Key Points:
- For most ocean locations, chlorophyll variances measured in Eulerian and Lagrangian perspectives are not statistically different
- In some western boundary currents, chlorophyll variance was greater in the Lagrangian perspective
- In some key upwelling zones and boundary current extensions, chlorophyll variance was greater in the Eulerian perspective

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A Global Comparison of Marine Chlorophyll Variability Observed in Eulerian and Lagrangian Perspectives

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Abstract Ocean chlorophyll time series exhibit temporal variability on a range of timescales due to environmental change, ecological interactions, dispersal, and other factors. The differences in chlorophyll temporal variability observed at stationary locations (Eulerian perspective) or following water parcels (Lagrangian perspective) are poorly understood. Here we contrasted the temporal variability of ocean chlorophyll in these two observational perspectives, using global drifter trajectories and satellite chlorophyll to generate matched pairs of Eulerian-Lagrangian time series. We found that for most ocean locations, chlorophyll variances measured in Eulerian and Lagrangian perspectives are not statistically different. In high latitude areas, the two perspectives may capture similar variability due to the large spatial scale of chlorophyll patches. In localized regions of the ocean, however, chlorophyll variability measured in these two perspectives may significantly differ. For example, in some western boundary currents, temporal chlorophyll variability in the Lagrangian perspective was greater than in the Eulerian perspective. In these cases, the observing platform travels rapidly across strong environmental gradients and constrained by the shelf topography, potentially leading to greater Lagrangian variability in chlorophyll. In contrast, we found that Eulerian chlorophyll variability exceeded Lagrangian variability in some key upwelling zones and boundary current extensions. In these cases, variability in the nutrient supply may generate intermittent chlorophyll anomalies in the Eulerian perspective, while the Lagrangian perspective sees the transport of such anomalies off-shore. These findings aid with the interpretation of chlorophyll time series from different sampling methodologies, inform observational network design, and guide validation of marine ecosystem models.

Plain Language Summary The differences in phytoplankton variability through time observed at fixed locations (Eulerian perspective) or following water parcels (Lagrangian perspective) are poorly understood. We created a large set of satellite chlorophyll matched time series pairs in the Eulerian and Lagrangian perspective, using global drifter trajectories as an approximation of how surface ocean currents move. We found that for most ocean locations, chlorophyll variability measured in Eulerian and Lagrangian perspectives is not different. In high latitude zones, chlorophyll appears to vary similarly over large areas. However, in localized regions of the ocean, such as western boundary currents and upwelling regions, chlorophyll variability in these two perspectives may significantly differ. The causes are linked to the specific ocean dynamics of each area.

1. Introduction

Phytoplankton sustains marine food webs and are a fundamental component of Earth's biogeochemical cycles of carbon, oxygen, and other elements (Falkowski, 1994; Field et al., 1998). Observed marine phytoplankton biomass and chlorophyll time series are often very noisy (Uz & Yoder, 2004; Widdicombe et al., 2010), reflecting fluctuations in the environment but also interactions between organisms, their resources, and grazers (Agarwal et al., 2021; Edwards et al., 2013; Kuhn et al., 2019; Margalef, 1978). Dispersal of phytoplankton by currents and turbulent mixing contributes to this variability in phytoplankton time series (Clayton et al., 2013; Uz & Yoder, 2004). Hence, understanding marine phytoplankton population dynamics is challenging due to the movement in space of the organisms themselves, but also their nutrient resources, competitors, and predators (Clayton et al., 2013; Doblin & Van Sebille, 2016; Lévy et al., 2014).

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Studies of phytoplankton in the ocean are often restricted by the Eulerian (i.e., fixed in space) nature of most ecological observing programs. However, populations and communities rarely remain in one place for long, and organisms can be dispersed great distances rapidly (Doblin & Van Sebille, 2016; Jönsson & Watson, 2016; Villarino et al., 2018). Changes in phytoplankton communities observed in a Lagrangian perspective (i.e., following water parcels) may therefore be different from what is observed at a single, stationary location, yet to date little is known about how measurements of phytoplankton communities differ between these contrasting observational perspectives (e.g., McKee et al., 2022). To date, most of our measurements of chlorophyll variability are Eulerian in nature (i.e., from long term in situ field stations, or looking from satellite time-series at the same grid points). What are we missing by not considering the Lagrangian variability? Different observational approaches may be needed depending on the specific research questions or parts of the system being studied. For example, changes in the planktonic community due to bottom-up and top-down ecological processes may be better tracked using Lagrangian platforms, while impacts from physical mixing might be better tracked by a Eulerian platform. Our ultimate goal is to advance the understanding of how the nature of phytoplankton observations, which are predominantly fixed, affects our interpretation of ecological variability.

As a first step toward this goal, in this study we compared the temporal dynamics of phytoplankton variability in a stationary and in a moving reference frame (i.e., Eulerian vs. Lagrangian perspectives), using satellite chlorophyll as a proxy for phytoplankton biomass and ocean drifter trajectories as a proxy for advection of surface water masses. We used these global compilations of data to ask: (a) Does phytoplankton chlorophyll variability observed in Eulerian and Lagrangian perspectives differ, and by how much? and (b) In which regions of the ocean do the Eulerian and Lagrangian perspectives give a similar view of ecological change through time, and where are they different? We hypothesized that in the Eulerian perspective, transport of organisms by ocean currents and other processes across the observing point would increase the phytoplankton population variability in contrast with a Lagrangian perspective, where the observer moves with the phytoplankton population. This would imply that: (a) phytoplankton chlorophyll time series observed in an Eulerian perspective would generally be more variable than in the Lagrangian perspective, and (b) very dynamic regions of the ocean, such as western boundary currents, would show larger differences between Eulerian and Lagrangian perspectives, in contrast with regions of the ocean with weaker currents and mixing, such as the center of ocean gyres.

In disagreement with our initial hypotheses, we found that for most of the time series pairs, chlorophyll variance measured in Eulerian and Lagrangian perspective was not statistically different. However, in certain key regions, chlorophyll variance significantly differed between these two observational perspectives. Understanding how the observed variability is impacted by the choice of measurement platform has direct relevance for how we interpret observed ecological and biogeochemical patterns at time series stations, how we design biological observational networks, and how we parameterize and evaluate phytoplankton in ocean models which often rely on observational data from combined sources.

2. Methods

We conducted a global comparison of chlorophyll variability in Eulerian and Lagrangian perspectives by matching global surface drifter trajectories with satellite chlorophyll records between 1997 and 2018. In the following sub-sections, we introduce the sources of data and then describe the protocols for analysis.

2.1. Satellite Chlorophyll Data

We used daily satellite chlorophyll data (Figures 1a and 1b) from the 4-km resolution version 3.1 of the European Space Agency Ocean Colour—Climate Change Initiative (ESA OC-CCI) from September 1997 to June 2018 (Lavender et al., 2015; Sathyendranath et al., 2020). The OC-CCI 3.1 product includes globally merged Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Moderate Resolution Imaging Spectroradiometer on the Aqua Earth Observing System (MODIS-Aqua), Visible Infrared Imaging Radiometer Suite, and Medium Resolution Imaging Spectrometer data, with per-pixel information on errors and uncertainty (Jackson et al., 2017). Compared to the information from individual sensors and precursor merged datasets, the OC-CCI product provides improved coverage, error characterization, and reduced bias (Belo Couto et al., 2016).
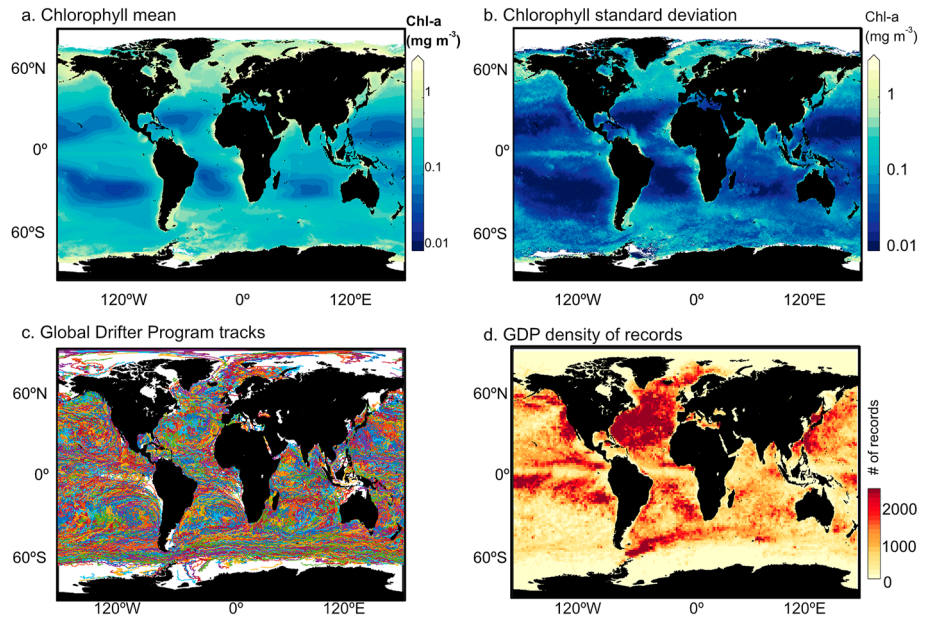
Figure 1. Summary of the chlorophyll and surface drifter data used in the analyses: (a) Chlorophyll mean (1997–2018) from the ESA OC-CCI 4-km daily product; (b) Chlorophyll standard deviations, calculated over the entire record at each grid cell; (c) Composite of 18,731 Global Drifter Program (GDP) drifter tracks between 1997 and 2018 (where colors indicate separate drifter tracks); and (d) Density of GDP records on a ¼° grid (i.e., the count of how many times a given latitude and longitude was recorded by a drifter in each grid bin).

2.2. Global Drifter Program (GDP) Data

The GDP maintains satellite-tracked surface drifting buoys, which measure latitude and longitude position through time, with some drifters retrieving additional environmental measurements (Elipot et al., 2016; Lumpkin & Centurioni., 2019). The drifters are drogued to approximately 15 m depth, such that their horizontal movements broadly reflect horizontal currents in the ocean surface. We evaluated quality-controlled 6-hr trajectories from 18,731 drifters deployed in all major regions of the ocean within the dates of satellite coverage (Figures 1c and 1d). The average lifetime of a drifter was 1.5 years. When the drifter drogue is lost and during high wind speed conditions, drifters may not follow surface currents (Grodsky et al., 2011). We excluded from our analysis any trajectory data acquired after a drogue was lost and when wind speed exceeded 10 ms^{-1} (Lumpkin & Pazos, 2007; Poulain et al., 2009). As not all drifters measure wind speed, ECMWF Reanalysis v5 (ERA5; Hersbach et al., 2017) data was matched to the drifters for this purpose.

2.3. Protocols for Analysis

We compared the temporal variability of chlorophyll at stationary locations and along trajectories defined by drifters. Because phytoplankton correlation timescales in most of the global ocean are estimated to be shorter than 30 days (Kuhn et al., 2019), we limited our analysis to drifters with 30-day trajectories or longer. We divided each drifter track into non-overlapping 30-day segments and obtained a pair of Eulerian and Lagrangian satellite chlorophyll time series for each segment. We defined the Eulerian time series using daily satellite chlorophyll at the initial location of each segment. In a preliminary analysis, we found that using the end location produces qualitatively similar results. Using the intermediate location along each segment increased the similarity of chlorophyll variance between the series, as the elapsed time between either the initial or final Lagrangian locations was essentially halved. We created the Lagrangian time series using daily satellite chlorophyll values at matching dates along the trajectory of each segment using the latitude and longitude position of the drifter. As we used daily chlorophyll resolution and the drifters update location every 6 hours, there were four different possible locations to match chlorophyll on any given day. We selected the second spatial location (i.e., approximately midday GMT) in every segment for consistency.

Following the above procedure, we created a large ensemble of paired Eulerian and Lagrangian chlorophyll time series over the global ocean. We only included in our results those segments with at least 20% of data (i.e., less than 80% missing values). Out of the total number of drifters evaluated (18,731), we found 21,360 segments that matched our criteria (out of 77,473 total segments). We compared Eulerian-Lagrangian chlorophyll time series pairs in terms of their variance and discuss how phytoplankton correlation scales and gaps in the satellite chlorophyll record affect our results.

3. Results

First, we examined whether there was a coherent global difference between pairs of Eulerian and Lagrangian chlorophyll time series (Figure 2). In Figure 2a, values above the 1:1 relationship line indicate the number of segments where chlorophyll was more variable in the Eulerian perspective than in the Lagrangian perspective (n_E). Values below the 1:1 relationship indicate the number of segments where chlorophyll was more variable in the Lagrangian perspective (n_L). n_E and n_L represent 52.25% and 47.75% of the total number of segments analyzed, respectively. Hence, our global analysis showed only a small excess ($\Delta n = 960$ segments or 4.5%) in the number of segments where the Eulerian perspective generated a more variable chlorophyll time series compared to the Lagrangian perspective. For most pairs of segments, the Eulerian and Lagrangian chlorophyll variances were similar, indicated by the clustering of points along the 1:1 line. Large differences between Eulerian and Lagrangian chlorophyll variance ($\Delta \sigma^2 = \sigma_E^2 - \sigma_L^2$) occurred, with a few segments exhibiting variance differences larger than 1 (mg Chl m^{-3})^2. However, in disagreement with our initial hypothesis, neither the Eulerian nor the Lagrangian chlorophyll variances appeared to be consistently higher than the other in the global ocean results.

We tested the significance in variance differences using a Levene test (Glass, 1966). In this test, p-values below the significance level (here $p < 0.05$) suggest that the two variances (σ_L^2 and σ_E^2) were unlikely to come from random sampling of the same population. Only 20% of the analyzed segment pairs exhibited significant variance differences between the Eulerian and Lagrangian chlorophyll (Figure 2b). Non-significant comparisons of variance primarily corresponded to segments with very low $\Delta \sigma^2$, as more than 50% of the segments exhibited $\Delta \sigma^2$ lower than 2×10^{-4} (mg Chl m^{-3})^2.

When considering only segments with significant differences in chlorophyll variance (denoted with *), the bias toward a more variable Eulerian chlorophyll in the global ocean slightly increased. The number of segments where chlorophyll was significantly more variable in the Eulerian perspective than in the Lagrangian perspective ($n_E^* = 2,205$ segments) now corresponded to 54.1% of the total number of segments with significant $\Delta \sigma^2$, while the opposite ($n_L^* = 1,872$) represented 45.9%. This was an excess of 8.2% in the number of segments where the Eulerian perspective generated a significantly more variable chlorophyll timeseries compared to the Lagrangian perspective ($\Delta n^* = 333$ segments). Based upon our global analyses of these paired chlorophyll time series (Figures 2a and 2b), we conclude that there is a slight global tendency for chlorophyll observed in the Eulerian perspective to be more variable than chlorophyll in the Lagrangian perspective. In other words, we did not find unequivocal support for our initial hypothesis that Eulerian chlorophyll variance would generally exceed Lagrangian chlorophyll variance.

We next assessed whether statistically significant variance differences between paired segments occurred in specific regions. We constructed a global map of the difference in the number of segments that exhibited significantly different variance in either Eulerian or Lagrangian perspectives, relative to the total number of significant comparisons (% Δn^*; Figure 2c):

$$\% \Delta n^* = \frac{(n_E^* - n_L^*)}{(n_E^* + n_L^*)} \times 100 \qquad (1)$$

In this global map, several western boundary currents appear to have more segments in which the Lagrangian chlorophyll time series variance is higher than the Eulerian counterpart (% Δn^* is negative/red; Figure 2c). This is most noticeable in the Gulf Stream area, the Brazil Current, the Malvinas Current, and the East Madagascar Current. The Kuroshio Current region exhibited a similar pattern, but only near its origin northeast of the Philippines, and the East Australian current exhibited a similar pattern only in its southern extension, east of Tasmania. Negative % Δn^* was also found in the Canary Current, an eastern margin of continents, the Hawaii archipelago, and the South Pacific gyre. In contrast, noticeable areas where the majority of segments were more variable in the Eulerian perspective (% Δn^* is positive/blue; Figure 2c) were found in the Eastern Equatorial Pacific,
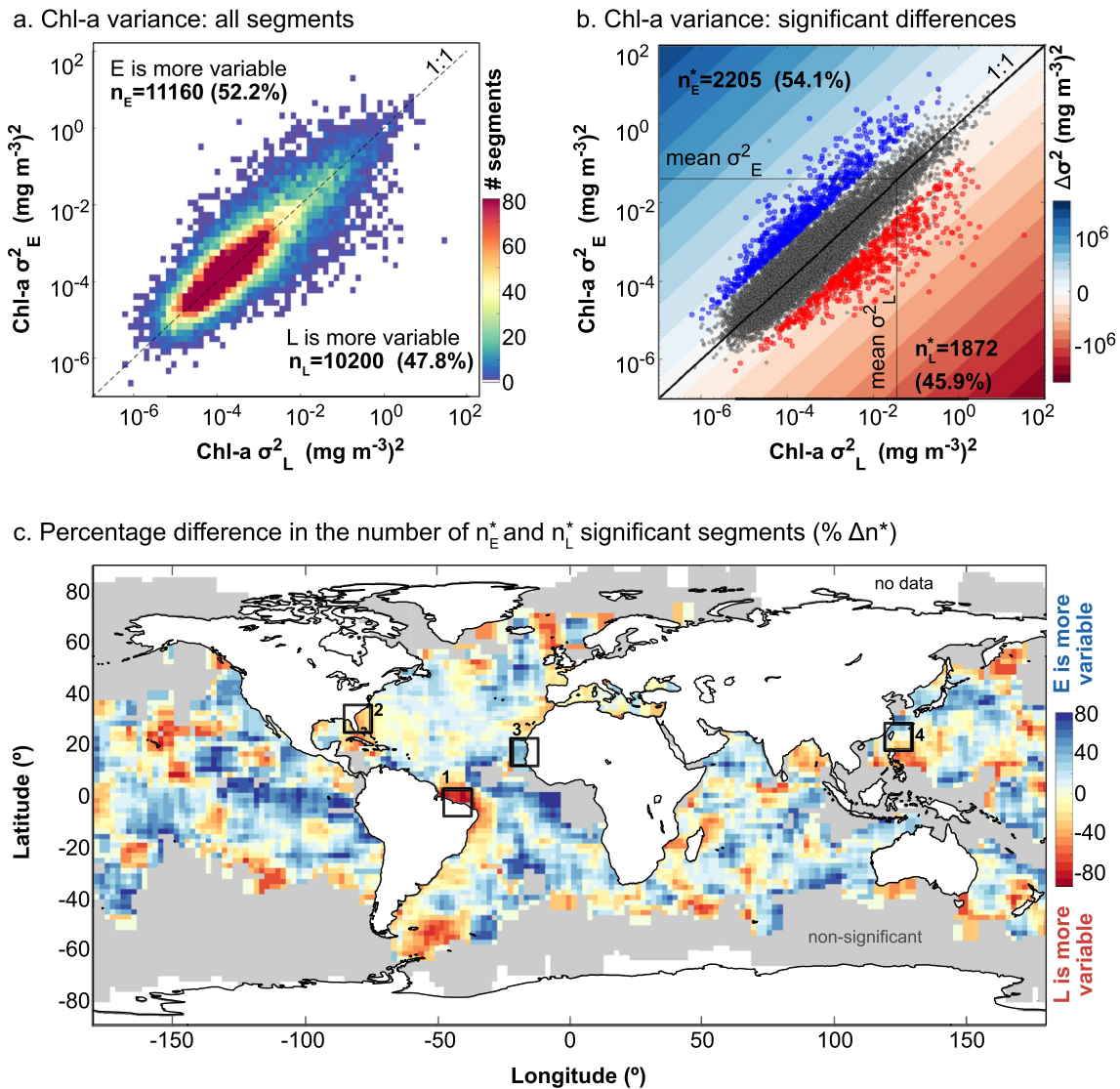
Figure 2. Comparison of chlorophyll variance estimated from Eulerian and Lagrangian time series: (a) Bi-dimensional histogram of Eulerian (σ_E^2) versus Lagrangian chlorophyll variance (σ_L^2) in paired segments. The dashed line represents the 1:1 relationship. n_E and n_L are the number of segments above and below the 1:1 line, respectively. (b) Eulerian (σ_E^2) versus Lagrangian chlorophyll variance (σ_L^2) in paired segments. The red and blue color background is shown as a reference of isolines of equal chlorophyll variance difference ($\Delta\sigma^2 = \sigma_E^2 - \sigma_L^2$). The points in the scatter plot represent the paired Eulerian-Lagrangian chlorophyll variances for each of the segments. Blue and red markers represent segments where the Eulerian or Lagrangian chlorophyll variance is significantly greater than the other (Levene $p < 0.05$), and gray markers represent statistically non-significant differences in variance. The diagonal red solid line shows the 1:1 relationship and the black solid lines depict the mean Eulerian and Lagrangian variance (horizontal and vertical lines, respectively). n_E^* and n_L^* are the number of segments with significant differences above and below the 1:1 line, respectively. (c) Global distribution of the percentage of segments where Eulerian or Lagrangian chlorophyll is more variable than the other perspective (% Δn^*; Equation 1). Values were estimated in overlapping 10° by 10° bins every 2° latitude and longitude. Ocean areas where no significant Eulerian—Lagrangian differences were found are shown in gray, and areas where no data was available for the comparison are shown in white. Black squares mark regions examined in more detail in Figure 3.

Eastern Equatorial Atlantic, and key coastal upwelling areas, including the Northwest Africa upwelling, the Benguela Current System, and the California Current System. Positive % Δn^* was also found in western boundary currents extensions, such as in the Kuroshio and Gulf Stream systems. A global map of the average distance traveled by each segment can be found in the supplement (Figure S1 in Supporting Information S1). Some of the differences between these two contrasting patterns ($\sigma_E^2 > \sigma_L^2$ dominant and $\sigma_E^2 < \sigma_L^2$ dominant) appear to be related to the distance and dominant orientation in which the segment travels; that is, whether it moves along or across latitudinal gradients (Figure S1d in Supporting Information S1). For example, drifters in the Gulf Stream travel great meridional distance, and also exhibit more Lagrangian than Eulerian variance.
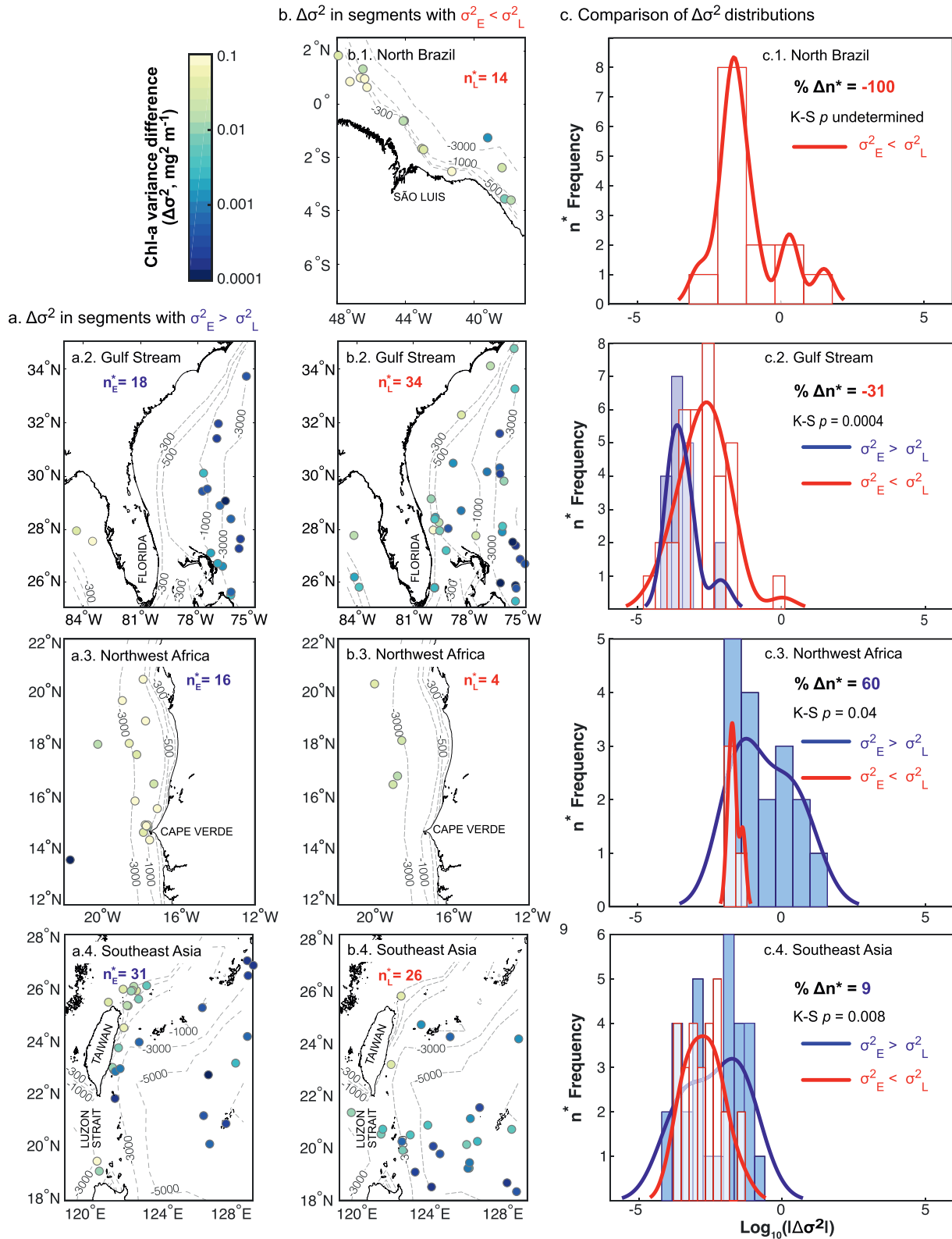
Figure 3. Regional examples of the distribution of absolute chlorophyll variance differences ($|\Delta\sigma^2| = |\sigma_E^2 - \sigma_L^2|$) in segments. The four regions correspond to the black boxes (1–4) in Figure 2c. (a) Variance differences in segments where Eulerian chlorophyll is more variable ($\sigma_E^2 > \sigma_L^2$); n_E^* is the number of segments in the map. (b) Variance differences in segments where Lagrangian chlorophyll is more variable ($\sigma_E^2 > \sigma_L^2$); n_L^* is the number of segments in the map. (c) Comparison of the distributions of absolute chlorophyll variance differences in $\sigma_E^2 > \sigma_L^2$ (blue) and $\sigma_E^2 > \sigma_L^2$ (red) segments. The significance of differences in the $|\Delta\sigma^2|$ distributions was tested with a Kolmogorov-Smirnoff test (K-S $p < 0.05$). The % Δn^* value, estimated as in Equation 1, Figure 2c is shown for each example.

Therefore, while the global analysis did not show a robust contrast between Eulerian and Lagrangian chlorophyll variance (Figures 2a and 2b), we found regions where coherent significant variance differences occurred (Figure 2c). We examined a number of these regions in more detail and found that the spatial distribution of segments where either Eulerian or Lagrangian chlorophyll variance was significantly higher than its counterpart (i.e., $\sigma_E^2 > \sigma_L^2$ and $\sigma_E^2 < \sigma_L^2$) exhibited small-scale patterns that correspond to local oceanographic characteristics (Figures 3a and 3b). For these examples, the significance in the difference between the distributions of $\sigma_E^2 > \sigma_L^2$ and $\sigma_E^2 < \sigma_L^2$ segments was tested with a Kolmogorov-Smirnoff test (K-S $p < 0.05$; Figure 3c).

Segments with Lagrangian chlorophyll variance higher than its Eulerian counterpart were predominantly found along western boundary currents. For example, in the Brazil Current, no segments with $\sigma_E^2 > \sigma_L^2$ were found (Figures 3b1 and 3c13). Similarly, in the Gulf Stream region between the Florida Peninsula and Cape Hatteras in the Eastern Coast of the USA, segments with a significant $\sigma_E^2 > \sigma_L^2$ were largely absent (Figure 3a2). A cluster of segments with $\sigma_E^2 > \sigma_L^2$ was found off the coast, in the deep ocean low chlorophyll variance region (Figure 3a2), while segments with $\sigma_E^2 > \sigma_L^2$ were distributed all over the area, including near the coast (Figure 3b2). Absolute variance difference, $|\Delta\sigma^2|$, also tended to be higher in segments where $\sigma_E^2 > \sigma_L^2$ (Figures 3a2–3c2).

In contrast, segments with Eulerian chlorophyll variance higher than its Lagrangian counterpart were predominantly found in upwelling and eddies formation areas. For example, in the Northwest Africa upwelling region, segments where $\sigma_E^2 > \sigma_L^2$ were scarce and generally distributed further from the coast than segments where $\sigma_E^2 > \sigma_L^2$ (Figures 3a3 and 3b3). In this case, absolute variance difference, $|\Delta\sigma^2|$, tended to be higher in segments where $\sigma_E^2 > \sigma_L^2$ (Figure 3c3). In another more complex example, southeast of Taiwan, a cluster of $\sigma_E^2 > \sigma_L^2$ segments coincided with the origin and intrusion of the Kuroshio current through the Luzon Strait, north of Luzon island (Philippines; Rudnick et al., 2011); while segments $\sigma_E^2 > \sigma_L^2$ grouped tightly east and north of Taiwan, where island wakes induce the formation of eddy trains (Hsu et al., 2017, 2020; Zheng & Zheng, 2014). We note that the number of segment pairs with significant variance difference (total number of *n** segments) is low even in the best sampled regions of the ocean, thus hindering a high-definition global spatial analysis.

4. Discussion

Our initial hypothesis was that a stationary observer (the Eulerian perspective) would generally see greater temporal changes in chlorophyll than an observer moving along with a water parcel (the Lagrangian perspective). We assumed the environment within a moving parcel of water would be relatively stable through time and that biological and ecological changes within the plankton community would also be correspondingly slow. In contrast, the Eulerian perspective would "see" both biological and environmental changes due to different water parcels traveling through the stationary location.

We created a set of 21,360 30-day drifter trajectory segments, matched the corresponding Eulerian and Lagrangian satellite chlorophyll time series pairs, and compared the time series variances globally (Figures 2a and 2b), regionally (Figure 2c), and within specific regions (Figure 3). Only 20% of the segments displayed significant differences in chlorophyll variance estimated from Eulerian and Lagrangian perspectives, with only a slight global tendency toward a more variable chlorophyll in the Eulerian perspective (Figures 2a and 2b). Cases with more variable chlorophyll in the Eulerian perspective and more variable chlorophyll in the Lagrangian perspective were present across the ocean (Figure 2c), corresponding to key local oceanographic features such as western boundary currents and upwelling regions (Figure 3). Thus, we found equivocal and limited support for our initial hypothesis. In the following Discussion section, we address the answers to our initial questions posed in the introduction: (a) Does phytoplankton chlorophyll variability observed in Eulerian and Lagrangian perspectives differ, and by how much? and (b) In which regions do the Eulerian and Lagrangian perspectives give a similar view of ecological change through time, and where are they different? We also elaborate on possible explanations for why we found little support for our initial hypothesis.

4.1. Does Phytoplankton Chlorophyll Variability Observed in Eulerian and Lagrangian Perspectives Differ, and by How Much?

To answer our first question, we found that most of the drifter segments (~80%) showed non-significant differences between Eulerian and Lagrangian chlorophyll variance (Figure 2b). In fact, more than half of the segments analyzed exhibited variance differences lower than 2×10^{-4} (mg Chl m^{-3})^2. We argue that this result is tied
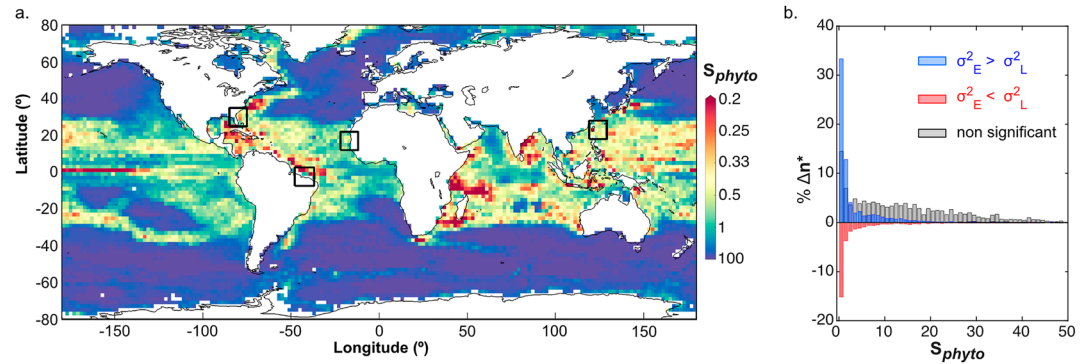
Figure 4. (a) Global estimates of S_{phyto} (Equation 2) with a 2° resolution, using modeled current speed and derived total phytoplankton biomass decorrelation timescales and length scales from Kuhn et al., 2019. (b) Difference in the number of segments that exhibit significantly different variance in either Eulerian or Lagrangian perspectives (% Δn^*, Equation 1) at different S_{phyto} values (with S_{phyto} intervals of 1).

to the characteristic time, length, and velocity scales of patches of chlorophyll in the ocean. We think of a "patch" of chlorophyll as a quasi-stable area of homogeneous surface chlorophyll concentration. The relationship between chlorophyll variability observed in Eulerian and Lagrangian perspectives at any location is then determined by how the patch travels past an Eulerian observer. To evaluate this relationship, we introduce a non-dimensional number, S_{phyto}, to help describe the characteristics of moving patches of chlorophyll in the ocean. S_{phyto} is analogous to the Strouhal number, which is often used to describe oscillatory flow and eddy/vortex shedding (e.g., Hsu et al., 2020), but rarely used to describe moving patches of chlorophyll (e.g., McKee et al., 2022). Here, S_{phyto} is determined by:

$$S_{phyto} = \frac{L}{TU'} \tag{2}$$

where L represents the length scale of the phytoplankton patch (i.e., the linear extent of the patch), T represents the timescale of phytoplankton patch (i.e., how long the patch persists), and U represents the current speed. We argue that the observed chlorophyll variability should be similar for both Eulerian and Lagrangian perspectives when S_{phyto} is large, and different when S_{phyto} is small. For example, if the patch length scale (L) is very large or the time scale (T) is very short compared to the advective speed (U), then S_{phyto} is large and the interpretations are similar in both observational perspectives. As the patch becomes smaller in space (L), longer in time (T), or the advective speed increases (U), S_{phyto} is small, and the observers begin to measure different chlorophyll signals. For small S_{phyto}, whether the Lagrangian chlorophyll variance is higher or lower than the Eulerian one would depend on the characteristics of the phytoplankton community of the source and end waters, environmental gradients, as well as turbulent mixing experienced along the trajectory.

We estimated the global distribution of S_{phyto} (Figure 4) using modeled ocean surface current speeds (U in Equation 2, m s^{-1}) and derived temporal and spatial decorrelation scales (T and L, in days and km, respectively) of total phytoplankton biomass (Kuhn et al., 2019). These decorrelation scales were based on published 24 years of 3-day averaged output from a coupled physical-ecosystem model using the MITgcm (Jahn et al., 2019). Details of the model, the decorrelation scales methodology, and global patterns of phytoplankton timescales and length scales are described in Kuhn et al. (2019). In summary, phytoplankton length scales range from a few kilometers in low latitudes and boundary current areas, to thousands of kilometers in high latitudes and equatorial areas. Phytoplankton timescales are on average 15 days and tend to be lower in areas of high eddy kinetic energy. Ocean surface current speeds range between 0 and 100 km d^{-1}. As these phytoplankton decorrelation scales were based on a long-term record, the phytoplankton spatial decorrelation scales provide an upper boundary estimate of the size of patches in the ocean, and may not reflect the sizes of "true" chlorophyll patches (e.g., as measured in daily chlorophyll snapshots). We thus acknowledge that global values of S_{phyto} here presented may be overestimated. Nonetheless, we found valuable insights in the analysis.

Large areas of the ocean exhibits $S_{phyto} > 1$. That is, the ratio between patch length scale and timescale is larger than the advection time, particularly at high latitudes (Figure 4a), where non-significant variance differences are

common (Figure 2c). Large S_{phyto} values at high-latitudes are due to correspondingly very large phytoplankton decorrelation scales, in the order thousands of kilometers (Kuhn et al., 2019). Significant Eulerian-Lagrangian variance differences are more likely to occur at small S_{phyto} values (Figure 4b). In fact, about 50% of the significant differences in segments we found occur in $S_{phyto} \leq 1$ areas (Figure 4b). Thus, characteristic chlorophyll patch dynamics in much of the mid- to high-latitude ocean mean that chlorophyll in Eulerian and Lagrangian perspectives are likely to be very similar, whereas the opposite is true in subtropical and equatorial regions, particularly in highly dynamic areas of the ocean.

4.2. In Which Regions Do the Eulerian and Lagrangian Perspectives Differ?

For the second question, we focus on the remaining 20% of segments with significant variance differences (only 4,077 segment pairs globally). In these segments, Lagrangian chlorophyll appeared more variable in areas where western boundary currents are moving along the continental shelf break (Figures 3a2, and b2). Eulerian chlorophyll appeared more variable in coastal and Equatorial upwelling areas, as well as in western boundary current extension regions (Figures 3c3, and 3c4). We noticed that the distribution of segments that are more variable in either perspective corresponded to small-scale local oceanographic and topographic characteristics (Figure 3). These general patterns may not be ubiquitous to all similar regions, and cannot yet be generalized. However, we speculate that larger chlorophyll variability tends to occur in the Lagrangian time series when drifter trajectories travel rapidly across strong spatial environmental gradients, in the core of topographically constrained western boundary currents, such as the Gulf Stream (e.g., Parfitt et al., 2022) and Brazil Current (e.g., Ffield, 2005). In contrast, regions where changes in phytoplankton biomass are strongly correlated with local nutrient supply, such as in upwelling zones (e.g., James et al., 2022), tend to show more variable chlorophyll in the Eulerian than Lagrangian perspective. We speculate that, in these cases, the Eulerian perspective encounters intermittent parcels of water which have or have not had input of nutrients, and thus variable chlorophyll concentrations may occur. Chlorophyll anomalies generated in these regions may then be advected or transported off-shore by ocean currents, eddies and horizontal stirring (García-Muñoz et al., 2004, 2004; Jacox et al., 2018), resulting in lower variability in the Lagrangian perspective.

4.3. Effect of Missing Data in the Satellite Record

While satellite chlorophyll measurements contain uncertainty originating from various sources (Boss & Maritorena, 2006), their broad spatial and temporal coverage are necessary for conducting this study. It is possible, however, that uncertainty in satellite chlorophyll measurements may mask real ecological signals in both the Eulerian and Lagrangian frameworks.

In particular, missing data may affect the estimate of chlorophyll variance at any location, thus potentially introducing errors in our global comparison. Despite the improved coverage of the OC-CCI chlorophyll product in comparison with other products, there are regions of the ocean with many gaps in the record due to the orbital frequency of sampling and the presence of clouds and aerosols. High-latitudes are also affected by missing data due to seasonal changes in solar zenith angle (Cole et al., 2012; Gregg & Casey, 2007). In our analysis, high-latitude areas were characterized by fewer segments with significant chlorophyll differences (Figures 2c and 4b). This may be driven by large spatial decorrelation scales of phytoplankton, which generate a large S_{phyto} in these areas (Figure 4a). However, as missing satellite data is more prevalent at high-latitudes, our estimates of the number of segments with significant chlorophyll variance differences may be affected.

To evaluate how missing data affected the recovery of true variance in a chlorophyll time series, we created a suite of 4,000 30-day synthetic chlorophyll time series representing idealized chlorophyll variability scenarios with different amplitudes and frequencies (Figure S2a in Supporting Information S1). We found that, regardless of the characteristics of the time series, 50% of missing data in a 30-day time series produced an averaged error of about 10% in the estimated variance, but the error may be as high as 60% for some cases (Figure S2b in Supporting Information S1). Therefore, our cut-off value of 80% missing data in the segments analyzed may have been too permissive. The cut-off value for missing data was a trade-off between the reliability of the variance estimate and the number of segments included in the analysis. Due to the aforementioned gaps in the high-latitude satellite record, fewer complete time series are found in these areas. There is, thus, higher uncertainty in the high-latitude Eulerian-Lagrangian variance comparison.

4.4. Other Limitations and Future Directions

While this study included 21,360 pairs of Lagrangian and Eulerian chlorophyll time series, this is still a small number given the extent of the ocean, duration of the data coverage, and variability of drifter trajectories. No single drifter represents all possible pathways in any area and time. Even when deployed at only slightly different times and/or locations, Lagrangian trajectories rarely follow the same path (LaCasce, 2008). Thus, evaluating a large number of trajectories is key for a complete understanding of the dynamics of a given area. Furthermore, mesoscale chlorophyll structures do not always strictly follow the path of surface currents, creating instead phytoplankton patches with lobular structures, spirals, and filaments (Lehahn et al., 2007). These complex spatial patterns may arise from the interplay between particle movements and the temporal variability of the velocity field (Lehahn et al., 2018). Therefore, the drifters may not be following the same track as the chlorophyll in some cases.

Thus, there are intrinsic limitations to this type of global analysis using observational data. For a more robust global outcome, Lagrangian trajectories can be analyzed probabilistically with the use of modeled Lagrangian particle trajectories combined with satellite chlorophyll (e.g., Jönsson et al., 2009) or ocean plankton models (e.g., Chenillat et al., 2015). This would not only increase the number of available segments, but using complex plankton models with multiple phytoplankton types (e.g., Dutkiewicz et al., 2019) would also enable the evaluation of changes in the phytoplankton community composition that may not be reflected by changes in total chlorophyll. The advent of the Phytoplankton, Atmosphere, Clouds, ocean Ecosystems (PACE) Earth-observing satellite mission, including an ocean color instrument with multi-spectral capabilities (Gorman et al., 2019), would allow for a robust validation of these model-based results. In addition, regional in-situ comparisons (e.g., fixed locations vs. floats) are necessary to further understand Eulerian and Lagrangian chlorophyll differences in the global ocean.

5. Conclusions

To our knowledge, this is the first systematic global comparison of variances between ocean ecological time series measured in Eulerian and Lagrangian observational perspectives. Within the constraints of the data used in this study, most of the observations suggest that chlorophyll variability in Eulerian and Lagrangian perspectives are not statistically different (Figures 2a and 2b). However, in certain key regions, chlorophyll variance may significantly differ between these two observational perspectives (Figure 2c, Figure 3). Over the course of 30 days, Lagrangian chlorophyll time series in some strong western boundary currents were likely to be more variable than time series observed at a fixed location. In these cases, we speculate that the Lagrangian observational platform "sees" rapid changes while traveling across physical and biogeochemical gradients. These gradients are often associated with locations where topographic changes are abrupt such that the flow becomes unstable or deviates from isobaths, both leading to localized vertical transport. Moreover, environmental and air-sea fluxes do exhibit significant latitudinal variability along meridional flowing currents, potentially leading to enhanced Lagrangian variability. We also showed that in some key coastal and equatorial upwelling regions and western boundary current extensions, Eulerian chlorophyll time series were likely to be more variable than Lagrangian time series. In these cases, we speculate that chlorophyll anomalies are generated locally due to variability in environmental conditions and nutrient supply, and transported by ocean currents and eddies, resulting in higher chlorophyll variability in the Eulerian perspective.

A non-dimensional analysis of the characteristic scales (speed, time scale and length scale) of moving phytoplankton patches in the ocean suggested that significant differences between Eulerian and Lagrangian chlorophyll variances are unlikely to be found where the ratio of phytoplankton correlation length to time scales is much greater than the current speed. Model-derived estimates (Figure 4a) showed that this occurs in high-latitude, where phytoplankton biomass tends to vary coherently over large spatial scales (Kuhn et al., 2019). In agreement with this non-dimensional analysis, we found few significant chlorophyll variance differences at high-latitudes. Results from this Eulerian-Lagrangian comparison may, however, be affected by pervasive gaps in the satellite chlorophyll record.

Our results have implications for: (a) interpreting chlorophyll data from different locations, (b) the design and implementation of observational programs, and (c) using chlorophyll to parameterize, calibrate, and validate ocean ecosystem models. For example, in regions where the Eulerian chlorophyll variance is higher than the

Lagrangian variance, the Eulerian measurement may reflect a high contribution of organisms horizontally transported to the area. For the same region, the Lagrangian observation may better represent changes in the phytoplankton community due to ecological interactions in the moving waters. In addition, our results highlight that dynamic regions of the ocean may require Lagrangian observations for a more accurate interpretation of temporal and spatial ecosystem changes. Regions where Lagrangian chlorophyll is more variable than its Eulerian counterpart may require an increased number of Lagrangian observing platforms or an increased number of fixed observational stations to ensure the proper sampling of spatial-temporal variability. Similarly, places where the Eulerian perspective is more variable that its Lagrangian counterpart may require increased temporal sampling frequency at any fixed given location. Finally, the similarity of chlorophyll variance in vast areas of the ocean may provide confidence for the combined use and merging of observational datasets from different sources for either direct analysis, model validation, and data assimilation. Global ocean models with Lagrangian particle tracking, complex plankton ecosystem models, and advances in ocean color satellite instruments provide new avenues for the refinement and improvement of the results here presented.

Data Availability Statement

For this study, we used publicly available satellite chlorophyll, drifter trajectories and wind speed data. Daily satellite chlorophyll data at 4-km resolution, version 3.1, from September 1997 to June 2018 was obtained from the European Space Agency Ocean Colour—Climate Change Initiative (ESA OC-CCI; Sathyendranath et al., 2020). Drifter trajectories (longitude and latitude locations) were obtained from the Global Drifter Program (GDP; Lumpkin & Centurioni, 2019). Wind speed data was obtained from ECMWF Reanalysis v5 (ERA5; Hersbach et al., 2017). In addition, model data used in this study are publicly available at the UC San Diego Library Digital Collections (Jahn et al., 2019). Eulerian and Lagrangian satellite chlorophyll variance differences estimated in this study are available in a public repository (Kuhn et al., 2023).

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