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**Key Points:**

- The agreement between Lagrangian and Eulerian kinetic energy estimates is evaluated with a twin global numerical simulation experiment
- Lagrangian and Eulerian tidal energies agree best in regions where low-frequency kinetic energy is weak
- Near-inertial energy levels derived from Lagrangian and Eulerian frames of reference closely match compared to other frequency bands

**Supporting Information:**

Supporting Information may be found in the online version of this article.

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# Lagrangian Versus Eulerian Spectral Estimates of Surface Kinetic Energy Over the Global Ocean

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**Abstract** In this study, we conducted a novel massive Lagrangian simulation experiment based on a global 1/48° tide-resolving numerical simulation of the ocean circulation. This first-time twin experiment enables a comparison between Eulerian (fixed-point) and Lagrangian (along-flow) estimates of kinetic energy (KE) across the global ocean, and the quantification of systematic differences between both types of estimations. This comparison represents an important step forward for the mapping of upper ocean high-frequency variability from Lagrangian observations of the Global Drifter Program. Eulerian KE rotary frequency spectra and band-integrated energy levels (e.g., tidal and near-inertial) serve as references and are compared to Lagrangian estimates. Our analysis reveals that, except for the near-inertial band, Lagrangian velocity spectra are systematically smoother, for example, with wider and lower spectral peaks compared to Eulerian counterparts. On average, Lagrangian KE levels derived from spectral band integrations tend to underestimate Eulerian KE levels at low-frequency and tidal bands, especially in regions with strong low-frequency KE. Better agreement between Lagrangian and Eulerian low-frequency and tidal KE levels is generally found in regions with weak low-frequency KE and/or convergent surface circulation, where Lagrangian particles tend to accumulate. Conversely, Lagrangian and Eulerian near-inertial spectra and energy levels are comparable. Our results demonstrate that Lagrangian estimates may provide a distorted view of low-frequency and tidal variance. To accurately map near-surface velocity climatology at these frequencies from drifter database, conversion methods accounting for the Lagrangian bias need to be developed.

**Plain Language Summary** Ocean surface currents play a pivotal role in transporting heat and energy across the global ocean, thereby influencing global climate patterns and marine ecosystems. Despite the significant role of ocean currents in the Earth system, the spatial distributions of high-frequency ocean variability are not known accurately at the moment. In this study, we show that the information derived from the movements of surface drifters, which track ocean currents, may help fill this gap. This is demonstrated with global ocean numerical models, which are now able to represent high-frequency variability associated with tides, winds and eddies, and are therefore powerful tools to evaluate ocean multi-scale variability. We compare here fixed-point (i.e., "Eulerian") and along-flow (i.e., "Lagrangian" or drifter) kinetic energy estimates. Our results show that these two different perspectives can be reconciled in the estimation of energy levels, as long as adequate frequency bandwidths are chosen. However, the Lagrangian frame of reference can induce distortions of rapid motion signals compared to the Eulerian frame of reference, particularly in regions where low-frequency kinetic energy is strong and drifter density is low. These findings have implications for the mapping of near-surface velocity climatology at high frequencies from drifter database.

## 1. Introduction

Ocean circulation controls the transport and distribution of physical properties and biochemical tracers across the global ocean. Ocean motions at horizontal scales smaller than several hundred kilometers and temporal scales shorter than months account for a dominant fraction of kinetic energy (KE; Ferrari & Wunsch, 2009). Its two main contributors are quasi-geostrophic balanced motions, which include mesoscale eddies (horizontal scales of 20–300 km, periods of weeks to months) and submesoscale motions (horizontal scales of 0.2–20 km, periods of hours to days), and unbalanced internal waves (horizontal scales <300 km and periods <1 day). Mesoscale eddies account for most of the global ocean KE and play a key role in the physical equilibrium and biogeochemical functioning of the ocean at climatic scales (McGillicuddy et al., 2007; McWilliams, 2008; Treguier et al., 2014). Submesoscale motions induce, on the other hand, a vigorous vertical circulation and determine the vertical exchanges of heat, carbon, and nutrients (Lévy et al., 2018; McWilliams, 2016; Taylor & Thompson, 2023). Internal waves are a major driver of turbulent mixing in the ocean, which is fundamentally important to the global overturning circulation (Whalen et al., 2020). Internal waves are commonly organized around frequency and exhibit energy peaks at tidal and near-inertial frequencies, with a continuous energy distribution across higher frequencies, commonly known as the internal wave continuum.

Provided sufficient information is available along spatial and temporal dimensions, one way of characterizing quasi-geostrophic balanced motions and unbalanced internal waves is to estimate the distribution of surface KE as function of spatial and temporal scales. For instance, Torres et al. (2018) examined the distribution of surface KE in wavenumber-frequency space from a high-resolution numerical simulation, and showed that lower-frequency motions emanate from larger scales and spread to finer spatial and temporal scales. The emergence of wide-swath altimetry and surface current measuring satellite missions has fostered efforts aiming at improving our understanding of oceanic variability down to O (10 km) and of its manifestation on satellite and in situ observations (Du et al., 2021; Morrow et al., 2019).

An emerging data set to proceed with in situ observational descriptions across scales is that of the Global Drifter Program (GDP; Elipot et al., 2016). With the development of satellite tracking systems, the GDP data set provides global velocity measurements at hourly resolution, enabling studies of ocean variability at high frequencies. GDP drifter data have been extensively used to achieve global and regional climatology of time-mean and mesoscale flows (Lumpkin, 2016; Lumpkin & Johnson, 2013). However, such mapping at high frequencies remains relatively understudied (e.g., Liu et al., 2019). Understanding and quantifying the differences inherent to Lagrangian sampling compared to the Eulerian frame of reference is crucial for accurately mapping high-frequency variance using the GDP data.

The theoretical relationship between Lagrangian and Eulerian statistics has been extensively studied. Corrsin (1959) proposed that the Lagrangian autocorrelation could be derived from the Eulerian spatial-temporal autocorrelation, provided the probability density function of particle displacements is known. This conjecture was further developed by assuming specific forms for the Eulerian energy spectrum (Middleton, 1985). Lumpkin et al. (2002) identified two distinct regimes to characterize the relationship between Lagrangian and Eulerian statistics: the frozen field and fixed float regimes. In the fixed float regime where the eddy energy is weak compared to the ratio of the Eulerian spatial scale of decorrelation to the temporal one, the Lagrangian and Eulerian time scales are nearly equal, and Lagrangian particles sample flow fluctuations in a manner analogous to a fixed mooring. Conversely, in the frozen field regime where the eddy energy is high, Lagrangian particles move rapidly from their initial positions, resulting in Lagrangian and Eulerian length scales that are approximately proportional. In any case, Lagrangian particles sample both spatial and temporal variability, resulting in shorter velocity decorrelation timescales and broader spectra (Davis, 1983; LaCasce, 2008; Lumpkin et al., 2002). More recently, Caspar-Cohen et al. (2022) employed idealized numerical simulations to compare the Lagrangian and Eulerian surface current signatures of a low-mode semidiurnal internal tide. They demonstrated that the displacement of surface drifters could distort low-mode internal tide signals, leading to broader spectral peaks, a phenomenon they termed apparent incoherence (i.e., not phase-locked with the tidal forcing). However, similar analyses over a broader frequency range and/or in a more realistic configuration are still lacking.

Global ocean numerical models are now able to represent high-frequency variability associated with tides, winds, and eddies, making them powerful tools for evaluating ocean multi-scale variability. Yu et al. (2019) compared velocity frequency spectra estimated from GDP drifter data (i.e., Lagrangian) and outputs from a high-resolution Massachusetts Institute of Technology general circulation model (MITgcm) simulation (i.e., Eulerian). They found deficits of low-frequency energy near the equator (by a factor of 2) and of near-inertial energy (by a factor of 3), along with an excess of semidiurnal frequency energy (by a factor of 4) in the model. Arbic et al. (2022) performed a similar, yet more detailed, comparison based on Yu et al. (2019) data sets and an additional global tide-resolving simulation of the HYbrid Coordinate Ocean Model (HYCOM). In global maps and zonal averages, numerical models captured low-frequency and high-frequency variance qualitatively. The HYCOM simulation, with more frequently updated wind forcing and a more finely tuned implementation of tidal variability, was closer to GDP drifter values than the MITgcm simulation. However, biases in global ocean models when comparing Eulerian and Lagrangian spectra and band-integrated energy levels can be introduced by several factors, such as

Lagrangian sampling by drifters and inadequate model settings. Both models in Arbic et al. (2022) still suffered from weak low-frequency equatorial flows, weak near-inertial motions in the northern midlatitudes to high latitudes, and large semidiurnal KE in the high-latitude North Pacific. Given the inherent differences between model simulations and drifter observations, both studies questioned the equivalence of KE estimates from Eulerian and Lagrangian frames of reference, which remains to be conclusively demonstrated.

In this work, we compare Lagrangian and Eulerian spectral decompositions of surface KE on a global scale, with the aid of output from a realistic high-resolution ocean numerical model (LLC4320 simulation; Yu et al., 2019). A central objective is to assess the agreement of kinetic energy estimates derived from Lagrangian and Eulerian frames of reference. The paper is organized as follows. Section 2 describes the LLC4320 simulation, the Lagrangian numerical simulation experiments, and the methods of spectral analysis and energy level estimation. Comparisons between Eulerian and Lagrangian KE fields are described in Section 3. Discussions and conclusions are presented in Sections 4 and 5, respectively.

## 2. Materials and Methods

### 2.1. LLC4320 Simulation

The LLC4320 simulation was performed using MITgcm (Marshall et al., 1997) on a global Latitude-Longitude-polar Cap (LLC) grid (Forget et al., 2015) for a period of 14 months between 10 September 2011 and 15 November 2012. The model has a horizontal grid spacing of 1/48° (approximately 2.3 km at the equator and 0.75 km in the Southern Ocean), and thereby resolves mesoscale eddies and permits submesoscale variability. The model time step was 25 s, and variables were stored at hourly intervals. The model was forced by 6-hourly surface flux fields (including 10-m wind velocity, 2-m air temperature and humidity, downwelling long- and short-wave radiation, and atmospheric pressure load) from the European Center for Medium-Range Weather Forecasts (ECMWF) operational reanalysis, and included the full lunisolar tidal constituents that are applied as additional external forcing. The LLC4320 uses a flux-limited monotonicity-preserving (seventh-order) advection scheme, and the modified Leith scheme of Fox-Kemper and Menemenlis (2008) for horizontal viscosity. The K-profile parameterization (Large et al., 1994) is employed for vertical viscosity and diffusivity. In this study, we use a yearlong record of the instantaneous surface fields at every hour, starting on 15 November 2011.

### 2.2. Lagrangian Experiments

Lagrangian simulations are performed with LLC4320 hourly surface velocity outputs using the 'Parcels' Python package (Lange & Van Sebille, 2017). Surface virtual drifters are initially released every 50 grid points of the LLC4320 grid (about 40–100 km spacing), and drifter positions and velocity fields are stored at hourly rate. The Lagrangian simulation lasts about one year, from 15 November 2011–9 November 2012. Virtual drifters are released every 10 days at the initial release positions if no drifter is present within a radius equal to the distance to the closest neighbor at the initial release. This continuous seeding enables to maintain a continuous coverage throughout the Lagrangian simulation. The number of virtual drifters is of about 60,000 at the start, and increases to about 95,000 drifters at the end of the simulation. The interpolation scheme employed in the Lagrangian simulation utilizes a fourth-order Runge-Kutta method in time (Delandmeter & Van Sebille, 2019). The Lagrangian particles (i.e., virtual drifters) are scattered throughout the open ocean worldwide (Figure 1; also see Movie S1), and their spatial distribution is broadly in line with that of GDP drifters over the global ocean albeit with an instantaneous drifter density larger by about two orders of magnitude (Elipot et al., 2016; Yu et al., 2019). Consistent with the inhomogeneous distribution of GDP drifters, heavily sampled regions are concentrated in flow convergence zones (e.g., the interior of subtropical gyres). In contrast, areas of flow divergence (e.g., the equatorial region, upwelling areas) as well as polar and coastal regions are generally less sampled. As a result, the number of 60-day particle trajectory segments at midlatitudes (30°-60°N and S) is at least a factor of 2 larger than that in the equatorial region (10°S-10°N).

### 2.3. Frequency Rotary Spectrum

For Eulerian estimates, rotary spectra of horizontal velocity are computed at each model grid point using hourly surface horizontal velocity time series. For Lagrangian estimates, rotary spectra are derived from horizontal velocities along particle trajectories. For both data sets, we first divide velocity time series into segments of 60 days overlapping by 50% and linearly detrend over each segment, and then compute the 1D discrete Fourier

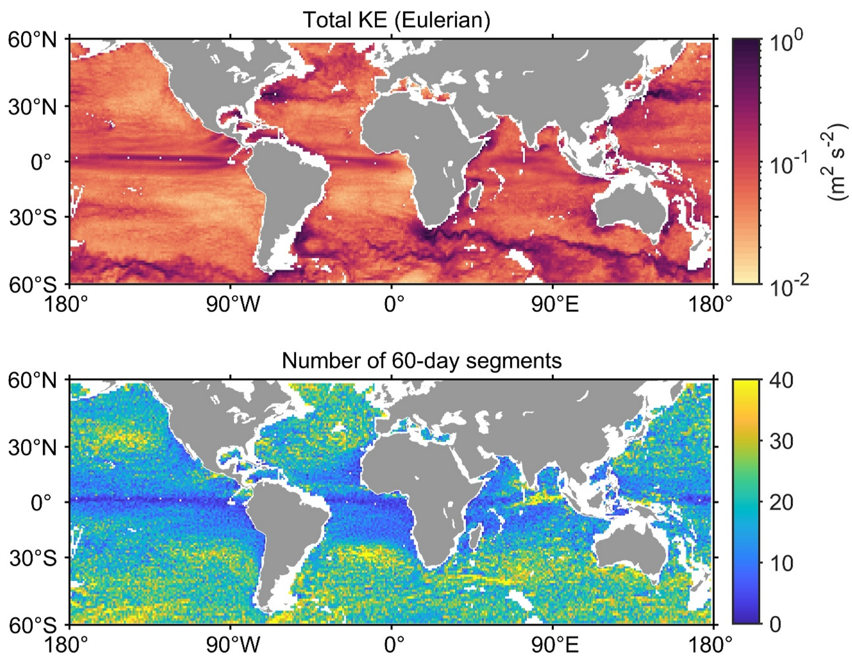


**Figure 1.** (a) Global map of Eulerian total KE at the surface layer in 1° × 1° bins. (b) Distribution of the number of 60-day Lagrangian trajectory segments over the global ocean in 1° × 1° bins.

transform of complex-valued fields ($u + iv$, where $u$ and $v$ are zonal and meridional velocity, respectively) multiplied by a Hanning window. Spectra are formed by multiplying Fourier amplitudes by their complex conjugates and averaged over time for Eulerian estimates and according to segment mean drifter's latitudes and longitudes for Lagrangian estimates (Figure 1b). Due to the geographical distribution of particle trajectories, velocity data in polar regions with latitude higher than 60° and in coastal waters with depth shallower than 500 m are excluded from the calculations for both data sets.

To achieve a balance between drifter density and spatial variability of bin-averaged diagnostics, a bin size of 1° latitude is used to compare Eulerian and Lagrangian zonally averaged rotary spectra and associated band integrals. For global maps, band-integrated KE estimates are averaged in 1° × 1° spatial bins. Finally, following Arbic et al. (2022), we compute the ratio of Lagrangian KE to the sum of Lagrangian and Eulerian KE. Note that a ratio of 0.5 indicates equality between Lagrangian KE and Eulerian KE, a ratio exceeding 0.5 indicates Lagrangian KE overestimates Eulerian KE, and a ratio below 0.5 indicates Lagrangian KE underestimates Eulerian KE.

## 3. Results

### 3.1. Zonally Averaged Spectrum and KE

Lagrangian and Eulerian zonally averaged spectra both show expected peaks at low, near-inertial and tidal frequencies (Figures 2a and 2b). Along with Figures 2c and 2d, Lagrangian spectral peaks appear to be systematically broader and weaker than Eulerian ones, indicating a spreading of energy in the Lagrangian perspective. This spreading is evident around the main tidal peaks and increases with frequency such that Lagrangian higher frequency tidal constituents (e.g., 3 cpd, 4 cpd, …) are hardly noticeable unlike Eulerian ones. The ratio of Lagrangian to Eulerian spectra consistently indicates that Lagrangian peak values at tidal frequencies are lower but wider than Eulerian ones (Figure 2c). This finding aligns with Zaron and Elipot (2021), who noted that the drifter tidal peaks do not stand out above the background spectrum as strongly as in tide model predictions. Caspar-Cohen et al. (2022) consistently demonstrated that the distortion of tidal internal waves induced by surface drifter motions, a process coined as apparent incoherence, leads to broader tidal peaks.

At near-inertial frequencies, the smoothing of the peak is not visible in latitude-dependent spectra (Figures 2a and 2b), and the ratio of Lagrangian to Eulerian spectra indicates values close to unity (Figure 2c). This suggests that

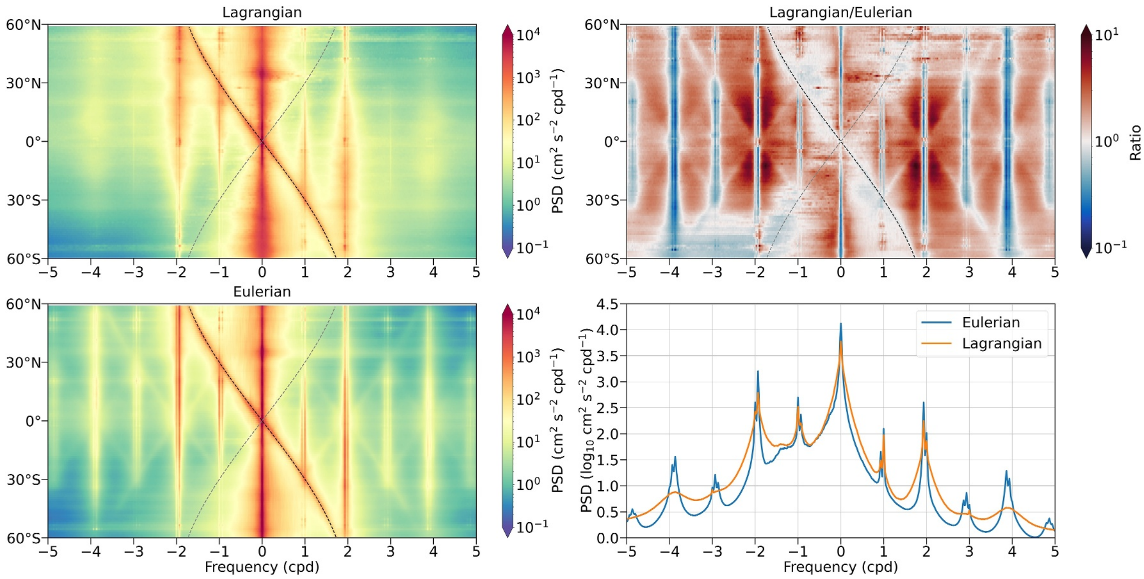


**Figure 2.** Zonally averaged rotary frequency spectra in 1° latitude bins from (a) Lagrangian and (b) Eulerian horizontal velocity fields at the surface layer and (c) their ratio, with positive (negative) frequencies corresponding to counterclockwise (clockwise) rotating motions, which are cyclonic (anticyclonic) in the Northern Hemisphere. The cyclonic inertial frequency ($f/2\pi$ cpd) is indicated by the gray dashed line and the anticyclonic inertial frequency ($-f/2\pi$ cpd) is indicated by the black dashed line. (d) Globally averaged anticyclonic (at negative frequencies) and cyclonic (at positive frequencies) spectra of the Eulerian (blue) and Lagrangian (orange) horizontal velocity fields.

drifter displacements do not distort the signature of near-inertial waves similarly to internal tides, in line with findings from Shakespeare et al. (2021). Another obvious contrast is that energy levels at the anticyclonic frequencies are substantially higher than those at the cyclonic frequencies, particularly below the semidiurnal frequency band (Figure 2d). This conforms to expectations from the natural polarization of internal gravity waves which leads to a ratio between anticyclonic and cyclonic kinetic energies that scales as $(\omega + f)^2/(\omega - f)^2$ (Gill, 1982; van Haren, 2003), where $\omega$ is the frequency, and is consistent with the observational findings of elevated near-inertial KE in the anticyclonic domain (Elipot et al., 2010; Vic et al., 2021; Yu et al., 2022).

Rotary frequency spectral densities are integrated over four frequency bands to compute KE components of interest, including high-frequency (>0.5 cpd, absolute values here and hereinafter), semidiurnal, near-inertial, and diurnal bands. Total KE is estimated from temporal averages of instantaneous velocity fields, and low-frequency KE is computed as total KE minus high-frequency KE. We examine the sensitivity of the regression coefficient and root mean square error between Eulerian and Lagrangian semidiurnal, near-inertial and diurnal KE levels to different frequency bandwidths of integration, in regions between 60°S and 60°N (Figure 3). For semidiurnal band, the closest match between Eulerian and Lagrangian energy levels is achieved for the ±0.3 cpd bandwidth

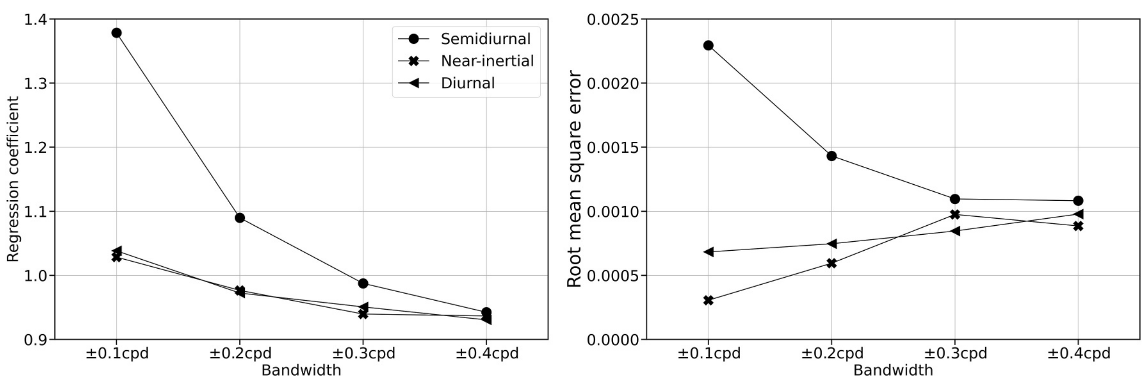


**Figure 3.** The (a) regression coefficient and (b) root mean square error ($m^2\ s^{-2}$) between Lagrangian and Eulerian semidiurnal, near-inertial and diurnal KE as a function of bandwidths of ±0.1 cpd, ±0.2 cpd, ±0.3 cpd, ±0.4 cpd.

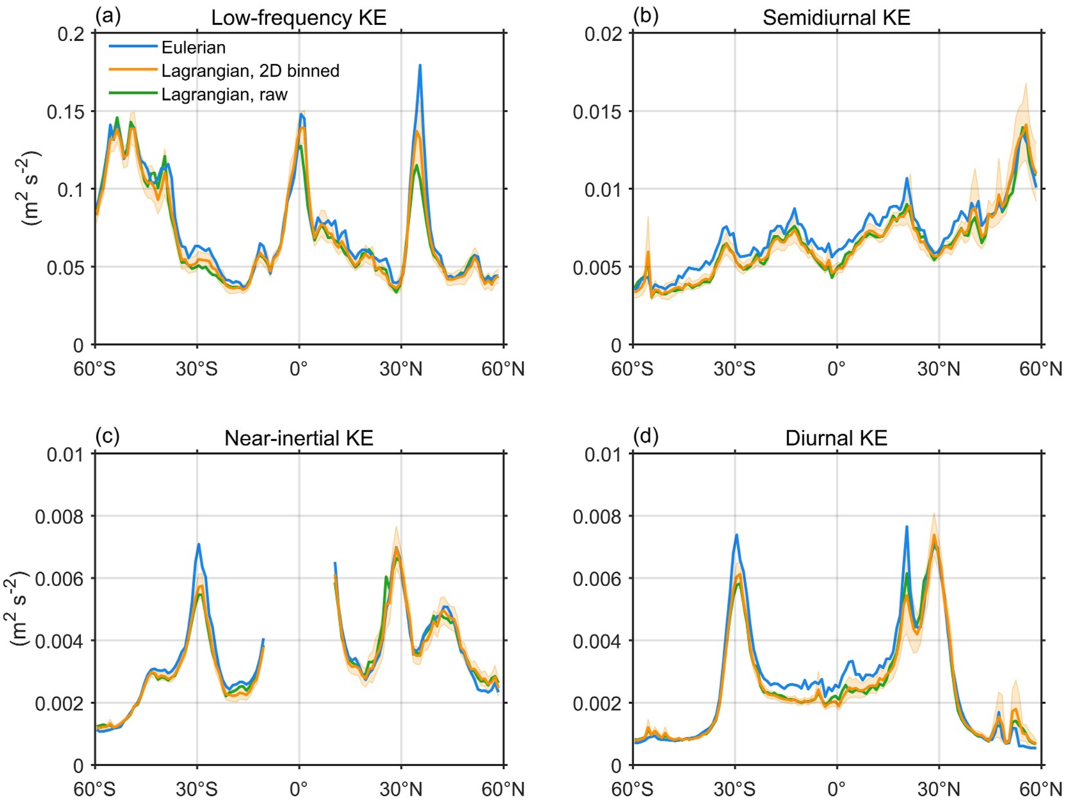


**Figure 4.** Zonally averaged (a) low-frequency, (b) semidiurnal, (c) near-inertial and (d) diurnal KE in 1° latitude bins estimated from Eulerian velocity field (blue) and Lagrangian particle trajectories with (orange) and without (green) binning. The colored shading shows the 95% confidence interval determined using a bootstrapping resampling approach.

with a regression coefficient value closest to unity and a root mean square error plateauing at approximately $10^{-3}$ $m^2$ $s^{-2}$ (equivalent to 15.6% of the averaged Eulerian semidiurnal energy level). In contrast, for diurnal and near-inertial bands, the narrowest bandwidth (i.e., ±0.1 cpd) yields the best comparison based on the two metrics. Consequently, the semidiurnal, near-inertial, and diurnal bands are respectively defined as 1.7–2.3 cpd, 0.9–1.1$f$ and 0.9–1.1 cpd, where $f$ is the Coriolis frequency.

Zonally averaged low-frequency, semidiurnal, near-inertial, and diurnal KE estimated from Eulerian velocity field and Lagrangian particle trajectories with ("2D binned") and without ("raw") spatial binning are displayed in Figure 4. In other words, the Lagrangian diagnostics estimated from inhomogeneously distributed particle segments (see Figure 1b) are denoted as "raw" (in green), and the Lagrangian diagnostics first averaged in 1° × 1° spatial bins are denoted as "2D binned" (in orange). The overall trends of the Eulerian and Lagrangian (with and without binning) estimates show good visual similarities. Raw Lagrangian estimates tend to underestimate KE compared to 2D binned Lagrangian estimates, particularly at low-frequency energy peaks. Low-frequency energy peaks near the equator, at 35°N and 55°S at the locations of Northern Hemisphere western boundary currents and the Antarctic Circumpolar Current respectively (Figure 4a). At 35°N, Lagrangian energies underestimate Eulerian ones, which will be argued to partly result from the unequal sampling of high versus low energy regions (Davis, 1985) and may be mitigated with alternative geographical binning (see Discussion section). Lagrangian zonally averaged semidiurnal KE is slightly lower than Eulerian KE at almost all low and mid-latitudes (Figure 4b). In contrast, Lagrangian zonally averaged near-inertial KE follow Eulerian estimates relatively well over most latitudes, except for a clear underestimation near 30°S, where the local inertial frequency coincides with diurnal frequencies (Figure 4c). For the diurnal KE, discrepancies are relatively larger, with a 15.4% difference in average (Figure 4d), compared to low-frequency (7%), semidiurnal (11.1%), and near-inertial (6.7%) bands. There are two substantial mismatches between Eulerian and Lagrangian diurnal KE, one is in 20°N, which may be related to the lower number of Lagrangian particles in the Luzon strait, and one is in 30°S, in line with the underestimation in near-inertial KE.

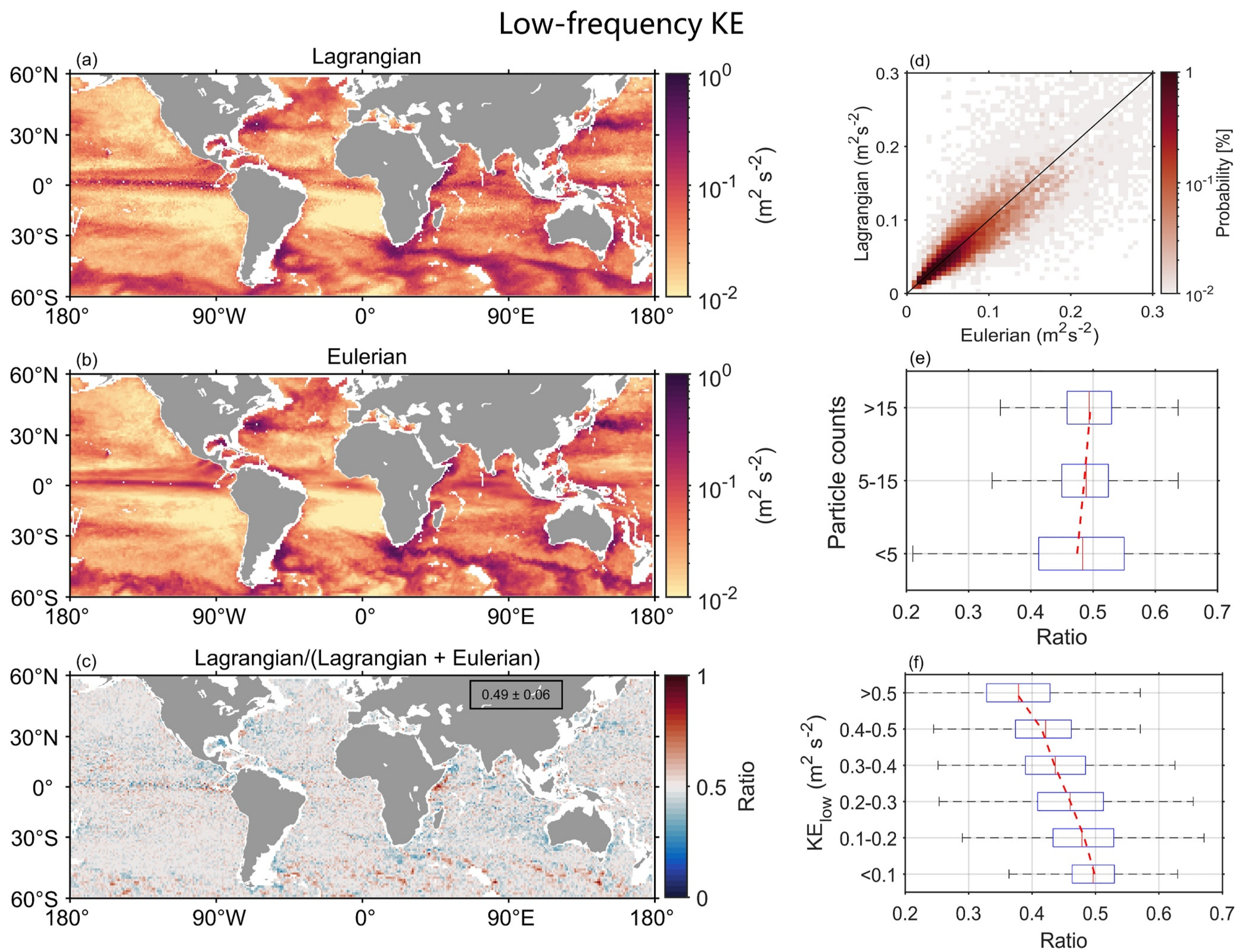


**Figure 5.** (a–c) Global maps of Lagrangian and Eulerian low-frequency KE at the surface layer and the ratio of Lagrangian KE/(Lagrangian KE + Eulerian KE) in 1° × 1° bins. Mean value and one standard deviation of the ratio are given in the black box in (c). (d) Joint plot of the comparison between Lagrangian and Eulerian low-frequency KE levels. (e) Box plot of the ratio under different ranges of particle counts per bin. (f) Box plot of the ratio under different ranges of low-frequency KE. The dashed red lines in (e) and (f) indicate the conditional means of the ratio.

### 3.2. Low-Frequency KE Maps

Global maps of low-frequency KE highlight prominent large-scale currents and energetic areas, including equatorial and western boundary currents such as the Gulf Stream and the Antarctic Circumpolar Current (Figures 5a and 5b). Low-frequency KE dominates total energy and therefore mimics total KE variations (cf. Figures 1a and 5a). Lagrangian and Eulerian low-frequency KE are generally in good agreement, with a mean value and standard deviation of the ratio of Lagrangian KE/(Lagrangian KE + Eulerian KE) about 0.49 and 0.07, respectively (Figures 5c and 5d). A noticeable difference is that Lagrangian estimates appear smoother than Eulerian ones around large-scale current features, which presumably results from the spatial advection of Lagrangian particle over the temporal window of energy integration.

We next examine the dependence of the ratio of Lagrangian KE/(Lagrangian KE + Eulerian KE) on two factors, Lagrangian particle counts per bin (i.e., drifter density) and the intensity of low-frequency KE. As the particle counts increases, the mean ratio gradually approaches 0.5, and the ratio range becomes more concentrated (Figure 5e). This suggests that Lagrangian KE tends to align more closely with Eulerian KE in regions where Lagrangian particles accumulate, indicating convergence of the flow. Furthermore, the ratio exhibits a more pronounced dependence on the intensity of low-frequency KE. In regions of strong low-frequency flow, the ratio is significantly reduced, with a mean value smaller than 0.4, indicating a substantial underestimation of low-

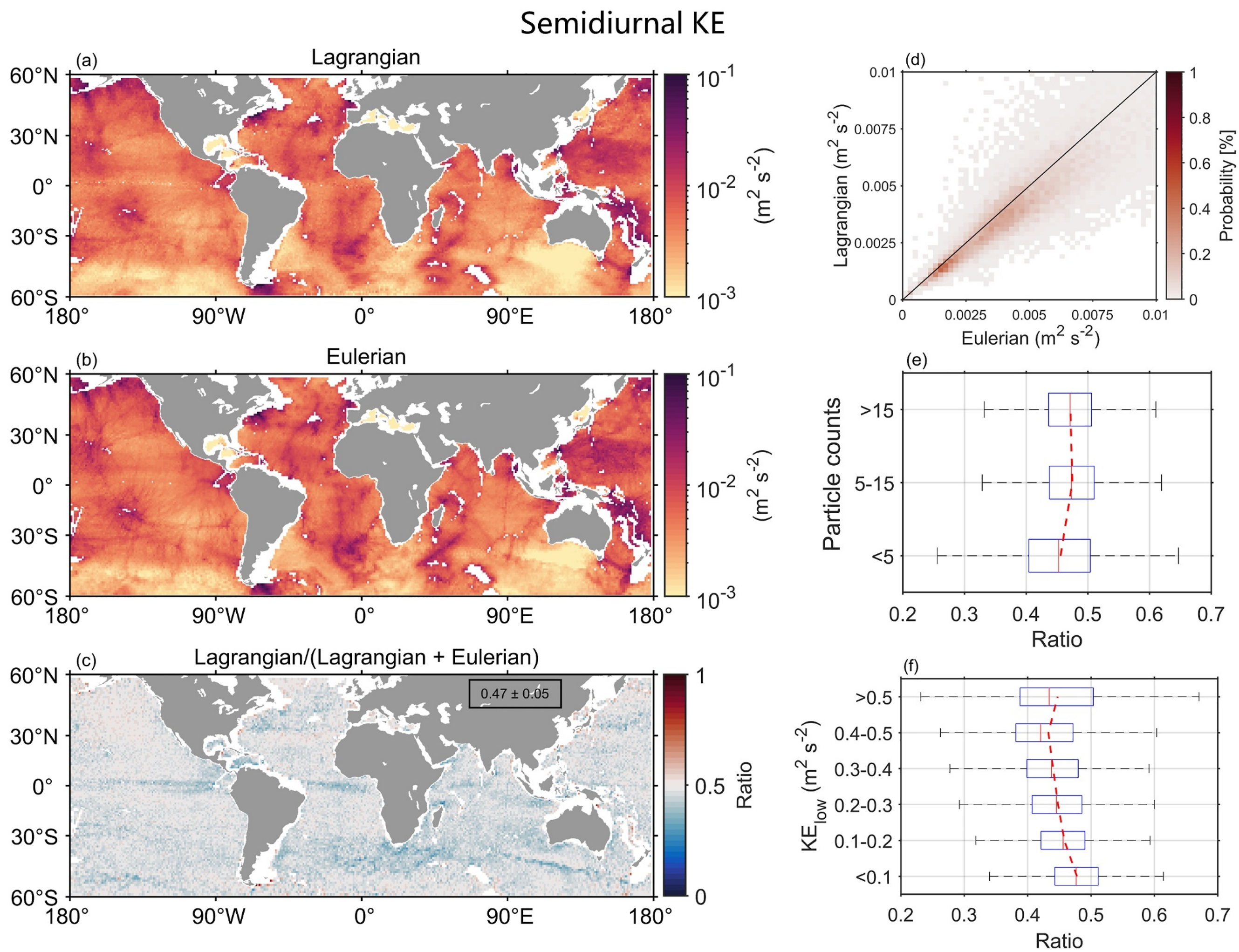


**Figure 6.** (a–c) Global maps of Lagrangian and Eulerian semidiurnal KE at the surface layer and the ratio of Lagrangian KE/(Lagrangian KE + Eulerian KE) in 1° × 1° bins. Mean value and one standard deviation of the ratio are given in the black box in (c). (d) Joint plot of the comparison between Lagrangian and Eulerian semidiurnal KE levels. (e) Box plot of the ratio under different ranges of particle counts per bin. (f) Box plot of the ratio under different ranges of low-frequency KE. The dashed red lines in (e) and (f) indicate the conditional means of the ratio.

frequency KE from a Lagrangian perspective (Figure 5f). This underestimation results from a larger projection of spatial variability onto temporal variability along particle trajectories in energetic regions (Caspar-Cohen et al., 2022; LaCasce, 2008). Indeed, near energetic current features, Lagrangian energy thus tends to underestimate Eulerian energy maxima in the core of these features (ratio below 0.5) and overestimate Eulerian energy on the surroundings (ratio above 0.5; Figure 5c).

### 3.3. Semidiurnal KE Maps

Semidiurnal, diurnal and near-inertial KE are all an order of magnitude smaller than low-frequency KE. The comparison between Lagrangian and Eulerian semidiurnal KE estimates show significant similarities globally (Figures 6a and 6b). Both clearly display hotspots of internal tide generation, for example, near Hawaiian Islands, the French Polynesian islands, the Aleutians island chain, 40°S and 40°N in the Atlantic as well as the western Pacific. The discrepancies at semidiurnal frequencies are relatively larger compared to low frequencies, with a mean energy ratio of 0.47 and standard deviation of 0.06. Figures 6c and 6d show that Lagrangian semidiurnal KE systematically underestimate Eulerian semidiurnal KE, particularly in the ocean's major current regions of high kinetic energy. Noticeable differences between Lagrangian and Eulerian estimates also occur near coastal areas, where the Lagrangian field may exhibit semidiurnal KE levels considerably larger than the Eulerian field. This

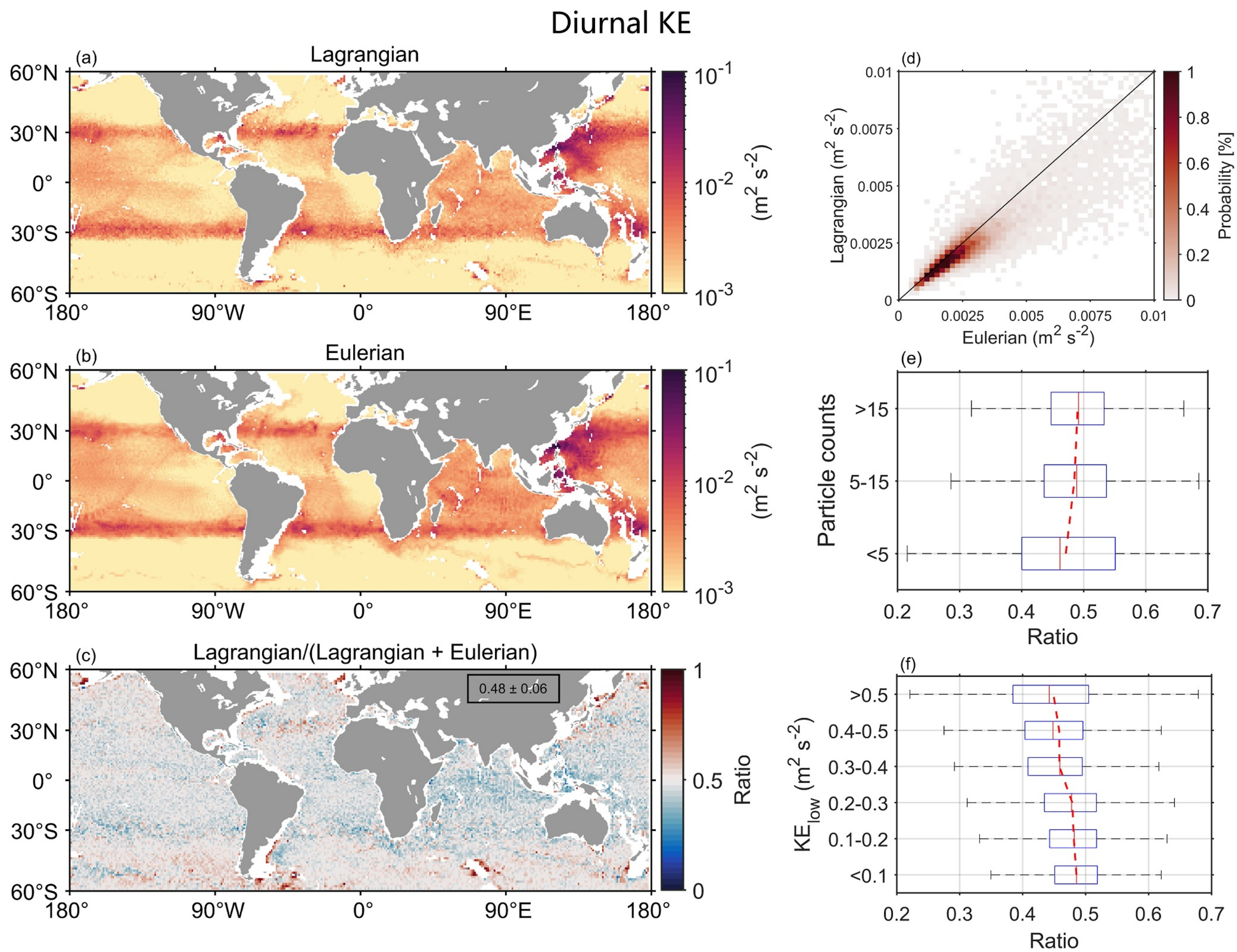


**Figure 7.** (a–c) Global maps of Lagrangian and Eulerian diurnal KE at the surface layer and the ratio of Lagrangian KE/(Lagrangian KE + Eulerian KE) in 1° × 1° bins. Mean value and one standard deviation of the ratio are given in the black box in (c). (d) Joint plot of the comparison between Lagrangian and Eulerian diurnal KE levels. (e) Box plot of the ratio under different ranges of counts of particle counts per bin. (f) Box plot of the ratio under different ranges of low-frequency KE. The dashed red lines in (e) and (f) indicate the conditional means of the ratio.

overestimate is likely to result from Lagrangian particles crossing continental shelves, where tidal currents are faster, over the 60-day window of energy integration.

Interestingly, for semidiurnal tides, the dependence of the ratio on drifter density is relatively weak, although there is a slight increase in the ratio toward 0.5 with increasing particle counts (Figure 6e). Instead, the ratio shows a clear decreasing and scattering trend as the low-frequency KE intensity increases (Figure 6f). That is, the ratio ranges from about 0.23 to 0.67 with a mean value somewhat smaller than 0.5 in areas of strong low-frequency KE, while the range of the ratio reduces to between 0.34 and 0.61 with a mean value closer to 0.5 in areas of weak low-frequency KE. This indicates that the bandwidth tuned based on a global criterion is likely not sufficient in areas of strong low-frequency KE to account for the smearing of the semidiurnal tidal spectral peak (Figure 2d).

### 3.4. Diurnal KE Maps

The global map of diurnal Lagrangian KE also closely reproduces the Eulerian KE visually (Figures 7a and 7b). The most prominent feature of diurnal KE is the enhancement around ±30° latitudes, where the diurnal wind-forcing (sea breeze) aligns with the local inertial frequency. Similar to the semidiurnal band, the Lagrangian field shows larger values than the Eulerian field in several coastal regions (Figure 7c). These coastal regions are mostly located outside 30°S and 30°N, where diurnal internal tides are not expected to freely propagate, indicating

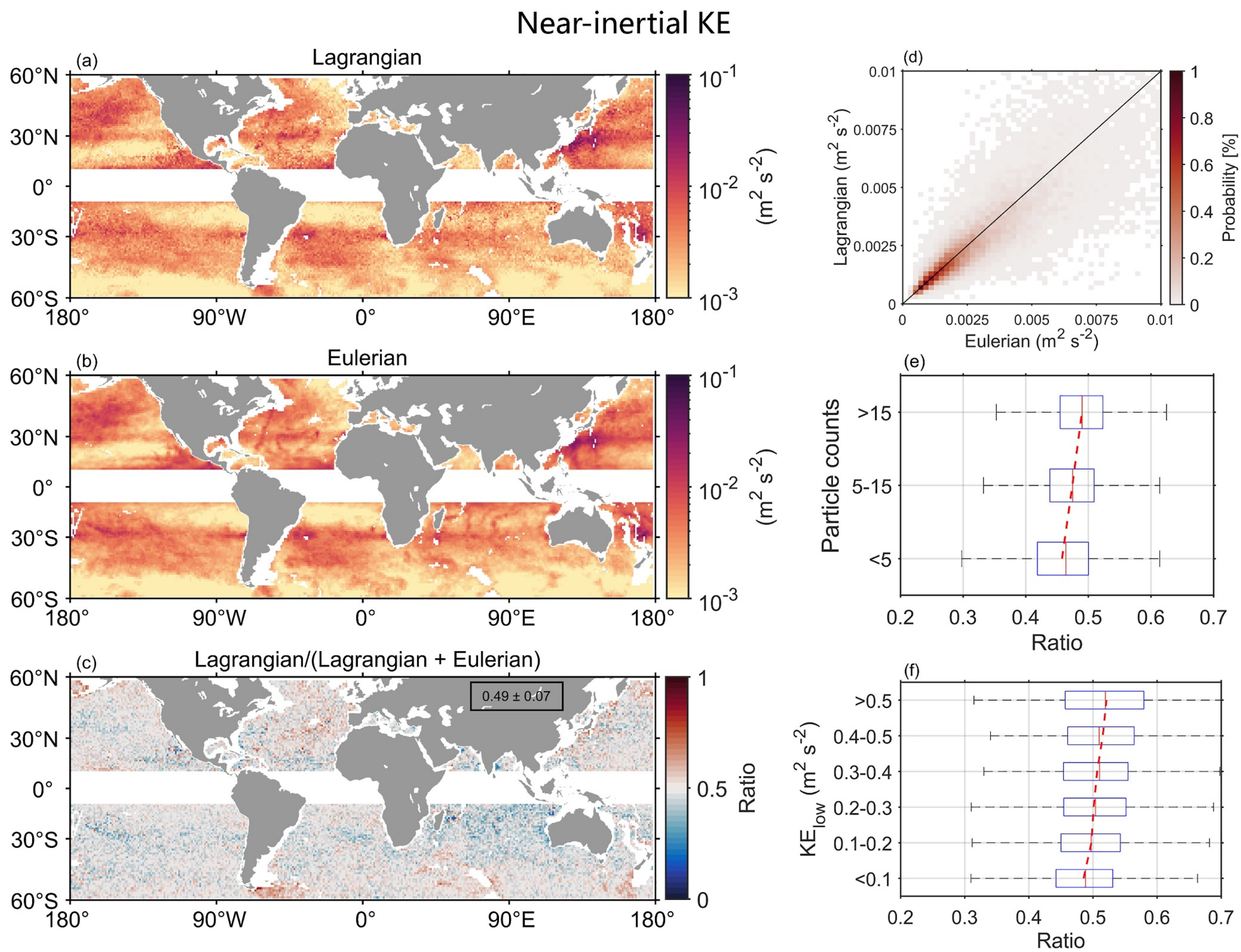


**Figure 8.** (a–c) Global maps of Lagrangian and Eulerian near-inertial KE at the surface layer and the ratio of Lagrangian KE/(Lagrangian KE + Eulerian KE) in 1° × 1° bins. Mean value and one standard deviation of the ratio are given in the black box in (c). (d) Joint plot of the comparison between Lagrangian and Eulerian near-inertial KE levels. (e) Box plot of the ratio under different ranges of particle counts per bin. (f) Box plot of the ratio under different ranges of low-frequency KE. The dashed red lines in (e) and (f) indicate the conditional means of the ratio.

that their differences may be caused by barotropic tides or trapped baroclinic tides. Over the global ocean, Lagrangian diurnal KE slightly underestimates Eulerian one (Figure 7d).

Similar to low-frequency motions, diurnal tides show a clear dependence on the drifter density and the intensity low-frequency KE (Figures 7e and 7f). For diurnal tides, the ratio of Lagrangian KE/(Lagrangian KE + Eulerian KE) gradually inclines toward 0.5 with an increase in Lagrangian particle counts and becomes more concentrated around 0.5 as low-frequency KE decreases. In other words, Lagrangian diurnal KE matches Eulerian KE better in regions of weak and convergent flows, and tends to underestimate in regions of strong and divergent flows. This may explain the underestimation of Lagrangian diurnal KE in the Luzon Strait (approximately 20°N; Figure 4d), where the background flow is strong and divergent. Lastly, apparent incoherence is in general expected to be weaker at diurnal frequencies than at semidiurnal frequencies, due to the larger horizontal wavelength of diurnal tides (Caspar-Cohen et al., 2022).

### 3.5. Near-Inertial KE Maps

Lagrangian and Eulerian estimates of near-inertial KE show particularly similar spatial patterns across the global ocean (Figures 8a and 8b). Intensified near-inertial KE generally occurs at mid-latitudes, with the highest values concentrated in the North Pacific. This is broadly in line with storm-track regions and the spatial distribution of wind work (Alford, 2003). Expected enhancements also occur at ±30° latitudes where the local inertial frequency coincides with diurnal frequencies. Nearly meridionally oriented beams appear in the low to mid-latitudes and are particularly evident in the Eulerian field, likely associated with individual tropical cyclones and storms in the model forcing fields. The mean value and standard deviation of the energy ratio are 0.49 and 0.07, respectively (Figure 8c). Differences between Eulerian and Lagrangian near-inertial KE are modest in global maps compared to those within the semidiurnal and diurnal bands. This is also reflected in Figure 8d, where Eulerian and Lagrangian near-inertial KE closely follow a 1-to-1 relationship. Nonetheless, Lagrangian energy slightly underestimates near-inertial KE over open ocean regions in the Southern Hemisphere, around 30°S. It is probably related to the influence of diurnal bands and a change in the nature of motions (larger contribution from internal tides for instance).

Similar to low-frequency and tidal motions, the ratio of Lagrangian KE/(Lagrangian KE + Eulerian KE) in the near-inertial band also shows a dependence on drifter density (Figure 8e). As the number of Lagrangian particles increases, the mean ratio approaches 0.5, and the range of values narrows around this mean. However, there is no apparent association between the ratio and the intensity of low-frequency KE (Figure 8f).

## 4. Discussion

In previous studies, ocean surface KE in high-resolution global simulations has been compared with KE from GDP surface drifters (Arbic et al., 2022; Yu et al., 2019). These model-drifter comparisons showed good qualitative agreement over a wide range of frequency bands but systematic discrepancies were also observed. The pending question is whether these discrepancies could be attributed to Lagrangian/Eulerian biases or are mainly caused by the numerical simulations, such as the deficit of high-frequency wind forcing. Here, we find that the difference between Lagrangian and Eulerian KE levels in LLC4320 is significantly lower than the one observed in model-drifter analysis. Similar to the comparison between LLC4320 and GDP drifters, a deficit of low-frequency energy within the equatorial region was observed, with peak energy values reaching 0.15 $m^2 s^{-2}$ for the model and 0.34 $m^2 s^{-2}$ for GDP drifters (Yu et al., 2019). This difference, approximately 0.2 $m^2 s^{-2}$, is an order of magnitude larger than the Lagrangian-Eulerian difference near the equator, which is of order 0.01 $m^2 s^{-2}$ as shown in Figure 4a. Moreover, Yu et al. (2019) reported that the LLC4320 simulation exhibits KE four times higher in the semidiurnal band and three times lower in the near-inertial band compared with GDP drifter data. However, the global mean ratios of Lagrangian KE to Lagrangian KE + Eulerian KE obtained in this study are 0.47 ± 0.06 for the semidiurnal band (Figures 6c) and 0.49 ± 0.07 for the near-inertial band (Figure 8c), both of which are close to 0.5. This means that, on average, Lagrangian KE is nearly equal to Eulerian KE for the semidiurnal and near-inertial bands in the LLC4320 simulation. Therefore, our results suggest that Lagrangian/Eulerian biases are unlikely to be the primary factor in the model-drifter discrepancies. Instead, the influence of infrequent wind forcing and excessive tidal forcing in the LLC4320 simulation may be more significant.

Arbic et al. (2022) identified the sensitivity of the Lagrangian semidiurnal energy estimate to the bandwidth of integration, which the present study corroborates. This sensitivity arises from apparent incoherence which leads to a widening of the semidiurnal tidal peak (Caspar-Cohen et al., 2022). In this study, energy levels of Lagrangian and Eulerian estimate using different bandwidths are also compared (Figure S1 in Supporting Information S1). Lagrangian estimates are found to be more sensitive to bandwidth in comparison to Eulerian ones. Note that a larger bandwidth may include signals of other motions. Therefore, we chose a conservative bandwidth based on two metrics (regression coefficient and root mean square error), and a fixed range (e.g., 1.7–2.3 cpd for the semidiurnal band) for the bandwidth of integration that produced the best match between Lagrangian and Eulerian energy estimates was chosen in the present study. However, the bandwidth of integration may not be the same for Eulerian and Lagrangian energy diagnostics. Limiting bandwidth may be desirable in order to mitigate contamination from the background energy spectrum. Given the sharper shape of Eulerian semidiurnal peaks, smaller bandwidths may be afforded for Eulerian diagnostics. The width of Eulerian semidiurnal peaks is related to internal tide incoherent timescales, whose geographical variations may lead to geographically varying choices for the bandwidth of integration of Eulerian energy. Caspar-Cohen et al. (2022) theoretically predicted that the intensity of apparent incoherence and the associated widening of the Lagrangian spectrum depend on parameters that may vary geographically, such as the low-frequency energy level and decorrelation timescale or internal tide properties (wavenumber, incoherent timescale). The bandwidth of integration of Lagrangian estimates may thus be modulated geographically to mitigate contamination from the background energy spectrum. Such advanced choices for the bandwidth of energy integration would be good material for future studies, although the present study indicates this would be most relevant for the semidiurnal band, which exhibits the most sensitivity to integration bandwidth.

Lagrangian low-frequency KE estimates considerably underestimate Eulerian ones in energetic regions (Figures 4a and 5f), likely due to the preferential sampling of weak-energy regions by Lagrangian particles (Freeland et al., 1975). The deficit caused by the inhomogeneous sampling of Lagrangian particles, which can be as high as 20% in KE levels, can be mitigated by averaging Lagrangian diagnostics into longitude/latitude bins. We recommend geographically binning energy estimates prior to integration over larger domains (e.g., zonally or globally) to reduce such sampling biases. However, it should be noted that along a similar line but at the bin level, the combination of spatio-temporal inhomogeneities and energy variability within individual bins may also lead to systematic differences between Eulerian and Lagrangian estimates (Davis, 1991), such as those observed nearby large current systems. The role of such sampling bias in explaining observed differences has not been investigated here but could constitute an interesting follow up study.

The length of the time window utilized for the computation of Fourier transforms directly influences both the traveling distance of particles and spectral resolution. Here, we chose a 60-day time window for spectral decompositions and energy estimates, which results in spatial smoothing in Lagrangian estimates compared to Eulerian estimates (cf. panels a and b in Figures 5–8). To assess the impact of the time window on our estimates, we also examined shorter (e.g., 30-day) and longer (e.g., 90-day) segments. No significant differences were found in rotary frequency spectra, zonal averages, and global maps of KE (see Figures S2–S7 in Supporting Information S1). However, the 90-day segment displayed relatively larger differences and more missing data in Lagrangian maps (Figures S4–S7 in Supporting Information S1, right panels). Overall, the 60-day time window provides a satisfactory balance between particle density and flow variability.

Lastly, the distance between particles released every 50 grids ranges from approximately 40 to 100 km. Reducing this separation and thereby increasing the number of particles in the Lagrangian simulation would have minimized statistical noise. However, given the absence of substantial noise in our diagnostics and the increased computational cost associated with a higher number of particles, we did not attempt to decrease the particle separation. The number of GDP drifters has reached about 19,400 since the early 2000s, which is fewer than the number of particles used in this work. It would be insightful to quantify the uncertainty and decreased spatial resolution introduced when the number of drifters is reduced toward more realistic drifter densities. Such information would help understand the extent to which climatologies of high-frequency surface motions based on GDP drifters can be temporally resolved.

## 5. Summary

In this study, we quantify the relationship between Eulerian and Lagrangian KE spectral content and its geographical variability based on a novel twin global numerical simulation experiment. A practical objective is to assess the extent to which Lagrangian particles can estimate Eulerian KE levels, especially at high frequencies. To achieve this, we compared the surface KE estimated using the LLC4320 global ocean model, and the Lagrangian simulations performed by the LLC4320 hourly surface velocity output. Our main findings are summarized as follows.

1. Eulerian and Lagrangian KE exhibit broad qualitative similarities, characterized by the dominance of low-frequency motions and the presence of distinct spectral peaks at semidiurnal, near-inertial, and diurnal frequencies. A common feature among all dominant frequency bands is that Lagrangian spectra appear smoothed compared to Eulerian ones. This smoothing is least pronounced in the near-inertial band and most pronounced in the semidiurnal and low-frequency bands. At low frequencies, this smoothing is attributed to the simultaneous sampling of spatial and temporal variability by particles and the associated decrease in the decorrelation timescale (LaCasce, 2008; Middleton, 1985). The widening of the semidiurnal peak is consistent with the mechanism of apparent incoherence (Caspar-Cohen et al., 2022). The relatively minor difference between the Lagrangian and Eulerian near-inertial frequency peaks requires further investigation.
2. With a tuned choice of bandwidth of integration, good agreements for semidiurnal (1.7–2.3 cpd), near-inertial (0.9–1.1$f$) and diurnal (0.9–1.1 cpd) KE can be achieved between Eulerian and Lagrangian simulations. This indicates that Lagrangian particles advected by Eulerian field can qualitatively reproduce the original Eulerian high-frequency variance. Compared to Eulerian estimates, Lagrangian estimates are more sensitive to bandwidth, as expected from their character of broadened spectral peaks. Particularly, Lagrangian semidiurnal tides

are featured with a wider bandwidth than other high-frequency motions. We have identified avenues to refine further this choice of bandwidth of integration.

3. The intensity of low-frequency motions affects Lagrangian KE estimates at low and tidal frequencies. The lowest Lagrangian to Eulerian energy ratio is observed in energetic and turbulent areas. Conversely, Lagrangian KE in near-inertial band has no clear connection with low-frequency KE. Across all frequency bands, Lagrangian and Eulerian KE levels show better agreement in regions of convergent flows, where Lagrangian particles tend to accumulate, compared to regions of divergent flows, where particles are dispersed.

Our numerical results confirm that drifter data may provide an estimate of high-frequency variance, such as tidal and near-inertial motions. However, it is important to note that this finding is based on a number of particles much higher than that of GDP drifters. Given the coarse spatial resolution and extended time span of GDP drifters, mapping high-frequency surface energy from drifter velocity measurements requires further effort. Additionally, differences between drifter and model outputs, as shown in Yu et al. (2019) and Arbic et al. (2022), are not mainly caused by the Lagrangian versus Eulerian sampling nature. This work may motivate future studies on particular aspects of the model-observation and model-model discrepancies, and is a substantial step toward the production of high frequency KE climatologies.

## Data Availability Statement

MITgcm LLC4320 simulation output is available at https://data.nas.nasa.gov/ecco/data.php (Forget et al., 2015). The code for Parcels is licensed under the MIT licence and is available through GitHub via https://www.github.com/OceanParcels/parcels (Lange & Van Sebille, 2017).

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