Abstract: This paper proposes an algorithm named EddyGraph for tracking mesoscale eddy splitting and merging events. Twenty-seven years (January 1993–December 2019) of sea level anomaly (SLA) data are analyzed in the Northwest Pacific Ocean (105°E–165°W, 0°N–60°N). First, we propose a multilevel eddy identification method based on SLA to obtain an eddytree data set, representing a spatial topological tree structure of closed SLA contours with mononuclear eddies, multicore eddies and eddy seeds as the leaf nodes and eddygroups (reflecting the spatial topological relationship among eddies) as the intermediate nodes. The EddyGraph tracking algorithm is applied to the eddytree data set, which results in eddy-directed acyclic graphs (Eddy-DAGs). Only eddies contained within a common eddygroup are tracked as sources in merging events or sinks in splitting events. Furthermore, we extract typical splitting and merging events and composite the sea surface temperature anomalies (SSTAs) inside the eddygroups and eddies during these events. The results confirm that merging eddies in the same eddygroup degenerate into a single eddy and that a splitting eddy evolves into eddies within the same parent eddygroup. Moreover, we match a merging event of cyclonic eddies with in situ data of both drifters and loopers in Lagrangian trajectories. Finally, we present EddyGraph, a data set of mesoscale eddy tracking in the Northwest Pacific Ocean (105°E–165°W, 0°N–60°N).

Keywords: eddygroup; eddy splitting and merging; SSTA; drifter
Moreover, eddies are not always independent bodies of water. Separate eddies may merge into a single new eddy, and an eddy may split into multiple eddies in specific marine environments [30,31]. Hence, in addition to survival and extinction, the merging and splitting of eddies should be included in the time-dependent behavior of ocean eddies. Nevertheless, at present, few automated algorithms track eddies that split and merge. Furthermore, no corresponding data set of eddy trajectories that considers splitting and merging behaviors has been published, and no data validation has been presented. Existing studies [32,33] on algorithms based on SLA that can automatically track splitting and merging eddies postulated that eddies always exhibit one local sea level anomaly (SLA) maxima/minima during splitting and merging events, indicating that each local SLA maxima/minima point of a multicore eddy structure corresponds to one eddy. Consequently, the main problem in these studies [32,33] is how to relate the multicore eddy structures to the eddies during splitting and merging events. Li et al. [32] proposed the Genealogical Evolution Model (GEM), a dynamic tracking model in which a watershed strategy is adopted to split a multicore eddy into multiple eddies with one local SLA maximum/minimum. Cui et al. [33] presented a method to define multicore structures in eddy–eddy interactions and took them as tracking objects for eddy splitting and merging events. This multicore structure reflected the spatial connection of local SLA maxima/minima points during splitting and merging events as the overall structure, but the local structure of each eddy was not determined. However, the above methods [32,33] could not clearly establish the spatial topological connection of interrelated eddies during splitting and merging events. Therefore, it remains difficult to conduct normalized verification experiments, which are standard operations for validating the eddy-induced heat transport [1,8,9], to determine how multiple eddies merge into a new eddy and how a single eddy splits into different eddies. Another automated method, the Angular Momentum Eddy Detection and Tracking Algorithm (AMEDA), based on velocity fields was also proposed [23]. Their method detected eddies that split and merge by the shared velocity field contour presenting the eddy–eddy interaction. However, no normalized verification experiments were conducted in their research [23].

This study makes the following four contributions. (1) We propose an SLA-based multilevel eddy identification method to establish the eddytree data set, a spatial topological tree structure of closed SLA contours with eddies as the leaf nodes and eddygroups as the intermediate nodes. The spatial topological relationships among eddies (mononuclear eddies, multicore eddies and eddy seeds) can be constructed in the eddytree data set as eddygroups. (2) We propose the EddyGraph tracking method for eddy splitting and merging events. Only eddies within a common eddygroup can be tracked as the sources in merging events or the sinks in splitting events. Furthermore, the eddies during the study period are tracked in time-oriented graphs that include three trajectory levels: segment, branch and eddy-directed acyclic graph (Eddy-DAG). (3) We verify the authenticity of our tracking data set with sea surface temperature anomaly (SSTA) remote sensing images and in situ data of drifters and looper trajectories. The results confirm that merging eddies in the same eddygroup degenerate into a single eddy and that a splitting eddy evolves into eddies within the same eddygroup. (4) We present EddyGraph, a data set of mesoscale eddy trajectories in the Northwest Pacific (105°E–165°W, 0°N–60°N), and analyze the geographical distribution of typical eddy splitting and merging events.

The remainder of this paper is organized as follows: Section 2 introduces the data adopted and the methods for identifying and tracking eddies. Section 3 describes the results, including statistics of the tracking data set and extraction of typical events. Section 4 describes the validation with remote sensing observations and in situ data. Finally, the discussions and conclusions are presented in Section 5.
2. Data and Methods

2.1. Data

This paper applies the EddyGraph algorithm to the Northwest Pacific (105°E–165°W, 0°N–60°N) to analyze the trajectories of eddy splitting and merging events. In this study, daily SLA images with a spatial resolution of 0.25° × 0.25° from January 1993 to December 2019 derived from all-sat-merged delayed altimeter products provided by the Copernicus Marine Service (CMEMS) are used to identify eddies (https://resources.marine.copernicus.eu/) (accessed on 1 October 2020). Daily SSTA maps (also with a spatial resolution of 0.25° × 0.25°) from January 1996 to December 2019 provided by the National Oceanic and Atmospheric Administration (NOAA)-Advanced Very High-Resolution Radiometer (AVHRR) are adopted for a composite analysis for validation (https://www.ncei.noaa.gov/data/sea-surface-temperature-optimum-interpolation/) (accessed on 7 March 2021). In addition, data (https://www.aoml.noaa.gov/phod/gdp/loopers.php) (accessed on 29 April 2021) of drifters and of looper trajectories identified from the Global Drifter Program data set [34] are used to match the splitting and merging events detected by our tracking algorithm, where the looper trajectories identified by an automated algorithm are considered loopers in Lagrangian trajectories, which complete at least two drifter rbits [34].

2.2. Eddytree: Eddy Identification with Spatial Topological Relationship

In this paper, mononuclear eddies, multicore eddies and eddy seeds are considered eddy signals in splitting and merging events. For eddy splitting and merging tracking, we propose a multilevel mesoscale eddy identification method based on SLA. In our method, the whole study area in a daily SLA image can be detected as the spatial topological tree structure of closed SLA contours with eddies as the leaf nodes and eddy groups related to eddy spatial topology as the intermediate nodes (Figure 1).

![Figure 1](image-url) Figure 1. The daily eddytrees detected by our method, including eddies (mononuclear eddies, multicore eddies and eddy seeds) as the leaf nodes, eddygroups (green lines) whose children are all eddies and other eddygroups (black lines). Anticyclonic eddies and cyclonic eddies (except eddy seeds) are represented by red lines and blue lines, respectively, while eddy seeds and the eddy cores of anticyclonic eddies and cyclonic eddies are expressed by red dots and blue dots.
2.2.1. Eddytree

Figure 2 shows the structure of an eddytree, a spatial topological tree of closed SLA contours with eddies as the leaf nodes and eddygroups as the intermediate nodes. Eddies and eddygroups with the same parents are siblings. The leaf node layer of the eddytree in Figure 2 consists of mononuclear eddies (eddy1, eddy4 and eddy5), multicore eddies (eddy2) and eddy seeds (eddy3, eddy6, eddy7 and eddy8).

![Diagram of an eddytree](image1)

![Structure of the eddytree](image2)

Figure 2. (a) A diagram of an eddytree; (b) the structure of the eddytree corresponding to (a).

2.2.2. Eddygroup

As the intermediate nodes of eddytrees, eddygroups are the closed SLA contours related to eddy spatial topology, which means eddygroups could contain eddies or eddygroups to reflect the spatial topological relationship among eddies.

An eddy is a compact fluid structure in the ocean. Consequently, splitting or merging events cannot occur in a single moment; rather, these processes often span more than one day [35,36], which allows us to identify and track eddy splitting and merging events from satellite altimeter measurements with a temporal resolution of one day. Ocean eddies that split and merge aggregate within the same closed SLA contour and form an eddygroup, which is actually a closed fluid structure for the geostrophic relationships between the geostrophic velocity anomaly components (u, v) and SLA [12]. The eddies in the same eddygroup are components (i.e., local fluid structures) of the whole fluid structure of the eddygroup. When eddies of the same polarity encounter one another within an eddygroup, they can interact with each other and eventually merge into a new eddy due to the reverse-direction contact current between them (Figure 3). Taking a merging event as an example, two interacting eddies form a closed fluid structure, namely a new eddygroup (Figure 3). Moreover, the eddies in the process of merging change gradually [35,36], which means they should be in a common eddygroup before merging completely (Figure 3). On this basis, it is easy to understand that the eddies generated from the splitting of an eddy should be close to each other and are contained within the same eddygroup after splitting completely. Therefore, only eddies contained within a common eddygroup can be tracked as the sources of merging or the sinks of splitting in our tracking algorithm.
2.2.3. Eddy Identification Criteria

(i) Mononuclear eddy The boundaries of mononuclear eddies should satisfy criteria similar to that used in [19,20,28]:

1. Only one local SLA maxima/minima point is contained.
2. There are I pixels (0.25° × 0.25°), where 4 ≤ I ≤ 2000.
3. The amplitude $A \geq 0.25$ cm, where $A = |h_1 - h_0|$, $h_1$ is the SLA value at the local maxima/minima point in the eddy and $h_0$ is the SLA value on the outermost closed SLA contour that defines the eddy perimeter.

(ii) Multicore eddy The boundaries of multicore eddies should satisfy the following criteria:

1. Multiple local SLA maxima/minima points are contained.
2. Multicore eddies are independent of mononuclear eddies: multicore eddies do not contain any mononuclear eddies, which means that any local maxima/minima point within a multicore eddy cannot be identified as a mononuclear eddy.
3. The amplitude $A \geq 0.25$ cm, where $A = \sum_{i=1}^{n} h_{i} - h_{0}$, $h_{i}$ is the SLA value at the local maxima/minima point with the largest $A$ among all the local maxima/minima points in the eddy and $h_0$ is the SLA value on the outermost closed SLA contour that defines the eddy perimeter.

(iii) Eddy seed

Eddy seeds are local maxima/minima points that are not the cores of either mononuclear eddies or multicore eddies. An eddy may disappear when the signal of the eddy core is too weak to be spotted as an eddy on the SLA map [18]. Meanwhile, the noise and/or the spatiotemporal heterogeneity of the altimetric tracks could generate a temporary distortion of the shapes or could introduce a lack of detection of these eddies [23,25]. Consequently, eddy seeds can be not only manifestations of eddies during splitting and merging events but also weakened eddy signals to reduce eddy disappearance and trajectory discontinuities.

2.3. EddyGraph: Eddy Splitting and Merging Tracking

This paper regards the eddies during the study period as complex time-oriented graphs consisting of three trajectory levels: segment, branch and Eddy-DAG.

2.3.1. Criteria

(i) Segment

As the basic unit in the eddy space–time graph, a segment is the relationship (including live, dead, split and merge) between eddies in adjacent time steps. As shown in Figure 4,
segments are classified into four types, including linear segments (live segments and dead segments) and nonlinear segments (split segments and merged segments).

![Diagram of four types of segments](image)

**Figure 4.** The four types of segments considered in this paper, where the eddies on day $i$ and day $i+1$ are expressed by the gray and red circles, respectively, while the common eddygroups on day $i$ and day $i+1$ are represented by the black dashed line and red dashed line, respectively: (a) live segment consisting of the eddies with live relationships in two adjacent time steps; (b) dead segment consisting of an eddy that is dead in the next time step; (c) split segment consisting of the eddies with split relationships in two adjacent time steps; (d) merged segment consisting of the eddies with merged relationships in two adjacent time steps.

(ii) **Branch**

A branch is a time series of live segments (Figure 5), which is actually an eddy with a lifetime of N days.

![Diagram of Eddy-DAG](image)

**Figure 5.** A diagram of a nonlinear Eddy-DAG consisting of splitting or merging branches with segments as the basic units.

(iii) **Eddy-DAG**

The structure of an Eddy-DAG is shown in Figure 5. Splitting and merging branches (isolated branches) form a nonlinear Eddy-DAG (a linear Eddy-DAG) with an energy cascade, in which the energy of eddies is transferred [12,31]. In addition, a splitting or merging event can be regarded as a combination of source branch(es) and sink branch(es). Because a branch is an eddy with a lifetime of N days, the eddy may die after surviving for N days, such as branch6, or it may correspond to splitting or merging events. For example, branch2 is not only one source branch of a merging event but also, in the reverse sense, the sink branch of a splitting event.

2.3.2. Tracking for Eddy Splitting and Merging

(i) **Segment**

Figure 6 shows a flowchart depicting the tracking workflow for daily segments in detail.
Traversing the eddy set of day i, set this eddy to Ei
Is the CAEi set empty?
N  Y
Updating the state of Ei to “dead”

The best candidate eddy of Ei selecting
Y
N
Tracking the relationship between Ei and Ei+1
Generating the best candidate eddy of Ei (the best CAEi)

Generating the eddy set of day i
Generating the eddy set of day i+1
Generating the set of candidate eddies of Ei (CAEi set)

Inputting eddytree data set of day i
Inputting eddytree data set of day i+1
Generating daily segment
Outputting daily segment

Figure 6. The workflow of tracking for a daily segment.

(1) Initialization: First, the eddy sets for day i and day i + 1 are generated from the eddytree data set. Then, the eddy set on day i will be traversed (set this eddy to Ei).

(2) Generating the best candidate eddy of Ei (the best CAEi): If Ei is not dead on day i + 1, the tracking object Ei + 1 of Ei should be within the search circle with a radius of 0.5° [27] and the eddy core of Ei as the center, based on which the set of candidate eddies of Ei (the CAEi set) is retrieved from the eddy set of day i + 1. If the CAEi set is empty, Ei is dead on day i + 1. If the CAEi set is a nonempty set, the best CAEi is selected based on the largest overlapping area principle and the nearest principle. When one of the best CAEi and Ei is an eddy seed and the other is a multicore eddy/mononuclear eddy, the best CAEi is the tracking object Ei + 1 of Ei only if eddy seed is within the boundary of a multicore eddy/mononuclear eddy. For the other classification of the best CAEi and Ei, the best CAEi is the tracking object Ei + 1 of Ei.

(3) Tracking the relationship between Ei and the best CAEi: If the best CAEi is not the tracking object Ei + 1 of Ei, Ei is dead on day i + 1. Otherwise, based on the common eddygroup, the splitting and merging relationships between Ei and Ei + 1 are tracked by the similarity method with the area overlap ratio as the similarity parameter [31]:

\[ r_1 = \frac{S_{12}}{S_1} \]  \hspace{1cm} (1)

\[ r_2 = \frac{S_{12}}{S_2} \]  \hspace{1cm} (2)
where $S_1$ is the area of eddy E1 and $S_2$ is the area of eddy E2. Moreover, $S_{12}$ is the area of overlap between E1 and E2. The area overlap ratio of eddy E1 with E2 can be represented by $r_1$, whereas the area overlap ratio of eddy E2 with E1 is $r_2$. E2 is the part from E1 when $r_2 \geq 2/3$ (Figure 7) [24]. (On the contrary, E1 is the part from E2 when $r_1 \geq 2/3$. In this paper, we take $r_2 \geq 2/3$ as an example.) In this study, $r_2$ should be no less than 2/3 when eddy E2 is split from eddy E1. Similarly, $r_3$ should also be no less than 2/3 when eddy E3 merges into eddy E1 (Figure 7). If no splitting or merging occurs between them, $E_i + 1$ is alive from $E_i$. Figure 4a,c,d show the possible relationships between $E_i$ and $E_i + 1$. A sink eddy $E_i + 1$ generated from splitting is either an eddy seed within the boundary of $E_i$ or a mononuclear eddy/multicore eddy with its area overlap ratio with $E_i$ being no less than 2/3 and must be in the common eddy group with its sibling eddy (Figure 4c). A source eddy $E_i$ merging into $E_i + 1$ is either a mononuclear eddy/multicore eddy with its area overlap ratio with $E_i + 1$ being no less than 2/3 or an eddy seed within the boundary of $E_i + 1$ and must be in the common eddy group with its sibling eddy (Figure 4d). $E_i + 1$ with no splitting or merging relationship with $E_i$ is alive from $E_i$ (Figure 4a).

\[ r_1 = \frac{S_{12}}{S_1} \]  \[ r_2 = \frac{S_{12}}{S_2} \]  

Figure 7. A diagram depicting area overlap ratio, where $r_2 \geq 2/3$ and $r_3 \geq 2/3$.

(4) Generating daily segment: Finally, when the traversal of the eddy set of day $i$ terminates, the process of tracking the segments for the eddies on day $i$ is finished.

(ii) Branch

Live segments are continuously added to the branch in chronological order until a split segment, merged segment or dead segment appears (Figure 8).

Figure 8. A diagram of tracking for a branch, where the state of the eddy branch on the last day (dark gray circle) of its life is split, merged or dead.

(iii) Eddy-DAG

Nonlinear Eddy-DAGs are tracked by establishing the splitting and merging relationships of branches. Specifically, the splitting and merging relationships between branches are established by the segment, taking the eddy(eddies) on the first day of the life(s) of sink branch(es) as the sink(s) and the eddy(eddies) on the last day of the life(s) of source branch(es) as the source(s). Figure 9 reveals the details of constructing a nonlinear Eddy-DAG.
mononuclear eddies/multicore eddies and eddy seeds are black dots.

Figure 9. A diagram of constructing a nonlinear Eddy-DAG. The branches with a merging relationship are taken as an example, where the merging relationship among eddy branches (branch1, branch2 and branch3) is established by the segment, taking the eddies on the last day of the lives of branch1 and branch2 as the sources and the eddy on the first day of the life of branch3 as the sink.

3. Results

3.1. Statistics of the Tracking Data Set

Based on the eddytree data set spanning 27 years (January 1993–December 2019), we tracked 1,023,713 branches. A total of 395,307 Eddy-DAGs were established from these branches, including 103,220 nonlinear Eddy-DAGs and 292,087 linear Eddy-DAGs. In addition, 103,220 splitting events and 202,281 merging events were contained within the nonlinear Eddy-DAGs (Table 1). Figures 10 and 11 demonstrate a splitting merging event and a merging splitting event, respectively, from our data set. Our eddy tracking EddyGraph data set (1993–2019) in the Northwest Pacific Ocean (105°E–165°W, 0°N–60°N) is available at http://data.casearth.cn/sdo/detail/60cc550f819aec69f61fe8f9 (accessed on 22 June 2021).

Table 1. The numbers of branches and Eddy-DAGs of anticyclonic and cyclonic eddies during January 1993–December 2019 in the Northwest Pacific Ocean (105°E–165°W, 0°N–60°N).

|                      | Anticyclonic Eddy | Cyclonic Eddy | Total   |
|----------------------|-------------------|---------------|---------|
| Branches             | 497,339           | 526,374       | 1,023,713 |
| Eddy-DAG             | 190,594           | 204,713       | 395,307  |
| Nonlinear Eddy-DAG   | 490,34            | 541,86        | 103,220  |
| Linear Eddy-DAG      | 141,560           | 150,527       | 292,087  |
| Splitting event      | 72,224            | 74,198        | 146,422  |
| Merging event        | 98,157            | 104,124       | 202,281  |

3.2. Extraction of Typical Events

We chose the events with source branch(es) whose lifetimes all exceeded 14 days and where there were eddies on all branches as typical eddy splitting and merging events during January 1993–December 2019. In total, 6194 anticyclonic eddy splitting events, 5973 cyclonic eddy splitting events, 4764 anticyclonic eddy merging events and 4439 cyclonic eddy merging events were extracted.

Figure 12 shows the geographical distributions of the numbers of typical merging and splitting events for anticyclonic and cyclonic eddies during January 1993–December 2019 at each 1° × 1° grid point in the Northwest Pacific Ocean (105°E–165°W, 0°N–60°N). Typical eddy merging and splitting events are observed in the mid- and high-latitude regions of the study area, while the occurrence frequencies of typical eddy splitting and merging events are comparatively high in the areas around the Sea of Japan, the Thousand Islands and the Aleutian Islands. The scarcity of typical eddy splitting and merging events in the Kuroshio Extension is noted, which is consistent with the relatively low number of eddies in this region reported by Chelton et al. (2011) [17].
Figure 10. A splitting event of a cyclonic eddy detected by our algorithm. Mononuclear eddies/multicore eddies and eddy groups are blue lines and black lines, respectively, while the eddy cores of mononuclear eddies/multicore eddies and eddy seeds are black dots.

Figure 11. A merging event of anticyclonic eddies detected by our algorithm. Mononuclear eddies/multicore eddies and eddy groups are represented by red lines and black lines, respectively, while the eddy cores of mononuclear eddies/multicore eddies and eddy seeds are expressed by black dots.
4. Validation

4.1. Verification with Remote Sensing Observations

Mesoscale eddies can effectively transport heat to redistribute temperature, which means that temperature anomalies inside individual eddies tend to move with those eddies [7,8]. For the temperature anomaly structures induced by individual eddies, two patterns have been proposed [1,8,9], including monopole pattern and dipole pattern, which correspond to two mechanisms responsible for the eddy heat flux: the average isopycnal surface displacements caused by eddies [7,12,17,37] and the horizontal advection of the background gradient by eddy rotation [3–5]. Consequently, the composite structure of eddy-induced SSTA is a linear combination of monopole structures and dipole structures [8,9].

As a fluid structure representing the spatial connection of the sink eddies in splitting events or the source eddies in merging events, a common eddygroup allows us to analyze how splitting and merging events change over a time period around the day of splitting or merging. As shown in Figure 13a, the source branches from day t1 to day t2 during a merging event are within a common eddygroup. We projected the common eddygroups on each merging event source branch from t1 to t2 into six time periods according to the time span. For individual merging events, the number of eddygroups in each time period may be more than one; in this case, the first eddygroup in each time period would be used for normalization. After the source branch projection of all typical merging events (Figure 13a), the SSTA signals within the interiors of the eddygroups in each time period were composited (Figure 14a) to represent the cumulative signal of merging eddies in the common eddygroup of all events during different stages of merging. For the splitting event, the last six days of eddies on the event source branch were projected into six time periods (Figure 13b), and the eddies during each time period were composited in the same way [1,8,9] (Figure 14b). Furthermore, the first six days of eddies (eddygroups) on the sink branch in a merging (splitting) event correspond to six time periods as shown in Figure 13a.

Figure 12. The census statistics of the numbers of typical eddy splitting and merging events in each $1^\circ \times 1^\circ$ region over the 27-year period (January 1993–December 2019) in the Northwest Pacific ($105^\circ$E–$165^\circ$W, $0^\circ$N–$60^\circ$N). AM, CM, AS and CS denote the typical merging events and splitting events of anticyclonic eddies and cyclonic eddies.
(Figure 13b). In conclusion, each splitting (merging) event process corresponds to 12 time periods as different stages of the event, and the SSTA signals of the eddygroups or eddies during each stage for all splitting (merging) events are composited to present how the eddies change and develop in the process of splitting (merging).

![Figure 13. The temporal normalization of eddy merging and splitting events: in which (a,b) represent the source eddy/eddies and sink eddy/eddies of a merging event and a splitting event, respectively, being projected into different time periods.](image)

![Figure 14. The spatial normalization of an eddygroup and eddy, where (a,b) are simplified representations of the eddygroup and eddy coordinate systems, respectively. In the eddygroup coordinate system (a), the x-axis is determined by the eddy cores of eddy1 and eddy2 and points eastward. The coordinate center O is the midpoint between p1 and p2, which are the intersections of the boundaries of eddy1 and eddy2 with the x-axis. In the eddy coordinate system (b), the coordinate center O is the eddy core and the positive direction of the y-axis points north. Any point A1 in the coordinate system used for normalization will be found in both the eddygroup and the eddy according to (θ, ρ).](image)

An 18-day running average filter was applied to the SSTA data to attenuate the variability with periods shorter than 2–3 weeks, and a high-pass filter was implemented to remove large-scale SSTA variability unrelated to the influence of mesoscale eddies [1]. The typical events over the 24-year period (January 1996–December 2019) were used for the SSTA composite analysis within the interiors of eddies and eddygroups during splitting (merging) events. Table 2 shows the numbers of events employed for the normalization. The resulting SSTA composite averages for the splitting and merging events of anticyclonic and cyclonic eddies are presented in Figures 15 and 16. The gradual evolution from a splitting eddy into eddies within the same parent eddygroup (Figures 15a and 16a) and the degeneration from merging eddies in a common eddygroup to an eddy (Figures 15b and 16b) for both anticyclonic and cyclonic eddies are consistent with our expectations for eddy
splitting and merging events described in Section 2.2.2. The SSTA composite averages of
cyclonic eddies during splitting (merging) events present obvious monopole structures
(Figure 16a,b), which are likely related to the elevation of the isopycnic surfaces typically
associated with cyclonic eddies [7,12,17,37]. In contrast, the SSTA composite averages
within the interiors of anticyclonic eddies during splitting (merging) events present a
linear combination of monopole and dipole structures (Figure 15a,b), which are likely
related to the depression of the isopycnic surfaces typically associated with anticyclonic
eddies [7,12,17,37] and the lateral phase alignment between the temperature anomaly
fields [3–5], respectively. Moreover, the two source eddies in the merging event depicted
in Figures 15b and 16b have an unequal intensity, which corresponds to the tendency of
merging eddies to manifest as a stronger eddy merging with a weaker eddy [33].

Table 2. The numbers of typical anticyclonic/cyclonic eddy splitting/merging events used for the
eddy-induced SSTA composite analysis during January 1996–December 2019.

| Anticyclonic Eddy | Anticyclonic Eddy | Cyclonic Eddy | Cyclonic Eddy |
|-------------------|-------------------|---------------|---------------|
| Splitting Event   | Merging Event     | Splitting Event | Merging Event |
| 5500              | 4231              | 4584          | 3945          |

The SSTA composite averages of anticyclonic eddy during the splitting

![Image](a)

The SSTA composite averages of anticyclonic eddy during the merging

![Image](b)

Figure 15. The SSTA composite averages of anticyclonic eddy during the splitting and merging over the 24-year period (January 1996–December 2019), where (a,b) represent eddy splitting process and eddy merging process, respectively. The top panel and the bottom panel represent the source branch and sink branch of the event, respectively, for both Figure 15a,b. Moreover, T is the day of splitting or merging.
4.2. Verification with In Situ Data

We matched the merging event of a cyclonic eddy with the loopers of drifters in Lagrangian trajectories (Figure 17a). Two or more drifters in Lagrangian trajectories can be considered as loopers in Lagrangian trajectories [34], which is described in Section 2.1. In our trajectories, eddy1 and eddy2 appeared on 20100409 and 20100530, respectively, and eventually merged into eddy3 with a lifetime of 20100908–20100927. Consequently, the sudden disappearance of the two loopers (Figure 17a) is difficult to understand. We searched the data set of drifters in the period of this event, and the trajectories of drifters over 20100530–20100927 are expressed in Figure 17b. As expected, drifter 81,801 lived in eddy2 until 20100728, whereas drifter 94,155 remained in eddy1 during the whole event. It is worth noting that the trajectories of the two drifters resemble the trends of the eddies and rotate along the axis of the eddy core, which validates the authenticity of these three eddies detected by our algorithm. The signal of drifter 81401 was lost during 20100728–20100808 but reappeared within the interior of eddy1 on 20100809, the beginning of the looper trajectories (Figure 17a), which may have been caused by the eddy1 and eddy2 interaction. This merging event demonstrates that loopers are not adequately complete due to the Lagrangian tracking method without considering the splitting and merging of eddies. Furthermore, the algorithm of eddy splitting and merging proposed in this paper could contribute to the tracking of eddies.

![The SSTA composite averages of cyclonic eddy during the splitting](image1)

![The SSTA composite averages of cyclonic eddy during the merging](image2)

**Figure 16.** The SSTA composite averages of cyclonic eddy during the splitting and merging over the 24-year period (January 1996–December 2019), where (a,b) present eddy splitting process and eddy merging process, respectively. The top panel and the bottom panel represent the source branch and sink branch of the event, respectively, for both Figure 16a,b. Moreover, T is the day of splitting or merging.
Figure 17. A comparison of the trajectories of a cyclonic eddy merging event detected by our algorithm with the trajectories of loopers in Lagrangian trajectories (a) and drifters (b). The loopers complete at least two drifter orbits in Lagrangian trajectories. Eddy1 (red solid line) and eddy2 (blue solid line) during 20100530–20100927 approach one another and eventually merge into eddy3 (orange solid line) in the event trajectories detected by our algorithm. The trajectories of drifters in (a) are the loopers in Lagrangian trajectories, while the trajectories of drifters in (b) are complete trajectories of drifters during this merging event detected by our algorithm EddyGraph. The black dashed line corresponds to the time period (20100728–20100808) in which the signal of drifter 81801 was lost. To express the changes in the shapes of eddies more clearly, the boundaries of each eddy in the middle of its life are shown here in seven-day intervals.

5. Discussion and Conclusions

Mesoscale eddies play important roles in the exchange of energy and mass transport. The tracking algorithm for eddy splitting and merging can not only improve our understanding of the time-dependent behavior of ocean eddies but also promotes the study of eddies. At present, automated eddy splitting and merging tracking algorithms are still in a stage of exploration, and few automated algorithms track eddies that split and merge [23,32,33]. Furthermore, no corresponding data set of eddy trajectories that considers splitting and merging behaviors has been published, and no data validation has been presented. This paper proposes an algorithm named EddyGraph for the tracking of eddy splitting and merging events. The data set of eddy trajectories over the 27-year period from January 1993 to December 2019 in the Northwest Pacific is available at http://data.casearth.cn/sdo/detail/60cc550f819aec69f61fe8f9, accessed on 14 February 2021, which would fill gaps in data sets to support studies on eddy splitting and merging in the Northwest Pacific (105°E–165°W, 0°N–60°N). The eddytree data set
representing a spatial topological tree structure of closed SLA contours with eddies as the leaf nodes and eddysgroups as the intermediate nodes is obtained based on a multilevel eddy identification algorithm. In our tracking algorithm, only eddies contained within a common eddysgroup are tracked as sources in merging events or as sinks in splitting events. Moreover, as a fluid structure representing the spatial connection of the sink eddies in splitting events or the source eddies in merging events, a common eddysgroup allows us to analyze how splitting and merging events change over a time period around the day of splitting or merging. Twelve continuous time steps of SSTA signals inside eddysgroups and eddies in typical splitting and merging events were composited during January 1996–December 2019. The degeneration pattern in which eddies in the same eddysgroup merge into an eddy and the evolution pattern in which an eddy splits into eddies in the common parent eddysgroup confirm the authenticity of our algorithm. In addition, we matched a merging event of cyclonic eddies with drifters and loopers in eddy Lagrangian trajectories. A comparison between the trajectories from our data set and those of loopers confirms that our tracking algorithm is effective in improving the Lagrangian trajectories of mesoscale eddies.

Much work remains to be accomplished in the future. First, a global data set will be identified with improvements in computational efficiency. Second, in this study, we extracted typical events for validation due to the limited accuracy of our data set caused by the SLA data resolutions; the accuracy of our data set can be optimized with improvements in data resolution promoted by the progress of ocean remote sensing technology [38]. Third, our algorithm for tracking eddy splitting and merging events is based on the nature of eddies in two-dimensional SLA data. However, eddies are ocean phenomena with a three-dimensional structure [7]. Therefore, a tracking algorithm for three-dimensional eddy splitting and merging events will be studied in the future.

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