monthly climatology (e.g., Zhang et al., 2015). Similar to the anticyclonic SCV reported in Zhang et al. (2022), the results of water mass tracing reveal that the origins of 30

SCVs trapping Kuroshio water (i.e., the first category) are most likely to locate in the 388 southern Luzon Strait. In order to verify this point, we further examine the spatial 389 distributions of altimeter-derived SSH and surface geostrophic currents during the 390 periods when and before each specific SCV was observed by the mooring. We find 391 392 that for all of the 30 SCVs, the Kuroshio evidently intruded into the NESCS when and (up to one month) before the SCVs were observed, in the form of either a leaking path 393 or looping path (Figure 10 and Figures S3–S6). The Kuroshio went through southern 394 Luzon Strait (specifically, Babuyan Islands) and its main axis or branch directly 395 396 extended to the mooring that captured a SCV. This is in great contrast to the leaping path of Kuroshio, during which period no SCVs were observed (Figures 10g-10i). 397 The patterns of Kuroshio intrusion further demonstrate that these SCVs trapping 398 399 Kuroshio water are generated near the Babuyan Islands (recall Figure 2).

The above SCVs' T-S characteristics and generation sites are very similar to the 400 anticyclonic SCV reported by Zhang et al. (2022). Therefore, we think these SCVs are 401 402 also generated through interactions between Kuroshio and the complex topography of the Babuyan Islands. This generation mechanism (i.e., current-topography interaction) 403 which feeds SCVs through horizontal shear instability of background currents 404 (vorticity generated by frictional effects) is actually believed as one of the major 405 generation mechanisms in the ocean (e.g., D'Asaro, 1988; Gula et al., 2019; 406 Molemaker et al., 2015; Srinivasan et al., 2019). Different from the observation of 407 408 Zhang et al. (2022), however, we propose that both anticyclones and cyclones are able to be formed during the interaction between Kuroshio and Babuyan Islands. In the 409

410 Kuroshio flowing direction, anticyclones (cyclones) are generated on the left (right) side of the island, which produces anticyclonic (cyclonic) shear due to topographic 411 412 frictions (Figure 11b). In such generation process, the anticyclones southwest of the island (i.e., left side) are more likely to migrate into the NESCS by the intruding 413 414 Kuroshio while the cyclones on the opposite side tend to be advected into NWP by the 415 northward flowing branch of the Kuroshio. This partly explains why there are more anticyclones than cyclones being captured by the moorings. In addition, the smaller 416 scale of cyclones than anticyclones means that they are more difficult to be captured 417 418 by moorings, which provides another potential explanation for the polarity skewness observed here (Zhang et al., 2022). Given that this category of SCVs commonly 419 420 occurs in the wake of islands in the Luzon Strait, we propose to name them Luzon 421 Strait island wake eddies, i.e., Liddies for short.

422

#### 4.3. Volume transports by SCVs

Given that the space between two neighbor moorings (i.e., the mean distance of 423 424 76 km) is larger than the radius of the SCVs, in addition to the identified 30 Liddies that transport Kuroshio water into the NESCS, there should be some similar SCVs 425 426 (i.e., some additional Liddies) that had been missed by the moorings. In order to estimate the real westward volume transport caused by Liddies, we further estimate 427 the total number of Liddies that go across the mooring section. The kinematic 428 parameters of SCVs (Tables S5 and S6; Figure S7) reveal that all values of d/R are 429 less than 1/2 (the maximum ratio is 0.43; here, d is the nearest distance between the 430 mooring and the center of a SCV). According to this fact, we further assume that our 431

432 criteria in Section 2.3 can only identify the SCVs with  $d/R \le 1/2$ . Based on this 433 assumption, we can then estimate the total number of Liddies passing through the 434 mooring array from the perspective of probability and geometric relationship (see 435 Figure A1) using Equations 7 and 8,

436 
$$N_{AE} = \sum_{i=1}^{6} N_{AE}^{i} = \sum_{i=1}^{6} r \cos \beta / \overline{R}_{AE}^{i} \cdot n_{AE}^{i}$$
(7)

437 
$$N_{CE} = \sum_{i=1}^{6} N_{CE}^{i} = \sum_{i=1}^{6} r \cos \beta / \overline{R}_{CE}^{i} \cdot n_{CE}^{i}$$
(8)

Here, r=76 km is mean spacing of two neighboring moorings,  $\beta$ =35° is mean 438 439 migration angle of the identified Liddies relative to the westward direction (Figure A1),  $\overline{R}_{AE}^{i}$  ( $\overline{R}_{CE}^{i}$ ) is the mean radius of the identified anticyclonic (cyclonic) Liddies 440 in a certain radius range between 0 and 60 km with an interval of 10 km (e.g., i=1 and 441 *i*=6 mean the ranges of 0–10 km and 50–60 km, respectively), and  $n_{AE}^{i}$  ( $n_{CE}^{i}$ ) is the 442 number of the identified anticyclonic (cyclonic) Liddies within that radius range. So, 443  $r\cos\beta=62.4$  km is defined as "effective distance" of two neighboring moorings 444 perpendicular to mean migration direction of Liddies (Figure A1). Taking the above 445 parameters into Equations 7 and 8, we finally conclude that there is a total of 59 446 447 anticyclonic and 35 cyclonic Liddies that had migrated across the mooring section during the ~4 years observation period. 448

Based on the total number of Liddies mentioned above, we further estimate the
equivalent annual-mean westward volume transport caused by Liddies using

451 
$$Transport = \left(\overline{Vol_{AE}} \cdot N_{AE} + \overline{Vol_{CE}} \cdot N_{CE}\right) / \Delta t$$
(9)

452 where  $\overline{Vol}_{AE}$  ( $\overline{Vol}_{CE}$ ) is the volume of anticyclonic (cyclonic) SCVs and  $\Delta t = 4$ 

years is the entire observation duration. So, the total volume transport by the Liddies 453 is estimated to be 0.20 Sv (1 Sv equals  $10^6$  m<sup>3</sup> s<sup>-1</sup>). Based on the concurrent  $1/12^\circ$ 454 455 HYCOM reanalysis data, mean volume transport across the Luzon Strait (i.e., the 120.8°E section between Luzon and Taiwan Islands) between 100-400 m, i.e., the 456 layer of SCVs, is estimated to be 3.31 Sv. This result means that the Liddies-induced 457 westward volume transport accounts for 6.0% of the Luzon Strait transport in the 458 subsurface layer between 100-400 m, which suggests that Liddies play a 459 460 nonnegligible role in the NESCS-NWP subsurface water transports.

461

# 5. Summary and Discussions

Using concurrent velocity, temperature, and salinity observations from five 462 moorings between June 2014 and June 2018, we have identified 34 SCVs including 463 464 25 anticyclones and 9 cyclones west of Luzon Strait in the NESCS. The core depths of SCVs' are generally located at between 150-300 m depths and they tend to more 465 frequently occur in the central and northern part of the mooring section west of Luzon 466 467 Strait. Seasonally, the SCVs have the lowest occurrence frequency in summer than other seasons. For anticyclonic (cyclonic) SCVs, their mean radius, maximum swirl 468 velocity, vertical length scale, Rossby number, and Burger number are calculated to 469 be 26.4 $\pm$ 13.9 km (17.0 $\pm$ 5.4 km), 0.19 $\pm$ 0.07 m s<sup>-1</sup> (0.19 $\pm$ 0.07 m s<sup>-1</sup>), 204 $\pm$ 62 m 470 (188±53 m), -0.39±0.27 (0.45±0.18), and 3.62±3.31 (4.25±2.12), respectively. The 471 smaller scale compared with the first baroclinic Rossby deformation radius and the 472 473 Rossby and Burger numbers from finite to order one demonstrate that the SCVs observed here are in the category of submesoscale processes in dynamics. In addition, 474

475 we find that the swirl velocities of SCVs conform to the Gaussian function in the 476 vertical direction in stretching coordinates (i.e., removing the influence of 477 stratification).

Water mass analysis suggests that 30 SCVs trap water mass close to Kuroshio 478 479 water and only 4 anticyclonic SCVs trap the NESCS water. Through the combination of water mass tracing on isopycnal surface and distributions of background 480 circulations, we demonstrate the SCVs trapping Kuroshio water are generated in the 481 wakes of Babuyan Islands (within southern Luzon Strait) and their generation 482 483 mechanism is Kuroshio-islands interactions as proposed by Zhang et al. (2022). Given the common origin and generation mechanism of this kind of SCVs, we term them as 484 the Luzon Strait island wake eddies, Liddies for short. From the perspective of 485 486 probability and geometry when SCVs migrate across the mooring section, we estimate that during the 4-year observation period, there are another 64 Liddies that should 487 have entered the NESCS but have been missed by the moorings and identification 488 criteria. If all of these Liddies are considered, they can result in an equivalent 489 annual-mean volume transport of 0.20 Sv westward into the NESCS, which accounts 490 491 for 6.0% of the Luzon Strait transport in the subsurface layer between 100-400 m.

Given the considerable westward volume transports by Liddies, their generations and migrations provide a novel route for the Pacific water to enter the NESCS. Because the Kuroshio water and thus the tracers trapped in the SCVs are more conserved than those associated with the Kuroshio intrusion itself, the Liddies may play a unique and potentially important role in modulating the biogeochemical

processes in the NESCS, which should be taken into account in future studies. In 497 addition to the Liddies reported here, given the strong circulation and mesoscale 498 and complex topography in the SCS, SCVs generated through 499 eddies current-topography interaction should commonly exist in the SCS, which needs to be 500 501 confirmed using more high-resolution targeted observations. Finally, generations of SCVs through Kuroshio-islands interactions provide an efficient route of direct 502 energy cascade for the Kuroshio. Note that similar SCVs' generation processes have 503 also been observed in other western boundary currents (Gula et al., 2019; Lazaneo et 504 505 al., 2022). Given this, SCVs may play an important role in the dissipation of western boundary currents, which need to be evaluated in the future. 506

#### 507 Acknowledgement

This study is jointly supported by the National Natural Science Foundation of China (42222601, 92258301, 42076004) and the 2022 Research Program of Sanya Yazhou Bay Science and Technology City (SKJC-2022-01-001). Z. Zhang is also supported by the "Taishan" Talents program (tsqn202103032) and Shandong Provincial Natural Science Foundation (ZR2023JQ013).

513 **Data** 

# Data Availability Statement

The moored data analyzed in this study can be obtained online at https://doi.org/10.7910/DVN/4YCNW3. The gridded altimeter data, HYCOM reanalysis data, and monthly and annual WOA18 climatology can be downloaded from http://marine.copernicus.eu/, http://www.hycom.org/dataserver/glb-analysis, and https://www.nodc.noaa.gov/OC5/woa18/, respectively.

# Appendix A: The geometric relationship for the estimation of the total number of Liddies passing through the mooring array.

In the following, we use a schematic diagram to display the geometric 521 relationship for the estimation of the total number of Liddies passing through the 522 mooring array. Without loss of generality, we choose two neighboring moorings along 523 the mooring section (119.9 °E) to demonstrate the geometric relationship between 524 their spacing (r, i.e.,  $\sim$ 76 km) and the radius (R) of a SCV. The SCV's radius, 525 migration direction, and effective distance  $(r\cos\beta)$  used in Section 4.3 are also shown 526 in Figure A1. It's important to note that we assume that the morrings only capture the 527 528 SCVs with  $d/R \le 1/2$ .





Figure A1. Schematic diagram of a SCV entering the NESCS through the mooring gap. Here, blue stars denote the moorings, *r* represents spacing of two neighboring moorings,  $\beta$  indicates migration angle of SCV, *R* is SCV's radius, and 1/2*R* is the critical value when the SCV can be identified by our criteria in Section 2.3. The north direction is marked in the upper right corner.

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# 695 Figures



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**Figure 1.** Three-dimensional structures of (a) anticyclonic and (b) cyclonic SCVs in the northeastern South China Sea (NESCS) reproduced using the MITgcm LLC4320 simulation. Shading and gray arrows denote the Rossby number (i.e., normalized relative vorticity or  $\zeta/f$ ) and velocity vectors, respectively. Black thick lines denote the contours of the Rossby number with an interval of 0.2, among which the zero and ±0.2 are indicated using thin black lines and thick red lines, respectively.



**Figure 2.** Bathymetry (color shading) and NS1–NS5 moorings location (red pentagrams) in the NESCS. Gray vectors denote the mean altimeter absolute geostrophic velocities from 2014 to 2018. Two red squares from west to east denote the regions used for characterizing background T-S properties of NESCS water (118.0°–119.5°E, 20.0°–21.5°N) and Kuroshio water (121.0°–123.0°E, 19.0°–21.0°N), respectively. Black lines indicate the 200 m, 1000 m, 2000 m, and 3000 m isobaths.



**Figure 3.** The occurrence time and depth range of SCVs observed at the moorings (a)

from July 2014 to June 2016 and (b) from July 2016 to June 2018. The blue (red)
ellipses represent the anticyclones (cyclones). Core depths of anticyclones (cyclones)
are indicated using blue (red) solid circles. 4 SCV cases presented in the main text and
online supplemental material are marked using black inverted triangles.



Figure 4. (a–c) Depth-time plots of zonal and meridional velocity anomalies and vertical temperature gradient at mooring NS4 during the period of the 7th anticyclonic SCV (30 January to 17 February 2016). Black thin lines indicate temperature isolines with an interval of 1 °C, and three black thick lines are the 10, 13, and 17 °C isotherms. (d) Comparison of the NS4-observed absolute velocity anomalies of the anticyclone (red dots) and the azimuthal velocities derived from Rankine vortex (blue dots; see the method in Section 2.4).



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Figure 5. Same as Figure 4 but for the 9th cyclonic SCV (19 September to 1 October

2017) observed at mooring NS2. And three thick lines are the 10, 15, and 22 °C
isotherms.



Figure 6. (a) Vertical profiles of swirl velocity for all SCVs as a function of relative 734 vertical distance to the vortex core depth. Different SCVs are denoted using different 735 736 colored lines. The two dots in each line show the e-folding vertical scale of each SCV. Thin black dashed lines indicate the velocities outside the e-folding scales. (b) 737 Vertical profiles of normalized absolute velocity anomaly in normalized stretched 738 coordinates  $z_n$  (i.e.,  $z_s/H$ ). Blue thin solid lines denote the results of all observed 739 SCVs, while blue thick dashed line denotes mean result of them. Red thick solid line 740 denotes the fitting result of a Gaussian function (i.e.,  $V_n = \exp(-z_n^2)$ ). 741



**Figure 7.** Statistical results of (a) the number of SCVs passing through different moorings and (b) the number of SCVs' occurrences in different seasons. The latitudes of the corresponding moorings are marked. The blue and red bars indicate anticyclonic and cyclonic SCVs, respectively.



Figure 8. Same with Figure 7 but for other parameters of SCVs including (a) core depth, (b) vertical length scale  $H_e$ , (c) radius R, (d) maximum swirl velocity  $V_0$ , (e) Rossby number Ro, and (f) Burger number Bu. The x-label value represents the number of SCVs within the corresponding interval range around a center value (e.g., 225 in Figure 8a represents the number of SCVs with a core depth between 200–250 m). Blue and red bars denote anticyclonic and cyclonic SCVs, respectively.



**Figure 9.** Mean T-S diagrams of water mass within and outside of the SCVs. Blue and red lines show the results within the SCVs that trap NESCS and Kuroshio waters, respectively. Shadings denote the standard deviations of the T/S. Black and gray lines show the results of the NESCS water and the Kuroshio water, respectively. The green dashed line shows the averaged T-S curve of local water at mooring sites. Dots on each T-S curve denote depths counted from 50 m at an interval of 50 m. Gray dashed lines show the isopycnals from 22.5 to  $26.5 \sigma_0$  at an interval of  $0.5 \sigma_0$ .



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765 Figure 10. (a-c) Maps of altimeter-derived SSH and geostrophic currents in the NESCS on the 20th day before, the 10th day before, and on the day the 2nd 766 anticyclonic SCV was captured by the NS3 mooring, respectively. Black lines denote 767 112 and 115 cm SSH isolines that are defined as the Kuroshio axes. The brown 768 vectors indicate surface geostrophic velocities whose magnitudes exceed 0.3 m s<sup>-1</sup>. 769 Purple stars denote mooring locations that observed SCVs. (d-f) and (g-i) are the 770 same as (a–c) but for the situations where the 6th cyclonic SCV was captured by the 771 NS1 mooring and no SCVs were captured, respectively. And black lines in (d-f) 772 denote 110 and 113 cm SSH isolines, while those in (g-i) denote 121 and 124 cm 773 SSH isolines. The date of each panel is marked in the lower left corner. 774



Figure 11. (a) The schematic diagram of generation process of Liddies through 777 Kuroshio-islands interactions. The red solid curve and the purple dashed curve 778 779 represent the Kuroshio intrusion including a looping path and a leaking path, respectively. The black solid and dash circles represent anticyclonic and cyclonic 780 SCVs, respectively. (b) Zoom in the blue dashed square in (a), i.e., the region near the 781 Babuyan Islands. Red arrows denote the Kuroshio current near the Babuyan Islands. 782 The circles with blue negative and red positive signs represent anticyclonic and 783 cyclonic SCVs, respectively. 784