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Key Points:
- Submesoscale spiral chlorophyll bands of oceanic mesoscale eddies emerge globally
- Spiral chlorophyll bands of oceanic eddies share a series of common features with spiral rain bands of atmospheric tropical cyclones
- The spiral bands are footprints of the vertical motions induced by vortex Rossby waves embedded in eddies

Supporting Information:
- Supporting Information S1

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Abstract Oceanic submesoscale processes (with scales ~1–10 km and approximately days) have been progressively recognized as an important upwelling mechanism to close the upper ocean nutrient budget and sustain the primary production in euphotic layer. Spiral band is one of the most typical submesoscale structures of mesoscale eddies, characterized with enhancement of surface chlorophyll concentration. By combining satellite ocean-color, satellite-altimetry, and surface drifter data, we find that the oceanic spiral chlorophyll bands emerge globally and share a series of structural and kinematic features with atmospheric spiral rain bands of tropical cyclones, which indicate that they are footprints of the vertical motions induced by vortex Rossby waves embedded in eddies. As vortex Rossby waves are closely related to eddy evolution under background deformation, further observational analysis indicates that an intense eddy energy variation and a strong background deformation field constitute the favorable conditions for the emergence of the spiral chlorophyll bands.

Plain Language Summary Oceanic mesoscale eddies are energetic vortices with radius ranging from tens to hundreds of kilometers. Spiral band (with scales ~1–10 km and approximately days) is a common submesoscale feature of mesoscale eddies, characterized by enhanced surface chlorophyll concentrations. This submesoscale process serves as an important upwelling mechanism to close the upper ocean nutrient budget and sustain the primary production of phytoplankton in euphotic layer, but their dynamical origin is not fully understood so far. In this study, we combine global satellite ocean-color data, ocean surface drifter measurements, and satellite altimeter data to demonstrate that the spiral bands are footprints of wave motions embedded in oceanic eddies, rather than simple tracer lines elongated by the straining flow field. The spiral’s azimuthal moving velocity is substantially smaller than the eddy’s rotational velocity and the spiral tends to move outward from eddy center to eddy edge. These features are also identified in the atmospheric spiral rain bands of tropical cyclones, which are induced by vortex Rossby waves and can cause strong vertical motions. The enhanced surface chlorophyll signals observed along the spiral bands are likely caused by vortex Rossby waves embedded in the ocean eddies.

1. Introduction

More than half of the primary production on Earth occurs in the surface layer of the ocean and involves fixation of carbon by phytoplankton (Field et al., 1998). Biogeochemical estimates of new production surpass the apparent rate of nutrient supply by vertical mixing by a factor of 2 or more (Jenkins, 1988; McGillicuddy et al., 1998, 2003, 2007). In order to identify the “missing” nutrients, one agent to transport open ocean nutrient and chlorophyll is identified as mesoscale eddies, which are vortices with a radius of about 102 km and are ubiquitous in ocean (Falkowski et al., 1991; McGillicuddy et al., 1998, 2003, 2007; Oschlies & Garcon, 1998). Several mechanisms have been proposed for the nutrient transport: horizontal advection of chlorophyll around mesoscale eddies (Chelton, Gaube, et al., 2011). Vertically, upwelling generated by eddy-wind interaction and eddy evolution can bring subsurface nutrient into the euphotic layer and promote chlorophyll increase (Klein & Lapeyre, 2009; McGillicuddy et al., 2003, 2007; Zhang et al., 2019). However, quantitative analyses indicate that the mesoscale eddies cannot close the gap in the upper ocean nutrient budget; they only account for 20–30% of the nutrient requirement to sustain the observed global new production (Garcon et al., 2001; Lévy, 2008; Martin & Richards, 2001; McGillicuddy et al., 1998, 2003, 2007; Oschlies & Garcon, 1998; Mahadevan & Archer, 2000).
It is worth noting that the chlorophyll distributions around the eddies usually have abundant fine structures with horizontal scales much smaller than the eddies. Spiral band is one of the most representative fine structures of vortex phenomenon, such as spiral arms of vortex galaxy (Hou et al., 2009; Kalnajs, 1973; Lin et al., 1969), spiral rain bands of tropical cyclones (MacDonald, 1968; Montgomery & Kallenbach, 1997; Senn & Hiser, 1959), and spiral chlorophyll bands of oceanic mesoscale eddies. One example of the oceanic spiral

**Figure 1.** Identification of spiral chlorophyll bands of oceanic mesoscale eddies. (a) Horizontal distribution of chlorophyll and SSHA of an example mesoscale eddy. This eddy is located around 103°E, 38°S. Color represents the chlorophyll distribution around the eddy in the normalized eddy center coordinate $Chl(x_n,y_n)$, and black contours represent the SSHA distribution $\eta(x_n,y_n)$. The interval of SSHA contours is 2.7 cm. Black asterisk indicates the eddy center, where $x_n = y_n = 0$, and black points around the eddy denote the radial maximum points of chlorophyll. (b) Horizontal distribution of chlorophyll in the normalized polar coordinate $Chl(R_n,\theta)$, where $R_n$ is the normalized radial distance to eddy center and $\theta$ is the azimuthal angle. Color represents the chlorophyll distribution, and black points denote the radial maximum points of chlorophyll. (c) The averaged SSHA as a function of the normalized radial distance. Relation between the averaged SSHA and the normalized radial distance can be expressed as $\eta_0 = F(R_n)$ or $R_n = F^{-1}(\eta_0)$. (d) Location of the radial maximum points of chlorophyll in the stretched normalized polar coordinate, where horizontal coordinate is the azimuthal angle $\theta$ and vertical coordinate is the stretched normalized radial distance $R_{sn}$. Black points are the radial maximum points of chlorophyll. Red line represents the linear fit line of the radial maximum points. (e) Global map showing the locations of eddy observations by red spots with spiral chlorophyll bands. The locations of 1,392 subsequent eddy observation pairs used to compute the movement of the spiral bands in section 3.2 are represented by black spots. Color represents the climatological mean chlorophyll value.
chlorophyll band is shown in Figure 1a around a cyclonic eddy located around 103°E, 38°S, and the surface chlorophyll concentration is greatly enhanced along the spiral band. This kind of fine structures of mesoscale eddies is known as oceanic submesoscale features with a typical width of 10^2–10^3 km, which is 1 order of magnitude smaller than eddy radius. Submesoscale motions can support vertical velocities as large as 10–100 m day^{-1} (Molemaker et al., 2005), an order of magnitude larger than the vertical velocities induced by mesoscale eddies (Capet et al., 2008a, 2008b; Klein et al., 2008; Klein & Lapeyre, 2009). Thus, the submesoscale processes can play a crucial role in transporting nutrients into the sunlit ocean to close the upper ocean nutrient budget (Lévy et al., 2012; Mahadevan, 2016). The submesoscale spiral bands can also be identified as convergence/divergence lines in Sun glint and synthetic aperture radar (SAR) images (McWilliams, 2016; McWilliams et al., 2009). The chlorophyll concentration level along the spiral band in Figure 1a is larger than all surrounding waters around the cyclonic eddy. This suggests that the enhancement of chlorophyll concentration along these spiral bands cannot be solely driven by horizontal advection and must involve vertical motions.

The atmospheric tropical cyclones and oceanic mesoscale eddies are both vortex phenomenon in rotational stratified fluid, and they share similar spiral bands as their fine structures. As a prominent feature of tropical cyclones, the spiral rain bands are characterized by strong vertical motions, involving deep convection and heavy precipitation along the banded structures (Willoughby, 1978). These spiral structures are explained theoretically as vortex Rossby waves (VRWs), which is supported by a series of observational studies (Graves et al., 2006; MacDonald, 1968; Müller & Montgomery, 1999, 2000; Montgomery & Kallenbach, 1997; Senn & Hiser, 1959). First, the spiral rain bands always tilt toward the vortex center in rotational direction of the tropical cyclones. This tilting feature can be explained by Doppler effect by the VRWs. Second, the azimuthal motions of the spiral rain bands are substantially less than the mean tangential velocity of tropical cyclones, which means the air moves through the bands. This is consistent with the theoretical expectation that the azimuthal intrinsic wave velocity of VRWs is always opposite to the rotational motion of the vortex they are embedded in. After formation, the spiral rain bands always move outward radially and the radial velocity decreases outward from the vortex center, in consistence with the theoretical expectation of the radial group velocity of VRWs. Finally, the surface wind speed is greatly enhanced under the spiral rain bands as predicted by the VRW theory.

The existence of the oceanic VRWs is hypothesized mostly from theoretical arguments and numerical simulations (Koszalka et al., 2009; Rodriguez-Marroyo & Viudez, 2009; Viudez & Dritschel, 2004). Due to the sampling and resolution limitations, global observational studies of oceanic VRWs are yet available (Buongiorno Nardelli, 2013; Chavanne et al., 2010). Here we show that the spiral chlorophyll bands of oceanic eddies can be identified globally by a combined use of satellite-measured sea surface height anomaly (SSHA) and chlorophyll maps. By further incorporating the global surface drifter data, we find that that the oceanic spiral chlorophyll bands share the same kinematic and structural features as the atmospheric spiral rain bands of tropical cyclones. Like the studies for tropical cyclones, these features are examined in this study to verify that the spiral chlorophyll bands are footprints of VRWs embedded in the oceanic eddies. Finally, the relationship between the emergence of the spiral chlorophyll bands and the preferred dynamical features of mesoscale eddies is discussed.

2. Data and Methods
2.1. Altimetry and Eddy Tracking Data Set
The SSALTO/DUACS delay-time altimetry product provided by AVISO is used here (issue 5.0 updated 20 August 2016). This multiple-satellite-merged data contain global gridded daily SSHA η and geostrophic velocity anomaly (u_g, v_g) fields with a (1/4)° resolution from 1993 to 2012. Based on the altimetry data set, a 19.5-year eddy identification and tracking data set is produced by automatic eddy identification and tracking algorithm, which released by College of Earth, Ocean, and Atmosphere Sciences, Oregon State University (Chelton, Schlax, & Samelson, 2011). This eddy identification and tracking data set provides the longitude, latitude, time, eddy radius R_e, eddy tangential rotation velocity V_{adv}, and polarity information of a total of 2,590,938 eddy observations in the global ocean.
2.2. Chlorophyll Data

The chlorophyll data of Case-1 water is provided by the European Space Agency (ESA) GlobColour Project (version 4.1, updated 31 August 2017), which merges several sensors with (1/20)° spatial resolution of daily data from 1998 to 2017 (Maritorena & Siegel, 2005). The unit for chlorophyll concentration is mg/m³, and all chlorophyll values in this study are expressed by their Base-10 logarithm Chl. In order to achieve sufficient data coverage, the chlorophyll data Chl is averaged within a time window [t₀ − 3 day, t₀ + 3 day]. The climatology field of surface chlorophyll is computed as Chl₀.

2.3. Surface Drifter Data

The drifter data used here are provided by the Drifter Data Assembly Center (DAC) of National Oceanic and Atmospheric Administration (NOAA). The DAC assembles and provides a uniform quality control of sea surface temperature (SST) and surface velocity data by satellite-tracked surface drifting buoy observations. The surface velocity (u, v) are provided for every 6 hr from year 1993 to 2011. They have a global coverage and contain a total of 22,249,337 observational data points.

2.4. Submesoscale Energy

The satellite-tracked drifters observe the absolute horizontal velocity \( \vec{u} \) at ocean surface. They have been used to quantitatively evaluate the submesoscale kinetic energy at the sea surface and proved to be an effective tool (Zhang & Qiu, 2018; Zhang et al., 2019). The ocean surface submesoscale velocity is computed as

\[ u_s = u - u_g - u_0, \]

where \( u_g \) is the simultaneous altimetry mesoscale geostrophic velocity anomaly at the drifter location and \( u_0 \) is the climatological mean surface velocity computed from drifter’s absolute velocity \( u \). The submesoscale kinetic energy is computed as

\[ E_s = \frac{u_s^2}{2} \]

along each drifter trajectory.

2.5. Spiral Chlorophyll Band Identification

The spiral chlorophyll bands are submesoscale structures embedded in mesoscale eddies. A normalized eddy center coordinate can be introduced to depict the chlorophyll and SSHA distributions around individual mesoscale eddies. At a given time \( t_0 \), each eddy identified by the eddy track data set has its center location \((x_c, y_c)\) and radius \( R_0\). The chlorophyll and SSHA data can be projected onto an eddy center coordinate \((x_c, y_c)\), where \( x_c = x - x_c \) and \( y_c = y - y_c \). The horizontal coordinate can further be normalized by the eddy radius as \((x_n, y_n)\), where \( x_n = x_c/R_0 \) and \( y_n = y_c/R_0 \). Figure 1a shows the chlorophyll and SSHA distributions in the normalized eddy center coordinate \((x_n, y_n)\) around a cyclonic eddy. Because of the cloud cover and irregular ground tracks of satellite, there are data gaps in the chlorophyll maps. In order to identify the typical spiral structures in the chlorophyll maps, there should be sufficient valid data points around the target eddy. The chlorophyll data of \( Chl(x_n, y_n) \) is selected in a square region around the eddy center as shown in Figure 1a. If 80% of the square is covered with valid data of chlorophyll, this eddy observation will be treated as having a sufficient chlorophyll data coverage. Under this criterion, there are a total of 721,447 eddy observations with the sufficient data coverage.

The spiral structure of high-chlorophyll band can be observed around the eddy as shown in Figure 1a. The automatic identification of the spiral chlorophyll bands follow the following steps and quantitative criteria: (1) The chlorophyll distribution around an eddy is projected onto the polar coordinate \( Chl(R_n, \theta) \), where \( R_n = (x_n^2 + y_n^2)^{1/2} \) is the normalized radial distance to eddy center and the direction angle \( \theta \) is 0 along the positive \( x_n \) direction and increases anticlockwise. (2) Since the spiral band is featured with the enhancement of local chlorophyll concentration, the radial maximum points of chlorophyll can be utilized to depict the location of the spiral band, as shown in Figures 1a and 1b. If the chlorophyll reaches a local maximum \( Chl_{max} \) along the radial direction, it is treated as a candidate for the radial maximum point of chlorophyll. If \( Chl_{max} > Chl_{ave} + Chl_{std} \), this point will be identified as a valid radial maximum point of chlorophyll, where \( Chl_{ave} \) and \( Chl_{std} \) are the average and standard variation chlorophyll values within the square region around the eddy center. (3) Considering the mesoscale eddies usually do not have a perfect circular shape, a stretched polar coordinate is introduced to remove the asymmetric effect. The SSHA is averaged for each normalized radial distance \( R_n \), as shown in Figure 1c. The relation between the averaged SSHA \( \eta_0 \) and \( R_n \) can be expressed as \( \eta_0 = F^{-1}(R_n) \) or its inverse function \( R_n = F^{-1}(\eta_0) \). The SSHA distribution can also be projected onto the polar...
coordinate $\eta'(R_n, \theta)$. For each point, a stretched normalized radial distance is computed by using the inverse function as $R_{sn} = F^{-1}[\eta'(R_n, \theta)]$, and each value of $R_{sn}$ corresponds to a SSHA contour surrounding the eddy center. (4) The locations of the radial maximum points of chlorophyll in $(R_{sn}, \theta)$ are shown in Figure 1d; on the lowest order, the distribution of radial maximum points can be approximated by a straight line determined by linear fit (red line in Figure 1d). The following criteria are used to determine a valid spiral chlorophyll band: First, the averaged radial distance from the radial maximum points to the linear fit line $\Delta R_{sn}$ should be smaller than 0.15. Second, there should be more than 40% radial maximum points located around the linear fit line ($\Delta R_{sn} < 0.1$), and their number should be larger than 40.

Figure 2. Tilting direction of the spiral chlorophyll bands. Cyclonic eddies in Southern Hemisphere have clockwise rotation. (a) Chlorophyll and SSHA distributions of an example cyclonic eddy in Southern Hemisphere; same as Figure 1a with the coordinates changed to longitude/latitude. (b) Location of the radial maximum points of chlorophyll in the stretched normalized polar coordinate of this example eddy; same as Figure 1d. (c) The number distribution of the spiral tilting index $S_i$ for all cyclonic eddies in Southern Hemisphere with valid spiral chlorophyll bands, the colored bars represent the data number with different $S_i$. The corresponding results of anticyclonic eddies in Northern Hemisphere (clockwise) are shown in (d)-(f). The corresponding results of anticyclonic eddies in Southern Hemisphere (anticlockwise) are shown in (g)-(i). The intervals of SSHA contours are 2.7, 2.8, 3.8, and 3.9 cm in (a), (d), (g), and (j), respectively.
By adopting the criteria, a total of 10,176 eddy observations from year 1998 to 2012 has been identified with valid spiral chlorophyll bands. It should be noted that the straight line in Figure 1d represents a lowest-order approximation to identify the spiral structures. Many spiral chlorophyll bands do not necessarily follow straight lines, and our identification likely result in an underestimation of the number of spiral chlorophyll bands. The global distribution of eddies with identified spiral chlorophyll bands are shown in Figure 1e.

Furthermore, only the isolated eddy with single spiral filament can be identified in this study. However, vortices are often surrounded by multiple filaments or merging with each other (Lapeyre & Klein, 2006; Melander et al., 1988), which means the spiral chlorophyll bands may be even more ubiquitous throughout the world’s oceans than what are shown here.

3. Results
3.1. Structure of Spiral Chlorophyll Bands

As an example, the spiral band in Figure 1 tilts inward radially in the direction of the rotating eddy (clockwise). In order to determine whether this is a universal property, further examples are introduced, including cyclonic and anticyclonic eddies in both Southern and Northern Hemispheres. As shown in Figure 2, the spiral bands of these four example eddies all follow the same pattern: The spiral bands all tilt inward in the rotation direction of the eddies. The distributions of the radial maximum points further confirm this.

Figure 3. Azimuthal and radial movements of the spiral chlorophyll bands. (a) The number distribution of the normalized azimuthal velocity of the spiral chlorophyll bands $V_{\theta n}$. Colored bars represent the number of data points with different $V_{\theta n}$, red for anticyclonic eddies and blue for cyclonic eddies. Black dashed line represents when $V_{\theta n}$ equals to the advection velocity of eddy. (b) The number distribution of the radial movements of the spiral band during the 7-day interval $V_r \Delta t$, where $V_r$ is the radial velocity of the spiral chlorophyll bands and $\Delta t = 7$ days. The colored bars represent the number of data points with different $V_r$, red for anticyclonic eddies and blue for cyclonic eddies. (c) The radial distribution of the radial velocity of the spiral chlorophyll bands. The radial movement $V_r \Delta t$ is composited against the stretched normalized radial distance $R_{sn}$ using a moving average window with a width 0.2. (d) The azimuthal distribution of submesoscale kinetic energy relative to the spiral band location. The normalized submesoscale energy $E_{sn}$ is composited against the azimuthal distance from the drifter trajectory to the spiral chlorophyll band $\Delta \theta$ using a moving average window with a width 0.2$\pi$. Red curves in panels (c) and (d) represent the average value and the light-gray shading represents the error bar computed by the standard error of average as $\text{Std}/\sqrt{N}$, where $\text{Std}$ and $N$ are the standard deviation and data number within each averaging bin, respectively.

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feature, as shown in Figures 2b, 2e, 2h, and 2k, respectively. The slopes of the maximum points are only related to the rotation direction of the eddies: positive slope for clockwise rotation (Figures 2b and 2e) and negative for anticlockwise rotation (Figures 2h and 2k).

The slope of the linear fitting line (red line) can be used as a quantitative index to represent the tilting feature of the spiral band, and it is defined in this study as the spiral tilting index $S_I$. All eddies with valid spiral chlorophyll bands are divided into four groups: cyclonic and anticyclonic eddies in the Southern and Northern Hemispheres. The number distributions of the spiral tilting index $S_I$ for these four groups are shown in Figures 2c, 2f, 2i, and 2l, respectively. It indicates that most of the clockwise eddies have positive $S_I$ and anticlockwise eddies have negative $S_I$. Statistically, this implies that the spiral chlorophyll bands tilt radially inward in eddy rotation direction. This feature is shared by the spiral rain bands of tropical cyclones, and compatible with the explanation of VRW's Doppler effect (Montgomery & Kallenbach, 1997). The tilting directions are dependent on the rotation direction of the eddy (see Figure S3 in the supporting information).

3.2. Movement of Spiral Chlorophyll Bands

The azimuthal and radial movement features of the atmospheric spiral rain bands provide key evidence that they represent the footprint of VRWs. The observed azimuthal velocity of the spiral rain bands is substantially smaller than the mean tangential component of the tropical cyclone wind field (Senn & Hiser, 1959). The air moves through the spiral rain bands, which indicates that they are more likely to be wave-like structures rather than passive tracer lines. Observations also indicate that the spiral rain bands move outward radially, and the radial moving speed is much smaller than the gravity wave speed in the atmosphere (MacDonald, 1968; Senn & Hiser, 1959). Solution of VRWs indicates that its azimuthal moving velocity $V_0$ is substantially less than the mean tangential component of the vortex, and the VRWs always move outward radially (see details in Figure S3 of the supporting information).

Since the spiral chlorophyll bands and the spiral rain bands share the same structural features, it is natural to expect they also share similar kinematic features. In order to compute the movements of the spiral chlorophyll bands, continuous observations of the individual eddies with spiral chlorophyll bands are needed. For all the available data, a total of 1,392 subsequent eddy observation pairs is found. The azimuthal velocity $V_0$ and radial velocity $V_r$ can be computed by using two consecutive locations of the spiral chlorophyll bands: The location of the spiral chlorophyll band for a specific eddy at a given time can be computed by the averaged location of the radial maximum points of chlorophyll in the stretched polar coordinate $(R_{sn}, \theta)$, as shown in Figures 2b, 2e, 2h, and 2k. The azimuthal and radial moving velocities of the spiral bands are computed as $V_r = \Delta R_{ave}/\Delta t$ and $V_0 = R_0 \times \Delta \theta_{ave}/\Delta t$, where $\Delta t = 7$ days is the time interval between the two consecutive eddy observations and $\Delta R_{ave}$ and $\Delta \theta_{ave}$ are the radial and azimuthal movements of the spiral band during this time interval, respectively.

The azimuthal velocities of the spiral bands are further normalized by the eddy rotational velocity $V_{en} = V_0/V_{adv}$. As shown in Figure 3a, the normalized azimuthal velocity of the spiral chlorophyll bands is substantially smaller than one, and its average amplitude is about 1/4. These results mean that the azimuthal velocity $V_0$ of the spiral chlorophyll bands is substantially smaller than the eddy rotational advection velocity $V_{adv}$. The seawater moves through the spiral chlorophyll bands, which indicates most of them are not likely to be simple passive tracer lines.

As shown in Figure 3b, most of the spiral chlorophyll bands (about 75%) move outward radially, and the radial movements of the spiral bands within one week $V_r \times \Delta t$ is on the order of 0.1–0.2 $R_{sn}$, which means that the spiral bands will take about 1–3 months to move from the eddy center to eddy edge. This speed is substantially slower than the radial moving speed of inertia-gravity wave, which usually takes several inertial periods to move from the eddy center to eddy edge. These results are consistent with the radial movement feature of the atmospheric spiral rain bands expected from the VRW theory. The VRW theory further predicts that the group velocity decreases radially and a stagnation radius exists, where the group velocity reaches 0 and the VRWs stop to move outward (Chen & Yau, 2001; Montgomery & Kallenbach, 1997). By compositing the radial movements $V_r \times \Delta t$ against the normalized radial distance $R_{sn}$, its radial variation curve is shown in Figure 3c. The radial velocity $V_r$ of the spiral chlorophyll band decreases radially and drops to zero around the normalized radial distance $R_{sn} \sim 1.5$ to 2.0, demonstrating further the validity of VRW theory for explaining the movement features of the oceanic spiral chlorophyll bands.
3.3. Submesoscale Energy Along Spiral Chlorophyll Bands

The atmospheric spiral rain bands are featured with enhanced surface wind speed along their band structure caused by the velocity and convergence field of the VRWs (MacDonald, 1968; McWilliams et al., 2003; Möller & Montgomery, 1999; Montgomery & Kallenbach, 1997; Senn & Hiser, 1959). If the spiral chlorophyll bands are footprints of submesoscale processes rather than passive tracer lines formed by eddy advection, it is expected that the submesoscale motions will be enhanced along the spiral chlorophyll bands. The submesoscale kinetic energy $E_s$ along the drifter trajectory can be projected onto the stretched polar coordinate $E_s(R_{sn}, \theta)$. The linear fit of the radial maximum points of chlorophyll can be expressed as $\Delta = a_1 + a_2 * R_{sn}$ in the stretched polar coordinate, where $a_1$ and $a_2$ are the fitting parameters. If the radial range of the radial maximum points is $[R_{min}, R_{max}]$, only the drifter data within this range will be used, and there is a total of 14,379 valid drifter data points.

The azimuthal distance from the drifter trajectory to the spiral chlorophyll band can be computed as $\Delta \theta = \theta - a_1 + a_2 * R_{sn}$, where $\theta$ is the directional angle of the drifter location and $\Delta \theta = 0$ means the spiral band location. $E_s(R_{sn}, \Delta \theta)$ at different radial distance is further normalized by the averaged geostrophic kinetic energy at its radial distance. The geostrophic kinetic energy can be computed from the altimeter data as $E_g = u_0^2/2$, and the averaged geostrophic kinetic energy at a given radial distance $R_{sn}$ can be readily computed as $E_{gg}(R_{sn})$. The normalized submesoscale energy is $E_{sn}(\Delta \theta) = E_s(R_{sn}, \Delta \theta)/E_{gg}(R_{sn})$, which can remove the influence of eddy amplitude and radial geostrophic velocity variation. The composite curve of $E_{sn}(\Delta \theta)$ indicates that the submesoscale energy level is enhanced by about 50% within a narrow range around the spiral chlorophyll band location, as shown in Figure 3d, consistent with the dynamical expectation of VRWs. This result suggests that the spiral chlorophyll bands are not just simple passive tracer lines; instead, they are dynamically active and can play an important role in facilitating energy transfer between the mesoscale eddies and submesoscale motions. The time scales of phytoplankton growth/decay are of $\Delta t$ of 7 days between two observations indicates that a supply of nutrient with enhanced vertical velocities must occur along these spiral bands. The vertical motion related to eddy-wind interaction or eddy evolution cannot explain the enhanced chlorophyll spirals as there is no reason it would be confined to the observed filaments.

4. Summary and Discussion

By combining the satellite remote sensing chlorophyll data, altimetry data, and surface drifter data, we show that spiral chlorophyll bands are widely distributed globally as a submesoscale structure of oceanic mesoscale eddies. The spiral bands tilt inward when following the eddy rotation direction. The azimuthal moving velocity of the spiral bands is substantially smaller than the eddy rotation velocity. The radial moving velocity of the spiral bands is outward, decreasing radially and a stagnation radius exists. The submesoscale kinetic energy is substantially enhanced along the spiral bands. All these observational features are shared with the spiral rain bands of atmospheric tropical cyclones and consistent with the theoretical expectations of the VRWs.

The VRWs are thought to emerge from eddy enhancing/decaying under background deformation (Chen & Yau, 2001; MacDonald, 1968; Möller & Montgomery, 1999, 2000). When a circular vortex is disturbed by deformation field, it will undergo a relaxation process toward an axisymmetric state, and the asymmetric components irreversibly evolve toward smaller scales (Graves et al., 2006). The vorticity filaments emerging from the vortex axisymmetrization process propagate outward radially, and there also exists a stagnation radius for the outward-propagating filaments as expected by VRW dynamics (Melander et al., 1987; Montgomery & Kallenbach, 1997). Since the submesoscale energy is found to be enhanced along the spiral chlorophyll bands, it suggests that the VRWs in the oceanic mesoscale eddies can be effective in transferring energy to smaller scale motions (McWilliams et al., 2003). Indeed, our further analysis indicates an intense eddy energy variation and a strong background deformation strain field constitute the favorable conditions for the emergence of the spiral chlorophyll bands (see supporting information for details).

This study highlights the spiral bands as a fine structure of mesoscale eddies that can greatly enhance the surface chlorophyll concentration along band structures, which can be explained as biogeochemical footprints of the vertical motions induced by VRWs. Our results shed new light onto the problem of how to
close the surface nutrient budget in order to sustain the observed level of oceanic primary production. Our results here may help to establish parameterizations of the effect of submesoscale processes or provide an observational base line to test the output of numerical models. We hope our results will motivate future studies to gain a better understanding of the oceanic submesoscale processes and the ocean ecosystems, when the next-generation Surface Water Ocean Topography (SWOT) satellite mission is underway (Fu & Ferrari, 2008; Morrow & Fu, 2011; Rogé et al., 2017).

Data Availability Statement

Conflict of Interest
The authors declare no competing financial interests.

References


